FOURTH EDITION

4

FLEXIBLE CIRCUIT TECHNOLOGY

JOSEPH FJELSTAD

About the Author

Joseph Fjelstad, founder and president of Verdant Electronics, is a 40-year veteran of the electronics interconnection industry and a serial entrepreneur. He is also a prodigious inventor (250+ issued or pending patents), author, industry magazine columnist, commentator, lecturer and keynote speaker. He has received numerous awards and recognitions for his contributions to the electronics interconnection and packaging industries.

Joseph Fjelstad is the original author of *Flexible Circuit Technology* and the author or co-author of several chapters in the 4th edition.

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Flexible Circuit Technology

Fourth Edition

by

Joseph Fjelstad

Dedicated to the memory of
Werner Engelmaier, Mr. Reliability

Flexible Circuit Technology

Fourth Edition

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Foreword

Flexible Circuit Technology, 4th Edition is updated and significantly expanded over the previous editions. The demand that inspired this edition is evidence that flexible circuits are of continuing value and enduring interest. The opening sentence to the first edition stated: "The flexible circuit has been at the head of a quiet revolution in the world of electronic packaging, a revolution that has gone largely unnoticed, lost in the excitement of continued advances in semiconductor technology." Much has changed in the almost 15 years since those words were first written. Flexible circuit technology is now squarely in the sights of circuit designers around the globe and, even with the bursting of the dot com bubble and the 2009 market crash, it has held fast. In fact, the flex circuit market actually grew while other interconnection technology markets receded.

Flexible circuits are now a key enabling technology for products ranging from simple consumer goods to spacecraft. They are critical elements in such diverse products as medical equipment, keyboards, hard disk drives, printers and cellular phones. Every day, flexible circuit technology creates new opportunities for engineers and product and system designers to make a complete transition to the third dimension of interconnection. Short of wireless interconnections, flexible circuits continue to provide the very best and most practical solutions to interconnecting electronic elements that must move relative to each other. These two important features — motion and three-dimensional interconnection — remain at the top of the list of key attributes of flexible circuits. However, there is much more on the horizon and more to come in the future. Flexible circuit technology is now opening new doors to the realm of high speed in the budding era of higher performance at reduced power, redefining and reshaping our collective thoughts and ideas as to what is possible.

While there is no universal solution in the world of electronic interconnections, the solutions provided by flexible circuits come closer than all others. The diverse possibilities for flex

circuit applications remain bound more by the limits of the engineer's imagination than by any other single factor. Flexible circuit technology requires a good foundation of understanding in order to gain the greatest benefit from its use. Materials and processes must be understood and design rules followed to achieve consistent success. Thus, the purpose of the authors in this edition of Flexible Circuit Technology remains unchanged from the first edition—that is, to provide a solid foundation on which practitioners can build their skills and understanding.

Flexible Circuit Technology, 4th Edition is significantly expanded over earlier editions with additional chapters and content contributed by some of the industry's best technologists, bringing to attention to the continuing advances in technology and providing more in-depth and detailed information than before. While more complete than earlier editions, this effort is not an exhaustive treatise of the subject. Indeed, with a technology that moves as rapidly as flex circuit technology, the best we can hope to do is to write about the state of the technology up to the moment of publication, after which time the text begins to drift into technology history. Nevertheless, we believe this book is properly comprehensive and provides an engaging introduction to the world of flexible circuitry.

As with previous editions, we recommend having access to the various design standards and specifications described and referenced in this text to have a complete flex circuit reference library. In addition, many flex circuit suppliers have design guides specific to their processing capabilities that will prove of value. These additional materials will fill any gaps that may exist in this book. If you are new to flexible circuits, you will no doubt find the field a rewarding one. We enthusiastically invite you to send your comments on any of the topics covered and suggestions as to how the book might be improved in future editions. Please send comments, questions and suggestions to: comments@flexiblecircuittechnology.com.

Joseph Fjelstad
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Chapter 1

Flexible Circuit Technology Overview

Joseph Fjelstad, ***Verdant Electronics***

INTRODUCTION

As with earlier editions of the book, the primary objective of *Flexible Circuit Technology 4th Edition* is to provide the basic knowledge required to design, manufacture and use flexible circuits while avoiding many of the potential problems. The book does not presume any background in flexible circuit technology. Readers who are already familiar with the technology will want to do a quick review of the basics before moving on to more complex topics. *Flexible Circuit Technology 4th Edition* is intended to be a valuable resource for those who are new to the technology as well as those who already have a working knowledge of flex circuits and their application.

Since its first edition, the format of this book has been purposely simple. It is structured in an ordered fashion through the key aspects of flexible circuit technology. The linear progression, from materials to design to manufacture and assembly, is intended to provide a thorough understanding of flex circuit technology by building on each preceding layer of information, starting with the basics, such as the definitions that close this chapter.

From basic definitions, the text moves to how to determine where and how flex circuits can best be used, followed by informative chapters about materials, design practices, manufacture and assembly. The linear progression through various

aspects of the technology provides the best possible understanding of flex circuits. It includes many of the ins-and-outs and ups-and-downs of flex circuit design and manufacture, giving concrete examples that will come in handy when applying flexible circuit technology to products and applications.

In addition to the technical aspects of flex circuit technology, we have enhanced and expanded a section that details the history of flex circuits and how they have evolved, the present status of the technology and future prospects for the technology and its markets.

Flexible Circuit Technology's editor, authors and publishers are dedicated to advancing this highly useful interconnection technology. In addition to providing a solid foundation of knowledge and information, we anticipate that its publication will lead to continuing development and success of flex circuit technology and create extraordinary opportunities for those who use it.

DEFINITIONS

The most widely accepted definition of a flexible circuit is found in the industry standard *IPC-T-50 Terms and Definitions for Printed Boards,* which reads:

A patterned arrangement of printed wiring utilizing flexible base material with or without flexible coverlayers.

While this is technically accurate, it is overly simple and fails to encompass the breadth of flex circuit technology. The term requires significant amplification to fully embrace all aspects of the technology. As a result, it is necessary to further define flexible circuits, not only according to their type of construction, but also according to how they are used in their final application.

Figure 1-1: Disc drive read/write assemblies from IBM. The image on the left is an early example of a dynamic flex circuit application where the read/write head assembly's operation is enabled by a flex circuit. Before flexible circuits were used, disk drive read/write head assemblies were connected by round wires routed through springs as shown in the image on the right.

To extend the definition, one should know if the circuit is to be used only for static application. The most common situation is that circuit flexibility is required only to install the circuit and fit it properly into its application. The other situation is that the flexible circuit will be dynamically flexed, such as those used in disk drives, hinges, printer cables, etc.

While flexible circuits are most commonly associated with dynamic applications, the number of dynamic flex circuit applications is much lower compared to static or flex-to-fit applications. The intended application of the flexible circuit is an important element of its definition and a vital piece of information for flexible circuit design and use.

FLEX CIRCUIT TYPES AND CONSTRUCTIONS

There are a few basic types of flexible circuits but significant variation between the types in terms of their construction. Following is a review of the most common types. Photos of some of the flex types are shown with the description and cross-sectional views of the various constructions are shown in a graphic near the end of the chapter (fig. 1-5).

Figure 1-2: Example of a simple single-metal layer flex circuit.

SINGLE-SIDED FLEX CIRCUITS

Single-sided flexible circuits consist of a single conductor layer of metal or conductive (metal-filled) polymer on a flexible dielectric film. Component termination features are accessible only from one side, but holes in the base film for component features to pass through are required. Single-sided flex circuits can be fabricated with or without protective coatings such as coverlayers or cover coats; however, the use of a protective coating over circuits is the most common practice.

DOUBLE ACCESS OR BACK BARED CIRCUITS

Double access (also known as back bared) flex circuits have a single conductor layer that allows access to features of the conductor pattern, such as lead terminations, from both sides. While this type of circuit has a number of benefits, it is not commonly manufactured because of the special processing required to provide access to the features discretely, although laser technology is available for the task. Tape automated bonding (TAB) circuits take advantage of the method, but

the circuit features are accessed en masse, often by chemically etching the circuits and the polymer film on which they reside.

SCULPTURED® FLEX CIRCUITS

Sculptured flex circuits are an interesting subset of flexible circuit technology, involving a special flex circuit construction method that yields a flexible circuit with finished copper conductors that have varying degrees of thickness along their length. The conductors are thin in flexible areas and thick at interconnection points. This method involves selective etching of thick copper foil to various depths in different areas of the circuit.

The sculptured flex circuit method, patented by Advanced Circuit Technology, is often used to create bare metal contacts

Figure 1-3: Sculptured circuit with raised metal contacts (left) and leads extending unsupported from the edge of the circuit allowing them to act as pins for a pin-in-socket type connection. (Photos courtesy of E-FAB, Inc.)

that protrude from the edge of the circuit to allow plug-in connections. The raised land improves solder joint formation and enhances its strength relative to normal, single-metal layer flex circuits.

DOUBLE-SIDED FLEX CIRCUITS

Double-sided flex circuits have two conductor layers. They can be fabricated with or without plated through-holes, though the plated through-hole variation is more common. When constructed without plated through-holes and with connection features accessible from only one side, the circuit is defined as a Type 5 according to military specifications. It is not a common practice, but it is an option.

Because of the plated through-hole, terminations for electronic components are provided for on both sides of the circuit, allowing components to be placed on either side. Depending on design requirements, double-sided flex circuits can be fabricated with protective coverlayers on one, both or neither side of the completed circuit. While possible, omission of a protective cover film or coating for the circuits rarely occurs.

MULTILAYER FLEX CIRCUITS

Flex circuits with three or more layers of conductors are known as multilayer flex circuits. Commonly, the layers are interconnected by plated through-holes, but this is not required since it is possible to provide openings to access lower circuit level features.

The layers of the multilayer flex circuit may or may not be continuously laminated together throughout the construction with the exception of the areas occupied by plated through-holes. Discontinuous lamination is common in cases that require maximum flexibility and is accomplished by leaving the areas where flexing or bending is to occur unbonded. This will be discussed in more detail later.

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RIGID-FLEX CIRCUITS

Rigid-flex circuits are hybrid constructions consisting of rigid and flexible substrates that are laminated together into a single structure and then sequentially electrically interconnected using plated through-holes. Unlike multilayer flex, the use of plated through-holes is typically a requirement for rigid flex products. Over the years, rigid-flex circuits have enjoyed tremendous popularity among military product designers. In more recent years the technology has made inroads into the commercial world. Figure 1-4 shows an example of an unusual rigid flex.

Rigid-flex boards are often considered a specialty product for low volume applications because of manufacturing challenges. Compaq, however, made an impressive effort to use the technology in the production of boards for laptop computers in the 1990s.

Rigid-flex boards are normally multilayer designs, but double-sided constructions with only two metal layers are also possible. Two-layer rigid-flex constructions have been used in the past in miniature form for medical applications. A large number of variations are possible.

Figure 1-4: Rigid-flex design with multiple rigid sections.

Rigid-flex should not be confused with rigidized flex. Rigidized flex constructions are simply flex circuits to which a stiffener is attached to support the weight of the electronic components locally.

A rigidized or stiffened flex circuit can have one or more conductor layers. Although the two terms sound similar, they represent products that are quite different. The subject of stiffeners or rigidizers will be covered in more detail in a later chapter.

POLYMER THICK FILM FLEX CIRCUITS

Polymer thick film (PTF) flex circuits are true printed circuits with conductors that are printed onto a polymer base film. They are typically single conductor layer structures, but two or more metal layers can be printed sequentially with

Figure 1-5: Examples of flexible circuit constructions.

insulating layers printed between printed conductor layers. PTF circuits are lower in conductivity but have been successful in a wide range of low power applications at slightly higher voltages. There is a wide range of potential applications, such as keyboards, for this cost-effective approach to flex circuit manufacture, especially as the conductivity of inks continues to improve.

COMMON FLEX CIRCUIT CONSTRUCTIONS

Of all the possible constructions, single-sided flexible circuits dominate the market (fig. 1-6). Single-sided flexible circuits seem to be the most simple, but single-metal layer

Figure 1-6: Production volumes for common flex circuit constructions. The data are from 2008, before the 2009 market collapse, but the distribution of product types is unlikely to have changed greatly.

flex circuits can be quite complex and challenging to build, especially those used for disk drive and display driver applications. More details about the current state and future prospects of the flex circuit market will be provided in Chapter 2, Flexible Circuit Technology Past, Present and Future. **FCT**

TWO

Thomas H. Stearns is president of Brander International Consultants, a Nashua, NH firm specializing in electronic interconnections. He previously designed and developed connectors and flexible printed circuit products for IBM, Raytheon Company, JPL, GE and Sandia Labs amongst others. A noted engineer and inventor in the field of flexible and rigid-flex circuitry, he holds twenty-two patents and has written many technical articles for trade publications as well as the McGraw-Hill textbook *Flexible Printed Circuitry.*

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Chapter 2

Flexible Circuit Technology Past, Present and Future

Joseph Fjelstad, ***Verdant Electronics***
Thomas Stearns, ***Brander International Consultants***

HISTORY

Flexible circuits are not new to the world of electronic interconnections. The technology has a surprisingly long and rich history. Patents issued at the turn of the 20th century show clear evidence that early researchers thought that flat conductors sandwiched between layers of insulating material could ease the layout of certain primitive types of electrical circuits in early telephony switching applications (British Patent No. 4681, 1903). Some very famous turn-of-the-century researchers and scientists apparently turned their thoughts to novel methods for producing electrical interconnections as well. For example, based on notes in one of Thomas Edison's lab books, it appears that he envisioned the flexible circuit's precursor. In the notebook, Edison responded to an inquiry from his apprentice, Frank Sprague, as to how one might put conductors on insulating materials. One of Edison's suggestions was to use conductor patterns of graphite powder in cellulose gum applied to linen paper. There is not evidence that Edison's suggestion was put into practice, but the idea is close in concept to polymer thick film circuits of today that are common in a wide range of applications.

Significant production and use of flexible circuit technology in electrical or electronic applications seem to have been delayed until flexible circuits were pressed into service during

World War II. At the time, German scientists were using flat conductor wiring harnesses both in the gun turrets of tanks and in the V2 rocket. United States flex circuit pioneer Pat Bryan, related the story that a captured V2 rocket used by US space program researchers in the early 1950s was the source of at least a portion of flex technology used in the US. Bryan, then working for Lockheed, took a piece of the circuit back to California to study and ultimately employ in aerospace products.

Another important development took place on the east coast of the US in the same time frame. Through the efforts of Victor Dahlgren and company founder Royden Sanders, Sanders Associates in New Hampshire made significant strides, developing processes for printing and etching flat conductors on flexible base materials to replace wire harnesses. Later, working with Sidney Tally and Thomas Stearns, Dahlgren also helped

Figure 2-1: Drawings from what may be the first patent for a rigid flex circuit, a device co-invented by Dahlgren, Tally and Stearns of Sanders Associates in the mid 1960s.

Figure 2-2: An early advertisement from Photocircuits mentions the etching of copper foil circuits on flexible plastic bases. (Image courtesy of IEN)

to define and patent what is possibly the first rigid flex circuit (fig. 2-1). It is difficult to identify exactly when and where flexible technology was born in the US; however, it is evident from advertisements of that period that Photocircuits in New York was offering at least the idea of metal circuits on flexible base material (fig. 2-2).

THE BIRTH OF FLEXIBLE CIRCUITS

The following is a first hand account of the early days of flexible circuits by flex circuit pioneer Thomas Stearns. It was first featured in I-Connect007 in May 2011 (reprinted with permission).

THE START

Let's begin at the beginning, almost 60 years ago. It's the early 1950s. America is fighting a major war in Korea, Dwight D. Eisenhower is our president and 11 senior engineers and scientists from Raytheon have started an engineering firm and moved it to an old textile mill on Canal Street in Nashua, New Hampshire. (Scott)

The new company specialized in the development and manufacture of Navy electronics, including aircraft self-protection systems and tactical surveillance and intelligence systems. Named Sanders Associates after its sleepy-looking leader Royden C. Sanders, the firm grew rapidly on America's anxiety to stay ahead of its mortal enemy, the Soviet Union. Remember Sputnik in 1957? Gary Powers and the U2 incident in 1960?

As time passed, the fledgling company developed an industry-leading reputation for its Sparrow and Hawk missile guidance and control systems, radar altimeters and radar countermeasures, the video game and flexible printed wiring.

Sanders was organized around the skills and interests of the 11 founding associates. Each had his own bullpen of engineers and technicians and pursued contracts suited to his skills and interests. Most of the associates were electronic systems engineers, but there was a hydraulics department – the muscles of submarine and missile guidance; a vacuum-tube development department run by the well-known Jim LeVan; an antenna range initially firing from the 6th floor roof of the Canal Street building and later quartered at an abandoned airport in nearby

Merrimack; and an Environmental Test Laboratory staffed and equipped to duplicate the most horrendous shipboard conditions.

ENTER THE NEOPHYTE

When I graduated from college in 1953, the draft was on every young man's mind. I'm not saying this was the only reason, but I skipped my graduation ceremonies and double-timed directly to Canal Street where everything was military-oriented. Assigned to Sanders' Components Group as an engineer, I spent the next year and a half busily developing screen-printing inks and screen-making techniques for Project Tinkertoy, a Navy scheme for semi-automatic manufacturing of electronic systems.

In the fall of 1954, Uncle Sam sent me his greeting letter and the next two years were spent in the Scientific and Professional Personnel branch of the US Army. But this, like all good things, came to an end, and after a brief flirtation with other opportunities, I returned to Sanders.

I found that things had changed quite a bit since I'd left.

THE IDEA EMERGES

Sanders had steadily grown in my absence. Some of the Components engineers were still working on carbon resistor inks for Tinkertoy – a tough problem – but I was assigned, with three or four others, to a new project: the development of a flexible film-based printed circuit.

It's certain that the idea for a flexible printed circuit product popped up at Sanders sometime between my departure in the fall of 1954 and my return in 1956, but the exact origin isn't known. It may have been the result of an attempt to use a plastic film as a super conformal coat on Navy printed circuitry to protect it from the humid shipboard environment. Or perhaps it was suggested by the constant problem of cracking

in brittle phenolic-based printed wiring board materials.

Whatever the source, the idea was to bond a plastic film onto a copper foil to create a bendable, non-cracking laminate for printed circuits. In this conception, after the pattern was produced by the usual image-etch techniques, a second layer of the same film was bonded over the etched pattern to produce a fully protected, watertight circuit pattern that could be punched or stamped to shape, bent and formed however you wished and would withstand Navy environments.

THE PRODUCT

We chose Kel-F, a high-quality, fluorocarbon-based polymer which was tough and flexible. Kel-F film had wonderful properties for our product – high dielectric strength, near-total rejection of moisture absorption or intrusion, low dielectric constant as well as excellent thermal and chemical properties. Compared with the XXXP and epoxy-glass laminates used in conventional printed wiring boards, it was mechanically weak;

Figure 2-3: A miniature "backplane" produced for a major computer maker in the early 1960s. (Photo courtesy of McGraw-Hill)

you could not use these circuits to support 1950s-style tube-circuit power supplies, transformers or sockets.

Roy Sanders saw the flexibility as desirable, ideal for use as a three-dimensional printed circuit to replace wire harnesses in the military systems that Sanders Associates designed and built. So we pressed on.

There were problems with the technology, though. The worst was that fusion-bonding of film to foil and coverfilm to etched circuit created shrinkage and distortion in the semimolten plastic films, and failure to quench-cool the Kel-F quickly enough could lead to micro-crystallinity and a tendency to crack when flexed. (There were unconfirmed shipboard failures which might have been caused by this problem.)

Still, we were producing circuitry and it was a great help in lowering the cost to wire up Sanders' equipment and eliminating the "rat's nest" of individual wires. We had a useful product and we could build it at a price that attracted more customers than we could service. There might have been competition somewhere, but I do not remember any. Our business boomed as more companies came to us with their interconnect problems, and we hunted for a suitable name for the product. Some wag suggested RCSanflex, but by 1959 the name Flexprint won and today is almost a generic name for any flexible printed circuit.

MATERIAL CHOICES

Kel-F was the go-to film for several years. We also used FEP Teflon, a DuPont development which had most of the good properties of DuPont's TFE Teflon except that FEP was thermoplastic which meant we could fuse it onto foils or itself in our laminating presses. It had a higher fusion temperature than Kel-F (540°F vs. 430°F), but otherwise handled the same. FEP showed no crystallinity and would not crack, which were pluses, and it was a superior dielectric, but it had the same shrink-

age and distortion problems that plagued our tooling schemes and the development of finer-line circuitry. Glass cloth could be built into the dielectric films when greater stability and higher mechanical strength were needed, and we used this technique where we could.

With the passage of time DuPont developed a composite film almost perfect for our use consisting of a polyimide, trade-named Kapton coated with a thin layer of FEP. We loved this product, dubbed "F" film, because the polyimide layer did not melt during lamination, thus protecting against the worst distortion or "cut-through." (The differential thermal expansion between foil and film was so great that sometimes, during the cool-down, a conductor would ripple in the vertical plane and cut through the surface of the dielectric, thus causing electrical failure.)

"F" film eliminated this problem, but shrinkage was still something we had to deal with. Other lower-cost thermoplastics were used, including the urethanes, PVC, and vinyl which appeared in high-volume, low-cost telephone circuitry, produced by an early form of roll-to-roll process.

There was also Scotchpak, another composite, this one primarily used in food packaging and consisting of polyester with a layer of polyethylene as the "glue." Scotchpak allowed us to produce oversize (18"x 36") sheets for gyro gimbal circuits. Irradiated polyethylene was also roll-processed and multilayer laminated in a specially built 10 foot long press, to create very flexible 8-conductor stripline circuits with 200 square-mil conductors and 93 ohm impedance.

THE 10′ 93 OHM STRIPLINE

These 8-conductor cables were historically interesting in several ways. We did the roll lamination on an antique gas-fired machine with an elegantly filigreed cast-iron frame. The open gas flame, roughly 18" long, played on the bottom sur-

Figure 2-4: The 10′ 93 ohm stripline. (Photo courtesy of McGraw-Hill)

face of a polished steel cylinder about 8″ in diameter. The compression roll and the materials to be laminated ran against the top of the roll under pressure applied by a set of cantilevered arms with adjustable weights hanging from them.

The rectangular conductors in the center layer were produced by an outside vendor who squashed AWG #26 round copper conductors into rectangular stock 0.008″ thick and 0.025″ wide; these we fed through our surface-cleaning and oxide treating line by winding the raw stock onto 16 mm film reels and pulling it through the baths with a movie editing machine.

Braking tension to control conductor position was provided by serpentining the conductors through a series of maple dowels. Like most of our work, time was important on this project, so instead of trying to calculate friction forces and so forth, we simply arranged for more dowels than we needed, started the machinery up and removed dowels until we got a good operating condition.

The two shield layers for the 93 ohm stripline construction were made by conventional print-and-etch, but the 10 foot length gave us a lot of imaging trouble, so we attempted to develop other means for printing endless images of the conductor pattern on the roll-laminated stock. One group tried coating the laminate with etch resist and scraping it off in lines to produce the spaces between the conductors by etching. I tried to devise a continuous screen-printing/extrusion process based on a gear pump, a pot of hot wax and a multi-nozzle head. This lashup was supposed to deposit multiple strips of wax on the laminate as needed for each conductor, but never worked. No method worked better than screen printing with a custom, grossly oversized screen and some nasty handling problems.

RAPID PROGRESS

Every project we took on was worked in both directions. First, the customer's engineers and Sanders application people chewed on the requirements to get the most producible design. Then Sanders engineers labored to develop a way to make it and the equipment that was needed. All of the Flexprint engineers worked on every aspect of development: finding new materials, developing production machinery and techniques, product design, applications and testing. We built production machinery that could handle the fragile and weak laminates. The rolled, annealed copper foils we used required kid-glove handling, careful surface cleaning and application of a unique surface treatment called Ebonol C Special.

Ebonol was a proprietary chemistry that operated in a hot water solution and grew long, strongly adhered copper "needles" or dendrites which made the foil look flat black and microscopically velvety. The huge surface area increase produced by the needles brought improved bonding of film to foil, a passive, chemically inert form of copper oxide which protected the foil from corrosion at laminating temperatures

and a bond which did not degrade with prolonged exposure to high temperatures or humidity. So we needed a process line which could reproducibly treat many sheets of delicate rolled foil each day for our production needs.

Accurate conductor artwork was created by skillful commercial artists who carefully plotted 10X oversize master layouts of the design, then stripped in the conductor patterns with ink or black tape and Rubylith shapes. These masters were photoreduced on in-house process cameras to produce 1:1 (or slightly expanded to compensate for the ever-present shrinkage) working masters for the silk screen or photoimaging process.

Lamination also demanded a lot of care and tooling. Wherever possible we used custom lamination fixtures to limit flow at lamination temperatures. Foreign material was a constant hazard, even worse than in today's adhesive lamination. Tiny airborne particles of lint or fibers would be attracted to the polymer film by the build-up of static charges and then char during our high-temperature lamination to create worrisome black splotches deep inside a circuit.

Any variation in press pad hardness or any leftover imprint of an earlier circuit pattern could cause local distortion or an unsightly ghost pattern in the film. High lamination temperatures caused frequent heater failure and buckled platens. Repeated inrush of cold water into blistering hot platens blew out hoses or created a roomful of confetti when trapped steam from moist press pad materials explosively escaped as the press was opened.

PATENTS

Sanders was a highly creative place, and like all engineering-based outfits, aggressive in pursuit of patent protection. The Flexprint group was only a small part of the company, but by 1965, of the first 100 patents that were issued to the com-

pany, 45 came out of Flexprint. These include the PTH circuit US3,201,851, "...drilling and electrically conductive surface treatments...in multilayer circuits...." and the rigid-flex circuit US3,383,564, "....three dimensional printed circuit(s)...having one or more flexible circuit flaps coextensive with the interconnected layers..."

OTHER UNUSUAL APPS

Amongst other early flexible circuit products produced on Canal Street were 50 foot multiconductor cables for submarine periscopes, 5000V igniter cables which we believed had something to do with nuclear weapons and a long production run of miniature "backplanes" produced for a major computer

Figure 2-5: A multiconductor flex cable for a submarine periscope. (Photo courtesy of McGraw-Hill)

manufacturer in the early 1960s.

The periscope cables were insulated with polyester-polyethylene dielectric and were about 12" wide at one termination with a midbody about 6" in width. The igniter cables used the Kel-F dielectric system and were double-layer construction (a considerable challenge with pure fusion lamination!), and about 0.02" thick x 0.375" wide at the midbody. Insulation testing at 5000 VDC was not a popular assignment but it was conducted.

The miniature backplanes were roughly 8" long by 3/4" wide and made in a number of different configurations. There was considerable production volume – a crew of 30 people worked on this product for about a year. Something like 100 possible through-hole locations pierced through the epoxy-glass upper and lower circuit boards (these had no conductors; they were strictly mechanical/protective elements) and through layers of FEP Teflon insulated flexible circuitry. A "key" punch – a powerful tool which had a hardened punch and die at every possible hole location and was programmed for each design by insertion of a key – was used to produce the desired hole pattern in the epoxy cover boards and the flexible circuit layers.

Wherever there was an interconnection, a long copper eyelet was inserted through the bottom epoxy-glass board, through the FEP flexible circuit layers and out through the top board where the mouth of the eyelet was flared in a peculiar shape that locked the assembly together and provided a socket for other wiring. All of the interconnections between eyelet and etched internal circuit layers were hand-soldered under microscopes using solder preforms to control the volume of solder. Each layer of flexible circuitry was soldered to its eyelets, and then the assembly was cleaned, another layer added and so forth until the assembly contained however many layers the design required.

Figure 2-6: Detail of a miniature "backplane" produced for a computer maker in the early 1960s (Photo courtesy of McGraw-Hill)

X-ray inspection was used to detect solder platter, a major problem, and electrical performance was verified by the use of perhaps the first multi-point programmable test fixture. Ours used mechanical relays and made a lot of noise as it cycled through the 100-plus test points!

CONTEMPLATIVE SUMMARY

And so it went, contract by contract and year by year, in the early days of the flexible circuit industry. There have been important developments since then and at other companies, but the basics were set by 1965. What followed was honing and polishing.

Perhaps the most important post-1965 development was the conversion to adhesive lamination, notably of Kapton and polyester films, supplanting the fusion methods we used. Relatively low-temperature adhesive-bonded materials brought significant improvement in feature size, better control over dielectric thickness and lowered production cost. Only with

reasonably stable and predictable materials (which adhesive technique brings) can tight nesting and big tooling be used with high yield to drive down the piece cost.

Almost as important, plated through-hole technique has progressed to be the standard means for multilayer interconnection, making highly complex circuitry relatively easy to build. For a variety of reasons, a steady change in engineering approach and culture has carried the flexible circuit industry towards the "commodity" thinking found in the printed wiring industry and away from the "every job is different and therefore costly and uncertain" attitude that we understandably had in those early days at Sanders. It was always a tough job to convince customers that the high tool cost and long delay of flexible printed circuitry would be more than repaid by lowered production cost and reliability.

But in today's world flex is the unarguable choice for high-volume electronic production – not just in the military world, the same segment that helped launch it on Canal Street almost 60 years ago.

FLEXIBLE CIRCUIT GROWTH

While the growth and proliferation of flex circuit technology was initially slow, it has been accelerating ever since. Today, flexible circuits, also known as flexible printed wiring, flex print and flexi circuits, are used in nearly every type of electrical and electronic product. A great deal of credit is due to Japanese electronics packaging engineers who have found countless new ways to employ flex technology in every imaginable type of product. Over the last several years, flexible circuits have remained one of the fastest growing interconnection product market segments. Given its versatility, flexible circuit technology can expect continued growth and increasing numbers of participants among both users and manufacturers.

THE FLEX CIRCUIT MARKET

While the growth and proliferation of flex circuit technology was initially slow in the early days, of the technology, it has been on a steady and accelerating growth path ever since. Today, flexible circuits, also known as flexible printed wiring, flex print and flexi circuits, are used in nearly every type of electrical and electronic product. A great deal of credit is due to Japanese electronics packaging engineers who have found countless new ways to employ flex circuit technology in every imaginable type of product since they began to use the technology in the 1970s . Today, flexible circuits represent a multi-billion dollar industry, with Japan, because of its continuing application leadership, enjoying a significant and leading market share. The US, once a close second, has fallen behind in market share as production continues to shift to China and other places in Asia and South Asia . Still, the US remains a high technology leader in areas such as rigid flex and high frequency applications. Figure 2-7 illustrates the distribution of the global flex circuit market based on industry statistics and offers clear evidence of the shift of manufacturing to Japan and the rest of Asia and Table 2-1 provides a listing of the top tier providers.

While the growth of the flexible circuit industry, in volume and dollars, from its infancy to the present has been impressive, it has not been without problems. Failures have been experienced and recorded by a substantial number of flexible circuit users during the industry's history. Most of those who have been troubled by failure entered the flex circuit arena without being fully prepared. New industry participants, manufacturers and users often lacked the experience and knowledge needed to prevent the problems they encountered. Mistakes were unfortunately repeated by others until the lessons learned became available to a broader base of participants and were codified and formalized

Figure 2-7: Flexible circuit manufacturing market distribution has shifted over the years from North America to Japan and the rest of Asia. The chart provides approximations of continental market share compared to that of Japan. At the time of publication of this book, the total global market for flex circuits is approximately US $8 billion. (Composite sources)

in the standards, specifications and design guidelines we use today.

Over the last several years, flexible circuits have remained one of the fastest growing interconnection product market segments and according to a recent report by Prismark Partners the flex market is projected to grow from about $8 billion in global revenue today to over $12 billion in global annual sales by 2015. As their report points out, this represents an impressive 9% annual growth rate projection. In terms of production volume among countries participating in the flex circuit mar-

($M)	Country	2006	2007	2008	2009	2010
Nippon Mektron	Japan	$ 1,436	$ 1,530	$ 1,790	$ 1,535	$ 2,113
MFLEX	U.S.	$ 505	$ 568	$ 761	$ 777	$ 803
Fujikura	Japan	$ 870	$ 814	$ 850	$ 931	$ 802
Interflex/Yoon Poong	Korea	$ 433	$ 435	$ 595	$ 496	$ 692
SEI	Japan	$ 426	$ 478	$ 560	$ 550	$ 600
Foxconn Advanced Tec.	Taiwan	$ 430	$ 352	$ 400	$ 520	$ 600
Nitto Dneko	Japan	$ 400	$ 524	$ 464	$ 404	$ 583
IG Innotek	Korea	$ 175	$ 267	$ 375	$ 337	$ 367
Career Technology	Taiwan	$ 230	$ 272	$ 250	$ 246	$ 325
MMS	Japan	$ 525	$ 446	$ 370	$ 289	$ 300
Unimicron	Taiwan	$ 14	$ 39	$ 74	$ 86	$ 154
FLEXium	Taiwan	$ 59	$ 64	$ 90	$ 94	$ 143
SEMCO	Korea	$ 120	$ 130	$ 136	$ 107	$ 109

Table 2-1: Top-tier suppliers of flexible circuits globally. (Source: Prismark Partners)

ket, Japan has a reported 50% market share for flexible circuits. Korea follows at 24%, with Taiwan/China at 16%, the US at 9% and Europe at 2%. Prismark further anticipates that China will control 25% of market by 2015 as increasing numbers of OEMs shift manufacturing to China.

SUMMARY

Flexible circuits have a rich history and are extremely diverse, which opens them to use in a wide range of applications with new applications growing on a regular basis. It is hard to predict where the technology will go next. Roll-to-roll processing is likely to play an important part. Currently, the US government, through the Defense Advanced Research Projects Agency (DARPA), is funding a number of projects focused on depositing transistors directly onto flexible substrates in a

web. This type of processing is now called printed electronics by a growing number of marketers in the industry and there has been an effort to call flexible circuits flexible electronics, which can be confusing to new participants in the industry. Since flexible circuits have an almost 100-year head start, it seems unlikely that the name will be changed. That said, the concept of printed electronics in roll-to-roll fashion is attractive and is proving well-suited to large displays. As roll-to-roll technology matures and manufacturing capabilities expand, it should open doors to a new generation of flexible circuit constructions. **FCT**

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  Dave Becker, director of sales and marketing for Allflex, shows us some of the new types of flex circuits his company has been developing. He also discusses the overall business climate in the flex industry.

Flex News Highlights

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- By-health Biotech to Acquire Potechnics' PCB Subsidiary
- HEI Releases Q3 Results; Sales Up 8.9%
- AT&S Satisfied with Record Q2 Results
- AEM's ECCL Shipments Soar in September
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Flex Articles

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EPTE Newsletter from Japan: The Apple Culture
Steve Jobs, Apple's co-founder and charismatic chief executive passed away October 5, 2011 from pancreatic cancer. In his latest column, Dominique Numakura of DKN Research discusses the many reasons he admires the man and the company.

Drive by Lean: Case Studies
With frequent headlines lamenting the loss of American jobs, technology and business, companies are rushing to implement Lean practices in an effort to stop the bleeding. When showing up this late to the party (we should have embraced Lean 50 years ago), it is often difficult to chart a successful course of action in the sea of information that is available to us.

Printed Electronics News

Consumer Packaged Goods Segment Dominates E-Packaging Market
The market for wireless power transmission (WPT) is evolving, and the next ten years will see a shift towards contactless charging for the consumer electronics and electric vehicle markets, according to a new report available on companiesandmarkets.com.

ITRI's Technologies Receive 2011 R&D 100 Awards
ITRI (Industrial Technology Research Institute), Taiwan's largest and one of the world's leading high-tech research and development institutions, will accept two 2011 R&D 100 Awards this evening in Orlando, Florida.

RFID Readers & Tags Market to Reach $9B by 2015
MarketResearch.com has announced the addition of the new report "RFID Readers and Tags - A Global Market Overview," to their collection of Electronics market reports.

Military and Aerospace News

Military EO/IR Systems Market to Reach $7.47B in 2011
Visiongain's analysis indicates that the military electro optical infrared (EO/IR) systems market will reach a value of $7.47bn in 2011, as militaries continue to seek battlefield and operational advantage for their troops through the use of night vision, rangefinders, infrared targeting, and other EO/IR solutions.

U.S. Army, Lockheed Martin Demonstrate Sensor Tech
Lockheed Martin was selected by the U.S. Army's Research Development and Engineering Command, Communications-Electronics Research, Development and Engineering Center (RDECOM CERDEC) Night Vision and Electronic Sensors Directorate (NVESD) to demonstrate an advanced slew-to-cue sensor system designed to provide greater situational awareness during route clearance and surveillance missions.

HEI Releases Q3 Results; Sales Up 8.9%
Sales for the third quarter were $9,221,000, compared to $8,465,000 for the third quarter of 2010. The company generated a net income of $162,000 for the third quarter of 2011 compared to a net loss of ($510,000) for the same period of 2010.

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MarketResearch.com has announced the addition of the new report "Global Digital X-Ray Systems Market 2010-2014," to their collection of Medical Imaging market reports.

OSI Systems Wins Contract from Novation
OSI Systems, Inc. today announced that its Healthcare division, Spacelabs Healthcare, has been awarded a three-year contract to provide its complete line of patient monitoring solutions to VHA Inc. University HealthSystem Consortium (UHC) and Provista members served by Novation.

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THREE

Chapter 3

Flexible Circuit Drivers, Benefits and Applications

Joseph Fjelstad, ***Verdant Electronics***

INTRODUCTION

Diversity is a hallmark of flexible circuits and they are as diverse in their application as they are in their design. Flexible circuits have, for long into the past and continuing today, served in a wide variety of demanding applications. As an interconnection method, they are unmatched in terms of their versatility. The trend is expected to continue as more and more engineers become familiar with flex circuit technology's many benefits.

The evolutionary path of flex circuit technology has not been free of challenges, and many early users suffered setbacks. The first users of flexible circuits experienced difficulties and failures due to a combination of factors. For example, early flex materials did not meet the same standards of today. Additionally, users lacked a fundamental understanding of the capabilities and limitations of the technology in terms of the product design and/or the design rules that needed to be followed to ensure success. Together, these factors made the development path rocky for some users. Fortunately for us today, flex circuit technology survived its infancy to become the vitally important solution it is today in the arena of electronic packaging technologies.

According to Prismark Partners, just as this 4th edition of Flexible Circuit Technology prepares to go to press in 2011, the

biggest application market for flex circuits is displays at a 28% share, followed by computers at 27%, communications at 20%, consumer electronics 12%, automotive 5%, industrial/medical 4%, military flex 3% and the final 1%, integrated circuit (IC) packaging applications. Displays are a crossover application and are represented in almost every one of the more commonly cited markets and applications identified in table 3-1. The table offers a small sampling of products in the diverse electronics market that have been successfully served by and benefited from flexible circuits and gives an indication of just how extensively flexible circuit technology is being used to solve electronic packaging problems.

Automotive • Instrument panels • Underhood controls • Headliner circuits • ABS systems	**Instruments** • NMR analyzers • X-ray equipment • Particle counters • Infrared analyzers
Computers & Peripherals • Dot matrix print heads • Disk drives • Ink jet print heads • Printer head cables	**Telecom** • Cell phones • High speed cables • Base stations • Smart cards & RFID
Consumer • Digital & video cameras • Personal entertainment • Exercise monitors • Hand-held calculators	**Military & Aerospace** • Satellites • Instrumentation panels • Plasma displays • Radar systems • Jet engine controls • Night vision systems • Smart weapons • Laser gyroscopes • Torpedoes • Electronic shielding • Radio communications • Surveillance systems
Industrial Controls • Laser measuring • Inductor coil pickups • Copy machines • Heater coils	
Medical • Hearing aids • Heart pacemakers • Defibrillators • Ultrasound probe heads	

Table 3-1: Examples of products that use flexible circuit technology.

APPLICATION DRIVERS AND BENEFITS

There are many reasons to use flexible circuits and benefits that can be delivered by using them to make the interconnections in an electronic package. In some cases, such as dynamic flexing applications, the choice to use flexible circuits is an obvious one, driven strictly by the lack of viable alternatives. However, there are many more subtle areas of opportunity to employ flexible circuits, and this has proven to be the real measure of their success. The following are some areas where flex circuits have solved difficult packaging problems.

REDUCTION IN PACKAGE SIZE

Flexible circuits employ the thinnest dielectric substrates available today to make electronic interconnections. In some cases, it is possible to produce flexible circuits with a total thickness of less than 50µm (0.002”), including a protective coverlayer. As a point of reference, rigid material counterparts might be twice as thick and generally lack the ruggedness afforded by flexible base material substrates. While thinness is attractive, it is the formability of the flex circuit that enables a package size reduction, and rigid materials may be a suitable choice if planar thickness is the only point that matters.

Figure 3-1: Cellular phones, with multiple displays, cameras and a wide range of other PDA features, rely heavily on flexible circuits to create increasingly versatile personal communication products that are lighter, thinner and more reliable.

REDUCTION IN PACKAGE WEIGHT

A side benefit of thinness is reduced weight. Flex circuit materials can be very lightweight because they do not employ reinforcements that are characteristically higher in density than unfilled polymers. The result is that the use of flexible circuits can reduce the weight of an electronic package significantly. For example, weight reduction of up to 75% or more is possible depending on the exact nature of interconnection technology that is being replaced.

Reduced weight is one of the main reasons flex circuits have remained so popular in aerospace applications over the years. But it is also an attractive feature in portable electronics, where size and weight are evaluated along with performance and appearance.

DECREASE IN ASSEMBLY TIME

Flexible circuit technology has the intrinsic ability to seamlessly integrate the form, fit and function of a design into a single circuit. Because of this natural benefit, flexible circuits can greatly reduce a product's assembly time. This feature is especially evident when point-to-point wiring is a requirement as a part of the final assembly process. While point-to-point wiring is no longer a commonly designed in-process step, engineering change orders are often performed in just such a manner, and flexible circuits can greatly improve the second operation assembly process.

ASSEMBLY COST REDUCTION

With the reduction in assembly time comes a reduction in assembly cost, making it clear that flexible circuits should have a significant impact on assembly cost compared to other methods, depending on the application.

Cost reduction is a natural result of flex technology's ability to reduce the number of assembly operations required and the

capability of users to construct and test the circuit completely prior to committing the circuit to assembly. This is especially true of wire harness replacement applications.

ASSEMBLY ERROR REDUCTION

While there may be errors in design, a flexible circuit cannot produce the kinds of errors that an individual can. Human error in hand assembly is a constant risk. Hand-built wire harness assembly is an especially vulnerable process. An important feature of flexible circuit technology is that all design features are controlled by the design itself. As a result, with the exception of errors due to out-of-control processes in manufacturing, it is not possible to route circuits to points other than those designated by the circuit design.

INCREASED SYSTEM RELIABILITY

Reliability engineers have always been quick to point out that when an electronic package of any type fails, it typically fails at a point of interconnection. Most often, those points of failure are solder joint interconnections. Flexible circuits are ideally designed to reduce the levels of interconnection. In fact, in Chapter 12 – Solderless Assembly Processes for Flexible Circuits, a method called the Occam Process is described, which could completely eliminate solder interconnections. When a flexible circuit is properly designed and applied to an electronic packaging problem, it should increase reliability by reducing the number of levels of interconnection required within an electronic package or assembly, even if soldering is required.

POINT-TO-POINT WIRE REPLACEMENT

A longstanding rule of thumb used in the flex circuit community was that a flex circuit should be used when more than 25 point-to-point wires were required. The number was somewhat arbitrary, but the underlying concept is still important. It

Figure 3-2: Wire harnesses can often be replaced by flex circuits, but in some applications replacement is just not practical. (Courtesy Kodak)

is, however, worth a moment to consider if flexible circuits are a viable alternative regardless of wire count.

As a part of the calculus, the use of flex circuits must be evaluated considering the cost, application, product volume and other factors. Some product designers have found flexible circuits to be more cost-effective, or otherwise desirable, with as few as two or three wires. Still, some applications are best served by wire harness technology and force-fitting flex into these applications is not advised. Figure 3-2 shows an example where a wire harness is clearly a better choice.

DYNAMIC FLEXURE OF THE CIRCUITRY

Dynamically flexing a circuit is one of the more commonly pursued applications for flexible circuits. While other interconnection solutions, such as flat ribbon cable, have served the same purpose as dynamic flexing in some applications, flexible circuits have proven superior as a standard method of making reliable interconnections between moving parts. The thinness of base materials, coupled with the ability to use very thin copper foil, make flexible circuits the best choice for dynamic flexing applications.

Figure 3-3: Early 1990s vintage 20 megabyte disc drive flex assembly showing how the flex circuit accommodated movement of the armature. Disc drive applications have long relied on the use of flex circuits for both control arms and suspension head assemblies.

CONTROLLED IMPEDANCE SIGNAL TRANSMISSION

Many base materials used in the manufacture of flexible circuits have exceptional intrinsic electrical and mechanical properties. Uniformity of thickness and electrical properties are key to signal transmission line creation. Because of this, it is relatively simple to produce flexible circuits suitable for high-speed transmission line cable applications. With such uniform materials, the only requirement of the flexible circuit manufacturer is to accurately etch the copper foil to achieve the desired characteristic impedance.

Flex circuits are a good choice for the commonly-selected value of 50 ohm microstrip structure. Higher characteristic impedance designs and stripline structures tend to get rather thick in their construction and lose some of their flexibility. To overcome this problem, it is necessary to make the signal line widths of the transmission line cable quite small, which can reduce overall manufacturability due to accuracy limits.

Fortunately, for high-speed signaling, conductor loss is less of a concern. The dielectric properties of the circuit materials

are beneficial because the signal propagates through the polymer rather than through the conductor, a phenomenon called the skin effect. One caveat is that some flexible circuit materials absorb more moisture than others, resulting in the alteration of the loss tangent.

IMPROVED HEAT DISSIPATION CAPABILITY

Flat conductors have a much greater surface to volume ratio than round wire. The extra surface area facilitates the dissipation of heat from the circuit. When compared to rigid board constructions, not only is the thermal path for flex circuit constructions shorter, but heat can be effectively dissipated from both sides of the circuit due to its thinness. There are also base materials that are loaded with inorganic materials, such as ceramics, that can improve heat dissipation. However, they will also alter the dielectric properties.

In contrast to a flex circuit, a typical one- or two-layer rigid board has a dielectric substrate that is a thermal insulator, inhibiting the flow of heat through the circuit. However, rigid PCBs with heavy copper innerlayers or metal cores can also be highly effective at dissipating heat.

THREE-DIMENSIONAL INTERCONNECTION AND PACKAGING

Much has been written over the years extolling the benefits of 3D interconnection structures. In recent years there has been a surge in interesting 3D IC packaging methods for system-in-package devices and now even the stacking of semiconductor wafers.

In earlier times, 3D interconnection was also of interest, and the advantages of injection molded boards to create 3D interconnection structures has been discussed since the late 1970s. With flex circuits, the benefits of 3D interconnection are intrinsic and natural features of the substrate. The truth is that some molded board technologies employ flex circuits in

Figure 3-4: Flexible circuit technology allows the designer to create 3D assemblies from two dimensional substrates.

their processes by inserting them into the mold prior to plastic injection.

AIRFLOW AND THERMAL MANAGEMENT IMPROVEMENT

The uniform planar nature of flexible circuits improves the flow of cooling air through an electronic box. The massive bundles of wire that they often replace typically act as barriers to good air circulation inside an electronics assembly container.

COMPLIANT SUBSTRATE FOR SURFACE MOUNTING

Surface mount technology experienced many difficulties in its early years. A significant reason was the mismatch between the coefficients of thermal expansion of the board and the component. This mismatch resulted in solder joint stress, which was the cause of many early failures in electronic assemblies.

While material scientists and engineers have since remedied most of the problems through better design practices, one method that worked well was the use of flexible base materials that are naturally compliant and therefore introduce less stress on the solder joints of devices mounted on the circuit surface.

MORE ENGINEERED PRODUCT LOOK

Although this may be considered a trivial concern by some, the internal appearance of an electronic package can have a subtle influence on a prospective user's decision-making process. This is especially the case if the user is already aware of the many advantages of flex. In truth, the "mass of spaghetti" represented by some wire harness construction often looks hopelessly disorganized.

Wire harnesses have a long history in a wide range of large system structures. Mostly they have been used for electrical power distribution for lighting, ignition and such. They are also well-suited to use in many complex systems such as "fly by wire" aircraft and increasingly complex automobile electronics. However, in smaller product applications, flexible circuits may prove to be not only more cost effective, but may also supply the engineered look that may serve as a subtle sales point.

IMPROVED SIGNAL INTEGRITY

With the general trend toward higher speed digital signaling in electronic systems, signal integrity is an important matter and flexible circuits are ideally suited to the task. This benefit reinforces the versatility of flexible circuits relative to the needs in the current marketplace.

In practice, high speed requires rapid rise times and anything that degrades the ideally square wave pulse signal must be managed. In this respect, dielectric constant and loss tangent of materials become of greater concern than conductor loss. In response, some excellent flexible circuit materials have been developed that will be discussed in more detail later.

Design approach is critical because common design features can degrade signal integrity. As a result, some designers have opted for some unusual constructions. An example is a transposed pair construction created using flex circuits to approximate twisted pair constructions (fig. 3-5).

Figure 3-5: Flex circuit in a mock twisted pair configuration (top). Actual manufactured circuit (bottom). (photo courtesy Minco)

SMT AND FLEXIBLE CIRCUITS

One key to increasing electronic circuit density and performance has been achieved by mating flexible circuits with other density improvement techniques, such as surface mount technology (SMT). This has proven to be an area of great technological synergy. The advantage of density improvement is

Figure 3-6: Flex circuit assembled with surface mount components. (Image courtesy of Tech-Etch)

multiplied by the use of small electronic components to complement and enhance flex technology's minimalist packaging ability.

One important advantage of the technological marriage of improved density and small components is improved interconnection reliability made possible by flexible base material that provides the surface mount components with a low modulus compliant substrate. A number of research studies have demonstrated that this helps mitigate the effects of mismatches of coefficient of thermal expansion between the component and substrate.

CHIP ON FLEX TECHNOLOGIES

Driven relentlessly by the vision of maximum interconnection in the smallest possible space, circuit designers and packaging engineers have married flex circuit and chip on board (COB) technologies to create chip on flex (COF). In practice, the bare IC is packaged on the flex circuit. There are several approaches to meeting the needs of different applications that share the goal of achieving the ultimate reduction in electronic packaging interconnection size. A number of methods exist for building chip on flex structures but the three major categories are chip and wire constructions, TAB structures and its variations and flip chip constructions.

CHIP AND WIRE FLEX CIRCUIT CONSTRUCTIONS

Chip and wire construction of chip on board (COB) product on rigid substrates have been in use commercially since at least the late 1970s. A natural extension is chip on flex (COF). In manufacture, bare IC chips are bonded to the flexible substrate using a suitable die-attach material and are then interconnected to the flex using either gold or aluminum wire bonds. Adhesiveless base flexible substrates are favored by many users of this technology because most adhesives used for

flexible circuit applications tend to be too soft and a soft substrate can attenuate the wire bonding energy leading to insufficient bond strength and lower reliability.

In contrast to adhesive based structures, adhesiveless constructions, especially those based on polyimide films with their higher temperature abilities, tend to be more compatible with wire bonding technologies, especially those requiring high temperature bonding.

TAB TYPE OR FLYING LEAD FLEX CIRCUITS

Another approach to integrating a chip directly into the flex circuit is the use of integral beam leads in the flex circuit. The technique is not widely used but it has potential appli-

Figure 3-7: Patent drawing from an early flex circuit-based IC packaging scheme. Note that an early blind via concept is disclosed in figure 3 of the patent drawing above.

cations. The technology has been given various monikers, including TAB Featured Flex and TAB-FLEX. In the history of interconnection, one of the first descriptions of this type of circuit was made in a patent application issued to ITT in the late 1960s. Figure 3-7 shows one of the drawings from the original patent. Still, due to the technological lag between innovation and implementation, it was not until the 1980s that such constructions were seriously considered.

Tab type constructions, also called flying lead or beam lead constructions, are designed to accept bare integrated circuit chips for interconnection directly to flex circuit signal traces that extend into the free space of windows within the circuit. The most common term for these constructions is tape automated bonding (TAB). TAB is an interconnection technology that is well-understood and accepted, making it interesting to those seeking higher levels of circuit density. However, one concern is yield due to the unsupported or flying bonding leads that can be easily bent, resulting in a yield loss of the tape or assembly. The rework alternative is very expensive.

FLIP CHIP ON FLEX

The final chip on flex construction option is flip chip on flex. The flip chip method of interconnection was first explored by IBM and Bell Labs in the early 1960s. The most famous method is the Controlled Collapse Chip Connection (C4) process, developed by IBM. It has spawned a number of interesting approaches to address high density interconnection problems.

Interconnection of the upside down, or flipped, chip is normally made by soldering the chip directly to the interconnection substrate. In this process, the solder-bumped die is mated to a flex circuit with mating bumps or solder paste-coated lands and joined using an appropriate reflow technology.

Today there are some newer approaches to making in-

terconnections. New methods include the use of conductive polymers and Z-axis adhesives to achieve interconnection. Because of the short interconnection path to the circuit and small footprint, the flip chip method is capable of providing the maximum density with the highest possible performance, with minimal concern for common electrical parasitic effects associated with longer wire leaded devices.

CHIP ON FLEX CONSTRUCTIONS

There are some challenges when using flip chip technology for IC interconnection. One is that the flipped chip must be underfilled with an encapsulant to protect the delicate solder joints. Processes have improved today, but at one time it was a lengthy process and voids in the underfill could result in hotspots and reduced reliability. One drawback of flip chip constructions is that die shrink will change pad locations from generation to generation and there is no compatibility between die from different suppliers, so a new circuit design may be required for each new die. A final concern is that the

Figure 3-8: Top and side views of three of the most common chip on flex methods.

die being used may or may not be good, meaning that there is a possibility that the entire assembly will be lost due to the limited ability to rework flip chip assemblies. It is this known good die (KGD) concern that has delayed some applications. Even so, flip chip technology is being actively promoted and the method provides an excellent and easily adapted solution for many applications, including smart cards and applications with very small ICs having low I/O counts, though that limitation has been lifting in recent years.

IC PACKAGING INTERPOSERS

With the major chip on flex assembly methods described, it is possible to examine application of flexible circuits as a packaging medium for bare integrated circuits. One novel technology that has become quite popular is a flex on chip construction first developed by chip scale packaging pioneer Tessera, Inc. (San Jose, CA). The approach was unusual when it was introduced because it allowed the chip to be interconnected in TAB-like fashion using a specially designed and manufactured

Figure 3-9: µBGA chip scale package uses a miniature flex circuit for direct interconnection to the silicon chip. It is shown resting on the TSOP package it replaced. (Photo courtesy of Tessera)

Figure 3-10: Examples of single- and multi-chip fold-over flex-based packages for stacking. (Image courtesy of Tessera)

flex circuit to create a small grid array of solder balls on the chip itself (fig. 3-9). The novel IC packaging approach allowed chips to be packaged at near chip size, resulting in a more easily tested and burned-in device prior to assembly, which addressed a vital concern in direct chip attach assemblies.

This packaging format is now widely known as the micro ball grid array (µBGA®) chip scale package (CSP). The µBGA was one of the first chip scale packages that allowed for significant size and cost reductions in electronics and now dominates package selection in handheld and portable electronic applications.

Area array interconnection CSPs afford a more generous joining pitch than can be had using more traditional flip chip approaches, which facilitates both board manufacture and the assembly process. A specific advantage of the µBGA construction is the compliance of the flexible circuit with a low modulus encapsulant, which makes it an attractive chip packaging solution since no underfill is required. Flexible circuit con-

struction also makes fold-over structures possible, which allow IC packages to be stacked one on top of another (fig. 3-10).

STAIR STEP PACKAGING FOR INTEGRATED CIRCUITS

Another approach to packaging ICs at high density and with controlled impedance is one predicated on stair step interconnections. A key feature of the new structure is that it is possible to create a multilayer laminated IC package without any plated through vias. Stair step packaging (SSP) simplifies electronic design and manufacturing processes, while simultaneously offering the potential for improved electronic performance. The SSP IC packaging concept builds from a concept first employed in the mid-1980s to improve the density of wire bonded IC packages such as pin grid arrays (PGA), the tiered wire bond pad package structure that successfully addressed

Figure 3-11: Stair step packaging (SSP) with flex circuit materials can improve signal integrity by allowing for the transport of signals directly from chip to chip, bypassing the printed circuit board. In such structures flex circuits are used to make the interconnection to the top surface connections on the stair step package See figure 3-22 for an example.

I/O density problems of the time. SSP takes that concept further by extending it to the I/O terminations on the package surface, creating a stair-stepped or wedding cake-like structure (fig. 3-11).

The advantages of SSP are significant and include cost, performance and reliability. Manufacturing cost is reduced by improving manufacturing yields. Electrical testing cost should also be greatly reduced, if not eliminated, because the circuits are only on one side (though a ground layer may be provided on the second side of each layer if desired), making them easily examined visually for shorts, opens and non-uniformities that could affect electrical performance.

Performance is also improved by the elimination of vias. Because of the directness of the pathways, complex field solver analysis of the critical signals as they pass through the package is not needed. Moreover, differential pairs, common to most of today's high speed circuit designs, can be designed to have virtually zero skew and crosstalk can be almost completely eliminated. Also, because of the versatility of the method, substrates of different material types can be used when and where required. As a result, higher cost materials that are often desirable for high speed signals can be used sparingly and mixing of I/O pitch on a package is also possible. While the advantages are compelling, reliability must be still be fully proven and plans for full testing are underway. Fortunately, because of the simplicity of the structure, it is anticipated that it will be very good.

SELECTED FLEX CIRCUIT APPLICATIONS

While the historical role of flex circuits was mostly replacing wire harnesses, the technology has grown well beyond such mundane applications. Today, flexible circuits are continuing to increase the breadth of their application. Electronic packaging engineers around the world are devising new ways of using flex circuits and are expanding on the basic premise of

the technology by developing ever more elaborate electronic interconnection structures that are still practical.

It is worth exploring some of flexible circuit technology's unique abilities to increase electronic circuit packaging density and performance in terms of some of the many novel applications that are either in use or in development to accomplish design objectives. Some new applications and approaches to using flexible circuit technology have further demonstrated the ability of the technology to increase circuit density in unusual ways such as in IC packaging where the new package structures typically occupy a small fraction of the volume of more conventional design approaches.

HIGH SPEED CABLE STRUCTURES

High speed flex circuit assemblies have proven to be a viable alternative to high speed applications for board-to-board distances up to 75mm (30") at data rates up to 10Gbps with the flex circuit integrated directly into connectors (fig. 3-12).

Figure 3-12: High speed flex cables can be directly connected from package to connector to bypass parasitics and avoid crosstalk issues associated with traditional interconnection design. (Image courtesy of SiliconPipe)

High speed flex circuit products are available in pitches down to 0.5mm (0.020") and less for both differential pair and single-ended configurations. With the move to ever higher data transmission speeds, these types of flexible circuit applications will become increasingly important. High speed structures made possible by high speed cables will be discussed in more detail later.

SENSORS

Sensors of every type are becoming increasingly common, and miniature etched metal coils are often called on to serve in sensing applications. Figure 3-13 shows a scanning electron micrograph of a coil on a flex substrate produced by Metrigraphics using their proprietary fabrication processes and demonstrating the possibilities relative to feature sizes. The conductors in the photomicrograph are 10 microns (0.0004") wide with a height of 25 microns (0.001"). The spaces between the conductors are also 10 microns. Dimensional tolerance is less than a micron. The resulting coil has sharp, vertical walls and flat top surfaces.

Figure 3-13: SEM image of a micro coil. (Image courtesy of Metrigraphics)

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WE HAVE A HISTORY OF GOING PLACES.

FLEXIBLE CIRCUITS IN MEDICAL PRODUCTS

While flexible circuits have found their way into countless products, perhaps the most rewarding has been their use in medical products where they have provided life-changing benefits to people suffering from a range of medical conditions. At the time of this writing the medical products market was reported to be $400 billion with about 28% residing in the US, making innovations in the arena of medical products highly attractive as the medical industry moves toward more individualized and personalized medicine. Presently there are 8,000 medical product OEMs in North America. Flex circuit use in medical applications can be broken down into two broad areas:

- Flex Circuits used as a means of interconnection for the packaging and interconnection of an electronic assembly (e.g., portable monitors, implantable devices such as pacemakers)
- Flex circuits interfacing with the patient to provide diagnostics, therapy or both.

HEARING AIDS

It is interesting to note that the hearing aid was one of the first medical applications for the vacuum tube amplifier, later one of the first for the transistor and finally the first for IC. Manufacturers introduced their first transistorized behind-the-ear instruments in the early 1950s. These were extremely large by today's standards and battery life was not very long. In contrast, hearing aids of today fit nearly invisibly into the user's ear. In a great many cases hearing aid technology miniaturization has been aided by the use of flexible circuit technology which allows the circuit to be compactly folded after assembly (fig. 3-14). Hearing aids are now so small they can fit into the ear canal, providing miniaturized marvels that return the gift of sound to the user.

Figure 3-14: Flexible circuit hearing aid circuit shown next to the finished product. (Image courtesy of Diconex)

ULTRASOUND TRANSDUCER HEADS

Medical diagnostic equipment frequently uses flexible circuit technology to achieve desired results. A variety of configurations have been developed over the years to achieve extraordinary image clarity (fig. 3-15) that is essential to diagnostic and treatment applications.

One successful application has been the interconnection of ultrasonic transducer heads for ultrasound imaging where the flex circuit is used to both send and receive signals from a piezo ceramic to create an electronic image based on reflected sound. Ultrasound technology provides a unique, non-invasive look inside the body. It is most commonly associated with obstetricians and expectant parents getting an early look at an unborn child, but ultrasound has many other important uses in medicine where the imaging technology is actually used inside the body. One example is an expandable ultrasound transducer array from Siemens Medical Solutions. The device is a foldable transducer array that is small enough to be inserted into a patient where it can then be unfolded for use inside the patient's body, providing a larger radiating and

Figure 3-15: Close-up of a flex circuit for interconnecting an ultrasonic transducer head. (Photo courtesy of Microconnex, Snoqualmie, WA)

diagnostic surface. This advance provides medical professionals with one more way to spot disease for treatment, hopefully catching it at an earlier stage. Another example is intravenous ultrasound (IVUS) which allows vascular specialists to look at blockages from inside a blood vessel.

RF THERAPY

Heartburn is something that occasionally affects many people, but there are many people who suffer to a higher degree from the effects of what physicians call gastroesophageal reflux disease (GERD). The disorder causes acids from the stomach to rise into the lower esophagus due to a malfunction of the esophageal sphincter valve. There are estimates that as much as 10% of the U.S. population suffers from GERD and, if not attended to, it has been implicated in the occurrence of cancer. In response, researchers at Respiratory Diagnostic in California have developed a method of treating a lower esophageal sphincter by using one embodiment of their invention—a flex circuit attached to an expandable member, temporarily dilat-

ing the lower esophageal sphincter and treating the tissue with piercing needle electrodes and radio-frequency energy to cause controlled damage and scarring to tighten the valve and return it to normal function. While there are many over-the-counter medications to treat the symptoms, flexible circuits could be used to treat GERD and eventually cure it.

CATHETER BASED DIAGNOSTICS AND TREATMENTS

Another expanding area of flex circuit application is in catheter-deployed therapies for treating various heart and circulatory system problems. Flex circuits have been used for electrophysiology studies to map the nerves of the heart and correct certain arrhythmias that cause potentially life-threatening nerve conditions using radio ablation to open shorted or wrongly wired electrical circuits in the heart (fig. 3-16).

Flex circuits have also been explored for use in vascular diagnostic applications. In one such application, the flex circuit was used to deploy thermocouples to accurately measure temperature at different points in the vascular system.

Figure 3-16: Flex circuit employed in electrophysiology studies and heart nerve path mapping. (Image courtesy of Cardiac Pathways)

Figure 3-17: The image on the left shows a diseased section of an artery restricting blood flow. The image on the right illustrates how the electrodes on the flexible circuit attach to a balloon catheter delivering therapeutic RF energy to treat the disease and restore arterial blood flow. (Images courtesy of Vessix Vascular, San Diego, CA)

Finally, there is an evolving application for flex circuits used in a new approach to treating atherosclerosis and, more specifically, treating debilitating peripheral artery disease (PAD), which can make walking painful or impossible and, in advanced stages, can require amputation of the diseased limb. The treatment was developed at Vessix Vascular (www.vessixvascular.com) in San Diego, where they have completed human trials and achieved positive results. Many patients have been successfully treated using a flexible circuit, deployed through a balloon catheter, that delivers therapeutic RF current to diseased areas of the arteries. Not only are the treated areas being opened to increased blood flow, but they appear not to require the use of stents to hold the arteries open after treatment (fig. 3-17). Flexible circuit technology appears to have found yet another way to extend and improve the quality of life for countless individuals.

Medical electronic product developers continue to generate new ideas and applications and to find a capable partner in versatile flexible circuit technology. It will be interesting to see what new applications for flexible circuit technology lie ahead.

Figure 3-18: One-piece fold-up phone card based on polymer thick film flex circuit technology. (Photo courtesy of Dieceland Technologies)

CELL PHONES

Cell phones are a major beneficiary of flexible circuit technology. Flexible circuit technology is utilized in most cell phones, but is most important in cell phones that fold. In the early 2000s, one innovative developer, Dieceland Technologies, introduced a concept of a foldable phone designed to be disposable. The idea was to create a low cost phone that could be used for a predefined period and then recharged for additional use (fig. 3-18), similar to a disposable camera.

INSTRUMENT CLUSTER CIRCUITS

Flexible circuits have enjoyed a long relationship with the automotive industry. One long-standing application has been for interconnecting electrical and electronic elements of automobile instrument clusters. This was one of the earliest volume applications for flex circuits and saved countless hours of tedious hand assembly. While originally used primarily for panel lighting circuits, as the electronic content of automo-

Figure 3-19: Flex circuit used for interconnection of an automobile instrument cluster.

biles has increased, the importance of flexible circuit interconnections has also risen (fig. 3-19).

ELECTRICAL TEST CONTACT STRUCTURES

Flexible circuits offer unique advantages as a test contact technology. A number of different approaches have been explored by connector and socket developers, including a test contact structure developed by Xandex (Petaluma, CA) for contacting and testing area array packages such as BGAs (fig. 3-20).

HIGH DENSITY CONNECTORS

From the mid-1980s through the early 1990s, Beta Phase (Menlo Park, CA) pioneered high density flex circuit-based zero insertion force (ZIF) connector technology predicated on the use of shape memory alloys to open the connector. One of the products they worked on was a high-density controlled impedance connector for super computer company Cray. The device shown in figure 3-21 provided 500 connections per linear inch.

Figure 3-20: Flex circuit-based cantilever contact structure. (Image courtesy of Xandex, Petaluma, CA)

Figure 3-21: High density flex circuit-based connector used in a Cray supercomputer. Complete assembly (left) and close-up of the contact opening (right).

HIGH SPEED CHIP TO CHIP INTERCONNECTION

High speed chip to chip interconnection is a fairly new application for flexible circuits that has been brought about by a convergence of conditions. For example, it has been noted with increasing frequency by electronic industry experts that electrical and electronics interconnections are the primary limiters of electronic performance. The electronics industry

has not been blind to this fact, but it has been slow to react in a cooperative and cohesive manner, possibly because the electronics industry is no longer the monolithic industry it once was. Electronic design and manufacturing are disciplines that have drawn further apart since the process of eliminating vertically integrated electronics OEM manufacturers began in the late 1980s. In earlier times, in vertically integrated OEMs, the designer was commonly the manufacturer as well. However, with the corporate outsourcing of almost everything but marketing and corporate governance, the OEMs of today are much more hollow entities. As a result, they are often much less attentive to the consequences of the diffusion of design and manufacturing processes and therefore have little opportunity to learn and grow cooperatively to meet evolving challenges.

There has been much discussion about bridging the waters between the island of design and the various islands of manufacturing interconnection structures, but it is proving to be a daunting task. Currently, each element of the electronic interconnection hierarchy is conceived and developed with little anticipation of the impact of decisions on what is to come next in the process. It has been pretty much a case of, "I have solved my problem. It's your problem now." For example, the semiconductor is designed with little concern for the package and the package is designed with little concern for the PCB. An arguably better approach is to implement concurrent design and engineering. An example of how a semiconductor chip and package might be better integrated in terms of design and manufacture will help to illustrate the premise.

Semiconductor design of today is a far cry from former times. In earlier years, an individual designer or design team would set about designing the chip completely, including all the gates required to meet the product need. Over time, the process has been simplified. Presently, IP blocks of transistors with different functions are designed by completely different

teams. These are collected and integrated into a chip design with the basic tasks of interconnection and I/O assignment.

As the industry moves to ever higher speeds, due largely to chip feature size reduction, there will be a greater need for cooperation between silicon design and package design. In fact, the package can actually help to greatly improve silicon efficiency if the two are co-designed. The solution resides in the data channel.

When the data or signal channel is clean and free of electrical/electronic disruptions, it is possible for the signal to propagate at very high rates. This is because signal rise time and

Figure 3-22: Simple flex circuit constructions can provide significant improvement in circuit design time, performance and yield. Eye diagrams beneath each circuit are modeled for 25Gbps data rate over a distance of 75mm (~3”). (Image courtesy of SiliconPipe)

edge are not degraded by the commonly used materials that put a drag on the signal due to their high dielectric constant and/or high loss tangent. Moreover, a well-designed and clean channel should not be subject to normal circuit route twists and turns, noise, crosstalk and the crowded transmission environment of a standard PCB.

One way to achieve a well-designed, clean channel is to separate the high speed signals and treat them as having special needs. By doing so, the high speed signals can be lifted up and out of the congested onboard signal traffic and rapidly shuttled to their destinations. It is, by way of analogy, the application of civil engineering practices to electronic engineering challenges with flexible circuits playing a pivotal role.

An example of a civil engineer's approach to solving the problem in an application compared with a standard design approach can be seen in figure 3-22. This elevated super highway approach to signal routing has some unique advantages

Figure 3-23: Test setup for demonstrating a 10Gbps backplane solution over a 75cm (~30") channel through two connectors and a backplane. The demonstration unit transmitted the signal nearly three times the anticipated distance at less than 2% of the anticipated power. (Image courtesy of SiliconPipe)

Figure 3-24: An extreme application of flexible circuit technology can be found in the International Space Station (ISS) solar arrays built by Boeing under contract to NASA JSC. These are the largest solar arrays ever deployed in space with 16,400 cells/blanket and 262,400 cells total. (Image courtesy of NASA)

and the performance benefits have been proven in actual tests. The structure and results can be seen in figure 3-22.

SOLAR CELLS AND PHOTOVOLTAIC ARRAYS

Solar cell and photovoltaic technologies have made significant advances over the years. There are indications that solar cell efficiency may reach levels of nearly 50%, values only dreamed of in earlier times. Creating compact, high-density energy-generating solutions using solar cells is a task that is well-suited to flexible circuit technology.

The military has looked at rollup solar cell arrays as a lightweight solution for field deployable energy generation, making them a candidate for future commercial use as the world looks for ways to minimize dependence on fossil fuels. NASA is perhaps the technology's greatest proponent and uses it to sup-

Figure 3-25: Flexible circuits are used extensively in digital and video camera applications such as the one seen above. (Image courtesy of Chipworks)

ply energy to the International Space Station. The solar arrays in the deployed configuration are nearly the size of a football field and are capable of generating tens of thousands of watts at voltages up to 160 (fig. 3-24).

STILL AND VIDEO CAMERAS

Product development engineers in Japan were quick to recognize the capabilities of flexible circuit technology for a wide range of products. One of the early beneficiaries was the camera industry. As more automated functions were integrated into film-based cameras, flexible circuits were employed to provide power for motors, light meters and range finders. With

the emergence of digital imaging in the early 1990s and hand-held video cameras shortly thereafter, flexible circuits expanded their interconnection role in the technology, increasing both the number of features and the quality and performance of the products (fig. 3-25).

RADIO FREQUENCY IDENTIFICATION AND SMART CARD CIRCUITS

New applications and significant growth for flexible circuits exist in radio frequency identification (RFID) technology and smart card technology, which are being increasingly employed for inventory control and security access. In some cases, sensors capable of detecting humidity, shock/vibration, light, radiation, temperature and atmospheric chemicals (e.g., ethylene, which can artificially accelerate the ripening of fruit in storage) have been mated with active RFID devices to monitor and track products, livestock and even people. Flexible circuits are ideal candidates due to their thinness and amenability to

Figure 3-26: Two examples of RFID applications with IC chips attached, in the center of the circular device and at the top in the rectangular device beneath it.

mass production at low cost. The circuits themselves are rather simple, often not much more than a coil with an interconnected chip. Coil circuits can power up the device inductively for inquiry and/or receive and transmit data.

VOLUMETRIC SYSTEM MINIATURIZATION AND INTERCONNECTION

As the electronics industry moves to ever higher data rates for digital electronics, electronic interconnection technologies, such as flexible circuits, are staged to take an ever more prominent role. While semiconductors will, no doubt, continue their transistor doubling march to the tempo of Moore's Law for at least a few years longer, the performance benefits will likely continue to be bottled up unless there are suitable interconnection structures to help performance break loose.

Even without the doubling transistor effect, a significant number of interconnection solutions have been developed over the last few years to improve the density of semiconductors in ways that border on wizardry. The magic being performed by the IC packaging community includes methods of stacking either chips in packages, packages on packages, packages in packages and even wafers on wafers with the benefit of through silicon via (TSV) technologies. Since the advent of the transistor, electronic product developers have been driven to increase the density of semiconductors and make their products ever smaller while offering ever greater levels of performance at lower cost. As fundamental building blocks of electronics, IC packaging technology developers have been at the leading edge of this ongoing effort.

In recent years IC packages have been reduced to the size of the chip with the development of chip-scale, chip-size and wafer-level packages. These densification technologies have advanced the long-held industry objectives of smaller, faster and cheaper. However, the reduction in IC packaging to chip-scale

Figure 3-27: Sampling of 3D interconnection concepts for making high-density electronics modules.

and stacked package solutions has shifted the responsibility of providing interconnection pathways between these miniature devices and the substrates. The result is that interconnection substrates are increasingly complex and more costly as manufactures try to apply old solutions to the challenges presented by this technological evolutionary shift.

To adequately address the demands of future systems, next-generation product developers must design and manufacture their systems based on a new paradigm that considers electronic interconnection more holistically. This is especially true as current generation electronic packaging and interconnection technologies move into the third dimension with new and various stacked-chip packaging and stacked-package solutions. The transition to the third dimension marks both a departure from and a continuation of the old ways and long-held views of electronic interconnections. Figure 3-27 offers a historical look at 3D solutions over time.

