ELECTRON-BEAM LITHOGRAPHY

The introduction of electron-beam lithography in the semiconductor industry was prompted by the belief that photo-optical lithography was rapidly running out of resolution for patterning circuits on wafers. For that reason major emphasis was placed on the development of electron-beam lithography in the early 1960s. For nearly 30 years electron-beam lithography has been used to generate patterns in radiation-sensitive materials. The first electron-beam pattern generation was successfully accomplished using standard scanning electron microscopes. In the early 1970s more sophisticated electron-beam systems were developed by Bell Laboratories and IBM research laboratories as the precursors to the fully integrated direct write and photomask pattern generators used in the semiconductor industry today (1–3).

All electron-beam lithography systems are composed of four basic entities: an electron column, an *XY*-laser controlled mechanical stage, a central processing unit that controls the *XY* stage and blanking on and off of the electron beam, and the substrate holders used to transfer the mask or wafer substrate onto the stage.

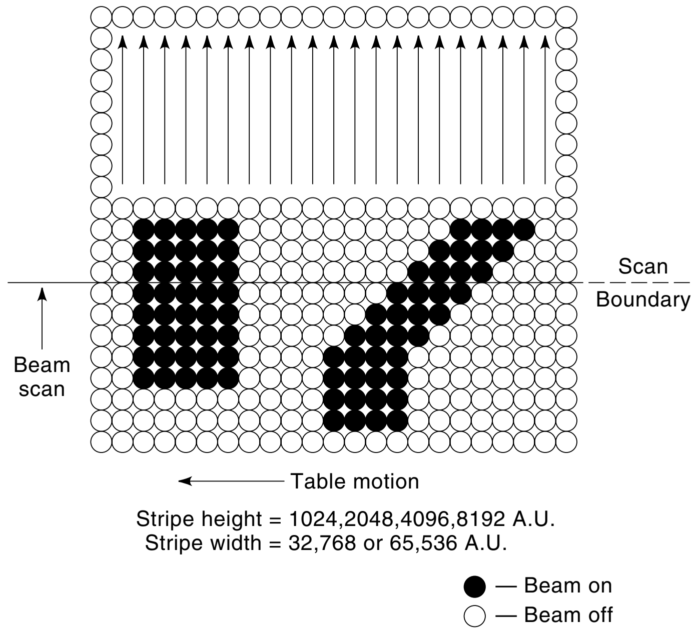


Figure 1. How a pattern is generated by a raster-scanning electron-beam system. The beam scans in the vertical (y) axis and the *XY*-table indexes in the horizontal (x) axis. The beam blanks "on" to expose the resist on the substrate. All areas of the pattern are scanned. The example shown here is for an Etec Systems, Inc., Manufacturing Electron Beam Exposure System (MEBES).

SEMICONDUCTOR PATTERN GENERATION

In order to understand the need for electron-beam lithography more fully it is important to understand the primary characteristics of high-resolution lithography. The critical factors for acceptable pattern generation are as follows:

1. *Pattern integrity:* the pattern must be generated as accurately as possible to the circuit design; no features can be added or deleted from the design.
2. *Image acuity:* the generated features must be clearly defined; rough image edges are unacceptable.
3. *Feature size control:* all features must be within a given tolerance of the desired design size.
4. *Placement:* location of the features relative to each other must be within the design tolerances.
5. *Resolution:* the smallest feature that a pattern generator can create is critical to high-density circuit design.

TYPES OF ELECTRON-BEAM LITHOGRAPHY SYSTEMS

Early developments led to distinctly different approaches to electron-beam pattern generation. There are currently two basic pattern generator architectures used in pattern generation:

1. Vector-scanning architectures using either a shaped beam or a Gaussian beam
2. Raster-scanning architectures using a binary round spot

The architectures differ in their means of pointing or deflecting the beam. Figures 1 and 2 show the differences between the two techniques.

The vectoring architecture was developed for direct-write-on-wafer applications and has been adapted with some success for photomask fabrication. This writing strategy is inherently an analog process like that used in the first-generation computer displays and printers. Scientists at IBM pursued this electron-beam lithography approach.

Bell Laboratories' scientists developed the raster-scan architecture specifically for photomask fabrication. This raster scan technique is inherently a digital process and is like that used in the state-of-the-art computer graphics displays and

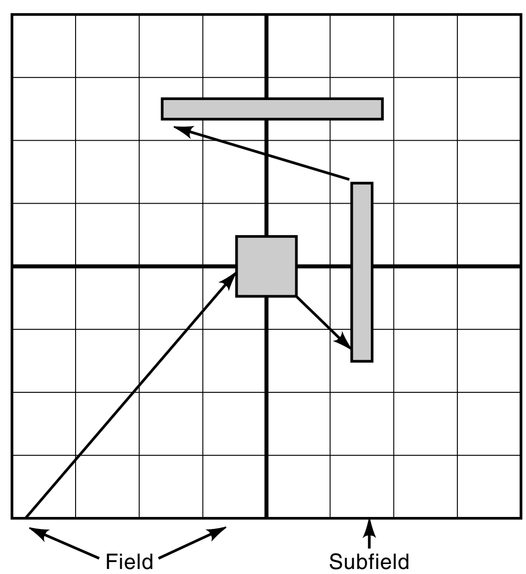


Figure 2. How a pattern is generated by a variable-shape spot vector-scan system. The pattern is divided into subfields and fields. The beam vectors only to the location where pattern is to be written. The beam is also shaped to provide efficient feature generation.

printers. Figures 3(a) and (b) show basic column designs for raster-scan- and vector-scan-shaped beam systems, respectively (4,5).

