

# CHALLENGES IN LITHOGRAPHIC MATERIALS AND PROCESSES

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(continued on page 43)

In the last decade, major advances in fabricating VLSI electronic devices have placed increasing demands on microlithography, the technology used to generate today's integrated circuits. In 1976, state-of-the-art devices contained several thousand transistors with minimum features of 5 to 6  $\mu\text{m}$ . Today, they have several million transistors and minimum features of less than 0.7  $\mu\text{m}$ . Within the next 10 to 15 years, a new form of lithography will be required that routinely produces features of less than 0.25  $\mu\text{m}$ . Short-wavelength (deep-UV) photolithography and scanning electron-beam, X-ray, and scanning ion-beam lithography are the possible alternatives to conventional photolithography. However, each needs new resists and processes. When deep-UV photolithography is implemented, it will represent the first widespread use in manufacture of a lithographic technology that requires an entirely new resist technology. We describe the development of a resist system that meets all requirements of the deep-UV technique.

## Introduction

A modern integrated circuit is a complex three-dimensional structure of alternating, patterned layers of conductors, dielectrics, and semiconductor films (Appendix A). This structure is fabricated on an ultrahigh-purity wafer substrate of a semiconducting material such as silicon (Si). To a large degree, the performance of the device is governed by the size of the individual circuit elements. As a general rule, the smaller the elements, the higher the device performance. (Panel 1 defines acronyms and terms.)

The device structure is produced through a series of steps that precisely pattern each layer.<sup>1,2</sup> These patterns are formed by lithographic processes that consist of two steps:

**Panel 1. Acronyms and Terms**

A	acid	n-type	semiconductor material that is an electron donor
A <sup>+</sup>	positive-acting photogenerated species acid	N <sub>2</sub>	diazo group
ASA	speed-rating system for photographic film, established by the American Standards Association (now known as the American National Standards Institute)	NO <sub>2</sub>	nitro group
BOC	butyloxycarbonyl	O	oxygen
C	carbon	OH	hydroxyl
C-S	carbon-sulfur bond	P	hydrophobic protective group
CH <sub>2</sub>	methylene group	p-type	semiconductor material that is an electron acceptor
CH <sub>3</sub>	methyl group	PAG	photoacid generator
CO <sub>2</sub>	carbon dioxide	PAC	photoactive compound
deep-UV	short wavelength	PEB	post-exposure bake
Hg	mercury	R	substituent
<i>hν</i>	light	S	sulfur
I	dissolution inhibitor	Si	silicon
ISO	speed-rating system for photographic film, established by the International Organization for Standardization	SO <sub>2</sub>	sulfur dioxide
MOS	metal-oxide semiconductor	SRAM	static random-access memory
<i>n</i>	a variable denoting the number of times the unit in parentheses is repeated; generally signifies that the material is a polymer	<i>t</i>	<i>tert</i>
		<i>T<sub>g</sub></i>	transition temperature of glass
		TBSS	poly(4- <i>t</i> -butoxycarbonyloxystyrene sulfone)
		TMAH	tetramethylammonium hydroxide
		UV	ultraviolet
		VLSI	very-large-scale integration

- Delineate the patterns in a radiation sensitive thin-polymer film (i.e., a resist).
- Transfer that pattern using an appropriate etching technique.

Figure 1 is a schematic representation of the lithographic process.

**Technology Trends.** Remarkable progress has been made in the fabrication of microelectronic devices. This is especially true of the lithography technology used to generate the high-resolution circuit elements that are characteristic of today's integrated circuits.

In 1976, state-of-the-art devices contained 4,000 to 8,000 transistor elements and had a minimum feature size of 5 to 6 μm (micrometers). These devices were

patterned by photolithography using either contact printing or, the then relatively new, one-to-one projection printing. Today, devices with several million transistor cells are commercially available and are fabricated with minimum features of 0.7 μm or smaller. Figure 2 illustrates this trend.

Surprisingly, photolithography is still the technology used to fabricate microelectronic chips. Step-and-repeat 5× or 10× reduction cameras or highly sophisticated, one-to-one projection printers are the dominant printing tools.

**Progress in Lithography.** There is, perhaps, no better example than lithography to illustrate the uncertainty associated with predicting technological direction

and change. In 1976, it was generally believed (albeit, not by everyone) that photolithography could never produce features smaller than about 1.5 to 2.0  $\mu\text{m}$  with high chip yields in a production environment. The current belief is that conventional photolithography [that is, g and i line, where  $g\lambda = 436 \text{ nm}$  (nanometer) and  $i\lambda = 365\text{-nm}$  wavelength light] will be able to print features as small as 0.5  $\mu\text{m}$  and will remain the dominant technology well into the 1990s.

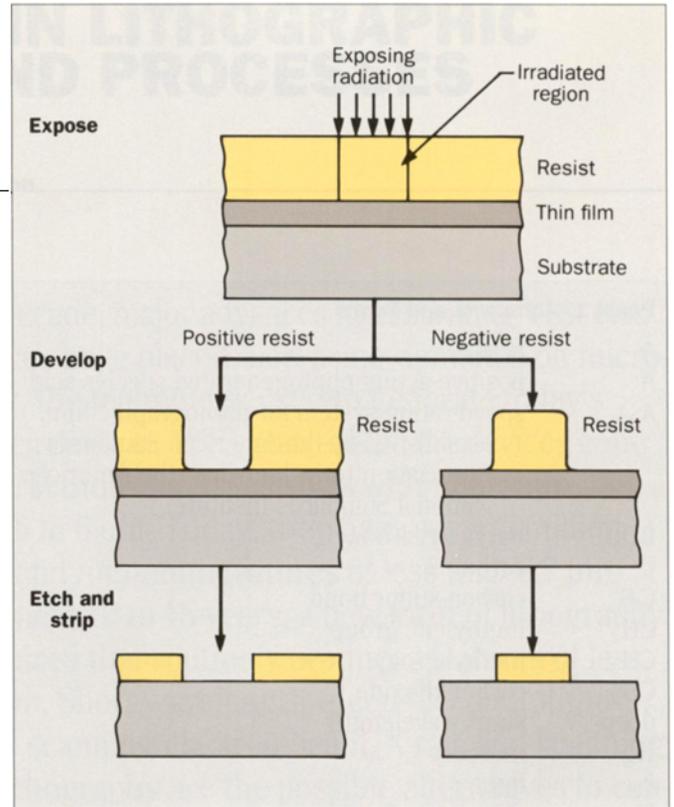
The highest resolution of a printing technique is governed, at the extreme, by the wavelength of the light (or radiation) used to form the image. Shorter wavelengths yield higher resolution. The same physical principles also govern the resolution limits in microscopy.<sup>3</sup>

