# Chapter 1

# Electron Beam Lithography

## 1.1 INTRODUCTION

During the past two decades, there has been an extremely rapid growth in both the technology and the application of microelectronics, to the point that it now pervades virtually all aspects of commercial and military business. The size and performance of microelectronic devices has been improved substantially, especially in the past few years.

Electron beams can be used to make patterns that are smaller and that show better edge resolution than can the best photolithography. Limited data suggest that the crucial yield determinant, pattern defect density, can be reduced and that machines can be made to effect economical device production. This newer electron-beam technology is emerging from the laboratory to form the next generation of lithography and quality control tools for the production of microelectronic devices.

### *1.1.1 Historical Perspective of lithography*

The conventional means of increasing the level of integration of an integrated circuit, that is, of increasing the circuit density, has been lo make the active elements in the devices smaller, thereby increasing the number of active circuits [1] that can be accommodated on a given area of silicon.

The oldest photolithographic technique is contact printing [2,3]. In this technique the mask is first placed close to the wafer surface and visually aligned to the previous pattern on the wafer. In a modification of this technique, known as soft contact or

proximity printing [4], minimizes mask and wafer damage caused by contact, but at the expense of resolution. About 1973 a technique known as projection lithography, in which the mask image is projected onto the wafer by means of a 1:1 reflective or refractive optical system was developed [5, 6]. To accommodate larger wafers and improve resolution, a photolithographic technique was developed in the

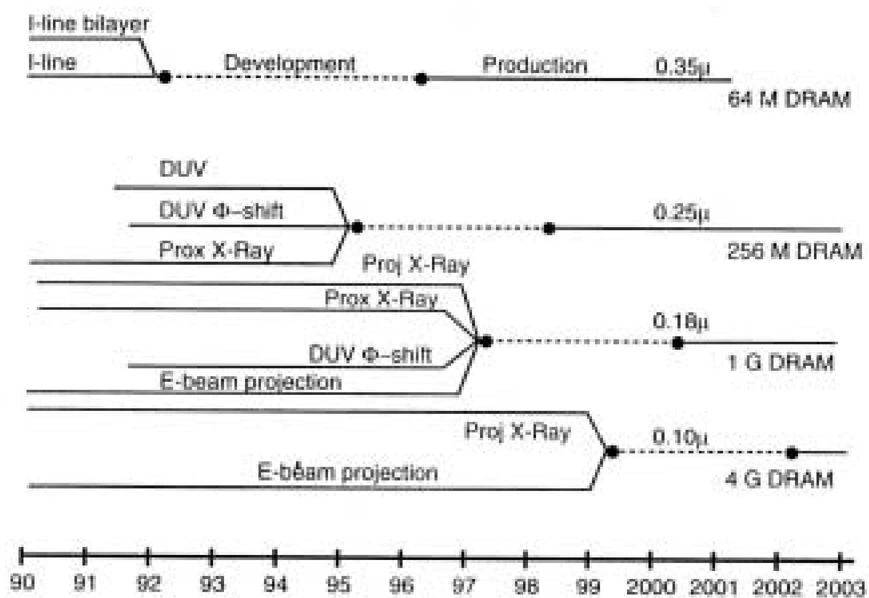



**Figure 1-1**. Development road map for advanced lithography research and development. DUV means deep UV, Prox X-ray means proximity X-ray, and Proj X-ray means projection X-ray.

mid-1970s that involved exposing a smaller area (on the order of 1 to 2 $cm^2$) and stepping this pattern over a large-diameter wafer. This technique (known as step-and-repeat photolithography) improves resolution and alignment accuracy. Step-and-repeat systems have been designed with either 1:1 or reduction optics [7,8].

Resolution can be improved by shifting to shorter wavelength UV light in the 240-250 nm region [9- 11]. Commercial exposure tools that operate in this deep-UV region of the spectrum are available. Because the materials used in conventional refractive optical systems are too opaque at these wavelengths, quartz reduction lenses must be used. Alter-sensitive, projection systems based on all-reflective designs that

are not sensitive to chromatic aberration can be used. Deep-UV systems use either a line-narrowed excimer laser operating at 248 nm or a filtered Hg lamp as a light source.

Figure 1-1 presents a suggested road map for lithography evolution for the next two decades. The solid lines to the left represent proposed alternative technologies that converge to a decision three to five years prior to full-scale manufacture. The intermediate dotted lines represent the development time, and the right-hand solid line represents the manufacturing time line.

### *1.1.2 Solid-State Device*

A transistor is a semiconductor device in which the flow of electrons between two regions of like-doped semiconductor material (p or n) is controlled by voltage applied to a third region of opposite type sandwiched between the other two. Figure 1-2 shows a simple transistor element in which current flow across the p-type region between the two n-type regions (called source and drain) is controlled by the voltage applied to the polysilicon gate. A large-scale integrated circuit contains tens of thousands to millions of these individual transistor elements, which are interconnected by conductors such as aluminum or highly doped polycrystalline silicon.

Two primary advantages have made silicon the material of choice for microelectronic circuits. First, it is easily oxidized, and the resulting oxide film is both an excellent insulator and an effective barrier during implantation and diffusion of dopants into the patterned regions of the silicon substrate. Second, low-defect, large-diameter crystals can be readily grown, enabling manufacture of wafers up to 8 inches (20 cm) in diameter at a cost of less than $100 per wafer.

Typical thin-film materials encountered include such materials as silicon dioxide, polysilicon, and aluminum Fabrication of the three-dimensional circuit geometries characteristic of completed metal-oxide semiconductor (MOS) or bipolar device may

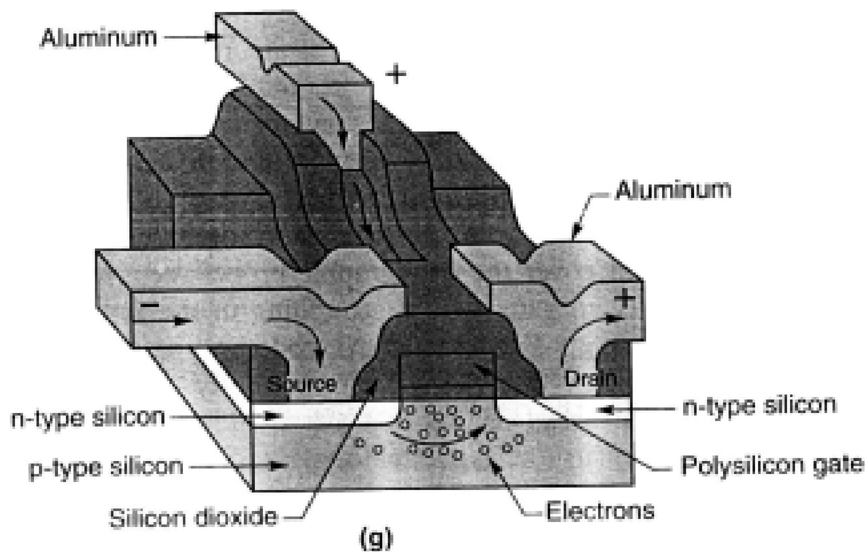



**Figure 1-2.** Schematic representation of a single transistor cell.

require as many as 25 individual patterning steps [2]. Figure 1-3 shows outline of the manufacturing sequence of a large-scale integrated circuit.

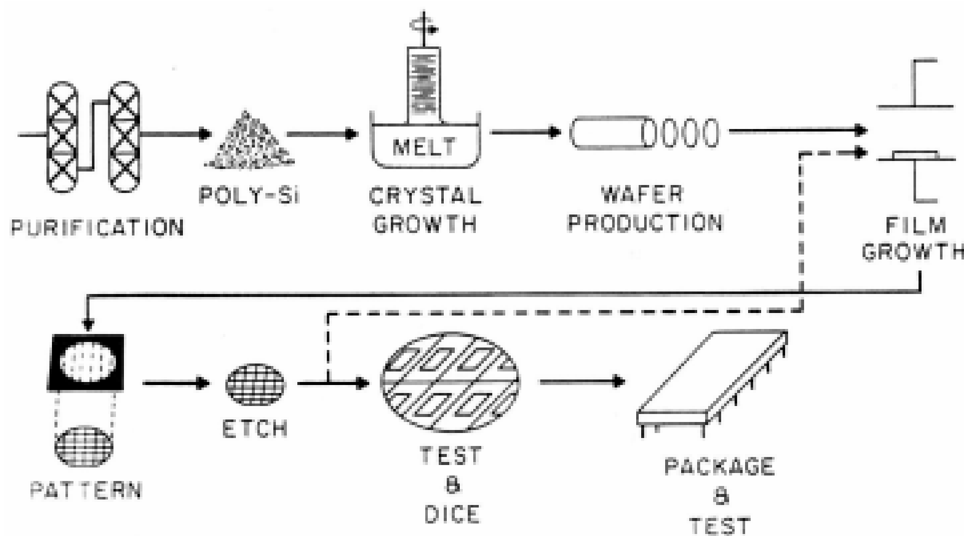



**Figure 1-3**. Process sequence in the production of integrated circuit devices.

The continuing increases in complexity of integrated circuits, coupled with the

decreasing size of the individual circuit elements, are placing more stringent demands on the fabrication processes, particularly with respect to resolution and overlay accuracy. Hence it is important to gain a thorough understanding of the lithographic processes that are key to the continuing evolution of integrated circuit technology.