SCAN ARCHITECTURE

A raster scanning system patterns a photomask or wafer by scanning the exposing beam in one direction at a fixed rate while the mask or wafer is moved under the beam by a laser-controlled table. In order to compose a circuit pattern the electron beam in blanked “on” and “off” thousands of times during each scan. The result is much like the raster scanning of a television.

The vector-scan architecture attempts to improve throughput by deflecting the exposure beam only to those regions of the substrate that require exposure. The assumption is that significant time can be saved by not covering area in which there is no pattern. The vector scanning system “skips over” areas that have no pattern. As a result, the beam visits only patterned areas. Whereas in the case of the raster-scan system, all of the area of the substrate is rastered either with the beam “on” or “off.” Significant discussion can be made as to which technique provides the fastest coverage rate. Factors such as spot size, beam current, *XY*-table address size, beam blanking rate, and circuit design data complexity all play an important role in electron-beam system throughput. Writing speed is only a subset of the overall throughput of a lithography system. Table 1 provides a list of some of the manufacturers of electron-beam lithography systems with type of architecture and semiconductor applications.

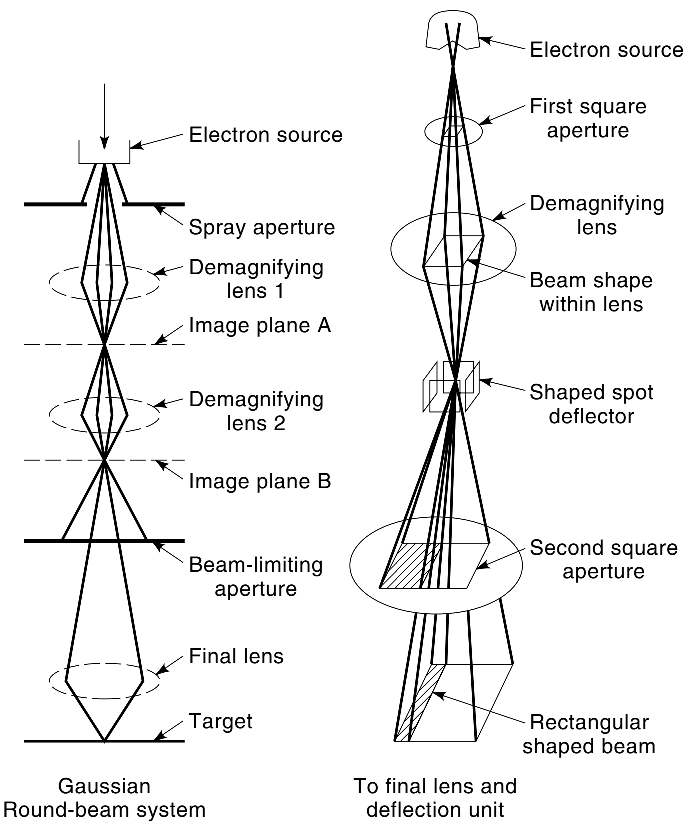


Figure 3. (a) A diagram of a raster-scan electron beam column; a round aperture shapes the spot (4). (b) A column diagram for a shaped beam system (5).

Beam scanning over the distances of concern (on the order of 1 mm) is performed at about 30 kHz for a raster-scan system. To reduce the pointing or deflection errors, 10 kHz is a typical vector-scanning rate. The technology for large-field beam deflection has remained essentially the same for many years and is likely to remain unchanged.

Raster scanning is independent of the actual pattern being exposed: the scan need not vary in amplitude or timing within a given pattern or for different patterns on the mask or wafer. Vector scanning is pattern dependent: beam deflection and timing vary continuously. In the case of different patterns the writing path can vary significantly. That is to say, for every different circuit pattern the vector-scanning system will vary its writing path. For the raster-scanning system the path is always the same. In raster-scanning systems the rate at which the beam is turned “on” and “off” to compose the pattern (blanking rate) has increased over the past two decades. In the 1970s typical raster-scan beam blanking rates were 20 MHz; more recently beam blanking rates as high as 500 MHz can be achieved. In a raster-scanning system using a binary exposure strategy, the resolvable pattern element (pixel) is the size of the exposing beam and the pixel delivery rate is the same as the blanking rate. With that in mind, the writing rate of the raster-scan system has improved 25 times in the last two decades. The rate of this improvement has been overshadowed by the fact that the pixel densities of integrated circuits have increased at an almost exponential rate. Additionally, as the integrated-circuit patterns become more complex, pixel sizes become smaller, in order to obtain higher design resolution. The number of pixels in a given pattern varies as the inverse square of the pixel dimension. Thus, if the pixel size is reduced by one-half, the patterned area will contain four times as many pixels. In the case of a raster-scanning system with a fixed blanking rate, the writing time also increases by four times. The inverse would be that a blanking rate four times faster would be required to cover the same pattern in the same amount of time.

In the same case for the vector-scanning system, variable-shaped beam exposure was developed to improve upon the pixel delivery rate. This is achieved by increasing the size of the shaped beam with the decrease in size of the pixel. That is to say, the variable-shaped beam system can produce a beam that is larger than one pixel, resulting in faster exposure coverage.

