Chapter 39

Significance of Developments in New Substrate Materials

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The widespread developments in integrated circuits have resulted in different requirements for the substrate materials. To overcome these problems of cost pressure, higher density, the move to surface mounting, increased signal speeds and more heat, the range of standard substrates of reinforced polymers or ceramics have been modified, and a range of new materials developed. In addition, many special substrates are now being built up whilst producing the circuit and mechanical engineering skills used, rather than wet chemistry. This paper sets to put these developments in substrate materials into context to see their significance.

The test of significance in this case is in a business sense. Will the developments improve profitability or clear away problem areas to permit other techniques?

Circuit substrates are products that are totally dependent on the electronics industry for their existence and future. They are the basic raw materials that the PCB and hybrid industries convert into carriers which mechanically support active and passive devices, and which contain the customised interconnection patterns to link the devices together in an assembly. Any changes in these products have to arise from the changes in equipment design, improvements in the electronic devices themselves, and modifications to the packages that contain the devices.

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The major driving forces in electronics are lower costs and higher performance. In striving to meet these needs, important developments are occurring such as Very Large Scale Integration (VLSI) and more specialized customization using Application Specific ICs (ASICs). These developments are creating problems for dependent components such as circuit substrates, and also problems in judging the importance of the innovations in electronics. The developments are naturally exciting, and many papers are published and presented at conferences etc. by enthusiasts, which often leads to a perception of topics being much more important than they actually are. This confuses company strategists who have to determine which developments are significant for their products and which will remain small niche markets for specialist companies.

Before looking at the developments we should look at the significance of substrate materials in the context of the whole electronics industry.

ELECTRONIC EQUIPMENT MARKETS

Currently the value of the worldwide electronic equipment production is $476 bn, and this is forecast to grow at 8.5%-9% pa through the next decade. The USA production accounts for about 38% of that figure, and therefore developments in this market must be significant.

However, from the breakdown of this production (Figure 1) it can be seen that the USA is not representative of the world market, because of the strong Military/Aerospace sector which currently accounts for 27% of the USA production.

By 1997 this is forecast to reduce to 14% because of the extraordinary growth in the Electronic Data Processing (EDP) section. The Military sector has traditionally governed the PCB market in America, but it should be noted that what is significant for the USA Military is often not desirable for the rest of the world. Companies who want to sell on a world basis may consider it more significant to be involved with other market sectors that have more universal opportunities.

Many of these markets are now becoming as large as the whole electronics industry was a few years ago, and these sectors are often developing their own unique methods of packaging and interconnection which are leading to specialist substrate materials and techniques.

The most dominant sector is computers, which are a large proportion of the production in all the regions of the world. The developments in computers are of even greater significance than just EDP because they are also key factors in modern telecommunications, industrial, and even some consumer applications.

The size and growth of the overall equipment market naturally tempts company strategists into planning entry into the "Electronics Market". For chemical companies this usually means entry at the substrate level. However, what is ignored is that much of the added value occurs in the design and final assembly of the finished black box. PCBs and Hybrids account for only 2.5% of the overall electronics market, and the total value of substrates involved in these two sectors only accounts for some 0.8% of the finished equipment value, and therefore appears to be a very insignificant factor.

However, they are vital to the overall systems, and it would be a great mistake to consider them as becoming less important. In fact, the opposite would appear to be the case. When the dual in-line package (DIP) was the most important IC package the other components tended to be in a support or service role. With VLSI, the system designer will have to pay greater attention (not less) to these other components if the advantages inherent in IC technology are to be fully exploited. Already, it is possible to see the growing interdependence between the IC die, its package, and the interconnection substrate.

These developments obviously create problems for the substrate manufacturer, but they can also offer significant opportunities for companies to exploit these demands and produce satisfactory new materials.

Developers, however, must assess their products from the viewpoint of the basically conservative equipment manufacturers. Many new products can be substituted for existing ones, and give an improvement, but often do not succeed because the gain is judged to be marginal. Changing materials for circuitry involves a lot of long term, expensive testing to verify the usefulness, long term reliability, and compliance to specifications.

As a rough rule, products only succeed if they give a four to five fold improvement. This may be a five times price reduction or property improvement, or half the price and a three times property improvement.