3D is a natural and ideal play for flexible circuit technology. An appropriate descriptive term is being used in some circles to describe the overarching objective: Volumetric System Miniaturization and Interconnection Technology (VSMI). The idea is to provide product developers with a broader view of electronic interconnection technologies as they address complex volumetric interconnection challenges. VSMI technology speaks openly and directly to the activities that must be addressed to meet the interconnection needs of future electronic systems, where matters of component assembly, device integration, interconnection and thermal management transition to a higher level, both in complexity and importance. The term VSMI, in contrast to earlier interconnection terminology, provides a visual image of the challenge faced by today's electronic interconnection and packaging technologists.

The umbrella of VSMI technology includes stacked-chip packages, stacked-packaged chips, stacked wafers and multichip modules and packages that are moving rapidly into volume production. Also included are the novel flexible interconnection concepts of folded and multisurface package connections that are beginning to populate the electronic interconnection horizon. By holding to a term that accurately describes the technological focus and direction, product designers can more easily visualize their primary challenges and consider potential solutions. It also gives rise to consideration of what have often been considered ancillary challenges. For example, in the transition to VSMI technology the importance of considering the thermal impact of electronic component density increases. While the potential cost and performance boosts to be gained by employing VSMI, especially those involving flexible circuits, are alluring, the increase in energy density of such miniaturized systems cannot be ignored. The VSMI technology concept openly embraces the integration of thermal solutions and actively includes them in the overall concept.

Figure 3-28: Flexible circuits can facilitate the construction of VSMI assemblies by allowing new levels of interconnection to be created such as the prospective stacked X architecture interconnection solution illustrated above.

Another key element of VSMI technologies is that it considers electrical test early in the process. With increased density, testing has the potential to be either greatly simplified or made exceedingly complicated, depending on how the system designer approaches the challenge. Test and burn-in of stacked, flexible, folded and multichip modules and multichip packages have already created a host of unusual challenges for

product developers. The risk of having one chip among many fail, rendering the multichip device useless, continues to cause consternation for both product developers and users and must be carefully considered before taking on such approaches. Current experience is encouraging that these approaches will deliver the desired yields with careful consideration of the semiconductor technology employed and wafer yield history, but it has not yet provided a green light for all die. Thus, the VSMI technologist is tasked with making sure these important considerations are fully vetted prior to implementation.

In short, the electronics industry is entering a new age wherein the task of electronic packaging and interconnection will be elevated to a new level of importance that is more consistent with the challenges it faces and the myriad of benefits it will ultimately provide, and flexible circuits will be playing a vital role.

FLEX CIRCUIT INNOVATION TRENDS

A cursory review of US patents issued over the last 15 years indicates that flexible circuit innovation is alive and well. Moreover, it appears that the technology is proving to be an exceptional enabler of and platform for electronic innovations.

Flexible circuit technology is full of food for interconnection thoughts and technology dreams. The third dimension that it effortlessly offers to the savvy circuit or product designer provides an endless array of interconnection possibilities and products of every size, shape and application.

The US Patent and Trademark Office (USPTO) online database of patents issued (http://www.uspto.gov) provides the capability of browsing the myriad of innovations based on or enabled by flex circuit technology. It can also provide an opportunity to see where flexible circuit technology might be headed.

The USPTO search tool, which allows users to look for innovations in a number of different ways, was used to deter-

mine the rate of innovation over the last ten years. While, users can search using keywords and such, additional filtering elements allow users to increase the specificity of their searches. The search employed to gather information for this book was relatively coarse but adequate for a quick overview, with the only limiter being that the term flexible circuit or flex circuit be included in the body of the text of the patent. The search was repeated for each of the last 15 years (1996-2010) and the results are included in Table 3-1. The data indicate that the pace of innovation expanded rapidly in the late 1990s, and after stabilizing for a couple of years is now back at a high level. For example, the number of patents issued in 2010 is nearly four times the number issued in 1996. The last few years hint that interest in flex circuit technology is on the rise again.

To get a sense of the diversity and areas of application represented, the patents issued in 2010 were reviewed as a

Table 3-1: Number of US patents issued by year from 1996 to 2010 that included the term flexible circuit or flex circuit in the body of the text.

separate group by examining their titles which briefly describe the innovation. The results of this effort were revealing, if not surprising. The dominant area of flex circuit-based patents was for disk drive applications such as head assembly suspensions. Medical and dental applications, including probes and sensors, were not far behind. These were followed by roughly equal numbers of IC package/electronic module and connector applications. Optoelectronics, which had some overlap with packages, was next. There were a few surprises. For example, there were a number of patents related to antenna design and a few RFID innovations, but fewer than might have been expected. Printers, especially inkjet printers, and print heads are still being advanced by innovation as well as keyboards. One area of innovation that was also well-represented was flex as an enabler for LED technology. The marriage of the two technologies seems like a great one and it will be interesting to see where it is applied.

Our analysis of US patents supports the theory that flexible circuit innovation is alive and well. With the exception of a roughly 13% drop in patents issued from 2004 to 2005 the trend for innovations using flexible circuit technology remains strong.

SUMMARY

Flexible circuit technology offers many viable solutions for those challenged with packaging electronic products. The list of flex circuit application drivers provided will undoubtedly grow in the coming years as the technology finds its way into more and newer product applications. Moreover, the technology is branching out to enhance the ability of electronics packagers to make interconnections at every level from the IC chip to the wall socket. The only limiting factor to finding further applications is the imaginations of the people designing and packaging the next generation of electronic systems. Hope-

fully, the examples shown here and in the remainder of this book will spark new ideas and show a clearer path to solving, or better yet preventing, future problems. **FCT**

FOUR

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Chapter 4

Process Challenges and System Applications in Flex

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INTRODUCTION

The ability to produce large-area, fine-pitch flexible interconnect is driven by a number of elements. Those elements are comprised of materials, processes, facilities, equipment, design, and engineering support. The demand for thin, fine-pitch flexible interconnect requires unique considerations that are not possible with traditional printed circuit board (PCB) technologies. Fine feature requirements, over large areas, must have clean process facilities and tooling. Most PCB facilities have limited clean-room capabilities and are often restricted to Class 10,000 in the pattern transfer area. Fine-pitch interconnect processing of structures with less than 100mm pitch requires clean process areas—i.e., Class 100-1,000–to be able to produce interconnect with acceptable yield. The clean-room facilities must also be augmented with tooling, processes, and operator controls for low-defect densities.

Figure 4-1: Examples of Flexible Printed Circuit Defects

Figure 4-2: Semiconductor, Flex, and PCB Comparison.

As shown in Figure 4-1, defects found on flexible interconnect can include trapped fibers, hole in trace, and conductor-to-conductor shorts. These defects are the result of particles generated from process materials or the process environment, including tooling, operators, and the process facility.

Many manufacturers have designed clean process tools that contain the work and protect it from an unclean facility.

As shown in Figure 4-2, flexible printed circuits, with respect to features and process environments, are at the intersection of their semiconductor and printed circuit board equivalents. Fine-pitch flexible interconnect resides at the intersection; tooling, facilities, and expertise from the semiconductor industry are more closely coupled to fine pitch.

In addition to requiring clean space and controlled defect densities, fine-pitch interconnect involves thin dielectric materials (<50mm) that are difficult to handle. Traditional panel processing requires special handling to prevent material movement through processing. In reel-to-reel or web-based pro-

cessing it is possible to tension the thin polymer substrate to control dimensional stability of the web. Temporary bonding of thin substrate materials has been developed by a number of companies, but the cost of generating the temporary substrate and the size limitations can be expensive while the release process utilized can be difficult to control and reproduce. Controlling substrate material movement during processing is critical for multilayer metal processing where registration is a key factor. The ability to register microvias to metal landing pads and the accompanying cover pads can limit manufacturing capabilities. Via pad size drives most vendor capabilities and, ultimately, dictates the routing densities that can be realized between the pads or restrictions.

A flex circuit with trace line widths of 25mm, 25mm diameter vias, and a core of 25mm-thick polyimide is shown in Figure 4-3. On the surface of that flex, a ~75mm-diameter human hair is visible. The presence of foreign objects of this size and smaller illustrates the need for clean processing facilities and tools and proper garmenting and particle controls.

GE Research has developed a method to tension thin-core polymer substrate materials and process them with conventional wafer-based semiconductor tools. This method allows for fine-pitch feature processing and enables the manufacturing source to process the material as they would traditional

Figure 4-3: Defects in Two-Metal-Layer Flex.

silicon-based semiconductors. Maintaining a consistent tension of the thin substrate material through processing allows for improved layer-to-layer registration, the ability to print and etch smaller features, and the use of advanced tooling. Some of the advanced tooling used at GE includes centrifuge, spin coaters, UV steppers, high-pressure scrub, metal sputter tools, and assembly equipment. The ability to pattern fine pitch and control layer-to-layer registration makes it possible to achieve fine pitch in multilayer constructions (6-8 metal layers).

The use of flexible printed circuits has become prevalent in diagnostic imaging systems; in particular, the flex shown in Figure 4-4 is utilized in an ultrasound probe. The circuit shown has features of 4mm-thick copper, 25mm-thick polyimide, conductor pitch of 50mm, and 25mm-diameter laser-drilled vias.

Test Element Groups (TEGs) or process monitor coupons are critical components in the fabrication of reliable, high-quality

Figure 4-4: Ultrasound Flex Circuit.

Figure 4-5: Test Element Group Design, Via String Coupon.

flexible interconnect. TEGs are routinely used for standard process control (SPC), certification of compliance (COC), and reliability or qualification testing. A number of standards can be used for interconnect compliance, such as IPC, JDEC, ASTM, etc. TEGs can be utilized as in-process monitors, for post-fabrication validation, and as reliability screening coupons.

In-process monitoring examples include resistivity or Kelvin test structures to insure metal thickness after plating operations. Four-point probe resistivity measurements can be performed, prior to pattern and etch operations, to measure uniformity of metal deposits. Other in-process coupon examples include lithographic resolution structures (critical dimension measurement vehicles), impedance coupons, elongation/ductility coupons, flexural endurance coupons, and via interconnect strings.

Via string coupons allow the manufacturer to test an array of vias (200-500) on the device panel for a measure of via integrity during and after circuit fabrication. Via integrity can be measured by passing current through the via structure to insure that sidewall metal coverage is adequate for the circuit operation environment. The via string can combine all metal

Figure 4-6 A & B: Common via defects.

layers and metal layer pairs to aid in troubleshooting process fabrication issues (via drilling, via cleaning, via metallization). This coupon allows for circuit troubleshooting and, if performed in-process, can save process time and costs by identifying issues early in a process cycle. Specific via string designs allow for accurate measurements of metal contact resistance.

Examples of post-fabrication test coupons include strip line structures for high-frequency calibration, assembly monitors (reflow/float coupons), elongation or flexural endurance test structures, and via strings. Many coupon designs are available for reliability tests, such as: via string monitors for thermal cycle, isolation resistance tests, flexure test structures, solder float coupons, and electro-migration testing.

Common via defects are shown in Figures 4-6a and 4-6b. In the former, a crack in the via sidewall resulted from stress during laser processing. In the latter, a layer of contaminant

Figure 4-7: SEM and Cross-sectional Images of Incomplete Via Plating.

is present, at the bottom of the via, due to incomplete laser plasma processing.

Another common via defect is shown in Figure 4-7. This defect resulted from the stress generated by passing current through interconnects. The via defect was attributed to incomplete plating of the via during copper electroplating.

In-situ via process monitoring allows for testing of via integrity after patterning of metal pairs in a traditional sequential interconnect buildup process. Via test structures can be stressed by passing current through the string to identify incomplete via plating and metal sidewall coverage issues (as shown in figure 4-7). The images shown in Figures 4-6a, 4-6b, and 4-7 illustrate multiple via process issues (cracking of interconnect at polyimide/adhesive joint, incomplete via drilling/cleaning, and incomplete metal sidewall coverage in the via barrel). The design of the test vehicle or TEG structure also allows for automated probing of flexible interconnect, whether it be resistivity mapping or DC resistance measurements.

The test standard 2.4.3 from IPC TM-650 is a method to measure flexural endurance of etched flexible printed wiring circuit patterns. The standard describes the tooling, test coupon, and method for testing. Resistivity is monitored in this test, as changes in the material due to cracks, and delamina-

Figure 4-8: Flexural Endurance Tester per IPC.

Figure 4-9: Flexural Endurance Test Pattern.

tion due to material flexure, will result in the loss of electrical connectivity.

GE Research has developed a version of the flexural endurance test based on the IPC standard. Added features to the tester include:

- Automated resistivity monitor with threshold
- Multiple circuit load (4–up)
- Pogo-pin quick connection
- Variable-speed motor
- Fine-pitch pattern (25mm traces)
- Automated data logger

GE Research has also developed a number of TEG monitor cells that are assembled as blocks in a library for use on multiple platforms (RF, DC, analog, PWB, thin core, silicon, etc). The TEG blocks can be assembled in the field area of the panel to aid in process monitoring, second-level assembly, and reliability screening. GE Research has also developed specific tooling to aid in the characterization of thin-core flexible interconnect materials. Examples of the tools include elongation test stands, flexural endurance systems, and automated electrical testing platforms. The TEG monitors are regularly used in healthcare, military, and commercial flex-circuit fabrication. These monitors are often used as screening tools for vendor capability demonstrations.

Figure 4-10: GE Fine-Pitch Flexural Endurance Coupon (array of trace pitch, 1-metal-layer vs. 2-metal-layer design).

Figure 4-11: Example of Data Output from GE Research Flexural Endurance Tester (Ultem polyimide film characterization).

Electrical performance, and the corresponding electrical functional testing, is also a critical aspect in flexible printed circuits. Procedures for functional testing are application–specific, but generally, basic function including impedance characterization is tested. Often, users overlook characterization of surface isolation resistance because its adverse impact on electrical performance in low-signal amplitude (microvolts, microamps) applications is not considered or because of the

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difficulties in obtaining valid data at low-signal amplitudes, especially in the environments required for isolation resistance testing.

Leakage currents, due to the presence of ions on the surface or within the layers of a flex circuit, occur in the presence of a voltage source and moisture. Most flex (and PCB) circuit manufacturers perform surface isolation resistance testing at the circuit level; i.e., total ion content is extracted from the entire circuit. This test method assumes a uniform distribution of ions; accordingly, it can lead to undetected risk for leakage currents, due to undetected high, local concentrations of surface or embedded ions. For example, given a total ion content limit of 5mg/in2, a 2" x 2" flex circuit would pass surface isolation resistance testing if the total ion content measured was 20mg. Clearly, if that 20mg was a single piece of sodium located in a very small area on the flex circuit, its potential to cause leakage current would be significantly greater than if that same 20mg of sodium was configured as a uniform layer on the entire flex circuit surface. The conclusion: Surface isolation resistance testing does not provide sufficient resolution to identify potential risk of leakage currents in flex circuits.

To understand the risk of leakage current and its adverse impact on system function, it is necessary to perform leakage current testing. In its simplest form, the leakage current test would be structured to allow for testing of the flex after twenty-four hours' exposure to ambient environment. The flex would then be placed in a humidity chamber (100%RH) for twenty-four hours. The flex would be removed, and leakage current testing would be repeated; due to the potential for moisture evaporation once outside the humidity chamber, leakage testing of the flex circuit should be completed in one hour, in ambient environment. Ideally, testing should take place in the humidity chamber, but the equipment, facility, and process challenges of in-situ testing may require non-ideal test methods.

Unfortunately, there is no industry standard or generic test limit for leakage current in flex circuits. The user must analyze the data to characterize and compare leakage current values for both ambient and high-humidity conditions with the application-and-use environment. If individual or specific lots of flex circuits show deviation from the norm, then those circuits are suspect and should be subjected to further testing and analysis. That analysis can include destructive testing, e.g., sectioning suspect circuits and subjecting those sections to ion chromatography to measure ion content locally.

SYSTEM-BASED FLEX APPLICATIONS

The demand for thin, lightweight, high-density interconnect continues unabated. Similarly, application strategies for satisfying the ever-changing and ever-growing demand for high-density interconnect continue to change. Since their inception, flexible printed circuits have evolved into a cornerstone technology of high-density interconnect. Flex has become a fundamental interconnect technology, from its first application in tape automated bonding (TAB) and corresponding simple, point-to-point configurations to the fine-pitch, multilayer designs that are commonplace in today's mobile electronic products. However, the approaches in using flex to satisfy the demands of high-performance, highly reliable systems with high volumetric density I/O are still evolving.

Following a familiar path of technology development, the use of flex has changed from first-level to second-level interconnect applications; more recently, the role of flex has been expanded to include system-level interconnect. At each point in its changing role in applications, flex technology has been modified to meet the application demands. For example, to meet the demands of die-to-die interconnect, the single-layer, via-less, point-to-point circuits found in 1970s TAB packaging sprouted additional layers. The transformation to multilayer

Figure 4-12: Silicon, Flex and PCB Minimum Feature Comparison.

interconnect required the development of new features such as vias for interconnecting layers; new materials such as adhesives to bond dielectric and conductor layers; and new processes and equipment for manufacturing the resulting incarnation of flexible printed circuits. As device I/O increased beyond the capabilities of existing multilayer technology, the trace and space features of flex were reduced. Over the past twenty years, feature sizes in flex such as conductor geometry, via diameter, dielectric thickness, etc., have been improved significantly. These improvements positioned flex for its now-dominant position in portable consumer, display, and medical electronics interconnect applications.

As witnessed over the past ten years, the reduction in interconnect feature size has slowed. At the same time, device I/O counts have increased as semiconductor features have decreased, according to Moore's Law. This disparity in interconnect and semiconductor feature size has created an interconnect "brick wall" that demonstrates the need for advancing the capabilities of interconnect systems. As shown in Figure 4-12, semiconductor device minimum feature size (and rate of

decrease in feature size) far exceeds the equivalent in flex and PCB technologies. The corresponding gap in interconnect capability has and will limit advances in electronic systems until advances in flex feature size, via diameter, layer counts, etc., are implemented.

Although the complexity of electronic systems has increased over the past ten years, the challenges in interconnect systems have been minimized due to the functional partitioning of electronic systems into key subsystems: encoding/decoding, processing, display, and power. Typically, flex is utilized for interconnection within a subsystem as well as for system interconnect.

As shown in Figure 4-13, laptop computers include examples of these types of interconnect.

As well, flex is utilized in advanced packaging products such as the thin memory module shown in Figure 4-14 and the 3D Multichip Module shown in Figure 4-15. Note that the four-device memory module has the same dimensions, including thickness, as a postage stamp. In 1999, when the MCM in Figure 4-14 was fabricated, 1Mbit DRAMs were used. Today that same MCM could be constructed using memory devices with far greater capacity without any increase in MCM size.

Figure 4-13: Apple MacBook Air (Image courtesy of iFixit).

Figure 4-14: 4 x 1Mbit DRAM MCM.

Further, these products show that there exists a hierarchy of packaging and interconnect technologies to satisfy electronic system requirements. In particular, because there is no need for flexure and there is no significant disadvantage in weight, the major interconnect technology in today's portable electronics systems is still PCB. Flex is relied upon to satisfy the need for thin, conformal, and flexible interconnect as well as to serve as the substrate of choice for attaching many (if not most) flip-chip and chip-scale packages. Flex and PCB have similar performance and reliability; cost can differ significantly, depending on the application. However, as every early-technology adopter knows, higher costs are expected and well tolerated at the early stage in new and/or advanced product introduction.

Figure 4-15: GE High-Density Interconnect.

As electronics miniaturization has continued, the use of flex in electronics systems has flourished. Rigid substrates, common in the first multichip module technologies, have been replaced with flexible printed circuits and either integrated or chip-on-flex.

Likewise, the use of flex as a substrate for electronic systems utilizing chip-sized and chip-scale packages has increased dramatically. However, during the period that flex has supplanted PCB as a substrate and increased its share as an interconnect technology, direct chip attach has been developed to circumvent the lack of high-density interconnect. For example, the earliest displays utilized in electronic systems included display electronics mounted on PCBs. These PCBs were attached to the display by means of a standard connector. Over time, PCBs with standard connectors were replaced by flexible cables, constructed using one to a few metal and dielectric layers, with standard and novel connectors. As the size of displays shrank to meet the demands of portable electronics, chip-on-glass technology was perfected. Directly attaching the electronics to the display I/O reduced the system I/O demands to a quantity compatible with flex capability. This is a key point to consider in the application of flexible interconnect.

The primary challenge in today's flex technology is its I/O capability, as determined by minimum feature sizes. For example, in single-metal layer (1ML) flex, trace and space widths as small as 10-microns have been produced using commercial processes, materials, etc. Even finer features have been produced, as shown in Figure 4-16, a transfer lithography process comprised of 4-micron-pitch (one-micron trace, three-micron space), flex configuration. Similarly, feature sizes in two-metal-layer (2ML) flex, the lion's share of commercial flex production, have been reduced to twenty-five microns. But minimum trace and space geometries do not tell the entire story of I/O capability for flexible printed circuits.

Figure 4-16: 4mm-Pitch Flexible Printed Circuit (Transfer Lithography).

There are many questions to pose when assessing the capabilities of potential flex suppliers; perhaps the most critical is, what are the supplier's minimum via land pad dimensions? The dimensions of the via land pad highlight the alignment capability of the flex supplier's processes and dictate the minimum pitch of the flex interconnect. Consequently, not all 2ML flexes with twenty-five micron features have equal interconnect density. Moreover, even though feature sizes are decreasing, I/O capability in flex is not increasing or, at a minimum, is not increasing at the same rate. Accordingly, second-level assembly continues to move closer and closer to the device.

As witnessed in chip-sized and chip-scale packages, by adapting an existing technology to a novel configuration, the unmet needs for very fine pitch, high volumetric I/O packages effected the reduction in use or elimination of standard electronic packages. Plastic encapsulated lead frames and multilayer ceramic packages have been replaced by plastic encapsulated flex interconnected bare die or, in many cases, by bare die. Similarly, the increasing use of direct chip attach results, in

part, from the inability of flex interconnect to meet the constant demand for higher pixel counts in displays. In this case, package interconnect by means of wirebonds with millimeters of length and flex interconnect of tens to hundreds of millimeters in length has been replaced by stud bumps (of tens of microns in diameter, produced using the same wirebonding equipment and materials) and the complete elimination of the flex interconnect. Electronic packaging technologists and applications engineers are currently developing similar system-based solutions and applications by revisions, enhancements, etc., to existing interconnect technologies in order to meet the never-ending demand for greater interconnect density and capability. However, even though its features continue to lag behind those of semiconductors, flex has and always will play a significant role in the optimization of system design.

To explore the shift from component-based to system-based design and its impact on flex technology and applications, it is useful to examine the recent development of a high-performance X-ray detector for GE Health Care's LightSpeed VCT CT system, a state-of-the-art computed tomography system whose image quality is dependent on many subsystems, especially the X-ray detector.

As shown in Figure 4-17, CT X-ray detectors have been fabricated using many of the technologies and processes common to hybrid circuits, such as ceramic substrates, wirebonds, etc. The detector (16 x 16 photodiode array) and flex interconnect are attached to the ceramic substrate and the photodiode array interconnected to the flex by wirebonds. This approach, including flex circuits, satisfied detector designs from the inception of CT systems. However, manufacturers of CT systems, in their response to constant market demands for both larger detector array size (to capture large-image volumes per imaging sequence) and finer resolution (by decreasing the size

Figure 4-17: 4-Slice CT Detector Modules.

of pixels while increasing the quantity of pixels) soon became limited by the package configuration and interconnect technology. Throughout the development of CT systems, designers had simply added signal layers and/or decreased the feature sizes of the flex interconnect to meet the demands for higher image resolution of patient coverage. Designers at GE realized that the interconnect demands of CT detectors were about to overtake, the capabilities of commercial flex interconnect. As a result, a significant development effort was begun to create an ultra-high-density flexible interconnect to take the place of the existing commercially-available flex circuits that were a mainstay of CT detector systems. After much brainstorming and development of conceptual designs, it was determined that this advanced commercial flex technology would not be available until long after the desired product launch date for GE's next CT system.

Given the constraints of existing commercially-available flex technology, GE's CT detector design team reassessed the interconnect requirements for their next-generation detector. As was customary for each new product introduction, the new detector had to provide twice as many pixels as its predecessor. And, to realize the "Holy Grail" of imaging the heart in a

single breath hold, the imaging area had to double. (Prior to LightSpeed VCT, imaging area increased but never by anything as great as a factor of two.) It was quickly realized that existing flex technology could satisfy the product demands, but only if the diode I/O configuration was changed to an area array. By transforming the I/O configuration from the traditional linear array to an area array, the need for ultra-high-density (four metal layers with a less than 50-micron pitch) flex vanished. GE Research's electronic packaging and IC designers teamed to develop a revolutionary new detector design, as shown in Figure 4-18, comprised of a photodiode array with backside I/O, in an area array configuration, and multiple flexes (six metal layers with 400-micron pitch), and analog-to-digital converters located in very close proximity to the detector. This approach eliminated the interconnect choke point that resulted from escaping diode signals at the periphery of the diode package. Consequently, the need for more complex and costly interconnect was eliminated. However, the total amount of flex circuit area increased, but not at a significant cost to the detector system. The GE CT detector team had not only found a solu-

Figure 4-18: GE LightSpeed VCT Detector Module.

Figure 4-19: LNA.

Figure 4-20: Balun.

tion to their product development challenges, but they had resolved the challenge of commercial availability of fine-featured flex by transforming the detector configuration through reliance on semiconductor features. As described previously, the improvement in feature capabilities in semiconductors far outpaces the equivalent in flexible printed circuits. Optimal packaging solutions are more readily available when all system components are included in a system-level packaging and interconnect design approach. Those who desire to implement flexible interconnect solutions in existing and future electronics packaging applications must embrace these principles.

Another example worthy of study is a novel solution developed for an RF Low Noise Amplifier (LNA). As shown in Figure 4-19, a conventional PCB with through-hole and SMT technology was used for packaging a very high-performance (0.5db noise figure) low noise amplifier for an MR imaging application. In this application, rejection of common mode currents is required. Accordingly, as shown in Figure 4-20, a balun is needed. As in all diagnostic imaging systems, there is an insatiable demand for greater pixel quantities and densities. With the corresponding increase in volumetric I/O density, due to fixed package volumes, the electronic systems (including packaging and interconnect) must decrease in size. The designers were asked to reduce the size of the existing LNA by at least a

factor of four, in area. However, the designers recognized that reducing the area by a factor of four would satisfy only the next product; future products would require area reduction of 10X or more. Accordingly, to avoid a series of minor changes, a major design change was required.

Reducing component size and optimization of circuit size were considered and rejected because that combination of design changes would satisfy only the near-term goal of a 4X area reduction. Replacing the PCB with a multilayer fine-pitch flex would have effected another 1X improvement in area reduction, albeit at an overall cost increase. It quickly became clear that a redesign of the LNA alone was not going to satisfy the long-term goal of a 10X reduction in area.

As shown in Figure 4-21, a novel system-based solution, LNA-Balun, was developed. As shown in Figure 4-22, a folded, 2ML flex with 50-micron features was used to replace the single-sided four-layer PCB. Through-hole components were eliminated. And, the flex was designed to fit inside the balun. By considering the LNA-balun system as the design space and relying on commercially available materials, technologies, assembly processes, etc., the designers were able to eliminate the entire volume of the LNA, as used in the existing product.

Figure 4-21: LNA-Balun.

Figure 4-22: LNA-Balun Flex Assembly.

Further, designers utilized flex where its salient features were applicable, acting on the principle that there is no technology that can or should be applied universally.

FLEX INTEGRATION

To achieve an optimal interconnect and packaging design, it is important to utilize flex only when flex best satisfies application and other needs. Flex is a good choice when the primary need is for flexible, conformal, thin, lightweight, etc. Flex is also a good choice for applications requiring comparatively high I/O density, low cost, or performance advantages that cannot be achieved in PCB constructions. Flex can be utilized in many applications other than the aforementioned "good choices"; however, the user is strongly encouraged to consider cables, PCB, and other suitable interconnect technologies or else risk unnecessary design complexity, reliability risk, system connector challenges, higher cost, etc. As in conventional electrical design, interconnect must be partitioned according to product specifications including performance, reliability, cost, et al.

Interconnect partitioning, intentional or otherwise, can be found in the hierarchy of interconnects that is in almost any electronic system. For example, although personal computers include state-of-the-art semiconductors and their corresponding nanometer feature sizes, the power for those semiconductors is supplied through cables that are constructed using 18-gauge or larger conductors. Likewise, packaging designers need to partition the interconnect chain to satisfy system specifications, requirements, etc., using "just enough technology."

As shown in Figure 4-23, a digital X-ray detector is comprised of an amorphous silicon detector panel and digital amplification and processing electronics. The pitch of the electronic devices that detect the converted X-ray signal can be as small as 100 microns. Their corresponding I/O are configured

Figure 4-23: GE Digital X-Ray Detector Assembly.

in a 150-micron-pitch linear array, along each of the four edges of the panel. The choice in detector panel I/O pitch is limited by the I/O capability of high-performance, highly reliable, flexible printed circuits. Flex was chosen because it is flexible, a requirement for packaging a digital X-ray detector in the same form factor as the film canister used in conventional X-ray imaging, and for ease of manufacturing; in particular, the ease with which the flex can be connected to the 150-micron•pitch detector panel I/O using anisotropic conductive film (ACF) was a significant factor in the use of flex interconnect.

The flex that interconnects the detector panel and signal processing electronics is a 2ML, 150-micron pitch design. One end of the flex is bonded to the panel; the other end is bonded, using ACF, to a multilayer PCB. Multiple ASICs (in bare die form) are attached, in a linear array, on the PCB; the ASICs are wirebonded to the PCB. The ASICs amplify and convert the analog signals produced by the detector panel and route those signals through a connector to a second flexible printed circuit that connects to the system electronics. The second flex, because of multiplexing of the digitized signals, requires fewer

signal conductors; thus, it is a low-density 2ML flex (signal plus shield layer).

The next logical step in packaging optimization for this type of electronic system would be the integration of the ASICs and ancillary electronics into the flex. This integration step, if done properly, would replace the PCB with flex, reduce the number of interconnects, and reduce detector panel manufacturing steps, without increasing the cost of the flex-PCB-flex system, as above.

PRINTED ELECTRONICS

Interconnect technology is expanding to include printed systems. As detailed in the iNEMI Organic and Printed Electronics Roadmap, shown in Figure 4-24, there is a bounty of printed electronics technologies, such as "drop on demand," Xerography, micropen, etc. It is not within the scope of this chapter to detail the principles, advantages, benefits, etc., of each printed electronic technology (more detail is provided in Chapter 11 – Printed Electronics). Rather, it is the intention here to stress that electronic packaging and interconnect designers understand the salient features of printed electronics and digital fabrication technologies as well as the similarities and differences among conventional printed circuit technologies and processes.

Digital fabrication can be viewed as the creation of electro-optical-mechanical-thermal systems by means of either parallel or sequential additive processes, as controlled by a digital device. As with any technology, the designer should consider and take advantage of the technology's features before applying it.

In choosing an interconnect technology, it is important to consider the unique features of the candidate technologies and the corresponding benefits to the application. In particular, consideration of a technology's unique features helps guide

		Lateral Resolution (µm)	Average Dry Thickness (µm)	Benefits	Critical Processing Parameters
Contact	Gravure	>15	0.8 – 8.0	• Hardware and functional inks are commercially available • Low-cost, high speed parallel processing • Demonstrated repeatability	• Particle size and distribution in ink • Solvent evaporation rate • Rheological properties • Substrate surface energy • Imprint load • Printing speed
Contact	Flexo	>20	0.8 – 2.5		
Contact	Offset	>15	0.5 – 2.0		
Non-Contact	Inkjet	>50	0.3 – 10.0	• CAD data driven: "on-the-fly," maskless changes; adaptable to error • Conformal and 3D printing • Multiple materials	• Particle size in ink • Solvent compatibility • Rheological properties • Substrate • Jetting distance • Environment
Non-Contact	Micro Dispensing (SUBSTRATE)	>50	5.0 – 100.0		

GE Proprietary

Figure 4-24: Comparison of Printed Circuit Methods.

users to a choice based on how that technology uniquely satisfies an application need. For example, when considering digital fabrication, it is important to recognize that printed circuits, compared to circuits fabricated using conventional processes (e.g., lithography) offer fully additive and large area processing. Further, many printing technologies offer serial processing. As well, some printing processes offer the opportunity to form circuits directly on surfaces, including curved (uniaxial, as shown in Figure 4-25) curvilinear (multiaxial) surfaces. If an application is best served by one or more of these unique features, outcomes, etc., then choosing digital fabrication over conventional processes makes sense. Conversely, if the application does not require additive, large area or serial processes, especially for curvilinear applications, then digital fabrication may not be the best choice. One way to be sure that a technology is being optimally utilized is to first consider its unique features and benefits, and then compare them with the application need.

Figure 4-25: Printed Circuit on Curved Surface (Image courtesy of Alejandro Briseno/Stanford University).

Most often, digital fabrication is accomplished in a roll-to-roll process, but panel-based digital fabrication is also possible. The revolutionary aspect of digital fabrication, as compared to conventional printed circuits, is the ability to simultaneously create electronic and/or optical devices, electrical interconnects, mechanical structures, and thermal management systems. For example, using conventional technology and processes, a television remote control is produced by packaging and assembling tens to hundreds of electronic devices onto PCBs and subsequently assembling the PCBs, interconnect, LED, touchpad, etc., within a plastic housing. Digital fabrication would allow the entire system to be fabricated, layer-by-layer, in a fashion similar to that of stereolithography apparatus (SLA). Applying digital fabrication requires a transformation in thinking by electronic system designers: digital fabrication provides for the 2D and 3D design and fabrication of systems that are not limited to electrical interconnect and passive devices.

In digital fabrication, materials with the necessary electrical, mechanical, thermal, and optical properties to form the desired devices, systems, etc., are deposited onto a substrate. Polymer and plastic are the most common substrate materials, due to their compatibility with low-cost, high-volume processing. However, rigid substrates can be used as well. The materials used in forming electronic devices and interconnect are, typically, conductive inks and dielectrics. Any material, however, that can be dispensed by the dispensing system ("print head" plus material control) can be used. The materials used in forming mechanical and thermal structures, likewise, are defined by the application and limited by the capabilities of the "print head" and material control system. To date, biological, organic, optical, and many types of functional materials have been printed.

Given that devices and structures are being "built-up," layer-by-layer, there are key differences in the resulting device and feature attributes. For example, vias can be formed as filled or partially filled and can be conductive and/or nonconductive, electrically and/or thermally. Unlike conventional printed circuit technology and processes, digital fabrication can be

Figure 4-26: Printed OLED Array.

Figure 4-27: Device Speed and Stability Specifications.

used to produce vias of any geometry. Similarly, individual traces can be of any geometry and can be produced to effect sidewalls with attributes to support application needs. Conductors produced using conventional printed circuit technology have sidewalls that are tapered or orthogonal. Digital fabrication could be used to produce conductors with regular or irregular sidewall features, as related to specific performance or mechanical applications. Furthermore, in digital fabrication, mechanical, thermal, and other features could be included in the construction of conductors.

Currently, the primary applications for printed electronics are OLEDs, as shown in Figure 4-26, and RFID. Photovoltaics are also an application for printed electronics, but this field is immature compared to OLEDs and RFID.

Transistors that operate in the tens of megahertz have been printed. Researchers at the University of Illinois (Rogers, et al.) have printed silicon circuits on plastic that operate at switch-

ing speeds of 500 megahertz. As shown in Figure 4-27, there are demands for printed, stable, high-speed digital and high-fidelity analog devices; however, materials to produce devices other than low-speed, simple ones are lacking. Accordingly, other than novel devices produced in laboratories, printed electronics have not been used to produce the basic "building-block" high-speed digital or analog devices (e.g., FPGAs and operational amplifiers, respectively). These components are fundamental to systems comprised of analog devices.

Similarly, with respect to printing electrical interconnects, digital fabrication is in its infancy. Plated vias, a staple of the layer-to-layer interconnect found in conventional printed circuit technology, are nonexistent or crudely implemented in many digital fabrication technologies. Moreover, the electrical performance and reliability of vias and conductors are either not known or not well characterized for the variety of potential commercial applications. It will be interesting to observe if and when the creation and maintenance of electronic and interconnect standards are realized. Similarly, assembly methods and materials and their performance and reliability are not well known, especially for systems comprised of conventional and digital fabrication technologies and processes. These "hybrid" systems are evolving and over the next few years, there will be many challenges and knowledge gathering that will further technology development of electronic systems constructed using printed interconnect and digital fabrication. **FCT**

FIVE

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He has chaired the IPC's UL Task Group for Flex Materials since 1997 working with UL to write flexible circuit and material Standards UL796F and UL746F, respectively. He also chairs the Flexible Test Methods D-15 Group. Duane has been a strong contributor to the IPC's Flexible Base Materials and Metal Foils Standards over many years. He has been the recipient of several IPC Special Recognition Awards for his work in these areas.

Duane is recognized as an industry expert in the field of thin film dielectric materials, having developed a variety of high performance platform adhesive systems for flexible circuit applications. Duane has twice won the Presidential Award of Excellence for his accomplishments.

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Chapter 5

Flexible Circuit Materials

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INTRODUCTION

Base materials are the foundation elements of every flexible circuit in use today. Over the last six decades of flexible circuit technology, a wide variety of both dielectric materials and conductors have been employed in the fabrication of flexible circuits. As touched on in Chapter 2 - Flexible Circuit Technology Past, Present and Future, one of the earliest descriptions of what could be called a flex circuit can be found in a 1903 British patent issued to Albert Hansen that referred to a construction consisting of flat metal conductors on paraffin coated paper. Another conceptual substrate was the linen paper construction with patterned circuits of graphite-loaded gum adhesive that Edison described to his then assistant Frank Sprague (later of Sprague Electric fame), perhaps in support of some of Sprague's electrical motor ideas. Actually, the disclosure was one of many prescient moments in Edison's life as an inventor, for it turns out he was not far from future developments in his thinking. Polymer thick film and additive circuits of today fit well under the umbrella of the structures he described more than 100 yeas ago. More recently, paper has been mentioned yet again as a substrate for printed electronics, a branch of flexible circuits. Chapter 11 – Printed Electronics will show that the idea of printing transistors on paper is much older than one might imagine and was demonstrated in the 1960s.

While many different materials have been tried and used to some degree over time, only a few base materials are in broad use today in flex circuit construction. This chapter will examine those common materials along with some newer choices for flex circuit applications. First, however, it is worth reviewing what is desirable from a flexible circuit base material to establish a baseline for expectations.

DESIRABLE CHARACTERISTICS FOR FLEXIBLE CIRCUIT LAMINATES

There are some very good materials employed to make flexible circuits, but there is no material available today that could be called a panacea, having every positive attribute and no drawbacks. This assessment is based on the fact that there are a number of different criteria that are used to identify and define the important and desirable properties of materials used to create a flexible circuit laminate. This list of desirable properties circumscribes a broad spectrum of needs and/or demands that might be placed on a finished flexible circuit in an application. While no known material can address all of the sometimes conflicting requirements that the manufacturer and user might want from a material, it is still of some value to have a mental picture of an ideal product as a means of keeping in mind what trade-offs may be required when selecting an appropriate substrate for a product or application. Over time many material combinations of films, foils and/or adhesives, as well as processes and specialized equipment, continue to be developed, providing new possibilities to meet the growing demand for smaller, lightweight, higher speed circuitry for devices requiring less energy consumption with more functions and capabilities. A smart phone is one such device, along with components of the infrastructure to support it.

A typical flexible circuit today is composed of a thin base

dielectric polyimide (PI) film at a thickness of 50 to 125 microns in thickness (2 to 5 mils) with 1 to 3 oz. copper gage, with or without adhesive. Thinner gages are available, but flexible circuits with the dimensions described are regularly manufactured with good yield and good tolerances, and board/circuit fabricators have learned to handle these materials to also have reasonable yields in high-volume environments, especially in semi-automated and automated processes.

DIMENSIONAL STABILITY

The flexible laminate should be dimensionally stable. Shrinkage or expansion of a flex circuit base material during processing is a concern for both manufacturer and user since it can effect both the fabrication of the circuit and its assembly. It is especially frustrating when dimensional change is not predicable.

While materials vary in their dimensional stability, there are a number of different ways to combat the effects of dimensionally variable materials, which will be explored in more detail in Chapter 7 – Practical Design Guidelines for Flex and Chapter 9 – Flex Circuit Manufacturing Processes. However, it is a definite advantage in manufacturing to avoid resorting to such practices. New film chemistries and processes have helped in this area by allowing for the trend of thinner materials offerings. Examples of these new PI films and properties are described later in the chapter. The parameters that affect the dimensional stability of base dielectric materials, in order of importance, are:

1) base film type and characteristics related to that chemistry
2) process parameters used in manufacturing
3) adhesive type (if used)

THERMAL RESISTANCE

Because most electronic assemblers use elevated temperature processes such as reflow soldering for component assembly, the flex circuit material chosen for use in manufacture should be able to reliably withstand normal assembly process temperatures without distortion. With the well-meaning, but scientifically ill-advised and unwarranted, mandated move to lead-free soldering in Europe, there will be added pressure to improve thermal resistance performance. Unfortunately, lead-free solders have further limited the choice of materials, forcing the user to address the challenge with either more expensive materials or more expensive low melting point solder when soldering is required. This, along with regulations regarding halogenated flame retardants, has caused many materials to be reformulated or discontinued.

TEAR RESISTANCE

Most flex circuit constructions use thin, unreinforced base materials making them vulnerable to tearing. As a result, a base material that is highly resistant to any tearing, both in terms of tear initiation and tear propagation, is preferred in flex circuit manufacture. While there are design techniques to mitigate tearing concerns (see Chapter 7 - Practical Design Guidelines for Flex), given the thin and somewhat delicate nature of flexible circuit base materials, tear resistance is a valuable attribute.

ELECTRICAL PROPERTIES

Electrical properties of materials has become more important over the years as high frequency digital and analog signals (rather than DC circuits) become required for more and more products, and will continue to increase in importance with the rise in signal speeds. Materials for flexible circuit applications should have electrical properties tailored to the performance needs of the design. With high data signaling speeds (greater

than 100 MHz) becoming more common, the material's dielectric constant (Dk) and loss tangent or dissipation factor (Df) should be low. In addition, high insulation resistance is a desirable property for various high voltage applications. However, for some applications the requirements can be different, such as applications where higher capacitance is desired and a high Dk is specified. Fortunately there are many prospective materials to meet divergent needs.

One aspect of design that has been overlooked due to the low speed typically used for flex circuits is that the adhesive, the material, actually in contact with the conductor, is also a dielectric and contributor to the electrical performance. Most design guidelines are based on the base dielectric film, but as these become thinner and the higher speed requirements or controlled impedance designs for flex come up, the adhesive component can be more of a factor. A low Dk/Df adhesive or bonding layer can reduce polyimide thickness while also reducing cost and space.

FLEXIBILITY

A fundamental material feature, flexibility is very often a critical attribute. Depending on the application, flexible circuits can be exposed to extremes of temperature, from cook stove hot to cryogenically cold, making flexibility over a wide range of temperature important. Of particular importance is flexibility at low temperatures where most materials tend to become brittle. It is worth noting that many materials are flexible if they are thin enough. Even silicon, as brittle as it is on the macro scale, can be quite flexible if made extremely thin, such as in the range of a few microns. Flexibility requirements can also vary depending on the application and actually may be tested differently in various materials areas, so defining the applications and mode of end use, as opposed to test data provided by a supplier, are critical when selecting a material.

LOW MOISTURE ABSORPTION

Moisture absorption is definitely not desirable for any flexible substrate, or any rigid substrate for that matter. Moisture can negatively impact the manufacturing process by causing delamination in process and assembly and degrading the performance of the finished product by altering the material's dielectric constant and increasing signal loss. Moisture in the environment varies significantly in the different parts of the world where flex circuits are fabricated. Controlling moisture can be difficult and expensive, so it is best to understand the aspects of the materials being used and how designs or processes can accommodate potential variation.

CHEMICAL RESISTANCE

Depending on the application, a flex circuit material's ability to resist a range of different chemicals is important to both the manufacturer and the end user. For the manufacturer, the many different corrosive chemistries used in flex circuit fabrication cause concerns about how well the material will stand up to processing. The material must be compatible with a wide range of process chemistries and common solvents used in assembly and cleaning processes.

Due to worker safety and environmental concerns, many process chemistries and materials have been removed from use and replaced by newer materials. For example, etch resists are now removed by caustic aqueous solutions that are safer than earlier chemistries such as methylene chloride and methyl ethyl ketone (MEK) which were commonly used at one time for cleaning circuits. Currently, more benign solvents or green cleaners are being introduced and the compatibility of their chemistries need to be understood with regard to flex circuit materials. Other methods, such as plasma cleaning and other non solvent type cleaning procedures, have been commercialized as ways to clean adhesive from pad areas without expos-

ing circuits to hazardous solvents and dealing with chemical adsorption issues. Chemical resistance in end use may now be more of a concern when selecting an adhesive, coverfilm or covercoat. A prime example is ink jet cartridges or ink printing systems where the ink may be in a caustic solution that could attack and/or swell any exposed adhesive causing problems in end product performance.

LOT-TO-LOT CONSISTENCY

Variation is the bane of manufacturing, so product consistency is vital to good process control. While Six Sigma quality targets may never truly be obtained in manufacture, extreme consistency of physical, mechanical and electrical material properties is key. A high level of consistency will provide assurance that the product will perform well both in manufacturing and in the field.

With regard to managing dimensional stability, circuit manufacturers can adjust artwork or tooling for a standard known shrinkage, but making changes from lot to lot is not a viable option, especially considering the costs of hard tooling. When mass production is in place, flex material lot testing and pre-selection for production to match art work and tooling are cost-prohibitive operating procedures, especially as products are getting smaller and smaller. Alignments over larger areas are necessary to make systems more cost effective and less labor intensive. Layup of individual coverfilm pieces can be performed if necessary to address the problem; however, the layup of a single 12” x 18” sheet is much more cost effective.

MULTIPLE SOURCES

A great concern for manufacturers is the situation where only a single source is available for a product. The vulnerability of both the manufacturer and the customer can unfortunately preempt the use of a single source material that may

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otherwise have excellent properties. In most cases, existence of a second source capable of producing an equivalent product is a prerequisite to making a material choice.

Depending on the program volume, the cost of qualification for secondary sourcing is not always a viable option. Some designs are not critical and any material will work and others have materials designed in, which make one supplier's material hard to replace, especially when it is unique.

LOW COST

The pursuit of low cost solutions is a universal activity in electronics. It is inevitable that there will be a never-ending push to seek lower prices for the material so that both the manufacturer and the user can enjoy slightly better profit margins. However, it is important thing to bear in mind that the real value of a product is best measured in terms of how it impacts the total cost of manufacture and the finished product, not in terms of how much it costs to get the material in the door.

If low cost is the only concern, potential problems often lie ahead. A new material may be cost less, but may also require a different processing It may also look different, which can be a concern even if it is better. With respect to the adhesive choice and copper types, there are often preconceived notions among users and suppliers as to what materials are best based on their individual history of use of and familiarity with a product. In the Western hemisphere acrylics are better known and have a longer history, whereas epoxies are better known in the East (Asia). For copper, red oxide treatment on RA copper is most common in the West, whereas a black colored treatment (not black copper oxide) is most common for RA copper in the East. In Asia, a red coloration indicates ED copper and is commonly suspected to be of a lower quality, just by its appearance. In contrast, in the West, black color is confused with black copper

oxide. Copper oxide is not compatible with the typical acrylic due to high causticity of the black oxide copper treatment and the poor caustic resistance of the typical acrylic which results in a poorer bond. The epoxies and acrylics may require different storage conditions and laminating and perform better in certain aspects, but are not always accepted based on preconceived notions or an unwillingness to change.

With these desirable material attributes fresh in mind, it is possible to review the basic elements of flex circuit materials and some of the typical substructures of flex circuit construction and understand where the limitations are relative to meeting the full complement of objectives.

BASIC CONSTRUCTION ELEMENTS FOR THE MANUFACTURE OF FLEXIBLE CIRCUITS

Since there are so few basic elements of construction of a substrate for flexible circuits, each has its specific importance. Each element of the flex circuit construction must be able to consistently meet the demands placed upon it for the life of the product. In addition, the material must play reliably in concert with the other material elements of the flexible circuit construction to ensure ease of manufacture and reliability. The following are brief descriptions of the basic elements of flex circuit construction and their functions.

BASE MATERIAL

The base material is the flexible polymer film that provides the foundation for the laminate. Under normal circumstances, the flex circuit base material provides most of the primary physical and electrical properties of the flexible circuit. In the case of adhesiveless circuit constructions, the base material provides all of the characteristic properties.

While a wide range of thicknesses are possible, most flexible films are provided in a narrow range of relatively thin

dimension from 12µm to 125µm (0.5 mil to 5 mils). While experience shows that thinner materials are more flexible, it is worth remembering the engineering principle that with most materials, stiffness is proportional to the cube of thickness, meaning that if the thickness is doubled, the material becomes eight times stiffer and will only deflect 1/8 as much under the same load.

That aside, new film chemistries and processes are being developed with an understanding of the impact of the various properties, the needs of circuit materials manufacturer (converter) and end use properties (circuit manufacturer and user). This has led to an ever-increasing capability of manufacturing smaller and smaller circuitry with lower cost and higher performance. New film types, a better understanding of processes and investment by base film manufacturers over the years have resulted in greater benefits to those who embraced them early.

BONDING ADHESIVE

Adhesives are used as the bonding medium to create a laminate, but are also an important part of the dielectric system of the circuit. Note that laminate is a generic term in this industry used to describe a metal clad film used to make a flexible circuit. When it comes to temperature resistance, the adhesive is also typically the performance-limiting element of a laminate, especially when polyimide is the base material. Because of the earlier difficulties associated with polyimide adhesives, many polyimide flex circuits presently employ adhesive systems of different polymer families. However, some newer thermoplastic polyimide adhesives are making important in-roads. While thermoplastic polyimides generally offer higher temperature capabilities than most adhesives, many of them will still soften under high temperature and load, such as some bonding processes that can cause land or pads to move. The best performing new materials are those thermoplastic/thermoset

polyimides that resist movement. While they are adhesives in a true sense, these laminates are often called adhesiveless, and a better name is perhaps all-polyimide systems.

As with the base films, adhesives come in different thickness. Thickness selection is typically a function of the application. For example, different adhesive thicknesses are commonly used in the creation of coverlayers in order to meet the fill demands of different copper foil thickness that may be encountered. Many suppliers have a standard adhesive base laminate thickness, but can alter the material depending on controlled impedance requirements or other needs of the customer. Thinner adhesives allow for better flexibility, bringing the copper closer to the base film. Thinner adhesives can also bring down cost since they can normally run faster at the converter and use less overall material, which could be expensive depending on the material formulation used.

It is not uncommon for a particular adhesive thickness to be used to create a coverlayer to meet the fill demands of one type of circuit, while for circuits with different copper-foil thicknesses, a different thickness may be called out. Finally, best practice seeks to have the same amount of adhesive on the top of the trace as below the trace in a high dynamic flex area. This is described more fully in Chapter 7 – Practical Design Guidelines for Flex.

METAL FOIL

Metal foils are most commonly used as the conductive element of a flexible laminate. The metal foil is the material from which the circuit paths are normally etched. Although typical flexible circuit laminates are created using rolled and annealed copper, a wide variety of metal foils of many different thickness are available from which to choose and create a flex circuit.

The typical flex copper used is the alloy C110, which is considered a low oxygen content copper that is known to be

more ductile. The copper used is rolled, but not annealed until later in the process of curing the adhesive of the laminate, making the copper less prone to damage in processing and still relatively hard. Malleability is not truly required or needed until the foil is in its intended use. However, when properly supported by a cured (hardened) adhesive and base film, these materials will mitigate damage concerns. The hardened state also allows the converter to apply the pressure needed on the stiffer copper damage to get proper wet out of the adhesive that conforms to the rough treated side of the copper, allowing for good green bond and full adhesion as the adhesive cures.

In certain nonstandard cases, the circuit manufacturer may be called upon to create a specialty laminate by using a specified alternative metal foil, such as a special copper alloy or other metal foil in the construction. This is accomplished by laminating the foil to a base film with or without an adhesive, depending on the nature and properties of the base film.

FLEXIBLE CIRCUIT MATERIAL FORMATS

With an understanding of the basic constructional elements of a flex circuit, it is possible to mix and match these elements to create the different materials that can be required in the manufacture a flexible circuit. The following are descriptions of the basic material forms used in flex circuit manufacture.

LAMINATES

Metal foil clad laminates are the basic form of material used for most flexible circuit constructions. While copper foil dominates applications, other foils can be used.

Typically, a laminate is created by bonding together a sandwich comprised of a base material, an adhesive and a metal foil. The stack is then subjected to sufficient heat and pressure in a laminating press to create a permanently bonded metal polymer laminate.

In the case of adhesiveless laminate substrates, the adhesive would be absent from the construction. Some adhesiveless laminates use a thin layer of high temperature adhesive to create a laminate structure that fundamentally achieves the same objective. There are also ways to create adhesiveless laminates without a lamination process, which will be discussed in more detail later.

LAMINATED COVERLAYERS

Normally, a coverlayer is a two layer material comprised of a base material and a suitable thermosetting adhesive. However, suitable homogenous thermoplastic films may also be used as coverlayers. The coverlayer protects the conductors of the finished flex circuit and enhance flexibility, a topic that will be discussed in greater detail later.

Coverlayer materials are commonly used to create flexible laminates by bonding them to metal foil. This is the typical case when a flex circuit maker manufactures his own material. It is also typical for those that make heater circuits since there are few manufacturers of dedicated heater circuit laminate materials. Companies that make heater circuits typically buy coverlay and use Inconel, nickel-copper, NiChrome or other resistive foils to make their own laminates.

One process used to get a low-cost backside access circuit starts with predrilled/punched coverlay to make a laminate, which alleviates the need to chemically or plasma etch through the polyimide and adhesive later to get to the copper.

PHOTOIMAGEABLE COVERLAYERS

Another type of coverlayer used in flex manufacture is a photoimageable coverlay, often identified by the acronym PIC, which is akin to dry film solder mask. Like solder mask, it requires vacuum lamination to ensure a good seal around the

circuit traces. Then, just like a photoimagable solder mask, the material is exposed and developed to provide access to circuit component attachment features. Progress continues on photoimageable polyimide coverlay products, but they have not been broadly commercialized yet.

COVERCOATS

Covercoats are very important construction elements for certain types of flex circuits. The term covercoat is used to describe a range of thin coatings applied to the surface of conductors in lieu of a coverlayer. Although some suppliers of covercoat material have some impressive flex cycling data, covercoats are normally reserved for applications where little, if any, dynamic flexure is required.

In manufacturing, covercoats are normally applied as liquids by screen-printing and then either cured by heat or exposure to UV radiation. Some covercoat technologies now allow the circuit component attachment features to be accessed by photolithographic techniques to improve feature resolution. Continued advances in this area appear destined to make covercoats an attractive alternative, especially as they approach performance levels formerly available only from coverlayer materials.

Currently, there are many flexible covercoats available in a variety of colors. As features become finer and finer the need for smaller openings in smaller, more closely bound areas within a flex assembly are required and achieved using new higher temperature, higher resolution and more flexible covercoats. Openings smaller than 75 microns (3 mils), and potentially as small as 35 microns (1.5 mil), on 125 micron (5 mil) spacing are routinely done in high volume. In contrast, drilling/punching followed by alignment of the coverlay makes for an extraordinary challenge from both a technical and a cost standpoint with very small features.

Figure 5-1: Basic materials used in flex circuit manufacture.

BOND PLIES

Bond plies, also referred to as supported bonding film, are flex circuit construction elements comprised of a base film with an adhesive film cast on both sides. The adhesive element of the construction is typically a thermosetting material.

While bond plies can be used to create two metal layer laminates, most bond plies are used as building blocks in the manufacture of more complex flex structures such as multi-layer flex and rigid-flex circuits.

CAST ADHESIVE FILMS

Cast adhesive films, also known as freefilm or unsupported bonding film, are freestanding adhesive materials. They are typically thermosetting adhesive films that are cast onto a disposable carrier or release film, often with a disposable protective sheet on top. Cast adhesive films are often used to bond rigid stiffening materials to a flex circuit. They have also been used as replacement for bond plies in certain applications.

PRESSURE SENSITIVE ADHESIVES

Pressure sensitive adhesives (PSA) are a family of semi-permanent to permanent adhesive films on peelable carriers that can be transferred directly to the surface of the flex circuit

or other material for later attachment to another surface. Once the PSA is applied to the circuit, it can be bonded to nearly any surface. However, most PSAs, when used in flex circuit manufacture, are employed to attach stiffeners to flexible circuits.

There is a subset of the pressure sensitive adhesive family that can be screen printed directly onto the back surface of the flex circuit and then cured by exposure to ultraviolet radiation to provide the necessary tacky finish. This method can be used in very high volume applications or where it is desirable to keep cost to a minimum.

STIFFENER MATERIALS

While stiffener materials are not an integral part of the flex circuit, they are an important element of flex circuit construction. Stiffening materials are used to reinforce flex circuits when and where required. Stiffeners are most commonly attached under areas where electronic components are to be attached. They support the weight of the components through the assembly process and in the application.

Stiffeners can be made of almost any material, including metal, plastic, resin-glass laminates or even additional layers of coverlayer material. The use of coverlayer material to stiffen areas of a flex is actually a very common practice.

SPECIAL ADHESIVELESS CONSTRUCTIONS

Adhesiveless laminates are produced using a number of different methods. Deposition of a thin seed layer onto the base film and plating copper or other metal foil directly onto the substrates is one common method. In processing, the polymer is typically plasma pretreated in an oxygen-containing environment prior to metallization. A very thin (in the range of 200Å) tiecoat metal such as nickel-chromium generally precedes a thicker copper base seed coat that is about 2000Å (0.2μm) thick is then sputter deposited. Additional copper is

built up to the desired thickness (e.g., 2μm – 5μm) by electrodeposition. This approach was commercialized by Gould under the name GouldFlex and was semi-successful for a period in the US. However, it had the disadvantage that the nickel-chrome layer required special secondary etching and was not readily removed by the cupric chloride etching used in most shops. The chrome waste was a hazardous waste and was not as readily recyclable.

An alternative approach to creating adhesive laminates involves casting the polymer directly onto a carrier foil. The issue with this type of material is the resistance to laying flat and instead curling up in a single sided construction. De-curling processes to deform the copper are not always consistent and sometimes result in scratched surfaces. Making a double-sided material by gluing two single sides together helped by balancing the polyimide, but increased cost and thickness, necessitating the removal of copper from one side to have a single side material. Nippon Steel is the largest supplier in the world using this approach to manufacture in roll form.

Another type of adhesiveless laminate that employs a thin layer of high temperature adhesive as described earlier. DuPont uses this approach, employing a high modulus inner core film (E-film) and then laminating copper in roll form or panel form. In panel form they can achieve the high bond strength expected for military and high reliability. Roll lamination limits the bond to somewhat lower values and is considered for commercial use.

Other developments in adhesiveless laminates include a new method for the manufacture of adhesiveless laminates that involves coating a film with a thin polymeric coating that is readily able to take copper plating reducing the need for plasma prep. Vacuum chamber seed layer deposition has been reported by Averatek, a company that has also reported both good properties and low-cost manufacturing.

Adhesiveless laminates offer special advantages in some applications, especially where high temperatures are anticipated, but also in applications where thickness matters. Another advantage is that these materials are amenable to very fine circuit feature processing.

Another area of particular advantage is in the manufacture of more reliable multilayer and rigid-flex structures. The advantage is gained because the Z-axis coefficient of thermal expansion of base films, such as polyimide, is significantly lower than most adhesives. This is an important factor in the long-term reliability of plated through-holes in more complex circuit structures.

Although adhesive laminates are currently more costly in the US than traditional laminates, their advantages make them an attractive choice in certain applications. More research and development efforts have been expended by Japanese companies than US entities, and as a result more options are presently available in Asia. Prices for adhesiveless laminates have actually come down relative to the prices of adhesive-based products in the region.

MATERIAL PROPERTIES OVERVIEW

Knowledge of the basic material elements of flexible circuits (i.e., base film, adhesive layer and metal foil) and how they are combined makes it possible to examine them in more depth and, more specifically, to learn about the available material choices and their properties. This process enables designers to make informed choices based on the effect of each decision on the final product

FLEXIBLE BASE FILMS

Many different materials have been used as base films or substrates for flexible circuit manufacture, including:

- Fluoropolymer films, such as Teflon®
- Aramid fiber-based papers and cloths, such as Nomex®
- Formable composites, such as those represented by Bend/Flex®
- Various flexible epoxy-based composites
- Thermoplastic films, such as polyethylene, polyvinyl chloride, polyvinyl fluoride, and polyetherimide

All of these film and thin composites have been used in flex circuit manufacture at one time or another and many of them continue to be used in certain applications. The cost of materials can vary widely.

The most popular and most commonly specified flexible base materials are polyester (PET) and polyimide (PI). The choice substrate polymer to use is determined by a combination of economics, end product application and assembly processing temperatures, which are increasingly important to satisfy EU-legislated lead-free requirements,

Polyimide and polyester may dominate present applications, but there are alternative film technologies that could see increased use for a number of solid reasons. Polyethylene

Figure 5-2: Relative cost comparison of selected flex circuit laminates.

naphthalate (PEN), for example, looks like an attractive intermediate choice in terms of cost and performance.

Another material of increasing interest as the industry moves to higher frequency digital electronics is liquid crystal polymer (LCP). This material has a number of attractive physical and electrical properties. For example, LCP materials have inherently low moisture absorption properties (0.02% to 0.1%) that should preclude the need for the baking that is commonly part of the polyimide manufacturing process due to its more hygroscopic nature. The low moisture uptake is also an important factor in creating a low signal loss environment. With a loss tangent of 0.003 and a dielectric constant of around 2.9 LCP is very attractive for high-speed applications. Another attractive feature of LCP is that it is chemically etchable, a feature it shares with polyimide. This capability is something that can be used to advantage in creating both exotic and relatively mundane constructions.

Thin fluoropolymer laminates are also candidate materials to serve future flex circuit interconnection needs. While not necessarily suited to dynamic applications, PTFE materials could find use in applications where low loss and low dielectric constant are required. Typical loss tangent values for PTFE materials are less than 0.001 and the dielectric constant commonly comes in the 2.0 to 2.4 range. Companies such as Taconic are targeting just such applications for materials they are developing for the flex circuit market. The laminate material is based on PTFE. FEP is a derivative of PTFE with a much lower melt point of 550°F vs. 640°F for PTFE.

As noted earlier, the choice of material is also largely influenced by the assembly technology to be used for components on the finished product. This is where designers need to seriously consider the trade-offs associated with product and material selection. It is possible to make an informed decision that would not, under normal circumstances, be considered

Polyimide / Polyester Comparison

Polyester	Polyimide
Several different types of polyester are available. The polymer is thermoplastic and can thus be heat-formed if desired. This is an oftentimes overlooked advantage. Common trade names for polyester include: Mylar®, Melinex® and Celanar®.	There are several manufacturers of polyimide films. They are available from the US, Europe and Asia. Polyimide films are most popular for high reliability type applications (military, medical, etc.) and dynamic flex applications. Trade names include: Kapton® Apical® and Upilex®.
Advantages • Low cost • Tear resistant • Good flexibility • Low moisture absorption • Good electrical properties • Good chemical resistance	**Advantages** • Excellent flexibility at all temperatures • Good electrical properties • Excellent chemical resistance (except hot alkaline solutions) • Very good tear resistance • Highest tensile strength
Disadvantages • Limited suitability for soldering • Unsuitable for extreme cold (polymer becomes brittle) • Supports combustion at atmospheric oxygen levels	**Disadvantages** • Absorbs moisture (up to 3% by weight, formulation dependant) • Relatively expensive compared to polyester • High temperature performance limited by adhesive system used

Table 5-1: Comparison of polyester and polyimide films.

correct. Such decisions are normally based on special knowledge of how to circumvent problems associated with the material property limits of the chosen substrate.

For example, conventional wisdom has it that polyester circuits are not suitable for soldering due to the material's relatively low melt point. However, a number of OEMs have been doing just that successfully for a number of years with tin-lead solders by using special processing methods that mitigate thermal damage to the part. This will be described in more detail in a later chapter.

Table 5-1 provides a comparison of the general properties of polyimide and polyester substrates when used for flexible circuit constructions.

A more detailed chart examining some selected physical and electrical properties of a larger group of flex circuit base

Figure 5-3: Example of a circuit manufactured Bend/flex material from Rogers Corp. which is no longer available. The material and the design helped reduce product assembly complexity while making the finished assembled product smaller. On the left is the original assembly. On the right is the redesigned assembly. (Courtesy Sparton Electronics)

Substrate Material	Dielectric Constant	Dissipation Factor	Dielectric Strength	Moisture Absorption	Tensile Strength	Elongation
Polyester	3.2	0.005	7000 v/mil	< 0.08%	25 kpsi	~120%
Polyimide	3.5	0.003	7000 v/mil	1.3 - 3.0%	25 kpsi	~60%
PEN	2.9	0.004	7500 v/mil	1.0%	30-35 kpsi	~75%
LCP	2.9	0.003	6000 v/mil	0.02 – 0.1%	15-25 kpsi	~15%
FEP	2.0	0.0002	5000 v/mil	< 0.01%	2–3 kpsi	~300%
PTFE	2.5	0.0002	5000v/mil	< 0.01%	15-25 kpsi	N/A
PVC	4.7	0.093	500 v/mil	< 0.5%	5 kpsi	120 – 500%
Aramid Paper	2.0	0.007	380 v/mil	3.0%	11 kpsi	~10%

Table 5-2: Comparison of selected properties of flexible base materials.

materials can be found in Table 5-2. The table is limited in scope, however, since many other materials can be used for flexible circuit constructions.

ADHESIVES FOR FLEX CIRCUITS

Flexible adhesives are used either to bind the metal foil to the base material to create a laminate or to bind layers of laminate material together like those found in multilayer constructions. The adhesive chosen is normally carefully matched to achieve the best mix of desirable properties for the laminate.

The following is a brief discussion of the general attributes of the adhesives most commonly used for flex circuits. A general comparison chart of the properties of different adhesives is provided in Table 5-3.

POLYESTER ADHESIVE

Polyester adhesives are typically used with polyester laminates. However, they have also been used with other materials,

depending on the application. Chief among the advantages of polyester adhesives are low cost and the low processing temperatures required for bonding. A drawback, however, is that polyester adhesives exhibit poor high temperature performance, limiting the number of potential applications.

Other potential drawbacks are that the adhesive flow in lamination tends to be high and bond strength tends to be relatively low. Still, they do work suitably in many applications where their temperature and physical limits will not be pushed.

ACRYLIC ADHESIVE

Acrylic adhesives have long enjoyed popularity as an adhesive of first choice for flex circuit manufacture. They have been commonly favored for many polyimide laminates due to their excellent adhesion and ease of processing. Acrylic adhesives offer a good balance of reasonable thermal performance (e.g., withstanding soldering temperatures), process ease and natural ability to bond reasonably well to many different materials.

On the negative side of the ledger, acrylic adhesives tend to swell in the hot alkaline processing solutions common in many electroless and electrolytic circuit board plating lines. Additionally, they have a rather high coefficient of thermal expansion which has implicated them as a prime cause of through-hole plating cracks when used extensively in multilayer and rigid-flex constructions due to excessive z-axis expansion.

EPOXY AND MODIFIED EPOXY ADHESIVES

Epoxies are among the most commonly used adhesives in the world, so it is no surprise that they find some application in flex circuits. Epoxies and modified versions of epoxies are nearly universal adhesives, capable of bonding with many different materials, including metals ceramics and polymers.

The high temperature capabilities of epoxies are quite good, providing some of the best post-solder float peel strength values. On the downside, epoxies tend to be more brittle than some of the alternative choices. However, modifications to the formula have proven successful in mitigating this issue. Epoxies are also somewhat prone to moisture uptake and therefore require a bit more processing care on the part of the manufacturer.

POLYIMIDE ADHESIVES

Polyimide adhesives are necessarily limited to use with polyimide substrates due to the higher temperature processing required. Nevertheless, use of polyimide adhesives results in better matched, and thus improved, laminate substrate properties. They are increasing in popularity in some product applications

Typical polyimide adhesives are thermoplastic and require relatively high lamination temperatures and pressures. The net result is that circuits made using polyimide adhesives offer the highest maximum temperature capability of any flex circuit construction. Polyimide adhesives are also seen as possibly being advantageous for multilayer and rigid-flex applications due to the lower CTE.

Negative aspects of polyimide adhesives include the fact that there are a limited number of sources and experience levels, while increasing, are not as great as they are for other adhesives. One other concern is that the bond strengths reported for polyimide adhesives are somewhat lower than alternatives. This may not prove to be a large problem over time, but additional experience is required.

BUTYRAL-PHENOLIC ADHESIVES

Another long-standing adhesive type is butyral-phenolic adhesive. This type of adhesive was actually used to create

Adhesive Type	Peel Strength post-solder	Adhesive Flow mils/mil	Moisture Absorption max %	Surface Resistivity min MW	Dissipation Factor @ 1MHz	Dielectric Constant @ 1 MHz
Polyester	N/A*	250μm max	2.0	10^4	0.02	4.0 max
Acrylic	1.6 N/mm	125 μm max	6.0	10^7	0.02	3.5 nom
Epoxy	1.4 N/mm	125 μm max	4.0	10^4	0.06	4.0 max
Polyimide	1.0 N/mm	125 μm max	3.0	10^5	0.01	4.0 max
Butyral: Phenolic	1.0 N/mm	125 μm max	2.0	10^4	0.025	3.0 max
PTFE	> 1 N/mm	125 μm max	0.01	10^{12}	0.0007	2.2 nom

* Because polyester is not considered suitable for soldering, the requirement does not apply. Nominal value for minimum peel strength of polyester adhesives is 0.9 N/mm.

Table 5-3: Comparison of selected properties of commonly used flex circuit laminate adhesives.

some of the first flex circuits without benefit of a base film. Butyral-phenolic adhesives have been shown to improve flexural life in some experiments.

Butyral-phenolic adhesives offer some specific advantages, particularly the low flow characteristics of the adhesive during lamination. This feature reduces the possibility of having adhesive flow onto interconnection lands. Excessive flow onto lands is a rejectable condition if limits are exceeded.

Other advantages of this adhesive type are that it has reasonably low moisture absorption and has one of the lowest dielectric constants among commonly used adhesives. On the negative side, circuits made with this adhesive system tend to be rather stiff in comparison to some of the alternate choices.

OTHER ADHESIVES

In addition to the above-cited adhesives, there are a number of thermoplastic materials that have been used in the past

to fabricate flexible circuits. Included in this grouping are FEP and polyetherimide (PEI). These materials require processing much like polyimide adhesives, which must normally be bonded at very high temperatures and pressures.

FEP is sometimes used as a low-loss bonding film in multilayer microwave frequency boards and is often chosen because of the lower temperature for processing. Because FEP is a thermoplastic and can re-melt at extended periods above 550°C in assembly, for example, it could cause delamination at some lead-free soldering temperatures. Concerns about high temperature soldering extend to PEI as well, so it is recommended that the materials be qualified for use in high temperature applications.

METAL FOIL AND METALLIC COATINGS

While copper is by far the most common metal used in flex construction, a wide range of other metal foils are available to meet special needs. Virtually any metal that can be produced in foil form or can be sputtered or plated is a candidate metal foil for flex manufacture. While many choices are possible, very few have seen actual volume used. The following are descriptions of a few of the many different types of metallic foils available and a review of some of their actual or potential applications.

COPPER FOILS

Copper foils serve the vast majority of all flexible circuit applications. Copper's excellent balance of cost and physical and electrical performance attributes make it an excellent choice. There are many different types of copper foil. The IPC metal foil specification IPC-4562 (formerly IPC-MF-150) identifies eight different types of copper foil for printed circuits divided into two much broader categories, electrodeposited and wrought, each having four sub-types (table 5-4). As a re-

Copper Foil Type	Number	Designator	Description
Electrodeposited (E) Copper Foils	1	STD - Type E	Standard electrodeposited
	2	HD - Type E	High ductility electrodeposited
	3	HTE - Type E	High temperature elongation electrodeposited
	4	ANN - Type E	Annealed electrodeposited
Wrought (W) Copper Foils	5	AR - Type W	As rolled-wrought
	6	LCR - Type W	Light cold rolled-wrought
	7	ANN - Type W	Annealed-wrought
	8	LTA - Type W	As rolled-wrought low-temperature annealable

Table 5-4: Summary of current copper foil categorizations.

sult, there are a number of different types of copper foil available for flex circuit applications to serve the varied purposes of different end products. With most copper foil, a thin surface treatment is applied to one side of the foil to improve its adhesion to the base film (fig. 5-4). The following is a brief examination of some of the most common forms of copper foil.

ELECTRODEPOSITED COPPER (STANDARD)

Standard electrodeposited copper is recommended and used primarily for static applications due to its grain structure, which tends to be columnar (fig. 5-4). This type of grain structure is not well-suited to dynamic flexing because the vertical grain boundaries establish a short path for crack propagation.

Electrodeposited or ED copper foil is not commonly used for flex circuit manufacturer in the US, but modifications and treatments could make them more viable candidates in the future. Nevertheless, electrodeposited foils are lower in cost, are still quite suitable for some applications and have been readily

Figure 5-4: Cross-section and top views of low profile treatment reveal how adhesion is improved in electrodeposited copper.

accepted for use in flex circuit manufacturing in many other countries.

ELECTRODEPOSITED COPPER (HEAT-TREATED)

One of the variants of standard electrodeposited copper accounted for in IPC-4562 is heat-treated electrodeposited copper foil. This foil type is treated at high temperature to modify the copper grain structure after electrodeposition to create a more ductile foil. The foil may be suitable for certain dynamic applications because of the recrystallization of the grain structure that occurs, approximating the grain structure of rolled and annealed copper.

WROUGHT OR ROLLED AND ANNEALED COPPER

Wrought or rolled and annealed copper foil, also known as RA copper, is produced using traditional metalworking methods. The process involves passing a copper bar through a series of metal rollers until a thin foil is produced. The foil is

then heat-treated to bring the copper to a dead soft state. This method can economically create foils down to 18µm (1/2 oz.). Specialty rollers can make even thinner foils, but the thinner foils are commonly only offered at a premium. As the most commonly used copper foil type for flexible circuit applications, RA normally affords excellent flexural life due to grain structure.

Wrought alloys of copper can also be used in flex laminate construction. These foils tend to have higher strength and toughness, making handling in manufacture easier. They also have an advantage in low strain-high cycle life flexing applications and may be a superior choice for some of these applications.

ELECTROPLATED COPPER

With some flex materials, the copper is plated directly onto the base substrate using combinations of electroless and electrolytic plating. Electroplated copper is differentiated from electrodeposited copper by virtue of the fact that its as-plated properties can be vastly different than those produced by normal foil deposition processes. Some electroplated foils exhibit properties equivalent to RA copper and, under some conditions, the results can be superior. This is due in part to the nature of the process, which allows the production of an amorphous or equiaxed grain structure due to the special additives used (fig. 5-5). The foil produced is much less sensitive to grain orientation effects than RA type foils.

