
VLSI FABRICATION PRINCIPLES

Silicon and Gallium Arsenide

Second Edition

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To my wife, Cecille
and
my sons, Khushro, Rustom, and Behram
for making it all worthwhile

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LITHOGRAPHIC PROCESSES

Microcircuit fabrication requires the precise positioning of a number of appropriately doped regions in a slice of semiconductor, together with a series of interconnection patterns. These regions includes a variety of implants and diffusions, cuts for gates and metallizations, and windows in protective cover layers through which connections can be made to the bonding pads. A sequence of steps is required, together with a specific layout pattern, for each of these regions. This is followed by one or more levels of interconnection patterns between them.

Lithographic processes are used to perform these operations, and are carried out at various points in the circuit fabrication process. Typically, five to twenty complete lithographic operations are required on each wafer. By way of example, a conventional silicon-based microcircuit, using bipolar transistors, requires seven separate lithographic processes to define openings for the buried layer, the isolation wall, the base, the emitter/collector, the ohmic contact, the metallization, and the cover layer. As many as twenty complete sequences, with three to four levels of metallization, are often necessary for more complex microcircuit configurations such as those involving bipolar complementary integrated circuit technology (BICMOS). Thus lithographic processes play a central role in microcircuit technology.

There are many different pathways from circuit design to pattern placement on the wafer. Some of these are illustrated in Fig. 10.1 [1]. For example, it is seen that the placement of a pattern on a wafer can be done by direct electron beam (E-B) writing in a single step (path E in this figure), and some research in this area is along these lines. Typically, however, the process is broken into

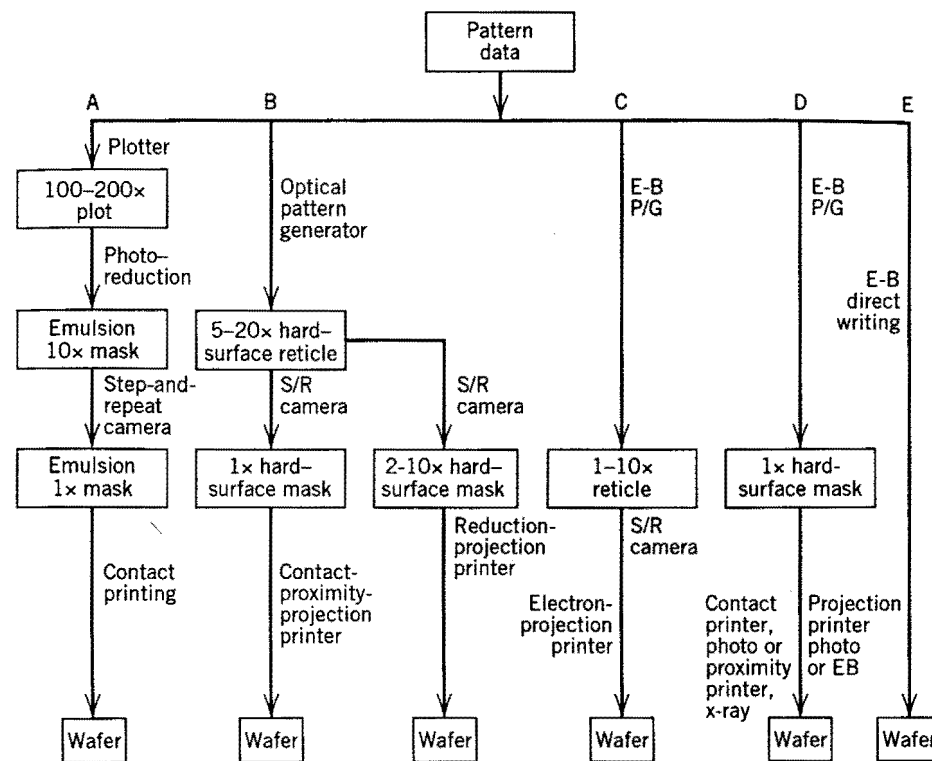


Fig. 10.1 Pathways from circuit design to pattern transfer. From Wolf and Tauber [1]. Reprinted from *Silicon Processing for the VLSI Era*, Vol. 1, Lattice Press, CA.

two separate operations: the generation of a reticle mask, and the transfer of its pattern to a large number of wafers.

The design of the reticle mask usually involves circuit and device designers, who together produce the layout of the circuit and of its individual masks. This layout is usually in the form of a set of drawings for circuits of low complexity, and computer tapes for the more complex VLSI circuits. Next, these are converted into masks by photo-reduction of the large drawings, or by the use of computer-controlled pattern generators using optical or electron beams. The sophistication involved here increases rapidly with circuit complexity. As a result, reticle masks for circuits of low complexity are sometimes made with in-house capability, whereas those for VLSI circuits are usually made by specialty houses. This is warranted on economic grounds, since one master mask set serves for the entire production run of a particular circuit for which it is designed.

The placement of mask patterns on the wafer is an in-house activity, since this must be done on each wafer, and at many stages in the circuit fabrication process. Optical printing methods are commonly used, but it does not appear

that these will meet the minimum feature size requirements for microcircuits over the long term. Electron, x-ray, and ion techniques are under active consideration for this reason.

The technology driver for silicon-based microcircuits is the dynamic random access memory (DRAM). Because of the ever-increasing need for memory in modern computers, the thrust of lithography is driven by these microcircuits. Table 10.1, at the end of this chapter, lists parameters for these circuits, and includes those which are available in the present time frame as well as those projected for the future [2]. It is generally accepted that optical pattern transfer will meet the needs of DRAMs to the 64-Mbit size, but alternative technologies will have to be used beyond this point.

Mask making will probably continue to be done by e-beam lithography, since this technique can already achieve feature sizes of $0.15\ \mu\text{m}$ and less. On the other hand, the options for pattern transfer technology are many. These include advanced optical methods, as well as x-ray and ion beam printing. Here, many problems in the areas of sources, masks, and resists will have to be solved before these become practical at the commercial level.

This chapter describes both pattern generation and pattern transfer processes, together with the new directions for these technologies. Central to these technologies is the use of thin films of photoreactive material, usually polymers, whose properties are altered by optical radiation over a specified wavelength range. The properties of these resist materials will also be considered in this chapter.

10.1 PHOTOREACTIVE MATERIALS

The earliest photoreactive materials, or *photoresists*, all had the same basic characteristic; upon exposure to light, they became hardened and could not be dissolved and washed away in solvents. Resists of this type are known as *negative* resists because the image formed in them is the inverse of the object, as seen in Fig. 10.2a.

The *positive* resist is a more recent development. Here, the image is of the same type as the object, as shown in Fig. 10.2b. In use, the material is initially insoluble, but degrades upon exposure to radiation. Both positive and negative resists are used in microcircuit technology today [3].

There are many requirements that a resist must satisfy before it can be useful for a specific technology [4]. Above all, it must be capable of resolving the required minimum feature size. Fortunately, this requirement is met, and exceeded, by all modern resists today. Other factors, over which there are some questions, are as follows:

Sensitivity. Resist materials are sensitive to radiation, which alters their chemical properties sufficiently so that a pattern can be delineated in them. A high sensitivity is desirable since this reduces the time for exposure, and

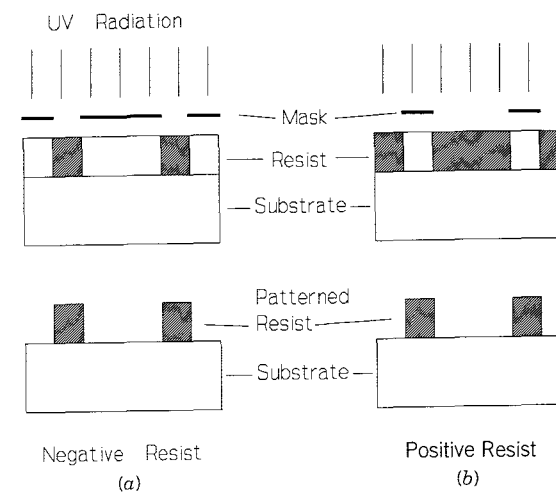


Fig. 10.2 Schematic of pattern transfer: (a) Negative resist and (b) positive resist.

thus the operating cost. Resists which are used for optical printing respond to radiation of 330–430 nm, and are designed for maximum absorption (and hence sensitivity) over this UV range. Recently, interest has focused on the deep UV region (150–300 nm) because of the higher resolution that can be obtained at these shorter wavelengths. Here, the region of practical interest is $\geq 200\text{-nm}$, since a vacuum environment is necessary for operation in the 150- to 200-nm range. This range is further restricted by the availability of high-intensity deep UV sources. The most practical source today is an Hg–Xe lamp, which has a peak output at 250–290 nm. Excimer lasers are used as sources for the deep UV range.

The use of e-beam techniques for reticle mask generation has resulted in the need for resists which are sensitive to electron irradiation in the 10- to 30-kV range. Finally, resists are also required for use in printing systems which operate in the soft x-ray region (5–50 Å).

Adhesion. A resist must adhere sufficient well to the underlying film so that it does not lift off during subsequent processing. This is usually not a problem, provided that appropriate procedures are used for surface preparation. This requirement has been somewhat relaxed with VLSI technology because of the increasing use of dry processes such as plasma etching and ion milling.

Etch Resistance. This requirement has become harder to meet since many resist materials degrade in plasma or ion-beam environments. In fact, a tenuous balance between sensitivity to radiation during imaging, and insensitivity to radiation during subsequent processing, must be struck by the resist designer in order to produce a useful product.

Other features of a resist that are highly desirable are stability in storage, uniformity from batch to batch, and the absence of large particulates. It is fair to say that the optimum combination of all of these features is not available in any resist at the present time.

Most early negative resists consisted of polymeric organic materials, such as poly(vinylcinnamate), with long-chain molecules having a molecular weight range of 10^4 – 10^6 . Irradiation of these molecules by an energetic beam results in bonding or cross-linking of adjacent polymer chains, and thus in an increase in the average molecular weight. These materials are sometimes referred to as *cross-linking* resists.

In more recently developed negative photoresists, cross-linking is done by means of photogenerated reactive species. These resists are usually chemically inert synthetic poly-isoprene rubbers, typically cyclized *cis*-poly-isoprene, in combination with a bisazide cross-linking component which is photoactive. They are commonly applied in layers of 0.3- to 1- μm thickness, and are sensitive to UV light in the 330- to 430-nm range. A common rule of thumb here is that the resist thickness should be one-third the minimum feature size. They are readily soluble in aromatic solvents such as benzene, toluene, and xylene, *prior* to cross-linking by exposure to UV light. These chemicals (as well as proprietary formulations) are used as developers in the photoengraving process.

Negative photoresists are well established in conventional microcircuit fabrication. However, their use is characterized by a solvent-induced swelling of unexposed regions that takes place during development. This results in ragged edges or a loss of pattern fidelity that makes them unsuited for resolving elements under 2 μm in size. Moreover, they can only be removed with great difficulty once they have been exposed to UV light. Consequently, optical printing techniques have turned almost exclusively to positive photoresists for VLSI applications.

Positive photoresist materials are designed so that the effect of radiation is to make them increasingly capable of dissolution by chemical solvents. Since the exposed photo-resist is not removed subsequently, it does not suffer from solvent-induced swelling problems, and can readily define elements which are much smaller than the limits set by the lithography system. They can also be used in much thicker coatings than negative photoresists (by a factor of three or more). As a result, they are more resistant to chemical etches, and are more reliable in problem areas such as steps, which lead to resist thinning. They are also relatively free from pinhole formation, since they can be applied in thick layers.