SUBSTRATE PROBLEMS RESULTING FROM IC DEVELOPMENTS

The main problems can be summarized as follows:

- Cost reduction pressures.
- Wider range of new IC packages.
- More integration on the chip.
- Need for surface mounting.
- Higher speeds of operation.
- More heat produced.

COST REDUCTION. One of the major trends in the introduction of ICs has been the rapidly falling cost, which has not been matched by any other components, especially by the PCBs where the cost per interconnect made on a PCB is about 1,000 times that of an interconnection made on a VLSI chip. There are many cost reduction developments going on with the standard substrates, but these are now very mature products and improvements are limited.

In BPA we are regularly analyzing worldwide prices of PCBs, particularly those with fines lines (6 mil and below). The prices are compared against interconnection density, which covers line and space dimensions, numbers of holes, number of layers with allowance made for component areas, etc. At higher circuit densities the price increases rapidly, and virtually seems to be hitting a barrier. Much of this extra cost comes from the rapid reduction in process yields as the PCB manufacturer tries to get finer lines. Whilst this is primarily a PCB problem, assistance in improving PCB yields has to come from the substrate manufacturer by better control of consistency, dimensional stability, surface flatness, copper bond characteristics etc. These developments are not glamorous, but are significant to the circuit manufacturer, the OEM and, therefore, ultimately to the material supplier.

Most of the new materials now being evaluated to improve the other properties of high speed and heat all tend to be more expensive, and this is going to further aggravate the cost situation. Systems manufacturers therefore are considering whether they can afford to go for more expensive PCBs, or whether they should have some intermediate level of packaging such as multichip modules, which can cope with the higher density, speed and heat, and permit the usage of a lower cost, simpler PCB.

A cost reduction area that could have significant opportunities for chemicals companies is the interest in cheaper track generation systems such as screen printed conductive inks and the conductive pastes that are being used to replace plated through holes (PTH). Copper-based inks are already being used to form crossovers and simple circuits, and the use of thick film techniques of multiple layer printing is being evaluated to replace some multilayer circuits.

WIDER RANGE OF NEW PACKAGES. Apart from the 3-4% of chips worldwide that are used "naked", the remainder are supplied in a package which transforms the silicon chip into a manageable device and affords it protection, both mechanical and chemical.

For many years the standard package was the Dual In Line (DIP) and the plated through hole (PTH) glass epoxy laminate has proved very successful as a carrier base for this package. However, with increasing complexity and performance of the chip, new packages are being developed which have different requirements for their substrates. At the end of the decade the idea of a standard IC package probably will no longer be valid, and equipment manufacturers will select one of several alternatives to best suit their needs, e.g., pin count, electrical performance, cost or a combination of these factors. Furthermore, advanced sectors like computers, military and telecommunications are evolving their own individual packaging and interconnect solutions accentuating the move away from a single standard package concept.

The BPA forecast of the distribution of these packages in the mid 1990s is given in Figure 2 based on the number of IC packages. This shows a large drop in the proportion of through hole mounted packages. However, it should be noted that the overall market numbers will have trebled over this period.

MORE INTEGRATION ON THE CHIP. This has been a major trend in electronics for a number of years, and is achieved mainly by reducing the dimensions of the devices, usually transistors, on the ICs.

Reducing a device's linear dimensions by a factor of 2 reduces chip area by a factor of 4, doubles operating speed, reduces power consumption by a quarter, and the cost/performance ratio improves by a factor of approximately 8 times. Currently the achievable number of functions in an IC doubles every one to two years. This is having a major effect on the pin counts of IC packages, and already we are seeing a number of packages with more than 100 pins.

The problem that this places on the substrate circuit is that finer conductors and features will be required. Primarily, this is a problem for the PCB and Hybrid manufacturer who has to refine and develop new methods of track generation.

As already stated, the assistance that substrate manufacturers can give for this problem is to improve the mechanical properties of flatness, warp, dimensional stability, and the supply of thinner copper layers with better adhesion to retain the bond of the narrower tracks.