SPUTTERED COPPER FILMS

Another approach to getting thin copper onto flexible base materials is to sputter or vapor deposit seed metals and plate up. The method has been in use for roughly two decades for flex circuits, but only in recent years has it gained the attention of a broader audience due to the need for finer lines and traces. One of the historical problems with the method was

Figure 5-5: Copper foil grain structures vary with the processes used to create them. Shown above are vertically ordered grain, horizontally ordered grain and amorphous or equiaxed grain.

obtaining a foil that was consistently both pinhole-free and with sufficiently high peel strength.

Analogous to electroplated foil, sputtered copper provides very thin (typically less than 1µm) copper film deposited directly onto base films over a much thinner adhesion-promoting layer of nickel, chrome, ni-chrome or monel. The thin sputtered copper film serves as a seed layer for subsequent electroplating.

Sputtered copper films are extremely useful in fabricating very fine line circuits and certain unusual constructions or applications. For example, the thin copper film is ideal for cryogenic applications where electrical conductivity is sufficient but thermal conductivity is relatively poor. Beyond such esoteric applications, sputtered copper films are proving quite suitable for high cycle life dynamic applications, like those in disk drives, as long as the plating process is well controlled.

BERYLLIUM COPPER

Beryllium copper is a useful choice when good conductivity, mechanical strength and/or spring-like qualities are simultaneously sought. While beryllium copper is not as conductive as copper (approximately ¼ the conductivity of copper), the metal is one of the standards of the electrical connector industry due to this unique blend of properties.

One of the concerns registered on occasion is that beryllium is a toxic metal. However, because the metal is not in its native state, but is an alloy, this has been shown to be a low order concern. In machining, the dust should be well-controlled, but etching is not a general concern.

ALUMINUM FOIL

Aluminum foil has been used in special applications where reduced weight or cost is sought and the design will accommodate its use. Aluminum foils have proven particularly successful in simple flexible shielding applications. When plated with electroless nickel/gold the termination's become both separable and/or solderable.

IRON ALLOY FOILS

Various iron alloys (stainless steel, Iconel, etc.) have been used and proven of value in applications where low thermal conductivity requirements are coupled with the need to pass electrical signals. A prime example is in the interconnecting of instrumentation in cryogenic devices. However, thin sputtered films of more conductive films may also serve this function, provided the currents are not too high. Because such foils are so resistive, they have proven very useful in creating flexible heaters.

OTHER THIN COPPER OPTIONS

The neverending drive to reduce the size of electronic

products and systems has resulted in the need for thinner copper foils to produce the finer circuit lines and traces required to meet the demand. Making thinner copper foils that can fulfill the requirements for flexible circuits is no mean task. The foil is expected to be pinhole free and provide the adhesion that is so important for reliable manufacture and use. Some foil and material suppliers have devised and implemented a number of new and improved methods for meeting the requirements.

Traditional rolled and annealed foils have found favor with flexible circuit material suppliers and users. However, rolling copper foils to values less than 17µm in thickness, while possible, tends to be expensive. To extend their ability to make even thinner copper foils, foil suppliers such as the Somers division of Olin Corporation, have developed technology that will allow for 3µm and 5µm copper foils to be bonded to flex circuit base materials. Their solution was to create peelable thin foils on a rolled copper foil carrier of normal 35 micron thickness. The product is uniformly thick and pinhole free. The treatment, common on copper foils, is desirable due to the resulting very low profile for flexible circuits. This attribute improves etch characteristics, allowing finer features with some (desirably minor) penalty in peel strength.

For the new Olin copper foil material, a proprietary inorganic release layer is used between the rolled foil carrier and the thin copper foil. The force required to remove the carrier foil after lamination is reportedly very low (about 1-2 grams/centimeter or approximately 0.1 oz/in), even after lamination at temperatures required for flex circuit materials. Gould and Oak Mitsui have similar ultra thin copper foil on carrier foil solutions in the market ,also targeted at very fine line circuit applications.

Another option is an adhesiveless tie coat-free flexible copper clad laminate from Fractal. The lack of a tie coat is made possible by an innovative micromechanical bonding technol-

Figure 5-6: Top view of fine line etched circuits overlaid with a greater magnified image of the copper foil with the polymer removed to reveal the unique micro-mechanical structure to improve peel strength. (Photo courtesy of Fractal AG)

ogy, the resulting peel strength of which reaches an amazing 2 to 2.5 kilograms/centimeter. (~ 12-17 lbs/in). The manufacturing process reportedly involves an unusual technology in which polymer films are irradiated by heavy high-energy ions, treated chemically to develop out the irradiated spots and then plated. A photomicrographic comparison to traditional treatments is shown in figure 5-6. Single- and double-clad copper-polyimide flexible circuit laminates with foil thicknesses from 5µm to 18µm are being offered. With such high peel strengths, the materials are likely to withstand the rigors of gold plating very well.

In summary, the demand for high-density circuitry on flexible substrates has driven the foil manufacturing industry to develop some innovative solutions that are making the leading edge products of today possible and securing the future for next generation opportunities. Each solution has merit and

Metal Foil	*Resistance* Ω/cm x 10^6	*Thermal Conductivity* W/m*K	*Tensile Strength* (psi)	*% Elongation* (annealed)
Copper Rolled annealed	1.67	393	32,000	20
Copper Electrodeposited	1.77	393	25,000	12
Aluminum	4.33	225	16,000	30
Stainless Steel	75	6	90,000	40
Beryllium Copper	~8	83	60,000* 200,000**	35 - 60* 1 - 4**

* Annealed Dead Soft ** Heat Treated Full Hard

Table 5-5: Comparison of selected properties of metal foils.

having more than one solution is a blessing to both design and manufacturing.

OTHER CONDUCTOR MATERIALS

Beyond traditional metal foils for creating conductors, a range of other products and processes are available that can provide conductive (or resistive) pathways on flexible base laminates. The following are descriptions of some common and not so common alternative conductor materials.

POLYMER THICK FILM FLEX CIRCUITS

Polymer thick film (PTF) flex circuits are a special subset of flexible circuits where specially formulated conductive and resistive inks are screen-printed onto flexible substrates to create circuit patterns. The conductive inks are normally silver-filled polymers and the resistive inks are filled with carbon or mixtures of silver and carbon.

PTF technology is extremely popular for producing a range of cost-effective products from membrane switches, such as

computer keyboards and touch pads, to low cost calculators and disposable medical devices, such as blood gas monitors. In certain cases, PTF circuits can be integrated with copper foil base laminates to create novel structures that combine the benefits of PTF and copper foil, especially when there are specific requirements for higher conductivity in certain areas of a circuit.

Polymer thick film technologists have also developed SMT adhesives for mounting components onto PTF circuits. This is a good potential solution for attaching temperature-sensitive components and is also an environmentally benign alternative to solders that contain lead.

INDIUM-TIN OXIDE

Indium-tin oxide, or ITO as it is also commonly known, is unique among conductor materials in that it is a transparent. It is one of the more important enabling technologies for liquid crystal displays, but also offers a range of other possibilities such as touch screen monitors. The coatings, which are deposited in a vacuum, are very thin but reasonably tough. ITO is normally used on glass, but it can also be found on clear polymer films such as polyester, making it a potential candidate for solving unusual problems.

BUILT-IN RESISTOR MATERIAL FLEX CIRCUITS

A unique construction technique for making flex circuits uses a specially fabricated foil supplied by Ohmega Industries (Culver City, CA). The foil is a combination of resistive and conductive layers. By using special design rules and a special three-step etching process, it is possible to create circuits with built-in resistors.

Although it is not well-suited for high power applications, the material can provide an effective solution for termination resistors which helps to reduce both assembly complexity and

Figure 5-7: Process sequence for built-in resistor manufacture.

weight. A cross-sectional representation of a single resistor made from the material is illustrated in Figure 5-7.

Alternative methods for creating circuits with built-in resistors are also possible, by sputtering for example. This is accomplished by sequentially sputtering resistive and conductive layers and processing in a fashion similar to the foil form. In either case one should avoid using the resistor material in flex areas due to the potential of fracturing the resistor in the field.

PLATABLE TONER FLEXIBLE CIRCUITS

Platable toner flexible circuits represent another special subset approach to flexible circuit manufacture requiring special materials and a manufacturing approach patented and developed in the early 1990s by now defunct Extended Length Flex Technologies (Foster City, CA). The concept was unusual at the time. A special toner material that bonded to base films

was used to create a flex circuit pattern directly on a flexible substrate. The proprietary toners were catalytic and electrostatically deposited by means of a modified laser printer. When subsequently processed through electroless and electrolytic copper, the metal circuit pattern was formed on the surface. The result was a unique, fully additive flex circuit process. The process detail is illustrated in Chapter 11 - Printed. While the technology did not take hold, some of the concepts espoused by the company have been picked up on by others and some of the manufacturing concepts and capabilities originally intended for this technology are now using other process techniques.

SUMMARY

A wide variety of materials are used in the manufacture of flexible circuits including films, foils and adhesives. While polyester and polyimide still dominate the base film market, newer materials continue to be examined and introduced such as PEN and LCP, both of which may play a significant role in the future as an intermediate in cost in the case of PEN and as a higher performance option in the case of LCP. In the same vein, thin reinforced PTFE materials could also serve an important role as digital signaling reaches further into the realm of RF speeds.

In addition to the base materials, there are a broad range of adhesives and many types of metal foils that can be used in base material construction. The choice of which materials to use is highly dependent on how and where the circuit will ultimately be assembled and used. Careful evaluation of the relative merits of the different materials may be required in order to make the best choice for a given application. **FCT**

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Chapter 6

Implementing Flexible Circuit Technology

Joseph Fjelstad, ***Verdant Electronics***

INTRODUCTION

It is clear to circuit designers that flexible circuit technology offers unique capabilities, opportunities and options in electronics system design. However, to gain the advantages of flexible circuits, it is necessary to go through an implementation process that requires some rigor in thought and planning before setting out to successfully design a well-considered flex circuit that will work properly from the start. Lack of proper planning can make the difference between enjoying a rewarding experience or suffering through a painful one.

Fortunately, the process of implementing flexible circuit technology into a design is not as challenging today as it once was. The experiences and lessons learned by flexible circuit technology's pioneers now serve as guides, providing a map to chart a course around the most commonly encountered obstacles.

The simple thirteen-step approach outlined here provides a basic, easy-to-follow guide to successfully implementing flexible circuits into new and existing products. The approach and suggested steps provided are not exhaustive because it is not possible to anticipate and address all of the possible variations. However, the process outlined supplies sufficient detail to guide users to a satisfactory end result.

1. DEFINE END PRODUCT REQUIREMENTS

A market-driven approach to defining end product requirements is recommended. The product, its application and performance expectations should be given as much definition as possible by the end user to ensure that they will get the value and/or features they seek. At this time, it is worthwhile to determine if a flex circuit is even the best choice for the product. It is possible that a better or more cost-effective solution can be found when other alternatives are explored. For example, a thin rigid board may serve just well as a flex circuit if a thin circuit is the only requirement.

The prospective user should also consider the product's cost targets or requirements, product life expectations, size, etc., to make sure that the decision to use flex circuits is a sound one in terms of cost and performance. In addition, the user should ensure that the materials and processes to be used will measure up against those requirements.

2. DETERMINE RELIABILITY REQUIREMENTS

Early consideration should be given to the reliability requirements for the product. What level of reliability is needed? The IPC uses a classification system for products according to their end use: Class 1 for consumer products, Class 2 for business and telecommunications or Class 3 to meet the requirements of military-aerospace and life support products. At this time a Class 4 requirement is under consideration to address products that do not fit completely into the current set of classifications.

End product requirements heavily influence many of the choices that must be made in terms of materials and processes. It is also worthwhile to consider product liability. What are the ramifications of product failure due to a flex circuit-related design problem? While not a necessarily comfortable task, it is very important that liability is consciously addressed.

Thermal cycling is considered one of the key determinants of electronic product life (along with flexural durability), and products from different markets must endure very different conditions. As a guide, the IPC provides a chart to assess and

Thermal Excursion Expectations for Product Markets

End Market	Stage in Product Life	Temperature Range Potential	Number of Thermal Cycles
Consumer	Processing	25 to 260°C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	0 to 60°C	365 per year
Computers	Processing	25 to 260 °C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	0 to 60°C	1460 per year
Telecom	Processing	25 to 260°C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	-40 to 85°C	365 per year
Commercial Aircraft	Processing	25 to 260°C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	-55 to 95°C	3000 per year
Industrial & Auto (Passenger Area)	Processing	25 to 260 °C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	-55 to 95°C	~200 per year
Automotive Under Hood	Processing	25 to 260 °C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	-40 to 125°C	1000 per year
Military Land and Sea	Processing	25 to 260°C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	-40 to 85°C	100 per year
Military Avionics	Processing	25 to 260°C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	-40 to 95°C	500 per year
Space Low Earth Orbit	Processing	25 to 260 °C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	-269 to 95°C	8760 per year
Space Geosynchronous Orbit	Processing	25 to 260°C	0 to 5
	Storage	-40 to 85°C	varies
	Operational	-269 to 95°C	365 per year

* Certain industrial controllers and scientific instrumentation are designed for very high temperature environments.

Table 6-1: Environment selection and thermal excursion projections for electronic assemblies used in various end markets. (Source: IPC, Bannockburn, IL)

approximate thermal cycling conditions for electronic assemblies. It was originally developed for and can be found in IPC-SM-785 *Guidelines for Accelerated Reliability Test of Surface Mount Solder Attachments*. An abbreviated version of the chart can be found in table 6-1.

3. DETERMINE OPERATING ENVIRONMENT

Product operating environment determination is an important factor that will influence later design and manufacturing choices. Where will the end product be used? In an office? At home? In an automobile? In an aerospace application? These questions will help to determine the likely operating environment for the product, what temperatures and relative humidity extremes are to be expected over the life of the product and how often they might be thermally cycled.

Determining the correct materials might be simplified by this analysis, but the assembly process must be considered at the same time. There are several descriptive tools that define the requirements for various use environments available and can facilitate the decision-making process. Table 6-1 provides a simplified chart of operating environments for different product types.

4. DEFINE PACKAGE CONFIGURATION

The target size and shape of the package should be established early in the process since it is the foundation from which many other decisions will be made. In addition to size and shape, optimum locations for components (e.g., I/O ports, switches and control devices for product performance, assembly ease, usability, ease of access for rework or repair) should be considered.

A mock-up of the product box is necessary to lay out the flex circuit, which facilitates the conversion of the 3-dimensional package requirement to the 2-dimensional format needed for manufacture. A paper doll mock-up of the circuit

can also be instructive (see Chapter 7 – Practical Design Guidelines for Flex).

5. DEFINE MECHANICAL REQUIREMENTS

It is necessary to consider the mechanical requirements that will be placed on the flex circuit. For example, will the application be static, requiring flex to install? Or will the application require active bending? If the application requires dynamic flexing, will it require continuous or intermittent operation? Requirements for dynamic flexing vary since an application can require anywhere from hundreds of cycles per year to hundreds of cycles per minute. The construction, design layout issues (such as the assurance that no vias will be located in bend areas) and material choices will be influenced by the answers to these questions.

6. DEFINE ELECTRICAL REQUIREMENTS

Like electronic product, it is necessary to determine what the key electrical requirements will be as early as possible. For example, what are the power requirements? How much current is needed? At what voltage? What is the expected maximum or peak current? Is EMI a concern and is there a need for shielding? If the circuit is large, is voltage drop a concern? Are common electrical parasitic effects, such as capacitance and inductance, important to the performance for the design or application? Each of these considerations can potentially affect material choice and/or circuit design/layout approach.

Attention should be given to potential conflicts of purpose in design. In some cases, the electronic needs of the product are at cross-purposes with mechanical requirements. For example, there may be a wish to dynamically flex a microstrip construction, which is not recommended from a mechanical perspective. Conflicts of purpose need to be identified early and resolved before the design is committed to manufacture.

7. DETERMINE COMPONENT LOCATIONS

In general, components, connectors, switches and other devices should rest on reinforced areas such as stiffeners, while areas that are to be flexed or bent should have no components placed on them. Exceptions are possible, but it is not a preferred practice. Moreover, components should never be placed in or near areas that are to be actively flexed.

8. DEFINE ASSEMBLY METHOD(S)

It is important to give early consideration to which type of component assembly method is to be used. The quantity of the product, the substrate material and the size of the part will all help to determine the assembly method. Choices for electromechanical joining include soldering, using conductive adhesives and even mechanical fastening. With the higher temperatures associated with lead-free solders, the temperature limitations of materials must be fully understood.

It is possible to perform soldering by hand or machine. Machine methods include wave solder, infrared (IR), vapor phase, convection oven, hot bar and even laser soldering. If assembly requires special or individual handling, cost will greatly increase. Costs can be better managed by carefully considering the best layout of the circuit to facilitate the assembly process.

Another alternative is designing a flexible circuit in a manner that precludes the need for traditional assembly methods (see Chapter 13 – Stretchable Circuits).

9. DEFINE ELECTRICAL TESTING NEEDS

What type and level of testing will be required? How, when and where will testing be performed? These questions are often ignored or are afterthoughts in the design process. It is important that testing be given due consideration before embarking

on a design. Some questions to raise in design are: Will testing of the bare flex be required? Will only the assembled board be tested? Or are both levels of test needed? How will the test contacts be accessed? Design complexity will impact and steer decisions regarding electrical test needs.

Since flex circuits employ relatively soft and highly flexible substrates, there are special concerns when it comes to electrical test because the test probes can easily damage the circuit's surfaces. On the other hand, because they are flexible, circuit test fixtures can be made smaller than normal when necessary and the flex circuit can be shaped to fit the fixture.

10. DEFINE MECHANICAL TESTING NEEDS

Mechanical testing, especially flexural endurance testing, of the flex circuit is often a requirement for flexible circuits fabricated for dynamic flexure applications. There are a number of different options for mechanical testing and it is good to be properly prepared with appropriate equipment (see Chapter 14 – Inspection and Test of Flex Circuits).

11. CREATE A DEMONSTRATION CIRCUIT

At some point, before committing the circuit to prototyping or production, it is worth taking the time to verify the electronic functionality of the circuit. This can be accomplished using long-standing empirical methods such as breadboarding, but it is becoming more common to use simulation software.

Creating a demonstration circuit avoids wasting the time and expense of tooling for manufacture until the fundamental circuit is proven. While this may not prevent all unforeseen incompatibilities between circuit elements in the final form, it should reduce overall costs over time. Simulation tools are continually improving, so in many cases this step can be satisfied by simulation.

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12. MOCK-UP FLEX CIRCUIT

Mock-ups or paper doll flex circuit models have been an important part of a successful flex circuit implementation process for a long time. A mock-up of the final package should be used to provide a mandrel for the circuit layout. In the past, a simple piece of paper served well in laying out circuit trace runs to meet routing requirements for all I/O points. However, present day CAD and EDA software can more quickly and efficiently accomplish this task.

Over the years, mock-ups have exposed many packaging problems before manufacture by minimizing the potential for gross and easily-avoidable errors. Having a physical model also saves time and money by providing an ergonomic check for circuit access and verifying the ease of final assembly and field service. Figure 6-1 shows a simple example.

13. GENERATE CAD DATA PACKAGE

As a final step, it is necessary to generate appropriate documentation and data packages with circuit features and circuit outline information that follow all pertinent flex design rules. Today, most manufacturers prefer to receive data in digital form, which allows them to make needed adjustments to

Figure 6-1: The use of paper doll mock-ups can facilitate flex layout.

Figure 6-2: Flexible circuits are best designed and manufactured through close collaboration between the designer and manufacturer to ensure understanding of the product's needs. (Image courtesy of Mentor Graphics)

compensate for circuit processing. The data package should be double-checked for mechanical and electrical concerns as well as accuracy to avoid a loss of time due to downstream problems.

The thirteen steps described encompass some of the most important considerations for flex circuit implementation and provide an understanding of the level of detail that must be addressed before entering into a flex design.

It is generally true that the simplest strategy for a flex circuit implementation is likely to be the best strategy. Historically, flex circuit implementation has been adopted slowly, starting with simple constructions in order to grasp the subtleties of flex circuit design, assembly and use before undertaking more complex designs. This strategy may need to be altered

based on the necessities of a particular design challenge, but this does not alter the notion that simpler constructions represent a better starting point for those new to flexible circuits. In any case, the steps outlined here apply and will ease the implementation process.

FLEX CIRCUIT COST FACTOR ANALYSIS

No matter how great the technology, if it cannot meet cost targets, it is unlikely that it will have broad appeal and gain wider acceptance. Because flexible circuit technology is so diverse in construction and materials, the matter of cost is not an easy subject to tackle. There are some generalized methods available to assess whether or not the technology is suitable. It must be assumed that there is a break-even point somewhere as volume increases and one technology surpasses another. The concept can be easily visualized and is illustrated in figure 6-3.

The break-even determination chart found in table 6-2 also offers as an example of how a prospective user can determine the quantity of flexible circuits that must be built to offset the expense of tooling up for flex circuit production. The example assumes that the flex circuit will replace a wire harness, but other technologies with different factors could be inserted in place of the wire harness.

When looking at cost, it is important to remember the many advantages flexible circuits offer. In some instances the flex circuit may be more costly than the alternative in-the-door, but in the final analysis and at the system level, the ultimate cost is much lower. Flexible circuits often prove to be an enabling, value-add technology that can reduce the overall cost of an electronic system. Lack of appreciation of the cost-in/cost-out paradigm has foiled the efforts of many price-conscious circuit purchasers in the past and is a mindset to avoid.

Figure 6-3: At the break-even point, technology B, which was initially more expensive in low volume, becomes a better value than technology A, which is less expensive in low volume.

While flex circuits may be more expensive than some alternatives on a cost per unit area basis, the technology's ability to solve problems in many areas of design and manufacture is capable of offsetting the cost differential in many cases. Flex circuit technology can make electronic products easier to build and provide greater reliability, important attributes that can often trump cost in enlightened manufacturing.

Based on the nature of flex circuit technology, it is now possible to write circuits directly onto polymer films in a roll-to-roll fashion on a continuous web. Manufacturing concepts like this are appealing because they could ultimately make flex circuit manufacture possible at an economical run unit of one part, an idealized objective of almost any manufacturing process. It now appears that solutions like this are in the works and being evaluated currently. (For a more complete discussion of this topic, see Chapter 11 – Printed Electronics.)

CALCULATING A BREAK-EVEN POINT

(After Sheppler, et. al.)

Break-even point = NRE (flex) - NRE (alternative)

RC (alternative) - RC (flex)

FLEX CIRCUIT NRE	WIRE HARNESS NRE
• Circuit design & artwork • Documentation • Mock-ups • Hard & soft tooling	• Wiring diagrams • Assembly drawings • Harness assembly board • Potting molds
FLEX CIRCUIT RC	**WIRE HARNESS RC**
• Manufactured unit price • Inspection and test • Assembly • Installation • Carried inventory	• Wire inventory • Cut, strip and mark wires • Lay out wires on boards • Solder wires to connector • Test and correct errors • Pot wires in connector • Install

Factors: **NRE** = Non Recurring Engineering **RC** = Recurring Costs

Table 6-2: Break-even point analysis for flex circuits compared to wire harness alternatives.

SUMMARY

Flexible circuit technology requires some advanced thinking prior to embarking on a new design. The technology offers some very important capabilities and many advantages. Even so, while there are numerous current and potential advantages to flexible circuit technology, no technology is risk free. Prospective users must perform their own appropriately rigorous analysis to determine whether the use of flexible circuits in a particular situation is practical and makes economic sense.

While of the 13 steps outlined are considered fairly complete at present, the continual growth and expansion of flexible circuit technology may result in the need to amplify the steps or add new unanticipated steps to reflect new realities in the future. **FCT**

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SEVEN

Vern Solberg is a technical consultant specializing in SMT and microelectronics design and manufacturing technology. He has served the industry for more than 25 years in areas related to both commercial and aerospace electronic product development. He is active as an author and an educator. Mr. Solberg has been involved with the training of students and faculty members at the University of Wisconsin School of Engineering in Milwaukee and Kansas State University's Microelectronics Laboratories in Salina.

Solberg holds several patents and awards for IC packaging innovations including the folded-flex 3D package technology. He is the author of Design Guidelines for Surface Mount and Fine-Pitch Technology a McGraw-Hill publication.

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Chapter 7

Practical Design Guidelines for Flex

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INTRODUCTION

Flexible circuits are unique among electronic packaging technologies, offering a wide variety of advantages unobtainable using conventional rigid interconnection technologies. Freeform integration of electronic elements through all three dimensions of space is highly liberating to the design process.

The advantages of flexible circuits, however, cannot be garnered without a thorough understanding of basic flex circuit design principles. Proper use of design principles can provide a path to early success. In contrast, failure to use good design practices can result in poor fabrication process yield or early failure. The objective of this chapter is to provide vital information for the successful production of flexible circuit designs that will consistently perform to user expectations.

DESIGN PRELIMINARIES

Before embarking on a flex circuit design, a holistic overview of the project must be taken. In this overview, a circuit designer should take into account as many of the relevant items discussed in the implementation section as possible. Taking stock of the project helps the designer appreciate the broader perspective of the task, minimizing the possibility that any gross and avoidable errors will be carried through the design process.

The designer must also keep in mind that flexible circuit designs require a balancing of both mechanical and electrical concerns. The designer will find that these two concerns often oppose each other's requirements in a design. The holistic approach will help the designer thread the needle to make the best possible choice from the various alternatives.

USE OF MOCK-UPS

A matter of importance, outlined in Chapter 5 – Implementing Flexible Circuit Technology and reasserted in this chapter for emphasis, is the value of using a physical mock-up of the circuit. The mock-up helps the designer prevent many errors by exposing potential fit and form problems early, and will ultimately save both time and money.

Some modern CAD systems have demonstrated the ability to execute 3-dimensional layouts required for flex circuit applications, but the physical model will always prove of some value in addressing both the ergonomic elements of assembly and the concerns of access should field repair be required.

DESIGN WITH A BIAS FOR COPPER

Favoring the use of copper in design is a good practice for some very solid reasons, assuming that there are not other conflicts created by the practice. If all other design objectives are met, the primary reason for maintaining the extra copper is that it helps to enhance the dimensional stability of the circuit. Designing with a bias for copper is a practice especially well-suited to single-layer flex circuit designs (fig. 7-1).

The decision to add or retain copper on the flex base should be made in light of the objectives of the final use of the circuit. For example, if a reduction in weight of the final product is a key objective, there would be a need to trade away some of the enhanced dimensional stability. Another reason for maintaining copper is that it reduces the amount of copper

Figure 7-1: Designing with a bias for copper improves the circuit's dimensional stability, but may not be practical for all applications.

Figure 7-2: Copper foil is maintained by design around circuits to provide better panel dimensional stability.

etched, making it more environmentally-friendly in terms of chemical usage.

CAD TOOLS

Designing flexible circuits is not a simple task. There are many special design elements that must be attended to in order for a design to move easily through the manufacturing process. One important family of enabling technologies can be

Figure 7-3: Screen shot of a flex circuit design executed using CAD software developed for flexible circuits. (Photo courtesy of Mentor Graphics)

found in computer-aided design (CAD) tools. Newer CAD solutions are being adapted especially to meet the needs of flexible circuit designers. In fact, with the increasing emphasis on the use of flexible circuits in all types of electronic products, CAD tool suppliers, such as Mentor Graphics, are creating new tools to address the growing need for rapid learning in this important technology sector.

These new tools not only help to make certain that the appropriate connections are made, but also address the various mechanical needs for curved trace routes to prevent stress risers. An example of a computer-aided flex circuit design having such solutions applied can be seen in figure 7-3.

SETTING TOLERANCES FOR FLEXIBLE CIRCUIT DESIGNS

Proper application of tolerances of flex circuit design features is a matter that concerns both the flex circuit manufac-

Figuge 7-4: Demonstrating the use of multiple datum features.

turer and the flex circuit user. The largest practical tolerance should be given to all features and locations to facilitate manufacture because base materials are flexible and prone to distortion, making accurate measurement over distances difficult. To compensate, it is recommended that more than one datum be used on larger circuits. Datum features positioned in key locations simplify the inspection process (fig. 7-4), result in a more accurate measurement being taken and can preempt potential conflicts in measurement results between inspectors. To avoid confusion in design, one datum feature should be defined as the primary or master datum and others as secondary datums. The use of primary and secondary datum features facilitates both accurate measurement of the circuit and device placement during the assembly process.

GENERAL GUIDELINES FOR DIMENSIONING AND TOLERANCING

When it comes to designing flexible circuits, proper dimensioning and tolerancing is vital to achieving good manufacturing yield. While it is not possible to point out every possible situation where dimensions and tolerances might be misinter-

preted on a drawing, there are certain general guidelines that, if followed, can help to minimize confusion. The following guidelines should be helpful:

- Show sufficient dimensions so that the intended sizes and shapes can be determined without requiring the distances between features to be calculated or assumed.
- Provide individual dimensions only once and check them.
- State all dimensions clearly so they can have just one possible interpretation.
- Show the dimensions between points, lines and/or surfaces that have a necessary and specific relationship to each other or that control the location of other components or mating parts.
- Check dimensions to avoid accumulations of tolerances that may permit alternative interpretations.
- Provide dimension to features shown in profile so their true shape is evident.
- Do not show dimensions to lines representing hidden surfaces.
- Do not use off-part datums that are of no use once the part is removed from the panel for part measurement verification.

Table 7-1 provides general guidelines for tolerancing based on different design criteria. This table does not apply to leading-edge products.

Tighter tolerances may be possible if required, but achieving tighter tolerances requires exceptionally tight process controls and good techniques. As a result, the cost of providing tighter tolerance circuits can be greater due to the anticipated loss of yield.

Design Feature	Standard Product	Reduced Producibility	Normal Tolerance	Minimum Tolerance
Hole size	0.020″ (0.5 mm)	< 0.020″ (0.5 mm)	±0.003″ (0.075 mm)	±0.001″ (0.025 mm)
Trace width	0.010″ (0.25 mm)	<0.010″ (0.25 mm)	±0.002″ (0.050mm)	±0.001″ (0.025 mm)
Space width	0.005″ (0.125 mm)	0.005″ (0.125 mm)	±0.002″ (0.050 mm)	±0.001″ (0.025 mm)
Trace to edge of part				
Steel rule tool	0.020″ (0.5 mm)	<0.010″ (0.25 mm)	±0.010″ (0.25 mm)	±0.005″ (0.125 mm)
Class A die	0.005″ (0.125 mm)	<0.002″ (0.050 mm)	±0.005″ (0.125 mm)	±0.002″ (0.050 mm)
Feature-to-Feature Location (relative true position)	**≤12.0″ (≤ 300 mm)**	**≤ 18.0″ (≤450 mm)**	**≤ 24.0″ (≤ 600 mm)**	
Preferred (per MIL-STD-2118)	0.028 (0.7 mm)	0.034 (0.85 mm)	---*	
Level A (per IPC-D-249)	0.034 (0.85 mm)	0.040 (1.0 mm)	0.046 (1.15 mm)	
Standard (per MIL-STD-2118)	0.020 (0.5 mm)	0.024 (0.60 mm)	---*	
Level B (per IPC-D-249)	0.022 (0.55 mm)	0.024 (0.60 mm)	0.034 (0.85 mm)	
Reduced Producibility (per MIL-STD-2118)	0.012 (0.30 mm)	0.016 (0.40 mm)	---*	
Level C (per IPC-D-249)	0.012 (0.30 mm)	0.018 (0.45 mm)	0.022 (0.55 mm)	

*Mil-Std-2118 offers the following statement in lieu of tolerances: "Drawing tolerances must reflect bend and fold allowances between component mounting rigid areas."

Table 7-1: Tolerance guidelines for standard flex circuit manufacture.

The tolerance guidelines provided in Table 7-1 are quite conservative when compared to current manufacturing capabilities of many flexible circuit manufacturers around the world. Many companies are capable of producing flexible circuits with line and space features as small as 25 microns and laser-drilled holes of the same size. Technical roadmaps in Japan indicate that feature sizes will continue to drift down

and that features as low as 10 microns are on the horizon. With such small feature sizes, the tolerances indicated in Table 7-1 (e.g., line and space ±25 microns) would make no sense since the features could be completely shorted or totally absent and would still be within tolerance. To be safe, check with your vendor to get a statement of capability before beginning a design.

SPECIAL DESIGN CONSIDERATIONS

There are some unique elements of flex circuit design that require early consideration and address mechanical issues that could affect usability and/or long-term performance. Early consideration is essential because the mechanical issues will definitely affect circuit layout.

LAYOUT CIRCUIT TO CONSERVE MATERIAL

Conservation of material in flexible circuit manufacture helps to keep manufacturing costs down, which is important because flexible circuit materials tend to be expensive compared to standard rigid materials such as FR-4.

To achieve the greatest economic benefit for circuit fabrication, the individual elements should be furnished in a panel format and oriented to provide optimum material utilization. The technique of optimizing the number of circuits per panel is commonly called nesting. The term optimizing is used in place of the seemingly more logical term maximizing for a reason. The layout of a flex circuit should be based on end use. Some uses demand that portions of the flex circuit be properly oriented relative to the grain direction of the foil, such as dynamic flexing, where flexing areas are ideally oriented with the machine or long direction of the foil roll rather than the transverse or width direction. This may not result in maximizing material use for circuit construction, but rather optimizing the number of circuits. In some cases, however, there is an op-

Figure 7-5: Panel layout variations.

portunity to lay the circuit out in various ways to get the most out of the material as shown in figure 7-5.

Proper circuit nesting can greatly improve panel yield and lower overall cost. If folding can be tolerated as an assembly operation, yield can be maximized. For dynamic flex circuit designs, the grain direction requirement may impact layout.

While nesting is routinely performed by the manufacturer, the designer can aid in this process by taking advantage of the fact that flex circuits can be bent and folded as shown in figure 7-5. Thus, adding a small length to a circuit arm can allow a circuit to be produced more economically as long as the user doesn't mind adding a folding operation to the assembly process.

SERVICE LOOPS

The addition of a small amount of length to the flex circuit beyond the basic design requirement is advisable for most flex circuit applications. This little extra length of material is commonly referred to as the service loop length.

The purpose of the service loop is to offer sufficient extra length to facilitate both assembly of the product and servicing

of the product once in the field. The extra length also helps to compensate for small, unforeseen variations in both the package and the flex circuit.

STAGGERED LENGTH CIRCUITS (BOOKBINDER CONSTRUCTION)

Staggered length design practice is commonly employed for ease of flexing multilayer and rigid-flex designs. The technique is accomplished by adding slightly to the length of each succeeding flex layer, moving away from the bend radius (fig. 7-6).

Figure 7-6: Staggered length designs facilitate bending of the flex circut; however, the circuit can only be bent in one direction by design.

Figure 7-7: Layer buckling due to not using staggered lengths.

A common rule of thumb is to add length equal to roughly 1.5 times the individual layer thickness, but the value can vary based on the tightness of the bend and the number of layers. Therefore, it is recommended that some modeling be carried out in advance of committing to manufacture. A paper doll mock-up can be very instructive as a quick check. The extra length with each succeeding layer helps defeat whatever tensor strain might have otherwise been built up in the outer metal layers of the multilayer flex and prevents buckling of the center of bend layers (fig. 7-7).

CONDUCTOR SIZING AND ROUTING

In general, flex circuit conductor width and thickness are determined by a combination of current-carrying requirements, the voltage drop allowance and/or characteristic impedance control needs. When designing flex circuits for dynamic applications, the use of the thinnest possible copper is recommended. It is important that the designer opt for wider rather than thicker traces to accommodate basic electrical needs or requirements. This practice ensures maximum circuit flexibility.

CURRENT-CARRYING CAPACITY OF CONDUCTORS

A number of different nomographs to determine electrical values for copper have been developed to simplify copper trace requirement specifications. The IPC-2152, Standard for Determining Current-Carrying Capacity document, for example, establishes general, conservative guidelines for sizing conductors and contains simple charts that show testing results for internal and external conductors in both air and vacuum environments.

Table 7-2 can be used to determine maximum current and line resistance for given trace widths with both 35µm (1 oz.) and 70µm (2 oz.) copper. The copper foils referred to in table

Conductor width	Maximum Current for 10°C rise 1 oz. copper	Conductor Resistance milliohms/ft 1 oz. copper	Maximum Current for 10°C rise 2 oz. copper	Conductor resistance milliohms/ft 2 oz. copper
0.005	.25	1280	NA	NA
0.010	.60	640	1.0	320
0.015	1.1	400	1.8	200
0.020	1.3	320	2.0	160
0.025	1.5	250	2.5	125
0.030	1.8	200	2.9	100
0.050	2.5	120	4.0	60
0.070	3.2	90	5.0	45
0.100	4.0	60	6.9	30
0.150	5.9	40	9.8	20
0.200	6.9	30	12.0	15
0.250	8.6	25	13.5	12.5

Table 7-2: Conductor width and copper thickness have a direct impact on the current-carrying capacity of a flexible circuit. This table provides a means of determining the conductor width for a 10°C rise. This is for quick reference only. Please consult IPC-2152, Standard for Determining Current-Carrying Capacity in Printed Board Design, for more accurate design solutions.

7-2 are common for flex circuit manufacture. However, thinner copper foils are becoming increasingly important for fine-line applications.

TRACE WIDTH MINIMUMS

The minimum practical trace width for a flex circuit can vary significantly from vendor to vendor. Suppliers that furnish flex circuits with a trace width of 250µm (0.010") and greater are fairly common. Circuits requiring circuit trace widths of 125µm (0.005") and less, however, may have a narrower supply source. Flex circuits featuring conductive features

in the range of 50µm (0.002") and lower are available from fewer suppliers, but that number is growing as the industry keeps pace with the demand for ever-smaller electronic products in volume production.

The type of process technology used to form circuit features has a heavy influence on trace width minimums. For example, sputtered and plated copper polyimide base circuits are limited in feature size only by the photolithographic capabilities of the manufacturer; therefore very small circuit features can be made and such methods are common for the 25µm features described earlier. For etched circuit traces, on the other hand, the trace width and pitch is influenced primarily by the thickness of the base copper foil.

Typically, the trace pitch limit is nearly linear with copper thickness within a narrow range. For example, using conventional subtractive etching processes, 18µm (0.5 oz.) copper will yield circuit features as small as 125µm (0.005") pitch while 35µm (1 oz.) copper foils will be limited to a minimum

Figure-7-8: Circuit line and space track in an approximately linear fashion. Pitch is defined as either center-to-center or edge-to-edge spacing, as shown, between traces.

of 175µm (0.007") pitch. There are a number of suppliers that have refined their process and are successfully producing 25µm (0.001") features with 18µm copper. Figure 7-8 shows a graph for thinner coppers. Vendor capabilities vary widely; therefore it is best to check with the fabricator before attempting to design with very fine line features.

CONTROLLED IMPEDANCE LINES

Controlled impedance transmission cabling is a popular application for flex circuits and its value is increasing as digital data signaling speeds continue to rise. Tighter tolerances for etched features are possible with flex circuits because of the lower profile adhesion treatment or tooth of the copper. When the design allows, the use of thicker flexible dielectric substrates can ease the etching challenge because thicker substrates allow for wider signal lines. The wider circuit trace can be more easily fabricated to meet the tight tolerances needed for controlled impedance circuits.

ETCH FACTORS

An etch factor is a tool used by the manufacturer to compensate for isotropic etching process effects. The designer should check with the flex circuit vendor to determine if an etch factor needs to be included in the design file. Manufacturers commonly prefer to make adjustments for etch factors since they are most familiar with their processes and their capabilities.

Figure 7-9: The etching process works laterally and down at a ratio of roughly 1:2 (laterally to down).

The typical line width loss (measured at the top of the trace) due to the etching process is approximately two times the copper foil thickness. However, copper type, foil adhesion treatment, conductor pitch, etch mask, process chemistry and equipment can all influence the results.

CONDUCTOR ROUTING CONCERNS

There are a few issues related to conductor routing of a flex circuit. The first item of concern is keeping the number of crossovers in the layout to a minimum. This will help to keep the layer count down and reduce the cost. Many CAD systems can respond to this requirement, but the results may need to be massaged or optimized to ensure that the smallest possible area has been consumed in the process.

It is also recommended that designs avoid right or acute angles (≤90°) in circuit routing. Best design practice dictates that corners should be provided with a radius if possible. The radius improves signal propagation by reducing reflections at turns. Sharp corners should be avoided if possible. A radius at the corner is the best option since it provides a smooth transition and mitigates potential issues related to stress risers.

The examples furnished in figure 7-10 compare corner profiles for circuit traces.

Figure 7-10: Routing options for flex circuit trace corners.

The recommended design practice is to rout conductors on a flexible circuit perpendicular to bend and fold to facilitate the bending or folding process and to minimize stress through the area. In addition, circuitry should be routed on a single copper layer through bend and fold areas whenever possible. With double-sided flex, where the conductors must be routed through bend and fold areas and copper traces are on both sides, the circuit designer should design spaces to be approximately 2 to 2.5 times larger than the trace width.

The designer should also stagger traces in the bend area from side to side. The purpose of this practice is to avoid the I-beam effect, which can be a critical concern in dynamic applications (fig. 7-11). When copper conductors are directly aligned on opposite sides of the flexible base, it increases the stiffness of the circuit through bend and fold areas. Additionally, where the copper foil is on the outside of the bend radii or folds, the area is subject to forming stress cracks that can impact product reliability. Placement of vias within the bend area is discouraged since they will adversely affect bend formation and create additional points of stress and potential crack propagation.

Figure 7-11: I-beam vs. staggered conductor construction.

GROUND PLANE DESIGN AND SHIELDING OF FLEX CIRCUITS

Although retaining solid copper as a ground layer on one side of the flex circuit is possible, ground areas should be crosshatched if the electrical considerations of the design will allow. The practice helps to reduce weight and improve circuit flexibility. The size of the openings in the ground plane may be critical depending on the end product requirements for shielding or controlling characteristic impedance. If openings are too large some shielding effects may be lost, depending on frequency. Ground connections for components should be thermally relieved by etching a clearance area around the pad or land while maintaining electrical connection in order to reduce heat sinking and ensure formation of a good solder joint. Figure 7-12 illustrates three ground plane and shield variations. Figure 7-13 shows a fully shielded circuit.

With the proliferation of wirelessly operated electronic products, there is increasing concern around the world about electromagnetic interference (EMI). Shielding of flex circuits may be required to block out unwanted electronic interference or noise. There is, in addition, the converse need to minimize emissions

Figure 7-12: Ground plane and shielding variations.

Figure 7-13: Example of a flex circuit with hatched shielding on two sides.

emanating from the circuit as well. Shielding can be accomplished by using the electronic system in a shielded room, but this is obviously not practical for most of today's electronics. Alternative methods are necessary, including the following techniques

INTEGRAL FOIL SHIELDS

Laminated copper (or other metal) foil on the outer surfaces of the circuit can provide excellent shielding. However, this approach should be carefully weighed to assess its cost-effectiveness. If only simple shielding is required, a lower-cost screened-on coating may serve. All metal foils also tend to be stiffer and heavier than the alternatives.

THIN METAL SHIELDING

Vacuum sputtering of metal and other dry metallization processes, such as vapor deposition, have been successfully used to metallize the outer surface of the circuit, providing the required shielding. The shielding is lightweight and has been successfully employed in satellite applications. The process requires the use of expensive equipment, so it may not be suitable for cost-sensitive applications.

SCREEN PRINTED CONDUCTIVE POLYMER SHIELDING

Screen printing the surface with conductive polymers is a technique that has been used with great success in many applications. As conductivity of inks improves it could see even more use. To take advantage of this technique, some access to ground must be provided through the coverlayer, which allows the conductive ink to be screen-printed down into the opening and make contact. No openings are required when a floating ground is satisfactory for the application. (Refer to ground plane section.)

GRAPHITE COATINGS

Depending on the level of signal attenuation sought or required by the application, lower conductivity coatings, such as graphite or carbon films, may also serve the user's needs. Graphite coatings can be easily applied by spraying.

CONTROLLED IMPEDANCE CONSTRUCTIONS

Controlled impedance signal transmission cable applications are best suited to the capabilities of flexible circuits. Because of the rapid increase in the growth of high-speed, high-performance electronics, the use of controlled impedance interconnections is expected to grow. Following are some of the construction types available using flex circuits. Figure 7-14 shows an example of each type.

CO-PLANAR STRIPLINE

The co-planar stripline is a simple method of creating a controlled impedance cable. The circuit is produced with one metal layer by alternating ground and power. These constructions are well-suited to higher characteristic impedance designs. A drawback of these designs is that they are susceptible to EMI noise.

MICROSTRIP CIRCUITS

Microstrip circuit designs are two-layer flex constructions with one metal layer devoted to ground. These circuits have been successfully employed in transmission line applications, are normally targeted at 50 ohms, and are often used for single-ended interconnections. Higher characteristic impedance designs can be built, but flexibility normally suffers.

STRIPLINE CIRCUITS

Stripline circuits and transmission line cables are also excellent applications for flex circuits. With ground layers on both sides, great signal integrity can be achieved. However, stripline circuit constructions tend to not be very flexible due to the extra dielectric and metal foil used. Stripline circuits are often designed to 100 ohms and are frequently used for differential pair interconnections.

360° SHIELDED STRIPLINE

360° shielded stripline constructions attempt to replicate co-axial cable constructions by virtue of the fact that the signal line is surrounded on four sides by ground. These applications are of interest where cross-talk is a concern and where maximum signal integrity is required. Like stripline flexible circuits, these constructions tend to be rather stiff.

PSEUDO CO-AXIAL CABLE

Some researchers have taken 360° stripline constructions a bit further and used either plated through-holes at points along the length of the flex circuit or plated trenches along the length of the copper ground to improve the shielding between the signal lines.

INTERCONNECTION DESIGN FEATURES

This section deals with interconnection design features, including through-hole interconnections and terminations, both

Figure 7-14: Various controlled impedance constructions.

plated and unplated, and the surface mount lands increasingly being used. An important part of the discussion will focus on the design criteria for making points of interconnection more reliable.

HOLE SIZES FOR COMPONENT LEADS

While surface mount technology has become dominant for electronic component assembly, through-hole components are still used in many applications. One key advantage of flex circuits is the very thin cross-section of the base material. Although soldering through-hole leaded devices on flexible material can be reliable, the devices can be more difficult to

insert. The proper sizing of the hole is an important design checkpoint.

Finished hole diameter for through-hole mounted components in flex circuits for most applications should be nominally 200 to 250µm (0.008" to 0.010") larger than the component lead to meet best practice design requirements for automated component insertion. However, this is not always possible or practical. Best or preferred case flex design practice suggests that all lands or pads should be made 2 to 2.5 times larger than the hole diameter.

Maintaining the recommended size requirements for lands or pads is primarily a concern with single-sided flex where designs seek to maximize the solderable area to ensure that a reliable connection can be made. If size requirements are not maintained, adhesion of the pad or land during the solder or repair process may be compromised. To avoid pad lift and further reinforce the soldered area, it is common practice to add features (fig. 7-15) to broaden the surface area of the copper land and enable coverlayer or covercoat material encroachment over portions of the copper land perimeter. Maintaining a proper drilled hole-to-pad relationship is most important with single layer flex designs.

Increasing the land area is not always be practical, as seen in the case of miniature connectors. In cases where very small lands are mandated and pin-in-hole assembly is required, a plated through-hole may be required to enhance solder joint reliability.

Figure 7-15: Through-hole land or pad termination sizing.

VIA HOLE SIZING

Vias can be designed as small as is practical for the manufacturer's yield. Small vias offer great advantages for circuit layout. However, circuit cost may be affected if vias are designed too small, depending on the technologies available for making holes in the base material. Current punching and laser techniques are capable of economically mass-producing interconnection vias as small as 25 to 50µm (0.001 to 0.002"). In contrast, drilling, because of the higher cost of small drills, becomes more expensive as the holes get smaller. Because flexible circuit base materials are thin, it is possible to fairly easily plate small through-holes reliably. The small plated holes are highly reliable in flex circuits, due in large part to the thinness of the base material which results in a low total material expansion and less concern about thermal cycling.

FILLETING OF LANDS AND PADS

Termination lands and pads on flexible circuits should be filleted. Filleting increases pad area which relieves a stress riser condition that commonly causes failure if the fillet is not supplied or ignored. Earlier CAD systems had difficulty producing these features, but today's advanced systems can more reliably address the requirement for fillets without difficulty (fig. 7-16). The practice of filleting pads improves the reliability of the

Figure 7-16: Comparing circuit-to-land interface variations.

circuit by more evenly distributing stresses at the junction of the circuit land to the coverlayer opening.

PAD OR LAND HOLD-DOWNS FOR SINGLE-SIDED FLEX

Termination pads on single conductor layer circuits and surface mount lands on flex circuits of any layer count may require special land hold-down techniques. With single-sided flex circuits, the use of special features, variously referred to as tie-down tabs, anchoring spurs or rabbit ears, may be employed to prevent the land from lifting during the soldering process when excessive heat is used. Because of the thermal limits required for lead-free soldering, the use of special features has become more important.

Features like tie-down tabs may be a concern as the industry moves to higher data rate signaling. The stubs associated with some tie-down features are capable of acting like antennas and can broadcast noise within the package when higher frequencies are used. An evaluation of the pad reinforcement approach may be warranted depending on the nature of the design. Figure 7-17 shows typical hold-down tab features and alternative designs.

For single-sided flex circuits, it is especially important that the coverlayer entrap the land either by a tied down tab or

Figure 7-17: Relationship between through-hole termination and coverlayer.

anchoring spur feature (fig. 7-17 left side) or by using a hole in the coverlayer that is smaller than the pad to prevent lifting during a soldering process. Where the trace enters from the corner, overlapping pads, elongated oval pads and square pads can be used for single-sided circuits as well (not shown). For double-sided flex circuits with plated through-holes (fig. 7-17 right side), the plated through-hole holds the land in place. Vias (fig. 7-17 bottom) should be covered unless they are needed for test.

SURFACE MOUNTING LANDS FOR FLEX

Surface mount combined with flex circuit technology is in wide use throughout the industry. Land pattern geometry for most common surface mount components is well defined in IPC-7351 for rigid circuit board applications. However, the land pattern geometry will require a slight modification of standard design rules when applied to flex circuit applications.

The use of holes or slots drilled or routed into the coverlayer dielectric before lamination is a common way for flex circuit manufacturers to access solder lands. However, if traces are routed straight into the land, misregistration of the cover-

Figure 7-18: Alternative coverlayer openings for discrete SMT components.

layer could result in the creation of a stress riser (fig. 7-18 A). Side or corner entry to the land (fig. 7-18 B) is more tolerant to misregistration. The laser cut, mechanically punched or routed coverlayer opening can be made rectangular (fig. 7-18 C). Rectangular openings can also be achieved by using photo-imageable cover films in place of a coverlayer.

SMT device lands for both discrete and leaded devices should be extended to allow capture by the coverlayer. Normally lands should be 250 to 375µm (0.010″ to 0.015″) larger than the coverlayer opening provided for the land to facilitate land capture and prevent undesired lifting of the land during assembly or repair. As with single-sided through-hole lands for flex circuits, the objective is to prevent land lift during soldering operations and to provide extra strength against component pull-away in operation. This is of greater importance with components of greater mass. Figures 7-19 and 7-20 provide examples of common approaches used to access surface mount features in flexible circuit design applications while maintaining hold-down capability.

The coverlayer openings for peripherally-leaded SMT lands can be accessed, either discretely or in a gang fashion, by pre-routing or punching the coverlayer before lamination. Use of photo-imageable cover films make this task much easier.

Figure 7-19: Examples of precisely photo-imaged cover films for surface mount lands on flexible circuits (photo courtesy DuPont).

Figure 7-20: SMT lands are furnished slightly longer than the coverlayer opening.

LANDS FOR PLATED THROUGH-HOLES

Except for the shared need for filleting, double-sided flex circuits with plated through-holes do not require tie-downs due to the rivet effect from the plated through-hole. The rivet effect of the plated through-hole effectively prevents the pad from lifting away from the surface of the flexible circuit during soldering processes at excessive temperatures. Plated through-holes are especially advisable if very small pads are required by the design to ensure formation of a reliable solder joint. This may require the addition of a second layer of copper, making a single-sided design a double-sided one. Ease of processing and increases in reliability may offset any increases in cost.

BUTTON PLATING

An alternative plated through-hole construction can be created using a process called button plating. Button plating is a process where through-holes and vias are selectively plated

with copper. The basic idea is simple; however, it requires reasonable care in the manufacturing process to achieve success. In practice, the manufacturer first drills and makes the hole walls of the flex circuit conductive using a suitable technology (e.g., electroless copper or graphite coating). The manufacturer next takes the panel in for imaging where the panel is coated with a photo-imageable plating resist and the holes and vias to be plated are exposed and developed. A copper pattern plating step follows as the hole walls and the annuli of the holes are plated to the specified thickness. The first resist is stripped away and a second plating resist is applied and exposed to create a positive circuit image which can then be etched to create a metal circuit pattern. The holes and vias are tented over in this process, preventing the metal etching chemistry from entering the vias and etching out the holes, thereby creating electrical opens. A finished structure can be seen in figure 7-21.

COVERLAYER AND COVERCOAT CONCERNS

In most flex circuit designs the coverlayer or covercoat serves more than one purpose. For example, covercoats com-

Figure 7-21: Button-plating.

monly perform as solder masks, helping to prevent solder from shorting circuit traces together, but also serve to electrically isolate and physically protect the circuit from damage.

Coverlayers help to physically restrain the pads and hold them in place during soldering, preventing pad lift. The coverlayer (or possibly a covercoat) also allows conductors to be placed in the neutral axis for improved flex and bending performance.

Given the diversity of roles flex circuits play in electronic packaging, it is understandable that it has been difficult for suppliers to come up with a universal solution that is low-cost, high-performing and easy to apply. Nevertheless, steady progress is being made by material suppliers and new solutions are being developed and offered to the industry.

There are several types of flexible covercoating systems available, each with its own special applications and advantages. Included among them are the following:

ADHESIVE-BACKED FILMS

Adhesive-backed polymer films are the type of coverlayer most frequently specified and used by flex circuit designers and manufacturers. It is also the flex circuit covering method best suited to dynamic flex circuit applications because of the balanced material properties from side to side.

SCREEN PRINTABLE LIQUID COVERCOATS

Applied and cured by simple means, screen printable liquid covercoats are the least expensive covercoat type and the type most often used with polymer thick film and simple single-sided copper constructions.

PHOTO-IMAGEABLE LIQUID AND FILM POLYMERS

Newer methods for covercoating flex circuits involve the use of photo-imageable polymers. The results have been very

promising. In process, the flex circuit is coated with a polymer film, which can then be imaged and developed to access termination features. This method, which looks quite good for many applications, could put an end to many of the coverlayer misregistration problems manufacturers have had with small features and could also quell concerns over adhesive squeeze-out onto lands.

SIZING COVERLAYER OPENINGS

The sizing of coverlayer openings varies according to pad design features and the number of metal layers. The key area of concern is with single metal layer flex circuits, where concerns over possible pad lift demand special care in design. Table 7-3 provides general guidelines for sizing of coverlayer openings.

TRACE TO CUT LINE CONCERNS

Best current practice for flex circuit design generally recommends that the edge of the part to the edge of conductor spacing be >1.25 mm (0.050”). It has been shown that circuits can be made reliably with edge to conductor spacing of ≤250µm (0.010”), but this normally increases the cost which varies depending on the tooling system used. (Refer to table 6-1 and figures 6-17 and 7-27.)

Flex Circuit Type	Coverlayer Opening
Single metal layer flex circuit with land hold-down features	Coverlayer opening can be roughly equal to pad diameter
Single metal layer flex without land hold-down features or filleting	Openings in coverlayer should be 250µm (0.010”) less than pad diameter
Double-sided flex PCBs and multilayer flex with plated through-holes and filleted lands	Coverlayer opening can be equal to or slightly larger than pad to minimize squeeze-out
Non-component plated through-hole vias	No opening unless needed for electrical test purposes

Table 7-3: Coverlayer opening guidelines vary with the nature of the design feature.

TEAR RESISTANCE FEATURES IN FLEX DESIGN

All flex circuit designs should be made as tear-resistant as possible. While the material may not be intrinsically tear-resistant, tear resistance can be improved by employing certain features in the design. There are several possible methods that are described below and illustrated in figure 6-22.

1. Large radius in corner
2. Embedded glass cloth
3. Recessed slot
4. Hole in slit
5. Drilled hole at corner
6. Embedded aramid fiber
7. Extra copper in corner

The following techniques have been used successfully to help prevent tearing. One or more of the techniques can be used.

Figure-7-22: Tear resistance features.

RADIUS ALL INTERNAL CORNERS

The first line of defense against tearing is to make certain that all internal corners are provided with the most generous radius possible. This design practice is the most important and simplest of all methods used to prevent tearing of the flex circuit material.

LEAVE METAL IN CORNERS

The circuit design should, if possible, have small areas of copper provided for at internal corners to serve as tear stops at the inside of corner radii. This prevents, or at least mitigates, propagation of a tear through the polymer should a tear in the material initiate.

LAMINATE GLASS FABRIC IN CORNERS

Glass cloths can be laminated into corners during the fabrication process. Though not flexible, this method provides a robust corner construction and has been favored in the past by military product designers. It is an expensive solution, however, because of the type of preparation required and should only be used after careful consideration of the alternatives (fig. 7-23).

USE FLUOROPOLYMER COVERLAYER

The use of fluoroplastics, such as Teflon®, as coverlayers improves tear resistance by virtue of the high tear resistance of the polymer itself. Fluoropolymers tend to stretch, rather than tear, which adds toughness to the substrate. In high-frequency design, an additional benefit of using fluoropolymer coverlayers is that the dielectric constant of the coverlayer is much lower.

USE OF RADIUSED SLOTS

The use of slots with ends that have a radius to access relieved circuit features can also provide tear resistance. Normal-

Figure 7-23: Circuit with embedded glass cloth tear restrain.

ly, such features can easily be provided for during the punching operation or other circuit fabrication process.

DRILLED HOLES AT CORNERS OR ENDS OF SLITS

Drilled or punched holes in corners or at the end of access slits have been used successfully when flexible appendages must be placed close together. This method maximizes the use of material, but the hole size chosen will impact tear resistance. If the holes are very small the overall robustness will be reduced.

ARAMID FIBERS INSIDE CUT LINE

As an alternative to glass cloth, aramid fibers routed through corners or along the entire outline of the flex circuit provide a unique method to stop flex circuit tearing. The thin polymer fibers are high-strength and pliable, minimally affecting flexibility. Using aramid fibers is labor intensive and should only be utilized with consideration of the cost impact.

The choice of method to restrain or prevent tearing of the flex circuit is not a key concern. What is very important is that the designer uses some suitable method to protect against tearing.

To summarize, all internal corners should be provided with radii. It is important to repeat and emphasize that square or sharp internal corners are an invitation to trouble and should be studiously avoided. If the area of the corner is to be permanently bonded to a rigid base, it is less important, but still recommended, that a radius be used.

STIFFENERS AND REINFORCEMENTS FOR FLEX

Stiffeners or reinforcements are commonly used to support components on flex circuits. These important add-ons can be fabricated from a wide range of materials depending on design need (i.e., low weight, best heat sinking, lowest cost, best spring qualities). Both conductive and insulating materials can be used to provide stiffness to a flex circuit. Stiffener materials include, but are not limited to:

- **Resin-glass laminates** – a common call-out, readily available and useful in many applications, especially for heavier component support.
- **Extra layer of coverlayer** – another common call-out, readily available to the manufacturer. Useful for support of smaller, lighter weight components.
- **Thermoplastic sheet** – similar to resin glass laminates, but may not be useful at higher temperatures depending on resin type. Can possibly be used to heat form the assembly.
- **Beryllium copper** – a spring metal commonly used in connectors and a possible dual purpose option as a ground or as a resilient base.
- **Stainless steel** – common choice in disc drive suspen sion circuits for read-write heads.

- **Anodized aluminum** – anodizing makes the surface an insulator while the aluminum core can serve as a heat spreader.
- **Injection molded bases** – offers potential to form circuit over a predetermined shape.
- **Glasses** – have possible benefits where optics are involved, but are brittle.
- **Refractory materials** – useful as insulating bases where high thermal conductivity is desired, but are brittle.

In addition to the materials listed, the package or box into which the circuit is to be placed can also serve as the stiffener if the design allows. In addition to simple component support, the package itself can be used for heat dissipation. While this is an attractive solution for a number of applications, if repair is required, it can be difficult because removal of the circuit from the packaging can cause damage.

SPECIAL TECHNIQUES FOR STIFFENERS

Special design techniques allow stiffeners to function as more than just component support. For example, stiffeners can be designed to aid assembly by enabling the flex to be assembled as a virtually rigid board. There are a variety of techniques that may be considered.

ROUTE AND RETAIN STIFFENERS

Route and retain stiffeners are produced by NC routing of the substrate, leaving it attached in certain locations for easy removal later. Gang assembly or mass application of stiffeners in panelized form facilitates both the application of the flex circuit to the stiffener and subsequent component assembly. This technique allows the stiffener to be snapped off or cut off after assembly (fig. 7-24).

Figure-7-24: It is possible to join stiffeners en masse by preparing the stiffener base in advance, as shown, and joining flex and stiffener panels together for assembly and/or singulation.

When the flex circuit and stiffener are bonded together, the resulting flex circuit panel can be processed much like a rigid board. The adhesive is applied oversized and cut to dimension during the routing step. While routers are pervasive in circuit manufacturing, lasers and water jet cutters are also viable manufacturing choices for preparing or pre-cutting stiffeners.

RETURN TO WEB PUNCHING

Return to web punching (also referred to as punch out, punch in) of the stiffener requires special punch tooling by which the rigid material is punched out of the panel and immediately pushed or punched back into its original position in the panel. The method is commonly used for inexpensive rigid boards and allows mass assembly with relatively simple assembly fixture requirements.

SCORING OR DICING OF STIFFENERS

The use of scoring or dicing tools to prepare the stiffener panel is possible if features of the flex circuit design allow. With respect to the scoring process, the circuit and/or the stiffener is cut partially through using special tools to cut at a controlled depth straight path through the rigid material alone or through both flex circuit and rigid base. After assembly the circuits can then be snapped apart along the score lines.

In contrast to the routing concept, dicing requires cutting completely through the circuit and stiffener. Because of the nature of the tools used, all material cuts must be made in a straight line and orthogonal to the major (X and Y) dimensions of the panel.

ADHESIVES FOR BONDING OF STIFFENERS

All of the bonding adhesives used to create flex circuit laminates are candidates for attaching a flex circuit to a stiffener. The choice of which adhesive to use is most often based on performance requirements.

In addition to the adhesives used in normal flex circuit construction, there are other types of adhesives that can be used. The designer should discuss options with and get recommendations from the flex circuit vendor.

PRESSURE- SENSITIVE ADHESIVES

Pressure-sensitive adhesives (PSA) are commonly used to attach stiffeners. They are perhaps the most versatile and easiest adhesives to use. They exhibit good bond strength, which, in some cases, actually improves with age. PSAs are not generally designed for extended use at high temperatures, but are limited to enduring only short excursions at high temperatures (e.g., soldering temperature). With lead-free solder technology moving ahead, it is necessary to check capabilities when using higher temperature lead-free solders.

One particular advantage PSAs offer over other adhesive choices is that, when applied directly to the flex circuit, they allow the flex circuit to be bonded to virtually any surface, effectively making anything in the package a potential stiffener.

THERMOSETTING ADHESIVE FILMS

Thermosetting adhesive bonding films, such as cast acrylic films or flex circuit bond plies, can also be used to bond flex circuits to stiffeners, but require the time and expense of an additional lamination step. Even so, thermosetting film adhesives can offer high bond strength of the flex to the stiffener.

LIQUID ADHESIVES

One- and two-part liquid epoxy type adhesives have been used for bonding stiffeners to flex circuits. They are difficult to apply uniformly and therefore do not enjoy wide popularity. Liquid adhesive materials are well-suited and can be well-applied to create strain relief at the transition edge of the flex and stiffener by creating a bead of epoxy along the entire edge of the transition.

THERMOPLASTIC ADHESIVE FILMS

The use of thermoplastic-based adhesive films for bonding flex circuits to stiffeners is another common option. Thermoplastic films have some unique advantages among adhesives because they are low-stress, fully-polymerized polymer resins that require no cure. Properties including adhesion to a wide variety of surfaces and materials and the reported ability to be reworked easily may result in an expansion of adhesive materials use in the future.

UV CURABLE ADHESIVES

Ultraviolet curable adhesives are another potential adhesive choice for stiffener attachment. With some screen printable

Figure 7-25: Access holes can be provided in the stiffener prior to lamination.

formulations, the UV activates the polymer, creating a tacky adhesive with PSA qualities. In addition, because UV curable adhesives can be cured rapidly, they are an attractive choice for strain relieving the flex circuit at the transition point from rigid to flex.

HOLES FOR STIFFENERS

The diameter and relative sizing of mounting holes for components and those for final flex circuit assembly mounting have different purposes and often somewhat oppositional requirements (fig. 7-25). As a result, design rules can vary considerably depending on the application.

COMPONENT HOLES IN STIFFENER

Holes in the stiffener for through-hole mounting of electronic components such as dual in-line packages (DIPS) should be 250µm to 375µm (0.010”-0.015”) larger than the through-holes in the flex circuit (which are, by design rule, 250µm [0.010”] larger than the lead). This is to allow for any movement and misregistration between the flex and the stiffener that might occur during the stiffener lamination or bonding process. This technique also helps to ensure the greatest opportunity to access the through-hole with the component lead without interference from the stiffener.

ASSEMBLY MOUNTING HOLES

Mounting holes in the stiffener for mounting the assembly should be equal to or slightly smaller in diameter than the holes in the flex. This ensures that the stresses are placed on the rigid portion of the assembly and not on the flex circuit. This is not an iron-clad rule since it is possible to mount the flex circuit directly to a carrier without a stiffener using common mounting hardware if necessary.

UNSUPPORTED MOUNTING HOLES

Mounting holes that are not supported by a stiffener should be designed to maintain copper around the hole for added strength (fig. 7-26). This practice is of value with regular mounting holes as well, if the design permits, and is also a convenient means of making a connection to ground.

Fabricators recommend maintaining a conservative clearance between features on the circuit as illustrated in figure 7-27.

Figure 7-26: Mounting holes should retain copper when flex circuit is to be mounted without mechanical support.

Cu Dim.	½ oz. 17 µm	¾ oz. 26 µm	1 oz. 34 µm
A	0.13 mm	0.19 mm	0.25 mm
B	0.13 mm	0.19 mm	0.25 mm
C	0.75 mm	0.75 mm	0.75 mm
D	0.50 mm	0.50 mm	0.50 mm

Dimensions may vary, consult supplier

Figue 7-27: Recommended feature clearance and L/S dimensions based on copper foil thickness. Note that dimension C (edge of trace to edge of part) will vary and the value above, 0.75 mm, is a good practical lower limit but lesser values are possible. Keep in mind that traces in flex areas nearest the edge tend to fail first.

Maximizing the edge-to-copper setback (C), for example, will ensure that the flex circuit remains usable even when the circuit image-to-edge tolerance is at its minimum dimension. The same logic can be applied to clearances between the circuit pattern and hole features. Many suppliers of single copper layer flex circuits will pre-drill or punch the hole features before imaging and etching. Providing a reasonable clearance (D) between the hole and land features and the copper circuit edge will help to maximize fabrication process yields.

STRAIN RELIEF FOR FLEX CIRCUITS

Providing strain relief at the edges of stiffeners helps to prevent stress risers from occurring at flex-to-rigid transition. Tearing of the circuit or breaking of the copper at the transition point can occur more easily if the procedure is omitted from the design or manufacturing process. One or both of the following techniques should be used.

ROUNDED STIFFENER EDGES AT TRANSITION

In areas where the flex circuit egresses from the perimeter of the stiffener, the stiffener edges should be rounded or provided with a radius at the edge to prevent a point of focused stress. Alternatively, breaking the edge of the rigid stiffener with a file or sandpaper at the transition edge before assembly can provide a similar benefit.

FILLET TRANSITION EDGE OF STIFFENER

Filleting of the transition edge of a stiffener with a resilient adhesive or epoxy is another common method of strain relieving circuits. The small bead of a suitable polymer will provide a simple means of transitioning strain from the stiffener to the flex circuit. Figure 7-28 illustrates the two approaches.

Figure 7-28: Strain relief at the flex-to-rigid transition helps minimize the potential for focus stress.

STRAIN RELIEF FOR UNSUPPORTED FLEX CIRCUITS

Strain relief should also be provided for when mounting the finished circuit or assembly. The following methods can be used for this purpose:

- Break or radius sharp edges of any retaining bars or clamps that may be used to hold the flexible circuit in place.
- Use a low modulus, elastomeric material between the restraining bar and the flex circuit.
- Bond the circuit to the assembly housing using a double-backed adhesive foam material or simple pressure-sensitive adhesive.

METHODS OF CONNECTING FLEX CIRCUITS

Connecting a flexible circuit to other elements of an electronic system is a vitally important element in system design, manufacture and assembly. There are numerous methods of making flexible circuit connections. Virtually all connector manufacturers have connectors that were either specially built for flex or are readily adaptable to flex circuit designs. One innovative connector manufacturer, Beta Phase (Menlo Park, CA), actually made its connectors out of flexible circuits, producing high-performance connectors with very high pin-count equivalents. The concept (fig. 7-29) was ahead of its time and did not get much use outside of extreme performance applications. However, the technology was purchased by Molex and some elements of the earlier concepts are now available and other connector manufacturers now have comparable products on the market.

FLEXIBLE CIRCUIT CONNECTOR TYPES

Some basic connectors are simple devices, including insulation displacement connectors and crimp- or clincher-type

Figure 7-29: Patent drawings of a novel high-density flexible circuit edge connector. The shape memory alloy used to open this zero insertion force (ZIF) flex circuit based connector designed by J. Krumme and G. Yasumura of Beta Phase.

connectors, which have proven popular in applications where cost is important. They are not generally considered suitable for high-reliability applications.

To make both male and female pin-in-socket connectors, swaged or brazed pins can be attached directly to the flex circuits. These have also enjoyed some success in certain low-end product areas where performance is not a key concern.

Sculptured® flex circuit technology has the ability to integrate the connector directly into the flex circuit itself. This method is suitable for a number of different electronic applications because discrete joining of pins to the flexible circuit is not required. By using this technology, it is possible to have edge contacts that extend, unsupported, beyond the edge of the flex circuit. It is then possible to simply post-form the leads as required to create a viable male pin connector for mating with a compatible socket.

Another option allows the flex circuit to interface with a common PCB edge connector. For this application, the end of the flexible circuit is configured with compatible contact spacing specified for the edge connector, a thin, reinforced laminate stiffener is placed behind the flex and the flex is folded and bonded to the stiffener (fig. 7-30).

Edge card contact constructions can also be created by folding the contact area of a flexible circuit around a stiffener. This is a simple and relatively inexpensive way to interconnect a flex circuit. It is analogous to edge card contacts on rigid boards for which there are numerous different types of mating connecter solutions available. Because the flex circuit is thin, it is possible to accommodate a wide range of connector designs by simply altering the thickness of the stiffener used with the flex circuit.

There are many ways to prepare a flexible circuit for interconnection (fig. 7-31). They include structures that are both integral (made a part of the circuit) and integrated (having interconnection features added to the circuit after fabrication).

Figure 7-30: Edge contact on flex where the end of the flexible circuit is configured to mate to a standard PCB edge connector by placing a stiffener behind the flex and folding and bonding the flex to the stiffener.

With the exception of edge card connections, integral interconnections are often designed for one-time interconnection application, while integrated interconnections are normally separable.

Figure 7-31: Ways to prepare a flexible circuit for interconnection. (Drawings courtesy EPEC).

SURFACE MOUNT CONNECTOR ATTACHMENT

Surface mounted connectors are an increasingly important and more common connector choice for use with flexible circuits. Since size reduction is a common objective of flexible circuit technologies, it comes as no surprise that low-profile connectors are well-suited to the needs and abilities of flexible circuits.

A number of low-profile connectors are presently in the market. These miniature connectors are nicely suited to the space constraints of many flexible circuit applications. Commercial manufacturers have produced low-profile connectors that offer low insertion force (LIF) and zero insertion force (ZIF) connectors and can handle contact pitches down to 0.20 mm (0.008”). The profile height for these connectors can be as low as 0.60 mm (0.24”). Surface mount connectors for flexible circuits, like the one shown in figures 7-32 and 7-33, facilitate high-density interconnection.

Figure 7-32: Surface mount connector on flex. (Graphic courtesy of Molex)

Figure 7-33: Very fine pitch connectors for flex circuit like the 0.25mm pitch flexible circuit connectors shown are becoming available. These connectors facilitate more complicated circuit designs on smaller printed circuit boards, contributing to the continuing miniaturization of consumer electronics (Image courtesy of TE Connectivity, formerly Tyco Electronics).

An additional layer of dielectric film or glass-reinforced laminate material is often bonded onto the flex material to add physical reinforcement to surface mount connectors that are attached with solder. The added material acts as a stress relief to prevent damage to the solder interface of the connector while inserting or extracting the connector from its mating assembly.

ZIF connectors are popular for use with flexible circuits and allow direct connection between the flex circuit and the mating connector (fig. 7-34), as opposed to a two-part connection (fig. 7-32).

Lapped connections are another option for maintaining a low-profile interconnection of flexible circuits. Solder alloy, conductive polymers and Z-axis adhesives have all been used to make lapped connections between a flex circuit and a mating interconnection structure. Lapped connections are used in a large percentage of flat panel displays and are connected using anisotropic adhesives.

Figure 7-34: ZIF connectors are a frequent choice among flexible circuit designers since they allow the circuit to serve in an edge card-like fashion.

Figure 7-35: Flex circuit to rigid structure interface variations.

Low profile connections of flex circuits can be accomplished in many different ways. The examples shown in figure 7-35 represent both permanent and separable connections.

Figure 7-36: Heated thermode bonding head. (Source: Miyachi-Unitek)

Figure 7-37: Permanent bond end terminal variations.

Hot (thermode) bar soldering uses pulsed heat technology and is used on a variety of joining applications including flex-to-LCD soldering and flex-to-rigid board soldering. Systems like the one shown in figure 7-36 can also handle conductive adhesive bonding and thermocompression bonding.

Heat and pressure transferred from the thermode element can be regulated to reflow solder alloy plating onto the mating surface or adjusted to only activate conductive polymer film in order to complete the joining process. Three common end termination configurations are compared in figure 7-37.

Figure 7-38: Direct off-board interface of semiconductor elements with flex (courtesy SiliconPipe, San Jose, CA).