The same basic, positive photoresist has been in pervasive use since the mid-1970s. This resist consists of a photoactive compound that belongs to the diazonaphthoquinone chemical family and a novolac resin (Figure 3). It will likely be the resist of choice for several more years, because of the high cost of introducing a new technology. This cost, which includes the cost of developing and implementing new hardware and resist materials, is a strong driving force that is pushing photolithography to its absolute resolution limit and extending its commercial feasibility.

#### Alternatives to Conventional Photolithography

The technological alternatives to conventional photolithography are largely the same as they were a decade ago: short-wavelength photolithography, or scanning or projection electron-beam, X-ray, or scanning ion-beam lithography. It is not the intent of this paper to discuss these lithographic technologies in detail. Instead, we briefly summarize each of them here.

**Deep-UV Photolithography.** In the past decade, the major advances in short-wavelength (i.e., deep-UV) photolithography have been improved quartz lenses and high-output light sources for projection cameras. Several step-and-repeat reduction systems that use high-brightness laser sources have been designed or built. Because it is

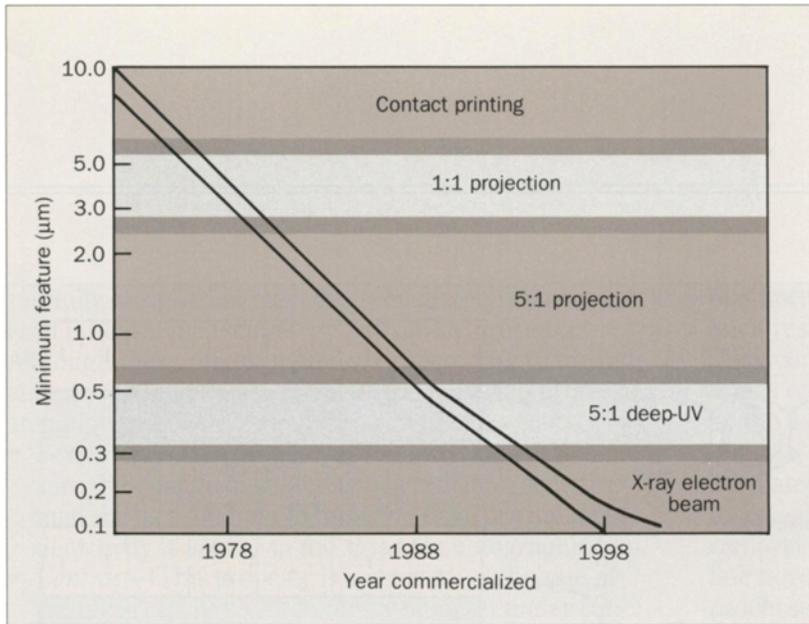


**Figure 1.** The lithographic process is used to generate the intricate patterns needed to fabricate a modern integrated circuit. This process is similar to photography, where a thin radiation-sensitive polymer film (a resist) is irradiated with patterned radiation, and the resulting chemical reactions alter the solubility of the resist in a given solvent. If the solubility increases, a positive image is formed; decreased solubility produces a negative image. The resulting three-dimensional relief image is then used as a mask for the etching steps.

not practical to correct for chromatic aberrations in quartz lenses, the systems that use refractive optics require a light source that has a very narrow bandwidth [i.e., less than 0.03 $\text{\AA}$  (angstrom)].

The tools for deep-UV photolithography use laser sources that can provide such narrow bandwidths with enough intensity to accommodate resists that have sensitivities of 20 to 30  $\text{mJ cm}^{-2}$  (millijoules per square centimeter).

Alternatively, some work is also being done on one-to-one reflective projection systems that use conven-



**Figure 2. Rapid and continuing improvement in the performance of very-large-scale integrated circuits is achieved by reducing the size of the individual circuit elements. We show the size of the smallest geometry in advanced devices as a function of the year the device was first available commercially. The lithographic technology used to print the device pattern is also noted for each size range.**

tional, wide-bandwidth, mercury arc sources in the 200- to 260-nm region. Because the intensity of these sources is less than that of the laser sources, more sensitive resists (i.e., less than  $10 \text{ mJ cm}^{-2}$ ) will be required for high throughput. (We will discuss sensitivity later.)

**X-Ray Lithography.** Early work in X-ray lithography followed the general strategy of conventional, one-to-one optical projection systems and used electron-beam bombardment X-ray sources. However, thermal considerations limit the power from such sources. Also, to minimize the penumbral shadowing and other physical effects that limit resolution, the distance between the source and mask-wafer combination must be relatively large, which makes the incident flux on the wafer small. These limitations require the use of resists with sensitivities of less than  $5 \text{ mJ cm}^{-2}$ .

Both the wavelength used and the extremely high sensitivity requirement limit the chemistries available for resist design, and only negative materials have satisfactory sensitivity. Although these negative resists are able to demonstrate less than  $1 \mu\text{m}$  of resolution, they are limited to features of at least  $0.5 \mu\text{m}$  or larger.

Recent work in X-ray lithography has been directed toward step-and-repeat systems that use high-intensity synchrotron and laser-based radiation sources. (A synchrotron is a charged-particle accelerator.) Both types of sources are capable of producing X-rays in the wavelength region of interest. When compared to other

lithographic hardware options that have submicrometer capabilities, the tools that use these X-ray sources are economical for manufacturing devices. In addition, the brightness of these sources is high enough to permit the use of resists with a sensitivity of from  $50$  to  $100 \text{ mJ cm}^{-2}$ .