Positive resists can be made up of polymeric materials with weak links, which degrade upon irradiation by the process of *scission*. However, the most commonly used photoresists do not operate on this principle. Rather, they consist of three basic components: a low-molecular-weight, alkali-soluble resin such as phenol formaldehyde novolac, a photoactive dissolution inhibitor which usually consists of orthoquinone diazide, and a solvent such as xylene or cellosolve acetate. They are usually applied in 1- to 3- μm thick layers, and are sen-

sitive to the same UV range as negative resists. Exposure to light degrades the photoactive component by converting it to carboxylic acid, so that the resin becomes readily soluble* in alkalis such as NaOH or KOH, both of which can be used as developers. The recent emphasis on MOS microcircuits has resulted in the use of nonionic developers such as tetramethylammonium hydroxide $[(\text{CH}_3)_4\text{NOH}]$ as well as a number of proprietary formulations [5], which are free from ionic contaminants. The development process is one of the direct dissolution, without any swelling of unexposed material because it is not attacked by the developer. This accounts in large measure for their resolution capability.

Positive resists are more difficult to use than the negative type, and tight control of manufacturing processes must be maintained to obtain consistent adhesion to the mask film. Often the wafer is given a bake in an oxidizing environment such as air, and is spin-coated with a coupling agent to promote this adhesion. In addition, a pre-exposure bake is carried out in order to drive off excess solvents from the resist, and to promote its adhesion to the wafer. This *softbake* is a critical step since the photoactive component is subject to thermal decomposition. Thus excessive baking temperatures result in a loss of sensitivity during subsequent exposure. However, some form of softbake step is necessary in order to densify the resist and make it more resistant to subsequent chemical etching processes.

Unexposed resist can be removed by chemicals such as hot acetone or methylethylketone. Proprietary chemicals are available for removing these photoresists as well. In some situations, an alternative approach consists of flooding the slice with UV irradiation to degrade the remaining resist, prior to its removal.

Deep UV-sensitive photoresists are increasingly used in VLSI applications in order to exploit the development of optical systems in this wavelength range. Most of these are positive resists involving photoactive dissolution inhibitors. Thermally degrading resists, which operate by the process of scission, are increasingly finding use in this application, even though originally developed for use with e-beam systems. However, materials such as polymethylmethacrylate (PMMA) and its derivatives have a maximum absorption at about 215 nm so that they are not well matched to the range of available deep UV light sources. Typically a 1-min exposure is necessary for a 1- μm thick film, using an Hg-Xe arc lamp. Materials such as polymethyl isopropenyl ketone can extend this absorption range out to 290 nm, resulting in improved sensitivity by a factor of 5. This can be further improved by the addition of sensitizing agents, such as *p*-terbutyl benzoic acid.

Very few negative photoresists are available for the deep UV range, although a number are under active development. One proprietary formulation, whose principle ingredient is cyclized rubber, is commercially available for use in this region. This resist is about ten times more sensitive than the best positive resists,

*The dissolution rate of exposed positive resists is about three decades faster than that of unexposed materials.

and does not appear to have the severe swelling problems associated with other cross-linking materials [6].

The technology of electron resists has been the subject of intense research in the last 10 years. Here, the goal is to develop materials which can operate with a minimum incident charge density per unit area. A high sensitivity (10^{-6} coulombs cm^{-2} or less) to electrons in the 10- to 30-kV range is required in order to obtain reasonable exposure times. Moreover, since most of these resists will be used in conjunction with plasma etching or ion milling of the underlying films, the ability to withstand these processes is extremely important.

A large number of electron resists have been investigated. However, most of the work has been done with positive resists such as PMMA and its derivatives [7]. Electron irradiation results in chain scission, with a fall in the average molecular weight of the polymer. As a consequence, it can now be developed in those chemicals which are nonsolvent to the PMMA, prior to radiation. PMMA has a low sensitivity (3×10^{-5} C/ cm^2 for a 20-keV beam). It also has a poor resistance to ion milling, and a tendency to flow at elevated temperatures. Techniques for improving its sensitivity include the introduction of chemical configurations which tend to weaken the chain stability of the polymer by copolymerization. One such cross-linked PMMA has been reported to have a sensitivity of 0.5×10^{-6} C/ cm^2 .

Electron resist systems, based on the poly(olefin sulfones) have also been developed. One such system, (PBS) poly(butenesulfone), is commercially available and has a sensitivity of 2×10^{-6} C/ cm^2 . Its unique characteristic is that it can be developed by gaseous means. This allows an all-dry process, which greatly reduces the adhesion requirements of the resist and the underlying layer.

Some work has been done with negative electron resists in recent years. These are generally prone to solvent-induced swelling effects and cannot resolve submicron features. On the other hand, they tend to be quite sensitive, and research is aimed at minimizing this problem. One such negative electron resist, based on a co-polymer of glycidylmethacrylate and ethylacrylate (COP), has a sensitivity of 6×10^{-7} C/ cm^2 at 20 keV, but is limited to resolving a minimum element size of 1.5 μm .

Resists developed for e-beam lithography have all been found to be relatively insensitive in their x-ray absorption capability. Attempts to increase this sensitivity have involved the inclusion of heavy metal ions such as cesium and thallium [8], in order to increase the absorption capability of the resist at the wavelength of interest. Typical resists that have been used to date include both PMMA (a positive resist) and COP (a negative resist). COP is about 360 times more sensitive than PMMA, but has much poorer resolution and chemical resistance properties. Typical exposure times are quite large, as much as one to five minutes for the more sensitive resists. Research in this area is very active, so that considerable improvements in sensitivity should be forthcoming. A highly abbreviated list of e-beam and x-ray resists, which are available [9] at the present time, is given in Table 10.2 at the end of this chapter.

Resist improvements have also focused on the development of ultrathin

layers which can be used with e-beam and x-ray lithography, and are capable of development by dry processes [10]. One approach is to silylate the resist after exposure, by the vapor diffusion of a silicon-containing species, to a depth of about 1000 Å. During O_2 -plasma etching, the silylated regions are converted to rapidly form an SiO_2 -rich layer, which stops further ion beam erosion effects. A variety of organosilanes have been used for this purpose.

Yet other approaches are based on inorganic resist systems. One such system [11] uses a 2000-Å thick film of GeSe_2 on which is placed a 100-Å film of AgSe_2 . Here the upper layer is photoactive, and extremely thin so as to provide high resolution. The GeSe_2 layer is normally quite soluble in a number of alkaline solutions. Irradiation of the top layer produces silver which rapidly migrates into the GeSe_2 and renders it almost insoluble in these solutions. This photoinduced process is highly anisotropic in character, with migration almost entirely in the direction of the beam, and results in a high-contrast image. The sensitivity of these resists is relatively low, and needs to be improved by one or two orders of magnitude in order to be commercially viable.

10.1.1 Image Reversal

In microcircuit technology, a mask can often consist of small opaque regions on a predominantly clear background. Masks of this type are especially prone to light-scattering problems from dust and defects, which are more likely to be present on regions that are clear. In these situations, a dark-field mask would be advantageous. Some positive photoresists have been especially developed to meet this need. With these resists it is possible to reverse the image during the pattern transfer process, so that a negative image is produced with a conventional positive resist. After the initial mask and exposure steps, reversal is accomplished by means of a chemical treatment and a bake step, followed by flooding the resist with UV. Figure 10.3 illustrates this process, where this bake step results in the release of CO_2 from the resist.

In addition to providing the convenience of using a dark-field mask, this process allows a mask to serve dual functions, and has been used in the precise control of wall angles during pattern transfer [12].

10.2 PATTERN GENERATION AND MASK-MAKING

The complexity of a microcircuit is limited by three factors. The first is the ingenuity of the circuit designer in reducing the number of devices required to perform any given electronic function. Although there have been many dramatic advances along these lines, it appears likely that further progress will be slight, and only in specialized areas of circuit development. The second is the maximum size of the chip that can be made with a reasonable processing yield. Materials and process technologies, outlined in previous chapters, have a strong bearing on this size. The third limit is the size of the *minimum feature* which

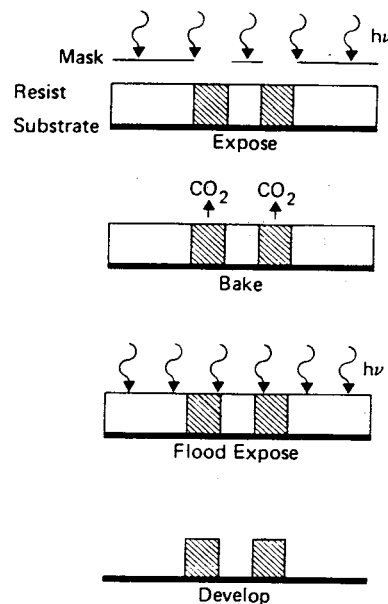


Fig. 10.3 The image reversal process. Adapted from Willson [4].

can be placed on the chip. This is determined by lithographic techniques, which are used in conjunction with pattern transfer processes to delineate the various regions in a microcircuit. The size of each region is set by device design and by the minimum feature size.

The most critical part of the lithographic process is conversion of the layout pattern into a *reticle* or *master mask*. This mask can be used directly to transfer the pattern to the substrate. Alternatively, *working masks* are made from this master by contact printing, and are subsequently used for defining the pattern on each wafer to be processed. It goes without saying that the quality of the reticle mask is important in determining the process yield for the microcircuit over its entire production life. Consequently, extreme care is taken to ensure that it will be free from defects.

As observed earlier, e-beam writing techniques are extensively used for pattern generation, since they already meet the requirements for both present and future generations of microcircuits. Optical techniques are also used for this purpose, especially when circuits of moderate complexity are required, and larger feature sizes can be tolerated. This approach is considerably less expensive than e-beam writing, and it is often used in-house in a number of companies, because it is highly flexible.

Finally, the reticle mask making step can be avoided by combining pattern generation and transfer processes into a single step, as shown by path E in Fig. 10.1, and writing the pattern directly on the wafer. This approach can meet the

minimum feature requirement of $0.15\ \mu\text{m}$ readily; its disadvantages lie in its high cost and low throughput.

10.2.1 Pattern Generation

Historically, the first microcircuits were made by manually drafting a series of large drawings, each 250 times the final pattern size ($\times 250$). One such drawing was required for each of the regions (the source/drain diffusions, for example) in the microcircuit. This drawing was made on a plastic laminate, consisting of a dimensionally stable mylar sheet bonded to a thin veneer of red plastic. The red plastic was cut and peeled off to form the desired pattern of clear and red regions.

Next, the pattern was illuminated and reduced in size to form a glass *reticle mask* which was usually $\times 10$ or $\times 5$. This mask consists of a polished glass plate,* coated with a high-resolution gelatin emulsion, in which a high-contrast pattern can be replicated. Hard-surface reticle masks, consisting of a thin ($1000\text{--}2000\ \text{\AA}$) film of chromium** and covered by a photoresist, are increasingly used for this purpose. After exposure, this resist is used to delineate the pattern in the chromium film, which provides better edge resolution since it is extremely thin. In addition, it is more hard-wearing than the soft gelatin-based emulsion, so that it is less prone to wear and tear during use.

Path A of Fig. 10.1 shows a flow diagram for this approach. Also shown (path B) is an optical-mask-making process which is in present use, in which a computer tape is used to drive an optical pen which directly writes the pattern on the reticle mask. This approach has two advantages over the last. First, mask errors can be readily corrected by altering the computer tape instead of the drawing. Second, it avoids the need for making unmanageably large drawings, as the chip size increases. Almost all VLSI masks are made from computer-generated patterns for these reasons. Reticle masks of $\times 5$ to $\times 20$ are commonly used in this approach.