PATTERN GENERATION

Both raster scanning and vector scanning not only write a pattern using different beam-scanning techniques, they also generate a pattern differently. Raster-scan systems will “break” the pattern up into stripes. Each stripe is a fixed number of pixels in height and width. Figure 1 shows possible combinations of stripe widths and heights. The pixel size determines the size of the stripe in the x and y directions. The resultant pattern is composed of multiple stripes and is similar to the composition of a “mosaic.”

In the case of a vector-scanning system, the pattern is also composed of multiple units. For this system they are referred

Table 1. Commercial Manufacturers of Electron-Beam Systems

Manufacturer	Type of System	Primary Application
Etec Systems, Inc. 26460 Corporate Ave. Hayward, CA 94545	Raster scan	Masks
Leica Lithographic Systeme Jena GmbH Goschwitzer Strasse 25 D-07745 Jena, Germany	Vector scan/variable shaped spot (VSS)	Masks/wafers
JEOL, Ltd. 1418 Nakagami Akishima Tokyo, 196 Japan	Vector scan/VSS	Wafers/masks
Toshiba Corporation 1, Komukai Toshiba-cho Saiwai-ku, Kawasaki 210, Japan	Raster scan	Mask
Ultrabeam Lithography, Inc. 3050 Zanker Road San Jose, CA 95134	Raster scan	Masks
Hitachi, Ltd. 6, Kanda-Suregadai 4-chome Chiyoda-ku, Tokyo, 101, Japan	Vector scan/VSS	Masks

to as *fields* and *subfields.* Therefore, the resultant pattern is composed of multiple fields and subfields. The field and subfield sizes are system dependent. That is to say, different electron-beam system manufacturers use different field and subfield sizes. The size is usually determined by the accuracy by which they can deflect the beam and index the *XY* table. Figure 2 shows how a pattern is divided into fields and subfields. The purpose of this article is not to propose advantages of one writing technique over the other; in commercial circles the discussions can become complicated. Each technique provides advantages over the other depending on the application for which it is being applied. Additional information on the benefits of each electron-beam lithography technique can be found in Refs. 6 and 7.

Raster-scanning systems deliver dose to the target substrate by changing spot size and beam current, and the dwell time of the spot remains constant. For the case of the variable-shaped spot vector-scanning system the dose is delivered by changing the spot and the dwell time, while the beam current remains constant.

ELECTRON-BEAM RESISTS AND PROCESSES

Selection of the correct electron-beam-sensitive resist is important in achieving high-resolution lithography. Unlike photolithography, no universally accepted chemistry has emerged in electron-beam lithography. In photolithography, resist selection is primarily determined by wavelength, that is, radiation-sensitive materials for 365 nm systems are different than those for 248 nm. The factors in selecting a resist for electron beam lithography are more complex. The following factors must be considered: accelerating voltage, maximum deliverable beam current, spot size, and composition of the substrate or target. The factors that expose the resist are beam energy, amount of electrons and heat generated by the beam. Historically, the dose required to expose an electron beam resist was determined by the equation

$$D_{\max} = \frac{it}{a}$$

where $D_{\max}$ is the maximum dose deliverable by the electron-beam system, i is the maximum current that can be delivered to the area (a) defined by a single pixel or beam, and t is the dwell time of the spot. These parameters define the maximum dose that can be delivered in coulombs per square centimeter. With the introduction of high accelerating voltage systems (40 kV to 100 kV), heat has become a major factor in electron-beam-induced chemistry (8–11). Groves best describes the theory of beam-induced substrate heating in Ref. 12. He reports the temperature rise for a bulk quartz photomask at 10 $\mu C/cm^2$ with a 50 kV beam from 46° to 85°C versus 0.4° to 48°C for a bulk silicon wafer. The temperature ranges are a function of the pattern density. High-density patterns would result in a larger rise in temperature. Hence, thermal conductance of the target substrate plays a major role in heating effect.

Unfortunately, the thermal component of exposure adds to the complexity of correcting dose anomalies for highly dense patterns. The result is that additional correction is required over the already required proximity-effect corrections used for electron-beam lithography. The proximity effect is determined by the sum of all the energy deposited on the target substrate; the incident dose and the scattered dose define this sum. The more dense the pattern and the higher the accelerating voltage, the greater the proximity effect. As a result, proximal features will receive dose from neighboring features, thereby requiring less incident energy to produce a given feature dimension. The distance over which this effect occurs is a function of the accelerating voltage and the atomic number (Z) of the target. The higher the atomic number and accelerating voltage, the greater the proximity effect. In order to achieve high-resolution electron-beam lithography proximity-effect correction is needed. Figure 4 shows the relative scattering distances of a 100-electron Monte Carlo simulation in poly-(methyl methacrylate) (PMMA) on a silicon wafer (13). There are two types of proximity effect. The *intraproximity effect* is described as nonuniform absorbed energy within an exposed area. Errors in pattern integrity that occur as a result of the intraproximity effect are line end shortening and corner rounding. Both of these errors create major problems in semiconductor lithography. The second type of proximity effect is the *interproximity effect,* which is defined as the absorbed energy between adjacent or proximal patterns. Errors in pattern feature size are the result of the interproximity effect. Both of these proximity effects can be corrected through complex software routines. Most recently Rosenbusch et al. demonstrated the ability to proximity correct complex reticle patterns for 1-Gbit memory designs (14).