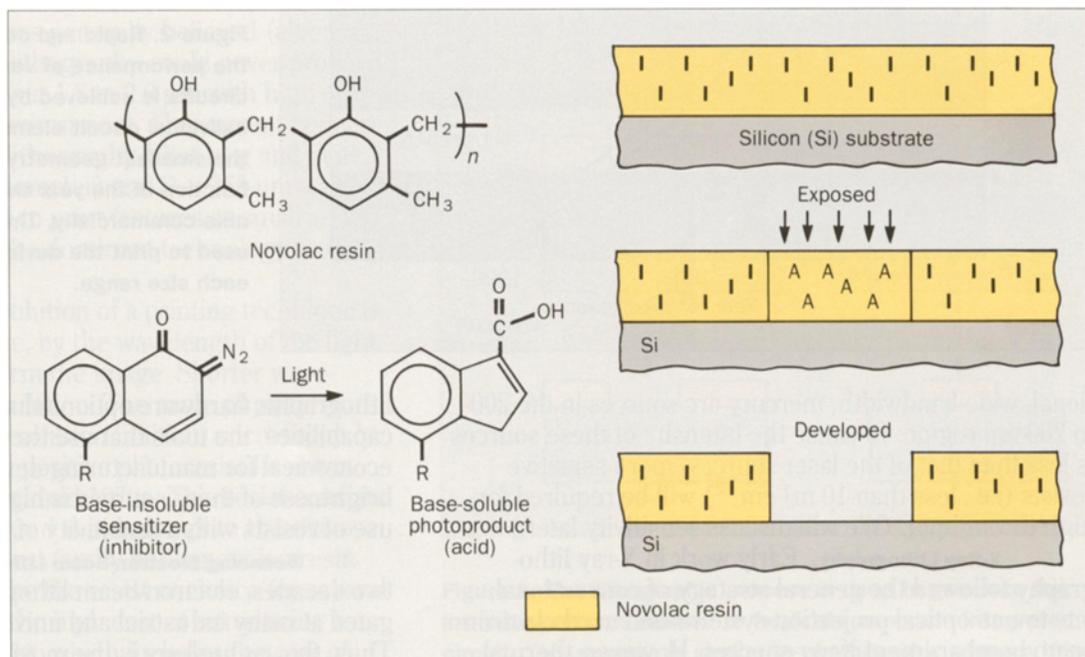
**Scanning Electron-Beam Lithography.** For well over two decades, electron-beam lithography has been investigated at many industrial and university laboratories. Thus, this technology is the most mature of all the alternatives to conventional photolithography.

This form of lithography uses a focused beam of electrons that is scanned under computer control across the resist-coated substrate. Early systems operated at a modulation rate of 10 to 40 MHz (megahertz) and used a Gaussian, round beam that was  $0.5$  to  $2.0 \mu\text{m}$  in diameter. These early machines used a tungsten emitter as a source of electrons and required about 1 hour to "write" a pattern onto a 4-inch diameter wafer with a resist that had a sensitivity of 1 to  $3 \mu\text{C cm}^{-2}$  (microcoulombs per square centimeter).

The most advanced of the newer systems use high-brightness electron sources, shaped beams, and modulation frequencies greater than 400 MHz and can produce three to eight 4-inch wafers per hour. These systems require resists with sensitivities of 1 to  $5 \mu\text{C cm}^{-2}$  at 20 kV (kilovolts).

Electron-beam lithography offers high resolution (less than  $0.1 \mu\text{m}$ ) and extraordinary registration

**Figure 3. The most widely used photoresists in current semiconductor manufacture are positive-tone materials, which rely on a base-soluble novolac resin that has been rendered insoluble by the addition of a dissolution inhibitor (I). Exposure to ultra-violet light converts the inhibitor to a very soluble acid (A), allowing the novolac plus acid to be dissolved.**



36

accuracy, which is important when writing VLSI patterns directly onto the resist. The major disadvantages of electron-beam lithography are the high overall cost it introduces into the lithographic step, low throughput, and size of the manufacturing equipment.

**Scanning Ion-Beam Lithography.** This technology is similar to scanning electron-beam lithography in that it uses a finely focused beam of ions that is scanned under computer control onto the wafer. The ions may be either directly implanted into a semiconductor substrate to alter the semiconductor bandgap or used to expose a resist.

Ion-beam lithography is several years away from industrial use as a lithographic-exposure method. It currently is used to repair submicrometer defects on masks and devices. However, interest in ion-beam lithography continues. Because this technique is nearly devoid of scattering effects, its resolution is potentially better than electron-beam lithography. In addition, ion-

beam lithography can implant a wide range of atoms directly into a semiconductor material, thus eliminating the need for a resist for some steps.

**New Resists and Processes Required.** No matter which technology becomes dominant after photolithography has reached its limit, new resists and processes will be needed, requiring enormous investment in research and process development. The introduction of new resist materials and processes will also require considerable lead time. Probably, more than three to six years will elapse before the new resists reach the performance level currently realized by conventional positive photoresists.

#### **Design and Selection of Polymers**

The focus of this paper concerns the design and selection of polymer materials that are useful as radiation-sensitive resist films. Such polymers must be

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carefully designed to meet the specific requirements of each lithographic technology and device process. Although these requirements vary according to the radiation source and device process, the following properties are ubiquitous:

- **Sensitivity**—This property is the criterion used to measure the change in solubility of a radiation sensitive material as a function of radiation dose per unit area. Sensitivity is similar to the *speed* of photographic film.
- **Contrast**—This property is a measure of the rate of chemical change (i.e., solubility change) under constant radiation. Contrast indicates the resolution capability of a radiation-sensitive resist.
- **Resolution**—This is the smallest, lithographically useful image or feature size that can be formed, and is expressed in micrometers.
- **Etching resistance**—This is the ability of the patterned resist to withstand the liquid or plasma conditions used to transfer the resist image into the underlying thin film.
- **Purity**—This property is of paramount importance because tiny quantities of impurity atoms or ions can adversely affect the performance of a semiconductor device. The resist must be free from atoms such as sodium, boron, potassium, etc., down to the part-per-billion level.