In another design approach for flex circuit interconnection the electrical interface is made directly between semiconductor chips using anisotropic adhesives or lap soldered connections. This methodology is capable of providing high-speed and low-power operation by modeling and physical testing of manufactured prototypes. Making flex circuit connections directly between chip packages (fig. 7-38) can provide significant performance improvements as well.

MILITARY TYPE CONNECTORS

Military product developers have used two-part connectors for many decades. They are comfortable with their long history of reliable performance, therefore they commonly use two-part flexible circuits when flexible circuits are a part of the product design. Some examples of how interconnections have been made to bulkhead connectors commonly found on

Figure 7-39: Approaches for soldering military style two part connectors to flex circuits.

military black box products can be seen in figure 7-39. A key concern of two-part connector assembly has been inspection of solder joints that are hidden by each successive layer. In such cases, the assembly process is normally halted after each successive layer of circuit is soldered into place. At the end of the soldering process, the soldered end is encapsulated to immobilize the solder joints, which are known to be the weakest link in the electronic interconnection hierarchy.

Connection of the flexible circuit to a next-level or associated device, assembly or system can be accomplished using one of many different options. The examples provided are not exhaustive in terms of options, but they are representative. The choice users make will be predicated on the cost and performance requirements of the end product.

BENDING AND FLEXING DESIGN CONCERNS

Although flex circuits are normally employed simply to allow the user to form the circuit to fit the shape of the package (flex-to-install applications), there are still many applications

that require dynamic flexing. In fact, in most applications, the very act of placing the flex circuit into the assembly requires that the circuit be bent or folded. In some applications this can occur several times. Flexible circuits are capable of enduring many millions or even billions of flexural cycles, provided the design is properly matched to the task.

Those who are not involved in dynamic flex design should still take the lessons of dynamic flex design to heart. For example, it is important to remember that even static flex circuits can be dynamically cycled by virtue of their application and design. Dynamic cycling of flex circuits is a common occurrence in circuits designed for any type of mobile equipment, such as those for automobiles and planes.

Shock and vibration encountered by a vehicle can cause a flex circuit to endure millions of low-amplitude, high-frequency flex cycles. If dynamic flex design rules are not taken into account, there is a potential for unexpected cyclic fatigue failure of an application subjected to shock and vibration. Attention to the few simple rules provided here for dynamic flex can benefit many flex circuit applications and are arguably good practice for all flex circuit designs.

BENDING AND FLEXING TECHNIQUES

There are a number of clever approaches and techniques that have been developed by engineers over the years to achieve the desired bending or flexing motion in a flexible circuit. The types of motions employed range from linear extension and contraction to rotational flexing through various small angles of 5° or 10° to more than 360° (fig. 7-40).

Figure 7-40: Examples of various flexing and bending methods. Clockwise from bottom left: accordion flex, rolling flex, counter-rolling flex (must be vertically space constrained), window shade flex, large radius flex, and coiled flex

AVOID PLACEMENT OF THROUGH-HOLES IN BEND AREAS

An important design practice that is sometimes overlooked or ignored is the avoidance of placing plated through-holes in the bend areas. This is particularly important in dynamic applications. For static applications, it may be possible to successfully place vias through a bend if they have a coverlayer and the bend radius is large enough, however, it is a practice that should be avoided.

ROUTE TRACES AT 90° THROUGH BEND AND FOLD AREAS

Conductor traces should be routed through the bending and flexing areas at 90° (perpendicular) to the bend line. This intuitively natural routing scheme bends well; however, the rule is somewhat fungible and seems to be regularly violated for convenience. For example, in some flex circuit applications (fig. 7-41), the traces may be bent or folded in more than one direction to achieve the design purpose.

Figure 7-41: Single-layer flex wih two-fold offset.

Figure 7-42: Comparison of a single-layer circuit to a two-layer staggered circuit configuration.

ROUTE CONDUCTORS ON A SINGLE LAYER THROUGH BEND

Whenever possible, conductors should be routed on a single metal layer through bend and fold areas to enhance flexibility. If this is not possible, the conductor should be staggered from side to side to avoid the I-beam effect discussed earlier. If two metal layers are required, the traces should be offset or staggered (fig. 7-42).

DESIGN TO KEEP COPPER IN NEUTRAL AXIS

The concept of neutral axis is very important to flexible circuits. In theory, the center of any item being bent is nearly

Figure 7-43: Keeping copper in neutral axis minimizes cyclic strain and vastly extends flex endurance.

immobile, with stress being absorbed by the outer layers of material. Thus, if the copper (or other metal) foil is kept to the center of the design, the flexing life should be enhanced (fig. 7-43).

Notes:

1. The unbalanced construction consisted of 25µm polyimide with 25µM adhesive on a base of 50µM polyimide with 25µm adhesive and 1 oz. copper.
2. The semi-balanced construction used adhesive to achieve the desired balance (i.e., 25µm polyimide with 50µm adhesive). The base was the same as above.
3. The balanced construction had a coverlayer makeup that matched the base material exactly (50µm polyimide with 25µm adhesive).

Figure 7-44: Data show construction influences flexural endurance.

Many experiments have confirmed the importance of keeping copper foil to the center of the design. Figure 7-43 dramatically illustrates the effect neutral axis placement can have on the flexing life of a flex circuit.

FLEX DYNAMIC AREAS WITH THE COPPER GRAIN DIRECTION

The orientation of the grain of the copper foil has a definite effect on the flexural life of a design. Grain direction is of greatest importance with flex circuit designs fabricated using rolled and annealed (RA) or traditional electrodeposited (ED) copper foil. With vendor-electroplated copper on sputtered film, orientation is not as critical since there is no specific grain direction. The effects of grain direction on flexural life can be significant, as the data found in the graph in figure 7-44 indicate.

Figure 7-45: Example of a hinge flex design concept for a cell phone (Source: US Patent No. 6948240).

Figure 7-46: Small diameter bend radii demand greater elongation from the materials used in flex circuit construction, especially copper foil.

KEEP FLEXURAL ARC SMALL

For maximum flex life, it is best to keep the range of the flexural arc or total angle of flexure of the circuit for dynamic designs as small as possible (that is, flex the circuit over the smallest possible distance). This is a key technique used in later model disk drive applications that allows them to achieve the high flex life cycling they presently display.

PROVIDE THE LARGEST BEND RADIUS POSSIBLE

Providing the largest practical radius through bend areas is especially important for dynamic flex, but it can also be important in flex applications that are apparently static in nature. The graphic and simple equation in figure 7-46 illustrate the effect of bend radius diameter on the copper foil. As the calculation concludes, the elongation requirements for the copper foil rise significantly as bend radii decrease.

GUIDELINES FOR MINIMUM BEND RADII

Bending and flexing are intrinsic and sought-out features of flexible circuits. Getting the design right, however, requires attention to established design protocols and common, long-standing guidelines. Finite element analysis (FEA) and model-

Flex Circuit Type	Minimum Bend Radius
Single Metal Layer	**3-6 x** circuit thickness
Double-Sided Flex	**7-10 x** circuit thickness
Multilayer Flex	**10-15 x** circuit thickness (or more)
Dynamic Application ***(Only single-sided recommended)***	**20-40 x** circuit thickness (increase in bend radius increases life)

Table 7-4: Minimum bend radii design guidelines for flex circuits.

ing tools may also be considered and will be discussed in more detail later in this chapter.

For normal bending of flexible circuits, guidelines can be found in the table 7-4. For very high flex life dynamic flex circuit designs, fabrication and testing of prototypes remains the preferred method of design verification.

CREASING AND FOLDING FLEX CIRCUITS

Creasing and hard folding of flex, while not a preferred practice, can be successfully accomplished with some attention to certain details. When required, the circuit should be bonded to prevent it from bending back at the crease or fold line. Strain relief is also recommended. It is important to keep the construction balanced for best flexural endurance life. The ideal copper for such strain bending applications will be a low-strength, high-elongation copper. Fully annealed soft copper is normally a good choice for applications requiring a small radius bend.

Figure 7-47: Very small bend was required for this disc drive flex circuit.

BENDING FLEX CIRCUITS TO HOLD SHAPE

When bending flex circuit products for static, form-to-fit applications, holding shape is a desirable condition. However, sometimes flex circuits have elastic memory, a condition that can be overcome by following principles for shaping flexible circuits to fit permanently in their application, such as maximizing the metal area. Copper, or any other metal one might use for a conductor, will permanently deform plastically when bent if its elastic limit is exceeded.

Many polymers will also permanently deform if their elastic limit is exceeded. Their limit, however, is many times greater than that of metal (elastomers are generally excluded, though they can take a set over time). Thus, when the composite structure that we now call a flex circuit is bent, the metal foil has physically deformed, while the polymer is still likely to be in its elastic range as demonstrated in figure 7-47.

PROVIDE FOR METAL DOMINANCE IN BEND AREA

In order for the copper (or other metal) to prevent the polymer from snapping back, it must overwhelm the elastic

memory of the polymer. Copper is stronger and higher in elastic modulus, but if the traces are small or the copper is a low percentage of the local area, the remnant elastic strain in the polymer may cause the flex circuit to regress to its original flat shape. This method is comparable to the practices used by flexible circuit manufacturers to maintain dimensional stability.

WIDEN CIRCUIT TRACES THROUGH THE BENDING ZONE

If circuit weight is a concern, the area of extra copper can be localized. In such cases, the circuit features are widened in

Figure 7-48: To create a permanent bend, copper traces can be made wider through the bend area. An alternative is to use thicker copper.

the area of the bend and then reduced in width again as they enter and exit (fig. 7-48). Circuit traces should taper to the new width in both directions.

DETERMINING BEND AREA LENGTH

There is a simple method to get a first-order approximation of the length of the bend area to which the traces are widened. Determine the circumference of an imaginary circle having the desired bend radius and multiply that result by the bend angle divided by 360 (i.e., the degrees in a circle). This should ensure that a sufficient amount of the bend area is filled with the wider copper traces. However, a little extra length may be required depending on the construction.

USE THICKER COPPER IN BEND AREA

If widening the traces alone does not help sufficiently, then one of two analogous methods may be considered: using a thicker metal foil or using a thinner flexible base material. The objective remains the same as they were in the first case, to make certain that the metal can overwhelm the polymer in order the hold the final shape. There are advantages and disadvantages to both paths. Making the copper thicker may make etching a bit more difficult. It will also take longer to etch and use more chemistry. On the other hand, making the polymer thinner could make handling a bit more difficult and the strength of the final assembly will not be as great as the alternative method.

PERMANENT SHAPING ALTERNATIVES

Slight overdriving of the bend to create a stable, more permanent shape can be used to advantage, with the caveat that the minimum bend radius for the flex construction cannot be violated. Note that when permanently bent and plastically deformed, the copper is normally thinned in the area of

the bend and, therefore, weakened. If a truly accurate predictive solution is desired, one can use finite element modeling methods.

HEAT FORMING

Another way to get the flex circuit to hold shape is to form it using a mandrel of some sort, bend the circuit into shape and then apply heat to the fixture, allowing it to cool in place. The objective is to relieve all of the remnant elastic strain in the polymer by allowing it to deform plastically to the final shape with the addition of heat. This approach works best with polymers and/or adhesives that have relatively low melting points. It is a common method for making dome switches in polymer thick film circuits using polyester base materials.

In contrast, polyimide has a very high melting temperature, making it a less attractive candidate. In this method, one must rely on the ability to get above the glass transition temperature of the adhesive and allow the circuit to cool back below that temperature before releasing it from the mandrel.

USE OF LOW MODULUS POLYMERS

A final choice in this discussion is to use non-traditional base materials with low strength and little, if any, elastic strength. Unreinforced fluorinated ethylene propylene (FEP) or polytetrafluoroethylene (PTFE or Teflon), for example, fall into this category. This combination will allow the user to permanently deform the circuit into the desired shape. There are other options that are variations on one or more of these themes, but these are the basics.

Keeping and holding flex circuits in shape is not that difficult, but it does take some attention. The method chosen will ultimately depend on the demands of the design and its application.

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Figure 7-49: Computer models of complex flex design (FEA model courtesy of Michael Perry).

Figure 7-50: Computer generated stress model for a three metal layer flex (FEA model courtesy of Michael Perry).

FINITE ELEMENT MODELING OF FLEX

Over the years, with increases in computing power and increased availability of memory, there has been a significant improvement in finite element modeling tools, in terms of both cost and performance. Given the importance of mechanical requirements to the long-term performance of a flexible circuit assembly, many companies are beginning to perform finite element modeling of the circuits to validate the design before committing the product to manufacture. This can be much more cost-effective than iterating through a number of prototype runs, as long as the modeling parameters are properly selected.

Finite element modeling tools are widely available and many can accept data directly from many types of design software with the user only providing material properties. Meshing is automatic. Figures 7-49 and 7-50 illustrate where the strain is located and the dislocation in a simple bend. They also reemphasize the importance of the coverlayer to reduce strain on the copper foil.

The compression factor of the copper conductor located on the inside radii of the bend makes buckling of material likely, as shown in the lower portion figures 7-49 and 7-50.

Finite element modeling can significantly improve the chances of first pass success in design for application by providing valuable information about the location and magnitude of stress and strain.

POLYMER THICK FILM DESIGN GUIDELINES

Polymer thick film (PTF) technologies have been used to manufacture circuits for many years. Some of the very first circuits produced in volume were made using printed inks and a stencil as shown in Figure 7-51, which is from a 1946 publication on printed circuit manufacturing. Because of the unique nature of the materials used, PTF circuits have their

Figure 7-51: Stencil printing used to make printed circuits in the 1940s.

own, very specific design rules. As a screen printing-based technology, the limits of design are impacted by a few factors, including the processing properties and final conductivity of the ink used. There are also limits to the screen printing materials and processes used. While screen printing will remain an important technology for PTF, inkjet printing seems poised to supplant the time-honored technique of screen printing. The particle size of the conductor material included in PTF inks (historically silver, but with other conductor materials coming on line) and the polymer carrier's rheology and flow characteristics will establish the limits of screen printing. Emerging nanotechnologies being applied to conductive particle production appear poised to boost conductivity, possibly opening the door for much broader use of PTF technology in areas once reserved for copper circuits. PTF circuits can perform quite well in certain types of dynamic applications for which they are not generally considered suitable. Some experimenters have actually reported increases in conductivity with cycling. PTF membrane switches also show the efficacy of PTF as a flexing

technology in the contact areas of dome switches.

CONDUCTOR WIDTH AND SPACING FOR PTF

Minimum conductor width and spacing is considered to be approximately 375µm (0.015”). It is possible to produce finer lines and spaces using PTF inks, but conductivity can become a design performance concern. That said, conductivity of inks is improving, so it is worth checking with the manufacturer to see what is new.

CURRENT-CARRYING CAPACITY OF PTF

Silver-based polymer thick film inks, under normal conditions, can be expected to carry approximately 25% of the current of copper circuits for equivalent line widths and nominal PTF ink thickness. Improvements are underway and some suggest that conductivity approaching that of copper metal is on the horizon. Conductivity values are nominally 5 to 20 mohms/square/25 microns of ink thickness. However, patent literature reports values of 0.100 ohm/square/25 micron for cooper particles plated with silver. While ink prices can be high due to the price of silver, the overall processing cost should reduce the cost of ownership. Care should be used when attempting to carry higher currents with metal-filled polymers. Hot spots within the conductor/polymer matrix can cause rapid degradation of the conductor and possibly failure, therefore, the operating temperature of the circuit should not exceed 90°C.

SCREEN PRINTED PTF RESISTORS

Screen printed resistors are incorporated into many PTF circuit designs. If used in a design, the resistors should be kept to a minimum of one or two base values to facilitate processing. Generally, the resistors can be printed to ±20% of value without trimming. Laser or mechanical trimming of the resistor can be used if tighter tolerances are required.

Figure 7-52: PTF circuits offer many possibilities for cost-effectively making flex circuit assemblies with switches and other unusual features.

TERMINATION DESIGN CONCERNS FOR PTF CIRCUITS

The design rules for circuit pads or lands for PTF circuits are similar to those used for rigid printed wiring boards. However, the termination features should be discussed with the manufacturer. While polymer thick film inks are not directly solderable, conductive adhesives can be use to surface mount components. Land design for surface mounting is similar to PCBs.

CONTACT FINISH FOR PTF CIRCUITS

PTF flex circuits, such as those used for membrane switches, need edge contacts that allow them to be plugged into a connector or mated to another surface. The finish of choice for PTF is commonly carbon. The thin graphite coating is both low friction and sufficiently conductive to carry power and signals at the higher voltages typically used with PTF technology.

MEMBRANE SWITCHES

Membrane switches are ubiquitous. Anytime one physically interfaces with the world of electronics, the odds are that it is through a membrane switch of some type. As common as they are, membrane switches are also one of the more unsung and

Figure 7-53: Examples of flexible membrane switch circuits.

least visible members of the flex circuit family. Since switches are fundamental elements of the electronic interconnection hierarchy, it is worthwhile to look more deeply into this important flex circuit family member. Basically, a membrane switch is, as its name implies, an electrical switch created on a thin film or membrane.

TYPES OF MEMBRANE SWITCHES

There are five membrane switch types:

• STANDARD FLEX MEMBRANE SWITCH

Incorporates the conventional thin, flexible, polyester or polyimide circuit layer with circuits produced by either print-

ing conductive ink or etching copper or other foil. The keys can be made to provide either a tactile sensation or no sensation at all. For a tactile response to the keys, metal domes or formed polyester domes that snap are commonly used. In addition, backlighting can be employed to either help with key identification or to provide a visual cue that contact has been made.

• TRANSPARENT MEMBRANE SWITCH (RESISTIVE TOUCH SCREEN)

An optional alternative to capacitive, force-sensing and other types of screen switches which translate x-y contact point coordinates. The membrane, or flexing layer, is thin, transparent polyester that is conductively coated. When pressed, the transparent conductive coating makes ohmic (or resistive) contact with another transparent conductor, the static layer associated with the point of contact.

• ELASTOMER MEMBRANE SWITCH

Commonly created using a resilient silicone rubber keypad with an integral graphite shorting contact of the button type shown in figure 7-53. Elastomer membrane switches can be used with either a flex or rigid circuit.

• RIGID PCB MEMBRANE SWITCH

While this is not a flexible circuit, to be complete in this discussion, it needs to be identified. The PCB serves as a hard contact base and the membrane is provided over the top. The back side of the PCB can have SMT components soldered to it.

• PACKAGED MEMBRANE SWITCH

A discrete component that can be mounted onto another assembly, such as a PCB.

Membrane switches are typically low-power with maximum current ratings of around 1/10 of an amp for the printed ink types. Copper circuit constructions can carry more current. The circuitry for these devices is often elaborate since they frequently provide connections for a host of different input functions. Perhaps the most common application for membrane switches is in a keyboard of some type. While not all keyboards are made of flexible materials, a great many are. The most common layouts are matrix type (i.e., rows and columns) and common line connections (i.e., a common trace plus some number of switches). Other structures are possible depending on the needs of the user, including integration of electronic circuits, passives devices, such as resistors, and land patterns for component mounting.

CONDUCTOR MATERIALS FOR MEMBRANE SWITCHES

The conductor material used for membrane switches varies by application. Copper and PTF inks are the most common choices. Cost is normally a key factor when making the choice. Because of this, a substantial number of membrane switches have screen-printed PTF conductors consisting of metal-filled ink. The lower conductivity of printed inks limits conductivity, but they are not normally meant to carry current. Rather, they are designed to send a simple signal pulse. Copper is employed when there is need to solder devices to the membrane or when higher conductivity is needed. However, conductive adhesives have proven quite acceptable in most applications.

The switch life of a membrane contact can vary significantly from several thousand to many millions. The life-determining factors are many, including construction materials, contact design, switch travel and operating conditions.

TACTILE FEED BACK

While some membrane switches do not provide for tactile feed back (sometimes called a Type 1 structure), it is arguable that one of the key elements of membrane switch design is providing for tactile feedback. Tactile feedback is a small snap or click that can be felt when a switch is pressed and released. Determining the right amount of force to be applied (the actuation pressure) is both an art and a science. Some customers are very adamant about feel, which, unfortunately, can be subjective.

There are basically two approaches to getting tactile feed back: polymer dome contacts (sometimes called Type 2 structures) and metal dome contacts (sometimes referred to as Type 3 structures). Metal dome tactile switches have a spring metal dome over the contact area. When pressed, they snap down to complete a circuit and snap back when released. The shape and thickness of the metal (commonly spring stainless steel) determines the actuation force. Metal dome tactile switches offer a long life, but are not well-suited to use with flex circuits.

Figure 7-54: Basic membrane switch contact designs are shown without an over layer.

In contrast, polymer dome switches are embossed into the plastic film overlying the circuit. It is possible to get a good tactile feel from such a contact, and, though their life expectancy is heavily influenced by their use and environment, they can still endure millions of cycles if designed right. Furthermore, they have a cost advantage since they reduce the number of parts, which reduces assembly time and complexity. Of course, one can opt not to use tactile feedback and instead use an auditory response method, such as a small beep. Because of their extreme simplicity, polymer dome switches tend to be the lowest cost contacts of all.

CONTACT DESIGN

The contact area design is another important and interesting element of a membrane switch. Contact finish can vary. Gold, nickel, silver and even graphite have been used. The layout varies with the type of contact used. For example, for a shorting contact, interdigitated fingers are often used. However, when a metal dome contact is employed, a central contact with a surrounding ring is frequently seen (fig. 7-54). A great deal of time and effort has been expended over the years to define the ideal contact.

The shorting contact on the right in figure 7-54 is normally attached to a resilient material that holds it off the surface when it is not pressed down.

CONNECTING TO MEMBRANE SWITCHES

Perhaps the most recognizable element in a membrane switch is the tail element. The tail can be provided with a connector, often using graphite as the contact finish. In such cases, the circuit traces are simply plugged into a ZIF-type. In addition, Zebra Strips, a type of elastomeric connector, may be suitable depending on the application.

This brief review of membrane switches is by no means

complete. It serves only as an introduction to the technology. It is meant to provide an appreciation for this important use of flex circuit technology.

SUMMARY

This chapter has provided an overview of some basic, yet very important, design practices required to successfully implement flex circuit technology. There are many other design requirements for PCBs, many of which are common to both flex and rigid circuit designs. Many concerns of flex circuits are captured by the mechanical demands placed upon them. The reason is simple. What was formerly a simple replacement for a standard PCB has now become a much more complex and highly mechanical, multifunctional interconnection device.

This simple reality forces the electronics designer to give proper consideration to mechanical concerns that could normally be ignored in rigid board design, but are vital in the design of flex circuits. **FCT**

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Thank You!

EIGHT

Werner Engelmaier has been a valued contributor to *Flexible Circuit Technology.* Sadly, he passed away before the 4th edition was complete. We will miss his friendship as well as his contributions and expertise.

Werner was born in Vienna, Austria and held Mechanical Engineering degrees from TGM in Vienna, USC and MIT. He had over 43 years of experience in electronic packaging and interconnection technology. He was fondly known as "Mr. Reliability." He was the president of Engelmaier Associates, LC. Earlier in his career, he was a Distinguished Technical Staff at Bell Labs for 24 years.

Werner authored over 180 technical publications and was awarded a number of patents. He conducted many tutorial workshops and contributed to numerous task forces, specifications, standards and design guides. He was chairman of the IPC Product Reliability Main Committee.

Werner received many honors and awards, including R&D 100 Awards, the Bell Labs Distinguished Technical Staff Award, the IEPS Electronic Packaging Achievement Award, and the IPC President's Award. He was inducted into the IPC Hall of Fame in 2003 and was a Fellow of IMAPS.

Chapter 8

Guide to Reliable Static and Dynamic Flexing

Werner Engelmaier

INTRODUCTION

Flexible circuits by their very nature have an inherent ability to flexurally deform. This permits the roll-to-roll manufacturing processes for large volume production. In roll-to-roll processing the rolls around which the flex circuits are transported typically have 3-to-4 inch radii. The numerous traversals around processing rolls, even though each traversal contributes to the cumulative fatigue damage, do not come close to exhausting the ductility of the copper conductors.

Designers have exploited the inherent flexibility to design flex circuits to be flexurally deformed during assembly, adjustment, and repair procedures, to have complex three-dimensional final geometries, and to sustain multiple flexural cycles during functional life. Flexural deformation imposes strains, which are inversely proportional to the bend radius, on the materials in the flex circuits. The applied strains are directly proportional to the flex circuit thickness and are largest at the outer surfaces.

The bend radii imposed by the designers are typically considerably smaller than those of the processing rolls. This makes it necessary for the designer to understand the flexibility limitations of the flex circuit and to take these limitations into consideration not only for the final product geometry and functional life, but also for all prior assembly, adjustment, and

repair procedures to avoid yield problems and functional life failures.

The items that need attention in the design phase can conveniently be divided into three groups:

- conductor layout
- flex circuit stackup
- material selection

The factors influencing these design considerations from a flexibility viewpoint are:

- assembly, adjustment and repair procedures
- final circuit geometry
- number of flexures during functional life

From the foregoing it should be clear that these design considerations are necessary only in bend regions of flex circuits where the circuits will be flexurally deformed. However, many of the points raised here should be carried out as a matter of good design practice whether or not the flex circuits contain bend regions.

STRAIN VS. DUCTILITY

DETERMINATION OF STRAIN

The bending of flex circuit causes deformation, strain, and stresses in the circuit materials. The strains and stresses are functionally related for each material via the stress-strain diagram. The forces necessary to cause flexural deformation are small; the flexural deformation is determined by the imposed bend geometry. Thus, the amount of induced strain

is the parameter of interest. Ductility, D_f, is the ability of a material to deform plastically before fracture occurs, and is defined as the strain at fracture, εfracture:

[Equation 1] $$D_f \equiv \varepsilon_{fracture}$$

Usually, ductility is determined as the elongation or the reduction of area caused by a tension test. Ductility of metallic foils and flex circuit conductors cannot however be determined with a tension test because of the cross-sectional and gage length aspect ratios of the test samples, and a fatigue ductility test is used, such as ASTM E 796 (ASTM) or IPC-TM-650, TM 2.4.2.1 (IPC). In principle at least, the ductility values determined by these various methods should be identical. Uniaxial strain relates to the dimensions before and after deformation by:

[Equation 2] $$\varepsilon = \frac{L - L_0}{L_0}$$

where ε = strain (x 100, %)
L = length after deformation
L_0 = original length

In flexure, the strain is not uniform but has a linear distribution from a maximum compressive strain $\varepsilon_c$max, on the concave surface to a maximum tensile strain $\varepsilon_t$max, on the convex surface. This strain distribution is illustrated in Figure 8-1. As can be seen in Figure 8-1, the strain is zero at the neutral surface and increases proportionally with the distance from the neutral surface.

Figure 8-1: Strain Distribution in a Bent Beam.

The strains can be calculated by the following simple relationship:

[Equation 3] $$\varepsilon = \frac{y}{R}$$

where y = distance from the neutral surface
R = radius of curvature of the neutral surface

Thus, the maximum tensile and compressive strains are at

[Equation 4] $$\varepsilon_{t,\max} = \frac{a_t}{R}$$ and [Equation 5] $$\varepsilon_{c,\max} = \frac{a_c}{R}$$

where $\varepsilon_{t,\max}$ = tensile strain at the convex surface
a_t = distance of the convex surface from the neutral surface
$\varepsilon_{c,\max}$ = compressive strain at the concave surface
a_c = distance of the convex surface from the neutral surface

In Figure 8-1 and Equations 4 and 5, two items are presumed known: a) the location of the neutral surface, and b) the radius of curvature of the neutral surface. For symmetric beams bent over circular mandrels these parameters are easily located: a) the neutral surface lies in the center of the beam, and b) the radius of curvature of the neutral surface is the sum of the mandrel radius and half the beam thickness. Flex circuits can be designed either as single-sided, double-sided or multi-layered circuits. Assuming that the conductor patterns on both circuit sides are essentially identical and follow the other layout recommendations, double-sided and multi-layered flex circuits are symmetric beams [Note that in bending into the predominantly plastic regime, such as folding, shifts in the location of the neutral surface can occur due to 1) the different plastic behavior of materials in tensile and compressive loading and 2) the different plastic behavior of the component materials in the case of asymmetric beams] and the maximum tensile and compressive strains are of equal magnitude (but of opposite sign) and can be determined from:

[Equation 6]

$$\varepsilon_{\max} = \varepsilon_{t,\max} = -\varepsilon_{c,\max} = \frac{\frac{t}{2}}{\rho_{\min} + \frac{t}{2}}$$

where ε_{max} = maximum strain at the conductor
t = flex circuit thickness
ρ_{min} = minimum radius of curvature on the concave side of the bent flex circuit

Figure 8-2 illustrates the relationship expressed in Equation 6, which states that the strain increases with increasing flex circuit thickness and decreasing radius of curvature.

It should be noted that the flex circuit bend geometry shown in Figure 8-2 is not circular. Flex circuits may be bent

Figure 8-2: Strain Distribution in Bent Symmetric, Double-Sided Flexible Printed Circuit Wiring.

without the benefit of a forming mandrel. The resulting bend geometries are non-circular and have a minimum radius of curvature at the bend apex which is significantly smaller than the radius resulting from a circular bend in the same space.

This implies that for tight geometries for which the flex circuit conductors will have to be deformed into the plastic regime, the use of a forming mandrel is recommended.

In the case of a flex circuit with the conductor in the center between two dielectric layers, Equation 6 changes to:

[Equation 7]

$$\varepsilon_{max} = \varepsilon_{t,max} = -\varepsilon_{c,max} = \frac{\frac{t_{Cu}}{2}}{\rho_{min} + \frac{t}{2}}$$

where ε_{max} = maximum strain at the conductor

t_{Cu} = conductor thickness

t = flex circuit thickness

ρ_{min} = minimum radius of curvature on the concave side of the bent flex circuit

For asymmetric beams, such as single-sided flex circuits, the neutral surface is not located in the center of the beam. For static equilibrium, the forces on the beam section must sum to zero, thus

[Equation 8] $$\int_A \sigma dA = 0$$

where σ= stress distribution in the beam section and
A = beam section area.

The locus of balance of tensile and compressive forces is the neutral surface and can be calculated using Equations 3 and 8 and the stress-strain relationships of the materials in the beam.

For single-sided flex circuits for which the criterion

[Equation 9] $$\left(\frac{t}{t_{Cu}} - 1\right)^2 \frac{E_S}{E_{Cu}} \leq 0.1$$

where t_{Cu} = conductor thickness
E_S = modulus of elasticity of flex circuit dielectric
E_{Cu} = modulus of elasticity of copper conductor

is satisfied, the center of the copper conductors is a close approximation of the neutral surface location. Therefore,

[Equation 10] $$a \cong \frac{t_{Cu}}{2}$$

where a = location of neutral surface of flex circuit from the flex circuit conductor surface (see Figure 8-3).

The location of the neutral surface for flex circuit designs that do not meet the criteria in Equation 10 can be calculated under the assumption of totally elastic bending. This assumption allows calculation of the neutral surface subject to the cautions regarding plastic deformations.

Figure 8-3. Strain Distribution in Bent Single-Sided Flexible Printed Circuit Wiring.

Table 8-1: Typical Mechanical Properties of Some Flexible Printed Materials.

Material	Modulus of Elasticity $E \times 10^{-6}$ psi	Tensile Strength $s_u \times 10^{-3}$ psi	Fracture Elongation e, %	Fracture Ductility* D_f, %
Epoxy Polyester	0.20	7.6	20.0	N/A
Epoxy-Polyester-Glass	0.47	15.0	0.3	N/A
Kapton	0.40	34.0	82.0	N/A
ED Vendor Copper				
Standard	12.0	41.0	3 - 18	5-25
Annealed	12.0	34.0	10 - 25	15-50
ED Copper Overplating	12.0	41.0	12 - 30	60 - 90
Rolled Annealed Copper	17.0	27.0	15 - 35	50 - 150
Flex Circuits,				
Vendor Copper only	12.0	41.0	—	5 - 25
Overplated	12.0	58.0	—	7 - 60
Solder (60/40 Sn/Pb)	3.3	7.6	21.0	—
Covercoat	0.043	1.0	30.0	—
Mylar	0.55	25.0	120.0	—

* The ductility of FPW, copper-clad flexible laminate, and copper foil can be determined using the IPC Test Methods 3.4.3.1, 2.4.3.2 and 2.4.2.1 of IPC-TM-650, respectively.

Using the concept of equivalent homogeneous cross sections with the modulii of elasticity (see Table 8-1) and the thickness of the various flex circuit component layers, location of the neutral surface is

[Equation 11]
$$a = \frac{\sum_i E_i t_i a_i}{\sum_i E_i t_i}$$

where E_i = modulus of elasticity of material in the flex circuit component layer under consideration
t_i = centroid location of the flex circuit component layer under consideration from the FPW conductor surface
a_i = thickness of the FPW component layer under consideration

With the location of the neutral surface determined either from Equation 10 or 11 as appropriate, the maximum strains in the conductor are then

[Equation 12] $$\varepsilon_{t,\max} = \frac{a}{\rho_{\min} + t - a}$$

and

[Equation 13] $$\varepsilon_{c,\max} = \frac{a - t_{Cu}}{\rho_{\min} + t - a}$$

for the bend direction shown in Figure 8-3 and

[Equation 14] $$\varepsilon_{t,\max} = \frac{t_{Cu} - a}{\rho_{\min} + a}$$

and

[Equation 15] $$\varepsilon_{c,\max} = \frac{-a}{\rho_{\min} + a}$$

for a bend in the opposite direction.

DETERMINATION OF ALLOWABLE STRAIN RANGE

As mentioned earlier, repeated cyclic flexing causes cumulative fatigue damage which can lead to failure due to ductility exhaustion even though the strains imposed during each individual flexure are much smaller than the available ductility. It can be argued that any bending can be viewed as at least a partial flexure fatigue cycle, thus allowing a unified approach for single bends and multiple flexures.

For cyclic fatigue, the cumulative fatigue damage depends on the applied strain range, $\Delta\varepsilon_{max}$, which is the strain amplitude between the reversal points in the bending cycle. Thus:

[Equation 16]
$$\Delta\varepsilon_{max} = \varepsilon_{+Reversal} - \varepsilon_{-Reversal}$$

where $\varepsilon_{+Reversal}$ and $\varepsilon_{-Reversal}$ have to be determined for the extreme reversal positions during the flex cycle using Equations 6 through 15 as appropriate. It should be emphasized here that except for fully reversed cyclic bending, where the strains at the reversal points are of equal magnitude but opposite signs, the values for ρ_{min} will be different at the two reversal positions. In fact, the strains at both reversal positions can be tensile strains if the cycling does not come back to the original flat, zero strain flexible printed wiring position.

From fatigue concepts, the relationship between the fatigue life, the material properties, and the strain range causing failure is (Engelmaier)

[Equation 17]
$$\Delta\varepsilon = N_f^{-0.6} D_f^{0.75} + 0.9\frac{S_u}{E}\left[\frac{\exp(D_f)}{0.36}\right]^{0.178\log\frac{10^5}{N_f}}$$

where $\Delta\varepsilon$ = cyclic strain range

N_f = flex life in mean cycles-to-failure

D_f = ductility of the conductor material

S_u = ultimate tensile strength of the conductor material

E = modulus of elasticity of the conductor material

In Equation 16 the first term is the Coffin-Manson relationship between the applied plastic strains and fatigue failure and the second term represents the fatigue contribution of the elastic strains. Figure 8-4 gives a graphical representation of Equation 16 for copper electrodeposited without brighteners at a ductility of D_f = 30%. The contributions due to the

Figure 8-4. Strain Range-Fatigue Life Curve for Electrodeposited Copper.

applied plastic and elastic strain ranges are shown separately in Figure 8-4.

Equation 16 has been demonstrated to closely describe the strain range-fatigue life behavior of a wide variety of metals over the whole range of fatigue lives with the exception of extremely low cycle fatigue ($N_f < 20$ cycles-to-failure). At extremely low-cycle fatigue, deviations from the Coffin-Manson relationship occur due to the increasingly more significant effects of strain hardening, susceptibility to crack initiation at non-homogeneities, neutral surface shifts, and prestraining caused by the initial bend. These deviations can collectively be described by the empirical relationship:

[Equation 18]

$$\Delta\varepsilon = \frac{N_f^{0.4} D_f^{0.75}}{N_f + C} + 0.9\frac{S_u}{E}\left[\frac{\exp(D_f)}{0.36}\right]^{0.178\log\frac{10^5}{N_f}}$$

where C = extreme low-cycle fatigue parameter, and = 0.5 for electrodeposited copper.

These deviations described by Equation 18 are shown in Figure 8-4 by the dashed curves.

Low-cycle fatigue, where the strains applied during bending are primarily in the plastic strain range, is the regime for fatigue lives of less than 500 cycles-to-failure. For situations where only a small number of flex cycles ($N_f < 20$ cycles-to-failure) is employed, Equation 18 can conveniently be simplified by neglecting the contribution from the elastic strain range. Therefore, for small numbers of flexures, the allowable strain range for copper foil can be approximated by:

[Equation 19]

$$\Delta\varepsilon = \frac{N_f^{0.4} D_f^{0.75}}{N_f + 0.5} \quad \text{for } N_f \leq 20,$$

where a single bend into a final geometry is counted as a quarter fatigue cycle ($N_f = 1/4$)

APPLIED STRAIN VERSUS AVAILABLE DUCTILITY

In order to avoid failures due to conductor fractures, the allowable strain range (Eq. 19) has to exceed the maximum applied strain range, such that

[Equation 20]

$$\Delta\varepsilon_{max} < \frac{N^{0.4} D_f^{0.75}}{N + 0.5}$$

where N = estimated number of flexures

Unfortunately, due to the statistical nature of both the applied strains and the available ductilities, reality is not a simple as might be concluded from equation 20.

STATISTICAL NATURE OF STRAIN AND DUCTILITY

DISTRIBUTION OF APPLIED STRAIN

Primarily because of deviations in the minimum bend radii from the design radius resulting from bending without forming mandrels, the strains that a bent flex circuit will be subjected to will in practice have a distribution rather than a fixed value. Since, typically, the design radius of a flex circuit bend is the largest radius that will fit into the available space, the distribution of actual radii of curvature is typically a skewed distribution of radii less than the design radius. This follows since the bend geometry is usually assumed to be circular, when in fact, it is not and cannot be. Figure 8-5 shows the distribution of actual radii of curvature for a design with a nominal design radius of 3.175mm (125 mil) and a forming fixture mandrel radius of 3.175mm (125 mil).

Figure 8-5. Observed Minimum Radius of Curvature Distribution for Formed FPW with a Nominal Design Radius of 3.175mm (125 mil).

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Superimposed upon the strain distribution resulting from the bend radii variation is another strain distribution due to the deviation in the flex circuit thickness form nominal. Furthermore, some design features can cause localized strain concentrations, which can significantly increase the maximum applied strains.

DISTRIBUTION OF AVAILABLE DUCTILITY

Ductility, by its very nature, is a statistical materials property since failure of the 'weakest link' causes failure of the whole. Wrought foil will have less of distribution than will plated foil.

Ductility distributions are readily determined using the test methods described in Standard Test Method for Ductility Testing of Metallic Foil (ASTM) and Flexural Fatigue and Ductility, Foil, Test Method 2.4.2.1 (IPC).

Conductor irregularities, such as nicks, pinholes and etching defects, reduce the available ductility depending on their size as illustrated in Figure 8-6.

Figure 8-6. Reduction in Available Ductility Due to Conductor Defects.

APPLIED STRAIN DISTRIBUTION VERSUS AVAILABLE DUCTILITY DISTRIBUTION

As discussed earlier, to avoid conductor fractures, the available ductility has to be large enough to satisfy the strain criterion in equation 20. With the distributions of applied strains and available ductility described previously, it is clear that it might be prudent to apply a safety (read uncertainty) factor to avoid failures. **FCT**

NINE

Chapter 9

Flex Circuit Manufacturing Process

Joseph Fjelstad, ***Verdant Electronics***

INTRODUCTION

There is a wide variety of flexible circuit constructions in use and, consequently, there is a wide variety of materials and processes used in their construction. Simple flexible circuits, like those produced using polymer thick film (PTF) techniques, require only a few process steps. (For more information on PTF, see Chapter 11 – Printed Electronics.) In contrast, more complex flex constructions, like rigid flex circuits, are often more challenging. The different and repeated processing steps can be numerous and the processing methods intricate and involved.

The complexity of a flexible circuit depends on factors such as panel size, layer count, circuit feature sizes, hole sizes, etc. However, when building a rigid flex circuit, there are a number of additional concerns to consider, including the number of different break-outs, whether bookbinder construction is required, whether there are any multilayer sub-assemblies, etc. The diversity of issues and design challenges make it difficult to describe how each type of flex circuit product is fabricated. However, this chapter will provide basic information on flex circuit fabrication that will aid in understanding the complexity of the processes involved. Understanding the fabrication process will help manufacturers and designers alike, since designs that take manufacturing processes into consideration will result in a better end product.

SINGLE CONDUCTOR LAYER FLEX MANUFACTURE

Single conductor layer (or single-sided flex) is the simplest form of flex circuit technology. Logically, they are also the least expensive type of flexible circuit. Simplicity and low cost combine to make single-sided flex circuits volume leader of flex circuit construction types. A large part of the success and expansion of the flex circuit industry is the result of the efficiencies achieved in the manufacture of single-sided flex. Because

Figure 9-1: Rapid prototyping process using printing and plating of conductive inks developed by Extended Length Flex Technologies in the early 1990s.

single-sided flex is easily adapted to roll-to-roll fabrication processing, a number of flex circuit companies use this method to take advantage of the manufacturing economies for volume production in much the same manner as does the printing and graphics industry. However, flex prototyping methods have also been developed that benefit from print-on-demand methods adapted by the publishing industry (fig. 9-1).

With the many manufacturing options and material choices available to prospective single-sided flex circuit users, the processing choices are numerous. Following are descriptions of some of the different techniques employed to produce these relatively simple yet highly useful circuits.

Additive, semi-additive, semi-subtractive and subtractive comprise the basic list of methods for creating copper circuits for flexible circuits. While previous chapters have touched on the different types of copper foil used to produce flex circuits (e.g., wrought foil versus plated foil) and discussed their relative merits, understanding the methods of circuit creation using the different offerings is important. The key methods are illustrated in figure 9-2.

ADDITIVE PROCESSING

While fully additive processing is rare in flex circuit processing, it has potential and there are a few ways to accomplish it. The most familiar method (fig. 9-2a) uses a catalyzed laminate onto which negative images of the circuit patterns are created. The exposed laminate can then be plated up to build up the desired circuit patterns. To properly control the deposit properties, the plating process can take several hours to build the required nominal thickness of approximately 25µm.

A variation on the additive process (fig. 9-2b) was developed to make flex circuits in the early 1990s. Here, a catalytic toner is printed onto a continuous web of material and the circuit pattern is fused in place. The circuits can then be plated

Figure 9-2: Processing methods for single conductor layer circuits. The red layers are thin conductive films that can be produced by several different methods and using many different metals, although copper is the most common.

up using a combination of traditional processes.

Transfer lamination of circuits can also be classified as an additive process (fig. 9-2c). In this process the circuits are plated onto a type of mandrel and then transferred to a base material in a lamination process.

In addition to the methods described, ZettaCore, Inc. has developed a unique process for making additive laminates that can be applied to materials to improve their adhesion to other materials. ZettaCore's new technology forms a molecu-

lar adhesion layer on smooth substrates, allowing electroless deposition and electroplating of copper onto unroughened polymer surfaces. Molecules are attached to smooth substrates using a thermally-induced reaction of the molecular species with the substrate surface. Next, the molecule-modified surface's high affinity for metal ions facilitates electroless plating of the copper, which is then used as a seed layer to electroplate larger quantities of copper utilizing conventional processes. The process has been proven to reliably enable fabrication of circuit substrates with fine line copper circuit patterns down to eight lines and spaces using a semi-additive patterning process with only a slight modification to standard lithographic processes. The important thing to note is that the circuits have shown good stability in Highly Accelerated Temperature/Humidity Stress Test (HAST) and other accelerated stress tests, indicating that treatment with the molecular adhesion process significantly improves the ability to pattern copper lines at fine-line spacing. While there are a number of companies exploring the technology, it is not yet widely available.

SEMI-ADDITIVE PROCESSING

As the name implies, this method is not fully additive. The basic process normally involves the use of a base material that is coated with a very thin layer of metal, most often copper. The thin metal layer can be additively plated to the entire surface using an electroless copper plating process or a sputtering process. When sputtering is employed, the copper film is normally preceded by a thin adhesion improvement layer of chrome or nickel. This film is then imaged with a negative circuit pattern, just like the additive process, and the circuits are electroplated to the desired thickness. After plating, the resist is removed and the circuits are flash etched to remove the background copper and adhesion film (fig. 9-2d).

There are variations on this process as well. One such

variation is to place the circuit pattern down first, and then to sputter into the openings to bond to the base film. As the walls are normally very poorly coated, it is possible to strip the resist with its thin coating of metal after the plating process. This process is aptly called the lift off process (e).

SEMI-SUBTRACTIVE PROCESSING

While there are no hard and fast definitions for semi-subtractive processing, the distinction is best seen in terms of the thickness of the base copper. While base copper for semi-subtractive processing is much thinner than foils used for subtractive circuits; the copper foils for semi-subtractive processing tend to be two to ten times thicker than semi-additive base metal (e.g., 4µm to 5µm versus 0.5µm to 2µm). It is a small but significant difference. The processing methods are not very different from semi-additive, with the exception that circuits plated on semi-subtractive circuits are likely to require an overplate to protect them in the etching process to maintain circuit feature accuracy (fig. 9-2f). It is also possible that a simple print-and-etch process, using the thin metal clad, could be used to create circuits of this group (fig. 9-2g).

SUBTRACTIVE PROCESSING

Subtractive processing by means of etching is the most common method for flexible circuits (fig. 9-2h). The foils are nominally 17 microns or greater. For flex circuits they are also most commonly rolled and annealed copper. In processing, the positive circuit patterns of etch resist, which directly represent the circuit, are imaged onto the copper foil and then etched to create the circuit. There are variations, however. One process variation involves embossing the foil and grinding off the copper that sits above the relieved circuit pattern created by the embossing process (fig. 9-2i). The method seems well-suited to circuits having features that are relatively course. And because

Figure 9-3: Example of a subtractive dry circuit process and a circuit created by milling the surface of an embossed copper clad laminate (Image courtesy of Tom Stearns).

it is not a chemical process, any metal foil can be used, such as resistive metals for the manufacture of heater circuits. Figure 9-3 shows a demonstration pattern partially processed.

Another subtractive process option is direct laser ablation of the copper as demonstrated by LPKF Laser & Electronics AG in Germany. The process allows a 40mm web to run at 30 meters per minute while ablating circuit patterns from thin copper on polymer films.

As shown, there are a significant number of options available for making single metal layer flex circuits. Each method

has its own place in the greater scheme of circuit manufacturing; however, is the choice of method should be consistent with the needs of the design. In general, additive processes allow production of circuits with the finest, most accurate features, but with increased processing costs. Subtractive processes are straightforward. It is the method of choice for most flex circuit manufacturers. It does, however, produce circuits with noticeable trapezoidal cross-sections with thicker copper foils due to the effects of isotropic etching. Nevertheless, it is still a popular choice.

SUBTRACTIVE PROCESSING

Subtractive, or print-and-etch, processing is one of the most commonly used methods for producing flex circuits. The circuits are manufactured by printing the circuit image on the metal surface of a metal foil clad dielectric using a suitable etch-resistant polymer and then etching the unprotected copper.

When required, holes for component mounting are normally generated by drilling or punching. The holes can be created at the beginning, middle or end of the process, though it is most common to put the holes in at the beginning of the manufacturing cycle.

Following the etch process, a flexible coverlayer or polymer covercoat is applied. The protective covering has openings in it to provide access to component mounting holes, mounting lands for surface mounted devices or other contact surfaces or important features. The basic process steps can be seen in figure 9-4.

While this process is commonly used for processing panels, it is extremely important technology for roll-to-roll processing of flex circuits. Many high volume manufacturers of single-sided flex rely on roll-to-roll processing for their larger production runs.

Figure 9-4: Print-and-etch process for single-sided flex circuit manufacture.

DIE CUT PROCESSING

A clever, but unusual, technique used in the past to make flex circuits involved the use of specially fabricated rotary dies that punched the circuit patterns out of a roll of copper foil on a release film and subsequently stripped away the excess copper. Die cut processing utilized a differential bond strength approach by creating a bond to the base material that was greater in the circuit pattern area than it was in the background copper area. The machine also applied a base film/coverlayer to the foil and had the capability of providing an integral adhesive for bonding the circuit to an assembly.

Die cut processing has seen the greatest success when used in applications where very coarse circuit features are a design requirement. Examples include power bus circuits and simpler automobile instrument cluster circuits. In such applications, where volumes are very high, the approach has proven to be practical and economical. An early example of such a process tool is shown in Figure 9-5.

Figure 9-5: Die cutting tool and equipment used for flex circuit manufacture developed in the 1960s. (Image courtesy of IEN)

BACK BARED FLEXIBLE CIRCUITS

Back bared, also known as double side access, double access or back side access, flexible circuits are most typically single conductor layer circuits that have their metal conductors accessed or accessible from both sides. The back access technique is normally employed when component soldering or another interconnection method is required on two sides of the cir-

Figure 9-6: Back bared flexible circuits allow for a single metal layer flexible circuit to be contacted or connected from both of its major surfaces.

cuit. This circuit design and manufacture approach preempts the need for plated through-holes and the extra steps that the plated through-hole process entails (fig. 9-6).

There are several methods for creating a back bared, single conductor layer circuit. The following are some of the more commonly used approaches.

PRE-PUNCHED BASE FILM LAMINATION

Pre-punched base film lamination is the most common method for producing back bared circuits, primarily because the method offers the best use of normally available technology. This manufacturing approach is commonly used in the manufacture of TAB tape and flexible circuit interposers for IC packaging.

The method entails pre-drilling and/or punching access holes in the flexible laminate film before the film is laminated to the metal foil that is subsequently etched to create the circuit paths. A top coverlayer with holes over other termination areas is then laminated to the etched circuit. Holes in the metal foil can be generated by drilling, punching or by etching during the same etching process used to create the circuit pattern. In the last of these cases, it is possible to create odd-shaped holes such as rectangles or crosshairs that can improve the solder joint formation.

CHEMICAL ETCHING OF POLYIMIDE

This method is specifically for use with circuits fabricated using polyimide films. Polyimide films, while normally a chemically inert substrate, are subject to dissolution in hot strongly alkaline solutions. The technique involves masking the circuit with an appropriate metallic or organic resist image and immersing the circuit in a hot caustic solution to dissolve the polyimide in the desired areas. Often this is done through a series of etch and rinse steps. Examples of etched polyimide holes can be seen in Figure 9-7

Figure 9-7: Examples of laser (left) and plasma-etched (right) openings through polyimide film. Laser holes may have a slight taper, while two-sided plasma-etched holes have the characteristic hourglass shape shown. (Images courtesy of Lumonics and Dyconex)

MECHANICAL SKIVING

Mechanical skiving is another method of accessing features from both sides of a single metal layer flex circuit. It is no longer commonly used due to the wide availability of laser ablation both in-house and through outside services. The method involves mechanically removing polymer film from the top (or bottom) of the circuit feature on a single-sided flex circuit in order to expose it for interconnection or test. Techniques have included everything from careful manual scraping with a sharp

Figure 9-8: Nonstandard interconnections are possible if the features can be etched rather than machined by drilling. Breakable tab to enlarge solderable area (left), a rectangular opening to match pin shape (center), a star washer opening for press-fitting pins to ease wave solder assembly (right).

instrument to the use of a fiberglass rod, filed to a point of the correct size, as a spinning abrasion tool in a drill press.

Another skiving method used for some applications in the past is end-mill machining. Here a flat-faced, fluted-end mill bit of the appropriate size is chucked in a drill press and used to carefully cut away the covering film exposing the base metal feature. Mechanical skiving is not the most cost-effective way to double access a flex circuit design for volume production, but it can be an effective technique for small quantity prototypes or engineering change orders.

LASER ABLATION

Lasers of virtually every type are capable of skiving polyimide material. CO2, YAG and excimer lasers have all been used to access metal features through the cover film or coverlayer by ablation. Excimer lasers are slower than the others, less powerful and require more maintenance, but they can produce sharp, well-defined features (fig. 9-9). Lasers have also been used successfully to precut coverlayer materials for lamination.

Figure 9-9: Post-lamination laser ablation eliminates concerns about adhesive squeezing out and encroaching on solder land area, possibly reducing interconnection reliability. (Image courtesy of LPFK)

Each of the laser technologies has advantages and drawbacks. Lasers are powerful and fast, but they can also easily damage the flex circuit if not set up properly. Lasers also commonly leave a carbon char at the edges of the cut material. Still, newer lasers are vastly improved over earlier models and have proved to be cost-effective alternatives.

Regardless of which type is chosen, lasers are superior to mechanical skiving. They are currently as cost-effective as mechanical drilling techniques. Lasers are highly valued for microvia creation, a technology which is analogous to providing backside access. Laser drilling rates are impressive. Within a small area, drill rates of 10,000 holes per minute are commonly reported and via drill rates of up to 15,000 vias per minute are now possible for copper-clad flex material constructions. The productivity level of lasers is vital to keeping manufactured cost down.

PLASMA ETCHING OF HOLES

Plasma etching of flex material to achieve back baring is uncommon due in part to the slowness of plasma etching compared to the other methods. While plasma is not well-suited to one-at-a-time and individual hole formation, plasma can be cost-effective for bulk or mass-quantity hole formation. The preparation of a panel for back baring by plasma etching involves the use of a metal mask that protects all surfaces, except the areas of interest, from attack by the plasma (fig. 9-7).

One method used to accomplish this is coating the surface of the cover film with a thin metal layer and then etch openings above the desired interconnect point. Another method is to pre-etch a metal mask and pin it to the flex panel or part before processing. This method, however, will not provide quite as good an edge definition. A unique advantage of plasma processing is that unusually shaped features (e.g., square holes) can be created because the lithographic pattern defines the feature shape.

ADDITIVE AND SEMI-ADDITIVE PROCESSES

While additively and semi-additively processed flexible circuits were a relatively uncommon subset of flex circuit manufacture just a few years ago, their numbers are increasing. Most flex circuit designers opted for traditional subtractive copper methods to create their designs because circuit manufacturers had limited experience with the newer processing approaches. There are presently large numbers of flexible circuits produced by additive technology and the numbers are expected to grow as finer lines and spaces become more common. Figure 9-2 showed some of the different ways copper can be processed into circuits. Following are more detail descriptions of some additive and semi-additive flex circuit manufacturing processes.

ELECTROLYTIC PLATE-UP (SEMI-ADDITIVE) PROCESSING

Advances in sputtered film processing technology have led the way for semi-additive flex circuit technology. Micro-thin coatings have gained favor for fine line flex circuit applications because simple light etching of just a few micrometers thick copper is all that is required to create very fine features. Of course, the photolithography systems used must be capable of resolving such features. Circuit traces down to less than 10µm (0.4 mil) line and space can be produced with such thin film clad laminates.

Another area of advantage for micro-thin coatings is in dynamic flex applications. Data indicate that superior flex life can be achieved with flex circuits fabricated using these materials, provided that the manufacturer has good control of the copper plating process.

Adhesiveless structures have also been shown to perform in superior fashion in rigid flex constructions because they allow for a large reduction in the amount of adhesive. This is impor-

tant because adhesives have higher coefficients of expansion and can thus exert higher strain on the plated through-hole reducing the plated through-hole's reliability. Cast polymer forms of flex laminate can also provide this benefit provided that their dimensional stability is satisfactory.

Semi-additive processing, sometimes called semi-subtractive processing, is similar in many respects to conventional pattern plate processing. The major difference is that the laminate is coated with only a very thin layer of copper to which additional copper is added by electroplating.

Extra copper is added to the conductor paths by applying a photoresist coating that defines the circuit paths in copper, allowing additional copper to plate only into the openings. When plating is complete, the plating resistant coating is removed and the thin background coating of copper is differentially etched away (fig. 9-10). This means that some of the electroplated copper is also etched, but the amount lost is not significant to the performance of the circuit.

Figure 9-10: Semi-additive methods are very useful in producing fine line circuits. To use the process shown, the features must be designed slightly oversize to compensate for etch losses that will occur.

POLYMER THICK FILM TECHNOLOGY

The field of additively processed flexible circuits has been dominated by polymer thick film (PTF) technology. PTF has been in use for a long time in calculator keyboards, displays and the like, but recent advances in polymer ink technology have resulted in increases in conductivity that make PTF an attractive alternative to etched metal flex for certain applications. At the present time, PTF technology is being recast as a

Figure 9-11: Representative process flow diagram for manufacturing single-sided flex circuits.

method for printed electronics manufacture. A later chapter will cover the topic in more detail.

The processes used in PTF flex circuit manufacture are fairly straightforward. The circuit pattern of conductive ink is screen printed onto the surface of a flexible polymer using a screen of suitable mesh and the conductive metal-filled ink is cured using either UV radiation or heat.

The pattern is then normally protected either by a screen-printed covercoat or by a pre-machined (i.e., drilled or punched) coverlayer. Frequently PTF flex circuit products incorporate screen-printed resistors as well. The graphite inks used are also commonly used as a contact finish for switches. Because polyester films are normally used, a heat-forming step can be introduced, causing the circuit to take and hold a certain shape. Low-cost dome switches are produced in this fashion. Dome switches are discussed in more detail later in the chapter.

PLATEABLE TONER TECHNOLOGY

Plateable toner technology (PTT) has been explored as a candidate for additive flex circuit manufacture. The technology is based on the use and deposit of a catalytic and plateable toner. The catalytic toner is deposited directly on to the surface of a flexible polymer film that is advanced in roll form using a modified laser printer. The circuit patterns are subsequently plated with electroless/electrolytic copper. (Return to figure 9-1 to review the process.)

A unique attribute of PTT is that it allows a part to be dropped directly into manufacture via computer with no intermediate steps. This allows circuits to be built economically at a run quantity of one. In addition, the technology allows for the manufacture of circuits of virtually unlimited length.

A variation on this concept has been introduced in recent years by Conductive Inkjet Technology in England. The basic

idea is similar, but the processes differ in that the newer process uses an ink jet printer to print the circuit pattern with a catalytic ink. The rest of the processing is virtually the same. The more recent process, however, seems to be limited to the use of electroless only, thus sheet resistance values are limited to 50 to 20 milliohms/square, compared to commonly used copper foil which has a sheet resistivity value of 0.68 milliohms/square at a 25µm thickness. This topic will be touched on again in this chapter and in more detail in Chapter 11 – Printed Electronics.

IMAGING AND ETCHING PROCESSES

While the foregoing discussion has provided detail on the many variations of flex circuit constructions it would be remiss not to devote some discussion to the imaging and etching processes that are the heart of the manufacturing process for flexible circuits. There are a few key points that should be addressed relative to these key steps.

Flexible materials are very thin and can be easily damaged, thus handling of flex materials during imaging and etching is critical. Handling procedures and equipment must provide for this need. A small dent in the copper foil can result in a short or open in the final circuit. Special tools and equipment have evolved to serve many of these concerns, but any time there is an interface with a human, the risk is always there.

There are many types of imaging processes, but the focus of this discussion is photolithography and screen printing. Screen printing is the oldest of the two and is a simple process involving the printing of a chemically resistant ink in the pattern of the circuit directly onto a copper clad laminate. In the printing process, the panel needs to be in register with the screen to ensure proper placement of the circuit pattern relative to tooling required for subsequent processes. Thus, tooling

holes are generally required. Once placed on the tooling pins. the circuit pattern can be printed onto the precleaned flexible copper laminate. To ensure that the thin flex material stays flat and does not move during printing, the printing table may be perforated with myriad holes and a vacuum applied. A key advantage of screen printing, other than the fact that the inks are less expensive than photo-imageable films, is that they require no development before etching. While the feature sizes are generally courser than those obtained with photo processes, some suppliers in Japan have demonstrated ability to print features down to 125μm, making it attractive for more applications.

Photolithographic processes (which can be either positive or negative working) have similar concerns to those of screen printing. These films can be coated in liquid or film form. The film variant offers the advantage of better work area cleanliness, but both process types are proven and capable. With roll lamination processes, the use of water to wet the surface of the panel just before lamination has proven of value to some manufacturers. In any case, precleaning of the flexible copper clad laminate is critical. Tooling holes can be provided in the laminate either before or after the photo-imageable film is applied.

The applied film must be imaged and a UV exposure machine is used to define the circuit pattern image on the film-coated laminate. There are two basic methods for exposure. In the conventional type, a photo image of the circuit is aligned to the panel to be imaged and a vacuum tray with a clear film draws down on the photo tool to make intimate contact with the panel. It is then exposed to a UV lamp from above and/or below until the amount of energy required to polymerize the exposed areas is achieved. The other type of machine, referred to as a direct imaging machine, draws the circuit pattern directly onto a board by radiating myriad small-diameter beam spots across the panel using a photo tool. While this method

Figure 9-12: Rigid leaders attached to thinner flexible laminates to ensure carriage through the processing chambers.

was first explored in the 1980s, it has only recently been made effective enough for production.

Image development is another process step where care must be exercised. Today's more advanced equipment has eliminated many of the concerns associated with image development. However, in years past, the panels were sometimes trapped around rollers inside the development chamber, making it necessary for leaders or pieces of rigid material to be taped to the flexible laminate to carry it through the chambers (fig. 9-12).

While there is variation in imaging, etching is a process that is probably the most commonly shared among all circuit types. It is a process where the perhaps the greatest care must be exercised because it is the least forgiving since there is almost no recovery from an over-etched condition. There are different approaches to etching in terms of chemistry (e.g., ammonia-based, sulfuric acid-based, copper chloride-based,

etc.) and equipment (horizontal, vertical, spin and tank). A case can be made for all of these approaches, but they should be matched to the construction of the circuit. For example, semi-additive circuits having only a very thin copper base may be easily etched in a tank containing a sulfuric peroxide mixture adjusted to not etch in an overly aggressive manner. One thing that is critical for success with any of these processes is that the copper be clean and free of any development residue since such materials can delay or prevent etching.

COATINGS FOR FLEXIBLE CIRCUITS

Coverlayers and covercoats are important subjects and, due to their many varieties and aspects, demanding of further discussion. Flexible circuits almost always require a coating of some fashion over the finished circuits. At the same time, openings are nearly always required to provide access to circuit features for interconnection to components or connectors. The coating is referred to as being a covercoat, coverlayer or cover film. In all cases, a common feature of the finished protective layer is that it is flexible.

The differing terminologies, used to define products that serve a common function, gives away the fact that the products are likely to be different not only in name but also in process, which is exactly the case. What is not clear from their names is that these products typically serve different purposes in terms of the application. Some explanation of the technologies and their rationales should help make this a bit clearer.

COVERCOATS

Covercoats are typically liquid coatings, most often applied by screen printing. However, other methods can also be used. Depending on the type of covercoat used, the screen printing process can involve a pattern that leaves the circuit features

open if it is a UV or thermal cure material, or it can completely cover all features for later exposure and development if it is a photo-imageable material. The process can be very cost-effective with the former case, and is best-suited to use with coarser features. These materials are commonly used in applications where the assemblies do not see much repeat flexing; however, depending on the polymer's specific properties based on its formulation, some covercoats can also serve well in some dynamic applications.

COVERLAYERS

The term coverlayer has historically been reserved for polymer films that have an adhesive layer on one side that is used to bond to the flex circuit. In process, the coverlayer is commonly machined, most often by drilling, routing or punching, to provide openings for the circuit features. After providing the openings, the coverlayer is aligned and laminated to the flex circuit using heat and pressure.

While it is more time-consuming to produce and more costly than screen printing, laminated coverlayers have been the primary choice for circuits requiring high cycle life and dynamic flexing. This is because the properties of the base film and its thickness can be made identical by placing the circuits in the desired neutral axis of the bend radius.

COVER FILMS

Cover films are most similar to dry film solder mask in form and use in that they are laminated, exposed and developed to access circuit features. Cover films have enjoyed increasing popularity for their ability to define opening and access very fine circuit features. While cover films are not ideal for all dynamic applications, they can be quite serviceable in many. Figure 9-13 provides a brief overview of the various processes.

Figure 9-13: Examples of highly abbreviated processes illustrating the basic differences between covercoat (left), coverlayer (center) and cover film (right) formation processes.

There are, of course, variations on processing that can extend one technology over into other areas. For example, lasers can be used with coverlayers to access fine features and chemical or plasma etching of polymer films can be used to access features when combined with certain other processing methods such as the use of integral metal masks.

METHODS FOR COATING FLEX CIRCUITS

There are a number of viable options for protectively coating flex circuits when required. Which method to use depends on a number of factors including application and cost, among others. It can be difficult at times to make the decision, but it is helpful to have choices.

Coverlayer lamination may seem straightforward, but lamination of machined adhesive-backed coverlayer is one of the more important process steps to be mastered in flex circuit manufacture. There are a number of different steps in the process and a variety of materials that make them possible. Following is a review of some of the more important process steps in successful coverlayer lamination.

Figure 9-14: A machine with tacky rollers used to remove dust from circuit materials before processing (Image courtesy of Teknek)

LAY-UP AREA

A clean working environment is an important prerequisite to coverlayer lamination. Dust and dirt particles typically carry a small charge can easily be attracted to the work due to large electrostatic charges created when separating the coverlayer from the film that protects the adhesive surface of the coverlayer. A clean area, fitted with anti-static devices, similar to the environment provided for imaging, is recommended. There are also specially developed tools which are designed to remove dust using specially developed tacky rollers (fig. 9-14).

ALIGNMENT OF ACCESS HOLES

Maintaining the alignment of access holes with circuit features is critical to the creation of reliable interconnection and test features. Flex circuit manufactures have developed a number of methods to facilitate this end. One method is to use tooling holes internal to the panel and parts. Another commonly used technique is to heat-tack the coverlayer to the circuit panel during the lay-up process (fig. 9-15). This has proven to be very effective and allows the technician to compensate for some of the dimensional instability associated with these unreinforced films.

Figure 9-15: Technicians align coverlayer to flex circuit and tack it in place using controlled temperature hot irons. This procedure helps to ensure coverlayer stays in position during lamination. (Image courtesy of EPEC)

STACK-UP OF MATERIALS

The next area of interest is in the stack-up of materials used in the lamination process. Many different materials have been used in the lamination process over the years. In general, these have been comprised of the following:

- Thermal lagging material to control or moderate the rate of temperature rise in the laminate stack. Materials that have been used for this purpose include construction/craft paper and silicone rubber pads.
- Conformal material used to ensure that the coverlayer adhesive uniformly fills the spaces between the circuits and preclude the potential for air entrapment. It also reduces excessive "squeeze-out" of adhesive into pad areas and effectively blocks adhesive or resin flow into other areas such as solder lands. Materials that have been used for this purpose include fluoropolymer sheet, poly ethylene film, silicone rubber pads and liquid crystal polymers. This set includes specially developed materials.

Figure 9-16: How materials are placed relative to one another in a lamination process.

- Release film, as the name implies, is used to ensure that the materials do not bond together permanently. Materials that have been used include fluoropolymer films such as fluorinated ethylene propylene (FEP) or polytetrafluoroethylene (PTFE). DuPont's TEDLAR® material is a commonly used material.

There are also a number of interesting specialty materials on the market that provide the properties of the lamination materials described into a single material. Some of these materials are designed to be used once as process consumables. One material in wide use was developed by Pacothane. It is a single layer hydraulic conformable film approximately 125µm thick with release characteristics from both sides (fig. 9-16).

Figure 9-17: Cross-section of a proprietary conformable release material from Pacothane illustrating how the material eliminates adhesive squeeze out onto lands.

More recently, materials have been designed for multiple uses. One interesting, and relatively new material of this class consists of a central core of glass material covered with a relatively thick coating of high temperature silicone rubber with a fluoropolymer film bonded to both outer surfaces. The release surface facing the circuit becomes distorted as it conforms to the circuit in lamination. However, in the next lamination, the material is flipped over so that the distorted side is facing the flat separator plate where it is returned to flatness while the opposing side is distorted. According to the manufacturer, this allows the material to be used hundreds of times, thus eliminating much of the waste associated with the lamination process. This is an attractive feature as we move to create more environmentally-friendly manufacturing methods. While there are some limits on this material, it is possible, depending on the materials used and their order in the lay-up process, to stack and laminate a number of circuits in between carrier plates by using separator plates between the panels. In some cases, the separator plated may even be omitted.

LAMINATION

When it comes to actual lamination, the lamination pressure and temperature should be set in accordance with the

recommendations of the material supplier unless there is some unusual aspect to the circuit (e.g., very thick copper). Vacuum lamination has some particularly attractive capabilities, especially when it comes to air removal, but traditional lamination presses can still be very effective. In this regard, specialty materials referenced earlier can help to reduce lamination pressure requirements. Vacuum lamination requires the use of special bagging materials, such as those supplied by Airtech Corporation (fig. 9-18), that have properties tailored to withstand the rigors of high temperature lamination under vacuum without rupturing.

High temperature bagging materials similar to those used to seal a holiday turkey during baking are very useful in the vacuum lamination process both in a standard lamination press and in autoclave systems. Special compliant high temperature sealing tape (tan strip in the fig. 9-18) is used to seal the bagging material and hold vacuum. In the upper right corner of fig. 9-18 are the special vacuum port fixtures which are used to draw vacuum. Fibrous high temperature matting materials

Figure 9-18: Special bagging materials that can withstand the rigors of high temperature lamination under vacuum without rupturing. (Image courtesy of Airtech)

are used under the bag and beneath the vacuum ports to assure that the vacuum is uniform through out.

There are thus a number of different and important process steps and facilities issues that should be addressed in the manufacture of flex circuits, especially when it comes to coverlayer lamination. Attention to each seemingly small detail is vital to sustained success and high yield. All of the foregoing discussion is applicable to two metal layer flexible circuits or innerlayers for multilayer and rigid flex constructions. Only substantial differences and departures from these general principles will be highlighted in the remaining sections in this chapter.

SINGULATION METHODS FOR FLEXIBLE CIRCUITS

There are a number of different methods available for singulating (cutting and removing) individual flexible circuits from a processed panel, and all of these methods apply to all types of flexible circuits. The methods for singulating flex circuits can be branched along two main approaches. The first is dynamic vector-based cutting methods, represented by routers, lasers, water jet cutters and numerically-controlled (NC) blade cutters. The second branch involves various punching methods using Class A tools, steel rule dies and a new category of etched cutting dies. Convenience, tolerance requirements, and product volume must be factored into the equation when choosing the appropriate technology.

DYNAMIC VECTOR-BASED CUTTING

Dynamic vector-based cutting uses a computer program to move the flex circuit panel relative to the means of cutting by moving the table with a stationary cutter or by moving the cutting tool itself while the panel is held in place. The former method is the one most commonly employed in circuit manu-

Figure 9-19: Numerically-controlled (NC) routers provide a soft tooling solution for singulating flexible circuits. (Image courtesy of Excellon)

facture and employs an NC router to cut out rigid printed circuits. It is a convenient tool because most flex circuit manufacturers have in-house routers to make rigid parts such as stiffeners. One advantage of this method is that a number of panels can be routed at one time because routers often have more than one head and the circuits themselves can be stacked to improve productivity. Figure 9-19 provides an example of a current drill and router machine.

Because the router is soft-tooled by CAD data, there is no wait for tooling. On the downside, if the circuit outline is complex, routers can be slower than punching and edge quality may suffer if good processing control is not exercised. While routers have been singled out as an example, water jets and lasers can also be used to cut flex circuits from their panels.

With all methods, stacking is generally possible; however the results can vary quite a bit. Water jets are clean, can cut through a variety of different materials and their cutting rates are quite good. The method has been paired with laser tech-

nology by some tool developers. Water jets were considered exotic at one time, but are finding more uses in a wide range of industries. Lasers are seeing increased use in circuit manufacture, especially in drilling microvias. With lasers one must be careful in the selection and use. For example, under most circumstances, CO2 laser energy is reflected by copper. Thus, if copper is to be cut, a potential problem exists. There are ways to overcome the problem, but they require some non-standard preparation steps. On the other hand, CO2 lasers can achieve highly accurate cuts relative to the artwork when the copper is used as a conformal mask. Equipment suppliers can provide recommendations on the use of their products.

PUNCHING

The other branch of singulation methods involves punching. Punching is a time-tested method and is accomplished by using one of two types of tools: two-part punch and die sets (see Figure 9-20) and single-part patterned blade cutters. The punch and die method has been employed to punch shapes

Figure 9-20: Class A tooling for flex circuit punching offers both high precision and long tool life.

from flat materials for hundreds of years. Modern Class A punch and die tools are among the most accurate available and can last for hundreds of thousands to millions of hits if properly maintained and cared for. However, they are relatively expensive and lead times can be very long.

An option for Class A tool punch is the patterned blade cutter or steel rule die. Here, a sharp blade of spring steel is placed into a channel cut into a base of plywood or other material (fig. 9-21). A shoe die press or clicker press is then used to press down on the flex circuit pushing it into the blade and through into a cutting board. A foam rubber, slightly thicker than the blade, helps push the circuits back up from the blade cavity after punching. These tools can be very accurate depending on the method used to manufacture channels. The cost of material used for blade support and turn-around time are normally fairly low. With proper care and use of proper backing materials when punching, they can be used for thousands of punches.

The etched blade pattern method has been used for many years to manufacture roll cutters used for adhesive label cut-

Figure 9-21: The steel rule die is a cost-effective tool for punching flex circuits from their panels.

Figure 9-22: Etched punch die tool. (Image courtesy of Atlas)

ting and has now been adapted and made available as an alternative to the standard rule die. The features are produced photolithographically and thus can accurately recreate the outline pattern (fig. 9-22). The dimensional stability is excellent. A rare earth magnet is used to hold the cutting pattern in place and provide mechanical support. This method has gained some favor with the flex circuit manufacturing and user community.

There are a number of possible methods for singulate flexible circuits from the panel and all are applicable to all types of flexible circuits, especially double-sided flex. The method choice is predicated on a number of different factors including volume, time and tolerance. The right method will vary with the requirements of the individual product weighed against cost, complexity, volume and urgency.

TWO-CONDUCTOR LAYER FLEX MANUFACTURE

While single-metal layer flex circuits are broadly used, two conductor layer (also referred to as two-metal and double-sided) flex are becoming more popular as packaging densities increase. Two-metal layer flex constructions are very popular in a wide range of applications from cameras and mobile cellular

phones to medical equipment and IC packaging. Like single-sided flex circuits, there are a number of different methods that can be used to create double-sided flex circuits. Two-metal layer flex circuits are not as easily adapted to roll-to-roll processing as single-sided flex. However double-sided flex circuits can be produced in a roll-to-roll fashion. The following are descriptions of methods for producing double-sided flex that have been used in the past, are currently in use or are under study for future use.