Additionally, substrate charging affects the radiation-induced chemistry during electron-beam exposure. It is important that the substrate be properly "grounded" such that a charge is not built up on the substrate. The resultant charge created by a poorly grounded substrate will result in unwanted exposure in the resist material. Substrate charging will also result in deflecting the beam during subsequent beam exposures; as a result beam placement errors occur. While placement is not typically a process-related anomaly, it is critical to high-quality pattern generation. Both silicon wafers and chromium mask substrate are conductive enough such that charging does not occur; however, many of the electron-beam resists are poor conductors. As a result charging can occur in the resist film during exposure. Various attempts to reduce the amount of charging during pattern writing have been attempted. Precoating the resist layer with gold or aluminum has been investigated with limited success. The evaporation process can cause sensitivity loss to the resist. The most successful solution to this problem has been the use of conductive polymer coatings on the resist materials or the use of conductive resists (15,16).

In summary, high-resolution electron-beam lithography requires a full understanding of all of the energy components deposited by the beam: electron, thermal, and charging. The classical proximity-effect correction deals only with electron-induced events. The increased use of higher accelerating voltage will require the lithographer to consider the thermally induced chemistry. For this reason, the best approach to establish a robust lithography process is to gather empirical data. Process modeling is helpful from the standpoint of establishing a sound starting point from which to develop a process. The important factors to consider when selecting a resist are sensitivity, thermal stability, conductivity, adhesion characteristics, film thickness required for acceptable resolution, resistance to reactive ion etching (RIE), and process repeatability. When all of these factors are understood, proper proximity corrections can be derived. Proximity effect corrections are achieved by changing the dose received by various features in the pattern to compensate either for too much or too little dose.

ELECTRON-BEAM RESIST TONE

There are basically two different types of electron-beam-sensitive resists. Positive resists are materials that undergo radiation-induced chemistry such that the solubility of the resist is increased in the area of exposure. When the exposed material is subjected to a developer, the material is dissolved or developed from the surface of the substrate. The second type is a negative resist. These materials undergo a decrease in solubility when irradiated by an electron beam, resulting in not being dissolved or developed when processed. Figures 5(a) and (b) show the difference between a positive and a negative resist process; the examples shown are for a chromium photomask process.

Additionally, there are other characteristics of electron-beam resists that can be used for classification. Figure 6 shows the different categories of electron-beam-sensitive materials. Positive and negative resist materials fall in one of three major categories: polymeric, diazonaphthoquinone/novolac, and chemically amplified resist. Within those categories polymeric resists are either solvent or aqueous-base developable. Most polymeric resists are solvent developable. Diazonaphthoquinone/novolac resists and chemically amplified resists are usually aqueous-base developable. In more recent years there has been a major effort to move from polymeric resists to aqueous-base developable resists because of the high costs associated with disposing solvent wastes.

POLYMERIC RESISTS

The most commonly used electron-beam resists fall in this category. The radiation chemistry of most of these is often

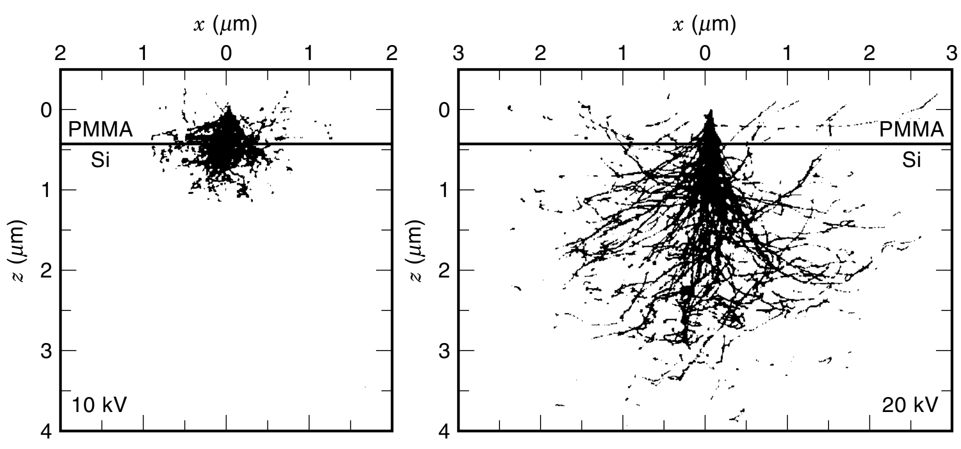


Figure 4. Simulated trajectories of 100 electrons scattered in a PMMA resist film on silicon. Relative electron scattering distances can be seen from this Monte Carlo simulation [From Keyser and Viswanathan (1975)] (13).