The fundamental limit to optical techniques (i.e., the diffraction limit) is set by the wavelength of light. This limit can be slightly extended by the use of deep UV ($200\ \text{nm}$). Electron beams, on the other hand, do not suffer from a practical diffraction limitation [13]. Thus, they are ideally suited for mask-making. During e-beam writing, however, the incident beam suffers from both forward and back scatter as it penetrates through the resist and underlying layers of material. The back-scatter component returns through the resist, and thus results in additional exposure. Back-scatter effects of this type are referred to as *proximity effects*, since they can cause problems with features in close proximity. For example, they can result in contact between two lines which run close to each other.

*Although optically flat over small areas, these plates may have as much as $5\text{--}10\text{-}\mu\text{m}$ warpage over their entire working surfaces.

**Borosilicate glass films can be used if subsequent printing is to be done with deep UV.

Proximity effects can be controlled by reducing the beam energy, or by controlling its dwell time near the boundary of an element during the writing process. They are especially severe when thin photoresist films are used. Positive resists, on the other hand, are relatively thick, so that this problem is of less consequence. At the present time, the use of e-beams for mask-making allows the fabrication of reticle masks with a $0.15\text{-}\mu\text{m}$ minimum feature size. Thus, this approach represents a workable technology for the submicron range when coupled with advanced printing methods such as those employing e-beam and x-ray techniques.

The flow chart for e-beam pattern generation is shown as paths C and D in Fig. 10.1. Here, too, the layout information is provided in the form of computer tapes which are used to control an e-beam which can be driven to directly produce a hard surface reticle mask at a $\times 1$ to $\times 10$ magnification. The larger magnification has the advantage that feature sizes in the reticle can be made larger than those in the actual circuit. In addition, the ability to precisely align one pattern over the next is easier, since errors are demagnified in the final reduction on the chip.

In opposition to these advantages is the fact that, since the reticle area increases with the square of the magnification, the probability of defects on this mask are multiplied by the same factor. Moreover, the area to be inspected is larger with these masks. Finally, reticle masks commonly use redundant fields, so that defects can be readily sensed and corrected. This is more easily accomplished in a $\times 1$ mask with low magnification than in a $\times 5$ or $\times 10$ mask.

The basic components of an e-beam pattern generator are shown in Fig. 10.4. The system resembles, in many ways, a scanning electron microscope with the addition of beam blanking and computer-controlled deflection [14]. Important additional features are the use of laser-driven interferometers and fiducial mark detectors [15]. This combination, together with fiducial marks which are printed during the first pattern writing, allows the system to be precisely positioned for each successive pattern transfer operation. Typically, the beam has a deflection field of about $2\text{ mm} \times 2\text{ mm}$. Consequently, a complete VLSI mask usually requires "stitching" together a number of such fields to form the entire pattern [16, 17].

Two types of scan systems are in use today—the raster scan and the vector scan [18]. In the raster scan system, rectangular strips of the circuit are scanned by a series of lines in order to form the complete chip pattern. In a vector scan system, on the other hand, the e-beam is controlled to scan a feature, move directly to the next feature, and so on. While this often requires wider scan deflection and considerably more complex data-handling and beam-blanking techniques, it results in a much faster system since the beam does not spend time scanning featureless regions. This is an important advantage, since one of the main limitations of these systems is their low throughput.

The writing time of mask-making equipment of this type is set primarily by limitations in the intensity of the electron beam, the sensitivity of the e-beam resist, and the speed of the associated electronics. Factors such as system

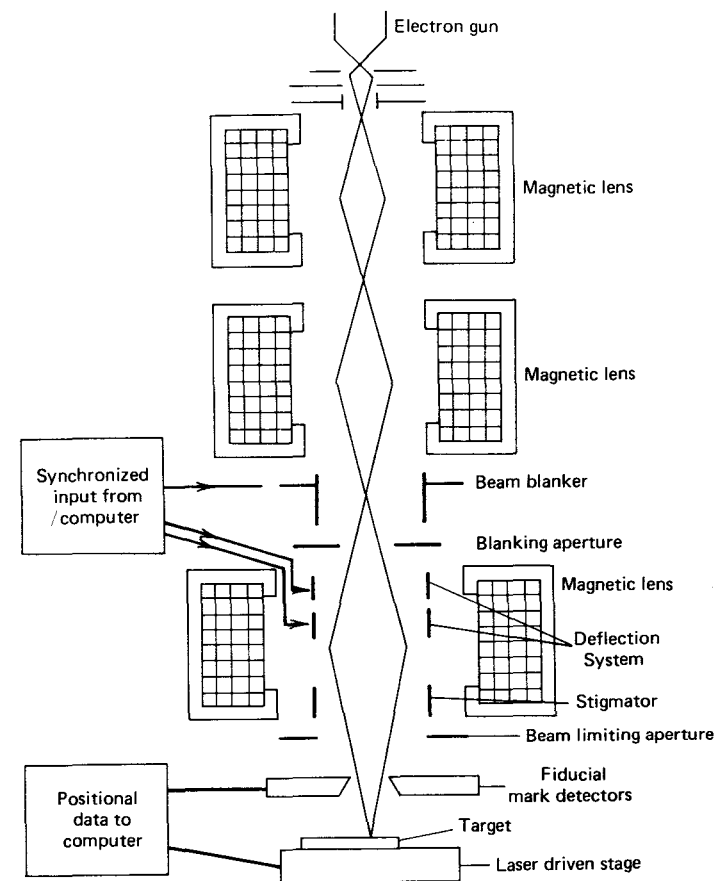


Fig. 10.4 Schematic of an e-beam pattern generation system. From Thornton [14]. Reprinted with permission from *Advances in Electronics and Electron Physics*.

pump-down must also be considered, but are relatively unimportant due to the availability of load-lock techniques and high-speed vacuum systems. Typically, a writing time of about 4 h for a $20\text{-cm} \times 20\text{-cm}$ mask size is considered acceptable for this task. This is due to the fact that a single master is used to define one particular set of regions (source/drain diffusions, for example) for an entire microcircuit production run. On the other hand, multiple working masks are required for the many printers that are used to perform the pattern transfer operations at the wafer level.

10.2.2 Mask-Making

Reticle masks, made in the manner described in the previous section, can be used (see Fig. 10.1) in subsequent steps in the photographic process, up to the

eventual pattern transfer step on the wafer surface. Starting with a $\times 10$ or $\times 5$ reticle mask, the conventional approach is to use a *step-and-repeat* (S/R) camera to form the master mask (paths A and B in this figure). This camera is essentially an inverted microscope, and projects a $\times 1$ image on an emulsion-coated glass plate, or on an emulsion/hard-surfaced glass plate if this type of master is required. This plate is mounted on a mechanical stage which is programmed to move after each pattern is exposed, in an S/R manner. In this way, multiple images can be formed on a photographic plate of almost any size that is required to accommodate the wafer, while still permitting the optics to cover a relatively small field. The S/R process can be speeded up by the use of a multi-barrel camera which projects four images of the reticle at one time. Multibarrel systems are in common use today.

Contact printing of the master, or of an intermediate submaster, is used to make multiple working masks which are used to define the pattern on each microcircuit wafer. Pattern transfer can be done by contact printing, or by printing with a small gap between the mask and the wafer.

Pattern transfer can also be accomplished by projection printing of the master mask, or by directly imaging the reticle mask on to the wafer in an S/R sequence (paths D and C in Fig. 10.1, respectively). Sometimes, only a part of the reticle mask is imaged on the wafer in each step, and a series of such parts or fields are "stitched" together to form each complete chip pattern. The main disadvantage to the S/R approach was the increased exposure time for processing each wafer; however, improvements in optical systems have eliminated this problem. For this reason, *stepper* systems are now invariably used for large-area VLSI circuits.

10.3 PATTERN TRANSFER

As seen in Fig. 10.1, the pattern transfer process consists of taking a suitably patterned mask, and imaging it on the surface of a wafer which is precoated with a resist. This is followed by the engraving process, where the exposed resist pattern is used for opening windows in an underlying layer to define semiconductor regions, or to remove metal from a coated wafer in order to delineate the interconnection pattern. These processes must be carried out on each wafer, and for each of the five to twenty masking operations that are necessary for any particular microcircuit. Thus the amount of time that this step takes is an important consideration. At the present, it is generally accepted that the time required to insert, align, and expose the wafer should be 1 min. or less in a practical situation. This requires resists of high sensitivity, as well as automatic (and accurate) means for alignment of the image on the wafer. This section describes the basic processes for pattern transfer. Optical printing processes are described in some detail since they are the most commonly used.

Four types of printers are in general use today: contact, proximity gap, projection and step-and-repeat (stepper). Of these, the contact printer gives the

highest resolution because the pattern and the wafer are as close to each other as possible. Features under $0.15\ \mu\text{m}$ can be replicated in this manner.

Contact printing is extensively used in GaAs microcircuits, where small dimensions are critical. A disadvantage of this technique is that mask damage occurs during this process. Physical contact between the mask and the wafer causes damage to the soft gelatin emulsion. In addition, this damage results in defects which are then transferred to *all* successive slices using this mask. As a result, mask life is very short. Depending upon the density and resolution requirements, these 'working masks' must be replaced after every 5–25 operations.

In proximity gap printing, a small gap, $2.5\text{--}25\ \mu\text{m}$ wide, is always maintained between the mask and the slice. With a collimated light source, it can be shown that the minimum resolution increases with the square root of the gap, so that there is some loss of sharpness in this approach. The width of this gap is dictated by mask and wafer flatness, and by the precision of the mechanical system. Typically, a gap of $10\text{--}15\ \mu\text{m}$ limits the minimum feature size to $2\text{--}3\ \mu\text{m}$, so that this method cannot be used in advanced VLSI applications.

In projection printing, the mask pattern, consisting of multiple chips, is imaged on the plane of the wafer. This technique allows greater flexibility in wafer handling. Moreover, no damage occurs to the reticle mask during this process.

In early projection printers, the complete wafer pattern was directly imaged on the plane of the slice. This became impractical with the trend to larger wafers. In modern systems, a small portion of the mask is imaged, with high resolution, over a small region of the wafer. Next, both the mask and the wafer are scanned so as to obtain full coverage over the wafer while still maintaining the resolution of the well corrected zone. In a typical projection aligner [19], this zone is annular in nature, and about 1 mm wide.

A major disadvantage of projection printers is the need to image the entire wafer in a single operation. However, very high resolution can be achieved [20] if the image field is limited to a small area, about $100\text{--}300\ \text{mm}^2$. Advantage is taken of this fact in the stepper system in which the reticle mask pattern consists of a single chip, from $\times 1$ to $\times 10$ in size, which is imaged sequentially over the entire wafer. Often the image field of each chip is divided into contiguous areas, which are processed sequentially, and "stitched" on the wafer to form the complete pattern.

The throughput of a stepper is comparable to that of a projection printer, even though this machine requires multiple exposures over a single wafer. This is because the light collection optics can be made more efficient when the image field is small. In addition, all of the light from the optical source is imaged on one field at a time, thus allowing a greatly reduced exposure time for each field.

In order to achieve a high throughput, it is essential to use rapid, accurate alignment techniques, which are effective with both metal and dielectric films. These involve the use of sophisticated alignment markers and laser-illuminated spatial filters [21, 22], which can achieve position errors of under $\pm 0.02\ \mu\text{m}$ for each field.