All these properties can be achieved by careful manipulation of the polymer structure, molecular properties, and synthetic methods used to produce the resist.<sup>4</sup>

Resists function by altering the solubility of the polymer through radiation-induced chemical reactions. These reactions can either increase the solubility (i.e., positive tone) or decrease the solubility (i.e., negative tone) of the irradiated region. The terms *positive resist* and *negative resist* reflect this change in solubility, as illustrated in Figure 1. Both tones of resist have been developed for all the lithographic options. However, it is generally accepted that positive resists exhibit the best overall performance.

The most widely used positive resists are those

that operate through a dissolution inhibition mechanism. Such resists are generally two-component materials. They consist of an aqueous alkali-soluble matrix resin that is rendered insoluble in aqueous alkaline solutions by the addition of a hydrophobic, radiation-sensitive material known as a *photoactive compound* (PAC). When irradiated (i.e., exposed to UV light), the PAC is converted to an acid that is alkali soluble. This permits selective removal of the irradiated portions of the resist by an alkaline developer. Figure 3 outlines the chemistry and processes associated with these resists.

The best known of these so-called dissolution inhibition resists is the *conventional positive photoresist*, a photosensitive material that uses a novolac resin (i.e., phenol-formaldehyde resin) with a diazonaphthoquinone PAC as a dissolution inhibitor (I). The novolac matrix resin is a copolymer of a substituted phenol (often cresol) and formaldehyde.

These resins are soluble in organic solvents making it possible to spin coat the surface with uniform, high-quality, glassy films. The resins are also soluble in basic solutions, such as aqueous sodium hydroxide or tetramethylammonium hydroxide (TMAH). The addition of 10 to 20 wt % (weight percent) of the PAC renders the novolac resin insoluble in an aqueous base. When irradiated, the PAC undergoes a chemical reaction, known as a Wolff rearrangement, followed by hydrolysis to generate a base-soluble indene carboxylic acid. The exposed regions of the film may then be removed by treatment with an aqueous base.

**Performance of Resists.** While the components of all conventional photoresists are the same, the precise performance characteristics depend on the specific chemical structure of the novolac resin and the PAC.<sup>4</sup>

Unfortunately, these materials are not appropriate for use with the new lithographic technologies that will be necessary for sub-0.5- $\mu\text{m}$  lithography. The most notable deficiency is in the sensitivity of these materials.

The sensitivity of a polymer used as a photoresist is measured by its *quantum efficiency*, or the num-

**Table I. Performance Criteria for Deep-UV Resists**

Parameter	Criteria
Sensitivity*	< 40 mJ cm <sup>-2</sup>
Contrast	> 4
Resolution	< 0.35 μm
Optical density	< 0.4 μm <sup>-1</sup>
Etching resistance	≡ novolac-based positive photoresists
Shelf life	> 1 year

\* For tools that use conventional Hg sources, a sensitivity of <10 mJ cm<sup>-2</sup> may be required.

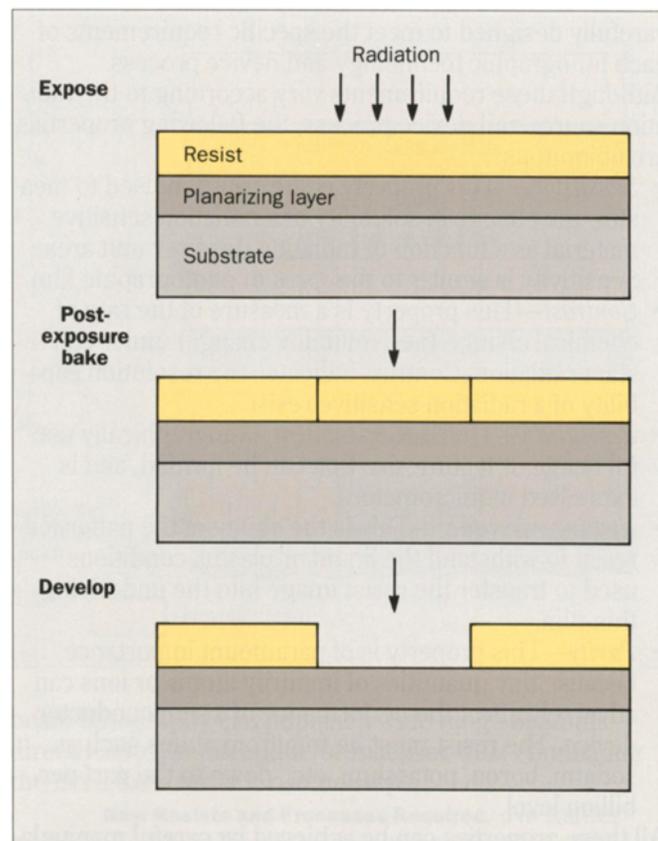
ber of chemical events that occur per photon absorbed. For most positive resists, the quantum efficiency is much less than 1.0. (A value of 1 indicates that one chemical event has occurred for each photon of light absorbed.) The new lithographic techniques generally have low-brightness sources and, therefore, require high-sensitivity resists, with quantum efficiencies much greater than 1.

Deep-UV photolithography is likely to be the first of the alternatives to conventional photolithography to be used in manufacture. We will use it as an example of the methods involved in developing a new resist.

#### A New Resist for Deep-UV

Table I lists the requirements or performance criteria for a resist that will be needed for the deep-UV lithography technique. One new class of materials that meet the low-absorbance, high-sensitivity, and other performance criteria in Table I for deep-UV resist materials is the chemically amplified resists (which we discuss later). These resists are compatible with the exposure tools currently available as prototypes. In addition, these materials show high contrast, good process latitude, excellent thermal stability, and dry-etching resistance.