Copper foils of thickness 5 microns are available, but are not popular because of the problems of handling. A newer process "Metclad" can give laminates with 2 microns of copper. In addition, a number of processes that vacuum-deposit a thin layer of metal are being developed. However, versions of these products have been available for some time, but the usage still remains low. Most of the pressure for fine line circuits can be met by PCB producers

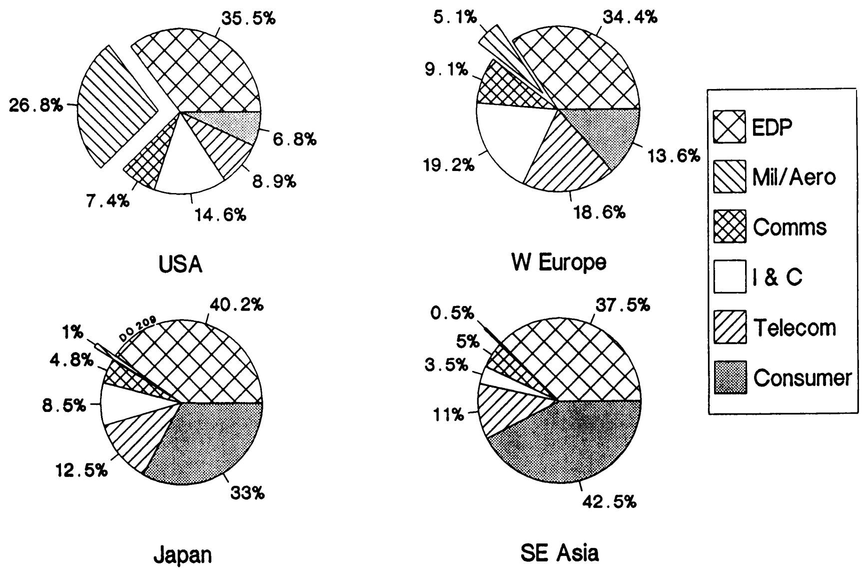

Figure 1. Worldwide Electronic Equipment Production Value by Business Sector and Region: 1987. (Courtesy of BPA Technology and Management Ltd.)

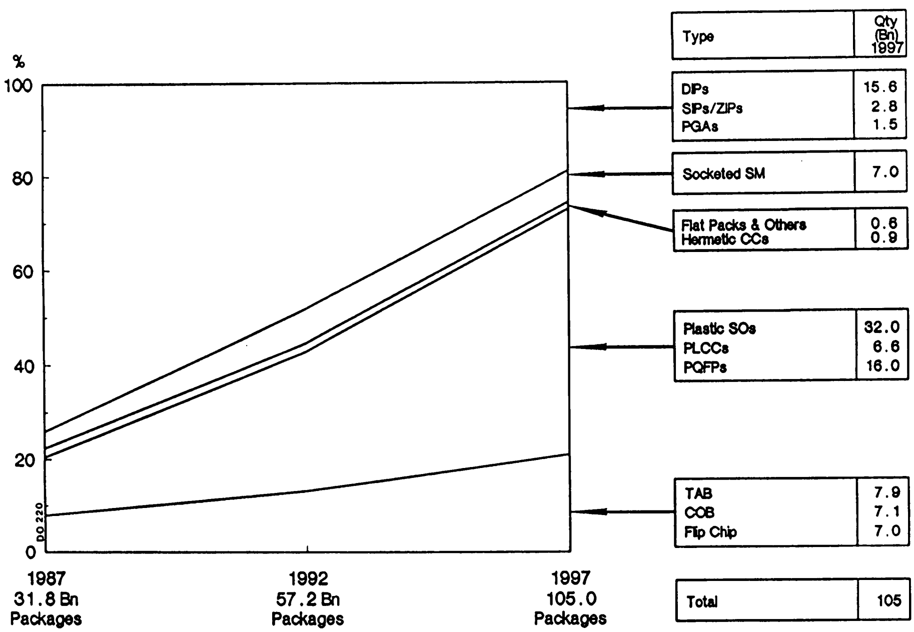

Figure 2. World IC Package Types 1987 - 1997. (Courtesy of BPA Technology and Management Ltd.)

improving their techniques or by using additive processes. The very thin copper is really for the very difficult situations.

In the case of ceramics, developments in the low sintering temperature, co-fired multilayer materials will assist in increasing circuit density. A "green" tape is produced using a mixture of ceramic with a separate glassy phase to aid densification. Other ceramics such as mullite and cordierite may be added to modify other properties such as the dielectric constant. The tape can be printed and fired using conventional thick-film equipment, and can be laminated together in a simple standard press. This opens up the process to the whole Hybrid industry, and with the advantages of multilayer circuits obtained at a cost claimed as half that of conventional cofired systems this development looks significant.