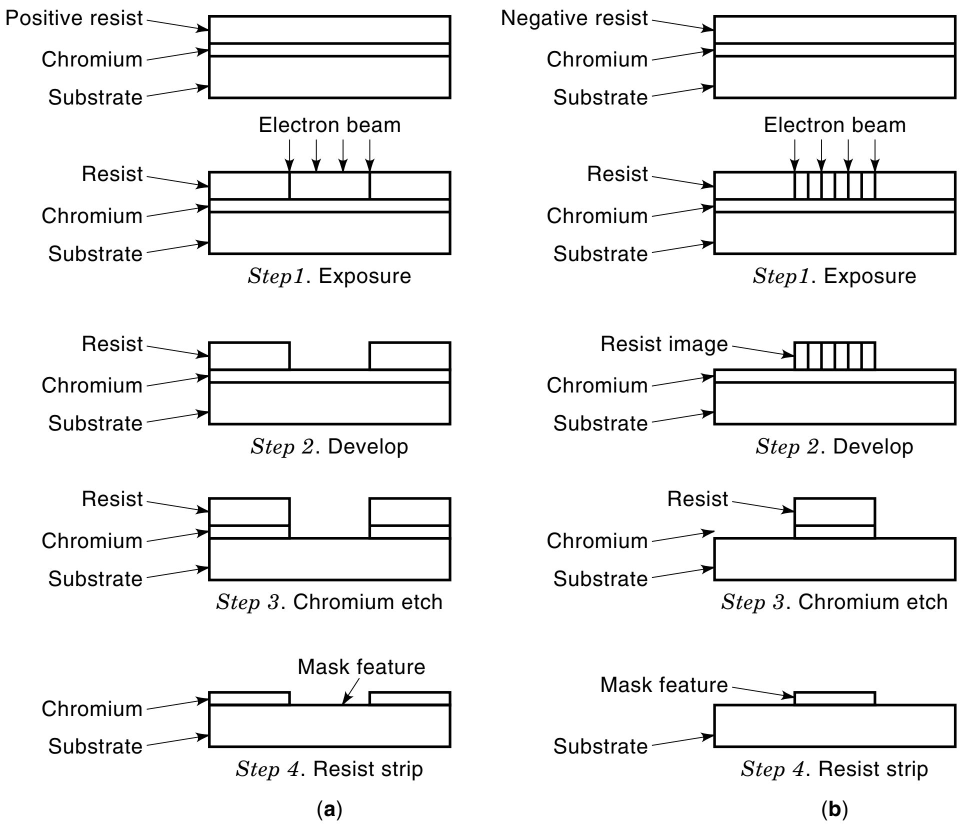


Figure 5. The differences between a positive- and a negative-resist process. The schemes shown are for photomask fabrication processes. (a) The positive process results in a "hole" in the chromium, whereby (b) the negative process results in a chromium feature.

straightforward. In the case of the positive polymeric resists the polymer is broken down into smaller polymer units or monomers. As a result the solubility is increased in the exposed region and is easily dissolved by the solvent developer. In the case of the negative resist, the polymer is cross-linked by the electron beam and the resultant exposed resist becomes insoluble in the solvent developer. The most common examples of these resist processes are poly(butene-1-sulfone) (PBS) and poly(glycidylmethacrylate-co-ethyl acrylate) (COP) (17,18).

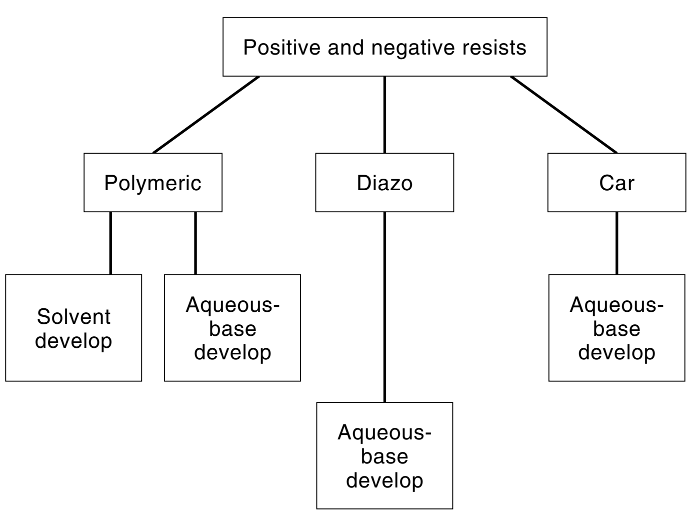
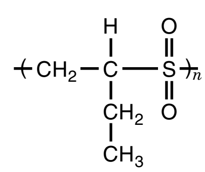


Figure 6. Shows basic categories of electron-beam sensitive materials (resists). There are exceptions to these categories, but most electron-beam resists fit into one of these categories.

Figures 7 and 8 show the basic chemistry of PBS and COP resists, respectively. PBS has remained the most used resist in the photomask industry in spite of the fact that it was first introduced in the early 1970s. It is highly unusual for a resist material to have such a long production life. Since the introduction of these two polymeric resists, many resists from the same class of polymers have been introduced. For example, there are many methacrylate-type resists, Fig. 9 shows the reaction chemistry for PMMA, which is still extensively used for the fabrication of X-ray masks. Other types of polymers that are used as electron-beam resists are polysiloxanes, polystyrenes, and polyethers. Table 2 provides a list of some of these materials with references (17,19–24). Common developers for these types of resist are generally low-molecular-



$$R-SO_2 \longrightarrow R'-[RSO_2R']^{\dot{+}} + e^-$$

$$[RSO_2R']^{\dot{+}} \longrightarrow RSO_2^+ + \cdot R' \longrightarrow R^+ + SO_2$$

Figure 7. Poly(butene-1-sulfone) (PBS) resist has been used extensively in the fabrication of photomasks. The reaction chemistry is shown. The electron-induced chemistry results in the degradation of the polymer into smaller polymer units, which increases the solubility in the exposed area. The positive resist was introduced by Bell Laboratories and continues to be used throughout the photomask industry.