PANEL PLATE PROCESS

Panel plating of flex circuits is a long-standing method and, like other processing methods, it has advantages and disadvantages depending on a number of different factors. From a processing perspective, it is easier to electroplate a non-patterned panel. However, the extra thickness works against the cause of flexibility and makes fine feature definition more difficult. A typical manufacturing sequence for this process is as follows (fig. 9-23):

- Metal clad laminate is drilled with the desired hole pattern.
- Hole wall surfaces are made conductive using an electroless copper process or a suitable alternative, such as a graphite coating offered by OMG.
- Laminate is electroplated with copper to build the copper plating thickness in the hole to meet requirements.
- Dry film resist is applied to the laminate on both sides.
- Circuit image is patterned onto the metal clad and plated-through laminate, making certain that, after development, the through-holes are tented reliably to protect against the etching process.
- Resist-patterned clad laminates are etched to create circuit patterns on both sides.

- Resist is stripped and coverlayers are laminated to the top and bottom as required.

Except for the plated through-hole portion of the process, the procedure is nearly identical to the procedure used for the manufacture of single-sided flex. The flow chart in figure 9-25 provides greater detail as to the circuit processing steps.

PATTERN PLATE PROCESS

Pattern plating is a common variation used to produce two-metal flex circuits with plated through-holes.

- Negative image of the circuit pattern is produced, which exposes through-holes for plating along with the conductors.
- Copper circuit is overplated with an etch chemistry-resistant metal such as tin, solder, gold or others. These metals will protect the circuit pattern and through-holes during the etching process depending on the type of chemistry used.
- Plating resist is stripped.
- Circuit is etched using an etchant that does not attack protective metal deposits. Ammonia-based or sulfuric acid-peroxide etchants are both commonly used as they preferentially attack copper.
- Protective metal is stripped from the circuit leaving a bare copper circuit identical to the one produced by panel plating.

The greatest advantage of the pattern plating process is realized when features are fine, very little annular ring is present in a design and the risk is high of the resist being undercut and etching out the copper from plated through-holes. This technique is also of value when finer circuit features are required

Figure 9-23: Process steps in the manufacture of a panel plated double-sided flex circuit.

because a smaller amount of copper needs to be etched though to create the circuit image. The result is a reduction in undercutting and a more accurate final circuit pattern.

ALTERNATIVE TWO-METAL INTERCONNECTION METHODS

Interconnection of the two sides of a double-sided flexible circuit can also be accomplished mechanically. Over the years, several methods have been developed. While all of the methods have demonstrated functionality, the individual methods are limited to applications where specifications will permit their use. The following are some of the many methods that

Figure 9-24: The alternative methods for interconnecting two-metal layer flex circuits illustrated are not common, but represent potential solutions for consideration when challenged with a unique interconnection problem.

can be used over the years to create electromechanical connections (fig. 9-24).

Z WIRE INTERCONNECTION

The Z wire is an early precursor of the plated through-hole. It is simply a wire bent in the shape of a Z and carefully soldered to interconnect both sides of the circuit. This technique is normally used only for vias since other through-hole connections are accomplished by the component leads themselves.

EYELETTING

Eyelets are another early alternative to the plated through-hole. Eyelets are the equivalent of small rivets with holes at their centers, like those found around shoelace holes. Like Z wires, eyelets can make interconnection possible between sides of a two-sided circuit.

COLD WELDING

Cold welding, developed by inventor Robert Lomerson, is an interesting technique for interconnecting the two sides of a double-sided flexible circuit. The method requires the fabrication of special tools and manufacture of the circuit according to a prescribed fashion. Permanent interconnection is obtained by pressing copper into copper through openings in the flexible laminate, forming a metallurgical joint by cold welding using the special etched or machined tools.

PTF PROCESS FOR DOUBLE-SIDED FLEX

PTF has been used successfully to produce cost-effective, two-sided flex circuits. Like single-sided flex, screen printing of the circuit pattern is required. Through-hole connection is made by screening conductive inks through a hole in the base polymer film, often with the assistance of a vacuum. Fully automated web printing machines have been developed to produce PTF circuits in a reel-to-reel fashion.

PTF-COPPER HYBRID PROCESS

The PTF-copper hybrid process has also been used in double-sided flex manufacture. The process draws from PTF and standard print-and-etch technologies.

- Circuit pattern is printed and etched on a single-metal layer flexible laminate.
- Opposite side is printed with conductive polymer ink.
- Ink passes through the holes to make contact with the opposite side.

In such products, copper is used for higher power circuits and PTF traces for low-level, low-current signals and higher voltage levels. While there are currently fewer suppliers of this

Figure 9-25: Double-sided flex circuit manufacturing options.

technology, the method holds some promise as a solution for a number of low- to mid-range products.

Figure 9-26: Roll-to-roll processing equipment for flex circuits. (Image courtesy of Northfield Automation)

ROLL-TO-ROLL PROCESSING

Roll-to-roll processing of flexible circuits is a highly automated and cost-effective method of one- and two-metal layer flex circuit manufacture. Because there are different approaches to roll-to-roll processing, the equipment is often customized to meet the needs of the customer. Horizontal and vertical web handling equipment are available. An example of a piece of vertical processing equipment is shown in figure 9-26. The chapter on Printed Electronics will look at roll-to-roll processing issues in more depth.

MULTILAYER FLEX CIRCUIT MANUFACTURE

Multilayer flexible circuits have three or more layers of metal conductors. Over the years, they have become more popular as a packaging scheme in some applications in spite of their higher relative cost. However, they are very complex, engineering-intensive and demanding, both in design layout and manufacture. It is often possible to lay out a design on paper, which, though it has apparent logic and order to it, cannot be easily manufactured or manufactured at all.

Despite these challenges, the fact that multilayer flex circuit structures allow the designer to create unusual high density and high performance electronic packages keeps them on the list of options for many designers. In fact, many packaging engineers feel that multilayer flex circuits are a bargain for the many benefits they bring, particularly in complicated wiring situations.

Processing of these highly complex interconnection structures is extremely demanding and requires an exceptional command of manufacturing operations. Unlike single-sided and double-sided flex circuits, which can be processed in a reel-to-reel fashion, multilayer circuits are typically only fabricated in panel form. (A multiple-conductor layer construction is possible using PTF in a web format, but its usefulness is limited at present, so it is not considered a common multilayer flex technique.)

Along with rigid flex circuits, multilayer flex circuits are among the most expensive types of electronic interconnection structures. However they can also be among the most cost-effective. Designing and laying out a multilayer flex circuit is best carried out in close coordination with the flex circuit manufacturer. Most manufacturers are eager to provide assistance in order to facilitate entry of the design into manufacture and yield better results. The following are descriptions of some of the methods of multilayer flex constructions that have been explored to date.

Very little about multilayer flex circuit processing is truly conventional. Each new design brings with it a host of new challenges. Multilayer circuits tend to be engineering-intensive and require well thought-out, skilled planning. Because each design is unique, it is difficult to describe a typical processing sequence; however, there are some common themes and the following descriptions are offered to provide a sense of the intricacies involved in the manufacture of multilayer flexible circuits.

BASIC MULTILAYER FLEX CIRCUIT MANUFACTURING

There are many similarities between multilayer flexible circuits and standard rigid PCBs, but the processing is often much more challenging. In flex MLB (multi-layer board) processing, flexible laminates that are to be the circuit layers are provided with tooling holes. Often the tooling holes are placed first, but there are variations on this method that involve the use of a post-coverlayer application lamination punch that can accurately punch tooling holes in a semi-automated manner.

- Holes may be drilled in the flexible appendages or break-outs before imaging.
- Layers are imaged, etched and possibly plated through depending on the design needs.
- Coverlayers are typically laminated to the etched patterns while providing access to interconnect points on tentacle ends through openings in the coverlayer.
- Covercoated flex circuit layers are laminated together using flexible bond plies, leaving the tentacles unbonded where the design requires.
- Outermost layers are commonly still coated fully with copper foil.
- Panel is drilled using the same tooling system that was used for image transfer to ensure that internal lands will be in register with the drilled holes.
- Holes are cleaned using a plasma process or other suitable method.
- Holes are metallized by electroless copper deposition or another acceptable technique
- Holes are electroplated with additional copper to meet the requirements of full plating or to simply lock the electroless plating on.

For a subtractive process, the following additional steps are necessary:

- Negative image of the outer circuit pattern is applied to the copper foil.
- Open area or circuit pattern is plated with an etch-resistant metal such as tin or tin-lead.
- Resist image is stripped.
- Pattern is etched from the background foil.
- Metal etch resist is stripped from the circuit.
- Surfaces are cleaned to provide a bare copper surface.
- Outer coverlayer is laminated to the circuits, providing openings to the interconnection features of interest.
- Solder or a solderable coating process may be prescribed.
- If not soldered, the circuit is punched, routed or cut from the laminate.

Figure 9-27: Extremely simplified example of basic multilayer flex circuit manufacturing. Despite the many steps and important elements that are not included, this example illustrates the potential complexities of multilayer flex circuit manufacture.

- Tentacle ends are freed for component and connector installation, if required.

This highly simplified approach to multilayer flex circuit fabrication offered here and in figure 9-27 gives only the slightest indication of the potential complexity entailed in manufacturing these interconnection structures. Further detail is provided in figure 9-28. Compared to single- and double-sided flex circuit processing, it is easy to see the potential difficulties of multilayer constructions and why they can be so costly. The balance of this section gives brief descriptions of some alternative methods and approaches for producing multilayer flex circuits.

MULTILAYER FLEX CIRCUIT PROCESSING VARIATIONS

Given the forgoing description of the basic multilayer process the reader should be able to appreciate some of the variations that are possible for making multilayer flex circuits.

SEQUENTIAL LAMINATION PROCESSING

In sequential lamination manufacture, the conductor layers are individually fabricated and the resulting substructures are laminated together layer-by-layer (or substructure-by-substructure) until the multilayer interconnection structure is complete. The panel is then drilled and the holes plated through to make connection to the various layers. The process can be time-consuming, but does allow for some unique design freedom. On the negative side, such constructions demand near-perfect yield at every process step or they can result in a poor ultimate yield. Sequential lamination processing has been used with some success by certain Japanese manufactures to build rigid multilayer circuits for cell phones and the like.

Figure 9-28: Manufacturing flow diagram for a multilayer flex circuit.

A variation on this method, described briefly earlier, allows for the electrical interconnections between layers to be made during

the lamination process itself. The process is a cross between processes used to create ceramic hybrid structures and those used to create anisotropically interconnected multilayer flexible circuits.

PLATED POST INTERCONNECT (SEQUENTIAL) MULTILAYERS

Plated post interconnect multilayer flex circuits are fabricated by a non-standard manufacturing process that is similar to the processes favored by manufactures that produce multichip modules (MCM). With this method, the circuit layers are interconnected using solid plated metal posts that pass through from layer to layer. The posts may continuously stack on top of themselves or may be moved aside to make connection to just one other layer. This technology best serves multilayer flex circuit constructions that must be bonded to a reinforcing base. The following is a brief overview of the process:

- Specially prepared substrate is coated with a flexible film.
- Holes are opened to provide interconnect points in the finished product.
- Surface is metallized, imaged and plated up with the appropriate circuit pattern.
- Surface is recoated with a flexible film layer.
- Holes are generated in the film.
- Surface is metallized and imaged, this time with only the interconnects or posts patterned on the board.
- Posts are plated to thickness.
- Resist mask is stripped off.
- Micro-thin surface metallization is etched away.
- Surface may be planarized at this time.
- Another layer of dielectric film is laid down.
- The cycle starts anew and continues until all layers are processed.
- The circuit is finally separated from its base when complete.

Figure 9-29: Multilayer flex circuit can be visually simple, but structurally complex as the construction below the circuit image illustrates.

This technique allows for very dense structures to be fabricated, but there are few vendors capable of producing this type of product at present. Like the sequential lamination process, near perfect yields are required at each processing step to obtain acceptable final yields.

VERTICALLY INTERCONNECTED FLEX MULTILAYERS

Other methods have been explored and developed for creating multilayer flex circuits using co-lamination processing to create vertical interconnections within the structure. In one type of vertically integrated flex structure, anisotropic conductive bonding films are used to make numerous short Z-axis interconnections instead of standard (and longer) plated through-holes. The interconnections are made during lamination, providing n arguably simpler process. Other structures use dielectric bondplys with programmed joining points of metal or conductive adhesive (fig. 9-30).

These type structures are playing an increasingly important role in electronic interconnection for high density applications such as hand held electronics. Vertically integrated flex struc-

tures could replace rigid PCBs in some applications because of their ability to avoid redistribution wiring, especially for area array interconnections. This makes them ideal candidates for high density structures that use high pin count ball grid arrays (BGA) and chip scale packages (CSP).

Multilayer flex circuits are much less common than their rigid laminate counterparts. There are a number of reasons why this has remained the case for many years, including cost of materials, handling concerns and a general lack of experienced vendors. However, as the line between flex and rigid continues to blur, the thinner reinforced core materials becoming more common and newer composite materials being introduced, it appears that the gap between the two sibling technologies is slowly being bridged.

While it is not yet common, multilayer circuits constructed using flexible circuit laminate materials have some intrinsic features that provide compelling reasons for their increased use. For example, flexible base materials are largely unre-

Figure 9-30: Colaminated multilayer construction uses flex circuits joined and interconnected using programmed bondply material. (Image courtesy of Tessera)

inforced, and are thus pure polymer substrates rather than composites. This feature results in a material that is consistent in electrical properties and makes it a preferable choice for highest performance applications. Additionally, the material is superior compared with glass fiber reinforced materials, where the dielectric constant and loss tangent of the material can vary on a localized basis as the signal is transmitted through the material. Thus, with reinforced composite materials the control of signal characteristics at higher frequencies (the domain where skin effects kick in) is more difficult than with the more homogeneous flex materials.

Flex material homogeneity is a significant advantage when drilling or punching holes in close proximity to one another to conserve space or boost performance. The benefit is that the structure is immune to the so-called conductive anodic filament (CAF) phenomenon where ionic migration along glass fibers causes shorting between adjacent plated through-holes. Concerns about CAF are growing as evidence of it in finer feature PCBs is on the rise.

A number of methods for making multilayer flex circuits have been described over the years. Most descriptions follow traditional methods used in the manufacture of rigid multilayer PCBs. Other methods, however, have departed from the mainstream to explore alternatives. Dyconix (Switzerland), for example, was among the first to use flex circuit materials to create high reliability multilayer flex circuits with microvias using their innovative plasma processing methods. Other companies have also proposed flexible circuit options for multilayer flex. Tessera Technologies, for example, has described a number of different ways to create such interconnection structures. Tessera's original concept was a structure wherein simple two-metal layer flex circuits were bonded and interconnected during the lamination process using special interposer material.

Figure 9-31: Traditional approaches to multilayer circuits, both rigid and flex, can be complex in terms of processing. Alternative methods could provide simpler manufacturing solutions. Equivalent structures in terms of circuit layout vary significantly in terms of processing steps.

While the original electrical interconnection and joining medium was a silver-filled conductive resin in a flex circuit bondply, later concepts include the use of deformable plated metal features that deformed, mated and joined the interconnection points during the lamination process as shown in the last example on the right in figure 9-31.

During development, the driving goal was to create high density multilayer structures using high yielding double-sided circuits with low aspect ratio plated through-holes. These layers would then be joined and interconnected using a high yielding lamination process. Test data from early experiments were encouraging but commercialization has been slow to occur.

Other companies also have technologies designed to provide similar solutions where interconnection between layers is made during the lamination process. For example Toshiba's buried bump interconnection technology (B2it) technology, Matsushita's any-layer inner via hole (ALIVH) technology, and a more recent offering, also out of Japan, the NeoManhattan bump process from North Corporation (the technology is

Figure 9-32: Process steps for a two-metal circuit using the B2it method. For a multilayer circuit, the process steps shown above are repeated.

now owned by Tessera). The former two methods have been fairly well-developed while the latter is following the other approaches into the market.

Some flex manufacturers in Japan are in production with B2it technology and have developed design rules for prospective users. They have adapted the technology specifically to be used with liquid crystal polymers (LCP) for high thermal and better electrical performance (table 9-1). While all of the technologies described are potentially capable of being used in the construction flex multilayer circuits, hybrid constructions may find some application as well. Using rigid and flexible materials together in a common construction could provide some unique opportunities for high performance applications.

Design Feature	Standard	Advanced	Leading edge
Line width/space	60/60µm	25/35µm	20/25µm
Bump diameter	250µm	150µm	100µm
Land diameter	400µm	250µm	200µm
Maximum current	0.1A /bump	0.05A /bump	0.05A /bump
Surface treatments	Au: flash	Au: flash	Au: flash
	Au: bondable	Au: bondable	Au: bonding

Table 9-1: Reported capabilities for B2it technology.

The evolution of electronic interconnection technology over the last several years has been fascinating to watch. Conventional notions as to what is desirable or possible in the manufacture of interconnection structures continue to be challenged. We are likely to see more of the same in the months and years to come. Will there be a single solution, suitable for all interconnections in the future? That is not very likely. However, the innovations that have been introduced to date will surely spark new ideas about the directions and forms interconnection technologies might take in the future.

ALTERNATIVE MULTILAYER FLEX STRUCTURES

A number of manufacturers have created unusual multilayer structures, resulting in high performance interconnection structures. In some cases, it is not the flexibility of the circuit that is sought, but the amenability to certain types of processing and immunity to certain potential defects (e.g., conductive anodic filament [CAF] shorting between closely-spaced plated through-holes) that make it an attractive choice. The following are a few examples:

PRE-DRILLED STANDARD GRID SUBSTRATES

One scheme for producing high density multilayer structures, spurred on by the advent of area array packaging, was based on the use of a standard grid pre-drilled on a flexible substrate. This gave rise to the notion that a standard grid could be used to facilitate construction of fundamental base grid materials.

Flex circuit pioneer Sheldahl (now Multek) tried to offer high density substrates based on their advanced microvia technology in the mid 1990s. They developed a flexible base material product that was pre-perforated with tens of thousands of holes (up to 400 holes per square centimeter or 2500 holes per square inch) positioned on a selected grid that they hoped could be standardized. Their intention was to deliver a flex material with the through-holes already plated and the panels pre-coated with photo-imageable resist based on an inexpensive hole formation technology with all holes produced on a common grid. The product was designed to address some of the major issues in the pursuit of higher density interconnection structures, including the provision of small holes to improve wire routing capability on substrates. Unfortunately, the method did not take hold for a number of logistical and business reasons. However, the idea is still of interest and could be of value in the future if the concept of standard grids and their benefits ever sinks in and takes hold.

Z-AXIS INTERCONNECTION TECHNOLOGIES

Z-axis interconnections for construction of multilayer circuits have also been investigated by several companies for use in high density flex circuits. The Z-axis interconnection technology contrasts markedly with sequential build-up technologies used in rigid multilayer board manufacture. The intent of Z-axis interconnection technology was to reduce the cost of high density multilayer by making simple, high yielding sin-

gle- or double-sided substrates and subsequently joining and interconnecting them in a high yielding lamination process. The idea seems to be well-suited to flexible circuit interconnection. Rigid board constructions using the same basic concepts have been demonstrated in Japan. The technology is divided into two general classes, anisotropic and isotropic.

ANISOTROPIC INTERCONNECTION

Anisotropic adhesives have been in use for a number of years. However, it is only recently that they have gained widespread attention. The technology, a combination of an adhesive and a dispersion of conductive particles, creates interconnections in the Z (vertical) direction only, while maintaining lateral circuit isolation.

As a result, any point of intersection between two mating circuit halves will be electrically connected. The concept is particularly appropriate for interconnecting flex since the use of a coverlayer will protect the circuits from shorting in areas other than those open to shorting by design (fig. 9-33).

Figure 9-33: Anisotropic conductive films can be used to join and interconnect layers of flexible circuits. A coverlayer may be required on one side to prevent unwanted connections from being formed.

Anisotropic interconnection is also useful for lapped interconnection between a flex circuit and a rigid circuit and is increasingly used for that purpose. Display driver circuits for use with all manner of different display technologies from earlier liquid crystal displays (LCD) and light emitting diode (LED) displays to more advanced organic LED (OLED) and active matrix (AMOLED) technologies are prime examples.

PROGRAMMABLE INTERCONNECTIONS

Alternatives to anisotropic interconnection include programmable interconnection structures wherein the interconnection points of the laminate structure are pre-designed and prepared. One such version was a concept developed at Tessera (San Jose, CA). The technology allows for the formation of interconnections at the same time that the multilayer structure is being formed (fig. 9-34).

Figure 9-34: Multilayer structure construction for a multilayer circuit based on the co-lamination of pre-tested inner layers and a programmable joining and interconnecting film.

The most pronounced advantage of programmable interconnections is their ability to produce extremely short interconnection paths between components. Short path, grid-based routing is frequently referred to as Manhattan routing due to its conceptual similarity to the combined grid-like structure of New York City's streets. The use of standard grid materials and interconnection approaches may well become commonplace in future electronic packaging.

RIGID FLEX CIRCUIT MANUFACTURE

Rigid flex circuits are among the most complex interconnection structures in production today. Having elements of rigid and flexible circuit technologies, these circuit constructions offer the best and the worst each technology has to offer. Rigid flex circuits provide an excellent method for interconnecting complex electronic systems. They also are capable of offering cost and weight savings, as well as increases in reliability over conventional wiring harnesses. They also significantly reduce or even eliminate rework and repair. On the other hand, rigid flex circuits represent demanding technical challenges and, like multilayer flex circuits, are engineering-intensive and thus, expensive on an up-front basis. Even so, on a system level basis, rigid flex circuits can provide a very cost-effective solution.

Although rigid flex circuits are most often thought of in a military product context, more commercial applications are being developed, often with great success. In simplest terms, rigid flex circuits are hybridized constructions of rigid material laminated to flexible material and interconnected by means of plated through-holes. Like multilayer flex, there is no such thing as a typical rigid flex circuit. Each construction offers its own unique challenges and requirements.

In its simplest form, a rigid flex circuit may have just two conductive layers, one rigid and one flexible. In more com-

plex constructions, there may be ten, twenty or more layers of flexible interconnects sandwiched between rigid outerlayers, totaling up to forty layers of circuits or more. Internally, these constructions may include simpler constructions such as single- and double-sided flex circuits, which serve as interconnect tentacles.

Rigid flex circuits evolved to solve weight and reliability challenges for military products and commonly served as formable backplanes for electronic system interconnections and buses. These applications are still common and the designs and constructions are fairly straightforward, except that they often require the use of bookbinder construction (fig. 9-35; also see Chapter 6 - Practical Design Guidelines for Flex), where each successive layer is lengthened in bend areas

Figure 9-35: The bookbinder concept in theory and in practice.

to mitigate the strain-related damage to the outer conductor layers or buckling of circuits that will occur if the technique is not used. The term comes from the requirement to keep pages flush on a closed book. Figure 9-35 provides both physical and conceptual examples of bookbinder construction.

Rigid flex circuits can be especially difficult to manufacture because of the requirement to mate materials of different composition and dimensional stability, hold them in register and reliably plate the through-holes. The most defining steps are illustrated in Figure 9-36.

Like multilayer flex circuit construction, there is no typical approach to building a rigid flex circuit construction. There

Figure 9-36: Defining elements and steps in rigid flex manufacture 1) prefabrication of a flex circuit; 2) lamination of the flex circuit between rigid laminates, keeping the flex circuit unbonded; and 3) manufacture of a rigid panel that is later routed with caps over the flex area removed.

Figure 9-37: Rigid flex circuit constructions.

are, in fact, a number of different standard and proprietary ways to build flexible circuits (fig. 9-36). As a result, the multilayer flex circuit manufacturing sequence is similar to the manufacturing sequences for rigid flex, except that rigid outerlayers are used and more pre-machining of rigid materials is required to freely access flexible elements of the finished product. Route and retain techniques are often used to facilitate assembly, especially when there are many circuits in a common panel. In the end, successful manufacture of rigid flex depends heavily on the tooling and mechanical fixtures used in fabrication.

Figure 9-37 shows a variety of rigid flex circuit constructions. Clockwise from the upper left corner are:

- Flex circuit with a stiffener (not a true rigid flex but presented for comparison)
- Simple rigid flex with the flex circuit on the outside of the circuit sharing plated through-holes with the rigid material
- Traditional rigid flex with the flex circuit at or near the middle and the materials used for the flex portion

extending through the rigid portions
- Bikini flex with the coverlayer cut short to reduce the amount of unreinforced material in the rigid section
- Hybrid material construction which excludes the use of flex in the plated through-hole areas of the circuit
- Rigid board that has been control depth machined to a very thin cross section allowing for it to be formed. The radius must be large and flexing minimal.

One significant problem in the manufacture of military qualified rigid flex circuits has been meeting the requirements for thermal stress testing and thermal cycling. These tests, while demanding enough for standard rigid boards, can be doubly difficult for rigid flex constructions because a large percentage of rigid flex circuit constructions are comprised of unsupported adhesives traditionally used in rigid flex manu-

Figure 9-38: Rigid flex board with folded wrap-around layers. The circuit actually has five sections with two sections folded over a metal core (shown at lower right).

facture. There have been a number of special methods developed to overcome this problem (fig. 9-37), which has been made more challenging by the higher temperatures associated with lead-free solders.

To frame the current problem, unsupported adhesives are known to have large coefficients of thermal expansion (CTE) that result in excessive strain being exerted on the plated through-holes during thermal processes. Excessive expansion results in copper plating cracking at the corners and in the barrels of the plated through-holes. (See Chapter 14 – Inspection and Test of Flex Circuits and Chapter 15 – Plated Through-Hole Reliability for more details on the problem).

Material vendors and circuit manufacturers have worked diligently to solve the problem And have developed two approaches to address this important issue. The first approach is to use new materials, such as adhesiveless flexible laminates, which ameliorate the problem by eliminating the adhesive. Use of glass-reinforced polyimide prepreg bondplies in place of unsupported adhesive films can augment plated through-hole protection The overall Z-axis expansion is considerably reduced by the combined use of lower CTE materials and higher glass transition temperature (Tg) of glass reinforced prepregs.

Another approach to the problem has been to use new or modified construction techniques. For example, heavily plated copper through-holes have been recommended as a method for improving reliability of rigid flex circuits. The objective is to create an extremely robust interconnect that will withstand the rigors of thermal stress and thermal cycle testing. Two things to note here are that: 1) Good control of the copper plating operation is imperative. Thick copper that is of poor quality does not solve the problem. 2) The design may require modification in order to accept the additional copper thickness. That is, oversized holes will be required, mandating the need for larger internal and external lands if minimum annu-

Figure 9-39: Rigid flex circuit manufacturing flow diagram.

lar ring requirements are to be met while accommodating the excess copper.

This discussion of rigid flex circuits is far from exhaustive because there is a great deal of nuance to the design and manufacture of these highly complex interconnection structures. The objective was to provide an appreciation for these important members of the electronic interconnection family. It is highly recommended that when planning to use these types of circuits, customer and flex or rigid flex vendor work together closely to ensure a good result.

The concept of rigid flex is evolving and solderless rigid flex constructions might soon prove to be a suitable option for some products. (See Chapter 12 – Solderless Assembly Processes for Flexible Circuits.)

FINISHES FOR FLEXIBLE CIRCUITS

Over the last few years, circuit finishes have become increasingly important for a number of reasons, including:

- Cost reduction
- Functional concerns, such as when the finish must serve more than a single purpose (i.e. both a solderable surface and a contact surface)
- Impending lead-free regulations by the EU

As a result, a number of different final coatings for PCB contacts and land patterns have been trotted into the lineup in a race to the finish. We are not likely to see a single finish capable of meeting the diverse needs and requirements of each unique circuit design. With flexible circuits, the issues are the same but the impact might be even greater. Some of the many solutions offered include:

TIN-LEAD

Tin-lead is a venerable still stands tall as a more environmentally-friendly solution from a scientific point of view than lead-free solders. However, tin-lead may face reduced usage and even elimination due to ill-conceived legislation from the EU. Perhaps more important is that with its long history, its solderability and reliability, tin-lead is much better understood and for those demanding high reliability, such as the military, aerospace and medical fields, it may continue to have its selected users. 63/37 tin-lead solder is used most commonly and is normally applied using hot air solder leveling (HASL). Difficulty controlling thickness, which can affect planarity and solderability if the finish is too thin, is a drawback. While tin lead might be black-listed for everything but the most reliable electronics, it should remain a good prospective solution for some future products that are not sold in the EU.

TIN

Tin has been used as a solderable finish for rigid and flexible circuits. Tin has the advantage of being acceptable in the eyes of the EU. On the downside, NASA has investigated, recorded and reported evidence that tin can grow whiskers (fig. 9-40) that can short out an electronic assembly. Ironically, the one metal that seems to best mitigate the formation of tin whiskers is lead.

Tin can be electroplated, immersion-coated or applied as a molten metal. Application as a molten metal is not common because of the extreme temperatures required. Immersion coatings are among the most common. The limited thickness of immersion coating (~0.25mm) makes it less prone, if not immune, to concerns of tin whiskers, but its thinness causes concern because the copper-tin (CuSn) intermetallic that quickly forms is not highly solderable without the use of highly aggressive fluxes.

Figure 9-40: Microphotograph of tin whiskers on an electronic component. (Photo courtesy of NASA)

Still, at least one formulation appears to have achieved thickness values of up to 1.0mm and claims excellent long term solderability. The finish provides a planar surface and a processing temperature that is not damaging to the circuit. Still, some questions about the ability of the finish to maintain solderability through multiple assembly cycles remain.

IMMERSION SILVER

Immersion silver is another finish candidate. Silver is one of the most conductive elements. Even its oxides are highly conductive, but unfortunately are not as readily solderable. There are also long-standing concerns over silver migration. Strides appear to have been made in recent years to address both concerns. Immersion finishes as thin as 0.3mm appear to be capable of maintaining solderability and have the added advantage of being wire-bondable using aluminum wire ultrasonic bonding methods.

ELECTROLESS NICKEL IMMERSION GOLD

Electroless nickel immersion gold (ENIG) finishes have been the subject of countless research papers in recent years. They have been postured as a panacea of sorts, offering in a single finish, planarity, solderability, wire bondability and a corrosion-resistant contact finish, so all of the effort to make them work reliably comes as no surprise. What has been troublesome is the sporadic occurrence of the black pad phenomenon wherein solder leads lift away from what was the nickel-gold interface. However, some research has suggested that a higher percentage of phosphorous in the nickel could alleviate the problem.

Immersion gold using the ENIG process is generally 0.1µm to 0.2µm thick and not well-suited to gold ball bonding or multiple insertion connections, making electrolytic gold another option. For gold ball bonding, a thickness of ~1.0µm has proven suitable. Soft gold with a hardness of approximately 90 Knoop is preferred. For contacts, hard gold plating is preferred. Electrolytic gold requires that electrical connections be present and shorting bars are often used to this end.

DIRECT IMMERSION GOLD (DIG)

Another finish that has gained some attention is direct immersion gold (DIG). DIG has the advantage that there is no nickel plating required, making it a simpler process. Immersion coating of gold directly over copper is a simple process because the two metals are far apart in the electromotive series. Gold will easily replace copper, but the thickness is limited by diffusion to less than a micrometer. The one big drawback is that gold is presently hovering around $1500 per troy ounce, making it a costly and less attractive solution.

ORGANIC SOLDERABILITY PROTECTIVE COATINGS

Organic solderability protective coatings (OSP) have a long

history, going back nearly to the beginning of the PCB industry. The current class of finishes is far superior to the earlier materials. Newer finishes are quick and easy to apply and have been formulated to survive several passes through assembly while protecting and maintaining the solderability of the copper they coat. OSPs have been successful for traditional solders, but some concern has been expressed about their ability to survive as many passes in lead-free processing.

Finish choices abound to meet the different needs of the myriad of applications that flexible circuits now serve. In addition to the choices listed, there have been some interesting coatings based on nanotechnology that have been seeing some greater use. However, with no true panacea in the mix, the choice must be made based on the assembly and use criteria of the design.

FUTURE DIRECTIONS FOR FLEX MANUFACTURE

Flexible circuit manufacturing technology continues to evolve, with new solutions for flexible circuit manufacture constantly in development. For example, roll-to-roll processing of flexible circuits is evolving to include the printing of active devices. Recent events indicate that the electronics industry may be crossing such a threshold. Concepts introduced by ELF Technologies in the early 1990s demonstrated that it was possible to produce flexible circuits in roll-to-roll fashion on a continuous web by raster printing catalytic material onto flexible films that were then electrolessly and electrolytically plated. (The developers considered printing conductive inks, but the conductivity was not good enough at that time.) Newer printing technologies offer significant improvements over the early efforts. Presently, roll-to-roll flexible circuit production is no longer simply concerned with printing conductors. Evolving solutions expect to offer printed transistors and passive devices, which opens the door to operational circuits

being produced additively on polymer films. For example, Fraunhofer Institute for Reliability and Microintegration has demonstrated the production of an all-polymer ring oscillator on a 200mm-wide roll of PET film. The process involves creating flexible polymer transistors and logic circuits with drain-source structures with channel lengths of 20μm. The steps are as follows:

- Structure the copper metal pattern
- Deposit polymer semiconductor materials
- Deposit a polymer gate dielectric
- Screen-print of the gate electrode
- Apply an intermediate dielectric
- Vias are opened through the layers
- Apply silver conducting paste through a screen-printing process
- Inspect and test to ensure proper function

Given the propensity of the electronics industry to make everything not only electronic, but also inexpensive, the prospect of microchips made of plastic and manufactured inexpensively using large-area printing processes is compelling for low-cost electronics applications for the mass market. The range of potential products seems unlimited. Developers have suggested intelligent tickets, paper toys, ID tags, electronic postage stamps, speakers and smart bandages just for starters.

Another company that had been on this path was Rolltronics of Menlo Park, Calif. After years of effort, the company demonstrated a printed flexible display. The product, FASwitch, is based on two thin layers of plastic with copper plates and paths activated by row and column circuitry. When activated, the flexible layer bends slightly until it closes a contact on the other layer and changes intensity, allowing four levels of gray. The company is no longer operational and their efforts

have been eclipsed in more recent times. For example, there has been a recent report that DuPont has developed materials and processes that allow for the production of printed OLED TV displays as large 50 inches in less than two minutes using their materials and a new printing technology.

The area of printed electronics is now trying to establish its own base of support. In a recent event sponsored by IDTechEx, the organizers suggested that: "The future electronic fabrication plants will be printing presses." The organizers also suggested a few years ago that the market for organic and printable electronics, which they said a few years ago could reach $300 billion in 2025, a value almost twice that of the silicon industry today. Validating the market size of a technology 20 years hence is much too daunting and more recently those projections have been pared significantly down to $50 billion, which is still an appreciable number. (See Chapter 11 – Printed Electronics.)

SUMMARY

There are many more ways to build flexible circuits than there are types of flexible circuits. The correct choice of manufacturing method depends on the objectives of the end product and what can be traded off, if necessary, with the least impact on the finished product. Because of the diversity of flex circuit manufacturing approaches, the capability of providing solutions to the various inherent challenges exists within flex circuit technology. Ultimately, a close working relationship between the designer and the manufacturer must be maintained to ensure the right balance between design objectives and manufacturing choices. **FCT**

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Bob Willis currently operates a training and consultancy business based in England. He is the Technical Manager of the SMART Group and a member of the technical committee. Although he is known as a specialist for companies implementing Surface Mount Technology, Bob also provides training and consultancy in most areas of electronic manufacture. In the last 10 years he has focused on lead-free manufacture, which has earned him the SOLDERTEC/Tin Technology Global Lead-Free Award for his contribution to the industry.

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Chapter 10

Flexible Circuit Assembly

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INTRODUCTION

Flexible circuits offer some unique challenges to the assembly process. The assembly materials and processes for populating and interconnecting components to a flexible circuit range are essentially identical to those used for standard rigid boards, but there are some twists required. The assembly processes range from very simple methods, such as manual component insertion and hand-soldering, that require little or no fixturing, to fully automated methods, that normally require specially-developed, design-specific, dedicated fixtures.

To choose an assembly process and method for flex circuits, it is necessary to consider a number of important factors:

- What is the flex circuit base material?
- What types of components will be used?
- How many assemblies will be built?

These and other important questions must be addressed before making the proper decisions regarding assembly. Seemingly simple matters can greatly influence the assembly choice. For example, it is commonly assumed that polyester circuits cannot be used in applications where soldering is required. This assumption is predicated on the fact that polyester films are known to have a low melt-point and will normally be

grossly distorted by the soldering process. However, when a polyester laminate flex circuit is properly fixtured, tin-lead soldering can be used for joining components. A number of major OEMs have been doing just that for many years. They have developed methods that provide proper shielding to the body of the polyester circuit in process. The distortion of the material can be localized to areas adjacent to the point of connection. With the advent of well-intentioned, but misguided, legislation mandating the use of lead-free solders, there are significant challenges ahead, as lead-free solders have melting temperatures roughly 40°C higher than traditional tin-lead solders. Unfortunately, it appears that traditional tin-lead solders are actually more environmentally–friendly in aggregate according to studies in the US and Europe, so the law actually does double damage. Presuming a future absence of tin-lead solders for soldering polyester, one alternative is to use lower-temperature solders and another is to employ conductive adhesives. The important thing is not to limit one's thinking and to be open to alternative solutions.

ASSEMBLY OVERVIEW

The assembly process for flex circuits follows a path similar to rigid boards, but with some important points of departure. Understanding the traditional flow of assembly is valuable as a point of common reference.

There are just a few simple elements associated with and required for assembly:

- Interconnecting substrates (PCBs or flex circuits)
- Components (ICs, discrete components and connectors)
- Methods and materials for joining and cleaning them

The challenge is bringing these elements together in a cost-effective and reliable way, which normally means that a high

Figure 10-1: Simplified flow diagram for flex circuit assembly.

degree of automation and capital expenditure are required. A simple flow diagram of the assembly process, illustrating how and when the various elements are brought together to create an assembly, is provided in Figure 10-1.

FLEX CIRCUIT AND COMPONENT PREPARATION

As the principal elements of a flex circuit assembly, the flex circuit and components should be properly prepared. One thing that most plastic components and flex circuits have in common is that they take up moisture, which means they must be protected from humid environments. Otherwise, they must be pre-baked to prevent explosive outgassing of trapped moisture and the creation of defective conditions such as cracked components or blistering and delamination of the coverlayer.

For component preparation, it has been suggested that the optimum component lead angle for leaded surface mounted components is 60° (± 5°). The angle can be opened up to 45° to 65° for existing designs where the component body has been reduced in width. The purpose of the 45° to 65° lead angle is

to provide added strain relief in the X-, Y-, and Z-axis during thermal cycling beyond what the flex circuit can offer intrinsically. To achieve high-reliability, the heel fillet of the solder joint should be adequate. Component lead angles of greater than 65° to 70° improve the chances of this. While component lead co-planarity is important to good assembly, one shouldn't force leads into co-planarity by using a thermode or other method to drive component leads into the solder. It is better to reform the leads off line.

SURFACE FINISHES FOR SOLDER CONNECTIONS

Many different surface finishes are used on flexible circuits, such as gold, copper, tin and silver. Each finish has its advantages and disadvantages. Although not specifically for flexible circuits, a simple test pattern can be incorporated into a flexible sheet to monitor changes in solderability in production. When any surface finish is exposed to a heating process, the solderability of the surface coating on the circuit is affected, and normally for the worse. Flexible circuits are often baked to eliminate moisture in the adhesive layer, which can result in delamination of the coverlayer if the moisture is not eliminated. However, the baking process can reduce the wetting of the finish due to oxide formation on the surface and growth of the intermetallic layer under the selected coating. The test strips can be used to assess the impact of reflow conditions, circuit quality, nitrogen level reduction and many other process features.

The pattern for the test strip is simply a number of parallel tracks on the surface of a flexible design (fig. 10-2). It is fairly easy to add to a circuit on the unused area of a multiple-up circuit pattern. During production, dots of solder paste are printed onto the tracks. The dots have different spacing and slowly increase in size. Depending on the solderability of the surface coating, the dots of paste reflow and join together. The

Figure 10-2: Part of the spot-wetting pattern is shown on the flexible circuit after printing and reflow, allowing easy monitoring of process changes or improvements which can then be compared with defect levels during assembly. Some AOI systems can gather the data for automatic process monitoring.

Figure 10-3: Results of wetting trials on different surface finishes after one and two convection reflow cycles of flexible circuits in production. The average number of dots not fully coalesced is the reference for assessment on the graph. Tin finish shows the most marked change in wetting between reflows one and two.

number of dots that do not wet the surface and coalesce are then counted. The average result of non-coalesced dots would be the wetting score. The design shown in figure 10-3 has six 0.5mm (~0.020") parallel tracks on a 0.5mm (~0.020") pitch and are nominally 23mm (~0.900") long, but the length can be reduced to suit space available.

ASSEMBLY PROCESS FIXTURES AND TOOLS

A range of fixtures and tools are required for normal assembly. The requirements of these elements vary with the assembly process chosen. For example, through-hole assembly fixtures for wave soldering are quite different from those required for surface mount assembly. A brief discussion of each process follows.

WAVE SOLDER FIXTURING

Wave solder fixtures are designed to carry the flex assembly over a molten solder wave while keeping the flex circuit and components stable. There are several possible ways of meeting this challenge. The flex circuits can be left attached to the stiffener assembly in panel form, as illustrated in figure 10-4. This fairly common method can be a cost-effective solution, as long as there is not an excessive number of defective parts in the panel.

Another method for fixturing flex circuits for wave solder is illustrated in figure 10-5. Here, individual holes are drilled

Figure 10-4: Mass application of stiffeners in panelized form facilitates both stiffener application and component assembly. When bonded together, the circuit can be processed much like a rigid board.

Figure 10-5: Fixtures for wave soldering should support the flex circuit through the wave while providing access to the leads and through-holes of the flex circuit.

or larger openings are provided in a carrier plate, allowing the component leads and plated through-holes to be properly accessed by the solder wave.

Surface Mount Fixturing

Surface mount assembly of flexible circuits is extremely difficult without proper tooling and good fixturing. Many different tools and fixtures are required for the process. While solder stencil technology is commonly used to place solder paste on the surface mount lands, there are other options, such as solder paste jetting technology, that offer some advantages.

Solder paste jetting technology is an option well-suited for new product introduction (NPI) and small to medium production runs since it eliminates the stencil requirements. Recent developments with different paste suppliers makes it a valued option, particularly when the paste volume on any pad can be changed in seconds.

Typically, a vacuum table system, comprised of a flat surface with myriad holes under vacuum, is used to hold the circuit flat during the screen printing of solder paste. A vacuum system is frequently used in combination with special fixtures, such as those described earlier in this section. The fixtures

Figure 10-6: Solder jetting being used on a circuit board for fine pitch and 0201 chip components. The circular pattern of the round jetting pattern is just visible in the surface of the paste. The images were taken from a test board process on a Mydata MY500.

Figure 10-7: The base of this solder paste stencil foil has been designed to allow for minimum pin protrusion when pallets are used during the printing process without damaging or lifting the stencil in production. The example stencil is 0.006″ thick and recessed by 0.003″.

can be made from a variety of materials, such as glass epoxy or anodized aluminum. The fixtures provide a stable base for processing, allowing more common soldering process profiles to be run. An example of a fixture for surface mounting a flex circuit can be seen in figure 10-8.

COMPONENT PLACEMENT

Placement of components onto a flexible circuit board is best performed automatically, although manual placement can be used for prototype or low-volume production, depending on complexity. The efficacy of modern automated equipment and manufacturing management practices continues to reduce the low-volume crossover point. Component density is another factor that should be considered since as component densities increase, manual placement becomes more difficult.

Nonconductive, high-temperature adhesives are useful for holding components in place while the soldering operation takes place. Only small dots of adhesive are required. They can be applied by point dispensing, stenciling or pin transfer.

Retractable tooling pins can be used on thin rigid and flexible circuits to locate the circuits for assembly and can then be retracted when required for removal (fig. 10-10). Retractable

Figure 10-8: The fixture for surface mount on flex keeps the circuit flat and supported during the reflow operation. A top mask can be employed to prevent thermal damage to the bulk of the circuit, which facilitates soldering of lower melt-temperature base materials when they are preferred for economic reasons.

Figure 10-9: Carrier for flexible circuit assembly. Thermal relief areas on the base of the pallet improve temperature differential (ΔT) during reflow. Drain holes under the flex may be considered if using vapor phase for lead-free reflow. (Image courtesy of Bob Willis)

tooling pins may be necessary when printing solder paste with a stencil. When the stencil comes in contact with the pins, they are displaced.

The use of sticky pallets is a fairly recent concept in the Far East and has not seen much adoption in other parts of the world. The tacky material surface will stand up to high temperatures associated with lead-free assembly and can be used multiple times before cleaning. Although recommended for 500 process cycles prior to cleaning, pallets produced from these materials have been used in much higher volume for mobile phones, cameras, etc. As with traditional pallets, fiducial alignment marks on the flexible circuit are used during printing and component placement to overcome any errors on the location of the circuit pattern. The pallet can be used through the complete assembly process.

Figure 10-10: Retracting tooling pins can be used on thin rigid and flexible circuits to locate the circuits for assembly, but retract when required.

Figure 10-11: Sticky pallet with a flexible circuit test assembly in position. Normally the sheet of material would also have some tooling holes to allow automatic placement and removal of the flexible circuits during production.

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INTERCONNECTING & JOINING PROCESSES

There are several process options available for making electrical interconnection between the component and the flex circuit. The choice of joining method is linked hierarchically, first to the electrical performance and reliability expectations of the finished product and second to the materials used in making the flex circuit. The following are some of the most common methods in use:

CONDUCTIVE ADHESIVE ATTACH

Conductive adhesives are a popular method of assembling components to certain types of PCBs. The adhesives normally consist of UV- or thermally-cured epoxies that are filled with silver particles. They are not as conductive as solder, but are suitable for many applications. The material can be stenciled or dispensed point by point onto the selected component lands prior to assembly. Isotropically conductive adhesives conduct in all directions. Anisotropic adhesives conducts only in the Z-axis direction. This material is often used to make interconnection between a flex circuit and a highly planar second surface.

SOLDER-JOINING

Solder is by far the most common material used for making interconnections. Until the advent of forced lead-free soldering, tin/lead-based solder was the most common method for interconnecting components to flex circuits. Of the many types of tin/lead solder available, Eutectic Sn63Pb37 solder (M.P. 183°C) is perhaps the most commonly used. Other solders of value for flex circuit assembly, especially where lower melting point base materials, such as polyester, include indium/tin solder (In52Sn48 [M.P. 117°C]) and bismuth/tin solder (Bi57Sn43 [M.P. 138°C]).

Figure 10-12: Zero standoff pins align and hold the flex circuit to the fixture. (Images courtesy of Bob Willis)

In the SMT process, the printed solder is melted to make an attachment between the component and the flex circuit using a reflow oven. Infrared (IR), forced-air convention and vapor phase are all candidate processes. Care should be taken in profiling any flex circuit assembly processes because of their much lower thermal mass. An example of an assembly profile for a flex circuit assembly using lead-free solder can be seen in figure 10-14.

Lead-free solders pose special challenges for electronics due to their higher melting temperatures. While no risk of harm or demonstrable link of risk related to lead in electronic products

Figure 10-13: Flex circuit SMT assembly (Image courtesy of Interconnect Systems, Inc.)

Figure 10-14: Three-probe lead-free soldering profile for a flex circuit assembly using a carrier. (Image courtesy of Bob Willis).

has ever been shown, the industry adopted the use of lead-free to meet the requirements of the 2006 legislation.

VAPOR PHASE SOLDERING

Vapor Phase Soldering (VPS), also referred to as condensation soldering, has been around in the industry for many years and was one of only two serious options during the early introduction of surface mount technology. VPS was the first reflow system used by many engineers for SMT. Early practitioners of SMT preferred the simplicity of the process and process set-up over the problems of accurate loading, board belt positioning, profiling and overheating flux residues in IR systems. Convection reflow, which still represents the most significant part of the marketplace, was like VPS without the fluid, when compared to IR reflow. VPS has come back into popularity due to the use of lead-free alloys.

A well-designed flexible circuit board can work well and provide the high soldering yields required for modern manufacturing. In contrast, a poor design, particularly on passive components, could amplify the number of lifted and tomb-

Figure 10-15: 0402 capacitors tombstoning on a flexible circuit prior to modification of the design rules on the circuit.

stoned components (fig. 10-15). All vapor phase systems can show a difference in component lift due to the fundamental nature of the process. As the vapor condenses on the surface of the board and turns to liquid, component movement can occur.

Only one type of fluid is commonly used today and it is formulated to boil at either 230°C or 240°C. The 230°C boiling product is preferred for tin/silver/copper alloys and can be used for tin/lead as well, since the components are compatible. Using a vacuum on some systems can further reduce voiding in joints. There are still differences in the ΔT on the board surface and under components in VPS, but it is very small at the peak temperatures, provided time is allowed for the profiles to converge. The initial temperature rise through preheat does have recordable differences just like convection, but they can be smaller depending on the machine design. Through good

Figure 10-16: Using support pallets with vapor phase soldering generally requires modification to prevent the fluid from being retained under the circuit. Holes placed under the circuit will reduce drag-out of the fluid.

Figure 10-17: Profiling a flexible circuit on a pallet may require a combination of thermocouple attachment techniques. The use of high temperature solder is the preferred technique, but aluminium tape can be beneficial on flexible circuits. In reality the pallet has a far larger mass than the flexible circuit sheet. The pallet was set up for profiling with an air probe for the KIC system.

design and process control the amount of fluid loss can be small and recent surveys of users show an extremely economic and flexible process for lead-free. Care needs to be taken with flexible circuits on pallets since fluid can be trapped between

the two surfaces leading to drag-out of the fluid which tends to be expensive.

REEL-TO-REEL ASSEMBLY

There have been numerous efforts to assemble flexible circuits using reel-to-reel (or roll-to-roll) assembly methods. Conceptually, the approach is very attractive, especially for flexible circuits processed in using reel-to-reel assembly (fig. 10-18). One concern for reel-to-reel assembly is that if there is need for a line shutdown, a significant amount of product may be at risk and reworking in web form is somewhat problematic. Still, it remains an attractive approach for certain types of high-volume products that are small and have few components, such as smart-card assemblies and radio frequency identificiation (RFID) devices, which typically have only one or two components. These devices can be assembled using more traditional soldering methods, conductive adhesives or wire bonding technology. In the 1990s, Sheldahl (Multek) and Phillips Corp. co-developed a piece of equipment wherein the reflow oven was placed on rails, allowing it to be moved back and forth over the web in case of a web shutdown, allowing the opera-

Figure 10-18: Equipment for reel-to-reel assembly of flexible circuits. (Image courtesy of Siemens L&A).

tor to prevent local overheating by moving the oven back and forth over the web and preventing localized overheating and damage to both the circuit material and the components.

REWORK ON FLEXIBLE CIRCUITS

Rework of surface mount solder joints on flexible circuits should not be more challenging than it is for their conventional counterparts. Hot air, IR or contact heating tools can be effective with tin/lead or lead-free and are dependent on the materials used to produce the flexible circuits. The moisture content must be considered on flex circuits with a coverlayer. It has often been considered that copper pads can be easily lifted on flexible circuits during rework. But, just like conventional boards, if the solder is in a liquid state, no force is applied to the surface-only heat. Well-trained staff can rework boards without damage. Management needs to teach the proper skills and provide time for staff to assimilate theory into practical experience.

SOLDER JOINT INSPECTION

Inspection of solder joints can be conducted manually or automatically using automatic optical and/or x-ray inspection equipment. Inspection criteria in IPC-610 or, where required,

Figure 10-19: (Left) Land grid array (LGA) package being reworked on a polyimide flexible circuit with a hot air tool. (Right) 0402 chip capacitor being removed using a set of hot tweezers.

other industry criteria for flip chip, through-hole reflow, underfill and land grid arrays (LGA) can apply. In the case of automatic optical inspection, the same process pallets can be used for the assembly stages providing the ideal support. Since a flexible circuit can be semi-rigid or fully flexible, the full range of defects related to normal reflow or wave soldering will still apply in manufacturing. Flexible circuits can lift and float if not properly fixtured for assembly, making it more likely to see examples of open joints rather than short circuits. The

Figure 10-20: Typical lead-free solder joints tin/silver/copper on a flexible circuit after assembly and soldering. Examples of a gull wing lead on an SOIC and LGA terminations were captured with an ERSA Scope.

Figure 10-21: X-ray images of gull wing and LGA terminations assembled with tin/silver/copper were inspected and captured in real time on a DAGE system.

Figure 10-22: Microsections taken from a flexible circuit after reflow soldering in convection with tin/silver/copper solder paste. (Left) Gull wing lead. (Right) 0201 chip termination reflowed in air with the same alloy.

types of possible defects should be considered when defining inspection procedures.

WIRE BONDING

Wire bonding is a very useful interconnection technology long employed in IC die assembly when interconnecting the chip to a leadframe or package. The technology has also been successfully employed in direct assembly of IC chips to flex circuits. Wire bonding is performed by one of two major methods: thermosonic bonding and ultrasonic or wedge bonding. The choice of wire bonding process is strongly influenced by the materials used and reliability requirements of the finished product. For example, a wedge bonding with aluminum wire process (fig. 10-22) can be performed at room temperature, so it is a good choice when lower-temperature laminate materials are used.

Thermosonic bonding of gold wire requires a heat-bonding stage that is commonly operated at 150°C. Of the two primary methods of wire bonding, thermosonic offers greater versatility in terms of design and termination placement since the second bond can be made at any angle after the first bond is complete. Wedge bonding is much more constrained and directional.

Figure 10-23: Process steps for aluminum wire wedge bonding.

Figure 10-24: Example of a chip on flex assembly where the IC chip is wire bonded directly to the flex circuit. (Image courtesy of Interconnect Systems, Inc.).

As an interconnection technology, wire bonding offers some unique design advantages by allowing the assembly process to provide jumpers proximate to the die.

SUMMARY

Assembly of flexible circuits requires special knowledge, special tooling and a great deal of care. This chapter highlights some of the most important points, but it has not been exhaustive. A number of excellent books have been published on the subject of component assembly and soldering technology that can provide a more detailed understanding of the assembly process. **FCT**

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Happy Holden is now "focusing on innovations" and working for a 'stalwart purveyor of INNOVATION' in North America – GENTEX Corporation of Zeeland, MI.

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Chapter 11

Printed Electronics

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INTRODUCTION

Printed electronics is presently an area of great interest to many in the electronics manufacturing industry. In many pieces written about printed electronics, there are projections for a myriad of potential uses for the technology and the tens of billions of dollars that are going to be made in the coming years. To those who have not been deeply involved in the electronics manufacturing industry for a long time, the term printed electronics would seem to have only entered into the industry's lexicon since the turn of the current century, making it appear to be a new technology. Interpreting the words printed and electronics in conjunction with one another, as a single term, one could logically assume that it means electronic circuits comprised of conductors and various active and passive components (i.e., transistors, resistors, capacitors) printed directly onto a substrate of some type. Printed electronics, according to this definition, is clearly a significant departure from traditional approaches to electronics manufacturing . However, there are a host of manufacturing solutions that marketers are trying to position under the umbrella of the new term to take advantage of the growing buzz surrounding the technology, which makes for some confusion.

According to IDTechEx, the total market for anticipated and potential printed electronics was near $2 billion in 2009 and

expected to grow to nearly $60 billion within ten years. Earlier projections of a $300 billion market were floated a few years ago, but the $60 billion figure is still considerable and roughly equal to the current value of the global printed circuit market.

There is presently a market for printed electronics, but the growth rate predicted by exuberant market forecasters has not yet been seen. Barriers to exponential growth seem to be related in part to the current inability of suppliers to reduce costs to enable large-scale manufacturing of printed electronics. Every disruptive technology that has sought to surpass existing, highly competitive and/or traditional technologies has faced this challenge. So far, printed electronics has replaced a few existing applications, but has made little progress creating new applications outside of radio-frequency identification (RFID) and organic light-emitting diode (OLED). The latter is a true printed electronics solution that has succeeded in making a solid market presence. Other than that, no real killer app or paradigm shift technology has emerged from the current fray. The simple reality is that it is especially challenging to displace incumbent products when entirely new design solutions must be developed, understood and implemented.

HISTORY OF PRINTED ELECTRONICS

The interest in printed electronics as it is being marketed at present is both real and deserved, but it appears that much of the technology being described and/or used is not completely new. To test this assertion, ask two simple questions:

- What is a printed circuit?
- How did we come to call them printed circuits in the first place?

Looking back, it turns out that the printing technologies now being described as novel, new and revolutionary had their

FIGURE 7. *Stencilling operations.*

A, Retractable stencil holder for applying paint to insulated plate. Holder moves forward and down over plate held in platen. Plate shown has just been removed from platen; B, application of paint through stencilled-screen. A single smooth stroke of the squeegee is required.

Figure 11-1: Image of screen printing from the 1940s. (Brunetti and Curtis, 1947)

roots in the earliest days of the printed circuits industry. Dr. Ken Gilleo, electronics circuit industry technologist and futurist, uncovered and presented evidence that Thomas Edison himself described a method for producing conductors on linen paper in the early 1900s (http://www.et-trends.com/files/Circuits_100Years.pdf). The first known publications on printed circuits, (Printed Circuit Techniques by Cledo Brunetti and Roger W. Curtis, 1947 and New Advances in Printed Circuits edited by Cledo Brunetti, 1948), describe printing not only of conductors for circuits, but also "resistors, capacitors, inductors and combinations of them."

As early as 1947, Printed Circuit Techniques described screen printing for printing electronic circuits (fig. 11-1) and a transfer printing press (fig. 11-2). A later publication, New Advances in Printed Circuits (1948), included a section summarizing 26 different methods for making printed circuits. One method described was the "printing of conductors using silver paint and ordinary newspaper printing techniques" and further describes the type of ink used as "a colloidal suspension of

FIGURE 9. *Printing press for printing electronic circuits.*

Figure 11-2: Image of transfer printing press from the 1940s. (Brunetti and Curtis, 1947)

metallic silver but with silver oxide and other organic materials kept to an absolute minimum." Additional details of the method revealed in the text included the statements: "up to 70 percent of silver may be used" and "coatings of fair conductance are obtained even after firing at 110°C." Visionaries during the nascent age of electronics manufacturing foresaw the benefit of using low-temperature conductive ink formulations for applications on non-standard materials. As an example, they noted that while "intended for application to phenolics and practically all other plastics," those same inks would work as well with "paper, wood, leather and cloth or other base materials which can be subjected to temperatures not exceeding 200°F." (Brunetti, 1948) Words similar to these are heard today, many decades later, to describe supposedly new technology.

Discussions and publications about printed electronics of today clearly echo words and concepts from the past.

Around a dozen years later, Jack Kilby, who had worked for early printed circuit pioneer CentraLab (Milwaukee, WI), appears to have used at least some of the lessons and skills learned at CentraLab to print conductors onto semiconducting materials to create the first prototype IC.

Currently, broader concepts of printed electronics, involving the printing of transistors, are being positioned by marketers of material, process and equipment solutions as brand new and unique. However, the reality is that the fundamental idea was first explored in the mid- to late-1960s at Westinghouse, as evidenced by an article published in Popular Science in November 1968 (fig. 11-3). The historical existence of printed electronics concepts does not suggest that current efforts are not important, nor that they will not yield fruit. Rather, it suggests a need to look back for direction before moving forward.

Flexible circuits printed by machine on paper, aluminum foil, or film may make possible cheap, disposable radios, hi-fi's, and many other electronic devices

Now They're Printing

TRANSISTORS ON PAPER!

By W. STEVENSON BACON

Some 100 printed transistors decorate corner of playing card in demonstration of new process that forms semiconductors and circuits on any material.

Someday soon you may be able to buy a pad of operating electronic circuits just the way you now buy a pad of paper. On its pages will be printed amplifiers, radio receivers, computer circuitry, oscillators—anything you can name. They'll be so inexpensive you'll be able to tear them out, use them, and junk them.

It's made possible by a method of printing transistors on paper, film, plastic, foil, and many other materials. Developed by Westinghouse, the process is unbelievably simple and economical.

The art of depositing passive thin-film components (resistors, capacitors, and interconnects, for example) is well known. Design an automatic circuit-printing machine to deposit both active (transistors) and passive components and you can turn out circuits in continuous rolls for just pennies. Here are only a few of the possibilities:

- Credit and data cards, documents, checks, and other papers with flexible printed-component circuits will help speed identification and processing.
- Revolutionary new medical devices that can be implanted in the body will, for the first time, become really practical.
- A narrow-band TV system that can operate over ordinary telephone lines could become a reality. Such a project is now under way.
- Textbooks and teaching aids, toys, hobby kits, novelties will be based on flexible circuits.

How it's done. Thin-film components are made in a vacuum chamber by superimposing conductors and other materials and then depositing them in layers on an ultrasmooth base. Thin-film transistors, a relatively recent development, go a step further. A sandwich of metals, insulators and semiconductors is laid down in several steps.

Until recently, it was thought that the base had to be an expensive, polished insulating material such as sapphire, quartz, or glass.

What is new is that Westinghouse researchers, headed by Drs. T. P. Brody and Derrick J. Page, have discovered that transistors and other components can be deposited on almost anything. Another first: By using a stencilling method, they deposit hundreds of transistors simultaneously with a single "pump-down" of a vacuum chamber. Formerly it was necessary to deposit each transistor layer separately, pumping out each time.

Printing press for circuits. So simple is the new process that it should lend itself to automation—machines that automatically turn out millions of circuits a year. According to Dr. Brody, such a machine would wind a roll of tape through a printing station, a testing station, and an encapsulating station, and onto a takeup roll—just like a movie camera.

At the printing station, transistors would be formed by depositing on the tape, in sequence, layers of gold, tellurium (the semiconductor), glass, and aluminum. Passive components, would be similarly formed.

After the circuits were tested, they would be sealed with covering tape brought up from another roll, then wound onto a takeup reel. Final step, with the run complete, would be to remove the reel and slice it into individual circuits.

So far, paper transistors have proved versatile and reliable for any device that does not have to operate at high temperature, power, or very-high frequencies. About the size of the crossbar on this letter "t" and much thinner than the layer of ink used to print it, they have been operated for more than 1,000 hours with no measurable loss. They can be bent, twisted, and coiled. Cut them in half, and you have two transistors.

Photograph uses an amplifier (in model's hand) printed on aluminum foil. In addition to making cheap electronic devices, paper circuits may be printed in books, on credit cards and documents.

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Figure 11-3: Article on printed electronics in the 1960s. (Bacon, Popular Science, 1968)

Many of the things that were examined by earlier developers should be reviewed and considered before a course is set.

The article opens with the following: "Someday soon you may be able to buy a pad of operating electronic circuits the way you now buy a pad of paper. On the pages will be printed amplifiers, radio receivers, computer circuitry, oscillators – anything you can name. They will be so inexpensive, you will be able to tear them out, use them, and junk them." (Bacon, Popular Science, 1968) It seems that in 1968, the future was already here.

PRINTED ELECTRONICS OVERVIEW

The idea of making electronics that can compete with paper and can be thrown away is compelling and intriguing to marketers. However, there is a need to consider the impact of throw-away electronics in terms of the environment and to prepare for end-of-life matters early in the process of adapting printed electronics (PE) technology. Assuming that these factors are taken into consideration, there are a variety of intriguing prospects and processes that are being suggested for the next generation of printed electronics.

Rapidly printing multiple conductive, insulating and semiconductor layers to form electronic circuits offers the potential to produce a simpler and larger integrated circuit (IC) at a much lower cost compared to those prepared using conventional fabrication methods, albeit with less functionality per unit area. However, it is essential to compare all aspects of both traditional and evolving approaches to making transistors. In the parlance of printed electronics, printing semiconductors usually implies the use of organic materials, although there are some non-traditional views that will be covered later in this chapter. Developing materials are capable, but offer very different performance compared to silicon. Current processes limit feature sizes, resulting in much larger

minimum geometries for printed electronics than those that can be attained through silicon processing. Still, there are applications, such as RFID tags and active-matrix backplanes for displays, that can benefit from modest performance on flexible substrates at a lower cost. These two applications appear to set the upper and lower boundaries for the technology in terms of the size of products that are best suited to high-volume applications. Most printed electronics are best when designed to be produced in a roll-to-roll manner, which determines some of the processes being introduced for producing them.

PRINTING CIRCUITS ON FLEXIBLE BASE MATERIALS

The main attraction of printing technology for the fabrication of electronics is the possibility of preparing stacks of microstructured layers, and thereby thin-film devices, in a more simple and cost-effective way compared to conventional electronics. The possibility of implementing new or improved functionalities (e.g., mechanical flexibility) also plays a role. The selection of printing method to use is determined by requirements concerning printed layers and properties of printed materials, as well as economic and technical considerations for printed products.

Presently, printing technologies divide between sheet-based and roll-to-roll-based approaches. Sheet-based techniques, such as inkjet and screen printing, are best for low-volume, high-precision work. Gravure, offset and flexographic printing are more common for high-volume production, such as solar cells, reaching 10,000 square meters per hour (m^2/h). While offset and flexographic printing are mainly used for inorganic and organic conductors (the latter also for dielectrics), gravure printing is especially suitable for quality-sensitive layers like organic semiconductors and semiconductor/dielectric-interfaces in transistors, due to high layer image registration quality. Gravure printing is also suitable for inorganic and

organic conductors in terms of high resolution. Organic field-effect transistors and integrated circuits can be prepared completely using mass-printing methods.

Screen printing is appropriate for fabricating electrics and electronics on an industrial scale due to its ability to produce thick layers from paste-like materials. This method can produce conducting lines from inorganic materials (e.g., for circuit boards and antennas) and insulating and passivating layers where layer thickness is more important than high resolution. Screen printing's 50 m^2/h throughput and 100µm resolution are similar to inkjet printing. This versatile and comparatively simple method is used mainly for conductive and dielectric layers, but can also be used for organic semiconductors (e.g., for organic photovoltaic cells [OPVC], and even complete organic field-effect transistors [OFET]).

Altogether, there are presently nine key manufacturing image transfer technologies that are either being employed or are proposed for PE production:

Traditional Printing Technologies:

- Screen printing
- Rotogravure printing
- Flexographic printing
- Offset printing

New Wave Printing Technologies:

- Inkjet printing
- Imprinting and stamping
- Plasma printing
- Direct laser imaging or ablation
- Curtain and roller coating

Of these enabling technologies, stenciling and screen printing have been around the longest and both methods are still

widely used in production today. Membrane switch technology, a clear member of the printed electronics family, relies heavily on screen printing to make products. Stencil printing and transfer printing are among the first printing technologies devised by man. One need only look to ancient human hand prints found on rock walls left by our ancestors who either placed their pigment covered hands on cave walls or sprayed pigments from their mouths at the backs of their hands held flush against the rocks to provide an outline of their five-digit stencil. Those basic processes are still in use today, albeit with better equipment. For example, in the electronics manufacturing industry stencil printing remains the method of choice for printing solder paste onto printed circuits for SMT assembly.

Web printing of circuits has been in use for several decades. In the printed circuit industry, the benefits of printing circuits on a flexible base were seen very early and brought into practice by a number of companies including Sheldahl Corporation in Northfield, MN (now part of Multek, a division of Flextronics), which entered the flex circuit business as an extension of its involvement in the development of materials for the military in the early 1960s. Sheldahl engineers developed roll-to-roll processing using a step-and-repeat screen printing process for etch resist and an etching process to remove the background metals.

Over the years, web printing has been supplemented with different photolithographic methods, including direct write and, more recently, direct printing of catalytic toners and inks along with conductive and resistive inks and the printing of semiconducting materials. Rolltronics Corporation, a Silicon Valley technology company, was an early industry leader, pioneering what is now called printed electronics during the late 1990s and early 2000s. Rolltronics developed flexible electronic device printing technology and roll-to-roll production processes for low-cost, durable, thin-film switch arrays for

display backplanes, sensors and other large area circuits. They were targeting the technology for products such as standard and custom backplane displays based on ultra-thin flexible structures with integral LCD-like switchable materials that they were printing into the product. Unfortunately, the company's vision did not come to fruition as a result of market timing and/or positioning.

In the late 1970s, while Hewlett-Packard Laboratories was developing their laser printing technology, one diversion was the laser printing of a tin-lead coated copper-particle insulated with a high-temperature flux. Printed as a thick-power-film by turning the 'corona-charge' to a higher voltage on the photoconductor printing drum, this power was able to be fused by infrared-red reflow onto sheets of paper and polyimide film to form continuous ribbons of conductors, all the way down to

Figure 11-4: Overview of how printing techniques compare for resolution versus throughput. Curtain/roller coating is similar to other roll-to-roll techniques and soft lithography is a photo-imageable technique that is off the scale to the left. (Source: OE-A Roadmap, 2007)

125µm (0.005”). Since this was not the central focus of the HPL project, patents were filed, and the technology was placed on the shelf. In a way, this was an ‘early New-Wave Printing’ technology for PE. That original HP Laser printer was a roll-to-roll machine. The ubiquitous HP LaserJet would come a few years later.

There is a tremendous amount of new development underway for equipment, materials and processes that will significantly improve on the long-standing idea of roll-to-roll production and the efficiency, volume capabilities and low cost it promises for a range of products. Most of the products presently being mentioned as targets are relatively simple and the term disposable is often tied to them. Smart labels, RFID tags, cards for medical and consumer applications and the ever-present electronic toys and games are some of the products most commonly mentioned. More complex structures may be possible in the future, but the low-hanging fruit are, for the moment, found in applications that are simple, high-volume and have a short life expectancy or little concern or need for reliability.

TRADITIONAL PRINTING TECHNOLOGIES

SCREEN PRINTING

Screen printing is a printing technique that uses a woven mesh to support an ink-blocking stencil. The attached stencil forms open areas of mesh that transfer ink or other printable materials that can be pressed through the mesh as a sharp-edged image onto a substrate. A roller or squeegee is moved across the screen stencil, forcing or pumping ink past the threads of the woven mesh in the open areas.

Screen printing is also a stencil method of printmaking in which a design is imposed on a screen of silk or other fine mesh with blank areas coated with an impermeable substance,

Figure 11-5: Screen printing.

and ink is forced through the mesh onto the printing surface. It is also known as silkscreen, seriography and serigraph.

ROTOGRAVURE PRINTING

Rotogravure (roto or gravure for short) is a type of intaglio printing process, which means that it involves engraving the image onto an image carrier. In gravure printing, the image is engraved onto a cylinder because, like offset and flexography, it uses a rotary printing press. The vast majority of gravure presses print on rolls (also known as webs) of paper, rather than sheets of paper. (Sheet-fed gravure is a small, specialty market.)

Figure 11-6: Rotogravure printing. (Source: OE-A Technology Update, 2007)

Rotary gravure presses are the fastest and widest presses in operation, printing everything from narrow labels to rolls of vinyl flooring 12 ft. (4 m) wide. Additional operations may be conducted in line with a gravure press, such as saddle stitching facilities for magazine and brochure work. Once a staple of newspaper photo features, the rotogravure process is still used for commercial printing of magazines, postcards and corrugated (cardboard) product packaging.

FLEXOGRAPH PRINTING

Flexography (often abbreviated as flexo) utilizes a flexible relief plate. It is an updated version of the letterpress and can be used for printing on almost any type of substrate, including plastic, metallic films, cellophane and paper. It is widely used for printing on the non-porous substrates required for various types of food packaging. It is also well-suited for printing large areas of solid color.

The greatest advances in flexographic printing have been in the area of photopolymer printing plates, including improvements to the plate material and the method of plate creation.

Digital direct-to-plate systems have been a good improvement in the industry recently. Companies like AV Flexologic, DuPont, MacDermid, Kodak and Esko have pioneered recent technologies with advances in fast washout and the latest screening technology.

Figure 11-7: Flexograph printing. (Source: OE-A Roadmap, 2007)

Laser-etched ceramic anilox rolls also play a part in the improvement of print quality. Full color picture printing is now possible, and some of the finer presses available today, in combination with a skilled operator, allow quality that rivals the lithographic process. One ongoing improvement has been the increasing ability to reproduce highlight tonal values, thereby providing a workaround for the very high dot gain associated with flexographic printing.

There are five types of inks that can be used in flexography: solvent-based inks, water-based inks, electron beam (EB) curing inks, ultraviolet (UV) curing inks and two-part chemically-curing inks (usually based on polyurethane isocyanate reactions), although these are uncommon at the moment. Water-based flexo inks with particle sizes below 5μm may cause problems when de-inking recycled paper.

INK CONTROL

In the flexographic printing process, ink is controlled by the inking unit. The inking unit can be either a fountain roll system or doctor blade system. The fountain roll system is a simple, old system. Yet if there is too much or too little ink, this system would not likely control ink in a good way. The doctor blade inside the anilox roller uses cell geometry and distribution. These blades ensure that the cells are filled with enough ink

OFFSET PRINTING

Offset printing is the most widely used printing technique for newspapers and magazines worldwide. Famous equipment, such as the Heidelberg and MAN-Roland presses, makes nearly two-thirds of the world's newspapers and high-quality magazines. These include web and sheet-fed offset presses, as well as digital printing systems.

Offset has high resolution, but only a very thin ink film

Figure 11-8: Offset printing. (Source: OE-A Roadmap, 2007)

can be transferred, typically 1µm to 2µm on the substrate, but at a resolution of 50µm or less. This thickness is suitable for printing catalytic inks, allowing the conductor thickness to be subsequently increased by additive or semi-additive post-deposition processes.

From the simplest stenciling to the most sophisticated offset, traditional printing technologies are still the mainstay of printing today. Figure 11-8 illustrates only the last step of the rotary printing process. For flexographic printing, the previous step was contact with an ink-coated roller where the ink thickness had been adjusted using a doctor blade. In the gravure printing example, the previous step would have been contact with a doctor blade to remove excess ink from the coated

surface, which controls the depth of the cavities in the print roller. Photolithographic printing is another traditional technology. However, it has limited applicability, with the exception of the prospect of crossover of catalyst-coated materials that can be activated by light. This method has thus far been limited to molded interconnection devices.

NEW WAVE PRINTING TECHNOLOGIES

INKJET PRINTING

An inkjet printer is a type of computer-controlled printing system that creates a digital image by propelling droplets of ink onto a substrate of paper or film. Inkjet printers are the most commonly used type of printer and range from small inexpensive consumer models to very large professional machines that can cost thousands of dollars.

The concept of inkjet printing has deep roots in the past, having originated in the 19th century. The technology was first extensively developed in the early 1950s. Starting in the late 1970s, inkjet printers that could reproduce digital images generated by computers were developed, mainly by Epson, Hewlett-Packard (HP) and Canon. In the worldwide consumer market, four manufacturers account for the majority of today's inkjet printer sales: Canon, HP, Epson and Lexmark, a 1991 spin-off from IBM. Today, HP dominates the market for large format inkjet printers used for signs and printing.