The process sequence in Figure 4 for these chemically amplified materials is similar to that for conventional positive resists, although the post-exposure bake (PEB) assumes a different role. We will use one



**Figure 4. In its simplest form, the conventional process requires exposure of the resist, followed by development in a suitable solvent. Chemically amplified resists require a thermal step after exposure to effect the catalytic reaction that leads to differential solubility.**

chemically amplified material to examine how each of the performance criteria is achieved through the careful design and manipulation of the detailed chemical structures that will form the resist.

**Sensitivity of Resists.** *Sensitivity* is a direct measure of how efficiently a resist responds to a given amount

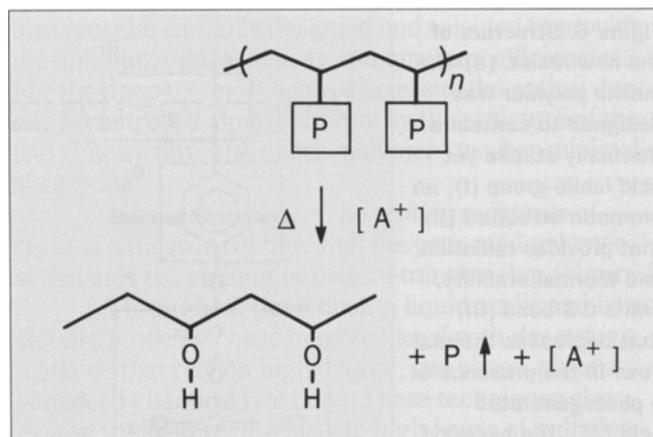
of radiation and is similar to the ASA or ISO rating of photographic film.

As with film, the resist's sensitivity must be great enough to allow a satisfactory image (i.e., a pattern) to be produced in the required exposure time. Because the new lithography tools use low-brightness sources and exposure time must be minimized to ensure high wafer throughput, very high sensitivities are required. Sensitivity values are reported in units of energy per unit area (for example, millijoules per square centimeter,  $\text{mJ cm}^{-2}$ ), with smaller values representing higher sensitivity.

To have radiation sensitivity, a chemical compound must have bonds that undergo bond cleavage or rearrangement when exposed to radiation (*photons*, for photoresists). In addition, these materials must contain chemical moieties whose structure allows a specific wavelength of light to be absorbed and the photon energy transferred efficiently to the appropriate bonds. A material that undergoes one or less chemical events per photon absorbed is not likely to provide the required sensitivity, i.e., less than  $40 \text{ mJ cm}^{-2}$ .

**Chemical Amplification.** Several years ago, a new class of resists was discovered that achieve differential solubility through a catalyzed chemical reaction.<sup>5</sup> The term *chemical amplification* was coined to describe this mechanism.

In a chemical amplification scheme, a photogenerated species ( $A^+$  in Figure 5) catalyzes many chemical events such as the *deblocking* of a protective group (P in Figure 5) from a hydroxy-substituted polymer that is soluble in an aqueous base. The inherent sensitivity associated with the positive-acting, chemical amplification resists emanates from the regeneration of the acid ( $A^+$ ), which is available for additional deblocking reactions that occur during the post-exposure baking step. Typical turnover rates (i.e., the catalytic chain length) for each acid molecule in a working resist formulation are in the 800 to 1200 range. The deprotection and turnover rate are critically dependent on post-exposure bake temperature, time, and method of bake.