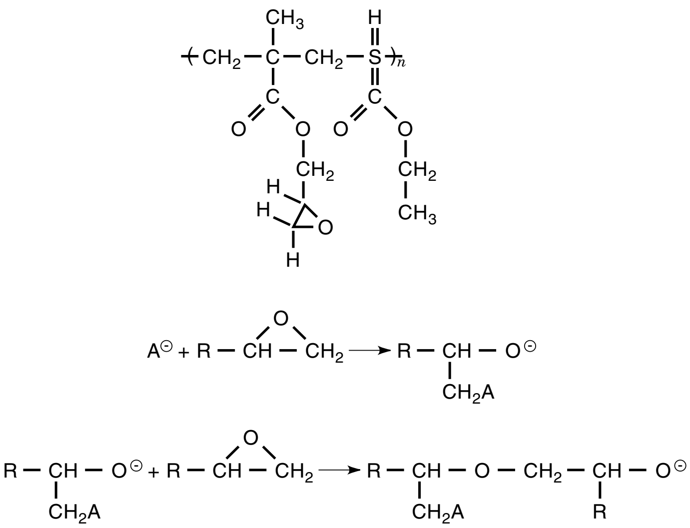


Figure 8. The electron-induced polymerization reaction of poly(glycidyl methacrylate)-co-ethyl acrylate (COP) resist. Bell Laboratories first introduced this negative resist for photomask fabrication.

weight aliphatic ketones or mixtures of ketones and aliphatic esters.

While most polymeric resists generally exhibit high-resolution capability, most are not resistant to RIE. Resistance to RIE is important for wafer processing. Polysiloxanes are one class of polymers that exhibit high sensitivity, resolution, and resistance to RIE (25–27). Because of the lack of RIE etch resistance of most polymeric resists, other resist formulations have been introduced. One of the most common classes of resists is the diazonaphthoquinone/novolac resists.

Diazonaphthoquinone/Novolac Resists

While most polymeric resists were specifically developed for electron-beam lithography, most resists in this category were primarily developed for photolithography applications, for a g line, i line, or deep ultraviolet. Early investigations of these resists as electron-beam-sensitive materials were prompted by the desire to achieve commonality between photolithography and electron-beam lithography processes. It was also believed that better resolution could be obtained with these materials. These materials are composed of a radiation-sensitive material and a meta-cresol formaldehyde resin. Figure 10 shows the components and reaction mechanism for a typical diazo resist. Both materials are dissolved in a casting solvent; the resultant solution is applied to the desired substrate by applying spin. A complete description of the chemical mecha-

Table 2. Commonly Used Polymeric Resists

Resist	Tone	Sensitivity at 20 kV (μC/cm^2)	Reference
Poly(methylmethacrylate) (PMMA)	+	40–80	19,20
Poly(glycidylmethacrylate-co-3-chlorostyrene) (PGMC)	−	2.0	21
Poly(trifluoroethyl-*a*-chloroacrylate) (EBR-9)	+	1.9	22
Poly(chloromethylstyrene) (PCMS)	−	2.0	23
Poly(dimethyl siloxane) (PDMS)	−	2.0	24
Poly(phenylmethyl siloxane II) (PPMS)	−	2.0	24
Poly(vinylmethyl siloxane) (PVMS)	−	1.5	24
Poly(butene-1-sulfone) (PBS)	+	1.6	17

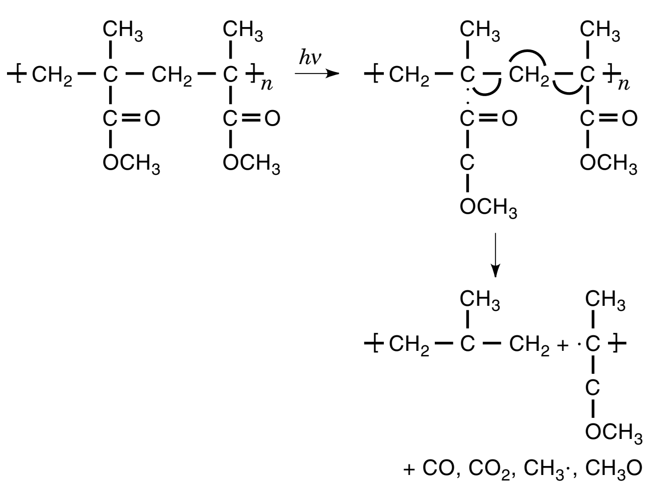


Figure 9. Poly(methyl methacrylate) (PMMA) was one of the first electron beam resists and is still used to produce high-resolution X-ray masks. Here the electron-induced degradation of this positive resist is shown.