SURFACE MOUNT TECHNOLOGY (SMT)

SMT has been used in the hybrid industry since the late 1950s. Nowadays, however, SMT implies the assembly of surface mountable components onto organic substrates such as glass epoxy and phenolic paper. Surface mounting makes more efficient use of substrate area through the use of smaller components and the elimination of large PTH's, because only smaller via holes will be required. As the IC complexity, customization and pin count increase there will be no alternative interconnection technology that can cope.

THE TWO APPROACHES TO SMT. There are two approaches to SMT. The first of these is the "value engineering" approach which is basically a move to SMT for cost reduction/miniaturization reasons. The IC often is very similar to that previously packaged in DIP form, with the same number of pins, and the customization still takes place on the PCB.

By taking this value engineering approach to its extreme with the total replacement of all through-hole components by their surface mounting equivalents, reductions in PCB sizes of between 60% and 70% can be achieved. However, the performance improvements are limited and, although a great many of the current SMT implementations have taken this approach, many have found SMT a less than satisfactory alternative to insertion.

In contrast, large performance/cost improvements are available from using the second approach. This is the "designing on silicon" approach whereby customization occurs at the IC level, and the PCB is used merely as an interconnection media. Although this leads to more complex chips, higher pin counts, and serious packaging problems concerning lead pitch, heat dissipation, and hermeticity it also leads to big improvements in cost and performance. SMT is the only viable way to use these packages, and it is only by using this approach that the true benefits of SMT will be seen.

FUTURE TRENDS IN SMT. In the longer term, further integration on silicon will be the key underlying drive behind the continued growth of the electronics industry. It is clear that the adoption of SMT is no longer an option to be considered only when time permits; it is an inevitable requirement for competitive cost/performance design now facing all moderate and large scale manufacturers.

By the mid 1990s surface mounting will be an extremely important method of production throughout the world, and the rapid switch from the present through hole mounting systems to surface mounting will occur in the late 1980s and early 1990s.

Without doubt, substrates will form an important part of SMT introduction. In general, improvements are required in mechanical properties such as stiffness, dimensional stability, flatness and, above all, consistent properties.

MISMATCH OF THERMAL EXPANSION. The thermal expansion mismatch of organic substrates and leadless ceramic chip carriers has been widely reported, and a great deal of development work was carried out. However, the actual number of these packages used worldwide is small, and many of those overcome the problem by using clips and sockets.

It is much more of a problem in the USA, because of the military influence, but there are now a range of products designed to cope with this weakness, such as laminates with polyimide/Kevlar or reinforced substrates with copper/invar/copper foils, or alternatively, use of compliant surfaces.

This situation is now satisfactory for the OEMS, but whilst a few companies will produce these special grades it is very doubtful that all the development time and money spent on this problem will be recouped. However, this preoccupation with expansion did raise a lot of interest in the Tg of materials and emphasise its importance in dimensional stability.

Generally, some improvement in Tg will be required, partly because this will help retain the mechanical properties over a wider temperature range, and partly because the soldering of surface mounting components often puts a large heat load on the entire board and not just on one surface.

SUBSTRATES FOR HIGH SPEED OPERATION

At present the number of IC's that are operating fast enough to create problems for the substrate is small, but by the mid 1990's it is estimated that 9%-10% of IC's will be in this category. Satisfactory operation at high signal speeds depends to some extent on the track geometry, but largely on the substrate material.

Digital processors, which operate by means of a stream of pulses, are now operating at high speeds (10-100 MHz clock rates), and at these rates, signals are propagated as an electrical wave system travelling through the substrate, the air and the metal conductor. The substrate now becomes a key factor.

The dielectric constant of the substrate is the prime property because the propagation speed of the signal is inversely related to it. At these speeds the system has to be designed as a transmission line which must match the impedance of the devices used. Impedance mismatch can lead to reflected signals, and hence to signal distortion. The characteristic impedance of the line is also dependent on the dielectric constant, and for the devices now being used higher impedances are required and, therefore, low dielectric constant substrates. In addition, it is also important to have low-loss materials to prevent distortion of the pulses.

When designing these high speed interconnection circuits the dimensions of the copper track, the separation between tracks and ground planes, and the dielectric thickness all come into the calculations. It is therefore vital that the material should be consistent so that these dimensions remain stable and uniform and the tolerances can be maintained.