An important problem, common to all pattern transfer systems, is the lack of wafer planarity, combined with its process-induced curvature and changes in surface topology, which vary as the wafer progresses from the as-purchased state to the finished product. These in-plane distortions are a function of the specific wafer process, and can be as large as 1–2 μm . Thus, the success of printing schemes of this type depends on the use of processes which tend to maintain wafer planarity throughout its fabrication steps. A number of such *planarization* techniques are described in Chapter 11.

10.3.1 Optical Printing

This process can be described by considering first the problem of cutting windows in a film of the type that is used for masking purposes [23]. Typical films are silica, polysilicon, silicon nitride, silicides, and metals. Steps in this operation are detailed in the flow chart of Fig. 10.5, which illustrates the pattern transfer process for a single window. The contact printing process is shown, by way of example. Details of these steps are shown in Fig. 10.6, and now follow.

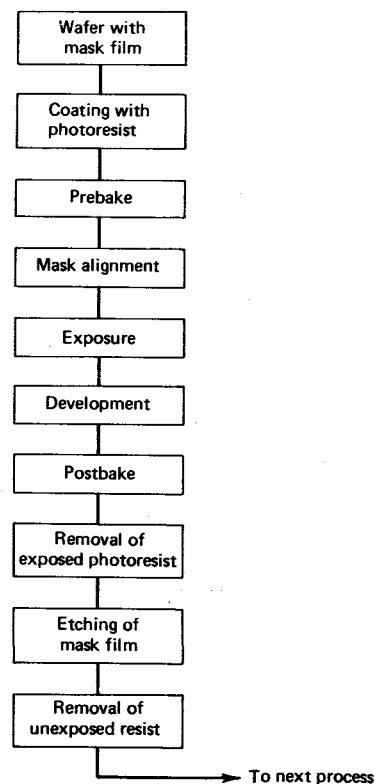


Fig. 10.5 Flow chart for the pattern transfer process.

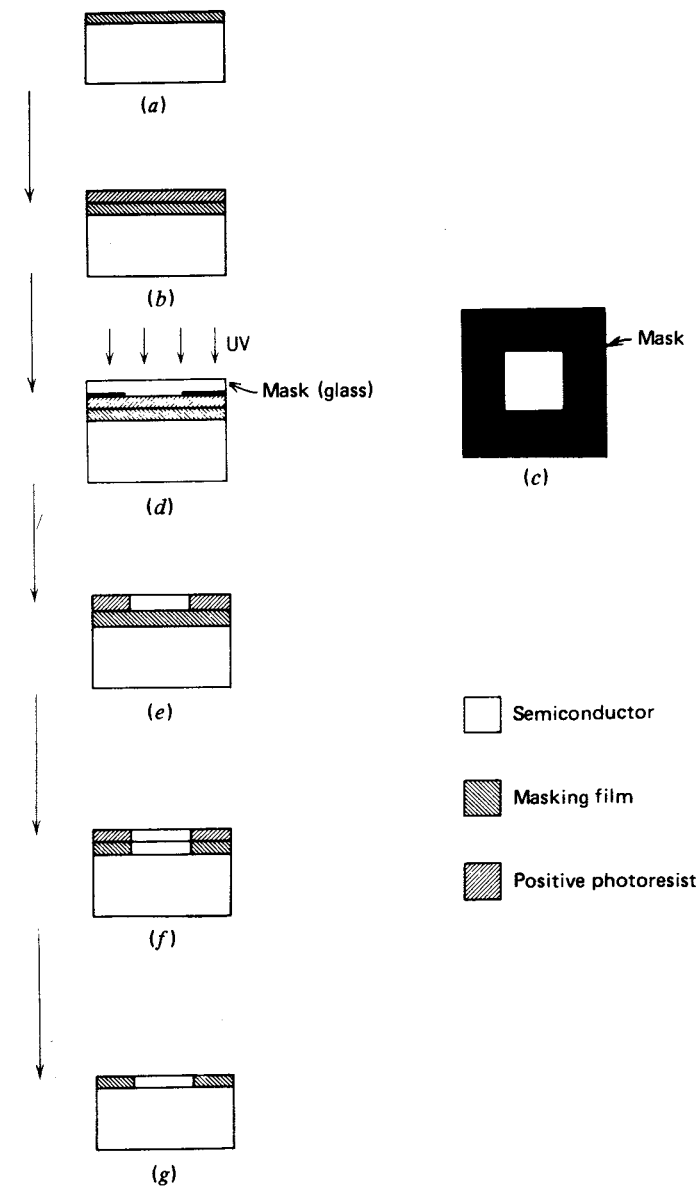


Fig. 10.6 Steps in opening a window in a masking film, using positive photoresist.

Coating with Photoresist. This consists (see Fig. 10.6b) of laying a film of a photoresist material on the surface of the wafer which is covered by the masking film. Ideally, such a film should be uniform, highly adherent, and completely free from dust or pinholes. A positive photoresist is used in this example, for

illustrative purposes [5]. This photoresist becomes degraded upon exposure to ultraviolet light.

The coating process consists of spinning the wafer at high speed after a small quantity of prefiltered photoresist has been placed on it. The film thickness is inversely proportional to the square root of the spin rate; typically, spinning speeds range from 1000 to 6000 rpm and result in films that are about 0.5–3 μm thick. Consistent results are obtained only if the viscosity of the photoresist is maintained constant on a run-to-run basis.

Extreme care must be taken to use clean, dry slices to obtain good adhesion of the photoresist. Freshly prepared wafers may be coated directly; however, slices that have been stored must be subjected to cleaning and drying procedures before coating. Adhesion to some surfaces, such as PSG with a high phosphorus content, often presents a serious problem. A dip in a coupling agent, just prior to photoresist application, is routinely used to avoid such problems. Hexamethyldisilazane, $(\text{CH}_3)_3\text{SiNH}_2\text{Si}(\text{CH}_3)_3$, commonly abbreviated to HMDS, is often used for this purpose [24]. Other adhesion promoters which can be used include trichlorophenylsilane, trichlorobenzene, and xylene. The coupling agent can also be applied by vapor-plating, in a batch process.

Although ultraclean conditions should be maintained during the entire operation, the coating step is the most critical one from the point of view of dust contamination. This is because the spinning action creates an air suction along the axis of the slice and promotes the delivery of any airborne particles of dust to its surface. Moreover, the photoresist is sticky at this point.

Softbake. After coating, the slice is baked to drive out all traces of solvent from the photoresist. Typically, the film thickness shrinks to about 85% of its spun-on value during this *softbake* step. The softbake temperature specified by most resist manufacturers is 90–100°C, it must be carefully controlled since it affects the subsequent exposure time, as well as the time of development.

About 20–30 min are required for this process, if it is carried out in a convection oven. This is because, during drying, a skin forms over the surface of the resist and impedes the rapid loss of volatile components from it. Increasingly, softbake is carried out by placing the wafer on a hot plate. Now, heat transfer through the wafer results in loss of resist solvent from the volume of the resist without the formation of a barrier skin on its surface. This reduces the softbake time to under 1 min, resulting in a high throughput, and also minimizes particulate contamination during the baking process.

The softbake process also reduces the solubility of the unexposed film in the developer. For a typical unexposed positive photoresist, the dissolution rate in the developer is about 50 $\text{\AA}/\text{s}$ if no softbake is used, and about 17 $\text{\AA}/\text{s}$ with softbake.*

*For the same photoresist, the dissolution rate in the developer is 1000–2000 $\text{\AA}/\text{s}$ in the exposed regions.

Mask Alignment. There are many variations here. In manual systems, a mask consisting of a gelatin photographic emulsion on a glass plate is placed over the slice, brought into contact with it, and then backed off slightly to produce an air gap. Next it is manipulated into its desired position by micrometer adjustment. This alignment process is performed with the aid of a microscope. Finally, physical contact is reestablished between the mask and the slice, and the exposure is made. This is known as *contact printing* (see Fig. 10.6c and 10.6d).

Most of the variations in this approach have come about because of the needs for improved resolution, increased throughput, or economy. For example, a hard surface mask is sometimes used instead of the gelatin photographic plate. Masks of this type were originally introduced because they were three to four decades more abrasion resistant than gelatin masks, and were dimensionally stable during wet chemical processing. In VLSI applications, their primary advantage lies in their superior edge resolution characteristics and absence of shadowing effects, because of their extreme thinness. (Typically, a gelatin mask must be 4 μm thick in order to have the same opacity as a 1000- to 2000- $\text{\AA}$ chromium mask.)

Both soda-lime and borosilicate glass are used for masks in the near UV (330–450 nm) and UV (260–330 nm) ranges, but borosilicate glass is preferred because of its low thermal coefficient of expansion. Plates of synthetic quartz are used for masks in deep UV systems (200–260 nm) since they are transparent at these wavelengths. A thin film of borosilicate glass or chromium can be used to define the masking pattern on these plates, since these materials are opaque to deep UV light.

Printing of VLSI circuits requires rapid, accurate mask alignment in addition to high resolution. A rule of thumb in the industry is that alignment accuracy should be about one-fourth the minimum feature size. This can only be met by automatic mask alignment systems, which can be built into projection and stepper systems in which the mask does not come into contact with the wafer. Techniques for automatic mask alignment are similar to those used in e-beam systems, and have been described earlier.

Exposure. Photoresists are exposed by means of collimated UV light. Some filtering of the source is necessary to prevent undue heating of the masks during contact printing. On the other hand, a monochromatic light source is required for projection and stepper systems, where the mask is imaged on the wafer. The wavelength of this source usually corresponds to one of the strong emission lines from an Hg–Xe vapor lamp or from an excimer laser, and ranges from near UV to deep UV.

During exposure with such a light source, the optical wave propagates through the resist and is reflected backwards, resulting in a standing wave intensity pattern. Such a pattern is shown in Fig. 10.7a for a 6300 $\text{\AA}$ layer of positive resist, with a 404.7-nm light source. It is especially strong when the resist is placed on a highly reflecting surface, such as metal or bare silicon. Intensity

variations of this type result in periodic changes in the development rate profile of the resist [25], as shown in Fig. 10.7b, causing striations of its side-wall pattern after exposure and development. In addition, this causes variations in the width of lines over profiled surfaces [26].