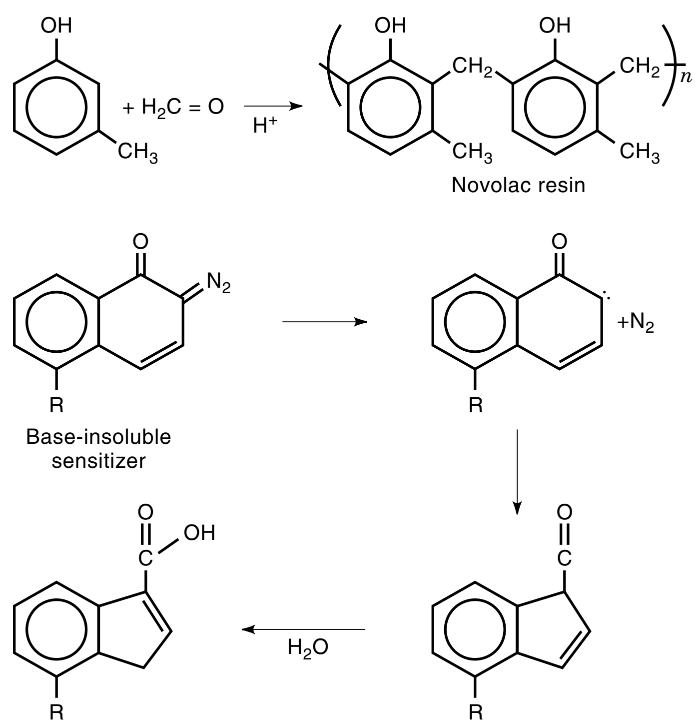


Figure 10. The formulation and reaction mechanism for a typical diazo/novolac resist. The first line shows the synthesis reaction for novolac resin and the next two lines show the radiation-induced rearrangement of the photoactive compound (PAC) of the resist.

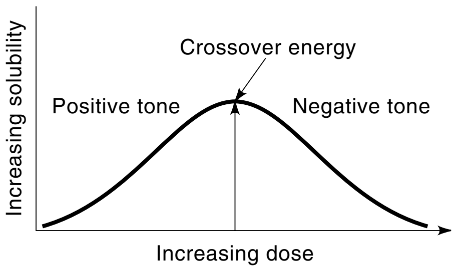


Figure 11. Diazo/novolac resists will undergo solubility changes once an energy threshold has been exceeded. This threshold is a function of thermal energy deposited in the resist. As the exposed resist decreases in solubility the tone of the resist is changed from a positive to negative resist.

nism for radiation-induced chemistry can be found in Ref. 28. Many of these resists are similar in composition; they vary in that the chemical structure of the radiation-sensitive compound may be slightly different. The ratios of the diazo compound, novolac, and solvent may also vary from formulation to formulation.

Most diazo resists are not as sensitive to the electron beam as polymeric resists; however, they are more resistant to reactive ion etching. They are more sensitive to thermal degradation caused by high accelerating voltage. In fact, positive diazo resists can be transformed to negative resists above a certain dose. Figure 11 shows the relationship between higher dose and solubility. Table 3 provides a list of commercially available resists used for electron-beam pattern generation.

Table 3. Diazo/Novolac Resists

Resist	Tone	Sensitivity at 20 kV ($\mu C/cm^2$)	Manufacturer
AZ 7508	+	10.8	Hoechst
EBR 900	+	8.2	Toray
HPR 506	+	20.0	OCG
OCG 895I	+	10.0	OCG

Chemically Amplified Resists

Chemically amplified resists (CAR) were first developed for use in deep ultraviolet (DUV) lithography. These materials are a major departure from the polymeric and diazo chemistries previously used for photolithography and electron-beam lithography. The introduction of CARs was prompted by the need for high-sensitivity or "faster" resist materials. This requirement was based on the requirement for higher production throughput in wafer-fabrication facilities. Most of these materials are at least an order of magnitude faster than the standard diazo resists. Chemical amplification is achieved by creating a catalyst through irradiation with photons or electrons. The resultant catalyst then initiates a series of chemical events, such that the resist is either cross-linked or degraded. As a result the solubility in the exposed area is changed. The resist tone or polarity is determined by increased solubility (+) or decreased solubility (−). Figure 12 shows the reaction mechanism for a chemically amplified resist. Generation of the acid catalyst is achieved by irradiating the resist with electrons or photons. As a result the triphenylsulfonium salt creates an acid catalyst that results in elimination of the tertiary-butoxycarbonyl group on the polymer backbone. Following post-exposure bake the polymer is cross-linked and the unexposed resist is developed from the substrate. In the case of a positive CAR the backbone of the polymer undergoes scission and the exposed area is developed from the substrate. Table 4 provides a list of several chemically amplified resists and their manufacturers. Interested readers may refer to Refs. 29–31.

Advanced Electron-Beam Technology

Direct-write electron-beam lithography is not extensively used because current systems do not provide the throughput required for cost-effective chip manufacturing. In order to produce the number of chips required, too many electron-

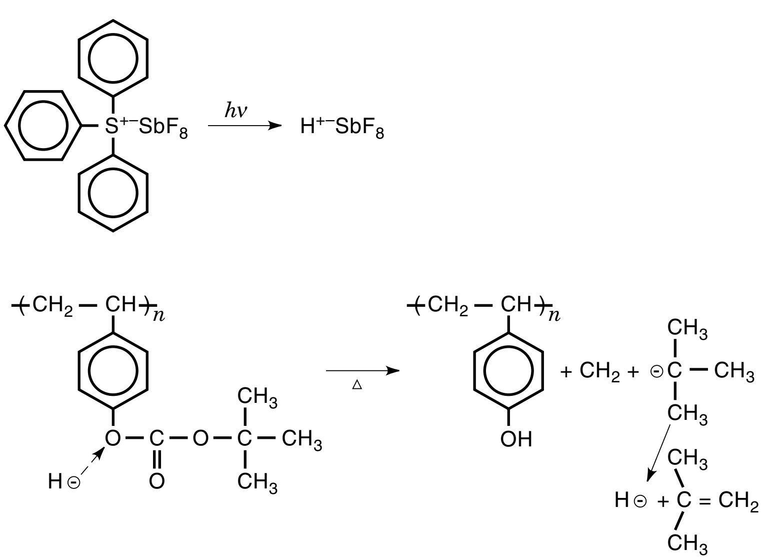


Figure 12. The radiation-induced reaction for a typical chemically amplified resist. The first line shows the generation of the acid catalyst; the second line shows the removal of the tertiary butoxy carbonyl group.