The dielectric properties of substrates depend heavily on the chemistry of the constituent raw materials. The presence of polar chemical groups within the molecules increases the dielectric constant. The relatively simple molecular structures of polyethylene (CH_2 - CH_2) and polytetrafluorethylene (CF_2 - CF_2) would be expected to have low dielectric constants. Epoxy resins and polyimides have relatively high dielectric constant values since they have complex molecular structures.

The propagation velocities, which are inversely related to the square root of the dielectric constant, are shown in Figure 3.

This Figure shows that the fluorinated polymers are the best, with inorganic ceramic products having a low propagation velocity. An interesting product based on PTFE is "Goretex" from W.L. Gore, a fibre containing air which reduces the dielectric constant. The fibres are woven into a fabric which is then incorporated into the laminate, giving enhanced high speed characteristics. Other thermoplastic polymers are good, partly because they are pure and not reinforced. In the case of flexible films, however, speed will be decreased because of the adhesive that has to be used to bond on the copper foil. The new polycyanurate resins look promising, with much better speed characteristics than other rigid laminates.

These are a new range of laminating resins produced from cyanate ester resins which are thermosetting monomers which can co-react with epoxy resins. The cured polymer has a low dielectric constant (2.8) and high Tg (250°C). When reinforced with quartz or glass fibres the dielectric properties fall but are still much better than current standard laminates. Although the Tg is near that of polyimides, processing and the properties of toughness, adhesion, etc. are greatly improved.

The high speed characteristics of ceramics are being improved by coating their surfaces with polymers such as polyimides and newer materials specifically developed for this purpose such as Dow's bis (benzocyclobutene) which has a dielectric constant of 2.7 and a low moisture uptake.

To increase the impedance for device matching, narrow tracks are desirable, and of course this also helps with the density of leads from higher functional devices. However, as tracks get closer the problems of cross talk get worse, and more ground screening is required.

Uniform cross section can also be obtained using additive or semi-additive techniques, and this method is becoming very popular for high performance circuits. Accurate tracks with widths of 1 to 2 mil (25 to 50 microns) can be obtained using this technique.

Wire also has accurate geometry, having been drawn through a die, and for high performance systems coated wire is increasingly being used. The wire is laid on the surface using computer controlled heads. An example of this technique is "Microwire" from PCK which gives very dense circuits with controlled impedance mounted onto heat sinks to remove the heat. The original "Multiwire" system has now been adapted to use a thin coaxial cable with a Goretex dielectric, giving a very high propagation velocity.

HEAT REMOVAL

The result of higher integration on a chip with faster processing, leads to the generation of more heat. At present, it is estimated that 3-4% of all IC's are running hot enough to create problems for the substrate. By 1995 this figure is expected to have risen to 6-7% of all IC's, mainly because of the increasing circuit density. There is a strong move from the Bipolar ECL (Emitter-coupled logic) systems to CMOS, which generates less heat, but this is merely permitting more functions to be included, and the heat problem keeps increasing. As a result, substrates come under pressure because they have to be able not only to withstand the higher temperatures but also to conduct heat away from the chip to prevent the circuitry from reaching temperatures where they cease to function.

In this respect, organic polymers are very poor, as seen in Table I. It can be seen that even the worst ceramic is about 100 times better than most polymers.

The only useful materials for heat removal are metal or ceramics. The ceramics obviously can be used as a substrate material in their own right, and beryllia is the standard for this kind of application. Now, other materials such as Aluminium Nitride and Silicon Carbide are being developed to replace beryllia because of its reputation as a poisonous product.

Table I Thermal Conductivity of Substrates Dielectrics and Conductors

Material	Thermal Conductivity (W.m/m2.°C)
Copper	390
Beryllia (95%)	200
Aluminium	200
Aluminium Nitride	180
Alumina (96%)	20
Polyimide Glass	0.35
Epoxy-Glass (FF14)	0.23

Aluminium Nitride is looking very promising, and there are many companies worldwide developing these substrates. This promises well for the OEMs, but as the market for this product is relatively small it is inevitable that many of these potential suppliers will not have commercial success.

Ceramics are also being used in conjunction with resins. Ceramic papers have been developed in Japan, and ceramic fibre reinforced polymers in the USA. Resin impregnated porous ceramic is another Japanese development aimed at high heat resistance and better dielectric properties.