### *1.1.3 Lithographic Strategic*

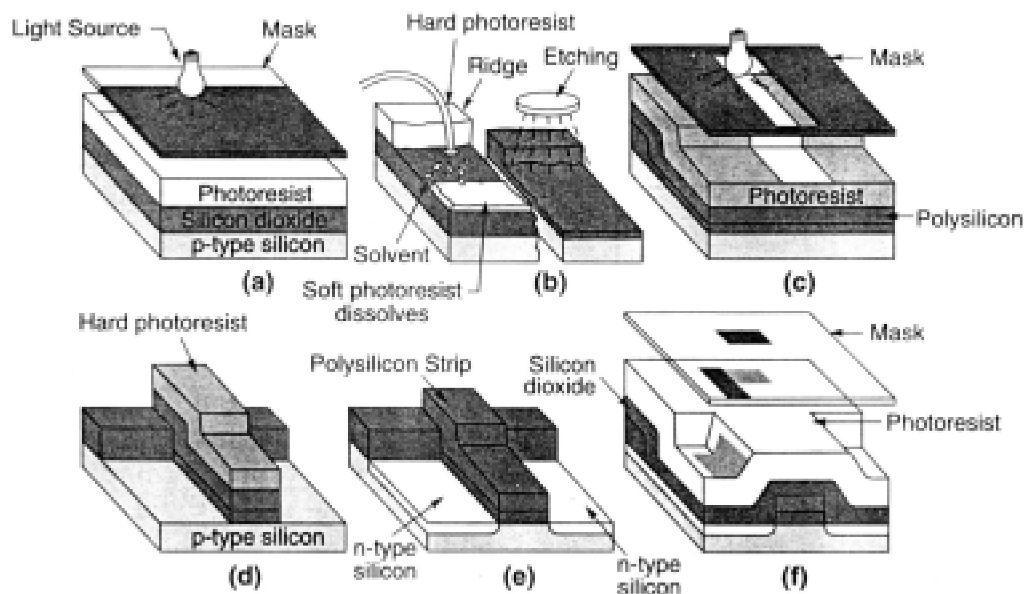



**Figure 1-4.** Process sequence for producing the first two levels of an integrated circuit with a negative resists, (a) First masking. The silicon substrate is coated first with silicon dioxide, which does not conduct electricity, and then with a photoresist. E-beam through a patterned mask decreases the solubility of the exposed areas. (b) First etching. A solvent dissolves the unexposed layer of photoresist, uncovering part of the silicon dioxide. Next, the silicon dioxide is chemically etched. The hardened photoresist is then dissolved to leave a ridge of dioxide. (c) Second masking. Layers of polysilicon, which conduct electricity and photoresist are applied, and a second masking operation is then executed, (d) Second etching. 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. (e) Doping. 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. (f) Third masking and etching. Layers of silicon dioxide and photoresist are added. Masking and etching create holes through the layers to the doped silicon and central polysilicon strip.

The goal of the lithographic process is the accurate and precise definition of three-dimensional patterns on the semiconductor substrate. These patterns delineate the areas for subsequent doping or thin-film etching to provide for the internal interconnection of devices. Figure 1-4 shows the initial lithographic steps involved in the fabrication of a simple MOS transistor.

A summary of the resolution capabilities of several lithography processes is shown in Figure 1-5. This figure shows the narrowest line-width or feature size that has been obtained with each of the lithography processes shown, under two or three different situations. The cross-hatched bar indicates the approximate minimum feature size in production, the bar at the end of the heavy line shows the narrowest line-width (either feature size or developed resist dimension) that has been demonstrated under reasonably practical laboratory R&D conditions, and the triangle at the end of the dashed line shows the narrowest dimension in resist that has been created using special precautions (e.g., a very thin substrate in the electron-beam lithography case). The electron-beam lithography mask data refers to masks for photolithographic

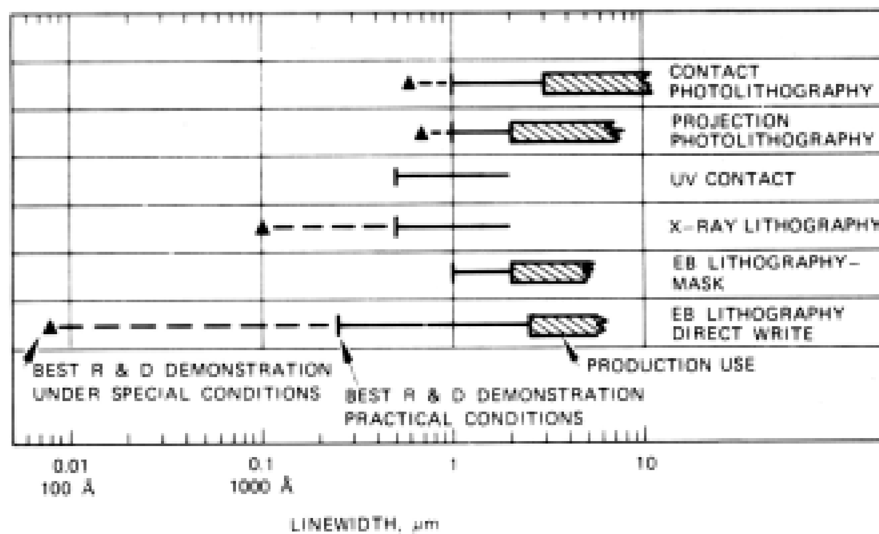



**Figure 1-5.** Summary of the resolution capabilities of contact and projection photolithography and electron-beam and x-ray lithograph.

replication. It will be shown later that realistic needs exist for device features well below 1 μm, and eventually these devices must be produced in quantities.

### *1.1.4 Resist Materials and Process*

Two families of photoactive or radiation-sensitive materials have been described in the literature: negative and positive. Negative resists become less soluble after exposure to radiation, and thus the unexposed areas can be removed by treatment with an appropriate solvent. Positive resists, on the other hand, increase in solubility upon exposure, enabling the exposed regions to be removed in the solvent developer. Both types are usually based on organic polymers that have been designed with physical and chemical properties consistent with semiconductor processing [12]. In the ensuing years, many natural products (including protein, shellac, starches, and carbohydrates) were sensitized with dichromate and bichromate salts. These materials were all negative-acting resists.[13, 14] The first modern negative photoresists were developed by the Eastman Kodak Company and were based on cyclized rubbers with cinnamic acid derivatives as photosensitive cross-linking agents.[15] Many of these photoresist materials and processes were developed for the manufacture of circuit boards [16] and printing plates long before the invention of the planar transistor.

In recent years, positive resist materials have dominated the fabrication of leading edge devices primarily because of their inherently higher resolution. Negative photoresists are not suitable for patterns less than about 3.0 μm in size because of limitations imposed by swelling. The current generation of positive photoresists is suitable with exposure tools that operate at wavelengths of 300 nm and longer. At wavelengths less than about 290 nm, the inherent absorption of the novolac base resin is too high which renders these materials no longer useful.

## 1.2 ELECTRON BEAM LITHOGRAPHY

Scanning electron-beam lithography is a mature technology that evolved from the scanning electron microscope developed in the early 1960s [17-27]. Direct-write electron beam machines operate directly from design data and are capable of sub-micrometer pattern definition. It is also used for the fabrication of photomasks and reticles for photolithography. The principal drawback of electron-beam lithography is its low throughput and high capital cost. However, progress in this field continues at a rapid pace, and no doubt less-expensive, higher throughput machines will be developed in the next two decades. Three major advantages of electron-beam lithography are (1) its ability to register accurately over small areas of a wafer, (2) low defect densities, and (3) direct generation of patterns from circuit design data. The low throughput of electron-beam writing machines has been improved by two innovations recently reported for reduction projection systems [28-32] The mask consists of a thin and low atomic number membrane and a high-atomic-number-metal-scattering element that is patterned. The scattered electrons are removed from the imaging systems by a back focal plane aperture [31,32].

### *1.2.1 Pattern Creation by an Electron Beam*

The use of electron-beam lithography provides a means to alleviate the critical technical (e.g., resolution) and economic (e.g., yield, mask generation cost) problems that can limit progress in microelectronics.