There are a couple of different types of printheads. Thermal inkjet heads are a familiar type that uses a thin-film resistor to heat and volatilize a portion of the ink to produce a bubble that drives the ink out through its nozzle. Inkjet printers, especially models produced by Dimatix (now part of Fujifilm), JetXpert, Xennia Technology and Pixdro, are in wide use in many labs around the world for developing alternative deposition methods that reduce consumption of expensive, rare or

problematic materials. These inkjet printers have been used in the printing of polymer, macromolecular, quantum dot, metallic nanoparticles, carbon nanotubes, etc. These printing materials are used for organic thin-film transistors, organic light-emitting diodes, organic solar cells, sensors, etc.

The emerging ink jet material deposition market uses alternative inkjet printing technologies, employing printheads that use piezoelectric crystals to deposit materials directly onto substrates. Piezo printheads are made by Xaar, Trident, Seiko-Epson, Kyocera, Konica-Minolta, Dimatrix and Ricoh.

Another inkjet printhead technology is one based on MEMS (micro electro mechanical systems) technology. Companies such as Dimatix, Orbotech, OCE and MicroCraft utilize both MEMS and piezo printhead technologies for printing circuit legend information, soldermask and etch resist ink on both PCBs and flexible printed circuits. Four models of Dimatix are available for PE printing. The new DMP-5005 joins

Figure 11-9: Thermal inkjet printing compared to piezo inkjet printing.

the DMP-2800, DMP-3000 and DMP-5000 printers introduced in 2005, 2009, and 2010, respectively. All four printers are equipped with a PC and monitor, a drop watcher, a fiducial camera and a heated vacuum platen. They have automated printhead maintenance and cleaning and employ easy-to-use software. The equipment can be configured with multiple jets having either one- or ten-picoliter MEMS-based printheads and can be fitted with up to five different fluids for sequential production printing. Using a large 500mm x 500mm printable areas with positional accuracy and repeatability of ± 5 microns and ± 1 micron, respectively.

The MetalJet 6000l is an inkjet printer for the PE industry that uses a catalyst ink on a special chemically-resistant paper to initiate copper metal deposition.

IMPRINTING/STAMPING

Imprinting is as old as Edison but also, the newest manufacturing method available. Imprinting was first used by Edison to make Victrola Music tubes/cylinders for his new invention, the phonograph. The time-honored technology is now used to manufacture the myriad of laser CDs, imprinting works off a master tool foil, a hard, nickel-plated tool that stamps or imprints its pattern onto various plastics. For CDs, the plastic is polycarbonate that will later be coated with aluminum to reflect the laser. Figure 11-10 shows the tool foil creation process and the imprinting onto plastic substrates.

PLASMA PRINTING

Plasma printing is a new development that comes from the Fraunhafer Institute in Braunschweig, Germany. Plasma printing and packaging technology (P3T) uses the principles of conventional rotogravure or lithography, with metal printer rollers used as printing masks. However, printing information is transferred to the substrate using a dielectric barrier dis-

Figure 11-10: Imprinting/stamping. (Image courtesy of George Gregorie)

charge plasma rather than ink.

Reel-to-reel patterned plasma activation of the substrate, the polymer film, is carried out in the plasma printing process using cold atmospheric pressure microplasmas. The main components of the plasma printing setup include a high voltage (HV) electrode and the printer roller, which also represents the counter electrode. The HV electrode system has a curved shape with a curvature that corresponds to the radius of the printer roller. Printer rollers that have been used in research so far have consisted of a copper galvanized steel cylinder with a chromium top coat along with the structures to be plasma-printed, engraved using a high-resolution laser ablation technique called 'high-resolution laser stream'. A gas shower positioned close to the HV electrode supplies the process gas. During operation, the printer roller rotates and the polymer film is pulled through the gap between the electrodes to achieve area selective plasma activation of the polymer surface. The pressure of the HV electrode on the substrate ensures the formation of process gas-filled spaces and ignition of a plasma in these spaces in positions necessary for structures on the

Figure 11-11: Plasma printing.

printer roller to be accurately reproduced on the substrate. The situation is shown schematically in figure 11-11, where plasma ignition occurs exclusively inside the ditches and depressions of the structures engraved on the printer roller during face-to-face contact between the printer roller surface and the polymer foil. Next, the plasma-activated areas of the substrate are selectively metallized by seeding with palladium chloride/hypophosphite or colloidal graphite solutions. Conductive paths are provided by electroless plating procedures, such as electroless copper or electroless nickel.

Typical operation parameters in this work included sinusoidal mid-frequency (15kHz) voltages estimated to be in the range of 10kV to 20kV, a gas flow of up to 70 standard liters per minute and reel-to-reel speeds from 0.5m/min to 3m/min.

DIRECT LASER PRINTING

There are three types of direct laser writing metallization:

- Ablation
- Exposure
- Thermal transfer material.

Ablation usually removes a thin tin or copper layer from the substrate. Exposure is the PCB technique of polymerizing a photoresist with laser energy. Thermal transfer is a thermal decomposition of coated film.

In direct laser printing, heat generated by the laser decomposes the precursor, which then generates and anneals the small metal particles, forming metal aggregates that are further embossed onto the surface of the substrate. Since the laser beam irradiates through a thin film layer instead of a liquid medium, the feature resolution problem is reduced. However, the minimum feature size is still limited, and the uniformity of shape of the deposit and its morphology still need to be improved.

There are several printing techniques based on the principle of thermal transfer. In the graphics world, these techniques are sometimes known as dye transfer, dye sublimation, thermal dye transfer or thermal imaging. These techniques use

Figure 11-12: Thermal transfer printing. (Source: OE-A Roadmap, 2007)

a laser to induce the transfer of material from a donor sheet to the substrate (figure 11-12). The laser energy melts or vaporizes the surrounding organics, transferring them from the donor layer to the receiver. Unfortunately, the laser energy is sufficient to decompose many organic materials, making selection of materials very difficult. The two flexible films, a multilayer donor and a receiver, are held together by vacuum. The laser beam is focused onto a thin absorbing layer that converts light into heat, an optional ejection layer placed directly underneath and the functional material to be transfer-coated on top. The heat generated at the metal interface decomposes the surrounding organics creating a gas bubble that transfers the conducting layer onto the receiver. After imaging is completed, the donor and receiver films are separated.

CURTAIN/ROLLER COATING

Curtain and roller coating are methods of applying a fluid material in a uniform thickness. In addition to printing, in

Figure 11-13: Curtain / roller coating.

strate (or strips on the substrate) with a functional material for subsequent patterning or for creating an unpatterned state. There are a variety of coating methods leading to different costs, uniformities and film thicknesses, such as curtain (figure 11-13), slot-die, wire bar or reverse nip gravure coating. Where patterning is not essential and material costs are not prohibitive, these methods of solvent jetting, laser ablation or embossing may prove to be more effective than printing.

SUMMARY OF PRINTING

Each printing method has certain attritubes, advantages, limitations and requirements (table 11-1). Screen and inkjet printing are the simplest methods, with gravure, lithographic and flexographic printing following in terms of complexity.

TECHNOLOGICAL DEVELOPMENTS

Given the prediction of a $60 billion market for printed electronics in the next ten years, a host of competing technol-

Printing Method	Speed (m/min)	Resolution (um)	Film Thickness (um)	Viscosity (Pas)
Flexo	50 - 80	20 - 50	0.5 - 2	0.05 - 0.5
Gravure	20 - 100	20 - 50	0.5 - 2	0.05 - 0.2
Offset	15 - 100	15	0.5 - 2	30 - 100
Screen	10 - 100	80 - 100	5 - 25	0.5 - 50
Inkjet	0.5 - 5	20	100 - 500	0.002-0.025
Imprint/stamp	50 - 100	1 – 15	0.5 - 200	0.05 - 0.5
Plasma	0.5 - 3	20 - 100	0.5 - 200	Post Metallize
Laser ablation	0.1 – 1	0.1 – 5	0.5 - 2	0.05 - 0.2
R2R Photolitho	5 - 50	1 - 100	0.5 - 5	0.05 - 0.2

Table 11-1: Summary of printing method attributes.

ogies will certainly arise. The seeds of competition are already beginning to sprout. The number of exhibitors and attendees at industry trade shows focused on printed electronics is growing steadily and has been evident at IDTech's recent events in Europe and the USA. The IPC's recent efforts to develop standards and provide forums for technological exchange also underscore the importance of printed electronics technology in the future. The road ahead will certainly be paved with a wide array of proprietary printing techniques and materials, along with equipment to support their production. The two methods getting most of the early attention for printing interconnections only are conductive inks and catalytic ink solutions that share the ability to take circuit data directly from a computer to production (fig. 11-4).

There are a number of time-honored techniques in printing, including screen, laser, inkjet and offset plate printing. However, in terms of speed and volume, it is unlikely that

Figure 11-14: Two approaches to printing electronic circuits using data directly from a computer.

these techniques will be able to compete with rotary gravure printing. Although no printing method that is a panacea for the industry has surfaced, it is likely that many different technologies will be part of the future production landscape. Some other processes that are not generally considered printing processes might be suitable for some applications. For example, continuous dispensing of conductive inks has been shown to be a viable method for creating circuits on an insulating layer, but its applicability is limited since each circuit must be individually drawn. Pad printing, a process that can transfer a flat image onto a 3D object using an indirect offset printing process by which an image (e.g., circuit pattern) is transferred from a plate onto a substrate using a compliant, resilient silicone pad, has potential, but is of little value for flat materials.

Printing technologies that have already been developed may be suitable for printed electronics in the future. Today's fastest printers run at over 100 meters per minute using a continuous web. They are large machines, occupying a space equivalent to three large bedrooms. While these printers have high resolution (~2,400 dpi), they are fixed for discrete printing runs and cannot operate on variable data, thereby tying their profitability to printing of tens of thousands of impressions. The fastest variable printers, such as laser printers and inkjets, use sheet media and have an equivalent speed of around ten meters per minute with considerably lower resolution due to the traditional architecture of electrophotographic printing machines that use modulated laser beams to form an image. A new method for solid-state printing that does not require lasers or photoelectric drums has been conceived and could be useful for printed electronics (see fig. 11-6). Instead, the image is digitally formed by direct writing, using 40-volt amplitude control signals applied to imaging electrodes. To date, digital imaging capability has been demonstrated at a web speed of 200 feet per minute at an arbitrary print width.

Figure 11-15: A novel printing technology process that may enable the speed and resolution of gravure printing with the variable data capability of laser printing. (Image courtesy of Peter Salmon, LLC)

Polymerized toners (chemical toners) are available and have been tested. It is also possible that the technology could make use of catalytic toners like those developed by Extended Length Flex Technologies in the early 1990s. Developers suggest that the printing devices will be much more compact than existing machines and may be much more reliable than traditional technologies.

As the palette of printing methods continues to grow, add applications and be exploited in novel ways to create new products, important attention has been given to the materials, printing enhancement processes and processing equipment needed to make the system work. A number of industry consortia, other than IDTech, the Organic Electronics Association (OE-A) and IPC, are anticipating the challenges of the variety of technologies and the need for cooperative understanding and development. The International Electronics Manufacturing Initiative (iNEMI), for example, has been trying to create a roadmap for its members and is taking a long speculative view of what the future may hold (fig. 11-16).

Figure 11-16: Conceptualization of a future printed electronics manufacturing platform. (Image courtesy of iNEMI)

PRINTED ELECTRONIC CIRCUIT MATERIAL AND PROCESS DEVELOPMENTS

Most of the attention given to materials has appropriately centered on conductive inks, especially silver. Silver is the most conductive commonly used metal for making circuit conductors. Membrane switch circuits, which operate at relatively high voltages and low currents, have been printed onto polyester base materials using silver inks for more than a few decades. The challenge has been getting these circuits to have the bulk conductivity associated with copper. Common inks have conductivities that hover around 10% of copper and are not generally suitable for higher performance applications that operate at lower voltages or may require more power. A number of suppliers have attacked the problem using a combination of new formulations of binders in the ink and nanoparticle silver and are showing good improvements. For example, Taiyo Ink Corporation of Japan has developed printable conductive ink formulations that use individual metals or metal blends, such as silver with copper, that can be cured thermally

or by UV, thereby reducing sintering temperatures by up to 200ºC.

Another company, NovaCentrix (Austin, TX), is addressing the challenge of making printable circuits by developing a tool and technology that sinters metal and semiconductor inks in a matter of milliseconds using light energy. The process can reportedly be carried out on a range of materials, including low-temperature, flexible substrates such as polyethylene terephthalate (PET) and paper. It is a promising technology for making low-cost products.

INK TECHNOLOGY

Organic and inorganic materials are both used for printed electronics. Ink materials must be available in liquid form for solution, dispersion or suspension. They must function as conductors, semiconductors, dielectrics or insulators. Material costs must be appropriate for the application.

For printing, viscosity, surface tension and solid content must be tightly controlled. Cross-layer interactions, such as wetting, adhesion, solubility and post-deposition drying procedures, affect the outcome. Additives often used in conventional printing inks are unavailable because they often defeat the purpose of electronic functionality.

Material properties largely determine the differences between printed and conventional electronics. Printable materials provide decisive advantages beside printability, such as mechanical flexibility and functional adjustment by chemical modification (e.g., light color in OLEDs).

Printed conductors offer lower conductivity and charge carrier mobility. With a few exceptions, inorganic ink materials are dispersions of metallic microparticles and nanoparticles. P-type metal-oxide-semiconductor (PMOS) inks may be used in printed electronics, but no complementary metal–oxide–semiconductor (CMOS) inks are available.

Materials & Inks	Costs	Conductivity (S/cm²)	Flexibility	Printability
Gold Ink	++++	+++	++	+++
Silver inks	+++	+++	++	+++
Copper inks	++	++	++	++
Tin inks	++	++	++	++
Graphite Inks	+	+++	+++	+++
Catalyst Inks	+	+++	+++	++
CNT Inks	++	+++	+++	++
Thin film Cu	+	++++	++++	-
Thin film Ni	++	++++	++++	-
Or-Semiconductors	+++	+	++	++
Indium Tin Oxide	+++	++	++++	+++
PEDOT:PSS	++	+	++++	++

PEDOT:PSS= Poly(3,4-ethylenedioxythiophene) poly(styrene-sulfonate)

Table 11-2: Ink technologies.

Conductive inks have been available for at least 40 years. The new conductive inks are designed specifically for use with low-temperature substrates including paper, (PET), polyether ether ketone (PEEK), polyethylene naphthalate (PEN) and other plastics (including polyethylene film) and cure in an air environment.

Copper, tin and silver nanoparticles are used with screen, flexo, offset and inkjet printing. Gold, silver and copper particles are used with inkjet. Sheet resistance is as low as ten milliohms per square. Resistivities as low as four times bulk have been attained with silver, but are higher for copper inks.

AC electroluminescent (EL) multicolor displays can cover many tens of square meters, or be incorporated into small watch faces and instrument displays. They involve six to eight printed inorganic layers, including a copper-doped phosphor, on a plastic film substrate.

Product Description	JS-011 Au ink	JS-014 Ag ink	FS-066 Ag ink Stretchable 100%		OS-60 Ag ink (development)	OC-70 Cu ink (development)
Print Method	Crop-on-Demand Inkjet	Drop-on-Demand Inkjet	Gravure Spray		Flexographic, Screen	Flexographic, Screen
Substrates	Photo paper Copier paper	PET Glass, Si TCO coatings	Polyethylene Plastics		PET, Photo paper Copier paper	PET, Photo paper Copier paper
Performance			0%	100%		
Stretch %	NA	NA			NA	NA
Microns	0.0	0.6	0.0	0.0	1.4	1.0
Ohm/sq	0.10	0.12	1.3	57	0.18	0.05
(X bulk Metal)	4	4.5	57	231	16**	5**

Table 11-3: Metalon™ nanoparticle conductive metal inks from Novacentrix.

Nanotechnology is the greatest boon to PE inks. Innovalight™ Silicon Ink is a proprietary material comprised of silicon nanoparticles dispersed in an environmentally-friendly blend of chemicals. Innovalight has optimized silicon particle size and dopant concentration to maximize the conversion efficiency of photovoltaic (PV) cells. The ink is screen-printed and a lower viscosity is available for inkjet printing.

Carbon nanotubes (CNT) is another nanotechnology. CNT inks are available from SouthWest Nanotechnology and known as V2V CNT Technology. C3Nano has transparent conductive CNT ink for touch panels and solar cells. Table 11-3 shows some of the MetalonTM nanoparticle conductive metal inks from Novacentrix. OLED inks come from Plextronics.

SUBSTRATES

Printed electronics uses flexible substrates, which lowers production cost and allows fabrication of mechanically flexible circuits. While inkjet and screen printing typically imprint rigid substrates like glass and silicon, mass printing methods nearly exclusively use flexible foil and paper. PET is a common choice due to its low cost and higher temperature stability. PEN is another. PEEK is a colorless organic polymer thermoplastic used in engineering applications. Polyimide (PI) foil is

	Glass	Metal	Paper	PET	PEN	PC	PI	PEI	PVF
RFID (antenna only)			+	+	(+)	(+)			
RDIF (incl. circuits)				+	(+)	(+)			
Printed Memory				+	(+)				
oTFT/Display	+	+		+	+		+		
OLED/Display	+		(+)	+	+	+			
OLED/EL Lighting	+		(+)	(+)					
Printed Battery		+		(+)	(+)				
Organic Solar Cell	(+)	(+)		+	+				+
Sensors			+	+	(+)	(+)	+		
Clothing				+	(+)				
Signage	+	+	(+)	(+)	(+)	(+)	(+)	(+)	(+)

Table 11-4: Various substrates for printed electronics and their suitability in these applications. (+) preferred; + suitable; 'blank' not recommended.

another alternative. Paper's low cost and manifold applications make it an attractive substrate, but its roughness and absorbency make it problematic for electronics. Low roughness and suitable wettability, which can be tuned pre-treatment (coating, corona), are important criteria for substrates. In contrast to conventional printing, high absorbency is usually disadvantageous.

Flexible materials are a key characteristic of PE. Many products traditionally utilize glass to protect the active layers. To replace glass, the flexible substrates need to be an effective barrier against oxygen and water vapor, be sufficiently strong not to rip or tear and, if a cover, transparent to visible light. Many plastics, such as such as Mylar®, polyimide, PET and ORMOCER, have these characteristics. Substrates can even be papers and paper hybrids.

	Glass	Metal	Paper	PET	PEN	PC	PI	PEI	PVF
Smoothness	++	++	O	+	+	+	O	O	O
Temperature Resistance	++	++	O	+	+	O	++	++	++
Flexibility	--	++	++	++	++	++	++	++	++
Optical Transmittance	++	+	--	+	+	+	+	+	+
Barrier	++	+	-	+	+	+	+	+	+
Price	--	+	++	+	O	O	--	-	--
Score:	not suitable: -- - O + ++ :favorable								

Table 11-5: Characteristics of substrates.

The majority of the world's PET production is for synthetic fibers (in excess of 60%) with bottle production accounting for around 30% of global demand. In discussing textile applications, PET is generally referred to as simply polyester in fibers while PET is used most often to refer to bottling applications. The polyester fiber industry makes up about 18% of world polymer production, followed by PE fiber and polypropylene (PP) fibers.

PET consists of polymerized units of the monomer ethylene terephthalate, with repeating $C_{10}H_8O_4$ units. PET is commonly recycled, and has the number 1 as its recycling symbol. PEN is a polyester with good barrier properties (even better than PET). Because it provides a good oxygen barrier, it is well-suited for bottling beverages, such as beer, that are susceptible to oxidation. It is also used in making high performance sailcloth. PPG's Teslin® is a polyolefin matrix with high silica filler. DuPont's Teijin Films are polyester films that are pre-treated on both surfaces to promote adhesion to most industrial coatings. Melinex®, Mylar®, Cronar® and Teonex® are registered trademarks of DuPont Teijin Films. Teslin and

Teijin Films are designed for PE application like RFID, batteries, OLEDs and sensors.

PEEK is a semicrystalline thermoplastic with excellent mechanical and chemical resistance properties that are retained at high temperatures. The Young's modulus is 3.6 GPa and its tensile strength is 90 to 100 MPa. PEEK has a glass transition temperature of around 143°C and melts at around 343°C (662°F). It is highly resistant to thermal degradation and attack by both organic and aqueous environments. At high temperatures, it is attacked by halogens and strong Bronsted and Lewis acids, as well as some halogenated compounds and aromatic hydrocarbons.

If it is very thin, glass can also be a flexible substrate. AGC and Corning have both developed ultra-thin glass (only 0.1mm thick) for OLEDs and other applications. Alkali-free glass is composed of silicon dioxide, boron oxide and aluminum oxide and is free of sodium and potassium, so it is used widely as a substrate for thin-film transistor liquid crystal display (TFT LCD) and OLED. Soda-lime glass is composed of silicon dioxide, sodium oxide and calcium oxide and is widely used in construction, automotives and many electronics devices.

Recently, a research group at the Hebrew University of Jerusalem has developed a nanotechnology ink that self-sinters at room temperature. The researchers have demonstrated that the new silver nanoparticle-based ink can be deposited and provides post-print conductive properties without a post-sintering process step. Instead, the properties of the nanomaterial are used to make the ink aggregate and self-sinter. The elimination of the temperature needs associated with normal sintering processes opens the door to processing cost reduction and the use of lower cost, temperature-limited substrates, including paper and lower melt-temperature plastics (fig. 11-17).

Other companies are developing catalytic inks that can be electrolessly or electrolytically plated to achieve the neces-

Figure 11-17: New nanotechnology ink that can be deposited and provide conductive properties without requiring a post-sintering process step. (Image courtesy of Plastic Electronics)

sary conductivity. One company of note is Conductive Inkjet Technology (Cambridge, England), which has been developing a range of equipment for printing catalytic circuit patterns on material webs in a roll-to-roll fashion. When the catalytic ink is electrolessly plated, the company reports that the conductivity ranges from 50 to 20 milliohms per square. (For comparison, commonly used copper foil has a sheet resistivity value of 0.68 milliohms/square at a 25µm thickness.) The company's technology, which has an approach that is similar to a technology developed in Silicon Valley around 1990 (fig. 11-18), can reliably produce typical feature sizes down to less than 250µm, which is finer than earlier technology that used a laser printer and catalytic toner.

While Conductive Inkjet Technology has performed its initial process and equipment development on an inkjet platform, the company's literature indicates that they can produce 50µm features using flexographic printing, which could prove to be an important departure. Flexographic printing, as a follow-on technology in the same market space, opens the door to higher production rates and offers the potential to print both sides of a two-metal layer circuit in a single pass.

Figure 11-18: Rapid prototyping process that uses printing and plating of conductive inks developed by Extended Length Flex Technologies in the early 1990s.

With some creativity, it is possible that inkjet printing could be similarly adapted. One concern about this technology is that it will produce circuits that will build both vertically and laterally, reducing the space between circuits and potentially causing shorts.

Post plate-up technology shares many of the same concerns as laser printing technology in terms of managing

feature dimensions in process. Metrics are usually predicated on three items:

- Resolution, or how many dots per unit length
- Drop size, or how small each dot is
- Print rate, or dots per second

These metrics combine to measure how quickly and efficiently a circuit pattern can be printed. Keep in mind that smaller dot size is not always better since it may result in decreased productivity with minimal benefits in terms of resolution (fig. 11-19).

Figure 11-19: Illustration of how dot printing technologies can lose production efficiency if feature size is too small and material may be wasted if feature size is too large.

LPKF (Garbsen, Germany) has developed a method that is an outlier in the realm of printing flexible films. In simple terms, the method is the reverse of printing. A thin film of metal on a flexible base is ablated by a laser beam that prints the reverse (negative) of the circuit pattern leaving a thin metal circuit pattern (http://www.lpkf.com/applications/laser-micromachining/thin-layer-structuring.htm). LPKF's demonstration is on 35mm film, which is a good deal narrower than the current wide web focus area, but it might fill a niche for special products or particular needs. Figure 11-20 shows examples of circuits produced with other materials.

Beyond simple conductors, resistors and light-emitting diodes, there are still more important emerging technologies for printable semiconducting materials. Printed semiconductors may be the most important and distinguishing features of a printed electronic circuit. A joint venture in by PolyIC (Fürth, Germany) and Thin Film Electronics ASA (Linköping, Sweden) has produced fully functional, thin film, rewritable polymer memory products using a high-volume, roll-to-roll printing process. The developers claim that the process is high-yielding and suitable for low-end consumer products that require memory, such as toys and games.

Another company that is approaching printed semiconductors from a different angle is Terepac, Inc., in Waterloo, Ontario, Canada (http://terepac.com/). Terepac has developed a transfer printing process for semiconductor devices using a

Figure 11-20: Lasers can selectively ablate the surface conductive layer to pattern isolation areas rather than the conductors. (Source: LPKF)

simple principle of photopolymer release. The method takes advantage of the fact that certain polymers used as adhesives decompose thermally to gases over a narrow temperature range with little or no residue. Additionally, they discovered that the temperature can be drastically reduced by the action of a photogenerated catalyst. The material has been labeled a digital release adhesive (DRA) because it first has the adhesive properties of a typical thermoplastic polymer and then no adhesive properties at all after gasification, since only air is left (fig. 11-21). In production, the minuscule semiconductor components (as small as 100μm) are first transferred en masse to the printing plate in a laminator called the prepress. The plate has been coated by DRA and may be rigid, as illustrated in the figure 11-11, or could be produced on a flexible web. In the printing step the components attached to the carrier with the DRA are irradiated through the plate in only those regions where the components should be released, allowing great precision.

Figure 11-21: Terepac's concept of printing silicon chips as small at 100 microns on a side (a fraction of the size of the period at the end of a sentence) and as thin as one mil.

Kovio, Inc. in California is another important printed electronics developer. Kovio has shown breakthroughs in nanomaterials and printing technology. They have also developed semiconducting, silicon-based inks that allow for the integration of printed silicon electronics and thin-film technology. The company suggests that the technology will enable the fabrication of stable, high-performance, low-power integrated circuits that can operate at frequencies in the MHz range and potentially above. An advantage of printed silicon technology over organic electronics alternatives is that printed silicon purports to offer significantly higher performance, lower power consumption and environmental stability. The economic viability of the process compared to processes using organic materials is not known at this time, but the solution should prove compelling for some applications, such as RFID tags.

APPLICATIONS FOR PRINTED ELECTRONIC TECHNOLOGIES

According to market watchers, there are several areas for application of printed electronic solutions. Most frequently mentioned are sensors (e.g., glucose monitoring strips), identification and security (e.g., RFID), power (e.g., batteries and solar), lighting and displays (e.g., OLED screens) and memory and logic. RFID technologies have enjoyed significant attention in recent years with the increase in interest in the internet of things concept which could require trillions of RFID tags to support it. However, displays seem to be the most interesting potential application of printed electronics technology and will be the focus of the remainder of this chapter. (Fjelstad 2010)

ORGANIC LIGHT-EMITTING DIODE DISPLAY TECHNOLOGIES

Since the birth of practical LEDs, their efficiency, light output and range of possible colors have increased at an impressive rate. The fundamental attributes of efficiency and light output have doubled approximately every 36 months and

are currently poised to overtake all other forms of traditional lighting in the not-too-distant future. Due in part to legislative push and in part to consumer pull, along with the desire for more environmentally-friendly solutions and energy savings, LED lighting (in combination with fluorescent lighting) is on its way to eclipsing Edison's venerable incandescent lamp.

For those involved in the printing industry, the technology of greatest current interest is in the area of OLEDs. The measurement unit most commonly associated with output is the nit. In lighting, the nit is a unit of visible light intensity equivalent to one candela (candle power) per square meter. It is a relatively small unit of light considering that a typical active-matrix LCD panel has an output of between 200 and 300 nits. There are two major types of OLEDs, passive matrix OLEDs (PMOLEDs) and active matrix OLEDs (AMOLEDs). Passive matrix is most common and practical in alphanumeric displays. Active matrix is more appropriate for higher resolution graphic displays and, therefore, growing faster.

In a passive matrix OLED display, the matrix of electrically-conducting rows and columns forms a two-dimensional array of picture elements, or pixels. Between the orthogonal column and row lines, in sandwich-like fashion, are thin films of organic material for the OLEDs. When a current is applied to the designated row and column lines, the OLED pixel is activated and emits light (fig. 11-22).

The brightness of each pixel is proportional to the amount of current applied to the OLED of the pixel. While PMOLEDs are fairly simple structures to design and fabricate, PMOLED displays are typically limited to under 100 lines for a number of technical reasons. In addition, their power consumption is significantly higher than that required by an active-matrix OLED, a point that is increasingly important in the ongoing effort to reduce power use and/or extend battery life.

Active matrix OLED displays are comprised of organic

Figure 11-22: The basic structure of an OLED. Individual pixels are defined by the intersection of anode and cathode conductors that are fired and refreshed at high data rates.

light-emitting diode pixels that have been deposited onto or integrated into a thin-film transistor (TFT) array, forming a matrix of pixels that emit light upon electrical activation. In contrast to PMOLED displays, where electricity is distributed row by row, the active matrix TFT backplane acts as an array of individual switches coupled with sample and hold circuitry that control and maintain the amount of current flowing through each individual OLED pixel during the total frame time. The active matrix TFT array will continuously control the current flowing to the OLEDs in each pixel and can send a signal to each individual OLED that determines how bright it lights up. This offers a tremendous advantage in terms of contrast and performance and provides ample evidence as to why active matrix displays are on the rise.

Another important reason for the increase in active matrix displays is that OLED manufacturing equipment and material

technologies have helped to drive down cost while improving quality. Well-known materials developers (e.g., DuPont, Dow Corning) are leading the way by developing organic semiconductor inks that can print using a range of printing technologies, the most important of which is inkjet technology. The inks have been adapted by a number of research institutes (e.g., Xerox PARC, Fraunhofer Institute) and adopted by old and new colored light-emitting materials and equipment companies (e.g., Fujifilm, Xaar) to address growing markets.

There have been recent reports that DuPont has developed materials and a new printing technology that make it possible to produce printed OLED TV displays as large as 50 inches in less than two minutes. If this development is successful and can be scaled up in terms of manufacturing, the cost of OLED TVs would be greatly reduced. The developer team also submits that displays made with the new technology and operated for eight hours per day could last up to 15 years. This development contributes to an important feature of printed organic polymer OLED structures, that they can be fabricated on thin flexible films, which makes roll-to-roll processing possible. It also opens the door to applications that are yet to be

Figure 11-23: Inkjet printing plays a key role in the printing of the color-emitting inks that make active matrix displays.

Figure 11-24: Sony OLED display. (Source: Sony)

imagined by tomorrow's engineers and product developers. Figure 11-24 shows a flexible display from Sony. The display, which is capable of displaying both still images and video, can be wound while content is still playing. It is slightly over 4 inches, 432×240 pixels and has a curvature radius of just 4mm. Sony engineers report that even after rolling and unrolling the display 1,000 times, there was no apparent damage to the quality of the display.

MARKET OPPORTUNITY

OLEDs are making impressive strides toward changing the rules of display technology. OLEDs are being used to make the highest definition displays and displays that are thinner than engineers could have imagined just a decade ago. For an example, refer to the Sony display in figure 11-24. Because of these important features, there is a large and growing demand for OLED displays in an ever-expanding range of products. According to various market-watching sources, the global OLED market is expected grow to by approximately 350 million units

in the next few years, which translates to about $5 billion of the nearly $95 billion market for displays. The compound annual growth rate (CAGR) for OLEDS is around 25% at present, while the total market is expected to grow at about 4%. Currently, TFT LED displays enjoy a market share of nearly 85%. As recently as three years ago, PMOLEDs made up almost 90% of the total OLED market. However, because of their important advantages AMOLED displays are expected to enjoy a much higher growth rate. As for materials, a recent report "OLED Lighting Materials Market Trends and Impact" from industry-watcher NanoMarkets, the market for materials used in OLED lighting will be around $1.4 billion dollars in 2015, which will represent about 20% of the total OLED market at that time.

The number of potential applications for OLED displays give credence to market projections. Presently, active and passive OLED displays can be found in many applications, including automotive instruments, GPS displays, industrial controller displays, medical monitors, medical diagnostic tools, home appliances, white goods, indoor and outdoor advertising, telecommunications, handheld devices of every sort, and small and large format televisions. This brief list just scratches the surface of OLED display technology's potential uses.

OLED technology is impressive and offers capabilities beyond any other display technology. With a constant flow of new materials, equipment and manufacturing technologies to improve the technology and help drive down technology costs, OLED display technology is poised to take on a broad range of display challenges in the very near future. The technology underpinning the entire effort is printing. People in the printing business should be comforted that their skills and capabilities are secure even as the form of the printed word changes shape.

PHOTOVOLTAICS

The term photovoltaic (PV) has been in use in English since 1849. French physicist Alexandre-Edmond Becquerel first recognized the photovoltaic effect in 1839. Charles Fritts, who coated the semiconductor selenium with an extremely thin layer of gold to form the junction, did not build the first solar cell until 1883. The device was only around 1% efficient. Russell Ohl patented the modern solar cell in 1946. The modern age of solar cells arrived in 1954 when Bell Laboratories experimented with semiconductors of silicon and germanium.

GE has predicted that solar power may be cheaper than electricity generated by fossil fuels and nuclear reactors within three to five years. This is illustrated in figure 11-25(c) from Deuches Bank. If solar generation can be reduced to 15 cents a kilowatt hour or lower, then it becomes competitive to buy it. In 2009, the average US retail rate per kilowatt hour for electricity ranged from 6.1 cents in Wyoming (where they have oil, coal and gas) to 18.1 cents in Connecticut. The average is 8.6 cents. Convergence could be achieved as early as 2013 or as late as 2016.

GE Process Research Center (GEPRC) announced plans to improve the efficiency of thin-film panels to a record 12.8% and will build a new plant to make enough panels for 80,000 homes each year. Installation of solar panels may increase by as much as 50% in 2011, which is worth about $14.0 billion. Most solar panels use silicon-based photovoltaic cells to transform light into electricity, but GE uses thin-film versions made from glass or other material coated with cadmium telluride or copper indium gallium selenide (CIGS) alloys, which account for about 15% of the $28 billion in worldwide solar-panel sales.

Because of the success of flexible thin-film PV, it is now reaching new applications. Northrop Grumman and Lockheed Martin each have contracts of $530 million to make various di-

Figure 11-25: Photovoltaic production and outlook: (a) 2007 US Energy production; (b) Typical silicon and flex solar cells; (c) Next 10 years projections for costs of thin-film PV, supply and demand and crossover for convergence when solar cells can be employed in homes; (d) 2007 government support and solar installations.

rigibles and aircraft based on laminar coating of flexible CIGS photovoltaics to power these pure electric aircraft. Soon they will be on cars and other vehicles.

PV TECHNOLOGY

SILICON TYPES

Single-Crystal and Multicrystalline Silicon—Single-crystal and multicrystalline silicon (c-Si), including nanocrystalline silicon, are sliced from single-crystal boules of grown silicon. These wafers/cells are now cut as thin as 200 microns. Single silicon wafer solar cells have higher energy conversion efficiency (~15%) but are the most expensive. Single- and

multicrystalline silicon has a lower bandgap than amorphous silicon and thus absorbs from the visible and infrared portion of the light spectrum as well.

Amorphous Silicon—Amorphous silicon (a-Si) is the noncrystalline allotropic form of silicon. It has a higher bandgap (1.7 eV) than crystalline silicon (c-Si = 1.1 eV), which means it absorbs the visible and ultraviolet portion of the spectrum. It can be deposited as a thin film by chemical vapor deposition, typically plasma-enhanced chemical vapor deposition (PE-CVD), from silane gas and hydrogen gas. PVs made this way tend to have a lower energy conversion efficiency of around 10%.

THIN-FILM TYPES

Organic photovoltaic cells (OPV) are usually a thin-film type. OPVs are finally becoming competitive with crystalline silicon modules in terms of efficiency, stability and cost. The efficiency of OPV has gone from 1% to 2% to about 9%. Recently, a project funded by FlexTech Alliance boosted efficiency to nearly 12% using high-efficiency donor polymer materials developed by Solarmer Energy Inc. These flexible cells are approaching the sub-$0.50/watt level cost needed to outperform traditional power production.

Copper Indium Gallium Selenide and Copper Indium Selenide—Copper indium gallium (di)selenide (CIGS), copper gallium (di)selenide (CGS) and copper indium (di)selenide (CIS) are all thin-film PV materials. These materials, from the periodic table groups of: 11 - 13 – 16 elements (Cu-Ag-AU) (Al-Ga-In) (S-Se-Te)2, are of interest because of their high optical absorption coefficients and electrical/optical properties (photo-effect). These materials are mixed in chalcopyrite thin films of CIS, CIGS, and CGS and have achieved greater than

12% energy efficiency. Currently, their manufacturing costs are higher than amorphous silicon solar cells, but ongoing work is leading to more cost-effective processes. The best efficiency of a thin-film solar cell was 19.9% reported for CIGS in March 2008. Higher efficiencies (around 30%) can be obtained by using optics to concentrate the solar light. The worlds largest CIGS gigawatt-scale factory has been turned on in Kunitomi, Japan by Solar Frontier.

A six-layer CIGS system is coated on polyimide film that is 300mm wide and 25mm thick and has achieved 10.2% efficiency. The six layers are:

- Molybdenum back electrical contact (back)
- Copper
- Indium
- Gallium
- Diselenide
- Zinc oxide electrical contact window with optional cover protection of ORMOCER hybrid polymer (front)

CADMIUM TELLURIDE

Cadmium telluride (CdTe) is an efficient, light-absorbing material for thin-film solar cells. CdTe is easier to deposit than CIGS, CGS, etc., and suitable for roll-to-roll production. Its efficiency is now up to 16% and it is currently the most popular thin-film PV material. Although cadmium is toxic, it is not released into the air and does not leach. The value of the telluride makes recycling very practical.

OTHERS

Light-Absorbing Dyes and Organic/Polymers Solar Cells—Typically, a ruthenium (Ru) metal-organic dye is used as a monolayer light-absorbing material over a mesoporous layer of nanoparticulate titanium dioxide. A redox couple in

the electrolyte, which can be a liquid or solid, completes the circuit. Organic/polymer solar cells are built from thin-film compounds like polyphenylene vinylene, copper phthalocyanine and carbon fullerene. Energy conversion efficiencies achieved to date are low at 6%. However, these cells could benefit from their mechanical flexibility and the ability to screen or offset print their structures into large formats. These represent the new technology wild card referred to in figure 11-25 (c).

ISSUES FOR PHOTOVOLTAICS

There are three issues that confuse the PV energy market: government subsidies, the smart grid and the changing availability of fossil and nuclear fuels

GOVERNMENT SUBSIDIES

Solar cell installations have been driven by government programs of support and subsidies. The higher cost of solar cells has been offset by feed-in-tariffs, principally in the EU (Germany, Italy and Spain), Japan, Australia, Korea and the US (figure 11-25[d]). Because of the financial crisis, feed-in-tariffs are being reduced by 15% in the EU, but the lower cost of solar panels is making up for this.

SMART GRID

Excess solar energy is currently sold back to the utilities using a power meter running in reverse, but when it hits zero, the credits stop. A smart utility grid is required to balance the multiple sources of wind and solar power being generated in remote locations. This will take many, many years to develop since it would consist of millions of next-generation power meters installed in businesses and homes, appliances that adjust their energy use when prices and availability change and advanced software to help utilities control electricity flow.

FOSSIL AND NUCLEAR ENERGY

Following the crisis at the Fukushima Daiichi nuclear power plant in 2011, Japan laid out new energy plans to increase the share of alternative energy to 20% of the total power supply by the early 2020s. Germany has decided to close its two older nuclear power stations and suspended plans to extend the life of its remaining plants. Italy shelved plans to build new nuclear power plants.

Nevertheless, factors such as geopolitical uncertainty in the Middle East have helped drive oil prices significantly higher. These conflicting and confusing factors seem to point to significant opportunity for photovoltaics.

OPPORTUNITIES

Flexible thin-film solar cells on plastic film have enormous potential. New applications will take advantage of their attributes of being lightweight and flexible. Applications include solar cells on T-shirts and jackets, modules on cars, boats and light aircraft, mobile and camping energy and novel toys like LED night kites. Since these materials can be tailored to shapes, architectural drapes and roof and wall coatings are all practical. See OE-A roadmap in figure 11-38.

BATTERIES/ENERGY STORAGE

A complementary and compatible energy technology to flexible solar cells is thin flexible batteries made in similar ways to CIGS thin-film PVdevices. There are electrodes in the battery, but instead of generating electricity, electrolytes will store electricity. Zinc manganese dioxide (ZnMnO2) is a typical electrolyte, as is lithium-ion (Li-ion).

The novelty of these inexpensive batteries is that they can be eco-friendly, single-use and disposable without causing pollution, releasing any toxic compounds or combusting. They can be used in innovations such as cosmetic teeth whitening,

Figure 11-26: Uses for thin, flexible batteries.

anti-aging electric wrinkle care and moisturizing, electrophoresis hair removal, RFID, toys and even medicine delivery.

Thin flexible batteries can be made out of simple paper (as thin as 0.6mm) using a spacer that is made largely of cellulose and printed with carbon nanotubes with electrolytes that are soaked into the paper. The batteries are available in 1.5, 3, 4.5 and 6 volts at 4.5 mAh/cm2 and weigh less than a gram. These batteries can have a shelf life of three years and will operate at temperatures ranging from -20°C to +60°C. These green batteries are produced by screen printing, disposable and free of toxic chemicals. They cannot overheat, explode or cause burns and are non-toxic and non-flammable. Power Paper of Israel has perfected this technology. Other companies producing thin flexible batteries include SeriCore and mPhaseTechnology

The most exciting of these new developments is from Planar Energy, a spin-off of the US National Renewable Energy Center in Colorado. Their solid-state nanofilm electrolysis

technology produces conductivity metrics equivalent to liquid electrolytes with three times the energy density of current Li-ion batteries and cost less than half the price per kilowatt hour. Their roll-to-roll deposition process is called SPEED (Streaming Protocol for Electroless Electrochemical Deposition). Thin-film nanomaterials are deposited sequentially on the flexible substrate, resulting in lower costs and increased control compared to vacuum deposition.

DISPLAYS

Low cost e-paper and other PE displays continue to be a major research focus. In addition to OLED technology on flex, there is also electrophoretic, electrochromic and electroluminescent displays. OLED displays are used in mobile phones. They use Universal Display's phosphorescent red, green and blue OLED materials, which have been proven to significantly reduce power consumption in numerous glass-based AMOLED products. The displays use an active matrix array of thin-film transistors fabricated on DuPont Teijin Films Teonex® film using substrate handling and processing technologies developed

Figure 11-27: Flexible PE Displays allow better form-factors.

at the Flexible Display Center (FDC) at Arizona State University. Versions using transistors made with both low-temperature amorphous silicon and higher performance indium gallium-zinc-oxide have been produced. “The combined effort with Universal Display and our other industry partners to successfully produce flexible, full-color AMOLED displays validates our bond/de-bond manufacturing technology,” said Nick Colaneri, Director of the FDC. “The display industry is actively evaluating a variety of approaches to handling flexible plastic substrates in conventional manufacturing equipment, which is a critical step towards enabling the mass production of flexible displays. The FDC’s bond/de-bond process with reusable carriers adds minimal incremental cost, allows the use of a variety of high-performance plastic substrate materials, and has been proven up to Gen II scale at the FDC’s pilot line, making it a leading candidate production technique as flexible electronics continue to evolve.”

Figure 11-28: Color OLED displays will come soon. Black and white is already available.

It was previously thought that amorphous silicon backplanes were unsuitable for OLED due to stability problems. However, Ignis Innovation has solved the stability problems, paving the way for this first product. "The performance is equivalent to polysilicon AMOLED. The product also incorporates Ignis's latest all-in-one driver chip for amorphous silicon AMOLED, which is the first of its kind in today's AMOLED market." says Paul Arsenault, president and CEO. "This opens the door for RiTdisplay and other manufacturers to make state-of-the-art AMOLED displays using existing amorphous silicon equipment that is currently being used for LCD. This is the start of a new era where AMOLED displays can be made in much greater volumes, and with lower cost, than they are today with polysilicon."

Ignis Innovation is the leading provider of technology that makes AMOLED displays last longer, look better and cost less. Ignis works with display manufacturers to improve AMOLED displays using innovative circuit designs, driving algorithms and embedded software.

RiTdisplay, established in 2000, is the first company in Taiwan devoted in OLED research and development and manufacturing. It is currently the only company capable of manufacturing both OLED and polymer light-emitting diode (PLED) products. By adopting a customer-oriented marketing strategy together with the most advanced technology capability, RiTdisplay offers the most advanced display products to meet the demand in a variety of applications

The different OLED manufacturing process lends itself to several advantages over flat-panel displays made with LCD technology.

Lower cost in the future: OLEDs can be printed onto any suitable substrate by an inkjet printer or even by screen printing, theoretically making them cheaper to produce than LCD or plasma displays. However, fabrication of the

OLED substrate is more costly than that of a TFT LCD, until mass production methods lower cost through scalability. Roll-to-roll vapor deposition methods for organic devices allow mass production of thousands of devices per minute for minimal cost. However, this technique can induce problems due to the challenges associated with manufacturing multi-layer devices.

Lightweight, flexible plastic substrates: OLED displays can be fabricated on flexible plastic substrates leading to the possibility of flexible organic light-emitting diodes in other new applications such as roll-up displays embedded in fabrics or clothing. Since substrates such as PET can be flexible, the displays may be produced inexpensively.

Wider viewing angles and improved brightness: OLEDs can enable a greater artificial contrast ratio (dynamic range and static, measured in purely dark conditions) and viewing angle compared to LCDs because OLED pixels directly emit light. OLED pixel colors appear correct and unshifted, even as the viewing angle approaches 90° from normal.

Better power efficiency: LCDs filter the light emitted from a backlight, allowing a small fraction of light through so they cannot show true black, while an inactive OLED element does not produce light or consume power.

Response time: OLEDs can also have faster response times than standard LCD screens. Whereas LCD displays are capable of response times between 2 milliseconds and 8 milliseconds, offering a frame rate of +/-200 Hz, an OLED can theoretically have a response time of less than 0.01 milliseconds, enabling 100,000 Hz refresh rates.

Many startups are involved in OLED displays. Universal Display Corp (UDC) is currently the only company purely focused on OLED display, but other OLED companies include Merck, Sumitomo, LG, Samsung, Philips, TDK and Osram.

LIGHTING

Similar to display technology, OLED technology on flex and electrophoretic, electrochromic and electroluminescent display panels can create low power lighting. These panels can be flexible, foldable and built to include PE battery storage and PE PV to create electricity, resulting in a multi-tiered device to generate electricity, store electricity and provide low energy solid-state lighting.

The history of lighting technology efficiency can be seen in figure 11-29 . Incandescent lights have not changed much since Edison's time, but solid-state lighting (SSL) using LEDs and OLEDs has improved significantly since 2000 to nearly 200 lumens per watt projected for 2018, nearly nine times more efficient. SSL will be the "green illumination of the future," since it has progressed from less than 100 lumens per watt (lm/W) today to nearly 200 lm/W for only $10 per kilo-lumens (klm) in 2018.

Figure 11-29: History of lighting technology efficiency.

Figure 11-30: Various examples of electrophosphorescent (EP) and OLED lighting, including portable lighting for military tents.

INTEGRATED DEVICES/RFID/ANTENNAS

Radio frequency identification (RFID) is a technology that uses communication with radio waves to exchange data between a reader and an electronic tag attached to an object for identification and tracking.

It is possible that in the near future, RFID technology will continue to proliferate in our daily lives the way bar code technology did over the forty years leading up to the turn of the 21st century, bringing unobtrusive but remarkable changes when it was new.

RFID makes it possible to give each product in a grocery store its own unique identifying number and to provide assets, people, work in process, medical devices, etc., all with individual unique identifiers. RFID is like a license plate on a car, but can be used for every item in the world. RFID is a vast improvement over paper and pencil tracking or bar code tracking that has been used since the 1970s. With bar codes, for example, it is only possible to identify the brand and type of package in a grocery store. Passive RFID tags (those without a battery) can be read if passed within close enough proximity to an RFID reader. It is not necessary to show the tag to the reader

Figure 11-31: RFID technology.

device like showing a bar code to a bar code scanner. In other words, it does not require line of sight to see an RFID tag. The tag can be read from inside a case, carton, box or other container, and unlike barcodes, RFID tags can be read hundreds at a time. Bar codes can only be read one at a time.

Some RFID tags can be read from several meters away and beyond the line of sight of the reader. Bulk reading enables an almost parallel reading of tags. RFID involves hardware known as interrogators (also known as readers), tags (also known as labels) and RFID software or middleware.

Most RFID tags contain at least two parts:

- integrated circuit for storing and processing information, modulating and demodulating a radio frequency (RF) signal and other specialized functions
- antenna for receiving and transmitting the signal

RFID can be either passive (using no battery), active (with an on-board battery that always broadcasts or beacons its signal) or battery-assisted passive (BAP), which has a small battery on board that is activated in the presence of an RFID reader. In 2011, passive tags start at $.05 each and can go as high as $5 for special tags meant to be mounted on metal or withstand

gamma sterilization. Active tags for tracking containers and medical assets or monitoring environmental conditions in data centers start at $50 and can go up to over $100 each. BAP tags are in the $3 to $10 range and have the capability of sensing temperature and humidity. (See OE-A roadmap in figure 11-37.)

SENSORS / MEDICAL / APPLIANCES

There are other RFID-like sensors that are inexpensive or disposable, especially for medical/patient monitoring. Biometric data like temperature, blood pressure, blood oxygen and electrical measures (EKG/ECG) can be measured and utilized for laboratory or patient monitoring. When matched with display technology, simple medical appliances can be created at low cost (figure 11-32).

The market for low-cost, disposable sensors can be quite large. Environmental, safety, energy, medical, communication, personal safety and identification are just some of the potential applications.

Figure 11-32: RFID in medical applications.

Figure 11-33: PE sensors in toys and novelties.

TOYS/NOVELTIES

Toys are a natural for PE. Simple circuits using PE sensors and batteries can be manufactured at low cost and placed into toys or novelties like singing or speaking greeting cards. A simple flash memory IC is attached like an RFID. PE printed memory and OLED displays are possible, with PV for battery charging. Adding sensors makes various forms of human interaction possible.

WEARABLE AND FASHION

The next PE application will surely be fashion and clothing. PE will offer the opportunity to customize clothing, colors and fashions, and can even incorporate messages utilizing PE energy collection, storage and display. It is even possible to preprogram fashions and patterns in small cards to allow users to purchase an item and customize it, like customizing ring tones for mobile phones. Implementation can be achieved by embedding PE devices on a garment (fig. 11-34 right) or by using OLED coatings on yarn to be woven. Glass fiber light pipes

Figure 11-34: Wearable applications for PE.

that bring the display from a more convenient location are also possible.

SIGNAGE AND ADVERTISING

As the cost of PE displays come down, they will appear in magazines, signs and advertising. The October 2010 copy of Esquire magazine had an e-paper active matrix display printed

Figure 11-35: Signage and advertising.

onto its cover. More and more, because of its color and motion, PE temporary and disposable displays will play a role in attracting customers.

INFORMATION MEMORY

PE memory is never going to approach the scale or size of semiconductor memory. However, there will be requirements for smaller, simpler memory for displays, sensors, medical toys and clothing. Thin Film (Oslo, Norway) said that 40-bit passive memory arrays are in test production, and engineering samples will be available in late 2011. A 121-bit memory array is planned for production in 2012. It is aimed at ticketing, archiving and other applications that can use encryption for user-programmed stored identification. Thin Film projects prototypes for addressable memory in 2011 and the transfer of 128-bit memory to production in 2012, aimed at ID tags, sensor tags, disposable price labels and other smart labels. Thin film typically works with ferroelectric polythiophene active layers such as poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT-PSS).

Figure 11-36: Thin Film of Oslo, Norway is a big supplier of PE memory array technologies.

Figure 11-37: OE-A roadmaps give a best guess on how rapidly the PE market will develop.

THE FUTURE

The coming generation of printed electronics, printed circuits and advanced integrated printed circuits appears to be headed down a path which is both familiar and new. Although the concept of printing both rigid and flexible circuits has a long history, those who pioneered early solutions would be amazed to see the developments currently underway. Similarly, those engaged in the current effort to expand the horizons of flexible printed electronics will be amazed at the technologies that will build on what is happening at this moment. Printing technology, beginning with Gutenberg's invention, has altered the course of human history by making knowledge more

accessible to more people. The coming generation of printed electronics will build on and advance Gutenberg's efforts to create and provide printed products that improve the spread of knowledge and information using new products. Printed electronic readers and displays, made possible by recent and developing technologies, will facilitate the expansion of global education more cost-effectively than paper books. Whether one of the technologies mentioned or technologies yet to be developed will dominate the future of printed electronics is an open question. What is a bit more certain is that flexible base materials printed using printed electronics solutions and processed in roll-to-roll fashion will be an element of successful future technologies. Practical industrial printing solutions that are currently evolving or yet unimagined make the future of printed electronics an exciting mystery. **FCT**

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Chapter 12

Solderless Assembly Processes for Flexible Circuits

Joseph Fjelstad, ***Verdant Electronics***

INTRODUCTION

Flexible circuits have proven themselves as a method of choice for an increasing number of electronic product designs and the reasons have been recounted both in this text and other texts on the subject many times. The list of benefits is long and benefits such as design freedom, light weight, reduced size and improved electrical performance are just a few of many advantages. While flexible circuits continue to be used to make simple electrical connections as they have since their inception, they are increasingly being used to make much more complex electronic assemblies, especially for handheld electronic products such as cell phones, PDAs and current and future generations of smart phones and tables. Such assemblies routinely involve the placement and interconnection of surface mount devices using solder to make the interconnection. In fact, researchers in the nascent surface mount industry observed that flexible circuits offered a more reliable platform for surface mounted devices because the flexible substrate had a low modulus of elasticity, which reduced the strain on solder joints during the thermal excursions associated with use. This was an important observation for the industry since it not only offered a pathway to making reliable surface mount interconnections, but it also reinforced the concept that interconnection compliance—either from the substrate or the

leads—was a vital, even critical, concern for product reliability.

It is not the case that reliable interconnections could not be achieved without flexible circuits, because through-hole leaded components had already made the case. However, developers were faced with the daunting task of addressing assembly concerns that come with miniscule area array leaded components and substrates with significant mismatches in terms of their differing coefficients of thermal expansion (CTE). Some researchers, most notably at IBM, proved that the use of an underfill between the component and the substrate could also protect the solder joint interconnections (fig. 12-1).

Most reliability studies and the legacy knowledge base have their foundations in tin-lead solder, which was the primary method for connecting electronic components to printed circuits since the electronics industry's early days. Over the last sixty years, tin-lead solder proved itself a viable and valuable assembly method. Over that time span, the industry also developed a deep understanding of the solder technology that was hard-won through years of practice. However, as of July 2006, the European Union officially banned the use of lead in

Figure 12-1: A highly exaggerated FEA strain map shows greatest strain on corner solder termination and illustrates the need to strain relieve area array devices with underfill.

electronic solder under its Restriction of Hazardous Substances (RoHS) legislation, based on the misguided assumption that lead in electronic solder represented a general health risk to human populations, an assumption that was never proven by the scientific method. There have been individuals in poor areas of China and India who have suffered the effects of lead poisoning due to unregulated and uncontrolled recycling of electronic waste products by uneducated, unskilled peoples without adequate protection. However, this is largely the result of greed and poor waste management, not an intrinsic problem with traditional solders if their waste is properly managed. If the materials had been relegated to a landfill or recycled by a proper facility, scientific evidence indicates that no one would have been harmed.

Unfortunately, this new era of lead-free solder has resulted in a host of new problems for the electronics industry, many of which were not experienced when elemental lead was included in the solder alloy. This is especially true for tin whiskers which NASA scientist and engineers blame for a number of satellite failures. Chapter 9 – Flex Circuit Manufacturing Processes provides more detail on the problem of tin whiskers.

Today, electronics assembly technology literature is replete with articles and papers citing the problems and challenges of lead-free assembly and proposing new or improved solutions or investigative tools that might better serve to unearth the problems of lead-free soldering. No perfect solution has surfaced and concerns about long-term reliability of lead-free solder remain unanswered. However, anecdotal evidence from warranty providers indicates a rise in product returns, which, perhaps just coincidentally, followed the introduction and use of lead-free solder on a broader scale.

The lead sanction has created a challenge of significant proportions for the electronics manufacturing industry in terms of meeting the cost and reliability demands of OEMs

while complying with RoHS. For example, the production of lead-free electronics requires the exposure of electronic circuits and components to much higher assembly temperatures (e.g., 30°C to 40°C higher) than the temperatures required for printed circuit assemblies with traditional tin-lead solder. Considering that the vapor pressure of entrapped moisture roughly doubles with such a temperature rise, it is not surprising that the occurrence of popcorning of components has increased. A recent suggestion that the number of moisture sensitivity levels (MSL) be increased does nothing to address the underlying problem. Moreover, due to the greater complexity of modern electronic assemblies with two-sided assembly and stacked components, such high temperature exposures might not take place just once, but several times.

Unfortunately, as reliability engineers well know, exposure of electronics to higher temperatures degrades component reliability. The negative effects are not limited to integrated circuits. The damaging effects of the higher lead-free solder temperatures on optoelectronic components and certain types of discrete components, such as larger capacitors, have also been identified as concerns. Moreover, the use of excess energy not only degrades reliability and shortens IC life, It also wastes energy.

Concerns have also arisen about the increasingly extensive use of tin plating as a termination finish, which is reopening the door to the problem of tin whiskers mentioned earlier. With component lead pitch shrinking to below 0.5mm and tin whiskers capable of growing to lengths of 10mm to 12mm, and even longer, concerns about the recurrence of whisker risk are justifiably elevated.

It is a simple fact of life that global sourcing and supply-chain expansion has greatly increased the distance between electronic product designers and their suppliers. The result is a reduction in vital resources and support for domestic technol-

ogy development in many developed nations in Europe and North America, which could result in supply-line vulnerability in troubled times. The massive earthquake and tsunami of 2011 that devastated parts of Japan provided ample evidence to support this concern.

In this environment, a new approach to manufacturing all types of electronic assemblies, including flexible circuits, without the use of solder and new solder alloy-free electronics (SAFE) is now in development. The new process has come to be known as the Occam Process, so named to honor the 14th century English philosopher and logician, William of Occam, whose rigorous thinking and arguments in favor of finding the simplest possible solution serves as the inspiration and catalyst for the new approach.

SOLDERLESS ASSEMBLY PROCESS BASICS

Given the extensive list of challenges and concerns just reviewed, a new method for fabricating circuit assemblies has been disclosed that sidesteps all of the problems created by the lead-free solder directive. The new method is, in the most basic sense, a reverse of standard assembly. in The electronic components are placed first and then provided with interconnections by plating up the circuit patterns and making connections to the component terminals. There is, however, one important twist. The new approach does not employ any solder at all. With this simple change, the process does not subject the flexible circuit or other vulnerable components of the electronic assembly to the temperatures of 250°C to 260°C (and sometimes higher) that are required to assemble with popular and more expensive SAC alloys, which have become de facto standards for assembly. Lower temperature lead-free alloys are available but tend to require more exotic and expensive alloying elements. With solder alloy-free electronics (SAFE), there is also no real concern about moisture sensitivity since compo-

nents are not exposed to soldering temperatures. In addition, concerns about flux removal from tiny spaces beneath components and between their leads are diminished because flux is not used. In addition, because the fully tested and burned-in components are completely encapsulated, the concerns of mechanical shock and thermal cycling reliability of connections are vastly reduced.

To understand the challenge and impact of solder, one can look to the literature. In 1999, Agilent Technologies engineer, Stig Oresjo, conducted a major study of solder joint defects on printed circuit boards. The study included 15 companies and more than 1 billion solder joints and the author concluded that although companies claimed defect levels in the range of 75 to 150 defects per million opportunities (DPMO), the reality was 5 to 10 times as high. An IPC presentation from the proceedings of a test conference with a slide reporting on the study offered the following defect distribution results:

- 41% Solder Opens
- 20% Shorts
- 20% Solder Quality
- 8% Placement
- 8% Electrical
- 3% Other

This information makes it evident that 80% of the problems of electronics assembly are related to soldering (90% if the 8% for placement is included). The 8% electrical problems, though not specific to solder, may result at least in part from solder temperatures, thus efforts to eliminate solder do arguably have merit.

There are certain approaches to creating soldered assemblies with embedded devices that can be used with traditional circuit board technologies (see the bottom cross-section in fig-

Figure 12-2: Cross-section of an embedded IC that was soldered to a PCB innerlayer before lamination. The finished board thickness is 1.6 mm. (Source: Hofmann Leiterplatten GmbH)

ure 12-2, which shows an embedded device soldered to a PCB innerlayer before lamination). However, more attractive assembly approaches in development at this time do not require either a separately fabricated printed circuit board or a soldering process. This fact allows the manufacturer to completely bypass issues related to certification and qualification of vendors and other RoHS-related concerns in supply chain management, which is often global in scope and includes inventory and storage management, preparation, certification and design modification.

SOLDERLESS ASSEMBLY PROCESS DETAIL

To better understand the solderless assembly process and its many benefits, it is valuable to have a good comprehension of traditional electronics manufacturing. Currently, the standard practice for the manufacture of a conventional electronic assembly includes the following familiar steps. Using surface mount technology (SMT) as a model:

- Create a schematic and components list
- Design, fabricate and test the PCB
- Delivered to the assembler
- Manufacture solder stencil
- Stencil solder paste onto the component

interconnection lands
- Place components accurately on the board, held in place temporarily by the paste
- Reflow the solder paste at soldering temperatures
- Clean the assembly to remove flux

The reflow process creates a permanent interconnection between the component leads and the PCB terminations.

This process works, but it is not perfect. Shorts and opens are often found on the electronic assembly and, on occasion, components are damaged by the high temperature excursions that are part of the assembly process. In fact, rework and repair are considered part of the normal manufacturing

Design PCB Assembly	Fabricate PCB (multilayer)	Assemble PCB
1) Create schematic 2) Indentify components 3) Layout circuits 4) Validate signal integrity 5) Validate design DfM 6) Validate design DfR 7) Validate design DfE	Verify RoHS compliance Cut core laminas to size & tool Clean and coat with resist Image and develop resist Etch and strip resist Treat exposed copper AOI or visual inspect layers Cut B-stage to size and tool Lay up core and B-stage Laminate X-ray inspect (optional) Drill (stack height varies) Desmear or etchback Sensitize holes Plate electroless copper Clean and coat with resist Image an develop resist Pattern plate copper Pattern plate metal resist Strip plating resist Etch base copper Clean and coat with soldermask Image and develop Treat exposed metal (options) Solder, NiAu, Sn, Ag, OSP, etc. Electrical test Route to shape Package Ship	Procure components Verify RoHS compliance Verify component solderability Verify component MSL number Kit components Procure PCBs Verify RoHS compliance Verify PCB solderability Verify PCB High Temp capability Design solder stencil & purchase Develop suitable reflow profile Track component exposure (MSL) (rebake components as required) Position PCB & stencil solder paste (monitor solder paste) Inspect solder paste results (height and skips) Dispense glue dots (optional) Place components Inspect for missing parts Reflow solder Repeat Steps 13-18 if two-sided assay (second set of fixtures required) Perform hand assembly as required (odd sized or temperature sensitive) Clean flux from surface and under (verify low standoff devices) Test cleanliness Underfill critical components X-ray inspect soldered assembly (shorts, opens, voids, missing) Electrically test Rework and repair as needed Package Ship

Table 12-1: Major process steps for basic surface mount assembly.

regimen and are often factored into the cost. A chart listing the basic processes used in traditional SMT assembly is provided in table 12-1.

In contrast, the solderless assembly process is fundamentally a reverse order interconnection process with some unique attributes. The process uses, for the most part, mature, low-risk, industry-familiar core processing technologies in a proven sequence. A key element and artifact of the process is that the electronic components are interconnected to one another by copper plating after they are assembled into their final positions, avoiding solder completely. An example of the basic Occam process is shown in figure 12-3

Design PCB Assembly	Fabricate PCB (multilayer)	Assemble PCB
Create schematic Indentify components Layout circuits Validate signal integrity Validate design DfM Validate design DfR Validate design DfE	Sensitize holes Plate electroless copper Clean and coat with resist Image an develop resist Pattern plate copper Pattern plate metal resist Strip plating resist Etch base copper Clean and coat with soldermask Image and develop Repeat as needed Treat exposed metal (options) Functional test Route to shape (if required) Package Ship	Procure components Place components Inspect for missing parts Perform hand assembly as required

Table 12-2: Process steps eliminating those made unnecessary by the Occam process.

Figure 12-3: The process steps for Occam are few, simple and eliminate the need for solder.

The new process approach first places components onto any one of several bases, including, but not limited to, a removable tacky film on a temporary base or a permanent base that uses a permanent adhesive. In either of these cases, the base temporarily immobilizes the components until the structure is encapsulated. At this point, the entire array of tested and burned-in components has become a monolithic assembly with all of the components now permanently locked into a predetermined place. The bottom surfaces of component terminations can then be exposed by removing the temporary base or carrier film or by making holes in the permanent base using a suitable method such as mechanical abrasion or laser ablation. (In the former case, a photoimageable film such as a photoimageable solder mask or photoimagable coverlayer could be applied, exposed and developed.) An interesting benefit of the technology is that it allows components to be assembled in an overlapped manner to further conserve space. While this is potentially possible with soldering, it would be highly challenging.

The major process steps for basic surface mount assembly

are enumerated in table 12-1, although there are some overlapping and repeated activities. There are often many sub-steps and checks for each of these steps. Please note that higher density, buildup-type PCBs commonly require multiple image and plating steps. Note also that a number of the process steps used in placing balls on BGA parts and verification steps are bypassed along with the thermal excursion of joining them to the package (along with the cost savings of eliminating the solder ball from the devices, which will reduce device height by as much as 50%). The steps associated with the manufacture of the BGA are not included in this accounting, but they do have an impact.

As illustrated in table 12-2, the Occam process can eliminate many process steps, including some of the most challenging related to the soldering process such as controlling and stenciling solder paste, reflowing components and assemblies at high temperatures, cleaning the microscopic gap beneath parts, etc. It can also eliminate rework and repair, which are often consider normal parts of traditional assembly processing due to the accepted inefficiencies of the soldering process. Note that verification of ROHS compliance has been eliminated since the Occam process can be an all-copper interconnect solution for both components by eliminating the need for increasingly expensive solderable finishes and the printed circuit board used for assembly for the same reason.

All the connections to the component terminations are created by the copper-plating step that establishes the interconnections to the exposed surfaces of the terminations (which are normally made of copper) across the encapsulated module's surface. At this point, circuit patterns can be created and additional layers of insulation and circuits can be added as necessary until all required connections are made. The interconnections can even be redesigned up to the moment they are made and no high aspect-ratio via drilling is required.

Methods similar to this have been used to create multichip modules and packages that were destined for soldering to a printed wiring board in the past.

It is also possible to interconnect the assembly by co-laminating circuit layers to the encapsulated component assembly block (fig. 12-4). Such methods have been investigated, developed and/or used by such companies as Tessera, Matsushita and Toshiba. The latter two have used these methods to produce multilayer circuits for such products as cell phones (see Chapter 9 – Flex Circuit Manufacturing Processes). Assemblies of this type should be relatively low in cost and readily adaptable to integrating thermal enhancements such as internal head spreaders or even heat pipes, EMI shielding, embedded electrical and optical components, and more.

The final circuit layer can be connected to whatever user interfaces, displays and power connections are required for operation, provided that connectors are used. The assembly can be coated with a conformal or rigid protective insulator layer. Moreover, when two layers of components are required, they can be stacked and joined back-to-back with a central sup-

Figure 12-4: Once components are secured in place, interconnection can be made in a number of different ways such as discrete wiring and lamination with programmed or anisotropic bond layers. Direct writing techniques (not shown) are also possible.

port, which could include various heat spreader constructions. More advanced structures are then possible and stacking and interconnection of assemblies from one side to the other can be accomplished by interconnection pins inside the assembly, either individually or in groups and arrays. Edge connections can be created that allow for stair-stepped interconnections. The potential of these structures appears to be limited more by imagination than physics. If desired, interconnection between sides can be augmented by various connector structures or flex circuits as well. While it is not possible to provide images of all of the potential thermal management solutions, optical interconnect alternatives, EMI and ESD protection methods, connectors, second-side and odd-form enhancements that are achievable, it is expected that there will be many such offerings appearing as the technology moves into more complex applications.

It is worth repeating here for emphasis that because the Occam process does not expose the assembly to the high temperatures needed for reflow soldering of lead-free solder, component moisture sensitivity level (MSL), which is a measure of the risk of component damage due to absorbed moisture in the package during soldering devised by the Joint Electronic Device Council (JEDEC), is essentially obviated as a concern. Moreover, while traditional tin-lead solder processing is limited to a maximum temperature of 220°C, SAC alloys approach 260°C and the vapor pressure of water more than doubles over this temperature change (Engelmaier) and component damage due to explosive outgassing of absorbed moisture in the package during soldering ceases to be a concern. All components can be treated as if they were MSL-1, which means that they do not require dry storage, special handling or accurate hold-time recordkeeping in normal environments. The process also allows use of components that are not capable of withstanding lead-free soldering temperatures, including aluminum electro-

Figure 12-5: Assemblies can be interconnected in edge card fashion or in planar fashion using mezzanine interconnections as shown above. Note also that optical channels are possible using this method.

lytic capacitors, optoelectronic devices, some connector types, etc. In addition, and also repeated here for emphasis, because no high-temperature soldering is required, heat spreaders, heat sinks or even heat pipes can be embedded directly into or made an integral part of the assembly (fig. 12-5).

DESIGN AND ROUTING ADVANTAGES OF SOLDERLESS ASSEMBLY STRUCTURES

The solderless assembly process is not completely different from standard assembly; only the order of manufacture is re-

versed. Like a standard printed wiring board, the interconnect structure still must be designed and fabricated. However, with the Occam process, several design constraints are relaxed. For example, there is no need for large component pads or lands for soldering, making simplified routing for area array possible. This feature allows a higher circuit density, a potential reduction in the number of layers required for the design and a lower profile assembly as shown in figure 12-6. Moreover, there is no need for drilling high-aspect-ratio vias all the way through the assembly since special structures have been anticipated to address the need when faced.

Routing advantages in circuits where solder is avoided are significant. In figure 12-6, using the same device and circuit feature sizes (0.5mm pitch device and 50 micron line and space features in the example), there is a nearly 70% increase in routing possible and a reduction by half the number of layers required. Moreover, as illustrated in the cross-section views,

Figure 12-6: Potential reduction in the number of layers required for the design and a lower profile assembly using Occam process.

a significantly thinner assembly is possible since solder often contributes half of the height of an area array component. Additionally, there is never a concern about solder shorts, opens, voids, pillow heading or tin whiskers when solder is not used for making interconnection.

The new approach to design and manufacture is amenable to implementation using the interconnected mesh power system (IMPS) design approach developed at the University of Arkansas by Professor Len Schaper and his colleagues in the 1990s. In the design process with IMPS, a design starts with a grid of power and ground conductors that are three times the

Figure 12-7: The use of a fundamental grid pitch offers predictability in routing and the ability to create dense interconnection systems that do not require high layer counts. Above are illustrated examples of IMPS structures for both coarse and fine grids and a variant called Power Grid developed at HP. (Image courtesy of Happy Holden)

width of a minimum width signal conductor and separated by the minimum space. Signal conductors are then routed through the spaces of the mesh with the power and ground narrowed to accommodate them.

While IMPS structures were originally designed with IC chip modules in mind, the concepts are applicable to higher-level interconnections as well. Hewlett-Packard, for example, worked on a similar concept called Power Mesh. It was developed for the coarser features that are found on standard PCBs, and the Power Mesh structures use full metal ground planes (fig. 12-7). (Holden 2000) The mesh is never broken or disconnected. All of the signal conductors are coplanar transmission lines referenced to both power and ground and the reference is preserved when the signal goes from X to Y. Crosstalk is very low because there is always an AC ground conductor between every pair of signal conductors. The initial mesh establishes the allowed signal tracks. Any EDA router can be used to lay out the signal wiring in the channels. A design rule check is used to impose minimum clearance on the power and ground to narrow traces as required.

The general design method has been shown to be capable of significant layer reductions compared to traditional design approaches (e.g., from 8 layers down to 4 layers or even 2 layers), while offering lower noise and lower crosstalk based on measurements. (Schaper, Glover and Kabumoto) These innovative wiring architectures can replace many layers of conventional through-hole wiring. When coupled with Occam-type processing to create a direct HDI interconnection to component terminations without the need for soldering, the combination could support requirements for I/O connections up into the hundreds of I/O per cm. (Holden 2007b) An analysis of the relative cost of various multilayer circuit constructions and the I/O density capability is provided in figure 12-8. The table reveals that, when compared to a standard 8-layer plated

N Layers	A THRU-HOLE N blind via* buried via		B HDI BLIND 1+N+1 L1-L2 none		C HDI BL/BU 1+bN+1 L1-L2 L2-L(N-1)		D 1BU BLIND 1+N+1 skip via L1-L3 L2-L(N-1)		E 2BU BLIND 2+N+2 staggered L1-L2, L2-L none		F 2BU BL.BU 2+bN+2 skip via L1-L3 L2-L(N-1)		G 2BU BL.BU 2+bN+2 staggered L1-L2, L2-L L3-L(N-2)		OCCAM 4BU: BL.BU 2+2 AIL/VH	
	RCI	DEN	RCI	DEN	RCI	DEN	RCI	DEN	RCI	DEN	RCI	DEN	RCI	DEN	RCI	DEN
4L	0.62	20	0.83	40	1.05	80	1.26	135	1.38	135	--	--	--	--	0.60	800
6L	0.78	20	0.99	60	1.24	160	1.46	200	1.60	200	1.74	260	1.91	280	0.90	1250
8L	1.00	30	1.21	120	1.49	180	1.74	240	1.90	240	2.06	300	2.25	320	1.15	2500
10L	1.30	40	1.51	200	1.83	210	2.11	260	2.30	260	2.50	400	2.73	440		
12L	1.70	60	1.92	210	2.31	230	2.62	300	2.85	300	3.10	600	3.37	650		
14L	2.24	70	2.48	220	2.95	250	3.32	360	3.61	360	3.91	800	4.25	860		
16L	2.97	80	3.22	260	3.81	300	4.25	420	4.61	420	5.00	1000	5.43	1100		
18L	3.92	100	4.21	300	4.95	400	5.47	480	5.93	480	6.42	1250	6.96	1350		
20L	5.14	105	5.48	360	6.41	500	7.04		7.62		8.23		8.90			
22L	6.67	110	7.08	400	8.23	600	8.99		9.70		10.45		11.27			
24L	8.53	125	9.03	460	10.41	700	11.32		12.17		13.07		14.04			
26L	10.68	130	11.30	500	12.92		13.96		14.96		16.00		17.11			
28L	13.09	135	13.83	540	15.65		16.82		17.93		19.09		20.32			
30L	15.63	140	16.50	580	18.47		19.73		20.94		22.18		23.48			
32L	18.17	145	19.17	620	21.21		22.53		23.79							
34L	20.59	150	21.69	660	23.73		25.09									
36L	22.79	160	23.96	700	25.94											
38L	24.68	180	25.91	740												
40L	26.26	200														

Figure 12-8: Relative cost of various multilayer circuit constructions and their I/O support capability. (Data and graphic courtesy of Happy Holden)

through-hole construction with a relative cost of 1.0 and I/O density of 30 pins per square inch, an Occam buildup structure is potentially capable of replacing up to an 18-layer board while providing 2500 I/O and maintaining a relative cost of 1.15. (Holden 2007a)

SOLDERLESS ASSEMBLY REVIEW

The nontraditional approach to electronics manufacturing that has been described portends the elimination of solder from the electronics assembly process. However, the idea of eliminating solder is not completely new. Previously proposed means to eliminate solder, such as by using conductive adhesives, have not been accepted by the market for various cost, performance and reliability reasons.