Although metals are good heat conductors, they obviously must have some electrically insulating layer added to make them into a useful circuit substrate. However, as seen from Table I, good electrical insulators are also good thermal insulators. Even a thin layer of insulation greatly reduces the conductivity of the composite structure.

Even with only a few mils of an FR4 or epoxy resin coating, the conductivity of a 62 mil (1.5 mm) thick sheet of copper drops to 5-8 from the 390 for the metal itself. The conductivity of steel (55) is reduced to a value of 12-18 when coated with porcelain.

It is clear, therefore, that if significant amounts of heat have to be removed from a polymer based circuit then the best way is to cut access holes through the polymer to get the package into direct contact with the metal heat sink.

In the future, the very hot IC's will be packaged in a thermally efficient module or in a multichip module, which will then be mounted on a more conventional substrate.

COMBINATION OF PROBLEMS

From the previous sections it is clear that solutions exist for the separate problems arising from IC and Packaging developments.

Fine line circuitry can be obtained from current materials, and particularly with thin copper foils. Additive systems can take this further. In addition, multichip modules may be used for the most severe situations.

Surface mounting of plastic packages is quite feasible with current standard materials, and improvements in mechanical properties will enhance this. Where leadless ceramic chip carriers have to be used there are now satisfactory products available. The real problems with surface mounting are to cope with the placement accuracies and inspection, and as such do not involve the substrate.

Higher operating speeds will require new materials for the substrates, but there are products available to cope with present requirements.

Heat does create problems for substrates, and either ceramics have to be used, or else a metal core with direct access to the hot package or to the chip must be employed, to bypass the extremely high thermal insulation effects of polymers. Therefore where problems occur on their own they can be overcome. However, usually a number of problems occur together and interact with each other.

The two major problems are speed of signal propagation and thermal conductivity. The relationship between these properties for a number of the substrate solutions is shown in Figure 4.

This Figure shows that whilst ceramics are useful for heat transfer, they have poor speed propagation. This result may seem odd, since silicon is the base for present IC's, but in practice the poor propagation speed is counterbalanced by the very short distances that the signal has to travel on the chip. Polymers have much better speed characteristics, and this is why there is development going on to combine ceramics with polymers such as polyimide.

The poor heat transfer characteristics of polymers has been seen in Figure 4. Combining polymers with metals gives only marginal improvements. Only direct-access through-holes in the insulator can produce improved assemblies. Even then, the conductivity is less than that of the base metal because some attachment material will be used.

The merit of using PTFE for high speed signals is clear. When PTFE has air introduced, as in the Goretex fabric, then the speed properties are greatly enhanced; but, unfortunately, the fabric generally has to have a resin binder, and the position of Goreply shows how severely the epoxy resin degrades the speed.

The development product with Goretex coaxial cable laid down with the Multiwire process shows great promise, as a dielectric constant of 1.3 can be obtained giving a propagation speed of 26 cm/nanosecond, which is 88% of the speed of light.

Other resins may be used, such as the polycyanurates, and developments are in hand combining this with Goretex. The propagation speed of this combination would be near to that of PTFE, and could be a little higher.

Obviously, the most significant factor of all is the potential size of the market for these special substrates. In our definition, these specials include the high speed types and also the high Tg laminates such as Polyimide, BT (Bis maleimide triazine) and the high Tg epoxies. At present, these products account for 4% of the total worldwide value of substrates, but this number is forecast to rise to about 12% by the mid 1990s. These are high-value products, and in area terms this sector will still account for only about 4% of worldwide substrates by the mid 90s.

It is becoming clear that to meet the OEM's requirements which now nearly always have a combination of problems, these problems will be resolved by building up the substrate as the circuit is produced. Different layers will be added to cope with high speed signals, or to stiffen the board or to modify the thermal expansion. Heat removal will be done through heat pillars or openings in the dielectric. In Japan, fibre optical cables are being