The way in which an electron beam is used in microelectronic fabrication is to create a mask in resist that can be employed in any of several ways to create a pattern on the substrate (e.g., a silicon wafer or a mask blank). This process is illustrated

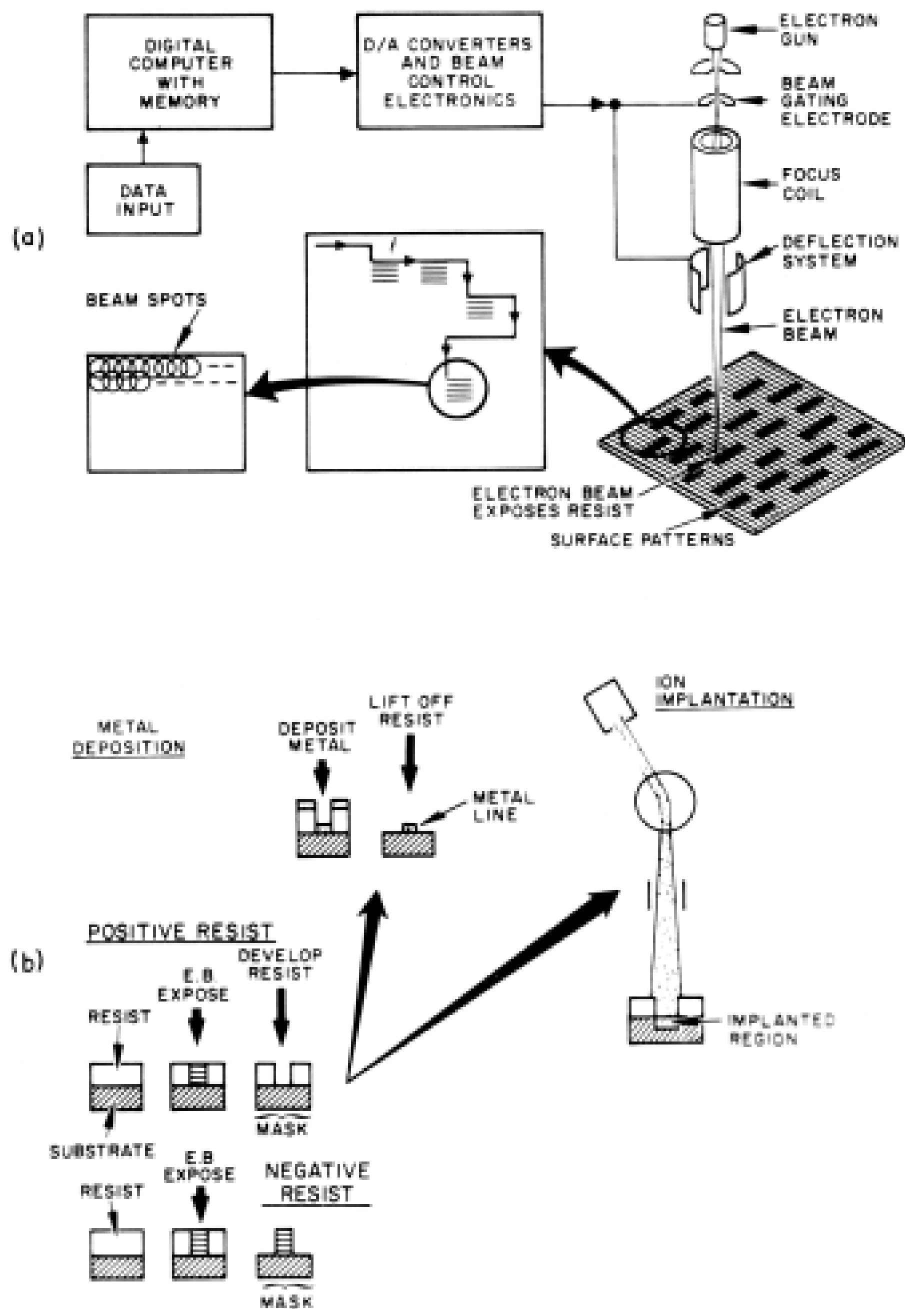



**Figure 1-6.** The processes of electron beam lithography. (a) Schematic of the electron beam system. (b) The ways of usong a resist mask to creat patterns and implanted regions.

schematically in Figure 1-6. The electron beam exposes the resist where it strikes, i.e., the electrons break the molecules of the resist and so locally change its characteristics in such a way that subsequent development can either remove selectively the exposed part (positive resist) or remove the unexposed part (negative

resist), as shown in Fig. 1-6 (b).

This process for creating a metallic line by the use of either positive or negative resist is shown in more detail in Figure 1-7. In the negative resist case, the remaining resist protects the desired metal areas against the etching which removes the undesired regions of metal. Larger areas, for a given resolution, can be exposed by a precisely controlled stepwise movement of the target and repetition of the electron-beam-formed pattern. Figure 1-7 suggests that a line can be exposed by one pass of the beam. This exposure strategy is certainly possible, but requires adjustment of the spot size or shape to fit the desired linewidth.

The process of generating a high resolution pattern in resist described above is fundamental to electron-beam microfabrication. This process can be applied to two

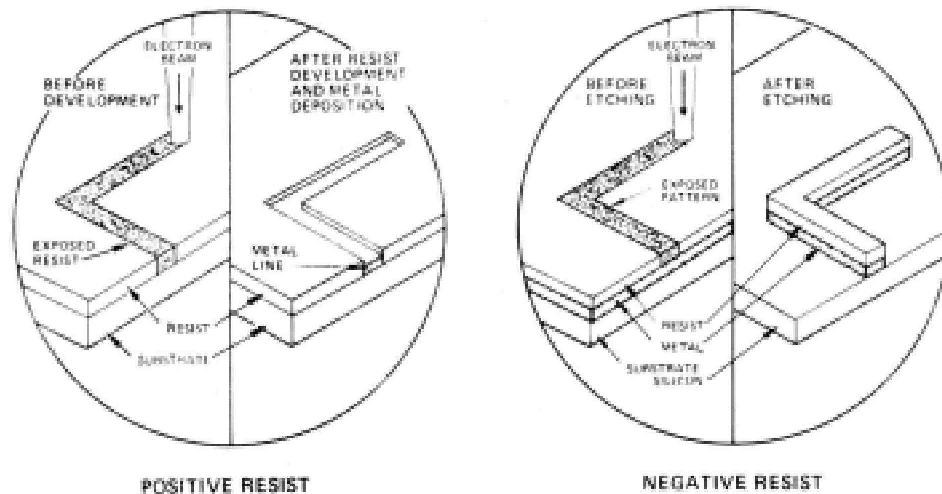



**Figure 1-7.** Uses of an electron beam to create a metallic line by the use of positive or negative resist.

generic classes of structures, viz., to fabricate masks for subsequent replication or to fabricate the devices or circuits directly. The diagram of Figure 1-8 depicts the spectrum of ways to use electron-beam systems for microfabrication and diagnostics. Scanning electron microscopy (including compositional analysis) is the only way to examine critically the device structures that have the high resolution that can be

created by electron-beam microfabrication.[33] The direct exposure process is shown in the center column of Figure 1-8. The utility of direct device exposure with present electron-beam machines lies in experimental device development where flexibility and the capability for rapid design changes are important, in the fabrication of the highest performance specialty devices and circuits (e.g., microwave solid state devices) where the ultimate in resolution is required, and in low to modest volume production of devices and integrated circuits. As the throughput of electron-beam machines is increased, this direct exposure process may prove useful in higher volume production of submicrometer large scale integrated circuits.

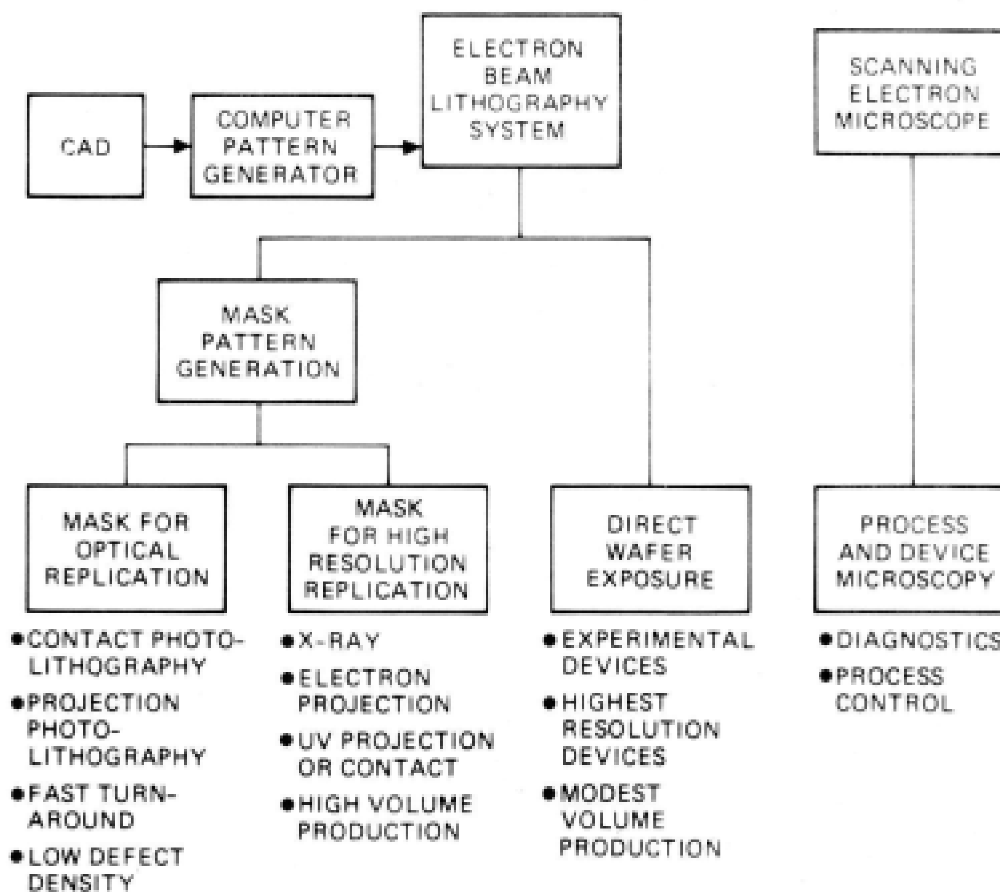



**Figure 1-8.** The several ways in which electron-beam lithography can be applied to create masks and patterns directly on the wafer. Electron microscopy (right side) must be used to examine these high resolution patterns accurately.