Lead-free solder is, according to a recent EPA study, actually less environmentally friendly than standard tin-lead solder assembly technology. In the process, it has caused the electronic

manufacturing industry to spend billions of dollars unnecessarily on new equipment to develop new materials and methods to meet the EU's RoHS requirements. Realizing this dismal situation, a number of household-name companies around the globe have begun to develop processes and manufacture prototypes using solderless assembly and interconnection methods. Some forward-thinking PCB manufacturers and EMS assemblers are on the path to learning more about each others' processes and how to adapt and integrate each others' technologies into their own manufacturing processes.

In the end, the elimination of (or the integration of) printed circuit board manufacture directly into assembly avoids many of the less obvious costs such as supply-chain management (e.g., vendor qualification, lead-times, incoming QC) testing, inventory management, protective storage, bake-out and additional shipping and handling. Also, because the interconnection is not created until after assembly, the design can be modified as needed with no necessity for drills, fills and jumper wires. This is graphically evident in table 12-2 when compared to Table 12-1. Finally, it is anticipated that the finished product will be totally encapsulated with a tough and properly CTE-matched epoxy or other material and will be quite rugged because the solder joint (which is the most commonly identified failing element of failure, rework and repair) is eliminated.

FLEX CIRCUIT ASSEMBLIES WITHOUT SOLDER

While most of the discussion of solderless assembly process in this chapter has been focused on the manufacture of replacements for traditional rigid printed circuits, the technology can also be applied to flexible substrates, accessing the many important attributes and capabilities that flexible circuits offer, while adding the benefits of solder elimination. One of the significant potential benefits is the opportunity to use a

wider range of new materials. For example, polyester materials have some very attractive properties and significant cost advantages over flex materials such as polyimide. Polyester is very low in moisture uptake, making it a more stable dielectric for controlled impedance applications. It is also a reasonably tough film suited to dynamic flexing. However, one of the things that has held this useful polymer back is that it cannot be easily soldered with tin-lead solder and is essentially impossible to solder with higher temperature lead-free solders since the material will shrink and distort like a potato chip. With the Occam process, temperatures in the range of soldering are never experienced, which improves the prospects for the expanded use of polyester. There are other advantages, but for the sake of brevity, let's take a look at one prospective process for creating solderless flex circuit assemblies.

One of the cardinal rules of flex circuit assembly, discussed in more detail in Chapter 7 – Practical Design Guidelines for Flex and Chapter 10 – Flexible Circuit Assembly, is to support the components. This requirement normally implies the need for a stiffener beneath the components. When building Occam process types of flexible circuits, the manufacturer is still required to support the components, but from the top by means of an encapsulation rather than from the bottom as is the norm. A basic process for an all-SMT device Occam type flex assembly is as follows:

1) Place components securely in place (e.g., adhesively bond them to a flexible film)
2) Encapsulate the components, leaving the areas designed to be flexible open
3) Place assembly on optional carrier
4) Access component terminations using a laser or chemical polymer etching process

Figure 12-9: The Occam Process applied to flexible circuits offers some unique design and assembly possibilities.

5) Copper plate blind via connections to the component contacts
6) Plate and etch circuit patterns
7) Apply coverlayer

Figure 12-9 shows these steps graphically. This is a highly abbreviated description, but those familiar with flexible circuits will understand.

MONOLITHIC SOLDERLESS FLEXIBLE CIRCUIT ASSEMBLY

There are alternative approaches to creating solderless flexible circuit assemblies. One example is to bond a piece of flexible film or cast a thin flexible film onto components that are embedded in a precast structure. Access to the component leads is accomplished using any suitable controlled-depth feature-access process, such as laser, plasma, chemical polymer etching or similar method. A significant benefit of these types of structures is that they obviate the need for stiffeners for component support since they are embedded in and integral with the assembly. However, perhaps even more interesting is that it appears feasible that the encapsulation of the components and film could be produced in a single step by using a suitable injection moldable thermoplastic material, thus creating a monolithic flexible circuit assembly. Such approaches, when fully developed, could significantly simplify the fabrication process by providing a uniform base onto which the circuits can be built up to complete the assembly.

Injection molding allows for monolithic assembly and the integration of component stiffener and flexible interconnections according to the following plan:

1) Place components in mold
2) Clamp mold
3) Injection mold components in situ including strain reliefs
4) Remove from mold
5) Form metal circuits and coat with insulator material
6) Form to desired shape.

Although abbreviated, the process steps shown are representative of processing possibilities. figure 12-10 illustrates the fundamental elements of the process for creating this type of monolithic flexible circuit assembly without solder.

Figure 12-10: Fundamental elements of the process for creating this type of monolithic flexible circuit assembly without solder.

Another interesting approach to making a monolithic solderless rigid flex type assembly is predicated on making a rigid board into a flexible assembly. The general method has been a part of the mechanical engineer's tool box for many years. In general, it is required that the assembly be thinned in the areas where a degree of flexibility or formability is required. In this way, all of the handling issues generally associated with flexible circuit manufacture are obviated. The circuit manufacture makes a rigid Occam assembly and then removes material in

the areas where they wish for the circuit to flex or bend. The process is illustrated in figure 12-11. The steps, in sequence starting in the upper left corner of the figure, are:

1) Place components on a temporary or permanent carrier (temporary version shown in the figure)
2) Encapsulate and remove from the carrier
3) Apply a flexible film or coating to the component contact surface to create access to component terminations
4) Metalize, image and plate circuits as required
5) Provided with a top flexible film or coating

Final steps include a functional test and removal of materials from areas to be flexed.

Although there are process details missing, it should be clear that the total number of processing steps is significantly less than the number of steps required using more traditional manufacturing methods that involve the manufacture of the

Figure 12-11: Simplified process for fabricating solderless flex circuit assemblies having encapsulated components. (Note: The structure and process shown are patent pending)

flex or rigid flex circuit followed by solder assembly. The method offers significant time and cost savings as well as worry-free compliance with RoHS requirements because copper can be the only metal used aside from any separable contact surfaces, such as nickel-gold, that might be required. Moreover, there are number of special techniques that can be used that are not possible using traditional manufacturing methods, including the integration of thermal management solutions such as heat spreaders. The final assembly can then be folded into a compact assembly or formed to fit easily into the desired shape. There are many other possibilities.

METAL RIGID FLEX SOLDERLESS ASSEMBLY

A final example of a solderless rigid flex assembly is one that is perhaps ideal for circuit assemblies that must be ruggedize for use in high temperature environments. The assembly is comprised of a metal (e.g., aluminum, brass, bronze) carrier, into (or onto) which are placed components that are ideally packaged but that may include bare die. The components can be placed on one or both sides. Layers of flexible insulation are applied to the metal sheet and the now all-rigid circuit is processed as if it were rigid. When all of the required interconnections and circuits are added, the assembly can be partially machined to thin the metal carrier sufficiently to allow the residual metal to easily bend. If left, the residual metal can serve as a ground layer for the assembly. If isolation is required or desired, the residual metal can be etched using chemistry appropriate for the metal used as a carrier. Alkaline chemistries such as dilute sodium hydroxide and sodium gluconate solutions are suitable for aluminum, but other chemistries such as ferric chloride are more universal in their potential application. There are many proprietary chemistries which can be used as well. The patent pending structure and process can be seen in figure 12-12.

Figure 12-12: Metal rigid flex solderless assembly process. (Note: Process and structure shown are patent pending)

In all of the processes described, attention should be given to instructions given in Chapter 7 – Practical Design Guidelines for Flex. Flex circuit design practices suggest that the number of circuit layers through the areas where flexing or bending is required should be limited to one or two metal layers. That aside, the processes described offer significant potential benefits for increased reliability and reduced overall cost.

SUMMARY

The continuing challenge of making lead-free solder work in electronic assembly has given rise to new ways of looking at circuit assembly and fabrication, methods that could eliminate solder and its myriad issues altogether. The improved approach to assembly offered by processes such as the Occam process give the OEM a new choice for producing products using a highly reliable and cost-effective approach to electronic assembly. An added and important benefit is that the product built

using the process will not only comply with RoHS requirements but will actually be far more environmentally friendly than solder-assembled products.

At the end of the day, change is really the only universal constant and the future is unknowable beyond the basic fact that it will be different from today. The concepts presented may or may not see use in products. However, it is believed that if adopted, the Occam process and/or prospective variations on it, will facilitate the manufacture of high-functionality electronics that are at once mechanically robust, highly reliable and environmentally friendly. What remains to be seen is how quickly the process can deliver on the potential that it promises.

Solderless flexible circuit assembly technology offers significant potential for the future. It will broaden the range of material options and significantly expand the horizon of electronic interconnection design. Once interconnection technologists and product designers begin to open-mindedly climb this new technology tree they will find branches that take them to many new types of processes, methods and structures that they would not have anticipated or seen before they began the climb. The examples described here are not likely to be the end, but only the beginning of this new and evolving realm of electronic assembly without solder. **FCT**

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THIRTEEN

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Chapter 13

Stretchable Circuits

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INTRODUCTION

Interest in stretchable circuits has grown steadily in the last few years propelled, at least in part, by the European Union's (EU) funding of research in the area through initiatives such as STELLA which ran from February 2006 to January 2010. There were eleven participants in the project representing the electronics industry, academia and research institutes located in four EU countries and funded to the tune of over €13 million, with €7 million contributed by the European Commission. That jump-start yielded a number of interesting demonstrators which will be discussed later in the chapter. The mixture of stretchable substrates and electronic components and circuits has resulted in the coining of the term elastronics, which seems appropriate given the description.

The stretching of circuits to alternately increase and decrease the length of a circuit has proven to be useful for electronic products and assemblies for many years. In the past, stretching has typically been accomplished by folding a flexible circuit in an accordion-like manner. This type of stretching is accomplished in an out-of-plane fashion (see Chapter 6 – Practical Design Guidelines for Flex) which contrasts with current efforts to stretch the circuit in-plane, potentially in all directions at once. The resilience of constructions of the type

Figure 13-1: Early version of a stretchable circuit.

(fig. 10-1) is limited since the metals used (normally copper) will tend to plastically deform. More springy metals will reduce this tendency, but there are a number of electro-mechanical trade-offs that must be considered which such choices. A number of applications over the years have successfully used this method, including drawers having electronics within them, which allows easier access for repairs, replacements or upgrades to the system.

While out-of-plane stretching of circuit constructions may be useful in many applications, they are of limited value in other applications which require the stretching of circuits with a low (i.e., thinner) profile. In response to the anticipated need for thin stretchable circuits, (i.e., stretchable in-plane), there is an evolving branch of electronic interconnections designed to resiliently interconnect electronic elements of every type, including: components, such as printed circuits, that have various electronic devices including integrated circuits, discrete devices such as capacitors and resistors, light-emitting components (e.g., LEDs) sensing devices that include micro-electromechanical systems (MEMS), etc. Applications being explored for use with and/or enabled by stretchable circuits range from apparel to medical monitoring and diagnostic equipment. These are typical applications where the use of conventional flat rigid assembled PCBs becomes problematic because there is a need to comfortably integrate the circuit

on a non-flat surface. Often wearable and implantable circuits (such as those for biomedical applications, sports and leisure, safety, etc.) require non-flat assemblies because the circuit must follow the irregular shapes of the part onto or into which the circuit is integrated. Ideally, the integration of the circuit should hamper the user's activities minimally, if at all. One option to achieve this degree of comfort is the profound miniaturization of the circuit by using fine pitch circuits, small components, 3D-integration, etc. If, by applying this strategy, the circuit can be made on a small enough surface area (less than a few cm^2 for most wearable applications), it can still be implemented as a conventional rigid board. The lateral dimensions of the circuit should be small compared to the local bending radii of the non-flat surface at the point where the circuit is placed.

In cases where the miniaturization approach is not possible, the rigid board must be replaced by a mechanically flexible or stretchable version. A flat, flexible printed circuit, coming from a standard production line, can be deformed to a cylinder or a cone, but not to a spherical or irregular surface. A stretchable circuit provides a solution since it can be deformed from a flat surface to any shape, due to the presence of the stretchable interconnects.

In some cases, a circuit may be too complex to be sufficiently miniaturized. If this is the case, the large area circuit can be split into several smaller area circuits. The sub-circuits are then joined by stretchable interconnections. This approach is similar to rigid-flex boards, where rigid PCB islands are interconnected by flexible printed circuits. Figure 13-2 shows a part of a fitness monitor that is worn on the wrist (designed by Philips), where the different electronic building blocks are realized on rigid PCB interposers that are subsequently mounted on a stretchable PCB, which is fabricated using stretchable copper board (SCB) technology.

Figure 13-2: Fragment of Philips fitness monitor, showing rigid interposers assembled on a stretchable interconnection substrate.

Figure 13-3: (Left) 7x8 LED matrix; (right) wireless ECG monitor with stretchable antenna and interconnect to distant electrode. (Images courtesy of Imec).

In some cases, the circuit, by nature of its functionality, occupies a large area and contains components that are placed at a certain distance to one another, making miniaturization problematic. One case is a circuit that is a large area network of distributed sensors or electronic components, such as a conformable light source or display consisting of individual LEDs in a matrix arrangement (fig. 13-3 left) or a distributed pressure sensor network for artificial skin applications. Another case is a circuit that has one or more single distant components, such as an electrocardiogram (ECG) monitoring circuit (fig. 13-3 right) where the minimum distance between monitoring electrodes should minimally be 5cm to 10cm. The circuit is

designed so that the electronics are concentrated around one electrode, while the other (distant) electrode is connected to the circuit using a stretchable conductor.

STRETCHING OPTIONS

There are three fundamental ways that stretchable circuits can be pliably deformed and/or put to use (fig. 13-4).

- Linear stretching - ends pulled in opposite directions (most common)
- Two-dimensional (2D) stretching - circuit is stretched taut like a trampoline
- Three-dimensional (3D) stretching - load applied to the trampoline-like structure or circuit is wrapped around a 3D object that has 3D aspects to its movement (e.g., a circuit that is wrapped around a person's upper arm and the biceps are flexed).

Figure 13-4: Directional stretch of circuits can vary depending on the needs of the design.

Each type of stretchable circuit can have different solutions. For example, in 3D stretching, there is some advantage to having pre-stressed connections between islands of stability. On a micro scale, such structures are not all that different conceptually from the accordion concept from years ago. However, there are two substantial differences: feature sizes are significantly smaller and the buckled connections are attached to a resilient base (fig. 13-5).

APPLICATIONS FOR STRETCHABLE CIRCUITS

There has been an impressive array of products proposed by industry and academia for the evolving area of stretchable circuits. A significant number of the proposed applications are related to health and well-being. Applications related to monitoring functions of the human body (e.g., temperature, heart rate, heart arrhythmias, blood oxygen levels, glucose levels) are continuing to show up. There are also a number of interesting

Figure 13-5: 3D stretching of a circuit facilitated by an elastomer base and very thin pre-buckled conductors. (Image courtesy of University of Illinois).

products that are expressly designed for fashion and consumer whims. The following is a sampling of applications being considered, and surely represents just the beginning. There is no doubt that there will be many more applications in the future.

BRAIN MONITORING

It is widely known in the medical community that there are markers for electrical activity in the brain that can serve as indicators of impending seizures in people with epilepsy. One application, suggested by a doctor at University of Pennsylvania, is a stretchable sensor cap that monitors electrical activity in the brain to predict the onset of epileptic seizures. Current solutions are more technician intensive as each wired electrode must be individually attached (fig. 13-6). The university researchers hope that such a device might also work in reverse, sending electric pulses that would prevent seizures completely.

Figure 13-6: Approach to interconnection with current brain wave monitoring technology.

MUSCLE STIMULATION

Since the late 18th century, when Luigi Galvani discovered that dead frogs' leg muscles twitched when stimulated by electricity, the study of electrophysiology has continued to fascinate and draw researchers to understand the electrochemical nature of life. Consumers have a direct commercial interest in this type of application. Magazine and television advertisements promote electrical stimulation devices to passively exercise muscles. There is a possibility that with stretchable circuit solutions, a device may be developed to coordinate and control muscles, possibly returning mobility to those who have suffered paralysis of their extremities.

TUNABLE ANTENNAS

Antennas pick up wireless electronic signals. With the explosion in wireless products, the airwaves are cluttered with signals and myriad frequencies are used for transmission. Often antennas are designed to receive signals within a specific frequency range. Stretchable circuit concepts have been developed that allow a change in the length of the antenna to change the frequencies to which it will respond (fig. 13-7). The device, developed by engineers at North Carolina State University, can be stretched eight millimeters, shifting its peak response by over 200 megahertz. Developers suggest that the device could be used in a number of ways, including an antenna-sensor combination device suitable to embed into machinery to monitor operations or even into a concrete structure, such as a bridge, where the antenna could monitor the structure for strain over time. More recently researchers have suggested the possibility of building circuit networks using the same type of liquid metal conductors enclosed in micro-fluidic channels in silicone elastomers. Another driver to make antennas deformable is the fact that in popular frequency bands like the ISM band (2.4GHz, wavelength 12.5cm) wearable antennas for BAN (body area

Figure 13-7: Stretchable antenna filled with a liquid gallium-indium alloy mixture that fills a channel in the center of the elastomer. (Image courtesy of North Carolina State University).

network) applications are quite big (lateral dimensions typically 5cm to 10cm). For comfortable integration on the body, flexible and preferably stretchable antennas are desired.

TACTILE FEEDBACK GLOVES

The internet and wireless products are opening doors to many new possibilities from remote operation of machines in uninhabitable environments to remote surgery. At the University of Illinois, there is a reported project underway to build latex surgical gloves with integrated electronics. The expressed interest is to add sensing capability, including the provision of tactile feedback.

THERAPEUTIC BANDAGES

Stimulating healing using electronic pulses at the surface of the skin is an area of interest and exploration. Stretchablity is an attribute that is perfect for such applications, allowing the circuit contacts to conform reliably to the contours of the treated area.

SYNTHETIC SKIN

Beyond the tactile glove concept, there is an interest in creating tactile sensitive skin. Research at both Stanford and UC Berkley has focused on ways of providing large, flexible surface solutions to the challenge. Both sets of researchers have reportedly made significant advances toward developing pressure-sensing devices to meet that challenge. Stanford has developed a technology based on organic electronics that is three times more sensitive than human skin. The solution from Berkeley uses integrated arrays of nanowire transistors and reportedly requires very little power to operate. Both solutions meet the requirements of flexibility and can be printed over large areas. The technologies could provide highly sensitive surfaces that could allow robots to pick up delicate objects without breaking them or give prosthetic devices a sense of touch.

SMART SHOES

Footwear has been adapted to electronics for several years. Shoes with LED lights around the edges are frequently worn

Figure 13-8: Application of stretchable circuits to shoes for monitoring purposes. (Images courtesy of Freudenberg Forschungsdienste).

by children. More recently, some high-end training shoes have been adapted with electronics to allow the user to monitor time, distance and stride. In the field of stretchable circuits, technology has been proposed for diabetic foot care and as an aid to help in step detection (fig. 13-8).

VARIABLY LIGHTED CLOTHING

The world of fashion is nothing if not dynamic, and competition among designers to create the next fashion statement is intense. The application of lighting to clothing is making for some interesting designs where lighting can be altered by the wearer to make ever-changing fashion statements. The use of lighting has also been adapted to scrolling signage displayed

Figure 13-9: Fashion statements in light have been made possible by the marriage of stretchable circuits and LED lighting elements. (Images courtesy of Philips Lighting and FhG-IZM/TUBerlin [Klight dress])

on clothes so the wearers can create messages according to their moods. The lighting can be worn under a shell or beneath the fabric so it is only visible when the wearer chooses (fig. 13-9).

The small sampling of products that are possible using stretchable circuit technology is just the beginning. As the technology finds greater interest among designers of different products, a myriad of new design possibilities is certain.

While it is evident that there is no one-size-fits-all solution to the challenge of stretchable circuits, a number of interesting solutions have been demonstrated in a wide variety of products. These solutions are predicated on the use of an elastic base material, which is fairly common. The real challenge is to come up with conductors that can be stretched and recover while maintaining conductivity.

MATERIALS FOR STRETCHABLE CIRCUITS

The materials and processes that have been developed for stretchable circuits are in some ways similar to those used for traditional flexible circuits, but in other ways they are quite different. Like flex circuits, the material set is comprised of base materials and conductors. Both of these elements are equally important for stretchable circuits and carry equal weight.

BASE MATERIALS

Resilience is a key property of rubbers and elastomers. The ability to stretch and recover is imperative for any stretchable circuit. In general, an elastomer is a polymer with the property of elasticity. An elastomer has notably low Young's modulus and high-yield strength compared with other materials, making the list of prospective materials somewhat limited. However, there are likely to be applications where full recovery is not required and where the material may be stretched

plastically to a desired limit, but has just enough remaining elastic strength to perform its function. One can even think of process flows where purely thermoplastic (i.e., non-elastic) materials are used to make a stretchable circuit. In this case, the circuit with stretchable conductors and rigid components is produced on top of or embedded in a rigid thermoplastic carrier, which has the form of a flat substrate at the time of production (during which the conductor tracks are defined and the components are assembled). At the end of the process a thermoforming step is applied, transforming the flat substrate into a rigid circuit with an arbitrary shape defined by the thermoforming step. The stretchability of the conductors ensures that under this deformation all electrical connections stay intact and the functionality of the circuit is maintained. In this case, a one-time only stretchability of the circuit is required and, although the circuit is not elastic, it can be categorized as being stretchable. While this opens the door to other possibilities, this chapter's focus will be limited to more resilient (i.e., elastic) types of materials. This review of base materials is not exhaustive. Other materials can be found with further investigation.

NITRILE RUBBER

Nitrile rubber (NBR), and more specifically acrylonitrile-butadiene rubber, is considered to be the primary workhorse of the industrial and automotive rubber products industries. NBR or Buna N, as it is also known, has good elastic properties with lower acrylonitrile content, a good temperature range (–40°C to +125°C) and good resistance to oil, making it a common choice for automotive applications. It is also used in non-latex glove applications. Sheet stock is available at a thickness of 0.5 mm. NBR is available in powdered form giving rise to the possibility of transfer molding the material in a net shape to reduce the stretching requirement for extreme stretch applications.

SILICONE RUBBER

Silicone rubber or poly-dimethyl siloxane (PDMS) has many desirable properties that explain its use in many products. The elastomer can be filled with other materials to change its properties. For example, conductive materials can be added to improve thermal or electrical conductivity for heat removal or electrical shielding needs. Silicones maintain many of their properties over a wide range of conductions. High thermal resistance is one of silicone rubber's more attractive properties, but it also has the ability to retain flexibility at lower temperatures. Thin sheet materials are available in thicknesses ranging from 0.075mm to 1.0mm, a range suited to stretchable circuits. Compared to polyurethane (PU) materials described below, PDMS has a higher optical stability (little or no discoloration over time under illumination). On the other hand tear strength of PU is generally higher than that of PDMS. A range of PDMS materials have a biocompatibility qualification that makes them suitable for skin contact or even implantation.

THERMOPLASTIC POLYURETHANES

Thermoplastic polyurethanes (TPU) are another potential base material for stretchable circuits. Even in their thinnest form, TPU films are extremely tear-resistant and highly stretchable. TPU materials have a number of properties that are attractive to product investigators and developers, including, abrasion resistance, good low-temperature performance, good mechanical properties combined with high elasticity, good shear strength and high transparency. These properties, along with TPU's relatively low cost, has propelled its use. TPU film is readily available in thicknesses from 0.1 mm to 0.8 mm.

SPUN, NON-WOVEN POLYURETHANE

Most woven fabrics have some degree of stretchablity depending on the tightness of the strands in the fibers and the

Figure 13-10: Copper metal pattern plated to a non-woven polyurethane cloth. (Images courtesy of Technical University Berlin and QPI).

weave of the cloth. Non-woven fibers offer additional stretchablity because the fibers are not as ordered or tightly bound. If the material used for the fibers themselves has some degree of elasticity, the fabric can be reasonably stretchable. Elastic wrap bandages are a common example. Fabrics made of non-woven polyurethane have become materials of interest to some investigators because of their stretchability. Exploration of the use of these fabrics has shown circuits that are pattern plated directly to the surface of the material (fig. 13-10). Conductivity when stretched relies on the copper-plated fibers maintaining contact as connections are broken and remade in myriad places during stretching.

CONDUCTOR MATERIALS

Conductors are the all-important other half of the stretchable circuit equation. Making conductors stretchable is more

complex task than finding a base material with the right properties. As a result, there have been a number of different investigations and developments in the area of stretchable conductors. Some have resulted in clever designs for conductor routing patterns and others in the development of new conductor materials that meet requirements. The following is a brief overview of some of the approaches that have been explored and developed for making stretchable conductors.

ALL-METAL CONDUCTORS

A number of investigations into the development of stretchable circuits have focused on the use of metals, either as wires or as etched foil, to provide conductors. This is a reasonable approach based on the electrical performance and termination solderability required for most circuits. The key feature of metal constructions is a meander pattern for the conductors. Researchers at Imec and University of Ghent in Belgium, who have been at the forefront of the stretchable circuit effort (both institutes have served as host for the International Workshop on Flexible and Stretchable Electronics), have done a good deal of modeling to optimize conductor design for in-plane stretching. The horseshoe-shaped conductors, shown in figure 13-11, provide a good compromise between a desired uniform stress distribution along the edges of the conductor on one hand, and easy circuit layout on the other hand. Horseshoes are nothing but circle segments and the connection of these circle segments provide the final conductor shape. Horseshoes can be easily implemented in commercially available layout software such as Eagle, enabling the straightforward layout of complex stretchable circuits. Mechanical modeling of meanders shows that conductor width strongly influences the maximum stress under deformation. The multi-track approach (lower part of figure 13-11), results in ten-fold reduction of the maximum stress. The price to pay for this improved perfor-

Figure 13-11: Metal foils, such as copper foil in the image on the left, can be resiliently stretched if the plastic limit of the metal is not exceeded. Finite element models of original (top) and improved (bottom) approaches to making in-plane stretchable conductors. (Images courtesy of Technical University Berlin [left] and Imec [right]).

mance is the need for fine pitch conductor patterning and a more complex design.

The design approach allows stretching to occur by adding circuit length. When stretched on the base, it creates in the conductor a pseudo-elasticity in the circuits. Because the elastomeric base material is much stronger than the circuits, the circuits return to their approximate shape. In the process, however, some plastic deformation of the circuits can be expected and on repeated cycles, the circuits begin to fail due to cracking of the metals. The stretching also causes out-of-plane deformation of the conductors and carrier material. However, this out-of-plane deformation is much smaller (typically a maximum of 10% of the total substrate thickness) than in the case of the out-of-plane (e.g., accordion) conductor approach.

Out-of-plane conductors, which resemble accordions, are another design approach to making solid metal circuits stretchable. Figure 13-5 shows an example of a stretchable circuit approach from Northwestern University, where research-

ers fabricated metal circuits with low-profile metal humps on stretchable base material. When the circuits are stretched, the metal humps flatten out, but then return to hump form when relaxed.

COMPOSITE CONDUCTORS

In addition to metal foils, a great deal of effort has been put into the development of new composite materials that are both conductive and resiliently stretchable. Most of these solutions are mixtures of conductive material, such as metal, mixed with a stretchable polymer. Getting the mix right is the challenge.

Silver is the most conductive of commonly available metals and it has the added advantage that its various natural oxides are also conductive, making it a natural choice. With the advances in nanotechnology, silver powders are closing in on native silver in terms of conductivity. Moldable mixtures of silver and polymers/elastomers have been explored, including:

- NBR compounds filled with silver flakes or silver coated copper
- Ethylene propylene diene Monomer (EPDM) compounds similarly filled
- Various metal-filled liquid elastomers

The conductivity of these mixtures is lower than metals, but the resilience is better and they can be stretched linearly without the meander pattern required for metal. One of the challenges is that these solutions do not tend to be solderable. Therefore, the solutions must be post-processed (e.g., plated with a solderable finish) to make them solderable. Elastomer-metal composites allow for linear conductors to be designed into the product, which saves space. However, if the circuit is over-stretched, it will fracture (fig. 13-12).

Figure 13-12: Fractures due to over-stretching. (Image courtesy of Freudenberg Forschungsdienste).

It is possible that the circuit will recover when it is relaxed, but any connection will likely be tenuous. Printing such materials can be challenging due to their highly viscous nature. Stencil printing and screen printing are the methods used most often. While the stencil process is more friendly it is limiting in terms of feature location flexibility.

At the University of Tokyo, they have demonstrated a stretchable display of organic light-emitting diodes (OLEDs) and organic transistors interconnected with a newly developed elastomeric conductor, which is a mix of carbon nanotubes and a rubber compound. The demonstration included spreading the display over a curved surface to show that it did not affect performance. They even folded it without negative effect. Nanotubes comprise roughly 20% of the weight of the total mixture and are evenly distributed. According to the develop-

ers, because each nanotube is about a millimeter in length, there is a much higher likelihood of forming an extensive microscopic network, allowing an electrical charge to more reliably pass throughout the polymer mixture. In contrast to metal composite materials, the new material can reportedly be printed using a jetting process.

PROCESS FLOWS FOR FABRICATION OF STRETCHABLE CIRCUITS

First developments on stretchable circuit development, other than the intuitive out-of-plane curved wire (i.e., spiral type) or folded flex (i.e., accordion type), started in the early 2000s in a number of USA based research institutes, including Lawrence Livermore National Labs, Princeton University and Johns Hopkins University. All of these technologies used thin-film metallization (evaporation or sputtering) on an elastic PDMS substrate. Since these early days, many more interesting technology developments have been reported worldwide, exploring the use of a wide variety of materials such as composite and liquid conductors, ultra-thin bendable silicon and perforated flex. Details of these different approaches will not be discussed here. Instead, the focus will be on two technologies that have a strong link with conventional rigid and flex PCB-style processing. Both technologies were developed in the frame of the STELLA project. The industrial partners participating in this project, emphasized the need for potential future transfer to an industrial production environment. Stretchable and elastic circuit technology is not just an exotic research idea anymore. It has evolved to a phase where basic processes exist that have the potential for transfer to a mass production environment.

These two stretchable circuit technologies, which will described in some detail, like conventional PCB fabrication and assembly technologies, involve the use of:

- Standard copper conductor material as interconnections
- Lithography and wet etching technology for the patterning of copper conductors
- Conventionally packaged off-the-shelf electronic components and sensors, providing the capability to realize circuits with a high degree of complexity and functionality
- Standard solder assembly technology for mounting components on the copper tracks of the stretchable PCB.

Since normal off-the-shelf components are almost always rigid, it is clear that the areas in the circuit where the components are present cannot deform. The overall concept of a stretchable circuit is illustrated in figure 13-13. The circuit is comprised of a number of rigid (or moderately flexible in some

Figure 13-13: Stretchable circuit concept.

cases) component islands, where each island holds a single component or a limited number of components. The total area of each island is still small and acceptable for the application in which the stretchable circuit is to be used. The interconnection between the components on a single island can be formed using the same copper conductor foil used to form the stretchable interconnects. Alternatively, these components can first be mounted on a separate (small) standard rigid or flexible interposer board. The interposer board is subsequently assembled on the large area stretchable circuit. A proper design and technological implementation of the transition between the rigid component islands and the stretchable meander copper conductors is extremely important for obtaining a desired level of mechanical reliability (e.g., under-cyclic stretching) of the circuit. As a general rule, a gradual transition from rigid to flexible to stretchable is necessary to obtain a mechanically reliable circuit.

The two technologies are:

- Stretchable Copper Board (SCB) technology developed by Fraunhofer-IZM/TU Berlin (Germany).
- Stretchable Molded Interconnect (SMI) technology developed by Imec/Ghent University (Belgium).

STRETCHABLE COPPER BOARD TECHNOLOGY

Stretchable copper board (SCB) technology starts by producing the base substrate (figure 13-14), using a commercially available copper foil (the typical thickness is nominally either 17μm or 35μm) and a PU sheet (typical thickness. 25μm, 50μm or 100μm). PU is laminated to the edges of the support board, with a separation layer preventing lamination in the center part. The support board holds all of the structures in place during processing and provides a platform for fabrication in a standard rigid PCB processing environment. The separa-

Figure 13-14: Base substrate production for the SCB technology.

tion layer provides sufficient adhesion of the PU during processing and allows easy release of the systems from the support board after finalization. The PU material softens at around 150°C. A lamination temperature of around 200°C provides an excellent adhesion of the copper foil to the PU.

The fabricated base substrate is processed using conventional PCB manufacturing and assembly processes (see figure 13-15, separation layer and support board not shown). The meander shaped copper tracks are first defined by photolithography and wet etching, then a solder mask is applied, typically by screen printing. Since the solder mask material is non-stretchable, it is applied only in the neighborhood of the components, not on the meanders. In a subsequent step a polyurethane sheet, which serves as an encapsulating coverlayer, is vacuum laminated to the circuit. As with traditional flexible circuit coverlayers, this sheet is preprocessed to provide openings for the component contact pads. Finally, a suitable standard surface finish (electroless silver [Ag] or organic solderable protective coating [OSP]) is applied, providing solderable

contact pads. The PU material proves to withstand all wet chemistry steps in this process.

In a next step, the components are assembled on the board. The use and presence of PU at this stage necessitates a restriction in the solder process chosen. Most PU materials soften at temperatures between 100°C and 200°C, so standard tin-silver-copper (SnAgCu) solders, requiring process temperatures of 250°C to 260°C, cannot be used. The choice is limited to low temperature solders like tin-bismuth (SnBi), which has a melting temperature close to 140°C. This solder alloy is commercially available as a screen printable paste and is widely used in smart card assembly processes. The SnBi solder paste is screen printed on the contact pads of the SCB substrate, components are placed using a standard placement machine and the substrate is submitted to a reflow soldering step with a maximum temperature of 160°C, which yields excellent soldering results. Finally, an underfill material is applied for mechanical fixation of the components to the substrate. Figure

Figure 13-15: SCB process flow.

13-16 shows an SCB substrate after component assembly. The circuit is part of a respiration monitor, designed by Verhaert (Belgium) in the frame of the STELLA project. In addition to the circuit shown in figure 13-16, the results of figures 13-2,

Figure 13-16: SCB substrate after component assembly.

Figure 13-17: Final component embedding (left) and release from support board (right).

13-9 (right) and 13-11, have been obtained using the same basic technology.

To improve the mechanical reliability of the circuit, an additional component encapsulation step is implemented (schematically represented in figure 13-17, left). To this end liquid injection molding of a thermoset PU material has been practiced successfully. Of course, a coverlayer lamination of a preformed polyurethane encapsulation sheet is also an option. Finally the completed circuit assemblies are cut out (using a laser or other suitable process) and released from the support board and separation layer (figure 13-17, right).

STRETCHABLE MOLDED INTERCONNECT TECHNOLOGY

In SMI technology the order of subsequent process steps is different, compared to the SCB flow. In SMI, stretch circuit production and component assembly are done first on a temporary carrier substrate, and the stretchable circuit carrier material is applied afterwards. Whereas SCB is intuitively closer to standard PCB manufacturing (starting from the final circuit carrier and copper sheet laminate), SMI has the advantage that it allows for wider process windows, especially high temperature steps, permitting the use of standard high-temperature melting SnAgCu solder alloys.

The first steps in the SMI process flow are shown in figure 13-18. On one hand a temporary rigid carrier (e.g., FR4 board) is provided and covered with a temporary adhesive (e.g., wax). A standard copper sheet (17µm or 35µm thick) is laminated on the temporary carrier. Figure 13-18 shows a more advanced version of the SMI technology in which a flexible support layer (e.g., spin-on polyimide [PI]) is applied on the copper foil and patterned. This flexible layer serves as support material for the copper meanders and for the component islands. Supporting the meanders with a PI carrier greatly improves mechanical reliability and operational lifetime of the copper

Figure 13-18: SMI circuit fabrication on temporary carrier.

Figure 13-19: Assembled SMI circuit on temporary carrier: overview (left); detail (right).

meander circuits. After the lamination step the patterned support layer is placed in between the temporary adhesive and the copper sheet. Next, the specially prepared laminate goes through a number of standard PCB manufacturing and assembly steps. Copper meanders, along with the standard design interconnections on the component islands, are patterned by photolithography and wet etching. A solder mask is locally applied by screen printing. If necessary, a contact pad finish is applied and components are mounted using a conventional

SnAgCu reflow solder process. At this point, the circuit can be tested and repaired, if required. At this phase of the process, no stretchable substrate materials have been used, which allows the use of higher temperature solders. Figure 13-19 shows the same respiration monitoring circuit as in figure 13-16, but using the SMI technology variant, after component assembly.

The second set of SMI process steps involves the application of the stretchable carrier material, giving the circuit its resilience (fig. 13-20). In the first step, the top of the circuit is covered by a first layer of stretchable carrier material. Figure 13-20 shows the process variant which is presently the method preferred by developers. The process involves a liquid injection molding (LIM) process, in which a top mold is placed over the circuit, a liquid two-component PDMS mixture is injected, and subsequently cured at relatively low temperatures (ranging from room temperature to a maximum of 70°C for high-speed curing). Alternatives for LIM include cover lamination, spraying, etc. Besides PDMS, PU or any polymer for which a liquid precursor or a thermoplastic variant is available, can likely be applied. In a second step, the temporary adhesive is heated to

Figure 13-20: SMI process flow - encapsulation in stretchable carrier substrate.

Figure 13-21: SMI circuit during (left) and after (right) the LIM process.

melting temperature, allowing removal of the assembly from the temporary carrier. After cleaning (removal of the remaining adhesive from the assembly using an organic solvent or other suitable cleaner), the circuit is completely embedded by applying a second layer of stretchable material at the bottom, (i.e., by a second LIM step). When removing the mold substrates, an embedded SMI stretchable circuit is the final product. Figure 13-21 shows the SMI respiration monitor circuit during the LIM bottom molding step, as well as the final result after removal of the mold substrates. In addition to this circuit, the stretchable LED display of figure 13-3 (left) was also produced by SMI technology. The ECG monitoring circuit of figure 13-3 (right) was made using a variant of the SMI technology, where the starting substrate was a commercially-available Upilex flex laminate, from which the component islands and copper meander circuits were defined by laser structuring and subsequent removal of the cut-out excess flex parts. The process yielded copper meander circuits integrally supported by PI with very high mechanical reliability.

RELIABILITY

Rigid and flexible PCBs must demonstrate product reliability under various conditions including environmental (tem-

perature, humidity, etc.) and mechanical stresses. Testing is an important concern for stretchable circuits and has been an area of focused investigation and research. Because the resilience of elastic circuits is unique, researchers have mainly concentrated on investigating mechanical reliability, rather than pursuing environmental stress testing. In particular, mechanical and electrical behavior under uniaxial stretching have been studied in systematic reliability testing of stretchable circuits. Two primary tests are performed. The first is a one-time stretching until electrical failure occurs (a break in the electrical connection). The second is periodic uniaxial stretching and release with monitoring of the resistance of the stretched interconnection line. Typical parameters for the tests measured are the total elongation of the sample (engineering strain) given as a percentage of the original length (%) and the elongation speed (% per second).

In many of potential applications, the estimated strain in the field life of a typical product is in the range of 0% to 20%. In order to enable safe operation of the applications, the maximum single elongation to failure should be much larger than 20%.

As an introduction to the subject, a limited number of mechanical reliability test results will be discussed, as well as some preliminary design and technology rules for PCB-style stretchable circuit technologies.

Figure 13-22: Stretchable interconnect design parameters (left) and uniaxial stretch test sample (right) with five parallel meander tracks.

In order to test the mechanical reliability of copper metal meander circuits, dedicated test samples are designed and fabricated consisting of a number of parallel running meander traces, embedded in the stretchable carrier material. Key technology and design parameters required for determining mechanical reliability are: width (wCu) and radius (rCu) of the meanders, angle (θ) of the horseshoe circle segments, thickness (tCu) of the copper and the distance between adjacent meanders (fig. 13-22). Typical design parameters used, and in agreement with standard PCB processing, are: wCu = 100µm, rCu = 0.5mm, tCu = 17µm, θ = 0° to 30°. The fabricated test samples are subsequently clamped in a cyclic stretch test set-up (fig. 13-24).

In a first series of tests, it was shown that one-time ability to stretch the circuit from 100% to 150% could easily be obtained with this type of meander circuit, however, reliability under cyclic stretching is even more important. For samples with typical design parameters, the number of elongation

Figure 13-23: Cyclic elongation test set-up.

cycles before electrical failure for non-supported copper meanders embedded in PDMS, is more than 2,000 for 10% elongation and up to 20,000 for 5% elongation. Electrical failure is characterized by a sudden increase in the electrical resistance from a constant value to infinity (instant opening of the copper trace).

A way to improve the reliability of the conductors is to add a flexible supporting layer below the meanders, as described in the SMI process flow. In one example, a 25µm-thick layer of photo-definable polyimide with exactly the same layout (width) as the copper horseshoe pattern is added below the copper and the number of cycles to failure is at least doubled (for maximum elongations up to 20%). Until this failure point the track resistivity remains constant, and upon continuing the test gradually increases until complete rupture. The complete interruption is delayed and spread over a large number of cycles. This is attributed to the PI which reduces the crack

Figure 13-24: Copper meander with wider PI support

propagation rate. The mechanical performance can be further improved by designing the supporting PI differently (e.g., wider) than the copper. Figure 13-24 shows a stretchable interconnect at wCu = 100µm and the width of the PI track wPI = 300µm. The PI layer effectively redistributes the plastic strain in the metal, therefore improving the reliability of the stretchable interconnect. Initial testing has shown that reliability improvement for such designs is substantial, but at the time of this writing, the exact figures are not yet available.

The experience of manufacturing the first functional technology demonstrators was highly instructive and researchers became aware of a design element that can greatly affect mechanical reliability and appears to be even more critical than the meanders. The area of concern is found in the transition areas between the individual components or component islands and the copper meanders. Figure 13-25 (left) shows a non-optimized sample after stretch testing. Breaks in the interconnections are clearly visible and they exist in the transition area at a much greater frequency than in the fully stretchable area. Figure 13-25 (right) shows an optimized design, featuring gradual transitions in width of the copper and corresponding

Figure 13-25: Non-optimized (left) and optimized (right) design at transition area between rigid/flexible and stretchable zones.

supporting PI, which design reduces the local plastic strain in the copper, and the replacement of sharp-edged rectangular component island transitions with optimized structures (rounded corners). The combination of these two changes significantly mitigates the stress concentrations that were present in the original design.

Another approach for protecting the transition zones between mounted components and stretchable interconnects is shown in figure 13-26. In this approach particular types of copper structures on the surface of the stretchable substrate are designed to serve only mechanical purposes. Due to the stiffness of copper in comparison to the elastomeric substrate, copper structures act as local stiffeners.

To further smooth the transition, the measures in the plane of the circuit can be combined with measures in the direction perpendicular to the substrate plane. A gradual transition in thickness of the encapsulant between the thick regions (> 1.0mm) at the component islands and the thin regions (< 1.0mm) situated at the position of the stretchable interconnects avoids local stress concentrations in the transition area (fig. 13-27). This improvement, which is similar to techniques suggested for use with more traditional flexible circuits, helps to distribute the stress over a wider

Figure 13-26: Stiffening structures in the copper artwork serve as mechanical fixation structures without electrical function.

Figure 13-27: Gradual transition in encapsulant thickness between rigid/flexible and stretchable zones.

region, enhancing the lifetime of the interconnections and transition zones

SUMMARY

This brief overview of stretchable circuits is hardly comprehensive based on the continuous development of the relatively new technology. Research and development is ongoing and there have doubtless been a number of recent advances that have occurred as this edition was being published. The technology is both intriguing and enabling. Those steeped in the development process assert that we are at the beginning of the road and that what is to come will be even more amazing than what has occurred to date. A much more complete and more academic text on stretchable circuits and stretchable electronics, to be published by Wiley, with Professor T. Someya (Tokyo University) as the main editor, is in the works and slated to be available in late 2011 or early 2012. **FCT**

FOURTEEN

Paul Reid's career in printed circuit board fabrication and reliability testing spans 29 years. Paul received a Bachelor in Science degree in 1975 and a Master in Science in 1980 from Rivier College, Nashua, New Hampshire. Paul has worked in Quality and Engineering in managerial roles in New England and Canada. He has created technical animations of PCB fabrication and failure modes induced by thermal excursions in support of reliability testing. His animations have been used internationally for education, technical reports and promotions. Paul is a Program Coordinator at PWB Interconnect Solutions Inc. in Ottawa, Canada, where his duties include reliability testing, failure analysis, material analysis and PWB reliability consulting. He is currently investigating the reliability of microvias in military and lead-free applications and refining a test method for Cyclic Time to Degradation (cT260).

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Chapter 14

Inspection and Test of Flex Circuits

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INTRODUCTION

Testing and inspection are among the most important elements of any manufacturing operation because they:

- provide valuable feedback on the health of the manufacturing operation
- prevent the escape of defective parts into the assembly process
- prevent failure in assembly
- prevent failure in the end-use environment.

Quality and reliability managers frequently have a love/hate relation with upper management. As the source of in-house reality checks, quality and reliability managers find, rework and possibly scrap discrepant circuits. As customer advocates, they prevent discrepant material from shipping. To many people, inspection and testing does not seem to add value to the product. But inspection and testing do add value by helping to ensure customer satisfaction and secure repeat business. On-time delivery helps to meet short-term goals and immediate customer needs, while quality and reliability help to achieve longer-term goals, like preventing returns and securing repeat business.

Today's methods of just-in-time procurement and assembly make the issue of discrepant material being delivered to the customer particularly damaging. Circuits that do not meet contractual agreements or functional requirements add cost by requiring that circuits and assembled components be remade or replaced. Discrepant product increases cost, monetarily and in terms of capacity reduction that results in a ripple effect upstream that can reach the original equipment manufacturer (OEM). Liability of the fabricator is often extended to include replacement of discrepant circuits as well as assembled parts that cannot be salvaged by the assembler.

The advent of lead-free assembly has had a great impact on quality and reliability requirements of flex circuits, raising the bar from former times. What was once an acceptable quality level in a tin-lead assembly may fail catastrophically in a lead-free assembly and rework application. Tin-lead assembly usually requires a process temperature of 230°C, while lead-free assembly increases the temperature to as high as 260°C. A new failure mode in flex circuits, microvia pull-out (see Chapter 15 – Plated Through-Hole Reliability), was observed and attributed to the high temperatures associated with lead free assembly.

Satellites that fail on the launch pad, missiles that do not launch, equipment that fails in the pitch or battle and failure of life support systems are obvious examples of why inspection and test are so important to the electronics industry. Contrary to popular belief, quality and reliability requirements for consumer electronics are increasing and becoming tighter. The requirement for consistent, repeatable quality with appropriate reliability is being mandated, but of course the goal is to achieve this level of quality without incurring additional costs. Pricing was once the major consideration for procurement, but cost is becoming the more dominant factor. Quality and reliability are more important than ever to prevent significant costs to the fabricator, contract manufacturer, OEM and customer.

Quality and reliability, while often referred to interchangeably, actually have different purposes. Quality is mostly about adhering to specified requirements to meet contractual obligations or industry-established minimums. Quality is concerned with the correct part number, revision, amount, dimension requirements, physical and electrical attributes and requirements including opens, shorts, copper weights and thicknesses, impedance and other variables. Reliability is a measurement of the sum total of the quality requirements and other unspecified attributes of the circuit. Quality confirms that a circuit meets requirements, while reliability demonstrates that the effects of those requirements produce a product that will survive assembly and be functional in the end-use environment.

TESTING OVERVIEW

Testing confirms or refutes that the circuit meets or exceeds quality requirements and reliability expectations.

There are two categories of testing:

- testing with the goal of controlling process
- testing to demonstrate compliance with quality requirements and reliability expectations.

Variables in the process are monitored and adjusted to ensure consistent outcomes during circuit fabrication. Physical (e.g., temperature, pressure) and chemical (e.g., pH, chemical concentrations) process variables are measured, analyzed using statistical methods and controlled in order to ensure that the process is continuing to produce an acceptable product. The product is tested and analyzed to confirm that the process are still producing quality product. This feedback loop of measurement and adjustment helps to achieve consistency of process and product.

Sample circuits, or representative coupons, are submitted to a testing program. It is important that the sample has the same

construction and conformation as the circuit being tested. Samples of circuits from a given fabrication lot, taken off the production panel, should be nearly identical and testing of the sample should reflect the attributes of all the associated circuits.

Testing should not be confused with inspection, although they do have complimentary roles. Inspection finds variation that results in the need to sort to separate acceptable from discrepant circuits. Weeding out and rejecting discrepant production circuits reduces production yield, but knowing the production yield is one of the most useful tools for obtaining objective feedback about the general health of the fabrication line and the product being built. Inspection must also be used to assess the quality of the product and ensure that it conforms to established requirements.

Testing of any product, including flexible circuits, is normally done on a sample basis if it is to be performed economically. With flexible circuits, there are two levels of interest for inspection and test: the raw material level and the finished circuit level.

Raw materials are inspected and tested to ensure that they will meet the requirements established by industry. Raw material testing provides a level of assurance that only acceptable material will be committed to manufacturing, reducing the potential for circuit discrepancies.

The final product is also tested to make certain that it meets or exceeds the specified requirements, which are typically related to form, fit, function and performance in the end-use environment.

RAW MATERIAL TESTING

Raw materials (e.g., base materials, adhesives, foil-clad laminates) are tested to ensure that they are of a high enough quality to produce end-products that are compliant with

requirements and will not limit the circuit's performance as it moves through assembly and to the end-use environment. Material performance is evaluated in several categories (physical, chemical, electrical and environmental) that reasonably represent the spectrum of potential areas of concern for a product. The following is a review of some of the tests that may be required for flexible raw materials.

PHYSICAL PERFORMANCE TESTS

The physical performance of the raw material is measured to ascertain that certain minimum physical properties are present in the material and to ensure that it is compliant with the specified requirements. The following common mechanical tests are performed to determine the values of two key physical properties of the flexible base material: the ultimate strength of the base film and the degree to which the material can be stretched before failure. These are important mechanical considerations and are useful in predicting the suitability of a material for a given application. They are also important data input values used in finite element modeling (FEM) and/or finite element analysis (FEA).

Figure 14-1: Preparation for stretch and pull directions for tear.

INITIATION TEAR STRENGTH

This test is used to determine how much force is required to initiate tearing in a material. It is a measure of the toughness of the base material, an important factor for flex circuits given the somewhat delicate nature of thin materials.

PROPAGATION TEAR STRENGTH

Propagation tear strength is another important measure that defines the toughness of the material. This test is designed to measure the force required to propagate a tear in a material after a tear has been initiated. Propagation tear strength can be a vital determinant of the ultimate reliability of a product. The lower this value is, the more important it is that tear-stop features be added to the flex circuit design.

LOW-TEMPERATURE FLEXIBILITY

Low-temperature flexibility testing is performed to evaluate material resistance to embrittlement and possible fracture at low-temperature conditions, as might be encountered by flex circuit end-products in some applications.

DIMENSIONAL STABILITY

Characterizing dimensional stability is important to both the designer and the manufacturer. The test verifies that flex material meets requirements for overall shrinkage or growth after etching of the metal foil. The more dimensionally stable the material, the easier it is to predict the locations of design features after manufacture.

PEEL STRENGTH

Peel strength is measured to ensure minimum bond strength. It is normally applied to the measure of copper foil, but it can be applied to other combinations as well. Tests are run under the following conditions to ensure that

Figure 14-2: Peel strength tester. (Image courtesy of LPFK)

adequate peel strength is retained after exposure to different conditions.

- **As received** – to check for minimum bond strength of copper to the flexible dielectric base
- **After floating the sample** – on 289°C solder for 10 seconds to check for degradation after simulated assembly and rework.
- **After exposure** – to five cycles of -50°C, +150°C with 30-minute dwells at each extreme, with a 15-minute intermediate dwell at room temperature between exposures at extremes to simulate accelerated aging effect on bond strength.

VOLATILE CONTENT

Volatile content is a potential source of outgassing and delamination. The test is employed to determine that the weight percentage of volatile elements in flexible laminate is at a desirably low value.

CHEMICAL PERFORMANCE TESTS

Chemical performance testing requirements for flexible circuits are very limited. Processing and application are two major areas of concern relative to chemical performance of raw materials used in flex circuit manufacture.

CHEMICAL RESISTANCE

Chemical resistance testing is performed to verify that no damage occurs to the laminate during exposure to chemicals commonly used in processing flexible circuits.

FLAMMABILITY

Flammability testing is performed to determine the minimum level of oxygen required to sustain combustion of the laminate. For printed circuitry, a commonly required rating is Underwriters Laboratories' UL 94 V-0, which indicates that the material is nonflammable. While, in the past, UL 94 V-0 ratings for flex laminates were uncommon, advances in flex circuit materials have resulted in a number of materials that meet the requirements of a 94 V-0 rating.

ELECTRICAL PERFORMANCE TESTS

The electrical performance of a flex circuit is often a function of the electrical properties of the material itself. This is increasingly the case for high-speed circuits. The electrical properties are verified by checking material samples and determining values for all of the following attributes.

DIELECTRIC CONSTANT

Determination of the unitless value known as the dielectric constant (Dk) of the material is an important determinant in many predictive calculations of electronic performance. A low Dk is especially important in high-speed applications. It is fundamentally the ratio of the capacitance of the material to the capacitance of air.

DISSIPATION FACTOR

The determination of the relationship between the material's permittivity (capacitance) and its conductivity, when measured at a given frequency, accounts for the material's dissipation factor. This is an important determinant that assists the circuit designer in making calculations of the electronic performance of the end-product. Moisture uptake is a common contributor to increases in dissipation factor and signal loss and will become increasingly important as signal speeds and operating frequencies continue to rise

DIELECTRIC STRENGTH

Dielectric strength is determined to establish the minimum breakdown voltage of the material. It is of particular interest and importance in the fabrication of high-voltage circuits as well as circuits that are to operate at high altitudes and are prone to electrical arcing.

SURFACE AND VOLUME RESISTIVITY

Surface and volume resistivity values are measured and established to provide the minimum values for volume and surface electrical resistance of the base material under damp heat conditions (such as those that might be encountered during exposure to highly humid environments), which can alter electronic circuit performance. The test provides a measure of a material's propensity for current leakage under such conditions.

ENVIRONMENTAL PERFORMANCE TESTING

Environmental performance testing is undertaken to evaluate certain physical and electrical attributes of the material that may change as a result of exposure to the environment over product life.

MOISTURE ABSORPTION

Moisture absorption is a determination of how much moisture the base material will absorb under humid conditions. Moisture absorption is relevant to electrical considerations since moisture absorption will alter the dielectric constant of the material. However, it is also a potential concern in assembly since excessive moisture absorption can cause explosive outgassing of absorbed moisture and delamination of cover layers. This is an increasingly important concern with lead-free solder since there is a doubling of vapor pressure between traditional soldering temperatures and nominal temperatures required for lead-free soldering.

MOISTURE AND INSULATION RESISTANCE

This testing is performed to determine the effects of exposure to moisture on the insulation resistance of the raw material. It verifies that electrical properties do not degrade beyond established limits for the material under test conditions.

FUNGUS RESISTANCE

This test is performed to determine if the material is a nutrient for fungi or other biological material that might be capable of degrading the electrical properties of the flex circuit.

FLEXIBLE CIRCUIT EVALUATION

The testing of finished flex circuits duplicates many of the tests performed on the raw material in order to ensure that the manufacturing process has not degraded the material beyond acceptable limits. As with the raw materials, testing requirements have been established in several key areas to ascertain that the product is acceptable for its intended purpose.

Major categories for testing the finished flex circuit include: visual inspection, metal finish solderability, physical dimensions, physical properties, circuit construction integrity, plated

through-hole quality (both before and after thermal stress), electrical properties, environmental properties and cleanliness. Testing requirements for each of the above-mentioned categories are reviewed here in brief fashion. IPC documents describing the precise test methods are available and should be read if more detail is sought or if one wishes to perform the actual testing.

VISUAL INSPECTION REQUIREMENTS

Visual inspections are performed as part of the testing process to ensure conformance to requirements not readily captured by other test techniques. The following are key attributes that are determined visually:

DELAMINATION

Any separation of the material from itself (e.g., conductors from laminate, cover films from conductors) constitutes evidence of delamination. It is generally seen as an indicator of improper processing, lack of cleanliness or thermal stress excesses. In nearly all cases, delamination is considered a rejectable condition.

EDGE CONDITION

Flex circuits are inspected to check for nicks or tears that could be sites for tear propagation and failure of the circuit. This is of great importance in dynamic flex circuit applications where nicks along the edges of a flex circuit can become sites for tear initiation. Edge condition testing is important for static applications as well, since circuits could be inadvertently stressed and torn during assembly.

STIFFENER ATTACHMENT

Stiffeners normally perform vital mechanical component support functions. As a result, the attachment is checked to

ensure integrity of the bond on the flex circuit to the chosen stiffener substrate. If filleting of stiffener edges or an edge break is specified, this inspection step will also verify its presence.

SOLDER WICKING

Evidence of solder wicking along the surfaces of traces away from openings in the coverlayer may be an indication of improper lamination of the coverlayer or excessive exposure to molten solder. The condition is not preferred, but is generally considered to be acceptable if it is within specified or agreed-upon limits (fig. 14-3).

MARKING

Marking of the circuit is checked to verify compliance to the master drawing and to prevent mislocation or misorientation of components during assembly or later, when field repair of the circuit would be required. If serialization of the circuit is used, it can also be checked at this time.

Figure 14-3: Solder wicking under the coverlayer can occur when molten solder flows beneath the coverlayer. It may or may not be rejectable, but can be an indication that an element of the manufacturing process is unstable.

Figure 14-4: Plating voids can be caused by a number of different process effects. Small voids, though not desirable, can be accepted, provided that they do not exceed specified limits. Ring voids, however, are a cause for rejection.

PLATED THROUGH-HOLE VOIDS

Plated through-holes with voids of unacceptable size or quantity are inspected in order to avoid soldering or reliability problems with the copper-plated through-hole. Ring voids are a major concern and a definite cause for rejection. If not discovered in inspection during assembly, the problem of voiding in plated through-holes is frequently manifested as an outgassing condition or blow hole in the solder joint.

WORKMANSHIP

This general catch-all inspection covers miscellaneous items such as the presence or absence of dirt, oils, fingerprints, wrinkles, bends or creases, and other nonspecific indicators of the workmanship of the circuit's manufacturer. Workmanship inspection may be subjective, but it can provide an indication of the quality of the circuit manufacturer's process.

DIMENSIONAL MEASUREMENT REQUIREMENTS

Dimensional measurements of the finished flex circuit are taken to ensure the form and fit of the circuit. Dimensional accuracy is often important to the actual function and ultimate

reliability of the circuit. The following are some key points of inspection and measurement:

MINIMUM ANNULAR RING DETERMINATION

The lack of sufficient annular ring can affect both the solderability and the reliability of an interconnect. Requirements differ greatly for plated and non-plated through-holes. Non-plated through-holes in single-sided flex normally requiring a much greater solderable area to ensure a reliable joint. Thus, annular ring is checked to ensure that minimum requirements are met.

HOLE PATTERN ACCURACY

Hole pattern accuracy is checked to ensure that through-holes are in their proper locations. This is an important issue for circuit assembly, especially when automated plated through-hole assembly procedures are employed. It is also important when the holes are to be used as tooling holes for surface mount assembly.

Figure 14-5: Annular ring acceptance criteria vary with the class of product being fabricated.

COVERLAYER REGISTRATION

Coverlayer registration has a net effect similar to that of the annular ring because coverlayer misregistration can encroach on the solderable area, resulting in a less reliable connection. The coverlayer should register on the pad to meet the minimum specified requirements (fig. 14-6). Registration requirements can vary with pad design features, with some approaches being more forgiving. With single-sided flex circuit designs, where the coverlayer serves to prevent pad lift, registration can be a very important concern. A minimum of 270% of land capture is normally recommended.

ADHESIVE SQUEEZE-OUT

Adhesive squeeze-out onto pads is a fairly common by-product of manufacturing during coverlayer lamination due to adhesive flow under heat and pressure (figs. 14-6 and 14-7). There are standard allowances for squeeze-out onto lands, but the amount of squeeze-out may need to be negotiated. Good process technique and materials can minimize the effects by

Figure 14-6: Inspection points for coverlayer and conductor acceptance of flexible circuits.

Figure 14-7: Points of inspection for flex circuit coverlayers.

Figure 14-8: Squeeze-out onto circuit lands.

damming off the adhesive with conforming press-pad materials. With newer photo-imageable coverlayers, this factor is generally not a concern. (See Chapter 7 – Practical Design Guidelines for Flex.)

SODA-STRAWING

Air entrapment along the edges of flex circuit traces, commonly referred to as soda-strawing (fig. 14-6), can occur in dense, closely-packed circuit designs or when very thick copper is called out by design. While it is not harmful in all applications, acceptability is often based on application of the end product. Capillary wicking of moisture is possible if the effect runs to the edge of the circuit or land. Limits should be agreed upon between the user and manufacturer.

FOREIGN ENTRAPMENTS

Foreign entrapments are sometimes present in the raw material and/or under the coverlayer of flex circuits (fig. 14-7). They are considered acceptable in various applications, provided that they do not bridge conductors or reduce spacing between conductors to less than acceptable limits. They may also be a concern if located in a critical bend area.

HOLE SIZE

Hole sizes are checked to verify conformance to print requirements and to preempt assembly problems. If made too small, circuit holes may make insertion of component leads difficult. If the hole is too large, it may be difficult to form solder joints of preferred quality in the assembly process. For tooling holes, hole size inaccuracy is a concern because loss of positional accuracy is a possibility.

CONDUCTOR PATTERN

The finished conductor pattern on the flex circuit should accurately represent the master drawing. While allowances exist for localized reductions of up to 20% in conductor trace width due to nicks or mouse bites (fig. 14-6), an excessively large number of occurrences is likely to be indicative of problems in the manufacturing process.

CONDUCTOR WIDTH AND SPACING

Conductor width and spacing may be critical and often must meet minimum size or spacing requirements to ensure proper electrical and/or electronic performance. Evaluation requirements should be defined on and controlled by the master drawing.

PHYSICAL TESTING REQUIREMENTS

Physical testing is a key part of flex circuit testing. It helps to verify the physical appropriateness of the product for the application. The following tests are performed to ensure product quality and reliability. The flex testing sections are especially important in dynamic flex circuit applications.

PLATING ADHESION

Plating adhesion, or tape, tests are performed to ensure a good metallurgical bond of plated metals to the base laminate copper foil. Low bond strength could result in latent failure of the circuit due to conductor lift or shorting.

UNSUPPORTED HOLE BOND STRENGTH

Unsupported hole bond strength is examined to ensure that the circuit can endure assembly and repair without excessive damage. The land must endure five cycles of soldering and desoldering in accordance with common specifications.

CONDUCTOR PATTERN BOND STRENGTH

This test is performed to ensure that the circuit manufacturing process has not reduced foil bond strength to unacceptable levels. Test conditions are essentially identical to those described for raw materials.

FOLDING FLEXIBILITY

Folding flexibility tests are performed to ensure that the circuit can be successfully formed to meet the requirements of

the master drawing without delaminating or breaking conductors. Information required for proper testing of folding flexibility includes: location of bend, radius of bend, angle of bend, direction of bend and number of cycles.

FLEXIBILITY ENDURANCE

Flexibility endurance testing is most important for dynamic flex applications. Testing apparatus can vary with customer requirements. Standard test methods using equipment such as the fatigue ductility (a.k.a. Engelmaier) flex tester may require anywhere from a few minutes to several hours to perform. Many disk drive manufacturers opt to test circuits under simulated operating conditions. Flexibility endurance testing can take weeks or even months to complete, but can provide manufacturers with the comfort of hard statistical reliability data. Examples of some of the most commonly used flexibility¬ endurance test concepts are provided in figure 14-9.

Figure 14-9: Flex testing equipment. Clockwise from upper left: the Engelmaier fatigue ductility flex tester, rolling flex test (Rogers), MIT flex test, collapsing radius (IBM/Xytratex).

CONSTRUCTION INTEGRITY REQUIREMENTS

The construction integrity of a flex circuit is best evaluated by performing a microscopic evaluation of a cross-section of the product before and after thermal stress testing. This type of inspection is used to reveal the presence of microscopic defects that may impact the reliability of the finished flex circuit. Inspections are performed both as received (pre-stressed) and after various thermal stress tests have been performed (post-thermal stress). The tests are performed to ensure that product quality and reliability are not degraded by the thermal exposure endured during solder assembly and solder rework operations. The following major points of inspection are described below and illustrated in figure 14-10:

PRE-STRESS EVALUATION REQUIREMENTS

The following points are evaluated before exposure to solder stress, to screen the product for the presence of defects in the product as received. (Chapter 15 – Plated Through-Hole Reliability offers more information on this important topic.) Major faults detected here may preempt the need for further testing.

LIFTED LANDS

Lands or pads are checked to ensure that they have good adhesion to the substrate before stress testing. Land lifting is usually the result of thermal stress, where expansion of the heated laminate can cause lands to lose adhesion and lift from the surface of the circuit.

PLATING INTEGRITY

Plating integrity is evaluated to ensure that plating quality, uniformity and thickness all meet specification requirements and that no cracks are present in the through-hole in order to ensure through-hole plating reliability.

LAYER-TO-LAYER MISREGISTRATION

Layer-to-layer registration is checked to ensure that minimum requirements for the given class of product are met. This is primarily a concern for multilayer and rigid flex constructions, but it can be a concern with double-sided flex as well.

POST-STRESS EVALUATION REQUIREMENTS

The following checks are performed after required thermal tests. Microscopic evaluation of plated through-hole cross-sections after thermal stress testing is the approved method for determining ultimate plated through-hole quality.

THERMAL STRESS

The effects of assembly simulation are evaluated using thermal stress testing, also called solder float testing. Solder float testing is best described as the simulation of a solder wave and was adopted when circuits had low layer counts with plated through-hole construction (PTH). Convection oven testing to simulate reflow is also sometimes used as an alternative method but the testing protocol is necessarily different.

Figure 14-10: Points of inspection for flexible circuit plated through-hole quality and mechanical integrity.

The solder float test is performed to determine if the plated through-holes can successfully survive assembly. The test, exposure to molten solder for ten seconds at 289°C (550°F), is more punishing than typical assembly, but helps screen the product and prevent marginal product from entering manufacture.

REWORK SIMULATION

Soldering and desoldering of a component lead five times in the plated through-hole is a test performed to simulate field repair and evaluate its effects on the flex circuit's plated through-hole integrity. The test must be performed by a skilled operator because an uncontrolled soldering iron could cause significant damage.

LIFTED LANDS

The product is evaluated again for lifted lands after thermal stress. Limits for degree of lift are established to provide a measure of assurance that lands will not lift off the surface of the circuit while it is in service.

ELECTRICAL REQUIREMENTS

Electrical requirements of the flex circuit are specified to ensure proper electrical performance of the finished product. While the tests outlined below are ones most often called out for circuit acceptance, other tests such as time domain reflectometry (TDR) testing of controlled-impedance circuits may also be required under contract provisions.

CIRCUIT CONTINUITY AND SHORTING

Circuits should be electrically tested to make certain that no opens or shorts are present in the board. This testing will ensure conformance to design, and proper circuit performance in the field. Test conditions such as test voltage and minimum

resistance between conductors should be called out on the master drawing.

INSULATION RESISTANCE

Insulation resistance testing duplicates the raw material test and verifies that circuit manufacture processing has not degraded the insulation resistance of the material beyond customer-specified requirements.

ENVIRONMENTAL REQUIREMENTS

Environmental tests are performed to simulate, in a practical fashion, the effects of various environmental conditions on flex circuit quality, performance and reliability.

MOISTURE AND INSULATION RESISTANCE

In this test, circuits are cyclically exposed to hot, moist air (from 80% relative humidity at 25°C to 98% relative humidity at 65°C). This is to ensure that no damaging effects occur in the laminate and that undesirable degradation of the insulation resistance of the flex circuit has not occurred. Some variations to the test exist.

THERMAL SHOCK AND THERMAL CYCLING

Several tests and test conditions are embraced under the terms thermal shock and thermal cycling. Most tests consist of exposing the device to temperature extremes to induce thermal-cycle strain-related failures. Thermal cycling is meant to be representative of the temperature extremes a circuit might be exposed to during its lifetime. Cycling conditions range from -65°C to +150°C, with prescribed dwells at anywhere from ten minutes to one hour. Shock testing normally employs short dwell times. The most common temperature conditions for bare-board testing range from –55°C to +125°C. However, with the introduction of product-specific reliability testing

by some manufacturers, several new thermal-cycling tests are becoming more common.

CLEANING REQUIREMENTS

Finished flex circuits must be tested to ensure that the circuits do not carry an excessive amount of ionic or organic contaminants with them. Contaminants have been shown to have a negative effect on long term reliability.

IONIC CONTAMINANTS (SOLVENT EXTRACT RESISTIVITY)

Ionic contamination testing is performed to determine the level of ionic material left on the board by washing the board using a pure alcohol/water solvent, collecting the solvent and measuring its change in resistance. Ionic contaminants, if left on the board, are capable of causing latent failures due to corrosion and current leakage or shorting.

ORGANIC CONTAMINANTS

Organic contaminants are another potential source of problems that should not remain on the circuit. The contamination can be detected by flushing the surface of a small sample of the circuit with chemically pure acetonitrile onto a clean glass surface and allowing the solvent to evaporate. Residue on the slide may indicate the presence of organic contaminants.

SOLDERABILITY REQUIREMENTS

Tests for solderability of the finished circuit are performed to ascertain that the flexible circuit will not experience or create problems in assembly operations due to a non-wetting condition. This is normally accomplished by checking that proper wetting of solderable surfaces is present after testing in accordance with an approved test method.

IPC-S-804 has been a commonly called-out specification for solderability. However, it is being replaced by EIA/IPC-J-Stan-

dard-001, which is now the common standard for all electronic applications across the industry and around the globe.

CONDUCTIVE ANODIC FILAMENT GROWTH

Conductive anodic filaments (CAF) are fine conductive paths that form between two adjacent interconnects (e.g., PTH to ground plane). These filaments tend to develop over time in the end-use environment. The filaments have some common attributes. The growth is found between two conductive feature that exhibit an electrical bias. It requires a source of moisture and a source of ionic contamination. The fiber grows down a path between the glass fiber and the epoxy matrix. This is of great concern with rigid flex where glass-reinforced epoxy laminates are made into hybrid structures with homogeneous flex circuit materials that appear to be immune. The concern is that occasionally a conductive pathway is formed down cracks caused by delamination or cohesive failure. The filament growth is from the anodic circuit to the adjacent cathode. Frequently, the fiber shorts to the adjacent structure (e.g., through-hole) and, in the process of shorting, are destroyed by the electric potential, only to then grow again. This may produce an intermittant electrical short that is vexingly difficult to find. CAF testing has been limited to testing a specific coupon in an isotherm with constant humidity. No thermal cycling is employed during the test. The circuits are tested in a humidity chamber typically set to 65°C with 85°C relative humidity.

SUMMARY

There are many tests and inspection steps employed to ensure the reliability of a flexible circuit. It is important to note that not all tests are required for every lot. Testing is typically split into two levels: tests required for qualification and tests required for acceptance. Of these two, acceptance testing is

more limited in scope, which helps to reduce some of the testing requirements. An effectively run manufacturing operation is one that rigorously employs statistical process control (SPC) methods. Use of SPC can significantly reduce the need for formal inspection operations by keeping the processes under constant control. Using SPC, it is possible to achieve desired levels of performance and reliability at no extra cost, or even at a reduced cost. Employment of SPC methods is becoming a customer requirement for an increasing number of flex circuit users and is a key conceptual foundation for the ISO-9000 certification program, which is becoming a de facto standard for the world market. **FCT**

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FIFTEEN

Paul Reid's career in printed circuit board fabrication and reliability testing spans 29 years. Paul received a Bachelor in Science degree in 1975 and a Master in Science in 1980 from Rivier College, Nashua, New Hampshire. Paul has worked in Quality and Engineering in managerial roles in New England and Canada. He has created technical animations of PCB fabrication and failure modes induced by thermal excursions in support of reliability testing. His animations have been used internationally for education, technical reports and promotions. Paul is a Program Coordinator at PWB Interconnect Solutions Inc. in Ottawa, Canada, where his duties include reliability testing, failure analysis, material analysis and PWB reliability consulting. He is currently investigating the reliability of microvias in military and lead-free applications and refining a test method for Cyclic Time to Degradation (cT260).

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Chapter 15

Plated Through-Hole Reliability

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INTRODUCTION

Reliability can be defined in broad terms, as a device or activity that meets or exceeds expectations. From a physical standpoint, reliability might be considered to have been achieved when an object is stronger than the forces acting upon it. If the forces applied exceed the physical strength of some feature of a flex circuit, for example, it will fail. The failure may be of the copper interconnections, traces, plated through-holes (PTH) or other via structures or failure of the dielectric material. If the failure occurs sooner than is acceptable the circuit is considered unreliable. In contrast, if the circuit does not fail or fails after its expected life, it is deemed reliable. The goal in circuit fabrication is to fabricate circuits that meet or exceed their expected field life. This measure of relative robustness is the underpinning of reliability testing at the circuit board level.

Reliability and quality go hand in hand, but one does not necessarily beget the other. It is perhaps counterintuitive, but circuits may meet or even exceed all established quality requirements, yet still be unreliable. Conversely, but not often, discrepant circuits sometimes prove to be reliable by testing, in assembly and in the end-use environment in spite of their shortcomings. The higher temperatures required for lead-free assembly have significantly increased the occurrence of

compliant products failing in assembly and earlier, yet proving acceptable in the end-use environment. Consequently an increasing number of OEMs are requiring functional testing to confirm robustness as a condition for procurement. Circuits must meet the specified quality requirements and also pass reliability testing.