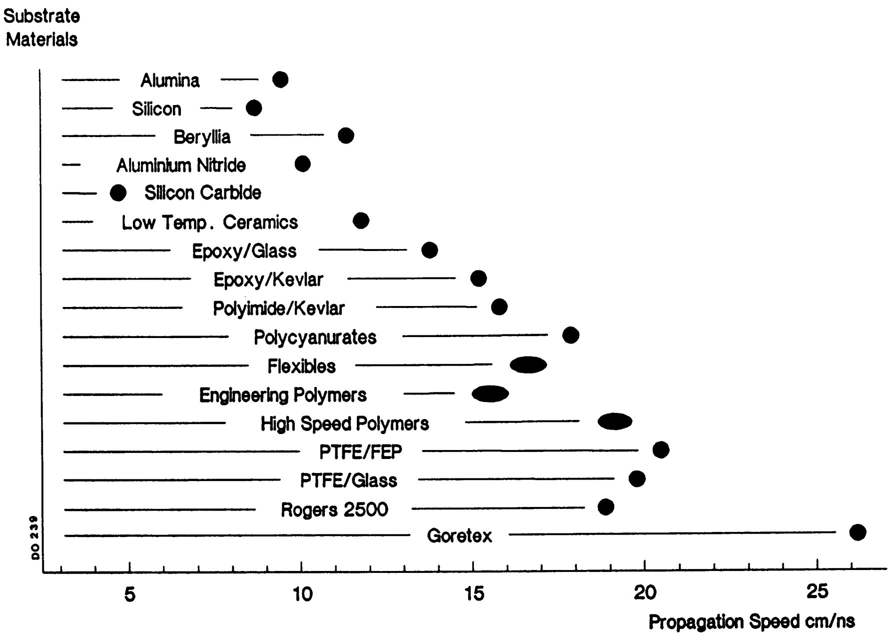

Figure 3. Propagation Speed of Substrate Materials. (Courtesy of BPA Technology and Management Ltd.)

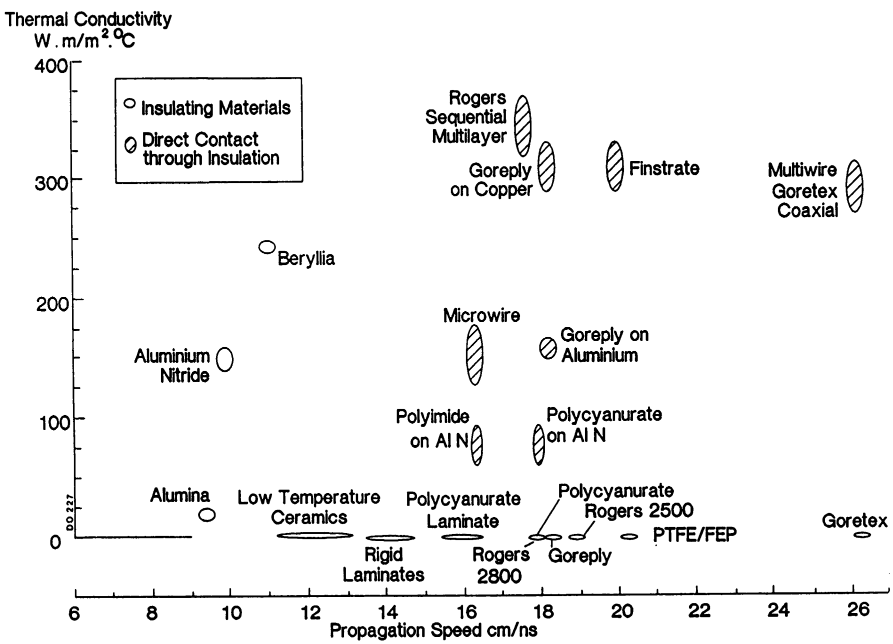

Figure 4. New Development Materials. Heat/Speed Comparison. (Courtesy of BPA Technology and Management Ltd.)

In Polymeric Materials for Electronics Packaging and Interconnection; Lupinski, John H., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 1989.

embedded in the substrates, and it is quite possible that Automated Discrete Wiring (ADW) connections can be made on the surface to enable high speed operation and to permit quick circuit modifications.

Because of speed requirements, the substrate will have to be assembled with tight thickness and physical tolerances. This type of substrate circuit now effectively becomes a component, and the board structure has to be built up as the circuit is produced. The substrate production therefore will take place at the PWB manufacturer, and this is where the added value will occur. Although some new materials will be included, at present their use seems to be restricted to specialised niche areas. In general, however, standard materials can be used, a fact of life which is not advantageous to substrate suppliers.

CONCLUSION

The assembly of the new composite substrate circuits is a market sector that scarcely exists at present. Because it relies on a knowledge of materials, bonding techniques, etc., some materials manufacturers are considering that the most significant move for them could be to move into this sector and actually build the circuits themselves.

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