### *1.2.2 Electron Scattering*

When an electron beam enters a polymer film (or indeed any solid material), it loses energy via elastic and inelastic collisions known collectively electron scattering. Elastic collisions result only in a change of direction of the electrons, whereas inelastic collisions result in energy loss. These scattering processes lead to a broadening of the beam; that is, the electrons spread out as they penetrate the solid, producing a transverse or lateral electron flux J(z, y) normal to the incident beam direction (see Figure 1-9), which leads to exposure of the resist at points remote from the point of initial electron entry. As a consequence, the developed resist image is wider than expected.  Two types of scattering occur-forward scattering in the resist

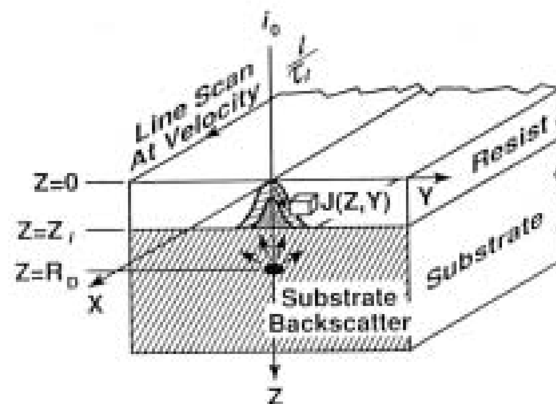



**Figure 1-9.** Three-dimensional electron-scattering model for a resist on a thick substrate with a scanning electron beam of zero diameter.

and backscattering from the substrate. Because most of the electrons are scattered in the forward direction through small angles ( <90°) relative to their original direction, this type of scattering increases the effective beam width at the bottom of the resist layer. Some electrons experience large-angle scattering (approaching 180°) which causes them to return to the surface. Monte Carlo modeling [34] provides a useful visual depiction of the effects of electron scattering (see Figure 1-10). The trajectories depicted in Figure 1-10 have been projected onto the x-z plane and qualitatively show

the degree of forward and backscattering. The forward-scattered electrons are difficult to identify because of their high density and small lateral spread. On the other hand, the back-scattered electrons are clearly evidents, being spread out over distances of the order of 1 μm for 10-keV electrons, while at 25 keV the distance is 3-4 μm.

The magnitude of the electron flux at any point J(r,z), where r is the radial

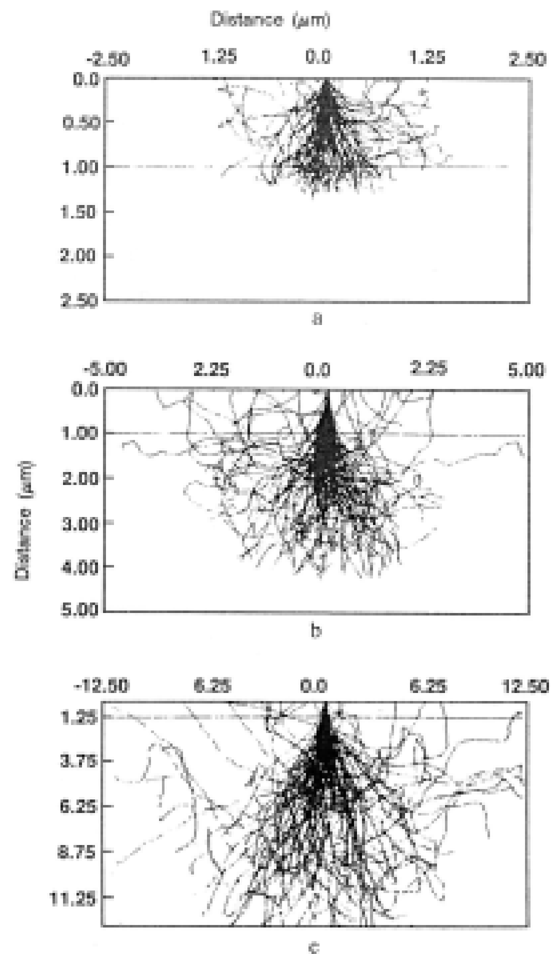



**Figure 1-10.** Monte Carlo simulated trajectories of 100 point-source electrons in a target of 1 μm thick resist on an infinitely thick silicon substrate at (a) 10-, (b) 25-, and (c) 50-keV incident energy. (Reproduce with permission from reference 18.)

distance at depth z, depends upon such parameters as the atomic number and density of both the resist and substrate as well as the velocity (accelerating voltage) of the electron. Figure 1-11 shows the exposure distribution at the interface corresponding to

the three accelerating voltages in Figure 1-10. The width of the forward-scattered distribution is reduced as the electron energy increases. Likewise, the extent of forward scattering is also reduced for thinner resist layers. Figure 1-11 also shows the effect of incident electron energy on the width and intensity of the backscattered

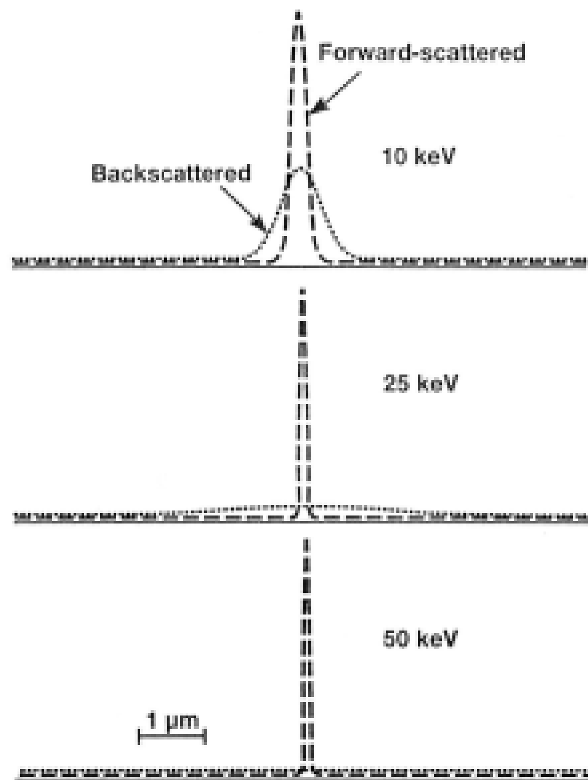



**Figure 1-11.** Exposure distribution at the resist-substrate interface for 1 μm-thick resist layer on a silicon substrate for 10-, 25-, and 50-keV incident energy.

electrons. As the energy of the incident beam increases, the backscattered exposure spreads more and more, until at 50 keV the diameter is so large (>5 μm) that the backscattered electrons only produce a fog.

These scattering processes carry practical consequences, particularly for adjacent patterns where the exposure of one pattern contributes to the exposure of another located within the scattering range of the electrons. Such proximity effects impose certain restrictions on the size and shape of relief structures that can be achieved in the resist, particularly for complex patterns with high packing densities and

sub-micrometer dimensions. As the size and spacing of pattern features change, proximity effects become more or less influential.

From this qualitative discussion of electron scattering, we would expect that a number of factors such as beam energy, type of resist, resist thickness, and substrate type should play a critical role in determining the profile of the resultant resist pattern.