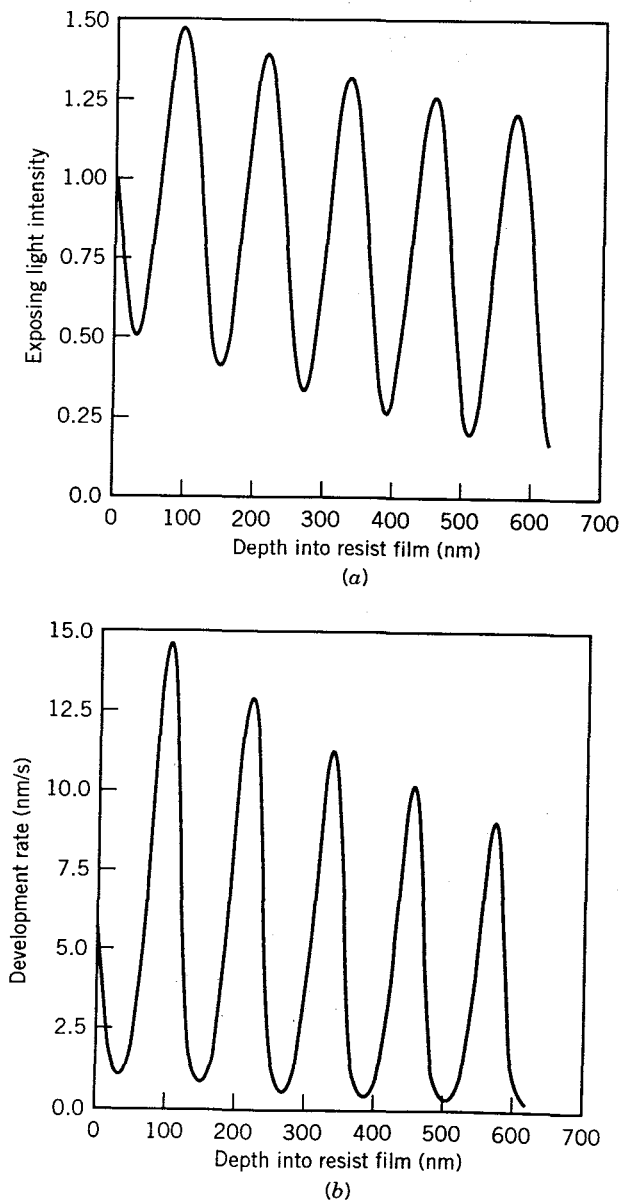


Fig. 10.7 (a) Intensity of light in a resist and (b) resulting striations in a developed line.

The extent of this striation effect on the line width increases rapidly with the reflectivity of the underlying layer. Thus, the problems of resist patterning on aluminum metal are especially severe. They can be greatly reduced by the use of an antireflective coating (ARC) which may be placed between either the resist-layer interface or the air-resist interface. Both bottom and top ARCs are used for this purpose.

Postbake. The function of this step, after exposure and before development, is to further densify the resist so as to reduce the dissolution rate of its undissolved regions. In addition, it improves resist adhesion, and prevents its undercutting during development. It also toughens the resist so that it can better withstand the harsh environment associated with reactive ion etching (RIE).

An important benefit of this postbake (sometimes called *hardbake*) step is that it reduces striations caused by standing wave effects, by redistributing the photoactive component which had been destroyed by optical radiation [27]. Typically, this step is carried out at 100–120°C, which is well below the glass transition point of the resist.

Development. The slice is now rinsed in an appropriate developer, specified by the photoresist manufacturer. This is usually a proprietary formulation which does not contain light alkali ions, but contains $(\text{CH}_3)_4\text{NOH}$ as an active constituent [5]. The development step results in dissolution of the exposed positive photoresist but does not affect the unexposed regions (see Fig. 10.6e).

It is often found preferable to provide an additional postbake step, especially if RIE is used for subsequent etching purposes. Care must be taken to avoid plastic flow at this point, since this hardbake can be carried out at temperatures up to 170°C. In some cases [28], a high-temperature hard bake can be used to promote flow of the resist, as part of the fabrication process.

Etching. The slice is now etched in order to remove those parts of the underlying film that are not covered by the photoresist. This results in the formation of windows in the mask film, as shown in Fig. 10.6f. To avoid unnecessary undercutting, this process is monitored and arrested as soon as full etching is accomplished. Increasingly, RIE or ion milling is used to remove this unwanted material.

Stripping. The final step consists of removal of the exposed photoresist. Positive photoresists are usually removed by means of a chemical solvent such as acetone or methylethylketone. These are highly inflammable; moreover, their effective use requires application at about 80°C, which is close to their flash point. Increasingly, 1-methyl-2-pyrrolidinone is used, in addition to proprietary stripping solutions, for safety reasons.

Negative resists are considerably harder to remove. Here one approach is to immerse the slice in a 1:1 mixture of concentrated H_2SO_4 and H_2O_2 at 150°C.

This mixture is often referred to as “piranha” etch because of its virulent qualities. Problems with the rapid depletion of H_2O_2 have led to its replacement by peroxydisulfuric acid ($\text{H}_2\text{S}_2\text{O}_8$), commonly called PDSA, in order to increase its useful life. Another removal technique for negative photoresists consists of using hot chlorinated hydrocarbons to swell the polymer, together with acids to loosen its adhesion to the substrate. Solvent mixtures of trichlorethylene, methylene chloride, and dichlorobenzene, combined with formic acid or phenol, are used in the form of proprietary mixtures for this purpose.

Photoresist removal by plasma oxidation, commonly called *plasma ashing* and described in Chapter 9, has many advantages over wet chemical methods. Thus undercutting by capillary action of the liquids is avoided, so that photoresist adhesion is not critical. Waste disposal problems are eliminated, since only a small amount of plasma reaction products (water, carbon dioxide, and carbon monoxide) are produced. These factors add up to a major cost advantage for this approach, so that it has received wide acceptance by industry.

Plasma methods present a problem in the area of silicon MOS circuits. Here radiation damage to the gate oxide can cause significant threshold shifts, especially for short-channel, low-threshold devices. Recently, the use of UV, as well as the use of UV combined with ozone, has been explored for resist removal when ion damage to the underlying layer must be avoided.

The pattern transfer process for contacts and metallization is only slightly different from the above procedure. Here aluminum and gold/Ti-W are the most commonly used materials, as outlined in Chapter 8. The insulating layer covering silicon microcircuits usually consists of silicon dioxide, whereas silicon nitride is commonly used with GaAs circuits. Contacts and interconnections are made as shown in Fig. 10.8.

Windows are cut in the insulating layer over appropriate regions, by use of a mask with a contact pattern. This is shown in Fig. 10.8a for an n^+p diode. The metallization film (or films) are deposited over this insulating layer, and make contact to the semiconductor, as in Fig. 10.8b. The wafer is now covered with photoresist and exposed through a mask carrying the interconnection pattern (Fig. 10.8c). Positive photoresists are almost universally used in this step. After development, the metallization that is not protected by the photoresist is removed by suitable etching techniques, as described in Chapter 9. The resulting metal connects to the contact regions, and runs over the insulating layer, as shown in Fig. 10.8d.

Interconnection lines may be widened once contact is made to the device. In addition, it is possible to widen these lines further to form large bonding pads to which leads may be attached. Both situations are shown in the plan view of Fig. 10.8e. Next, the resist is removed, and the slice is heated in an inert gas ambient to microalloy the contact to the semiconductor, and also to bond the metallization to the insulating surface.

The removal of resist over metallization is extremely difficult when negative resists are used, since swelling of the resist leads to damage of the fine

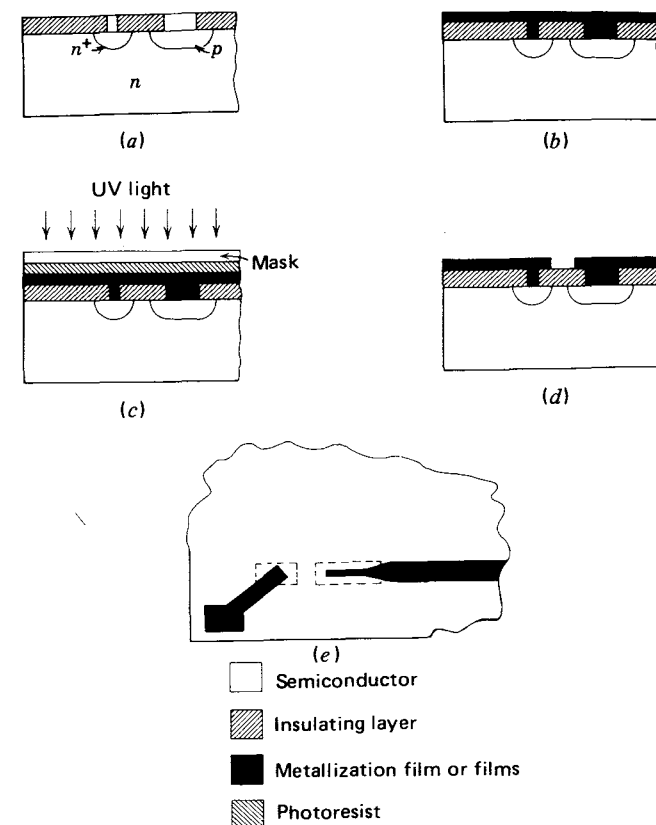


Fig. 10.8 Steps in making contacts and metallization.

lines. With positive resists, swelling does not occur, so that resist removal is a relatively easy matter.

10.3.1.1 Lift-Off Techniques

The *lift-off technique* is an important variation of the above process [29]. Here the delineation of, say, a metal pattern on an insulating substrate proceeds along the following lines. First a positive photoresist film is placed on the substrate, and patterned so that it covers all those regions where *no* metal film is desired, as in Fig. 10.9a. Thus, the mask is the inverse of what is required for conventional pattern transfer with a positive resist. Next, the metal film is deposited over the substrate–resist combination, as shown in Fig. 10.9b, and contacts the substrate *only* in those regions where it is required. Finally, the photoresist is removed by a solvent which does not attack the metal film. In so doing, it “lifts off” the material which is on its surface, leaving behind the patterned

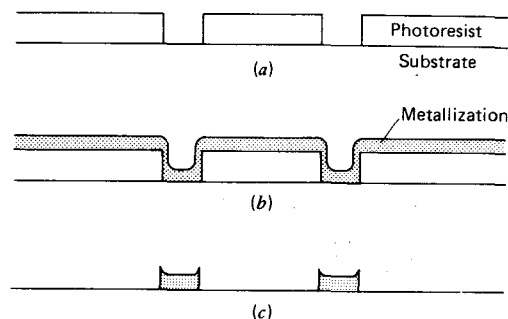


Fig. 10.9 The lift-off process.

metal film, as in Fig. 10.9c. The success of this approach requires the use of a relatively thick photoresist film so that the deposited metal film is very thin at the sides of the step, or even discontinuous.* This allows rapid dissolution of the photoresist mask, and makes it easier to lift off the raised portions of the film without breakage.

Two advantages are realized by this process. First, it can be used with films such as platinum, gold, silicides, and refractory metals, which are very difficult to etch by conventional means. Next, the use of a thick photoresist avoids problems due to pinhole formation. Unfortunately, however, lift-off is always accompanied by slight tearing at the film edges, as shown in Fig. 10.9c. Thus, it is extremely difficult to carry out this process with fine-line structures. One solution to this problem is to spin on a thick layer of a single photoresist, and toughen its surface by a pretreatment [29]. Positive photoresists such as AZ1350-J can be surface-toughened by immersion in an aromatic solvent such as chlorobenzene for a fixed period of time after the softbake period, and before or after pattern exposure. This process results in greatly reducing the dissolution rate of exposed resist in the surface layer. Control of the soak time and prebake temperature permits photoresist cuts with the overhang pattern shown in Fig. 10.10. Here the photoresist** was modified to a depth of 2000 Å by the use of chlorobenzene prior to development. Vacuum evaporation on this patterned resist results in a discontinuous film and eliminates problems of tearing. At the same time, the thick photoresist (1–3 μm) permits the use of thick metal films of sufficiently large cross section, so as to handle the current requirements of high-speed circuits. Thus the approach represents a practical alternative to the anisotropic RIE methods described in Chapter 9. Furthermore, it avoids the problems of damage and oxide charge associated with plasma processes, and is extensively used in VLSI applications for this reason.

*Techniques such as vacuum evaporation from a point source, which provides poor step coverage, are ideal for this purpose.