Table 4. Examples of Chemically Amplified Resists

Resist	Tone	Sensitivity at 20 kV (μC/cm^2)	Manufacturer
SAL 605	−	2.0	Shipley
APEX-E	+	1.4	IBM
AZPN-114	−	3.5	Shipley
CAMP-6	+	10.8	OCG

Table 5. Electron-Beam Resist Manufacturers

Toray Industries, Inc. 1-8-1, Mihama, Urayasu, Chiba 279 Japan 0-473-50-6041	Olin Microelectronic Materials 501 Merritt Seven Norwalk, CT 06856-4500 (203) 750-2824
Hoechst Celanese Corp. AZ Photoresist Products 70 Meister Avenue Somerville, NJ 08876-1252 (908) 429-3500	OHKA America, Inc. 190 Topaz Street Milpitas, CA 95035 (408) 956-9901
Allresist GMBH Friedrickshagener Strasse 9 12555 Berlin-Kopenick, Germany 030-657-1244	Sumitomo Chemical America, Inc. 2350 Mission College Blvd. Santa Clara, CA 95054 (408) 982-3890
	Shipley Company 455 Forest Street Marlborough, MA 01752 (508) 481-7950

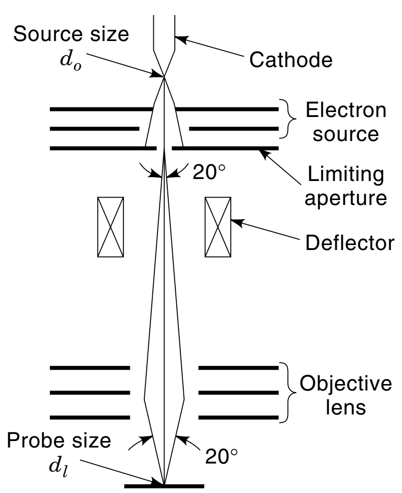


Figure 13. A schematic of a microcolumn (13).

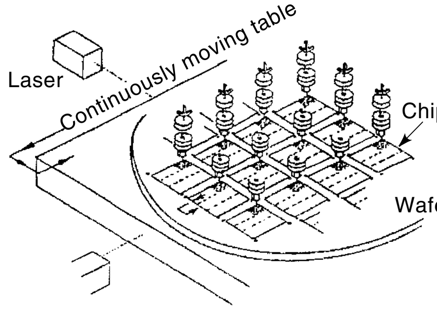


Figure 14. A typical schematic for an array of microcolumns.

beam systems would be required. Throughput is directly proportional to the current delivered by a single beam. A single beam is incapable of achieving the throughput required in a modern wafer-fabrication facility. Consequently, only multiple-electron-beam direct-write systems are capable of achieving cost-effective throughput required to be competitive with standard photo-optical lithography systems.

The most viable approaches to advanced high-throughput electron-beam lithography are the following. (1) Microcolumn arrays: multiple electron beams are created with an array of closely spaced miniature electron-optical columns. Each column contains a single electron-beam-generating cathode. See Figs. 13 and 14. In this case, one or more microcolumns would be used per exposure field. The exposure field would be approximately the same size as the optical exposure field of an optical wafer stepper. Patterns can be written in a raster-scanning mode with the beam scanned only over a narrow stripe with a continuously moving laser-controlled stage (31). A typical microcolumn has three main components: (a) an electron source, (b) an objective lens to form and focus the beam, and (c) a deflector unit for scanning the beam. The accelerating voltage for microcolumns is typically in the range of 1.0 kV to 2.0 kV. Some advantages of microcolumn technology are higher beam currents, adjustable size of arrays, and reduction of substrate charging, proximity effects, and beam heating through low voltage. (2) Parallel arrays: a multiple-beam approach to direct-write electron-beam lithography is provided by use of an array of independently modulated beams formed by laser-driven photocathodes or by a multiplexed microblanker array to achieve parallel uniform beams. The emitted electrons are collected, collimated, and demagnified in conventional electron optical column configurations into an array of small beams. These beams are then scanned across the wafer to produce the desired patterns (32). Figure 14 shows the methods used for the generation of parallel-array beams. Parallel-array columns produce high-accelerating-voltage beams, typically 50 kV or greater. Advantages of parallel-array technology are that conventional high accelerating voltage technology can be used to array multiple beams for high throughput.

SUMMARY

Electron-beam technology has been used for nearly half a century to produce images in resist materials. As features in semiconductor patterns become smaller the requirement for this technology will increase. The advent of advanced electron-beam technologies such as microcolumns and parallel-array beams ensure the continued interest and use of this technology as a solution for high-resolution pattern generation.

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