### *1.2.3 Electron Beam Resists*

Poly(methyl methacrylate) (PMMA) is the classical e-beam resist and offers the

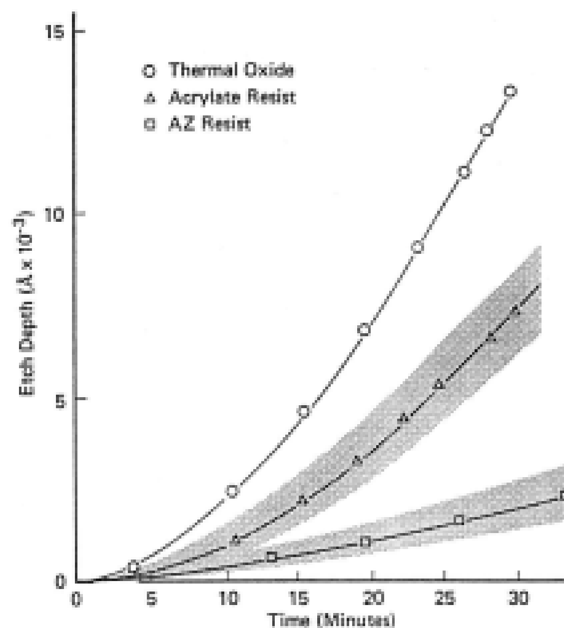



**Figure 1-12.** A comparison of the etch rates of thermal oxide, acrylate resist (PMMA), and AZ resist with DE-100 gas at 200 W and 0.55 torr (73.3 Pa). The shaded areas surrounding the acrylate and AZ curves represent the etch rates of typical aliphatic and aromatic polymers, respectively.

advantage of extremely high resolution, ease of handling, excellent film-forming characteristics, wide processing latitude, and ready availability. It is, unfortunately, a relatively insensitive material requiring 50 to 100 $\mu C/cm^2$ at 20-kV exposure dose in most applications. This lack of sensitivity and its corresponding impact on production

throughput, together with the fact that PMMA is a less efficient plasma or reactive ion etch mask than resists constituted from aromatic materials such as the novolacs [35, 36] (Figure 1-12) has prompted a great deal of research directed toward the development of more sensitive e-beam resist materials that incorporate reactive ion etch resistance.

PMMA is produced by radical-initiated polymerization of commercially available methyl methacrylate monomer. DuPont's Evacite 2041 and 2010 are widely available and have become the standard materials for laboratory e-beam and X-ray experiments. The radiochemical conversions that culminate in main-chain scission have been studied in detail by several workers using a variety of sophisticated analytical techniques [37, 38]. The initial radiochemistry event appears to be homolysis of the mainchain carbon to carbonyl carbon bond or homolysis of the

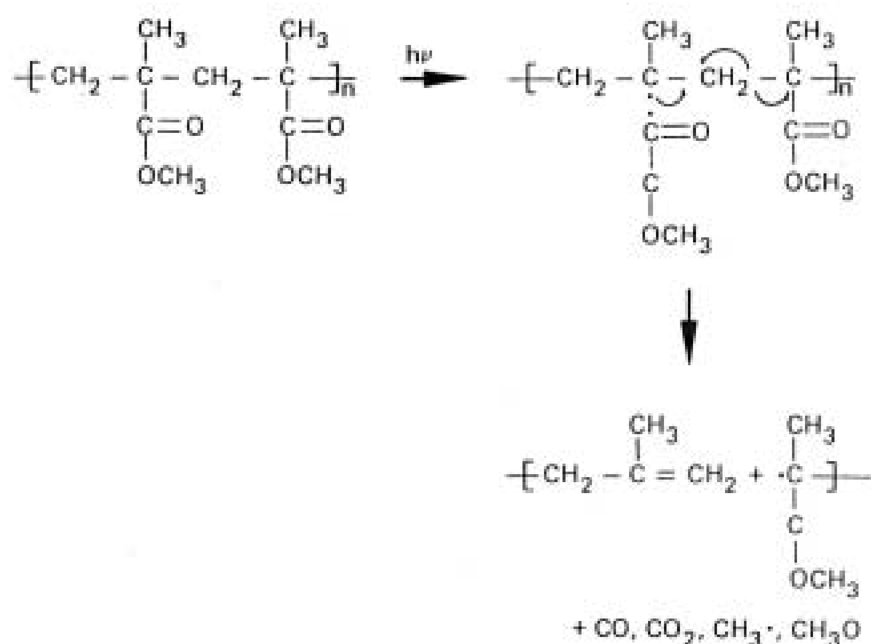



**Figure 1-13.** Mechanism of radiation-induced chain scission in PMMA. Homolysis of the main-chain carbonyl carbon bond is indicated as the initial step. Acylcarbon-oxygen, σ-bond homolysis also occurs, but rapid decarbonylation ultimately leads to the same indicated products.

carbonyl carbon to oxygen sigma bond. In the latter case, homolysis is followed by

rapid decarbonylation to form the same, stable tertiary radical on the main-chain as depicted in Figure 1-13. The mainchain radical undergoes rearrangement through beta scission to cleave the chain and generate an acyl-stabilized, tertiary radical as indicated. This process generates fragments of carbon monoxide, carbon dioxide, and methyl and methoxyl radicals.

Attempts to improve the sensitivity of PMMA through synthesis of analogues while preserving its attractive processing characteristics occupied resist chemists for several years during the early 1970s, and research in the area of acrylate radiation chemistry continues to produce new results. The first e-beam resist used in device

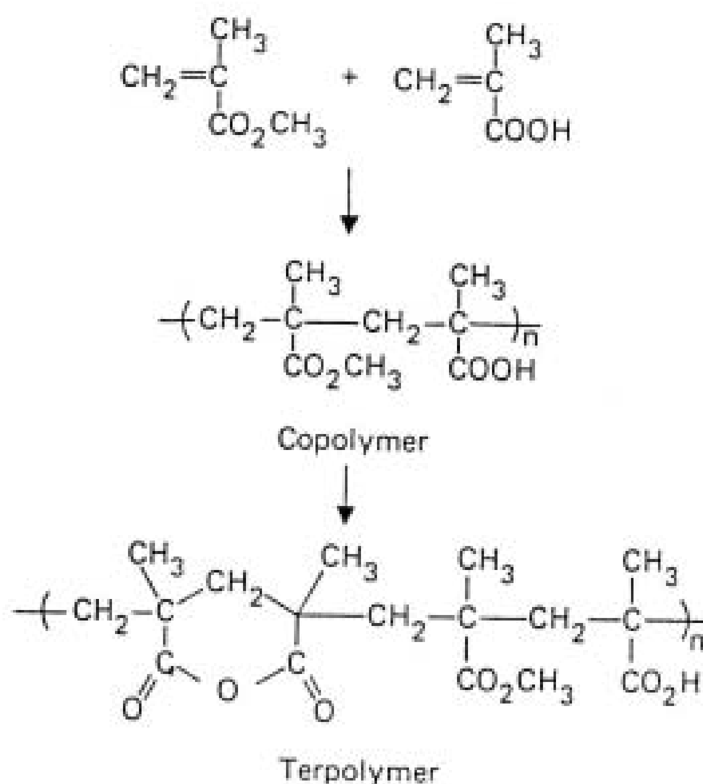



**Figure 1-14**. Mechanism of radiation-induced chain scission in PMMA. Homolysis of the main-chain carbonyl carbon bond is indicated as the initial step. Acylcarbon-oxygen, σ-bond homolysis also occurs, but rapid decarbonylation ultimately leads to the same indicated products.

manufacturing can be considered to have evolved from research in the area of acrylate radiation chemistry. Moreau et al. [39] at IBM have described a resist material

called "Terpolymer" that was introduced into manufacturing in IBM during the mid-1970s. Terpolymer resist (Figure 1-14) is prepared by copolymerizing methyl methacrylate and methacrylic acid to produce a copolymer that is subsequently heated to generate intra-molecular anhydride linkages such that the final product is, in fact, a polymer consisting of three unique monomeric units (a Terpolymer), methyl methacrylate, methacrylic acid, and methacrylic anhydride. Terpolymer has useful resist sensitivity, at 20 kV, of approximately 10 μC/cm$^2$ as practiced in manufacturing. Terpolymer resist clearly demonstrates a significant improvement in sensitivity over PMMA.

The first useful negative-tone e-beam resist materials were based on exploitation of the radiation chemistry of the oxirane or epoxy moiety [40] The most widely used

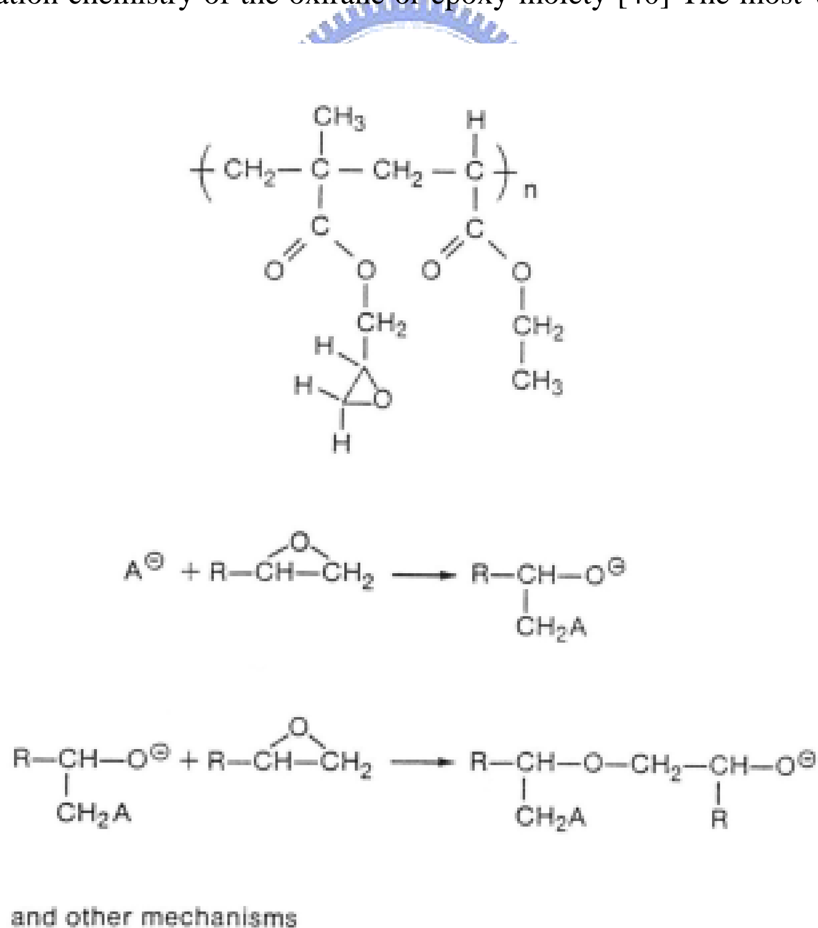



**Figure 1-15.** COP, Bell Laboratories negative e-beam resist. The resist is a copolymer of glycidyl methacrylate and ethyl acrylate.