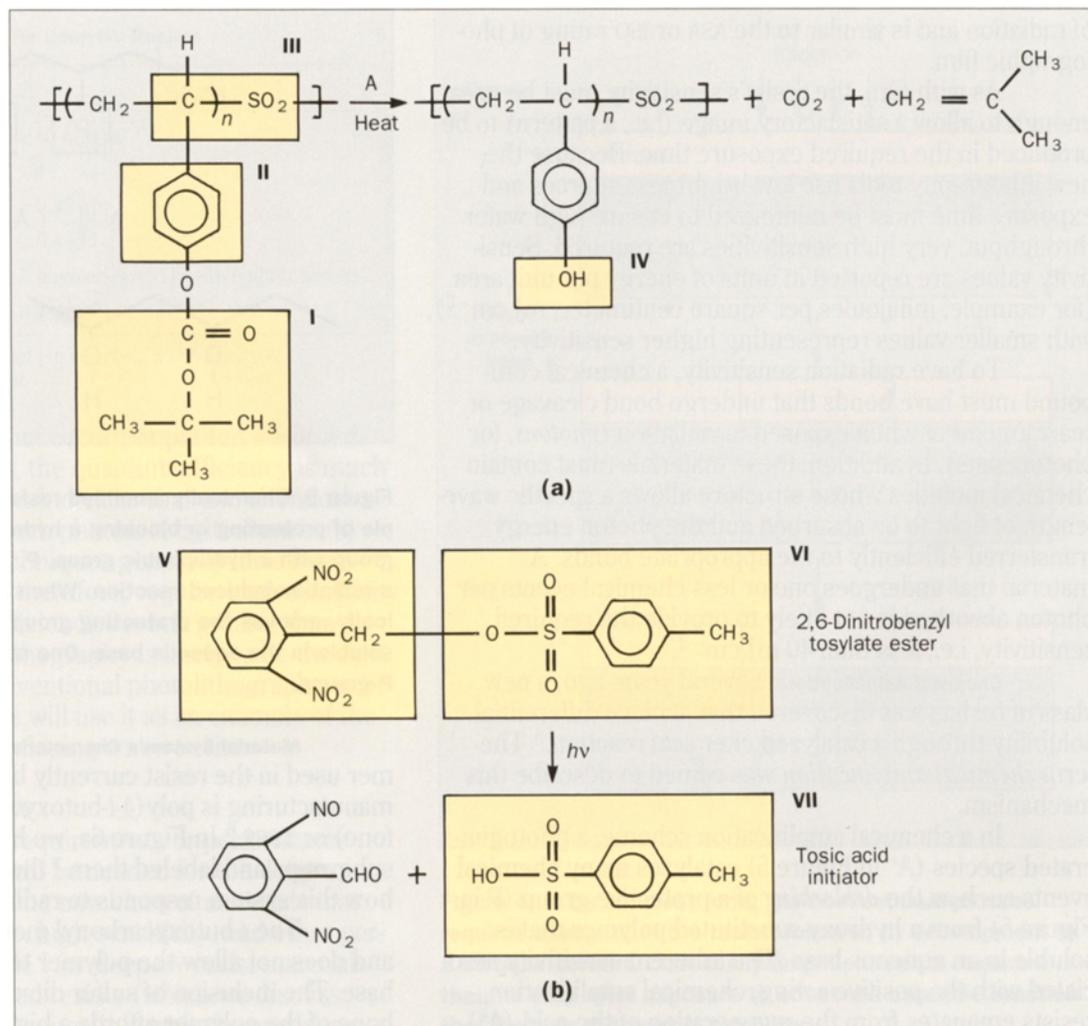


**Figure 5. Chemically amplified resists operate on the principle of protecting or blocking a hydrophilic, base-soluble OH group with a hydrophobic group, P. An acid ( $A^+$ ) is formed by a radiation-induced reaction. When heated, the acid catalytically removes the protecting group, rendering the polymer soluble in the aqueous base. One acid removes 800 to 1200 P groups.**

**Material System's Characteristics.** The matrix polymer used in the resist currently being developed for manufacturing is poly(4-*t*-butoxycarbonyloxystyrene sulfone) or TBSS.<sup>6</sup> In Figure 6a, we have highlighted the subgroups and labeled them I through IV, to illustrate how this system responds to radiation.

The *t*-butoxycarbonyl moiety (I) is hydrophobic and does not allow the polymer to dissolve in an aqueous base. The inclusion of sulfur dioxide (III) in the backbone of the polymer affords a high  $T_g$  (glass transition temperature) that provides greater flexibility for performing the PEB at elevated temperatures to improve the sensitivity. Also, the introduction of sulfur dioxide into similar polymers has effected improved sensitivity to deep-UV and electron-beam radiation as a result of radiation-induced scission (i.e., breaking) of the C-S bond (carbon-sulfur bond). In the presence of acid, TBSS is

**Figure 6. Structure of the new resist. (a) The matrix polymer was designed to contain a thermally stable yet acid labile group (I), an aromatic structure (II) that provides radiation and thermal stability, and a C-S bond (III) that decreases thermal flow. In the presence of a photogenerated acid ( $A^+$ ), the hydroxyl group (IV) is liberated, allowing aqueous-base removal of the exposed regions. (b) The organic photoacid generator (PAG) is a complex molecule that contains both a group (V) that efficiently absorbs a photon and a strong acid precursor (VI). The energy from the absorbed photon cleaves the  $CH_2-O$  chemical bond, and tosic acid (VII) is released.**



thermally activated, and loses carbon dioxide and isobutylene to form poly(hydroxystyrene-sulfone). The hydroxyl (OH) group (IV) is the hydrophilic moiety that affords the base solubility of this system.

The photoacid generator (PAG) used in this

system is an organic ester such as 2,6-dinitrobenzyl tosylate.<sup>7</sup> This ester is known to absorb light efficiently and then undergo a series of rearrangements and bond-cleavage reactions to generate tosic acid (VII in Figure 6b), a strong organic acid. Tosic acid then acts as the

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catalyst for the deprotection reaction we described earlier. This complex chemistry results in incredibly sensitive deep-UV resists.

**Contrast and Resolution.** Achieving a *contrast* value of 4 or greater is also a difficult requirement. Like sensitivity, the contrast of a resist is a measure of how the resist responds to incident radiation and is related to the resolution that can be achieved. Higher contrast materials generally exhibit higher resolution.

To obtain high contrast, one must design materials that exhibit an exceptionally nonlinear dissolution response as a function of radiation dose. For the deep-UV resist in Figure 6a, this is done by converting the hydrophobic *t*-butoxycarbonyl group (I) to the hydrophilic hydroxyl group (IV). This conversion, coupled with the solubility that is achieved only when nearly 100 percent of the protecting groups have been removed, results in a very-high-contrast resist.

Many physical and chemical properties of the matrix polymer affect *resolution*. In addition to having high contrast, the polymer must neither swell during development nor deform (i.e., flow) at the elevated temperatures encountered during later processes such as post-development bakes. Achieving these properties entails careful selection of the basic polymer structure and of the solvents used as the developers (an aqueous-base solution in our deep-UV resist example).

**Optical Density of Resists.** *Optical density* determines how much light is absorbed per micrometer of resist thickness and is critical for deep-UV resists. If the absorption is too low, few photons are available in the resist film to induce the desired photochemical reactions. However, if absorption is too high, the photons are not deposited uniformly throughout the thickness of the film, thus degrading the shape (i.e., the profile) of the final pattern. A density value of  $0.4 \mu\text{m}^{-1}$  is the maximum value that will allow uniform resist imaging.

The specific organic structures contained in the resist control its optical density, and the detailed struc-

ture must be carefully designed and selected to provide the optimum optical density and quantum efficiencies. For the deep-UV resist being discussed, the optical density is controlled almost entirely by the structure of the PAG (Figure 6b). The matrix polymer TBSS has minimal absorption.

**Etching Resistance.** The *etching resistance* of a resist is a measure of how well the patterned polymer withstands the etching or pattern-transfer step (Figure 1).

Throughout the industry, liquid acidic and basic etching processes have been replaced with *dry-etching* methods that rely on high-energy, gas-phase, plasma-enhanced chemical reactions. These techniques also expose the patterned resists to high levels of radiation and heat. The pattern transfer must be done with a change of much less than  $\pm 10$  percent in the finest feature size, and this represents an extraordinary demand on the polymer.