**Shipley Company, Newton, MA.

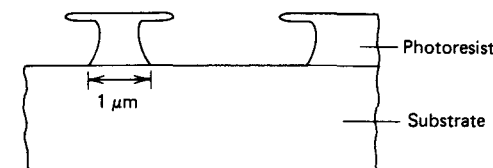


Fig. 10.10 Profile of photoresist using a chlorobenzene modification step prior to development. Adapted from Hatzakis et al [29].

Multilayer resists can also be used with the lift-off process. Now, the separate layers can be optimized individually; in addition, it is possible to form the image in the thin top layer, with an improvement in resolution. Details of this approach are provided in Section 10.4.2.

10.4 ADVANCED TECHNIQUES

We have noted that e-beam lithography can readily achieve the critical feature size which will be required in the foreseeable future. Thus, it is the basic method for reticle mask-making. Improvements in this area are now directed towards increasing the throughput, and improving the ease of operation of these systems.

Pattern transfer techniques, on the other hand, present many areas for improvement. Advances in pattern transfer by conventional optical methods involve the use of shorter wavelengths, the use of multilayer resist technology, and the use of improved techniques for sharpening image contrast.

Totally new systems for pattern transfer are also being investigated. Here, it is important to note that multiple stations are used at each manufacturing location, and handle a high volume of mask sets for each application. Thus, overriding factors in the development of these systems are high throughput and reduced cost. Their minimum feature size is, however, dictated by the reticle mask which is made by e-beam lithography.

In this section, we briefly described these new approaches, with a view towards assessing their usefulness in pattern transfer systems.

10.4.1 Short Wavelengths

The limitations of optical lithography are a consequence of basic physics. In any single wavelength optical system, the minimum feature size is given by

$$\sigma = \frac{k\lambda}{NA} \quad (10.1)$$

where λ is the wavelength, NA is the numerical aperture, and k is a proportionality factor. For a diffraction-limited optical system, $k = 0.5$. In practice,

values of k are somewhat larger because of manufacturing uncertainties. The numerical aperture is given by $\sin \alpha$, where 2α is the acceptance angle of the lens at its point of focus. Thus, NA is a measure of the light-gathering power of the lens. From this equation, it follows that the minimum feature size can be reduced by operation at shorter wavelengths, and/or with larger values of NA .

The depth of focus of a lens is an important parameter, because the surface of a microcircuit has topological features and is not flat. Its magnitude is given by

$$d = \frac{\lambda}{(NA)^2} \quad (10.2)$$

Increasing the NA results in reducing the depth of focus; moreover, the field of view of the lens is reduced. Thus, the number of steps required to cover a microcircuit is increased, resulting in an increase in the time required to process an entire slice through the mask aligner. It follows that the use of shorter wavelengths is eventually essential in order to reduce the feature size.

Modern optical pattern transfer equipment uses high-pressure Hg-Xe vapor lamps, which exhibit a spectrum of sharply defined lines as shown in Fig. 10.11 [30]. Here, the lines at 546 nm, 436 nm, 405 nm, and 365 nm (denoted as the E, G, H, and I lines, respectively) are especially intense, and can be used for stepper applications.

The thrust of microcircuit technology has steadily shifted towards shorter

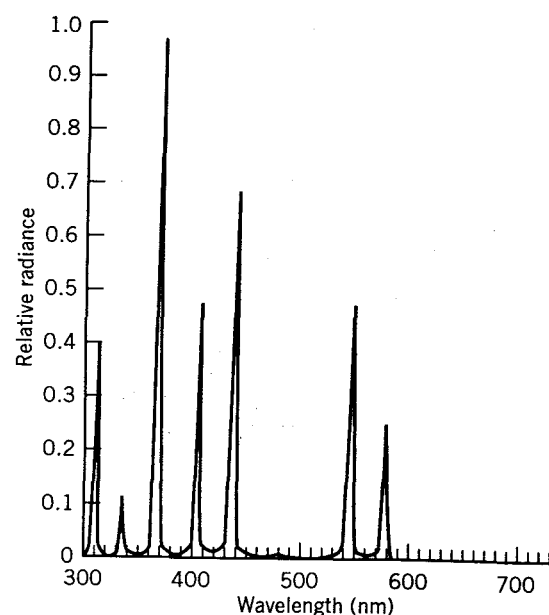


Fig. 10.11 Emission spectrum of an Hg-Xe vapor lamp.

wavelengths, from soft UV to UV, in order to reduce the minimum feature size. A number of mask aligners utilizing the I-line are now available, with a minimum feature size of $0.25 \mu\text{m}$. Standard optical glasses can be used in these systems, although their properties rapidly degrade below 350 nm. Alternative glasses have also been investigated for I-line applications.

The optical absorption of conventional photoresists is much greater for the I-line than for the G-line, leading to problems with linewidth control. However, new resists have been developed with spectral absorption characteristics which are matched to this wavelength.

Even shorter wavelengths, in the deep UV range, can be obtained by the use of excimer laser light sources [31]. Light output at 351-nm, 308-nm, 248-nm, and 193-nm wavelength can be obtained using XeF, XeCl, KrF, and ArF source gases, respectively. All of these lasers are operated in the pulsed mode, with typical peak power outputs of about 10^7 times that from the individual lines from high pressure Hg-Xe vapor sources. Thus, single-shot exposures, which simplify mounting requirements, are a practical possibility with these sources. Additionally, materials capable of ablation can be used as positive photoresists, because of the high energy density that is involved. Carbon films have been found to be suitable for this application.

Excimer laser mask aligners are still under development, and $0.13\text{-}\mu\text{m}$ feature sizes have been demonstrated. However, many problems have to be solved before these systems become practical. For example, there is a need for deep UV optics which are free from aberration and which can withstand high peak powers without catastrophic failure. Quartz is the material of choice for this application and is also used for mask plates in this wavelength range. There is also a critical need for new resists which can take advantage of the short exposure times associated with these systems. Both organic and inorganic materials are being actively considered for this purpose. Finally, excimer lasers are notoriously unreliable and require maintenance after a few hours of operation. Reliable lasers are necessary for use in a commercial situation.

10.4.2 Multilayer Resists

Modern VLSI technology requires the definition of fine lines with high aspect ratios. This is especially true for metallization, which is $0.8\text{--}1 \mu\text{m}$ thick. This, in turn, necessitates the use of thick resist layers to serve as masks for defining these films.

During pattern transfer, the light intensity falls off with depth as the beam penetrates the photoresist, so that its top regions are excessively overexposed. With positive resists, this results in undercutting of the mask, and in nonvertical resist walls, as shown in Fig. 10.12. This is especially true for deep UV resists, which have a large absorbance at their operating wavelengths.

The use of multilayers of resist can avoid this problem. Consider, for example, the situation where two layers are used. Here, there are two distinctly different possibilities: Case 1, where both layers are exposed to optical radia-

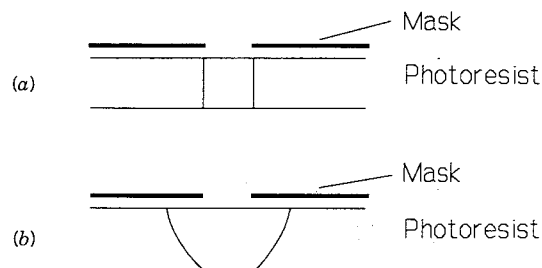


Fig. 10.12 Resist profiles after development: (a) ideal and (b) actual.

tion and then developed; and Case 2, where the top layer is used to form the photographic image, which is then used as a protective mask during removal of the second layer.

Figure 10.13a shows Case 1, where the bottom resist layer (R_1) is a material with high radiation sensitivity, and the top (thinner) layer (R_2) has low radiation sensitivity. Upon exposure and subsequent development, R_2 will etch slowly. R_1 , on the other hand, will etch rapidly, thus undercutting R_2 as in Fig. 10.13b. This result is essentially the same as that obtained in the lift-off process of Section 10.3.1.1, where the top layer was formed by a chlorobenzene soak. However, the two-layer technique provides more control. Still more control can be obtained, at the expense of added complexity, if the developer for R_1 will not dissolve R_2 , and vice versa.

Case 2 is quite different. Here, R_1 is sensitive to light of wavelength λ_1 , whereas R_2 is sensitive to λ_2 but opaque to λ_1 . In this approach, exposure at λ_2 , followed by development, is used to define the pattern in R_1 , which comprises a thin layer. Next, the wafer is exposed to light at λ_1 . This is a flood exposure, without a photomask; here, the pattern in R_2 serves this purpose. This is followed by development of R_1 .

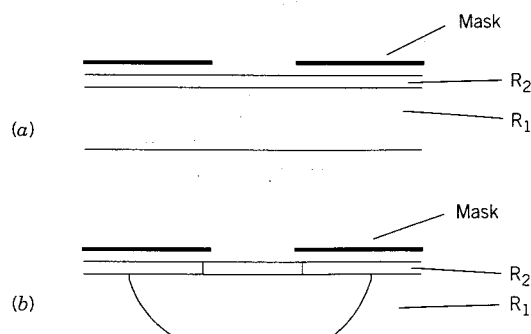


Fig. 10.13 Profiles for a two-layer resist process: (a) before exposure (b) after exposure and development.

The approach outlined here [32, 33], referred to as *portable conformable masking* (PCM), is superior to that of Case 1 since it allows a high-resolution pattern to be defined in a thin (2000–4000 Å) layer, although the overall thickness of the resist is 2–4 μm .

One problem with double-layer resists comes about because of the mixing of resists at the R_1 – R_2 interface. This results in a transition layer, which may be difficult to remove. A solution to this problem is to use a layer of spin-on SiO_2 between the photoresist layers, resulting in a trilevel mask. RIE can be used readily with a system of this type, with an oxygen plasma for resist removal, and a CF_4 – O_2 plasma for removal of the SiO_2 layer. Recently, new resist combinations have been developed [34] which do not have this intermixing problem.

Lift-off techniques have been successfully applied to PMMA resists, using a double-layer technique [35]. The lower layer consists of a 1- to 2- μm thick film of PMMA dissolved in chlorobenzene. After baking, a 4000 Å film of MMA dissolved in ethyl cellosolve acetate is spun on the wafer. This upper layer defines the pattern, while the lower layer is undercut during development so that easy lift-off is achieved.

Contrast enhancement lithography (CEL) is an alternative approach [36, 37] to obtaining improved pattern transfer. Here, a conventional resist R_1 is covered by a layer of a polymer containing a photobleachable dye, R_2 . Upon exposure to light of wavelength λ_1 , this layer bleaches in those regions which are exposed through the mask, and thus sharpens the intensity profile of light passing through the photomask. This process is illustrated in Fig. 10.14. After

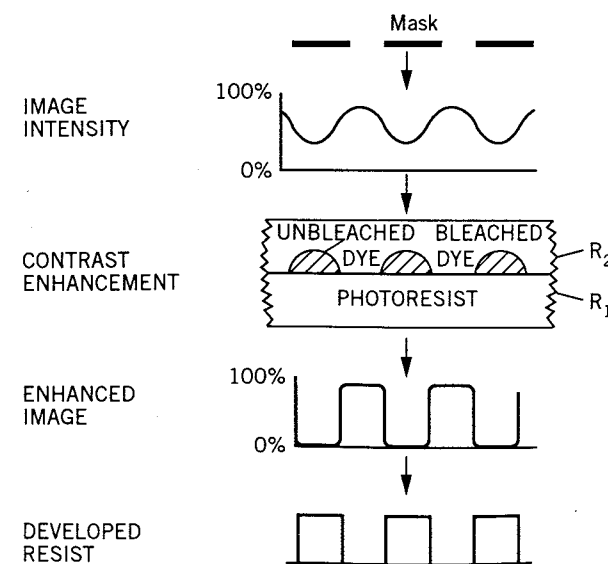


Fig. 10.14 Steps in the use of a contrast enhancement layer. Adapted from Halle [32].

exposure, the CEL layer is dissolved away, and the photoresist developed. Water-soluble CEL materials are available which greatly simplify this process.