of these materials, COP (Figure 1-15), is a copolymer of glycidyl methacrylate and ethyl acrylate and was developed at Bell Laboratories [41, 42]. COP found wide applicability in the manufacturing of photomasks for many years. The active element in the structure of COP is the glycidyl side chain, which carries the three-membered heterocyclic substituent called an oxirane or epoxy group. This is the same active structure that is found in the epoxy adhesives with which we are all familiar.

COP functions on the basis of radiation-initiated cross-linking reactions that result in the formation of inter-chain linkages, which generate a cross-linked, three-dimensional network that is insoluble. The chemistry associated with the generation of this network is interesting in that it involves a chain reaction mechanism. The initiating species is generated by radiation and may be an anion, anion radical, cation, or cation radical. The exposure-generated initiator attacks an epoxy moiety and cleaves it to generate a reactive oxygen species, as indicated in Figure 1-15 for the example of anionic initiation. The oxygen anion can then open a second epoxy group, thereby generating a cross-link and a second oxygen anion that may be involved in yet another cross-linking reaction. The consequence of this chain propagation mechanism is to produce high sensitivity through gain: the radiochemical event generates the initiating species that may be consumed in the initial ring opening reaction but that simultaneously generates a product that is sufficiently reactive to produce a propagating chain reaction of ring-opening polymerization sequences.

### *1.2.4 Etch Resistance*

Etch resistance is the ability of a polymer resist to withstand an etching environment during the pattern-transfer process and can be the most difficult requirement to achieve for a resist. Etch resistance depends on the aggressiveness of

the etching chemistry. All dry-etching techniques rely on plasma induced gaseous reactions, and the substrate is placed in an environment that has a high radiation flux. Temperatures in excess of 100℃ are frequently reached. Compared to liquid etching, dry etching places less of a demand on adhesion; however, it does require a polymer to exhibit high thermal and radiation stability. It is important to note that the requirement of high sensitivity dictates the use of a polymer that is unstable to radiation. This is especially true of positive resist systems whose design presents an obvious dichotomy to the resist chemist. Clearly, the physical and chemical properties of the resist represent fundamental limitations on plasma etch resistance.

For process evaluation it is necessary that the etching rate of the resist be measured under the plasma conditions used to etch the thin film of interest. The etching rate is expressed as angstroms or micrometers perminute and is usually compared to the etch rate of a standard novolac-based positive photoresist or the etch rate of the film being etched, and it may be expressed as an etch-rate ratio. When etch resistance is reported, it is important to give all the plasma conditions, including reactor type, power, pressure, and substrate temperature.

## 1.3 PROCESSING STEPS

Photolithography, which was the first technique developed, still continues as the dominant technology although it has undergone many innovations since the early days of the transistor.

The individual processing steps, outlined in Figure 1-16 for a single-level process, that are involved in the development of the latent image into the relief image. Table 1-1 lists the processing variables associated with each step that affect lithographic performance.

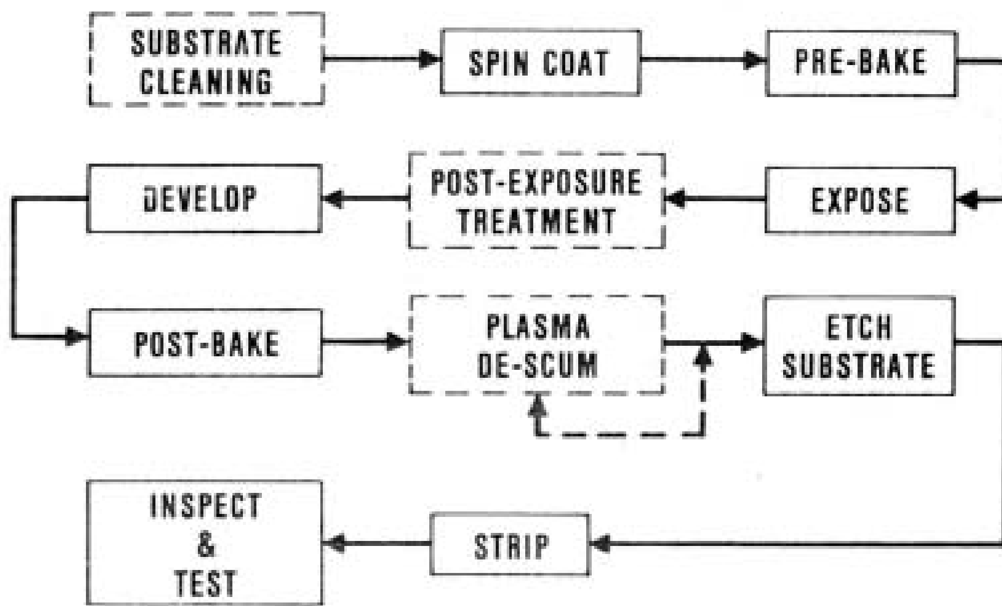



**Figure 1-16.** Flow chart for a typical single-level resist process. Steps in broken lines are not used for all materials.

### *1.3.1 Sensitivity and Contrast*

Sensitivity and contrast are conveniently measured experimentally exposing areas of resist of known size to varying radiation doses and measuring the film thickness remaining after development for each expose area. In negative resists, gel is not formed until a critical dose, denoted as the interface gel dose ($D^i_g$), has been reached. At this dose no lithographically useful image has been formed because the film thickness is insufficient to serve as an etching mask. Thereafter, the gel content (film thickness) increases with increasing dose until the thickness remaining is equal to the original film thickness. A plot is then generated of normalized film thickness as a function of log dose, as shown in Figure 1-17, from which the contrast ($r_n$) is obtained as

$$\gamma_n = \frac{1}{(\log D_g^0 - \log D_g^i)} = \left[\log \frac{D_g^0}{D_g^i}\right]^{-1}$$

where $D^0_g$ is the dose required to produce 100% initial film thickness and is

**Table 1-1** Chemical and physical processing variables that affect lithographic performance.

| *Step* | *Chemical Variables* | *Physical Variables* |
|---|---|---|
| Cleaning | type of reagent<br>surface composition | cleaning time<br>temperature<br>equipment condition |
| Spin-coating | polymer composition<br>molecular weight<br>solvent boiling point<br>solvent vapor pressure<br>solution viscosity<br>solution concentration | spinning speed<br>acceleration<br>temperature<br>exhaust<br>humidity<br>filtration |
| Prebaking | polymer $T_g$ and $T_m$<br>polymer stability<br>solvent composition | temperature<br>time<br>atmosphere |
| Exposure | ambient gas in exposure chamber<br>time after exposure | energy density<br>exposure time<br>time after exposure<br>mechanical stability |
| Postexposure treatment | gas composition<br>PAG reactivity | time<br>temperature |
| Developing | developer composition<br>rinse composition<br>humidity<br>developer age (for dip)<br>batch size (for dip) | spray: pressure and flow rate<br>temperature<br>time of developer, rinse, and overlaps |
| Plasma de-scumming | gas composition | reactor configuration<br>time<br>temperature<br>powder<br>frequency<br>gas flow rates |
| Etching | | |
| Stripping (wet) | reagent<br>age of bath | temperature<br>time<br>degree of agitation<br>batch size |
| Stripping (plasma) | same as de-scumming | same as de-scumming |

determined by extrapolating the linear portion of the normalized thickness versus dose plot to a value of 1.0 normalized film thickness [43]. To compare the useful sensitivity of one resist to another, it is necessary to choose a constant degree of cross-linking, and for this purpose the sensitivity is usually taken as the dose when 50% of the

original film thickness remains ($D^{0.5}_g$). For all known negative cross-linking resists, x varies between 0.5 and 0.8, with higher contrast materials having higher values of x.