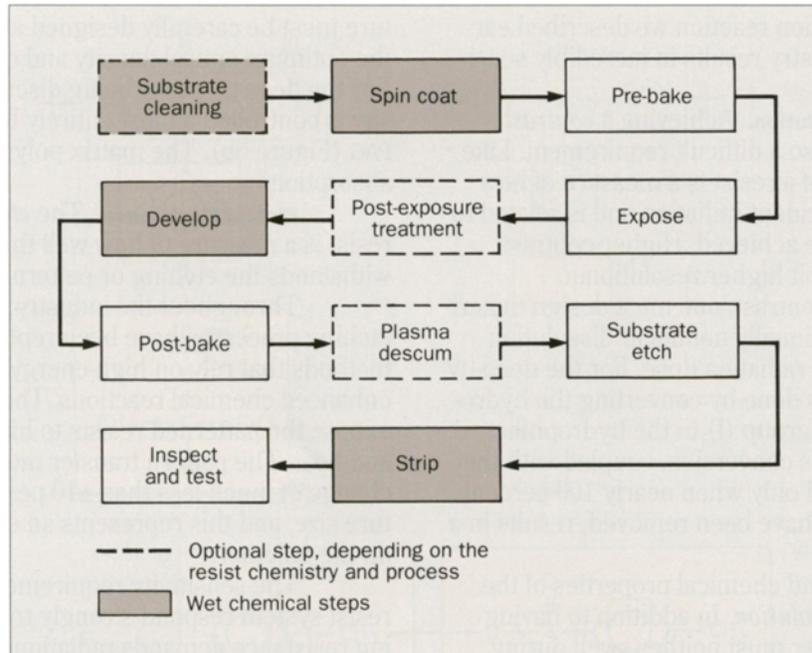
The sensitivity requirements demand that a resist system respond strongly to radiation, while etching resistance demands radiation and thermal stability, a real dichotomy. For the deep-UV resist, we deal with this problem in two ways:

- The photochemistry required for high sensitivity occurs in the PAG (Figure 6b), which is a tiny percentage of the total resist mass.
- The etching resistance is achieved with the photochemically stable, TBSS matrix polymer.

Radiation and thermal stability is provided by careful design of the matrix polymer. The aromatic organic structure (II in Figure 6a) has excellent radiation and thermal stability. In addition, to minimize thermal flow, we incorporated the C-S bond (III in Figure 6a) in the polymer backbone, which increases the melting point of the polymer.

**Optimizing the Process.** Once we have defined the material's chemistry, we must then optimize the process for using the resist. Figure 7 outlines each of the stages or steps involved in the lithographic process. (A dashed

**Figure 7. Though simple in concept, the lithographic process is a sequence of as many as 11 steps, each critical to the resist's performance. For a complex VLSI device, this sequence is repeated up to 20 times. The operating variable of each step must be carefully optimized; this process development is a tedious and expensive task.**



42

box signifies the step may not be required in every resist process.) Here, we provide a brief statement about the purpose of each step:

1. *Cleaning*—A key requirement for any device substrate is that it be cleaned before deposition of the resist. To avoid adversely affecting the lithographic process, a substrate must be atomically clean and free of any contamination.
2. *Spin coat*—After cleaning, the resist is spin coated onto the substrate to obtain a uniform, adherent, defect-free polymeric film over the entire substrate.
3. *Pre-bake*—The resist is dried to remove any residual solvent.
4. *Exposure*—The photochemical reaction required to change the solubility of the resist takes place during this step.
5. *Post-exposure bake*—For the deep-UV resist we have described here, the post-exposure treatment is a

baking step. This bake induces the deblocking reaction that changes the polarity and, thus, the dissolution characteristics of the polymer.

6. *Develop*—After the latent image has been formed in the polymeric resist film, the image must be developed to produce the final, three-dimensional relief image. The developer selected must produce images that deviate less than  $\pm 5$  percent from the desired size.
7. *Post-bake*—After development, the structure often undergoes a bake step to dry and harden the resist image.
8. *Plasma descum*—Before substrate etching, a plasma descum step may be used to remove trace organic residues in the developed regions of the resist.
9. *Substrate etch*—This step, like development, is extremely critical. Dry-etching techniques are generally used for high-resolution lithographic processing.
10. *Strip*—The resist may be stripped using either

liquid- or oxidizing-plasma processes.

11. *Inspection and test*—The substrate is then inspected for defects and tested.

These steps are repeated as many as 20 times during fabrication of a complex VLSI device. [For example, a static random-access memory (SRAM) requires 14 iterations.]

#### Future

As devices with features below 0.2  $\mu\text{m}$  become a reality, process and contamination control become increasingly important issues. Dry processes have replaced many conventional, *wet-chemical* processes. Pattern etching is a good example. Plasma-assisted etching provides excellent control of critical dimensions.

A natural extension is to convert all the fabrication steps into vacuum processes and integrate them into a continuous production line. Resist processes represent the most difficult group to convert because new materials and methods must be *invented* to replace existing ones.

Several schemes that involve pattern formation in plasmas are currently under investigation in research. In addition, direct material growth, removal, and modification are all possible during exposure to patterned radiation.

Totally dry lithography represents a considerable challenge, and much research remains to be done.

#### Summary

The unabated progress in design and integration of VLSI devices continues to demand increasingly smaller and more precise device features.

Currently, almost all commercial devices are made by photolithography using UV radiation in the wavelength range of 365 to 436 nm. But within the next 5 to 8 years, new lithographic strategies will be required to meet resolution needs that will likely extend below 0.5  $\mu\text{m}$ .

Technologies under development include

electron-beam, ion-beam, X-ray, and short-wavelength lithographies. Electron-beam lithography is already an important technology in the manufacture of chromium masks and custom VLSI devices. Each of these alternative technologies will require new polymeric resist materials and processes. This paper has discussed one approach to resist design applicable to deep-UV lithography.