One and two metal layer flex circuits are intrinsically robust. However, rigid-flex circuits are, by nature, less robust due in part to their more complex construction. Despite this, they can still be manufactured to perform well, even in lead-free applications. Polyimide material has a high glass transition temperature (Tg) of 250°C or greater and a lesser z-axis expansion than epoxy-based dielectric materials, giving polyimide-based systems an inherent advantage that is reflected in increased robustness in assembly and in the end-use environment. Generally speaking, some of the adhesives used in fabricating flex circuits (e.g., acrylic adhesive) have a low Tg and a high coefficient of thermal expansion (CTE) and are therefore most affected by the thermal excursions of assembly, rework and in the end-use environment.

This chapter provides a review some of the more frequently used bare board (circuit) level reliability tests and the various methods that augment those tests. Accelerated reliability testing by means of thermal excursion will be reviewed in greater depth to include test methods, test parameters, interpretation of results and failure modes.

There are many reliability and environmental test methods like fungus resistance, moisture absorption and others that are applicable in specific instances, but are beyond the scope of this chapter. There is some discussion of these and other topics in Chapter 14 – Inspection and Test of Flex Circuits. Many of these tests can be found in IPC Test Method 650. This chapter will focus on plated through-hole reliability.

PLATED THROUGH-HOLE TESTING METHODS

A number of different tests have been developed and employed over the years to determine the relative reliability of rigid and flexible circuits. Most of these tests are predicated on some thermal excursion, and failure is often measured by some change in conductivity of the plated through-hole as a result of the test. However, there are other test that have been developed that are capable of providing information that cannot be determined by legacy testing methods. The following is an overview of tests used to determine plated through-hole reliability.

THERMAL STRESS TESTING

The standard solder float test (thermal stress test) is easy to perform with inexpensive and readily obtainable equipment and has been the default test for finished boards and base materials since the 1970s. The original goal was to test the adhesion of dielectric to copper traces, but over the years the method evolved to be used as an ad hoc reliability test. The test was designed to simulate solder wave assembly, exposing the sample to a temperature instantaneously and holding the sample at temperature for ten seconds. The test may be repeated any number of times as agreed by the user and supplier (AABUS). Board samples and/or coupons can be used for the test. They are then evaluated by microsectioning random holes within the tested part. The low number of holes that can be reviewed per microsection combined with the randomness of sampling inherent to microsectioning, mainly due to cost and time constraints, significantly impacts this test method's efficacy in terms of finding discrepant conditions. Recent studies related the robustness of materials in lead-free applications, comparing thermal cycling ovens, IST testing and solder float, have unfortunately demonstrated that the thermal stress method can give both false positive and false negative results.

THERMAL STRESS, CONVECTION REFLOW ASSEMBLY SIMULATION

IPC committees developed an alternative method to the solder float test called the thermal cycle oven test. This alternative test is designed to simulate current SMT assembly practices. In testing, the sample is exposed to the thermal profile of convection ovens that are used extensively in HDI assembly. After six thermal excursions to simulate assembly (three cycles) and rework (three additional cycles), microsectioning is performed and the samples are subjected to a microscopic evaluation. The thermal cycle oven test is a more reasonable reflection of the stresses the boards will see in assembly than the solder float method. The method still has the same limitations imposed by the inability of microsectioning to evaluate every hole.

THERMAL SHOCK METHODS

One of the most successful methods for reliability testing of circuit boards, flex circuits and rigid-flex circuits is thermal cycle testing. Two methods are considered here, thermal shock (e.g., thermal cycling ovens, air-to-air, fluidized sand) and DC current-induced thermal cycling, also known as interconnect stress testing (IST). These methods heat the coupon by different means and determine failure electrically. By monitoring changes in resistance, failed coupons may be identified and microsectioned, greatly increasing the likelihood of finding failure sites.

TRADITIONAL THERMAL SHOCK TESTING

Traditional thermal shock testing is performed in a specially designed apparatus that cycles a sample between two chambers, one kept at -40°C and another at held at 130°C. Higher and lower temperatures may be employed if desired. The samples are placed in the apparatus cycled between the thermal

extremes until the end of the test. The cycle time in the apparatus is usually 60 minutes, 24 cycles a day. It therefore takes about three weeks to achieve 500 cycles. The method uses an event detector that measures continuity/conductivity to determine if a circuit has failed. There are, however, concerns that the circuit often fails catastrophically before the event detector registers a failure, reducing granularity of the test results.

Most thermal cycling systems employ an event detector to establish that a failure has occurred. Most event detectors sense an order of magnitude change in resistance/conductivity . Normally the samples are tested as a batch, and testing continues until either all circuits fail or there is an end-of-test number of cycles reached. The results of large changes in resistance triggering a failure and the limitations imposed by batch testing means that the failure site may be damaged significantly in test, thus reducing the effectiveness of failure analysis when using microscopic examination, particularly on those samples that failed early in the test cycle.

In traditional thermal cycling, air-to-air cycling is most common and the air conducts the heat to or from the test coupon. There is a required hold time at temperature extremes to ensure that all coupons are equally heated or cooled before the next half of the thermal cycle. If the hold times are long enough to ensure that the center of mass of all the coupons reach the minimum/maximum temperature requirements, the cycling rate may be increased. From practical experience it appears that thermal excursions degrade copper's mechanical properties (most likely by work hardening or other similar mechanisms) and time at temperature degrades dielectric materials. If dielectric materials delaminate, the copper interconnects are usually stress relieved and it is possible give a false positive result. Microsections are required to review both the interconnect failure and the integrity of the dielectric material. The microsections may be performed on failed coupons, im-

proving the effectives of microsection review over the randomness of coupon selection inherent in solder float and convection oven tests.

HIGHLY ACCELERATED THERMAL SHOCK (HATS)

Highly accelerated thermal shock (HATS) testing is a thermal cycle oven test that maximizes the efficacy of thermal cycling by measuring changes in resistance in milliohms. This greatly improves the granularity of the test and helps more accurately determine the cycles to failure. This batch test method achieves the same low and high temperatures as traditional thermal cycling, but with increased ramp rates which increases the number of cycles per unit time and shortens test times to determine failure, project failure rates and causes. The HATS method is considered similar to thermal shock, but without the need of extended hold times at temperature.

DIRECT CURRENT-INDUCED THERMAL SHOCK/INTERCONNECT STRESS TEST

Direct current (DC)-induced thermal shock, also known as interconnect stress test (IST), is another thermal cycling testing method that has some distinct differences compared with traditional thermal shock tests. The concept of heating a sample and determining cycles to failure is the same, but the IST method requires representative coupons designed with the critical attributes of the board, like layer count hole size, interconnect structures and grid size (structure to structure spacing). The coupons are designed to have hundreds to thousands of interconnections, making the test statistically more representative of the actual board than coupons with only dozens of interconnections. Not only do the coupons have the attributes of the board, they also have internal heating circuits designed to heat the coupons quickly and evenly. This means that every coupon has at least two discrete circuits, one a heat-

ing circuit and the other a sense circuit. The heating circuit is usually designed to find internal interconnect failures, which are failures at the interface between the internal trace the barrel of a PTH. The sense circuit is usually designed to measure damage down the length of the interconnection in the barrel of the PTH. Because the coupons are heated internally the cycle time is reduced to approximately five minutes and 500 cycles are achieved in two days.

IST coupons are designed to ensure that the sensing circuit is sensitive to variations in copper thickness and plating distribution. This allows coupons to be ranked by resistance and selected in a manner that supports a given test goal. For example, for lot acceptance testing, coupons may have resistance measurements in milliohms and then be sorted into high, mid-range and low resistance on a PTH circuit. The high to low ranking, reflects thin, mid-range and thick copper plating respectively in the PTH. Testing two coupons each with high, medium and low resistance ensures that the test sample would bracket thin, mid-range and thick plating representative of the plating distributions between production panels in that production lot. There are other coupon selection methods based on resistance variations, and all allow an intelligent and objective method for coupon selection, maximizing the effectiveness of the test.

The heating circuit, referred to as the power circuit, is also a test circuit in the IST method. The power circuit is tested under an electrical load, while the sense circuit is tested passively, without an electrical load. In practice, as a coupon fails, cracks develop in the circuits causing an increase in resistance. A circuit that exhibits a 10% increase in resistance is considered to have failed. Each coupon is tested separately and testing stops within seconds of reaching a 10% increase in resistance. Measuring and failing circuits with a milliohm of change gives the IST method great granularity and allows failure analysis of a

defect in the process of developing, as opposed to one that has failed catastrophically like those found with an event detector.

Because the IST method stops testing within just a few seconds of achieving a 10% increase in resistance on either the power or the sense circuit, a unique method may be employed to locate the failing interconnection in a coupon. Since the circuit fails with only a 10% increase in resistance, a small current may be applied to the damaged circuit while the coupon is being observed with an infrared camera. The single most damaged/resistive via will be heated to a greater degree than the vias that are not damaged. The result is that the most damaged interconnection produces the hottest spot out of hundreds or thousand of holes. A microsection may be processed on the identified hole, allowing an enhanced ability to find and review both innate and latent defects and improving the accuracy of root failure cause analysis.

An important part of thermal cycle testing is the inclusion of a simulation of assembly and rework element to the test. Submitting coupons to a simulation of assembly and rework is referred to as preconditioning. Preconditioning may be combined with thermal cycle testing, resulting in improved accuracy in confirming or refuting potential circuit robustness through the assembly process. Thermal stress testing and thermal stress by convection ovens are both tests that simulate preconditioning. These tests may be combined with thermal shock or IST to improve the accuracy of the reliability test. However, the IST equipment also has the ability of preconditioning coupons on the tester.

A typical assembly protocol includes three thermal cycles, representing one thermal cycle for each side of the circuit board, perhaps with a hand-soldering step for a connector, for a total of three thermal excursions. Rework may require another three thermal excursions, where a component would need to be removed, replaced and touched up by hand, for a

total of three additional thermal excursions. By convention, six thermal excursions represent assembly and rework in many test protocols. The thermal excursions associated with lead-free assembly and rework are known to significantly degrade both the laminate material and the reliability of circuits. Most reliability testing includes preconditioning as part of the testing protocol. It is possible that in some cases a circuit that is simply subjected to preconditioning may fail the 10% increase in resistance criteria that is used in HATS and IST testing. A prudent method is to start the testing to establish a resistance baseline, then subject the coupons to preconditioning and after completion, resume the thermal cycle test capturing damage induced by assembly and rework simulation. The standard IST protocol actually incorporates preconditioning as part of the test. Preconditioning temperature is typically 230°C for tin lead applications and 245°C or 260°C for lead-free applications.

Testing circuits fabricated with polyimide is a challenge to thermal cycle testing because the material is very robust and the layer counts are usually low. This combination tends to result in reliable circuits in most applications, even lead-free applications. In order to obtain data proving robustness, or to rank variables like hole or grid size, the testing of polyimide circuits requires either extended cycles or higher test temperatures. To ensure a valid and repeatable reliability test, temperatures have been increased by many IST users. Standard flex circuits are tested at 210°C and the temperature is dropped to 190°C if acrylic adhesives have been used in fabrication and the acrylic is found to be significantly degraded by the testing. Rigid-flex with an all-polyimide construction are usually tested at 190°C. Testing at higher temperatures usually produces acceptable results in 500 to 1,000 cycles.

It is normally prudent to test a group of coupons as received and with a control, and then comparing that data to

coupons that have been preconditioned. The preconditioned coupons are logically expected to endure fewer cycles to failure than those tested as-received. The cycles to failure of coupons tested as-received is considered a measure of expected reliability. It is an objective measure of the inherent reliability predicated on the quality of the copper plating, material robustness and design. Preconditioning can normally be presumed to degrade the expectation by a reasonable and perhaps even predictable degree. If even the preconditioned coupon outperforms the coupons tested as-received, the test parameters need to be reviewed for errors. In lead-free applications preconditioned coupons may outperform coupons tested as-received even when significant material damage has occurred in preconditioning or testing.

Cycles to failure data is collected and then subjected to a statistical review. The mean cycle to failure, standard deviation (typically one standard deviation), minimum, maximum, range and coefficient of variation (the standard deviation divided the mean expressed as a percentage) are all calculated. The collected data is then analyzed and evaluated based on logical groupings such as a comparing data from as-received to preconditioned coupons. The goal of most reliability testing is to take an item, such as a PTH, to failure to better understand the mechanisms of failure, which allows for ranking circuits and provides an insight as to the PWB's relative robustness. If there are no failures, although it is a positive outcome, data cannot be compared and ranking of variable is impossible. Compliance and acceptance testing, as part of board procurement, does not require failure, and therefore lacks the insight gained from failure analysis.

Table 15-1 shows how circuits are degraded as a result of preconditioning in terms of cycles to failure. It provides anticipatory guidance relative to the effect of preconditioning on reliability through assembly and rework. The chart is based

	Control	Sn/Pb		Low Temp Pd-Free		High Temp Pb-Free	
Precon	As Rec	3X230°C	6X230°C	3X245°C	6X245°C	3X260°C	6X260°C
Precent	100%	80%	60%	75%	55%	70%	50%
No Material Degradation	500	400	300	375	275	350	250

Table 15-1: Typical reductions in cycles to failure due to assembly and rework simulation.

on the as-received coupons' cycles to failure establishing the expectation which is degraded with more aggressive preconditioning. Properly fabricated flex and rigid-flex circuits should achieve greater than 500 cycles to failure. If cycles to failure are found to be significantly higher percentagewise than the values listed in the table, or if the cycles to failure data is increased with more aggressive preconditioning, it should spark an investigation as to what cause of the anomaly. Material damage, usually manifested as delamination in flex and rigid-flex circuits, is the most common cause of counterintuitive data. Even well-fabricated circuits, (i.e., circuits fabricated with good copper plating, robust material and a conservative design) will degrade by up to 50% after exposure to six thermal excursions to 260°C.

Experience and test results suggest the polyimide circuits are typically robust and should not fail in less than 500 cycles, and can even survive 1,000 cycles. While the IST test is considered viable, cycles to failure requirements for the test have yet to be established by professional organizations. There are number of efforts by North American, European and Asian organizations to establish minimum functional requirements. Cycles to failure requirements are usually established by OEMs that set standards based upon their history, objective testing, competition pressure and corporate goals. High reliability applications seen in medicine, aerospace, military, commercial air and high-end computers have appropriately high cycle to failure requirements and aggressive test schedules. The most

aggressive being testing a coupon for every circuit submitted for procurement.

ACCELERATION TESTING

Establishing appropriate minimum cycles to failure requirements is both an important consideration and a concern. If the test requirements are too aggressive, even otherwise robust products can be rejected. If the test requirements are loo lax, a compromised product may end up being used in production, ultimately resulting in failure in assembly and the field. Establishing the correct requirements is difficult, but there is a method to objectively establish the appropriate cycles to failure based on thermal cycle testing that has been referred to as acceleration testing. Acceleration testing requires that the failure mode be a wear-out type failure due to metal fatigue, rather than failure due to low copper thickness, for example. Using well-fabricated coupons, failure due to wear-out type metal fatigue testing can be performed at three different temperatures below the material's Tg, at 150°C, 170°C and 190°C, for example. A failure curve can be plotted with the results and that plot used to establish how many cycles the circuit would survive in the end-use environment. Knowing the thermal cycles per unit of time can indicate the anticipated time to failure in the end-use environment. From that data, the number of cycles to failure that are required at 210°C in order to exceed the expected field life can be established. The problem with testing of flex circuits is that they frequently do not fail even in thousands of cycles, which severely limits this approach.

Generally, the requirements established for tin-lead assembly have been extended to lead-free applications without concessions for the demonstrated reduction in reliability, which puts pressure on the fabricator to optimize processes in order to survive lead-free assembly. Figure 15-1 shows the typical

Figure 15-1: Typical minimum cycles to failure requirements of different industry/product market segments.

minimum requirements for circuit boards, including flex and rigid circuit boards, tested without preconditioning.

IST TESTING RESULTS ANALYSIS

One of the most powerful tools for reliability testing is found in the performing of multiple tests, which allows the investigator to compare reliability while employing two or more variables. In order to rank processes, materials, fabrications, etc., testing must continue until all groups have had a failure. A 50% failure rate is a common baseline to ensure credible data for predicting long term reliability. Sample sizes for each group range from 6 to 60. However, if there are no failures, testing is usually stopped at 1,000 or 2,000 cycles depending on the testing requirements.

While cycles to failure data is useful for establishing reliability, understanding how the circuits fail (i.e., their failure

mechanisms) is very important to making improvements in the design and processing of the circuit. Cracks develop as copper interconnections degrade during thermal cycle testing. The cracks produce an increase in resistance in the test circuit that is easily measured. One can plot damage expressed as increasing resistance against cycles producing a damage profile. The damage profile is generated by tracking the resistance of the circuits against thermal cycles at the maximum test temperature. The y-axis represents change in milliohms (the top of the graph delineates failure at a 10% change in resistance) while the x-axis is cycles to end of test.

Figure 15-2 is a damage accumulation graph designed to illustrate the seven different types of damage profiles, tagged A through G. The graph has three areas represented by different colors. The pink area indicates greater than a 2% increase in resistance and reflects significant damage accumulated in the circuit. The green area shows damage of a lesser order (less than 2%, but greater than 0%) and/or environmental and tester noise. The results in the blue area are below 0%, meaning that they show increased conductivity, which reflects circuit annealing or stress relieving, which is exhibited by most circuits at the beginning of thermal cycle testing. The graph plots data from circuits that were tested starting after preconditioning and continuing to 500 cycles. Preconditioning (six times) and testing were performed at 230°C,

The damage profile exhibited in circuit A reflects catastrophic failure shortly after the onset of testing. The profile for Circuit B suggests that there was some damage in preconditioning and a geometric or exponential increase in resistance until failure. The profiles for circuits C and D exhibit exponential increases in resistance after onset, with C having an early onset and D having a delayed onset. The profile of circuit E is rarely observed, but is indicative of how a circuit might be stress relieved during an exponential increase in resistance.

Figure 15-2: Damage profiles.

The conditions that can produce significant stress relief during testing include catastrophic failure of another interconnection in the coupon or material damage such as delamination. Coupons F and G show consistent linear damage accumulation until end of test. Note that coupons E, F and G did not fail, but the other coupons failed before 500 cycles.

If we arbitrarily limit the number of sections we can process to three good candidates for microscopic review, those would ideally be coupons associated with profiles A, B and E. Coupon A is indicative of a significant fabrication error contributing to early, catastrophic failure. Profile B, C and D exhibit exponential damage accumulation but Coupon B had the earliest failure. Coupon E is a good candidate for microscopic review, mainly to confirm the presumed material damage in the coupon. The point of this exercise is to show that although cycles to failure is the most useful tool for failure analysis,

damage profiles increase granularity and provide insight into failures and possible causes.

The implementation of lead-free solder has had a deleterious effect on both copper and dielectric material since both show a level of degradation that is not observed with tin-lead solders. In some cases, circuits assembled with lead-free solder degrade to the point of failure in the assembly process and increasingly in the end-use environment. Thus comprehensive reliability circuit testing must include both copper and base material in the testing protocol. While coupons tested using thermal shock methods must rely on more or less random microsectioning for material evaluation, IST coupons have capacitance circuits that allow for measurement of the capacitance between ground planes before test, after preconditioning and at end of test. A 4% decrease in capacitance is usually an indicator of material damage. Measuring changes in capacitance facilitates selection of the most damaged coupons for microscopic examination. Flex circuits frequently fail due to delamination, but more complex rigid-flex circuits may exhibit delamination, crazing or cohesive failure.

The randomness of defects in coupons makes microsectioning, fault identification and failure analysis challenging. Historically, the response to this challenge has been to test a large number of microsections hoping to stumble onto an area that shows evidence of the failure mode. IST coupons, where testing is stopped at a 10% increase in resistance, are not open, but have generally sustained sufficient damage to allow investigators to identify the location of the most damaged interconnect or group of interconnects using a simple power supply and a thermal camera. Typically coupons that fail earliest are of greatest interest for microsectioning. However, robust coupons can be equally instructive. In the evaluation process, the failing circuit is selected and a low current, usually 0.5 amps, is passed through the circuit while the coupon is viewed with

Figure 15-3: Thermal image of failing microvia.

a thermal imaging device. In most coupons, the damaged interconnect or weak link is most resistive and will rise to a temperature a few degrees warmer than the rest of the coupons making it easy to identify. The interconnection that is most damaged and interconnects in the immediate area can then be marked for microscopic examination. Microsections are processed with a mild microetch as a stain to define defects and copper crystalline structures.

Reviewing microsections after thermal cycling is different than reviewing microsections for compliance to requirement or standards. After thermal cycling, the microsections reviewed are from coupons that are know to have failed or are known to be robust. If the coupon passed initial screening, any failures observed are generally assumed to have developed in preconditioning or during testing. The thermal cycle data determines where the circuit is most robust or weakest, but cannot provide the type of information that can be found in the microsection. Thus the microsection is used to better understand the nature of the failure. Cycles to failure is the objective evidence of failure, microsection review is the subjective interpretation of the cycle to failure evidence. Still some care must be exercised in evaluation. For example, if the damaged area of the

interconnection does not appear significant enough to warrant failure, it may be that the sectioning has missed the mark and the wrong feature was sectioned. An alternative explanation may be that the failure is out of plane relative to the failure location. If the damage appears to be slight, the section will typically be ground down further, to the next row of interconnections, and re-evaluated.

Armed with pre-screening data, cycles to failure data, damage profiles and capacitance data, interpretation of microsections is greatly enhanced. Structures and conditions that may have been overlooked in the microsection take on new significance. Failure modes are defined and redefined as data-based experience is gained. Objective data, combined with the subjective microsection interpretation, is a powerful and elegant tool for root cause analysis, process improvement and improved reliability in assembly and in the field.

UNDERSTANDING PLATED THROUGH-HOLE FAILURES

There are many types of board level failures that have been identified by reliability testing. Using cycles to failure data and damage profiles, a number of contributing conditions have been found to influence PWB robustness. The influences, in order of importance, include copper quality (both electrolytic and electroless), material robustness and design. Often copper quality is the most influential of the three, but with lead-free processing, material has risen to compete with copper to be the dominant influence. Since most polyimide is robust, material is usually less of a factor in overall robustness of circuit fabricated with these rugged materials.

In general, failure modes can be categorized by the type of damage observed during microscopic examination. Some failure modes are unique to a type of interconnection, such as the separation between the base of the microvia and the target pad. Other failure modes, such as barrel cracks, may be found

Figure 15-4: Interconnection labels.

in all types of plated via interconnections including PTH, buried vias, blind vias and microvias.

Figures 15-4 through 15-6 represent construction of a rigid-flex board through a rigid section of the board as seen in figure 15-4. There are three types of interconnections, including PTH, buried via and microvia, provided in these illustrations. The PTH representation is of a standard design without fillers or caps. The buried via has been drawn to represent an epoxy-filled buried via that has been planarized and capped. There are two types of microvias shown. One microvia is a standard open microvia with no fill the other is a copper-filled microvia. The dielectric layers (layers two and five) are reinforced with fiberglass to facilitate the illustration of crazing. Finally, the construction has a cover coat rather than a solder mask.

Figure 15-5 provides additional details of rigid-flex construction with the flex section in the center of the board and

Figure 15-5: Rigid and flex layers.

rigid caps. The board represents a multi-lamination process using a third party fill and copper caps on the buried via in order to accommodate outer layer microvias.

The reliability failures illustrated in figure 15-6 are typical failures that would be seen in thermal cycle testing. These representative failures are not evident in the sample before thermal cycle testing. They usually develop during testing. One of the illustrated failures, microvia pull out, is normally exclusive to flex circuits used in lead-free applications. Copper-filled microvias are shown with two counterintuitive failure modes, copper voids with barrel cracks and corner cracks.

COMMON DEFECT MODE REVIEW

The following are illustrations of common defects seen in cross section analysis

Figure 15-6: Rigid-flex failure modes and their locations.

BARREL CRACK

The barrel crack is a common failure normally associated with metal fatigue type damage (fig. 15-7). This is a typical failure mode seen on robust circuits. Damage accumulates slowly over time at a constant rate. Barrel cracks can occur in any interconnection that is not completely filled in the plating process.

CORNER CRACK

The corner crack is related to the barrel crack (fig. 15-8). Even a relatively small crack may produce up to a 10% increase in resistance. The crack almost always propagates from the corner of the dielectric. In tin-lead soldered assemblies the crack propagates up the face of the copper foil, then across the electrolytic copper at a 45 degree angle. However, with lead-

Figure 15-7: Barrel crack.

free applications the crack may become horizontal, cracking into the barrel below the knee of the hole.

INTERCONNECT SEPARATION

Interconnect separation, also referred to as post-separation, is not a common failure mode (fig. 15-9). Typically, interconnections are more robust than the electrolytic copper in the barrel of interconnect structures. If electroless copper is used to metalize the dielectric material, it can normally be determined if the separation occurred before or after the electroless application, directing where efforts should be focused in the process to improve reliability.

MICROVIA TO TARGET PAD SEPARATION

A separation between the base of the microvia and the target pad is the most common microvia failure mode (fig. 15-10).

Figure 15-8: Corner or knee crack.

Figure 15-9: Interconnect or post-separation.

Figure 15-10: Microvia separation.

With careful sample preparation, it may be possible to determine if the separation is above or below the electroless copper, helping to focus efforts to improve the fabrication process.

MICROVIA CORNER CRACK

Corner cracks in copper-filled microvias can be seen in both flex and rigid PWBs (fig. 15-11). The crack is typically found propagating at a 45 degree angle through the area where the copper thins and where the copper dips below the plane of the adjacent traces. Microvias with this typical dip appear to be less robust than those planarized flat (unless the planarization is too aggressive).

MICROVIA VOID

The microvia void condition rarely produces low cycles to failure in PWBs (fig. 15-12). Many OEMs have resolved that

Figure 15-11: Copper-filled corner crack.

Figure 15-12: Copper-filled microvia void with barrel cracks.

this condition is acceptable if minimum copper plating requirements are met. The concern has been that filling the void with plating solution can contribute to conductive anodic filament (CAF) type failures if there are barrel cracks bridging the full thickness of the copper.

MICROVIA PULL-OUT

Microvia pull-out is a failure that is almost exclusive to flex/rigid-flex circuits (fig. 15-13). The microvia to target pad connection is stronger than the target pad copper. A circumferential crack forms around the base of the microvia and a hockey puck-shaped plug is pulled out of the target pad.

DIELECTRIC MATERIAL FAILURES

Failure of materials is almost always the result of an uncontrolled stain-related failure of the material in flex and rigid-flex circuits due to thermal stresses applied to the circuit

Figure 15-13: Microvia pull-out failure.

in the assembly process. Studies with circuits that have been subjected to preconditioning to lead-free assembly temperature show that damage accumulation, expressed as an increase in resistance of copper circuits, is reduced or even stopped if the dielectric material fails first due to any of the following: delamination, cohesive failure or crazing. Interestingly circuits with material damage frequently survive thermal cycle testing to end of test. We call this phenomenon stress relieving material damage. Circuits with material damage may produce false positive results.

DELAMINATION

Delamination between dielectric layers or a dielectric layer and copper is the most common type of material damage observed in flex circuits (fig. 15-14. It normally appears as a failure of adhesion between two layers. Frequently flex circuits will exhibit an adhesion type failure. This failure is usually

Figure 15-14: Delamination.

characterized as a loss bond at a boundary between the adhesive, epoxy or copper. Since polyimide materials are hydroscopic, absorbed moisture may contribute to this failure mode.

COHESIVE FAILURE

A cohesive material failure (fig. 15-15) is best characterized as a failure within a dielectric material as opposed to delamination, which is a failure at an interface between materials. This is a failure within the resin or adhesive and the material appears to be failing internally.

CRAZING

Capacitance measurements of circuits taken as-received, after preconditioning and at end of test suggest that crazing is a type of material damage which can propagate over time. Crazing is the separation of the epoxy from glass fibers (fig. 15-16). It is an insidious type of failure and may be the result

Figure 15-15: Cohesive failure.

Figure 15-16: Crazing.

of aggressive drill or desmear. If copper wicking can be seen in the sample, the crazing was likely present during plating due to improper drilling parameters. Frequently crazing looks like long silver bubbles following glass fibers. Looking at the ends of glass fibers, crazing often presents as half moon cracks. Crazing is not a prerequisite for CAF growth but it does provide a ready and effective path for CAF formation.

SUMMARY

Reliability testing by thermal cycling methods is a time-proven functional test that confirms robustness of flex and rigid-flex circuits through assembly and the end-use environment. The testing augments quality requirements and is frequently used for acceptance, testing the reliability of variables, survivability of circuits in assembly and rework, and field life studies. **FCT**

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Chapter 16

Documentation Needs for Flexible Circuits

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INTRODUCTION

While a documentation package may not be a very exciting subject, good documentation is critical to accurate communication between flex circuit customer and vendor. If the information presented to the flex fabricator is clear and easily understood, the chances of getting the product right on the first pass are greatly enhanced. Unfortunately, flex circuit manufacturers have reported that as many as 75% of the documentation packages they receive require some sort of clarification. As a result, precious time is wasted pursuing important information needed to meet manufacturing targets and customer and fabricator productivity are negatively affected.

The list of things required for a particular circuit design can vary significantly, but there are some items that recur time and again. At a bare minimum, the circuit manufacturer needs to be given the following information in order to complete his manufacturing task properly:

- Product class
- Materials to be used for construction
- Holes required and locations
- Conductor layer count
- Circuit artwork defining signal runs for each layer
- Cross-sectional view of circuit construction

- Circuit outline with dimensions and datums
- Marking requirements, materials and locations
- Bend, flex and crease locations and directions
- Stiffener location and bonding requirements
- Contact and termination finish requirements
- Special processes and/or finish requirements
- Tolerances for manufacturing
- Test point locations
- Special electrical testing requirements
- Special processing requirements
- List of standards and specifications
- Bill of material

This chapter details documentation of important and commonly-cited elements related to design to ensure accurate, complete manufacture of the design that will meet requirements.

PRODUCT CLASS DEFINITIONS

Electronic products are produced for different markets that do not always share the same product acceptability or reliability expectations. As a result, the electronics industry has developed a classification system that specifies what is expected of products for different classes. The system is not intended to be a measure of quality. Quality is a matter of conformance to requirements. Therefore, quality products can be created in each of the classifications within the system.

There are three generally accepted classes of product as defined by IPC standards:

- **Class 1** – consumer products and products for non-critical applications where cost is normally the primary driver
- **Class 2** – higher order products in terms of quality and reliability expectations, including telecommunications, computers and general industrial

• **Class 3** – high-reliability applications including military, aerospace, automotive and medical products

There is a proposal for a Class 4 level, but it is not yet widely adopted.

Defining the class of the product lets the manufacturer know the added controls to apply to the manufacturing process and the level of care they will need in the inspection process to ensure that the customer gets the right product that is best-suited to the application.

SPECIFIED MATERIALS FOR CIRCUIT CONSTRUCTION

While there are only a limited number of flexible circuit materials in wide use, there are many potential candidates and, therefore, a need to constrain the options to meet expectations. When specifying material, the customer should inform the manufacturer of the type of base polymer to be used and the type of adhesive desired (if an adhesiveless laminate is not to be used). The customer also needs to define the type and nature of the conductor material to be used. Normally the conductor material for flex is a copper foil that is rolled and annealed; however, there are many options for making the conductors. It is also important to specify the nature and type of coverlayer material and stiffeners to be used. In short, any material that is to be used in the construction and stay with the final part must be identified.

HOLES REQUIRED AND LOCATIONS

Holes are not always required for flex circuits, but usually they are required for vias or for making connections to leaded components or connectors. As a result, documentation must specify the size, number and location of any holes required for the circuit design. This data is easily extracted from digital

design files and will be critical to the vendor to determine the cost of the manufactured circuit.

CONDUCTOR LAYER COUNT

A large percentage of flexible designs have only a single metal layer. However, a substantial number of flex circuits have two metal layers. Multilayer and rigid flex circuits are not uncommon, so there is also a need to provide layer counts for the circuit design. Layer count is one the obvious indicators of circuit complexity and is important for quoting and production planning purposes.

CIRCUIT DESIGN ARTWORK

Proofing circuit artwork and checking the design rules against requirements are important and necessary conditions for release to manufacturing. Ideally, the information is supplied in digital form in one of the major CAD design tool formats. The CAD design information provides a final definition of what the circuit will look like, where terminations will be located and how they will be shaped. It is also important in case the design needs to be modified or adjusted by the flex manufacturer to compensate for processing. The final design contains information needed to provide an accurate and realistic quote.

CROSS-SECTIONAL VIEW OF CIRCUIT CONSTRUCTION

A cross-sectional or side view of the circuit provides the manufacturer with a scaled view of construction materials. The cross-section also lets the quality control department know what to inspect in terms of circuit layout since it offers a means of predicting overall thickness. Figure 16-1 provides examples of cross-sectional views of various flex circuit constructions. If a stiffener is to be used to reinforce the flex circuit, it should also be taken into account in the cross-sectional view.

Figure 16-1: Cross-sections of common flexible circuit constructions.

COVERLAYER OR COVERCOAT OPENING LOCATIONS

Coverlayer or covercoat openings physically define the features that need to be accessed to attach components, interconnect to another assembly or perform necessary testing. It is key that the documentation package defines all such locations accurately.

CIRCUIT OUTLINE WITH DIMENSIONS AND DATUM FEATURES

The physical outline of the finished circuit needs to be accurately documented to define the periphery of the flex circuit material relative to the circuitry itself. The outline data is used to:

- Directly singulate the circuits from a panel, either by soft-tooling used by numerically-controlled routing machines, cutting blades, lasers or water jet cutters.
- Create hard-tooling, including steel rule die punch tools and/or Class A tool and die punch set technology

The datum features are important reference points to facilitate measurement of the circuit features, especially the outline. It is best if datum features are called out based on the part's internal physical features rather than its external features. This allows inspectors to base their measurements on real features rather than imaginary points outside the part. Multiple datum features are recommended if space allows.

Multiple datum features are also important because flexible materials are dimensionally less stable than rigid materials that are used for circuits. Features on flexible circuits, especially those of larger size, often move relative to each other and the circuit may shrink or grow during processing making predicting the precise location of features increasingly difficult over long distances. On a localized basis, and/or with smaller flexible circuits, the effects are not so great and the part can more easily meet requirements. This approach does not sacrifice any tolerances. It is simply a means of recognizing and accounting for a simple reality of flex circuit manufacturing –dimensional variances. Figure 16-2 illustrates the benefits of multiple datums.

Figure 16-2: Multiple datums facilitate accurate measurement and device placement.

MARKING REQUIREMENTS

The increased use of automation minimizes the need for marking in many applications. However, some designs can still benefit from marking, despite the added cost. When marking is used, the documentation package must accurately define where to locate markings on the circuit. The choice of ink type and color of marking ink must also be defined.

BEND, FLEX AND CREASE LOCATIONS

Flexible circuits are normally bent or flexed in some manner. Knowing where the bending is to occur is important, especially when the flex circuit is to be used in dynamic applications. In dynamic applications, the grain direction of the copper foil normally needs to be accounted for in manufacturing. It has been shown that there is a difference in the dynamic flex life of circuits fabricated with the bend going with the machine direction and those where bends are made transverse to machine direction. Accurate bend or flex information also informs the engineer or technician where and in which direc-

tion to bend the circuit, resulting in easier installation.

It is also beneficial to define the location of permanent bends and/or creases that may be needed, which can be accomplished in a couple of ways. If a marking step is required, special indicating features in the marking circuit artwork can be printed onto the coverlayer or while marking is applied. This facilitates assembly by providing information as to which direction a bend must take. For example, dotted lines can be

Figure 16-3: Indicators provide information as to location and direction of flex circuit folds, facilitating proper assembly.

used to indicate bends in one direction and solid lines can indicate bends in the opposite direction. Similar features can also be made in the metal as part of the circuit. Figure 16-3 shows an example of each of the methods described.

STIFFENER LOCATION AND BONDING REQUIREMENTS

Stiffeners are commonly used to support components mounted onto flexible circuits. When they are required by a design, the documentation package must include size, construction, location and the preferred material to be used to bond them to the flexible base material of the circuit. If any special strain relief techniques are required, such as an epoxy bead along flex to rigid transformations, this should also be cited. The cross-sectional view should also show any strain relief.

CONTACT AND TERMINATION FINISH REQUIREMENTS

Finish on exposed flex circuit conductors can vary depending on how the exposed features are to be used. For example, gold is commonly used as a finish when wire bonding is to be used for direct chip attach or IC packaging applications or when the exposed contacts are to be used for making separable connections to electrical connectors. More often, a solderable surface is all that is required and there are a number of options. Common finish choices include:

- solder
- tin
- silver
- nickel
- palladium
- gold
- various combinations of the above

There are also special organic solderable protective (OSP) coatings, such as benzotriazole, alkylimidazole and hybrid finishes that are mixtures of organic materials and nanoparticle metals. OSP coatings are gaining popularity because of the ease of application and because they offer a means of skirting molten solder coat finishes, such as hot air solder leveling (HASL), that can damage the flex circuit.

TOLERANCES FOR MANUFACTURING

Manufacturing tolerances should be called out in the documentation package. Traditionally manufacturing tolerances are covered in the circuit prints (formerly called blueprints because of the paper color of earlier documents), which provide a complete description of the finished product. Most print formats provide a tolerance block near the title block for the drawing. However, because of the nature of the product, flex circuit tolerances are less stringent than those applied to rigid board constructions. Therefore, tolerances called out in the tolerance block should accurately reflect the capabilities of the finished flex product.

TEST POINT LOCATIONS

The electrical test strategy should be defined in the documentation package. Opinions differ as to how complete a circuit test must be and what kind of test coverage is needed. Some customers are comfortable with testing the nodes at the distal ends of circuit nets, while others demand full and 100% coverage. There is no right answer since either approach might be correct under certain circumstances; however, 100% testing results in increased cost.

Test probes used are likely to leave physical indentations (witness marks) on the metal surface due to the softness of the flex circuit base material. The indentations might be an issue when components are soldered to the board. The effects de-

Figure 16-4: Flying probe circuit that is held taut by edge clamps and lightly tensioned.

pend on the type and thickness of the finish, as well as how long the board is left to sit before soldering. If witness marks may cause concern during receiving inspection, it should be fully discussed with the manufacturer beforehand. Any mutual understanding about these concerns should be detailed in the documentation package. An example of a flying probe set-up for testing a flexible circuit in panel form is shown in Figure 16-4.

SPECIAL ELECTRICAL TESTING REQUIREMENTS

As the industry moves to operating at ever-higher speeds, special tests are needed to ensure performance. Electrical testing requirements such as characteristic impedance validation, high voltage potential withstanding or other non-standard tests should be identified and defined in the documentation. Conditions of testing and test point locations should also be clearly identified.

SPECIAL PROCESSING REQUIREMENTS

Special and/or non-standard processing requirements are occasionally required for flexible circuit designs and should be clearly outlined in the documentation. One example is the use or addition of special tear restraints, such as localized embedding of fibers into vulnerable areas of the circuit.

LIST OF STANDARDS AND SPECIFICATIONS

Standards and specifications are a unique type of glue that provides consistency that holds the industry together. Chapter 17 - Flexible Circuit Specifications lists many of the standards that are commonly applied to the manufacture of flexible circuits. As many as there are, the list provided is hardly inclusive and, on occasion, other specifications may be required. All relevant specifications that will be used to test, evaluate and accept or reject the product should be cited in the documentation package.

BILL OF MATERIAL

A bill of material relative to the final assembly should be included in the documentation package. The bill of material may not be necessary for production, except by a turnkey manufacturer. Although the various hole and surface mount device (SMD) patterns will give clues to the component types used, they are not fully informative and some components or component types may require special attention. The following are key items of information required for each different component used in the final assembly:

- Brief, detailed description of the component. For Joint Electron Devices Engineering Council (JEDEC)-registered outline parts, the JEDEC designation can be provided. *Example: 144-pin ball grid array (BGA), full array contacts, 0.8 mm ball pitch*

- Number of each type of component
- Reference designator from the design, often screen-printed onto the circuit surface to aid in assembly process
- Manufacturer and manufacturer part number for each device, increasingly important as the industry grapples with counterfeit components

SUMMARY

The list of documentation items suggested is comprehensive, but not exhaustive. Since each design is unique, it is inevitable that there will be some information that varies depending on the product. Designers and product engineers will often place special requirements on individual flex circuit designs. The message of this chapter is that a complete documentation package will help to ensure, to the highest degree possible, that the product will be right the first time and every time. The documentation package provided to the vendor is the primary means of communication, and its clarity and completeness will prevent confusion, loss of irrecoverable time and unnecessary expense. **FCT**

SEVENTEEN

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Chapter 17

Flexible Circuit Standards and Environmental/Regulatory Requirements

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INTRODUCTION

Standards are developed to provide a universal groundwork for understanding what products should look like and how they should perform. They are the framework that provides a measure of cohesiveness to an industry; an industrial framework that holds the industry together and establishes requirements for its products and services. Without good standards and specifications, there might never be any certainty as to how a product should look, be constructed and fulfill its performance obligation to the end user.

Most standards are either developed directly by the industry that produces the product, such as the Association Connecting Electronic Industries (IPC) and Japan Electronics Packaging and Circuits Association (JPCA), or by an end-user with significant industry input, such as the military. While standards and specifications provide a common reference point that serves the whole industry, it is important to remember that the ultimate specification for any product is always the one contractually agreed upon between the customer and the vendor, commonly referred to as AABUS (as agreed upon between user and supplier). If not for this simple convention, progress in new materials development would be severely hampered, since changing specifications to include new materials or processes tends to be a long, drawn-out process.

Regulations for the industry come from several sources, including Underwriters Laboratories (UL) and the Restrictions of Hazardous Substances (RoHS) Directive.

Industry compliance on important issues, such as Hazards to Life and Property, are required to obtain a UL Listing and/or RoHS certification. A UL Listing and/or RoHS certification are often required to sell into commercial electronics markets.

STANDARDS AND SPECIFICATIONS

The following is a list of key standards and specifications relevant to the manufacture and use of flexible printed

]wiring boards (PWB) and the raw materials used in their construction. The documents listed are summaries of the

]various standards and specifications. The actual documents should be kept on hand for reference when designing, inspecting or testing flexible printed circuit boards (PCB). There are many documents commonly referred to in the manufacture of flex circuits that are of general interest and much broader in scope. They are often referenced in the documents listed below; however, for the sake of brevity, they will not all be listed here.

Since the specifications relevant to flex circuit manufacture come from two different sources, the industry itself and the military, they are described separately for clarity.

IPC STANDARDS AND SPECIFICATIONS

The IPC has been the primary originator of standards and specifications for the electronic interconnection industry. Recently, the IPC has been restructuring its specifications and documents in an effort to make them more compatible with other industry standards. As a result, new standards are being generated that will replace some of the older standards.

However, since the older standards are likely to remain on blueprints and in other relevant documentation for some time

to come, it is worth knowing the old document numbers as well as the new. The various documents related to flex circuit are described here.

- **GENERAL DOCUMENTS**

IPC-T-50G
Terms and Definitions

While not specific to flex circuits alone, this document provides definitions for the most commonly used terms in the modern electronic manufacturing lexicon. It is a valuable reference document to have for quick clarification of industrial terms.

IPC-TM-650
Test Methods

This document is not specific to flex, but contains the test methods developed by the IPC for dimensional, chemical, mechanical, electrical and environmental characteristics. It is available to download for free at http://www.IPC.org.

IPC-2615
Printed Board Dimensions and Tolerances

This standard provides information on the dimensions and tolerances for rigid and flexible, single-layer, double-layer and multilayer printed boards based on industry capabilities.

IPC-D-325A
Documentation Requirements for Printed Boards

IPC-D-325A encompasses the total documentation package necessary to define an end product printed board, regardless of raw materials, special fabrication requirements, layer count or end product usage, including:

- master drawing requirements
- board definition
- artwork/photo tooling
- solder mask requirements
- legend requirements
- specifications
- automated techniques

The standard also covers documentation of basic board fabrication, heat sink bonding and installation of terminals, eyelets and other hardware.

IPC-A-31
Flexible Raw Material Test Pattern
This test film contains test patterns for:

- dimensional stability
- chemical resistance
- flammability
- flexural endurance
- flexural strength
- tensile strength and elongation
- dialectric constant and dissipation factor
- volume and surface resistivity
- moisture absorption
- insulation resistance
- low-temperature flexibility

IPC-ET-652
Guidelines and Requirements for Electrical Testing of Unpopulated Printed Boards
Electrical test is becoming increasingly important. This document provides information on selecting the test analyzer, test parameters, test data and fixturing required to perform

electrical test(s) on unpopulated boards and innerlayers.

• DESIGN SPECIFICATION DOCUMENTS

IPC-2221A
Generic Standard on Printed Board Design

IPC-2221A is the foundational design standard for all documents in the IPC-2220 series. It establishes the generic requirements for printed board design, component-mounting and interconnecting structures for single-sided, double-sided or multilayer boards. Among the many updates to Revision A are new criteria for surface plating, internal and external foil thickness, component placement and hole tolerances. Expanded coverage is provided for material properties, rules on dimensions and tolerances, via structures and updated coupon designs for quality assurance. The 112-page standard was released in May 2003.

IPC-2223B
Sectional Design Standard for Flexible Printed Boards

IPC-2223-B is designed for use in conjunction with IPC-2221A. It establishes the specific requirments for the design design for flexible printed circuit applications, their forms of component mounting and interconnecting structures. The flexible materials used in the structures comprise insulating films, reinforced dialectric, non-reinforced dialectric and metallic materials. These interconnecting boards may contain single-layer, double-layer, multilayer or multiple conductive layers. Interconnecting boards can be composed entirely of flex or a combination of both flexible and rigid circuits.

Now in Revision C, IPC-2223-B includes updated design rules for panel sizes, hole-spacing, bend radii, shielding, palletization, nonfunctional lands, coverlayer access/spacing and

conductor edge spacing. The document is 24 pages long and was released in June 2004.

IPC-2152
Standard for Determining Current-Carrying Capacity in Printed Board Design

This is a document released in August 2009 that defines the method for determining the current-carrying capacity of printed board designs.

• MATERIAL SPECIFICATION DOCUMENTS

IPC-FC-234
Pressure-Sensitive Adhesives Assembly Guidelines for Single-Sided and Double-Sided Flexible Printed Circuits

This document provides information on available adhesive types. It suggests processes for their proper use and highlights strengths, weaknesses and limitations. It also provides information on how to start implementing their use. It offers guidelines for the use of pressure sensitive adhesives (PSA) in single- or double-sided flexible printed circuits, membrane switches and component attachments. It also describes the types of materials and processes that may be used to ensure proper attachment of flex circuits to housings or other assemblies.

IPC-4562
Metal Foil for Printed Wiring Applications

This document, formerly known as IPC-MF-150, specifies the properties, performance requirements and tests required for each of the eight classes of copper foil (four types of electroplated foils and four types of wrought foils) used in rigid and flexible printed wiring applications.

IPC-4101
Laminate Prepreg Materials Standard for Printed Boards

This document, which replaces IPC-L-108, IPC-L-109B, IPC-L-112A and IPC-L-115B, covers the requirements for base materials (laminate or prepreg). Base materials are used primarily for rigid and multilayer printed boards for electrical and electronic circuits, but may also be used for rigid flex and stiffener material for flex circuits.

IPC-4202A-2010
Flexible Base Dielectrics for Use in Flexible Printed Circuitry

This ANSI-approved document establishes the classification system and the quality and conformance requirements for flexible base dialectric materials used in the fabrication of flexible printed circuitry and flexible flat cables. It provides comprehensive data designed to help users determine both material capability and compatibility. IPC 4202A-2010 is closely aligned with IPC-4203 and IPC-4204. This document supersedes IPC-4202 and IPC-FC-231-C with Amendment 1 included and, in turn, IPC-FC-231C, IPC-FC231B, IPC-FC-231A and IPC-FC-231. It was released in April 2010 and is 32 pages long.

IPC-4203
Adhesive Coated Dielectric Films for Use as Cover Sheets for Flexible Printed Circuitry and Flexible Adhesive Bonding Films

This ANSI-approved standard establishes the requirements for adhesive-coated dielectric film materials used in the cover sheets and flexible adhesive bonding films used in the fabrication of flexible printed circuitry and flexible flat cables. The document provides comprehensive data that will help users more easily determine both material capability and compat-

ibility. IPC-4203 includes adhesive-coated flexible dielectric film material specification sheets that are identified by material type. It is closely aligned with IPC-4202A-2010 and IPC-4204. The document supersedes IPC-FC-232C with Amendment 1 included and, in turn, IPC-FC-232C, IPC-FC-232B, IPC-FC-232A, IPC-FC-232 and IPC-FC-233. This standard is now in revision A. It is 45 pages long and was released in May 2002. Now in revision A

IPC-4204
Flexible Metal Clad Dielectrics for Use in Fabrication of Flexible Printed Circuitry

This document establishes the requirements for metal clad dielectric film materials used in fabrication of flexible printed circuitry and flexible flat cables. The standard provides comprehensive data that helps users determine both material capability and compatibility. IPC-4204 includes metal clad dielectric film material specification sheets that are identified by material type. IPC-4204 is closely aligned with IPC-4202-A-2010 and IPC-4203. It supersedes IPC-FC-241C and, in turn, IPC-FC-241B, IPC-FC-241A and IPC-FC-241. It is 57 pages long and was released in May 2002. IPC-4204 is now in revis A .

• PERFORMANCE AND INSPECTION DOCUMENTS

IPC-A-600
Acceptance of Printed Wiring Boards

IPC-A-600 is one of the oldest IPC documents. It provides visual standards for acceptance of printed wiring boards and includes a special section that highlights flexible circuits. Because many of the acceptance criteria for rigid boards and flex circuits are the same, the rigid board information can also be of value. This four-color document provides photographs and illustrations of acceptable and non-conforming conditions that

are either internally or externally observable on bare printed boards. The most recent document revision has more than 80 new or revised photographs and illustrations, providing coverage on topics such as smear removal, lifted lands and wire bond pads, along with updated and expanded coverage for measling and crazing of printed boards, annular ring requirements, etchback, foil cracks, flexible circuits and minimum foil thickness for conductive patterns. The document synchronizes with the acceptability requirements expressed in IPC-6012B and IPC-6013A. It is 140 pages long and was released in July 2004.

IPC-6011
Generic Performance Specification for Printed Boards

As a generic standard, this document is designed to simplify the process of performance specification by bringing together all of the common points of concern. Other matters of specific concern are provided for in sectional documents.

IPC-6013B
Qualification and Performance Specification for Flexible Printed Boards

This specification follows the format of IPC-6011, but more specifically targets qualification and performance requirements of flexible printed boards. The flexible printed board may be single-sided, double-sided, multilayer or rigid flex multilayer. All of the constructions may or may not include stiffeners, plated through-holes and blind/buried vias.

The rigid section of the printed board may contain a metal core or external metal heat frame, which may be active or non-active.

Now In revision C

IPC-6202
Performance Guide Manual for Single- and Double-Sided Flexible Printed Wiring Boards

This is the first joint standard developed by the Japan Printed Circuit Association (JPCA) and IPC. It covers the requirements and considerations for single- and double-sided flexible printed boards. IPC-6202 includes over 30 figures on accept/reject criteria for flexible printed boards and an appendix on the handling of polyimide-based flexible printed boards. It also includes all seven Japanese Industrial Standards (JIS) test methods referenced in IPC/JPCA-6202. It was released in February 1999 and is 96 pages long.

PAS-62123
Performance Guide Manual for Single- and Double-Sided Flexible Printed Wiring Boards

This is an IEC-approved publicly available standard (PAS). It is identical to JPCA/IPC-6202. This standard covers the requirements and considerations for single- and double-sided flexible printed wiring boards. It is 96 pages long and was released in October 1999.

IPC-TF-870
Qualification and Performance of Polymer Thick Film Printed Boards

This document covers the material, qualification, certification and performance requirements for polymer thick film (PTF), whether printed, extrusion-deposited or otherwise applied for conductors, insulators, resistors and through-hole technology. A good reference for the bookshelf that covers this subject in great detail is *Polymer Thick Film: Today's Emerging Technology for a Clean Environment Tomorrow,* by Ken Gilleo (ISBN 0-442-01220-9).

• FLEX ASSEMBLY AND MATERIALS STANDARDS

IPC-FA-251
Assembly Guidelines for Single- and Double-Sided Flexible Printed Circuits

This document provides guidelines for populating and interconnecting components on flexible substrates, addressing the special needs of both flex and rigid boards. Requirements for various classifications are provided. The guidelines include the types of materials and processes that may be used to ensure proper electronic assembly.

IPC-3406
Guidelines for Electrically Conductive Surface Mount Adhesives

This document includes guidelines for selecting electrically conductive adhesives to be used in the assembly of components to printed circuit boards or similar wiring interconnect systems. It focuses on the use of adhesives as solder alternatives. The process discussion attempts to stay within the bounds of the existing solder assembly infrastructure. Both major types of adhesives, isotropic (conducting equally in all directions) and anisotropic (unidirectional conductivity), are covered. The two major divisions of polymer adhesives, thermosetting and thermoplastics, are also included.

IPC-3408
General Requirements for Anisotropically Conductive Adhesive Films

This document covers requirements and test methods for anisotropically conductive adhesive films used to bond and electrically connect components. Applications include:

- flexible PWB-to-glass
- flexible PWB-to-rigid PWB

- flip chip-to-glass
- flip chip-to-flexible PWB
- flip chip-to-rigid PWB
- fine-pitch surface mount device (SMD)

JPCA DOCUMENTS

JPCA-DG03
Performance Guide for Single- and Double-Sided Flexible Printed Wiring Boards

This JPCA standard provides the requirements for single- and double-sided flexible printed wiring boards. The document is specific for single-or double-sided flexible printed circuits prepared by lamination of a base dialectric film with copper on one or both sides of a board, including types with no adhesive layer and with conductor patterns formed by the subtractive method or the build-up method.

ASTM INTERNATIONAL STANDARDS

ASTM International, formerly known as the American Society for Testing and Materials, like IPC, is another globally recognized leader in the development of consensus standards. To date roughly 12,000 ASTM standards are in use globally to help improve product quality, enhance safety, facilitate market access and trade, and build consumer confidence. Many ASTM standards are relevant to flexible circuit manufacture. The following are few ASTM standards that may be of interest to flexible circuit manufacturers and users.

ASTM D4800-94(2005)
Standard Guide for Classifying and Specifying Adhesives

The guide offers a method of identifying adhesives in order to give the industry a system that can be used universally

for materials. It also provides a means of specifying these materials by using the standards presented in the guide. The guide is based on the premise that adhesives can be arranged into broad generic families using basic properties to arrange the materials into groups, classes and grades. This classification system is intended to identify adhesives, but not for the selection of materials. Material selection should be made by those who have expertise in the adhesives field after careful consideration of the design and the performance required of the part, the environment to which it will be exposed, the attachment process to be employed, the inherent properties of materials not covered in this document and economic factors.

ASTM-E1559
Standard Test Method for Contamination Outgassing Characteristics of Spacecraft Materials

This standard test method covers a technique for collecting data to characterize the release of outgassing products from spacecraft materials. This technique will determine the total mass flux evolved by a material when exposed to a vacuum environment and the deposition of this flux on surfaces held at various specified temperatures. A test procedure for collecting data and a test method for processing and presenting the collected data are included as part of the standard.

ASTM-F2112 - 02(2011)
Standard Terminology for Membrane Switches

This standard defines terms that are commonly used in the membrane switch industry that are often not applicable to traditional flexible circuits.

ASTM-F1681 - 07a
Standard Test Method for Determining Current Carrying Capacity of a Conductor as Part of a Membrane Switch Circuit

This standard is designed to help determine the current-carrying capacity (CCC) of circuits, an attribute of circuits that is used by designers and manufacturers of electronic interface circuitry to ensure that the membrane switch can reliably handle the loads occurring in normal use and under extreme circumstances. A thorough understanding of CCC allows manufacturers to take CCC into account when developing design rules for membrane switches. Failures due to exceeding the CCC of a circuit may take the form of significant changes in conductor resistance, insulation breakdown (shorts) or conductor breakdowns (opens). Since a number of design parameters, such as trace width, ink film thickness, etc., affect the final test results, determinations should be applied only to specific designs, rather than to a general combination of materials.

ASTM-F1683-09
Standard Practice for Creasing or Bending a Membrane Switch, Membrane Switch Flex Tail Assembly or Membrane Switch Component

Bending or creasing of membrane switches or their components can affect their appearance, mechanical integrity or electrical functionality. This practice simulates conditions that may be seen during manufacture, installation or use.

This standard establishes a method for the creasing or bending of any part of a membrane switch. Because uncontrolled bending and/or creasing of a circuit can result in damage, this test standard helps define the limits. Specific areas of testing include membrane switch flex tails and other components of a membrane switch that may be subjected to bending or creasing.

ASTM-F1689 - 05
Standard Test Method for Determining the Insulation Resistance of a Membrane Switch

Insulation resistance is useful for design verification, quality control of materials and workmanship. Low insulation resistance can cause high leakage currents. High leakage currents can lead to deterioration of the insulation, false triggering of the associated input device or both. Specific areas of testing include conductor-dielectric-conductor crossing points, close proximity conductors and other conductive surfaces, such as shielding or metal backing panels.

PRIMARY MILITARY SPECIFICATIONS

In past years, the military announced its intention to use industrial specifications for its products whenever possible in order to simplify procurement and lower cost. Therefore, the documents referenced here may be of archival interest only. Nevertheless, because of the numerous long-term military contracts in place, these standards may have ongoing significance in certain situations or are based on contractual agreements and are therefore included.

MIL-STD-2118
Military Standard, Flexible and Rigid-Flex Printed Wiring for Electronic Equipment

This document, one of the earliest standards on flex and rigid flex circuit design, contains valuable information on standards and guidelines for designing flex and rigid flex circuits for military applications.

MIL-P-50884
Military Specification, Printed Wiring, Flexible and Rigid flex

This specification provides performance requirements and

defines testing for flexible and rigid-flex circuits for military applications. The document also provides information on the artwork required to build qualification boards.

SUMMARY OF STANDARDS AND SPECIFICATIONS

These documents comprise the minimum resources that should be kept on hand as ready references for the designer/user of flexible circuits. There are other documents of value and importance referenced within these documents that may be added to this list. For example, specifications for rigid board laminates and pre-pregs, which are used both as elemental parts of rigid-flex constructions and as stiffeners for flex circuits, might also be included on this list. What is most important is that the documents be used and not simply purchased and shelved. A thorough understanding of these documents will provide an important footing for the successful implementation of flexible circuits into reliable electronic products.

INDUSTRY COMPLIANCE AND REGULATIONS

Material suppliers, circuit designers, product fabricators, board assemblers and OEMs are becoming more sensitive to new environmentally-focused regulations and safety requirements for flexible printed circuits worldwide. The most comprehensive regulatory requirements are outlined in RoHS and safety and flammability standards are controlled by UL. The following is a brief review of these regulations and safety requirements:

RESTRICTION OF HAZARDOUS SUBSTANCES DIRECTIVE (ROHS)

The Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment 2002/95/EC, commonly referred to as the Restriction of Haz-

ardous Substances Directive (RoHS), was adopted in February 2003 by the European Union. The RoHS directive took effect on July 1, 2006 and is required to become law and be enforced in each member state. This directive restricts the use of six hazardous materials in the manufacture of various types of electronic and electrical equipment. It is closely linked with the Waste Electrical and Electronic Equipment Directive (WEEE) 2002/96/EC, which sets collection, recycling and recovery targets for electrical goods and is part of a legislative initiative to solve the problem of huge amounts of toxic e-waste.

RoHS Restricted Substances – Maximum Concentration Values:

Lead: 0.1%
Cadmium: 0.01%
Mercury: 0.1%
Hexavalent Chromium: 0.1%
Polybrominated Biphenyls (PBB): 0.1%

Polybrominated Diphenyl Ethers (PBDE): 0.1%

Most agree that WEEE makes reasonable sense. However, according to scientifically complete life cycle analysis, some elements of RoHS, such as the restriction of lead from electronic solder, are having an opposite effect on the problem of toxic e-waste.

- **North America**

California has passed SB 20: Electronic Waste Recycling Act of 2003 (EWRA), which prohibits the sale of electronic devices that are prohibited from being sold under the EU RoHS directive after January 1, 2007. EWRA has a narrow scope. It includes LCDs, CRTs and the like, and only covers the four heavy metals restricted by RoHS. EWRA also has a restricted material disclosure requirement.

Effective January 1, 2010, the California Lighting Efficiency and Toxics Reduction Act applies RoHS to general purpose lights, including, "lamps, bulbs, tubes, or other electric devices that provide functional illumination for indoor residential, indoor commercial, and outdoor use."

Other US states and cities are debating the adoption of similar laws. Several states have mercury and polybrominated diphenyl ethers (PBDE) bans already.

- **Asia / Pacific**

China Order No. 39: Final Measures for the Administration of the Pollution Control and Electronic Information Products (China RoHS) has the stated intent of establishing restrictions similar to those in place in North America, but takes a very different approach. In EU RoHS products in specified categories are included unless specifically excluded. In China RoHS there is a list of included products to which the regulations apply. This list, known as the catalogue (see Article 18 of the regulation), is a subset of the total scope of electronic information products (EIP). Initially, products that fall under the covered scope must provide markings and disclosures as to the presence of certain substances, even though these substances are not (yet) prohibited. There are some products that are EIPs that are not in the scope of EU RoHS, such as radar systems, semiconductor manufacturing equipment, photomasks, etc. The list of EIPs is available in Chinese and English. The marking and disclosure aspects of the regulation went into force on March 1, 2007.

UNDERWRITERS LABORATORIES INC.

UL was founded in 1894 and is chartered as a not-for-profit organization without capital stock under the laws of the state of Delaware. Its purpose is to establish, maintain and operate laboratories that examine and test devices, systems and materi-

als to determine their relation to hazards to life and property, and to ascertain, define and publish standards, classifications and specifications for material, devices, products, equipment, constructions, methods and systems affecting these hazards.

• UL Standards Affecting Electronic Base Materials, Laminates and Subsequent Circuitry.

UL746A: Polymeric Materials - Short Term Property Evaluations

UL 746B: Polymeric Materials - Long Term Property Evaluation Polymeric Materials

UL 746C: Polymeric Materials - Use in Electrical Equipment Evaluations

UL 746D: Polymeric Materials - Fabricated Parts

UL 746E: Polymeric Materials - Industrial Laminates, Filament Wound Tubing, Vulcanized Fibre, and Materials Used In Printed-Wiring Boards

UL 796F: Flexible Materials Interconnect Constructions

• UL Standards Technical Panels

UL has formed Standards Technical Panels (STP), which are balanced consensus bodies that provide input into the development and maintenance of standards. The membership of an STP includes representatives of materials suppliers, fabricators, end users, government agencies, testing and standards organizations and general interest, such as consultants, academics, scientists, etc. The STP reviews proposed changes, provides comments and votes on proposed changes to a standard.

Fully developed proposed additions or revisions to a standard are incorporated into a proposal bulletin and sent to the STP for review and balloting. A fully developed proposal is one that contains a rationale for the recommended addition or revision and specific suggested wording for the new requirements. The proposed text should be in legislative format, unless the change is obvious.

If a proposed addition or revision is not fully developed or is technically flawed, UL will return the proposal to the originator for further development.

COMMENTARY ON REGULATIONS AND COMPLIANCE

The flexible circuitry supply chain should be fully aware of the restrictions regarding hazardous materials as well as other safety and environmental issues related to the products they manufacture. Familiarity with RoHS and UL Standards highlighted in this section is necessary to ensure full compliance with these restrictions. **FCT**

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References

Books and Periodicals:

Alvino, W. Plastics for Electronics McGraw-Hill NY 1995

ASTM. "Standard Test Method for Ductility Testing of Metallic Foil," ASTM E 796, Annual Book of ASTM Standards, Philadelphia, PA, 1981

Banks, P. and Thatcher, W. "High Resolution Photoimageable Covercoats for Flex Applications," pp 21-31 Proceedings FLEXCON'95

Bert, E. "PALCore: A Cost Effective High Volume Multilayer Flex and Rigid Flex Technology," pp. P9-5-1 to P9-5-5 Proceedings IPC EXPO 1995

British Patent No. 4681 "Improvements in or Connected with Electronics Cables and the Joining of Same" Filing date February 27, 1903

Casson, K. "Flex Circuitry Manufacturing- Sheet Processing or Roll to Roll?" pp 137-142 Proceedings of the Technical Program FLEXCON'95

Coombs, C. Printed Circuits Handbook, 4th Edition "Part 9 Flexible Circuits," McGraw-Hill NY 1996

Corrigan, K. "Flex Circuitry in Portable Systems" p1611-1617 Proceedings of the Technical Program, NEPCON West, 1992

Deforest, W.S., Photoresist Materials and Processes, McGraw-Hill, 1975

DiStefano, T. et al. "Multilayer Flexible Circuit Technology for High Performance Electronics," pp P9-3-1 to P9-3-6 Proceedings of the Technical Program IPC EXPO 1995

DiStefano, T. and Fjelstad, J. "Novel Uses of Flexible Circuit Technology in High Performance Electronic Applications," pp 164-169 Proceedings European Joint Conference V, 1995

Edwards M., Electronic Materials Handbook, Volume 1 "Flexible Epoxies," p 817-821 ASM International, 1989

Engelmaier, W. Posting on IPC Technet 24, Aug 26, 2007

Engelmaier, W., "Results of IPC Copper Foil Ductility Round Robin Study," IPC-TR-484, The Institute for Interconnecting and Packaging Electronic Circuits Lincolnwood IL April 1986

EPA. Solders in Electronics: A Life-Cycle Assessment Summary, 2005
http://www.epa.gov/opptintr/dfe/pubs/solder/lca/index.htm

Fjelstad, J. “Flexible Circuits as an IC Packaging Medium,” Proceedings 4th IPC National Conference on Flexible Circuits Proceedings 1998

Fjelstad, J. Engineers Guide to Flexible Circuits, Electrochemical Publications 1997 Fjelstad, J. “Advanced Flex Circuit Design Principles,” pp 127-132, Proceedings PCB Design Conference, March 1995

Fjelstad, J. and DiStefano, T., “Flex on Chip for High Density Chip Packaging,” Proceedings IPC National Conference on Flexible Circuits, May 1995

Fjelstad, J., et al, “Multilayer Flexible Circuits with Area Array Interconnections for High Performance Electronics,” pp24-28 Flexible Circuits Engineering Jan-Feb 1996

Fjelstad, J. “Trends in Semiconductor Packaging,” pp 102-108, Semiconductor International, December 1996

Fjelstad, J. “Design Guidelines for Flexible Circuits,” Electronic Packaging and Production, p 32-34, August 1988

Fjelstad, J. “SMT and Flexible Circuits,” Printed Circuit Fabrication, August 1989 p45-48

Fjelstad, J. “Flexible Thinking” Columns, CircuiTree Magazine, 1996-2006

Geissinger, J, et al. Tape Based CSP Package Supports Fine Pitch Wirebonding

SEMI Technology Symposium: International Electronics Manufacturing Technology (IEMT) Symposium Proceedings Semicon West 2002

Gilleo, K. “The Chemist in Electronics,” Circuits Manufacturing, March 1987, p27-30

Gilleo, K. Flexible Circuits Handbook, Van Nostrand Reinhold, NY 1991

Gilleo, K. Polymer Thick Film, Van Nostrand Reinhold, NY 1996

Goldie, W. Metallic Coating of Plastics, Vol II, Electrochemical Publications UK 1969

Gurley, S. Flexible Circuits Design and Applications, Marcel Decker, NY 1984

Hayden, T., New Liquid Crystal Polymer (LCP) Flex Circuits to Meet Demanding

Holden, H. “A Design Technology Innovation-The Power Mesh Architecture for PCBs.” The Board Authority-CircuiTree, Vol. 2, Number 4, Dec 2000, pp-42

Holden, H. 2007a. Proceedings, First International Occam Process Conference, San Jose, CA, Oct 16, 2007

Holden, H. 2007b. "Will 3D ICs Replace PCBs? CircuiTree Magazine, Nov 2007, pp. 38-40

IPC. "Flexural Fatigue and Ductility, Foil," Test Method 2.4.2.1, IPC Test Methods

Manual IPC-TM-650, The Institute for Interconnecting and Packaging Electronic Circuits, Lincolnwood, IL, August 1980

Reliability and End-Use Applications Requirements Proceedings: International Conference on Advanced Packaging and Systems (ICAPS) 2002

Heatherton, J. "Plating Methods and Applications for Double-sided Flexible Circuits," pp. P9-6-1 to P9-6-6 Proceedings of the Technical Program IPC EXPO 1995

Jasinski, R. "Flexible Photoimageable Coverlay," pp57-65 Proceedings: FLEXCON' 94

Karnezos, M. et al, "Flex Tape Ball Grid Array," pp 1271-1277 Proceedings IEEE Electronic Components and Technology Conference, 1996

Keating, J. "Rigid Flex- An Answer to Dimensional Instability," Proceedings IPC National Conference on Flexible Circuits, May 1995

Lau, J. Flip Chip Technologies, Chapter 14 "A Compliant Chip Size Packaging Technology," pp387-412 McGraw Hill NY 1995

Light, D. and Kresge, J. "Integrated Flex: Rigid Flex Capability in a High Performance MCM," pp430-442 Proceedings 1994 International Conference on MultiChip Modules

Magee, A. "Testing of Adhesiveless Laminate Materials for Automotive Applications," Proceedings IPC National Conference on Flexible Circuits, May 1995

Margelewitcz, C. "Mechanical Punching of Vias in Flexible Circuits," pp175-181 Proceedings FLEXCON' 94

Numakura, D. Flex circuit technology reports 1999-2006

Parker, D. "Flex Circuit Interconnection Development," pp242-249 Proceedings of the Technical Program, NEPCON West 1993

Patterson, T. "Polymers for Flexible Circuit interconnecting," pp103-108 Proceedings: FLEXCON' 94

Schaper, W., M. D. Glover, and M. Kabumoto, "Comparison of the Interconnected Mesh Power System (IMPS) and Buried Stripline Interconnect Topologies." Proc. 2001 Int'l Conference on High Density Interconnect and System Packaging, 2001, pp. 58-63

Scott, Otto J. The Creative Ordeal, Atheneum, NY, 1974

Shepler, T. and Roberts, S. "Flexible Circuitry Substrates," p726-739 Proceedings of the Technical Program, NEPCON West 1992

Shepler, T. and Casson, K., "Flexible Printed Boards," pp578-596 Electronic Materials Handbook, Volume 1 ASM International, 1989

Singer, A. et al. "MCM-L Cost Reduction Strategies at Sheldahl (Multek)," pp183-191, Proceedings International Electronics Packaging Conference, 1995

Sterns, T. Flexible Printed Circuitry, McGraw-Hill, NY 1996

Sutherland, M. "Choosing the Proper Flexible Interconnection," pp69-72 Electronics Packaging and Production, January, 1995

Tummala, R. and Rymaszewski, E. Microelectronics Packaging Handbook, Van Nostrand Reinhold, NY 1989

Parker, D. "Flex Circuit Interconnection Development," p242-249 Proceedings of the Technical Program, NEPCON West 1993

www.floridacirtech.com/Databases/ pdfs/omikronmarket.pdf

Beigle, S. "Alternate Metal Finishes for Wire Bond and Soldering Applications," (viewable at www.alphametals.com/products/lead_free/PDF/ipc3.pdf)

Johal, K. et al. "Impacts of Bulk Phosphorous Content of Electroless Nickel Layers to Solder Joint Integrity and Their Use as Gold and Aluminum Wire Bond Surfaces," Proceedings Pan Pacific Microelectronic Symposium 2004 pp155-165

National Technology Roadmap for Electronic Interconnections 2005

Specifications:

IPC-T-50G Terms and Definitions

IPC-2615 Printed Board Dimensions and Tolerances

IPC-D-325A Documentation Requirements for Printed Boards

IPC-A-31 Flexible Raw Material Test Pattern

IPC-ET-652 Guidelines and Requirements for Electrical Testing of Unpopulated Printed Boards

IPC-2221A Generic Standard on Printed Board Design

IPC-2223A Sectional Design Standard for Flexible Printed Boards

IPC-FC-234 Pressure-Sensitive Adhesives Assembly Guidelines for Single-Sided and Double-Sided Flexible Printed Circuits

IPC-4562 Metal Foil for Printed Wiring Applications

IPC-4101 Laminate Prepreg Materials Standard for Printed Boards

IPC-4202 Flexible Base Dielectrics for Use in Flexible Printed Circuitry

IPC-4203 Adhesive Coated Dielectric Films for Use as Cover Sheets for Flexible Printed Circuitry and Flexible Adhesive Bonding Films

IPC-4204 Flexible Metal-Clad Dielectrics for Use in Fabrication of Flexible Printed Circuitry

IPC-A-600 Acceptance of Printed Wiring Boards

IPC-6011 Generic Performance Specification for Printed Boards

IPC-6013 Specification for Printed Wiring, Flexible and Rigid flex

IPC-6202 IPC/JPCA Performance Guide Manual for Single- and Double-Sided Flexible Printed Wiring Boards

PAS-62123 Performance Guide Manual for Single & Double-sided Flexible Printed Wiring Boards

IPC-TF-870 Qualification and Performance of Polymer Thick Film Printed Boards

IPC-FA-251Assembly Guidelines for Single and Double-sided Flexible Printed Circuits

IPC-3406 Guidelines for Electrically Conductive Surface Mount Adhesives

IPC-3408 General Requirements for Anisotropically Conductive Adhesives Films

MIL-STD-2118 Military Standard, Flexible and Rigid flex Printed Wiring for Electronic Equipment

MIL-P-50884 Military Specification, Printed Wiring, Flexible and Rigid flex

Other References:

Company Design Guides:

Lenthor Design Guide for Flexible Circuits

Minco Design Guide for Flexible Circuits

Nitto Denko Design Guide for Flexible Circuits

Nippon Mektron Design Guide for Flexible Circuits

Rogers Selector Guide for Circuit Materials

Sheldahl (Multek) Design Guide for Flexible Circuits

TAB Design Guide, 3M Corporation

Tech-Etch Design Guide for Flexible Circuits

Workshop and Conference Proceedings:

Course handbook, IPC Flex and Rigid flex Workshop.

Course handouts, E.I. Du Pont Seminar on Flexible Circuits.

Proceedings of IPC National Conference on Flexible Circuits 1995

Proceedings of FLEXCON 1995

Proceedings of IPC National Conference on Flexible Circuits 1996

Proceedings of FLEXCON 1996

Proceedings of IPC National Conference on Flexible Circuits 1997

Proceedings of FLEXCON 1997

Proceedings of IPC National Conference on Flexible Circuits 1998

Proceedings of IPC Flex and Chips Conference 2004