Photolithography is perhaps the most expensive step in microcircuit manufacturing. As a result, the processes described here must be evaluated critically, and the simplest method selected to do the job at hand. Advances in single-layer resists have made these the choice for many situations. Among the multilayer resists, the CEL approach is the most promising, because it results in greatly improved performance with small additional complexity. Moreover, it can be designed for use at all wavelengths [38], including those which are provided by excimer laser sources.

10.4.3 Phase-Shifting Masks

Diffraction effects represent a fundamental limit on the resolution of lines in optical lithography [39]. This is illustrated in Fig. 10.15a, which shows two adjacent slits in an optical mask. The light intensity from each of these slits is diffracted into the obscured regions which surround them. As these slits are made closer, the diffracted regions overlap until the individual intensities cannot be resolved.

Figure 10.15b shows the same mask pattern. Here, however, a transparent layer is placed across one of the openings between slits. Its thickness is such as to provide a 180° phase shift to light passing through it. The diffracted signal from *this* slit will now be out of phase with the signal through the second slit. As a result, destructive interference occurs at the wafer, and both slits can be resolved.

The use of phase-shifting masks of this type has the potential of extending the resolution capabilities of modern optical systems by a factor of 2–4 [40]. A

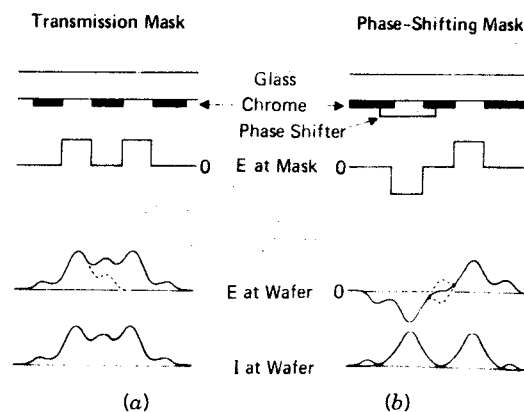


Fig. 10.15 Intensity patterns: (a) without a phase shifting mask and (b) with a phase shifting mask. From Levenson et al. [40].

central problem with this technique is that it is limited to highly repetitive patterns. More recently, however, a number of modifications have been proposed which allow the method to be applied to arbitrary mask patterns [41].

The CEL process can also be used to enhance the contrast in the optical image. Although it is an alternative approach to phase-shifting masks, it can be combined with them.

10.4.4 Electron-Beam Techniques

The concept of writing a pattern directly on a chip by e-beam lithography is attractive, since it represents the ultimate in resolution capability. However, this approach is severely limited by the time taken to write a single substrate because of the sequential nature of this process. One area where this approach has been implemented is in the direct writing of gates in GaAs devices and integrated circuits [42]. Here, wafer sizes are relatively small (50- to 100-mm diameter), and each circuit usually has a small device count. In each device the gate length is the most critical parameter, which must be kept as small as possible. Using direct e-beam writing, a value of $0.15\text{--}0.25\text{ }\mu\text{m}$ has been achieved for the gate length in this manner.

The speed of direct e-beam writing can be greatly improved if advantage is taken of the fact that the minimum feature size is critical in defining the edge of a pattern, but not for its inner parts [43]. Thus, most of the pattern can be written with a beam having a large spot size (of rectangular shape), with a large stepping pitch. At the same time, a minimum spot size ($0.1\text{ }\mu\text{m}$) can be used to define the pattern edge. Using this approach, GaAs monolithic microwave integrated circuits have been processed at the rate of 6–8 slices/hr.

The sequential nature of e-beam writing makes it extremely difficult to use for pattern transfer, even if significant improvements are made in resist sensitivity, high-intensity electron guns, and electronics. An alternative approach, e-beam projection printing, is presently under consideration [13, 44]. A schematic of a demagnifying projection system for this purpose is shown in Fig. 10.16. Here a self-supporting foil mask is used with a flood electron gun source which provides a collimated beam of electrons. The reticle mask, usually $\times 10$, is imaged directly on a photoresist-coated wafer which is located on a laser-controlled table for positioning purposes.

Systems of this type are considerably simpler than e-beam systems which are used for pattern generation, since the beam is not required to maintain its precise convergence under scan conditions. This greatly simplifies the electro-optical system that can be used, in addition to the digital electronics required for data handling and beam deflection. Most of the present research with these systems involves step-and-repeat techniques for printing one chip at a time. Even with this limitation, electron projection printing is considerably faster than direct writing, where the pattern is written serially. This can be a major advantage in a development situation, where it can provide quick turnaround for prototype circuits.

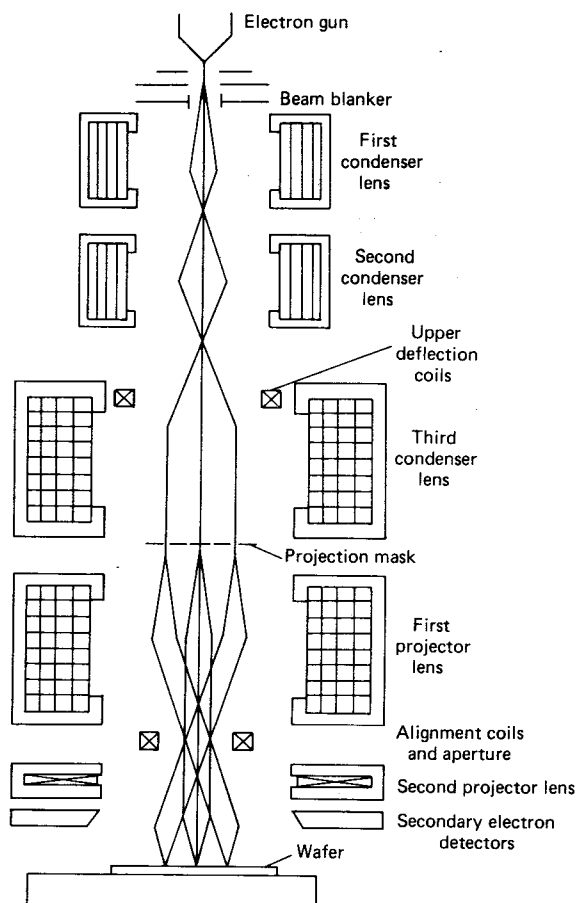


Fig. 10.16 Schematic of a demagnifying electron projection printing system. From Thornton [13]. Reprinted with permission from *Advances in Electronics and Electron Physics*.

Problems of mask fabrication for this system are severe, since the pattern consists of a large number of isolated structures. However, they must be physically connected for a mask to exist. One approach is to use a fine grid or mesh on which the pattern is placed. The resulting fine bars which connect isolated structures produce a small distortion at the edge of each structure, which can be kept within acceptable limits if a $\times 10$ mask is used.

10.4.5 Ion-Beam Techniques

The use of ions instead of electrons in the lithographic process has two potential advantages [45]. First, ion beams do not suffer from as much scattering as do

electron beams, when they penetrate a resist. In addition, secondary electrons produced by ion bombardment have very low energy so that scattering caused by them is limited. The ultimate limit to the minimum feature size is set by these scattering processes. Next, the ion sensitivity of resists is a function of the ion energy and mass, and is many orders of magnitude greater than that for electrons. Thus ion-beam techniques are potentially more rapid than e-beam methods.

Ion projection printing systems, utilizing an r.f. ion source and focusing optics, have been developed with ion sources using H^+ , He^+ , and Ar^+ in the 100-keV range, to image a field $5\text{ mm} \times 5\text{ mm}$ in a single exposure [46]. Important problems with this system are its large size, so that it is prone to vibration. Moreover, considerable work needs to be done to improve the resolution of the ion-optical system in order for it to meet the $0.15\text{-}\mu\text{m}$ minimum feature requirement.

Direct writing by focused ion beams [47] is also under consideration. Here the critical elements are finely focused ion sources of the desired impurity. Although much progress has been made in their development, the writing speed of these systems is four to six orders of magnitude slower than for ion projection printers. This has confined their use to special applications such as (a) mask repair and (b) the making of small cuts and vias [48].

10.4.6 X-Ray Printing

The attractiveness of this approach stems from the extremely short wavelengths that are possible with x-ray sources [49]. This eliminates the diffraction limitation of optical and UV lithographic techniques, and has the potential of providing a means for fabricating submicron structures at a cost that is competitive with optical projection. There are, however, major differences in the design of these systems. Thus optical systems can use collimated light and focusing optics, whereas x-ray systems are generally restricted to a point source. Here, proximity gap printing must be used, with $\times 1$ masks. In an x-ray system this results in a slight magnification of the pattern. This is seen in the proximity arrangement of Fig. 10.17, where the blur (σ), is related to the size of the x-ray source (S) and the gap (g), as well as to the distance between the source and the mask (D), by

$$\sigma = \frac{gS}{D} \quad (10.3)$$

Usually, σ is small enough to be neglected; however, this equation emphasizes the need for keeping the magnitude of the gap (and more important, its spatial variation) constant to prevent distortion effects. This necessitates a somewhat larger gap than is used in optical proximity gap printers. Typically, systems of this type can be operated with a gap of about $25\text{--}50\text{ }\mu\text{m}$ and still give satisfactory performance at the submicron level.

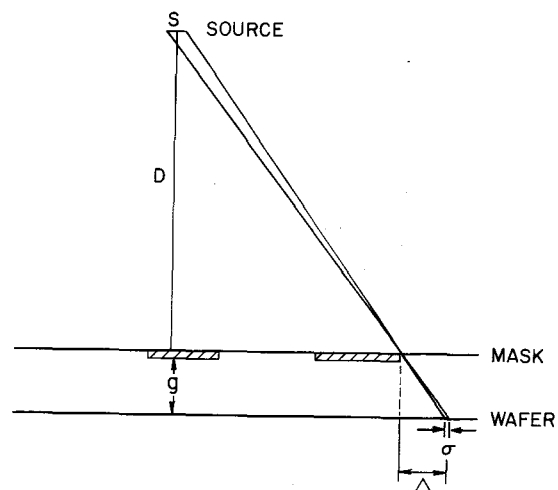


Fig. 10.17 X-ray proximity arrangement.

The ideal source for x-ray lithography is a point source. This can be produced by a high-intensity electron beam impinging on a target, which is water-cooled and rapidly rotated to prevent overheating. The choice of x-ray wavelengths ranges from 4.7 Å and upward. An aluminum target and a 10- to 20-keV beam can be used to produce x-rays with a wavelength of 8.34 Å. These are filtered to remove stray radiation, and are fed out of the vacuum through a beryllium window [50], as shown in Fig. 10.18. All processing of slices in these systems can be done outside the vacuum, which is a distinct advantage over e-beam lithography. The beam is usually confined to a helium gas environment to prevent unnecessary absorption; however, x-ray lithography is relatively insensitive to airborne particles, so that cleanliness requirements can be readily met. An additional advantage is that x-rays are not easily scattered in a resist during pattern transfer, because of their extremely short wavelengths. This results in nearly vertical resist profiles, which are highly advantageous for VLSI applications.