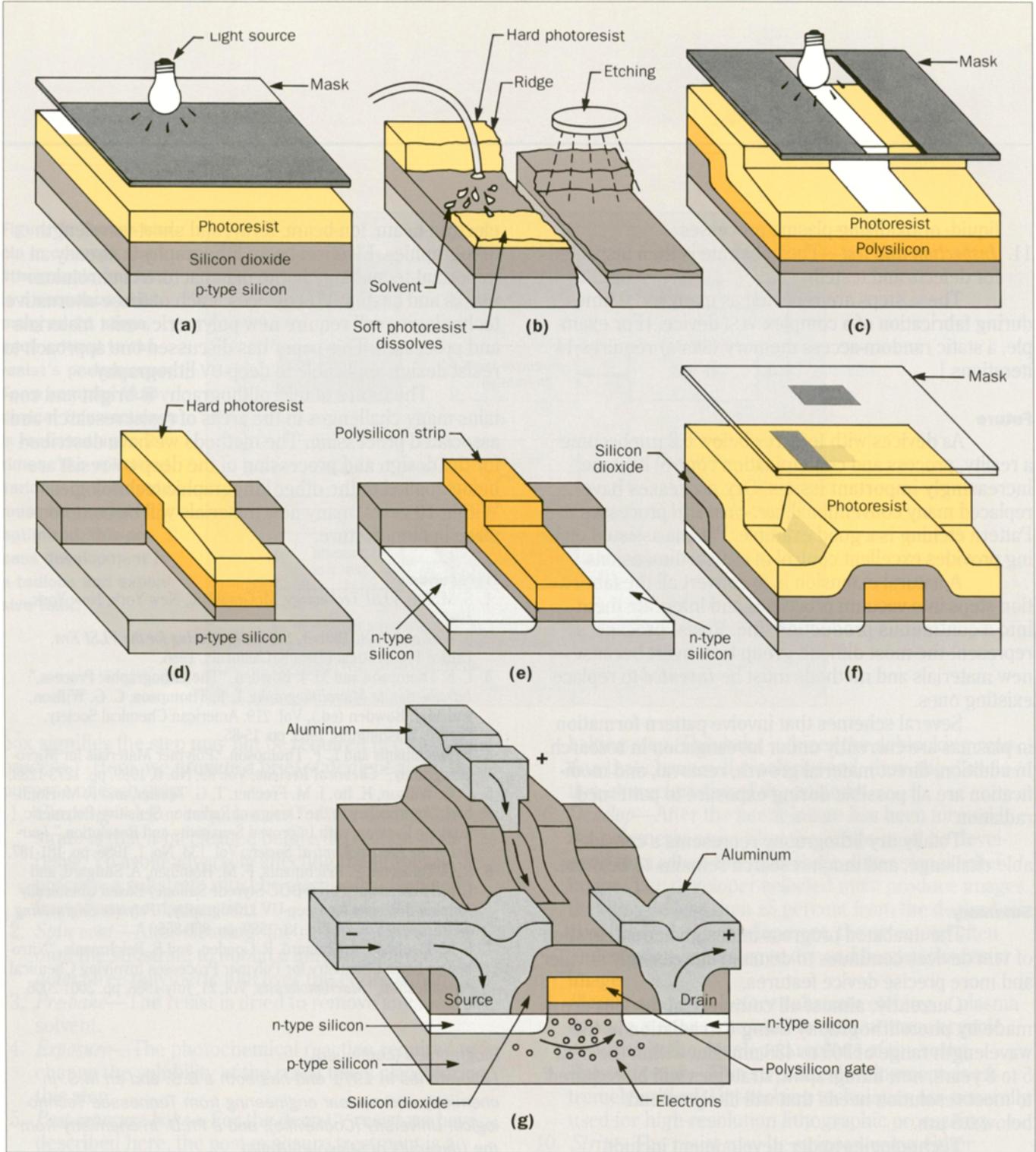
The future of microlithography is bright and contains many challenges in the areas of resist research and associated processing. The methods we have described for the design and processing of the deep-UV resist are being applied to the other lithographic technologies. Within 10 years, many new materials will be commonplace in manufacture.

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Biographies (continued)

Laboratories in 1971 and has both a B.S. and an M.S. in chemistry and nuclear engineering from Tennessee Technological University (Cookeville), and a Ph.D. in chemistry from the University of Missouri (Rolla).



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## Appendix A. Making a Transistor

A microchip contains many thousands of electronic components squeezed into a thin sliver of silicon, called a substrate, that is less than 0.4 inch (1 cm) square. The components and all their connections are built up in layers of material in complex patterns. These components and connections are made with masks produced by exposing large patterns photographically. (The code letter in parentheses refers to the corresponding sketch in the figure on the left.)

**First Masking (a).** The silicon substrate is coated first with silicon dioxide, which does not conduct electricity, and then with a substance called photoresist. Shining a light or X-rays (as illustrated) through a patterned mask hardens the photoresist. The unexposed parts remain soft.

**First Etching (b).** A solvent dissolves the soft, unexposed layer of photoresist, uncovering part of the silicon dioxide. Next, the silicon dioxide is chemically etched to reduce its thickness. The hardened photoresist is then dissolved to leave a ridge of dioxide.

**Second Masking (c).** Layers of polysilicon, which conducts electricity, and photoresist are applied and a second masking operation is then executed.

**Second Etching (d).** The unexposed photoresist is dissolved and another etching treatment removes the

polysilicon and silicon dioxide beneath it. This operation uncovers two strips of p-type silicon.

**Doping (e).** The hard photoresist is removed. Now, the layers undergo an operation called doping, which transforms the newly revealed strips of p-type silicon into n-type silicon.

**Third Masking and Etching (f).** Layers of silicon dioxide and photoresist are added. Masking and etching create holes through the layers to the doped silicon and central polysilicon strip.

**Completing the Transistor (g).** The photoresist is dissolved, and a final masking stage adds three strips of aluminum. These strips make electrical connections through the holes and complete the transistor. In this transistor, known as an MOS (metal-oxide semiconductor) type, a positive charge fed to the gate attracts electrons in the p-type silicon substrate. Current flows between the source and the drain, thereby switching on the transistor. A negative charge at the gate repels electrons and turns off the transistor.

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