For a positive resist, the film thickness of the irradiated region after development

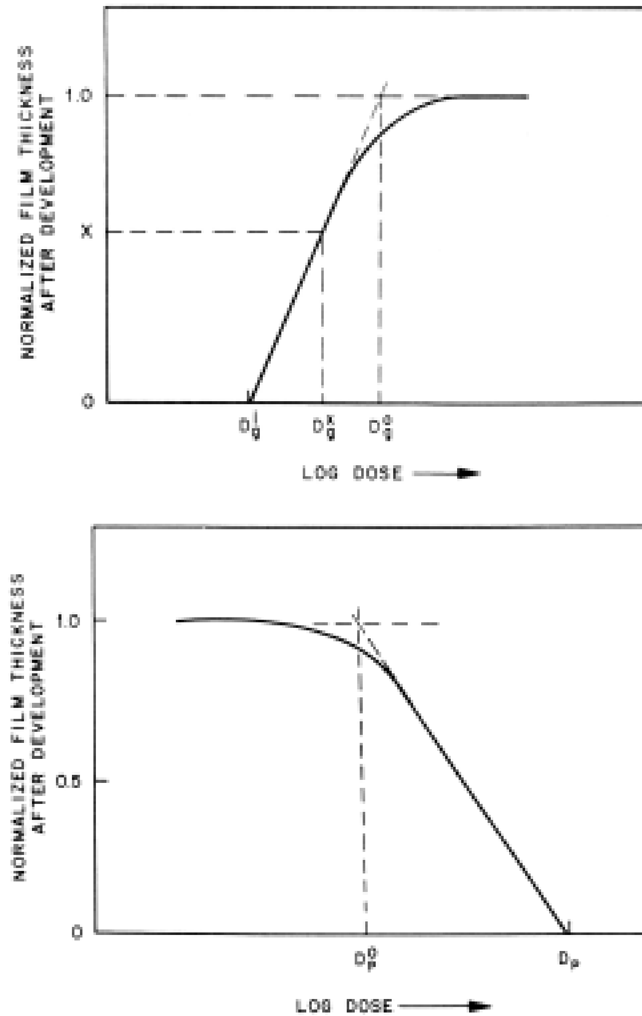



**Figure 1-17.** Typical response or sensitivity curve for a negative electron-beam resist (Top) and a positive electron beam resist (Bottom). The value of $D^x_g$ is usually occurs at 0.5-0.8 normalized thickness.

decreases until eventually a critical dose, $D_p$, is reached, which results in complete removal of the film [44, 45]. The sensitivity and contrast ($\gamma_p$) are evaluated in a manner similar to that for a negative resist. After spin-coating and prebaking, a series of pads of known area are exposed to varying doses. The substrate is developed in a solvent that does not attack the unexposed film, and the thickness of the film

remaining in the exposed areas is measured. The film thickness is normalized to the original thickness, and this value is plotted as function of log dose, as shown in Figure 1-17, where $D_p$ represents the sensitivity of the positive resist. Contrast ($\gamma_p$) is the slope of the extrapolated linear portion of the response curve and is expressed as

$$\gamma_p = \frac{1}{(\log D_p - \log D_p^0)} = \left[\log \frac{D_p}{D_p^0}\right]^{-1}$$

where $D^0_p$ is the dose at which the developer first begins to attack the irradiated film and, as before, is determined by extrapolating the linear portion of the film thickness remaining versus dose curve.

The correct feature size is usually obtained with doses of $D_p$ or greater. For those exposure methods that deliver less dose in small feature areas (i.e., photolithography), doses greater than $D_p$ will be required for submicrometer patterning, with doses greater than twice $D_p$ not being unusual. However, it is possible to develop a relief image to the substrate for doses less than $D_p$. This occurs in "force" developing, where the developer is allowed to attack or thin the original, unexposed film [46-48]. This method may give rise to several problems, including loss of line-width control and possible pinhole formation as a result of thin resist in unexposed areas.

Negative, cross-linking resists have a near-zero dissolution rate in the exposed regions and a very fast dissolution rate in unexposed regions. Hence, the effects of developer and developing conditions are much important for negative resists. For positive resists it is often advantageous to determine the dissolution rates of both the exposed and unexposed film and several methods have been developed to do so.

### *1.3.2 Substrate Cleaning and Preparation*

Many processing problems are frequently traced to dirty or contaminated substrate surfaces. Hence, it is imperative that the surface to be patterned be atomically clean and free from any contamination so that the lithographic process is not adversely affected [49]. Particulate defects also prevent uniform resist coating during the spin-coating step. Wafers with particle contamination result in "comet tail" defects or striations in the coated film, and even one such defect on a wafer renders it unusable.

### *1.3.3 Resist Coating*

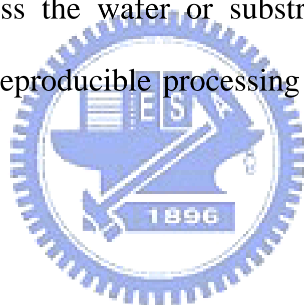
The objective of this step is to obtain a uniform, adherent, defect-free polymeric film over the entire substrate. Spin-coating has long been accepted as the best coating method for obtaining these properties. Spin-coating is accomplished by flooding the substrate with a resist solution and rapidly rotating it at a constant speed between 1,000 and 10,000 revolutions per minute until the film is dry [49-53]. The film uniformity across a single substrate and from substrate to substrate must be at least ±5.0 nm to ensure reproducible line-widths and development times [53, 54]. Variables that affect the spin-coating process are given in Table 1-1 and are divided into two categories: chemical and physical.

The most common adhesion promoter for silicon photo-resist is hexamethylenedisiloxane (HMDS), which is a volatile liquid at room temperature. It may be applied by spin-coating from a dilute solution; however, more reproducible results are realized if a vapor coating method is used. A typical procedure involves the use of a heated (100-160℃) vacuum chamber where a "batch" of clean wafers are placed in a quartz holder and placed in the oven chamber. The heated chamber is evacuated and back-filled to a preset pressure with HMDS vapor in an inert carrier

gas. After a suitable treatment time, the oven is evacuated and back-filled with argon or nitrogen to atmospheric pressure. The wafers are removed, allowed to cool, and immediately coated with resist.

### *1.3.4 Prebaking*

To remove residual solvent and anneal any stress in the film, a baking step is used prior to exposure. For most resist systems, residual solvents will adversely affect both subsequent radiation-induced reactions that are initiated by exposure as well as the developing process. Prebaking is frequently considered a trivial step; however, it is very important that it be done properly, because it ensures that the resist film has uniform properties both across the wafer or substrate and from one substrate to another. It therefore ensures reproducible processing of each wafer and wafer lot in subsequent steps.




### *1.3.5 Exposure*

After the substrate has been coated with resist and properly prebaked, it is next exposed to some form of patterned radiation to create a latent image in the resist layer. For the purpose of exposure discussions, it is important to differentiate between beam-forming systems, such as ions or electrons, and mask systems as used in electron image projection, photo-lithography, and X-ray lithography. The quality of the latent image is dependent upon the exposing hardware, the physics and chemistry of the interaction between the radiation and the resist, and, in the case of mask systems, the quality of the mask.

### *1.3.6 Postexposure Treatment*

After the polymeric resist film has been exposed and the latent image generated, chemical reactions may continue to occur after exposure. Several post-exposure treatments have been reported and are summarized here:

1. Thermal
2. Flood exposure with other types of radiation
3. Treatment with reactive gas
4. Vacuum treatment

Methods 1 and 3 have been utilized in dry-developed resist systems (surface-imaging systems) and image reversal schemes. Thermal post-treatment (postexposure baking, PEB) is required in the new chemically amplified systems. Dry-developed systems, although largely in the research phase, may well become important; the literature [55-60] offer more detailed descriptions.

### *1.3.7 Developing*

Once the latent image has been formed in the polymer film, it must be developed to produce the final three-dimensional relief image. The developing process is the most complex of the processing steps, has the greatest influence on pattern quality, and requires much more process development effort than any other step. Two development processes have been used, namely, liquid development and dry development (plasma). Dry development of resists has been reviewed comprehensively by Taylor and others [55-58], and one system that uses a surface treatment of an exposed resist with a silicon-containing reagent is discussed. This treated resist is developed with an oxygen reactive ion etching process.

Table 1-1 lists many of the variables associated with the developing step, all of which are interactive, making optimization an extraordinarily tedious task. To optimize the developing process, it is necessary to have a set of developing criteria, such as the following, that are typical of the criteria used in positive resist development work:

1. No reduction in original film thickness
2. Minimum developing time (less than 2 min)
3. Minimum distortion and swelling during the developing process
4. Faithful reproduction of the required dimensions (zero bias)

### *1.3.8 Postbaking*

The last step prior to etching is postbaking (post-development bake) which is designed to remove residual developing solvents and anneal the film to promote adhesion. The limitations and fundamental considerations for postbaking are the same with one exception. It is less important that thermal-induced reactions be considered during the postbaking step, and it is frequently possible to bake at much higher temperatures and times to achieve the requisite lithographic performance. One important limitation is that the postbaking temperature must be less than that which causes the polymer to flow excessively or melt. In addition, temperatures that will adversely affect the underlying substrate should be avoided. The upper temperature limit of this step is usually determined by wall profile angles of large features with a SEM with a viewing angle of >80 ° .