A severe problem with x-ray sources of this type is that no photoresists exist with efficient absorption in the 4- to 8-Å wavelength range. Alternative x-ray sources are being developed [51, 52], based on laser-induced plasmas which produce short pulses of "soft" x-rays with high irradiance in the 12-to 14-Å range, which are more closely matched to the absorption of available resists. These can also be used for "one-shot" exposures, thus avoiding vibration problems during pattern transfer.

Electron storage ring technology is also used for the generation of x-rays with an average irradiance of 10–50 times that of an x-ray tube, resulting in a reduction in the exposure time [53]. In this approach, x-rays are generated in

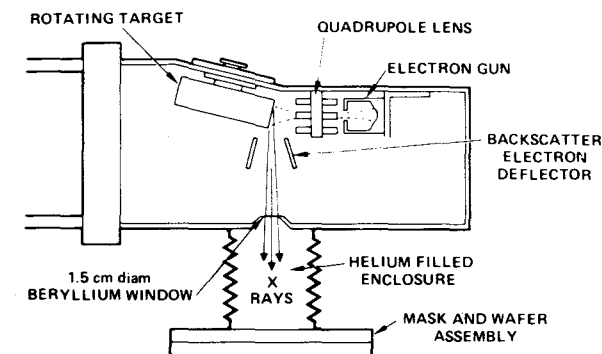


Fig. 10.18 Schematic of an x-ray printing system. From Stover et al. [50]. Reprinted from *Solid State Technology*.

a synchrotron ring structure and can be brought out at multiple ports from the ring. A number of "low cost" rings of this type are under development at the present time [54, 55].

Masks for x-ray lithography must be extremely thin so as to be transparent at these wavelengths. Membranes of both inorganic (Si, SiC, Si₃N₄, Al₂O₃, and BN, for example) and organic materials have been investigated. Both Si and SiC films, 1–2 μm thick, are preferred for this purpose since they exhibit no radiation-induced discoloration. These materials are transparent to x-rays and also optically transparent, so that alignment of the mask to the wafer can be done by conventional means.

A gold or tungsten film, in which the pattern is defined, is used to absorb the soft x-rays. Typically, this is vacuum-evaporated on the membrane, to a thickness of about 0.5–1 μm. The mask pattern is made in this film by conventional e-beam lithography, and the excess gold is removed by ion milling.

A major problem with x-ray printing is the lack of suitable resists, in order to keep the exposure time to an acceptable value. The design of these resists is critical to the success of this technology. Here, it has generally been found that resists which are useful for e-beam lithography can also be used, and that resists which have high sensitivity for e-beam applications can also have a high sensitivity for x-rays.

Resists for x-ray lithography have been described in Section 10.1. Most work has been done with the methacrylates, and in particular with polymethylmethacrylate (PMMA) and its derivatives, which are based on scission. Resists, based on the dissolution inhibiting principle, can also be used with x-ray lithography. These have a chemistry very similar to that of positive resists which are used for conventional photolithography. A disadvantage of these resists is their relatively low x-ray absorption coefficient.

High-power x-ray sources are also crucial to the commercial realization of this technique, and are under continual development. Nevertheless, a number

of practical systems have already been developed [56], and microcircuits have been fabricated using this approach.

At the present time, the biggest challenges to x-ray lithography come from both conventional and unconventional optical processes. These techniques are capable of 0.25- μm features at the research level, and 0.5- μm features in production [2]. These feature sizes can be obtained with I-line optics, and are suitable for the manufacture of 64-Mbit DRAMs. The case for x-ray lithography is thus one which must be made when feature sizes of 0.15 μm are necessary. These sizes will be necessary for memory fabrication in the 256 Mbit to 1 Gbit ranges, and can only be realized by the use of proximity printing using soft x-rays.

10.5 PROBLEM AREAS

A variety of problems can be encountered at all points in the lithographic process. One is that of unwanted particulate matter. This ranges from glass particles left on the plates by the manufacturer, to airborne particles which are always present to some extent in a clean room. Additional problems come about because of operator-induced errors during processing. In general, these result in random defects in the microcircuit.

Consider a microcircuit chip of area A . To an approximation, the number of such chips on a slice of diameter d is given by N , where

$$N \approx \frac{\pi}{4A}(d - \sqrt{A})^2 \quad (10.4)$$

Let N_G be the number of good chips on the wafer, so that N_G/N is the fractional yield.

Most defects from the lithographic process are extremely small and of random nature. Let N_D be the total number of such defects per wafer.

If a random defect is added to a wafer, its probability of destroying a good chip is N_G/N . Thus,

$$dN_G = -\left(\frac{N_G}{N}\right) dN_D \quad (10.5)$$

so that the fractional yield is

$$\frac{N_G}{N} = e^{-N_D/N} \quad (10.6)$$

Minimizing the number of defects on a wafer is thus extremely important for VLSI, where chip area is corresponding large (i.e., where N is small).

A discussion of the different types of defects that can arise during the lithographic process now follows.

10.5.1 Mask Defects

Mask defects of the visual type include pinholes, spots, intrusions, and protrusions. Such defects are a function of the quality control exercised by the manufacturer, as well as of the care taken in using the starting materials. Often these masks are supplied precoated with a strippable lacquer film for surface protection. This film is removed immediately prior to loading in the mask equipment.

Extreme cleanliness is required during the fabrication of reticle masks, and a detailed examination of each exposed mask is essential before it can be replicated. A number of different methods are used for mask inspection today [57]. The simplest approach is to directly compare one die pattern with another on the same mask. This is done by optically overlaying these patterns, followed by visual inspection. A second approach is to compare a die with a defect-free pattern that is stored in digital form in a computer. This approach has the advantage that it can be carried out automatically. A somewhat similar approach is to scan two dies by a dual-beam flying spot scanner and compare the signals by electronic means. Spatial filtering techniques have also been used for this inspection purpose.

Dimensional errors can also occur during mask making. These can only be determined by both line-width and run-out measurements on the mask.

Visual defects on reticle masks at $\times 10$ magnification can be repaired if damaged. Defects in the form of extraneous material in the clear-field regions are usually removed by laser ablation. Voids, and scratches which result in removal of the mask film in the dark-field regions, are considerably harder to repair. Often, the repair operation consists of applying minute droplets of epoxy ink to fill the pinholes. Increasingly, focused ion-beam techniques, involving the deposition of chromium, are being considered for this purpose [48]. Finally, the time taken for mask repair can often exceed that required to make the mask in the first place. Remaking of the mask is a common practice under these circumstances.

10.5.2 Pattern Transfer Defects

A number of problems may be encountered during the opening of windows in the masking film, or in the delineation of fine lines. Some result in defective circuits that are rejected. More serious, however, are those problems that result in an inadvertent spread of device parameters which may impair the reliability of the microcircuit and degrade its performance [58]. Some of these defects are now considered for a few practical situations.

Undercutting of the Resist. If the resist adheres poorly to the masking film, undercutting may occur during the etching process, resulting in an enlarged window (see Fig. 10.19a) and changes in the associated device parameters after diffusion. In extreme cases a defective circuit can result by short-circuiting adjacent regions. Undercutting of the photoresist comes about because of capillary action of the (wet) chemicals that are used during the etching process. This problem is greatly reduced when plasma etching techniques are used.

Dimensional Variations. Dimensional variations may occur in the width of cuts in the masking film (as in Fig. 10.19b) due to lack of control of the exposure time, or limitations of the photographic process. These, too, result in changing the effective area of the masked regions. The problem is especially severe when long, very narrow cuts are required and may lead to breaks in the metallization, as shown in Fig. 10.19c. These variations can also occur because of swelling of the resist during development. Positive resists are less susceptible to this problem than negative ones, so that they are preferred in VLSI applications.

Lack of Registration. This occurs because of mask alignment errors, or because of cumulative errors in the step-and-repeat process. It can lead to

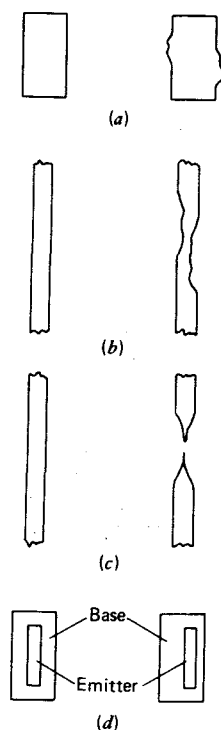


Fig. 10.19 Defects and their results.

altered device configurations, as shown in Fig. 10.19d for the emitter and base regions of a transistor. Here, too, defective circuits can result in extreme cases. In some situations, misregistration may result in exposing a protected junction edge, thus degrading its characteristics.

Pinholes. These may be present in the resist and result in the inadvertent opening of a small window in the underlying mask film. Their effect is a function of their specific location. As may be expected, the severity of this problem increases with component packing density in a microcircuit.

Dust Particles. These present a serious problem during the delineation of patterns in mask films. Some dust, such as carbon or metallic particles, is opaque. Its presence on the clear field of a mask will prevent exposure of the underlying resist. This will cause holes in a negative resist after exposure and development, and thus holes in the mask film. The effect with positive resists is to not completely clear an opening in the underlying mask. This latter effect is usually less serious than the former.

Dust particles are often transparent and cause diffraction effects. This can have the same result as opaque particles; often, however, the effect is over a wider area because of the diffraction pattern. In either case, the problems of dust are minimized by the use of good clean-room technique, and by careful visual inspection of the masks prior to installation in the aligner.

Scratches and Tears. The printing of metallization patterns is a particularly difficult task because of the delicate nature of the film. Here scratches are by far the most common type of defect and are caused by rough handling during the fabrication process. Scratches greatly increase the current density in their vicinity, giving rise to (a) the formation of hot spots and (b) the premature onset of electromigration. Thus although the circuit operation is unchanged, its reliability may be greatly impaired in this manner. In extreme cases, scratches result in defective circuits by breaking the metallization path.

Tearing of the metallization may occur during the removal of the photoresist. This is often due to dimensional changes and damage to the photoresist during the alloying step. This defect also results in reducing the effective area of the current path or in an open circuit in extreme cases. The two-level lift-off technique is extremely important in controlling this problem.

Step Coverage. This occurs when an excessively thin layer of resist goes over a step in an oxide. It can give rise to a failure of the resist during the subsequent etching process. The problem is especially severe with negative resists, since they are applied in much thinner layers than are positive resists. Here, too, the use of two (or more) levels of resist can alleviate this problem.

Problems of step coverage can also be reduced by the use of planarization techniques. This important topic is discussed in Section 11.4.

TABLE 10.1 DRAM Production Requirements^a

DRAM Chip	Time Frame	Chip Size (mm ²)	Feature Size (μm)
1 Mbit	1989–1991	50–40	1–1.2
4 Mbit	1990–1993	80–50	0.65–0.8
16 Mbit	1991–1994	120–80	0.5–0.6
64 Mbit	1992–1995	160–100	0.35–0.45
256 Mbit	1995–1997	240–160	0.25–0.35
1 Gbit	1997–2002	320–240	0.15

TABLE 10.2 Resists for e-Beam and x-Rays

Resist	Type	X-Ray Sensitivity (mJ/cm ²)	20-keV e-Beam Sensitivity (μC/cm ²)
Naphthoquinonediazine/novolac	AZI450J	2100	40
Poly(methylmethacrylate)	PMMA	1800	80
Poly(hexafluorobutylmethacrylate)	FBM-120	35	0.5
Poly(butenesulfone)	PBS	14	2
Poly(glycidylmethacrylate)-co(ethylacrylate)	COP	5	0.6
Chlorinated poly(methylstyrene)	CPMS	8	0.4

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