### *1.3.9 Etching*

The next processing step is the etching step, and like development it is extremely

critical. Again, both liquid and plasma etching techniques are employed, with the latter rapidly becoming the technique of choice for high-resolution lithographic processing. Liquid etching rate is affected by the choice of etching reagent, temperature, etching time, degree of agitation, and the age of the etch bath. Liquid etching nearly always results in an undercut, isotropically etched profile that severely limits its utility for etching thick films and sub- micrometer patterns. The isotropic nature of liquid etching makes it important to control precisely the etching end point, and considerable effort is required to achieve reproducible etching times from wafer batch to wafer batch.

### *1.3.10 Stripping*

The final step in the lithographic process is resist stripping. This step is, for the most part, noncritical and may be accomplished by either oxidizing liquid or plasma processes. It is important that the stripping procedure not alter the underlying thin film or semiconductor device or introduce undesirable contamination that will be deleterious to subsequent lithographic steps. Special care must be exercised when using a plasma to strip metal containing bi-level resists and the chemically amplified-resists that contain metal atoms because a pure oxygen plasma will not completely remove the films. Also, certain planarizing materials and antireflective coatings such as polyimides, epoxy systems, and highly cross-linked novolacs are very difficult to strip. In all of these cases, it may be necessary to use a combination of plasma conditions or combinations of plasma and liquid stripping processes.

## REFERENCES


1. G. E. Moore. *Proc. IEEE*, **64(6)**, 307 (1976).

2. W. M. Moreau. *Semiconductor Lithography: Principles, Practices, and Materials*; Plenum Press: New York (1988).

3. W. S. Deforest. *Photoresist Materials and Processes*; McGraw-Hill: New York (1975).

4. D. O. Massetti; M. A. Hockey; D. L. McFarland. *Proc. Soc. Photo-Opt. Instrum. Eng*. **32**, 221 (1980).

5. D. A. Markle. *Solid State Technol.* **17(6)**, 50 (1974).

6. M. C. King. *IEEE Trans. Electron Devices*, **ED-26**, 711 (1979).

7. V. Pol. *Solid State Technol.* **30(1)**, 71 (1987).

8. J. D. Cuthbert. *Solid State Technol.* **20(8)**, 59 (1977).

9. J. J. Bruning. *J. Vac. Sci. Technol*. **17**, 1147 (1980).

10. J. D. Buckley; C. Karatzas. *Proc. SPIE Opt.-Laser Microlithography*. 1088 (1989).

11. R. Feder; E. Spiller; J. Topalion. *J. Vac. Sci. Technol.* **12**, 1332 (1975).

12. E. Reichmanis; A. E. Novembre. *Annu. Rev. Mater. Sci*. **23**, 11 (1993).

13. G. W. Jorgensen; M. H. Bruno. *Lithographic Technology Foundation*: New York, Bull 218 (1954).

14. J. Kosar. *Light Sensitive Systems*; John Wiley and Sons: New York, 194 (1965).

15. L. M. Minsk. *U.S. Patent*, 2 725 372 (1955).

16. T. D. Schlaback; D. K. Rider. *Printed and Intergrated Circuitry*; McGraw-Hill: New York, 85 (1963).

17. H. C. Pfeiffer. Record of the 11th Symposium on Electron, Ion, Laser Beam Technology; San Francisco Press: San Francisco, CA (1974).

18. A. N. Broers. *Proc. Symp. Electron Ion Beam Sci. Technol*. 3-25 (1972).

19. A N. Brners. *J. Vac. Sci Technol*. **10**, 979 (1973).

20. D. S. Alles; F. R. Ashley; A. M. Johnson; R. O. Townsend. *J. Vac. Sci. Technol.* **72**,1252 (1975).

21. D. R. Herriott; R. J. Collier; D. S. Alles; J. W. Stafford. *IEEE Tram. Electron Devices*. **ED-22**, 385, (1975).

22. G. L. Varnell; D. F. Spier; A. C. Rodger; R. D. Holland. Proceeding of the 6th International Conference on Electron Ion Beam Science and Technology; Electrochemical Society: Pennington, NJ, 97 (1972).

23. H. C. Pfeiffer; T. R. Groves; T. H. Newmann. *IBMJ. Res. Dev.* **32(4)**, 494 (1988).

24. J. T.Clemens. *Solid State Technol.* **32(3)**, 69 (1989).

25. A. N. Broers. *IBMJ. Res. Dev.* **32(4)**, 502 (1988).

26. H. C. Pfeiffer. *J. Vac. Sci. Technol.* **15**, 887 (1978).

27. D. R. Herriott; G. R. Brewer. In Electron-Beam Technology in Microelectronic Circuit Fabrication; Academic Press: Orlando, FL, 141 (1981).

28. Y. Sohda; Y. Makayama; N. Saitou. *J. Vac. Sci. Technol.* **39(6)**. 2940 (1991).

29. H. W. P. Koops. *Microcircuit Eng.* **88**, 217 (1989).

30. H. S. Yourke; E. V.Weber. *Tech. Digest Int. Electron Devices Meet.* **431**, 436, (1976).

31. S. D. Berger; J. M. Gibson. *Appl. Phys. Lett*., **57**, 153 (1990).

32. S. D. Berger; J. M. Gibson; R. M. Camarada; R. C. Farrow; H. R. Huggins; J. S. Kraus; J. A. Liddle. *J. Vac. Sci. Technol.*, **35**, 2996 (1991).

33. O. C. Wells et al., *Scanning Electron Microscopy.* McCraw-Hill. New York. (1974).

34. N. Eib; D. Kyser; R. Pyle. In VLSI Electronics Microstructure Science; Einspruch, N. G. Ed.; *Lithography for VLSI Series;* Einspruch, N. G.; Watts, R. K., Volume 16 Eds.; Academic Press: Orlando, FL, Chapter 4 (1987).

35. L. A. Pederson. *J. Electrochem. Soc*. **129 (1)**, 205 (1982).

36. H. Gokan; S. Esho; Y. Ohnishi. *J. electrochem. Soc.* 13, 1696 (1983).

37. A. Gupta; R. Liang; F. Tsay; J. Moacanin. *Macromolecules*, 73, 1696 (1980).

38. H. Hiraoka. *IBMJ. Res. Dev.* 27, 121. 92 (1977).

39. W. Moreau; D. Merritt; W. Moycr; M. Hatzakis; D. Johnson; L. A. Pederson. *J. Vac. Sci. Technol.*, **16(6)**, 1989 (1979).

40. T. Hirai; Y. Hatano; S. Nonogaki. *J. Electrochem. Soc*. **118(4)**, 669 (1971).

41. L. F. Thompson; E. Feit; R. D. Heidenreich. *Polym. Eng. Sci.*, **14(7)**, 105 (1974).

42. L. F. Thompson; J. P. Ballantyne; E. D. Feit. *J. Vac. Sci. Technol.* **12(6)**, 1280 (1975).

43. R. D.Heidenreich; L. F. Thompson; E. D. Feit; C. M. Melliar-Smith. *J. Appl. Phys.*, **44(9)**, 4039 (1973).

44. M. J. Bowden. *J. Poly. Sci. A*. **49**, 221 (1974).

45. M. J. Bowden; L. F. Thompson. *J. Appl. Polym. Sci.* **17(10)**, 3211 (1973).

46. J. S. Greeneich. *J. Appl. Phys*. **45(12)**, 5264 (1974).

47. J. S. Greeneich. *J. Electrochem. Soc.*, **122(7)**, 970 (1975).

48. E. D. Wolf; F. S. Ozdemir; W. E. Perkins; P. J. Coane. In Proceedings of the Symposium on Electron, Ion and Laser Beam Technology; Thornley, R. F., Ed.; San Francisco Press: San Francisco, CA, 331 (1971).

49. W. S. DeForest. *Photoresist Materials and Processes*; McGraw-Hill: New York; 630 (1975).

50. M. M. Fogiel. *Microelectronics*; Research and Education Association Press: New York (1972).

51. L. I. Maissel; R. Glang. Handbook of Thin Film Technology; McGraw-H New York (1970).

52. C. A. Harper. *Handbook of Materials and Processes for Electronics*; McGraw-Hill:

New York (1970).

53. B. D. Washo. *IBMJ. Res. Dev.* **21(2)**, 190 (1977).

54. K. Skidmore. *Semiconcl. Int.* **11(2)**, 57 (1988).

55. G. N. Taylor; T. M. Wolf; M. R. Goldrick. *J. Electrochem. Soc.* **128**, 361 (1981).

56. G. N. Taylor; T. M. Wolf. *Polym. Eng. Sci*. **20**, 1087 (1980).

57. G. N. Taylor; T. M. Wolf. *J. Electrochem. Soc.* **127**, 2665 (1980).

58. W. R. Goodner; T. E. Wood; H. G. Hughes; J. N. Smith. Proceedings of the Kodak Microelectronics Seminar; Eastman Kodak Company: Rochester, NY, 51 (1979).

59. G. N. Taylor; T. M. Wolf. *J. Vac. Sci. Technol.* **19(14)**, 872 (1981).

60. M. Isaacson; A. Murray. *J. Vac. Sci. Technol.* **19(4)**, 1117 (1981).

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