

## An Introduction to Lithography

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### 1.1 Historical Perspective

Soon after the invention of the point contact transistor over three decades ago, several important technological trends were rapidly established. First, a technology known as planar junction technology (1) was developed; the development of this technology permitted the construction of p-n junctions in a semiconductor material without the use of bulky, three-dimensional contact devices. Within a few years, silicon had become the dominant material for semiconductor fabrication, and photolithography was established as the technique of choice in fabricating planar, silicon devices. Numerous volumes have been written about the chemistry and physics of semiconductor devices and of materials for semiconductor manufacturing (2-4). Much less information has been compiled concerning the processing steps involved in semiconductor device fabrication, especially in the area of lithography.

Another important innovation in semiconductor devices was the invention of the monolithic integrated circuit. This technology provides a means for the *internal* interconnection of many solid-state and passive devices into a working unit that performs complex, electronic functions and allows the "density" of active devices to be increased many thousands of times over that achievable with discrete or single transistor devices. The past two decades have seen an astronomical growth in the microelectronics industry and associated technologies. The application of microelectronics impacts technologies such as communications, computer science, medicine, energy, and more recently, home entertainment. This revolution is going to continue for the foreseeable future and will require continued advances in silicon technology. The realization of this new generation of devices must involve the development of new processing, fabrication, control, and manufacturing technologies.

The conventional way of achieving these goals has been to make devices smaller, this results in more active-circuits per unit area (5). Figure 1 illustrates this trend, and it is the conviction of the author that this will continue for at least two more decades. It is interesting to note that not only are we decreasing the size of the elements in an integrated circuit while increasing the number of active devices, but that the average cost per chip is also remaining essentially constant -- that is the cost per function is decreasing dramatically. This trend has required and will continue to require a greater understanding of device physics, device design, and lithography. Microcircuit fabrication requires the selective diffusion of tiny amounts of impurities into specific regions of the semiconductor substrate to produce the desired electrical characteristics of the circuit. These regions are defined by lithographic processes in which the desired pattern is first defined in a resist layer (usually a polymeric film which is spin-coated onto the substrate) and

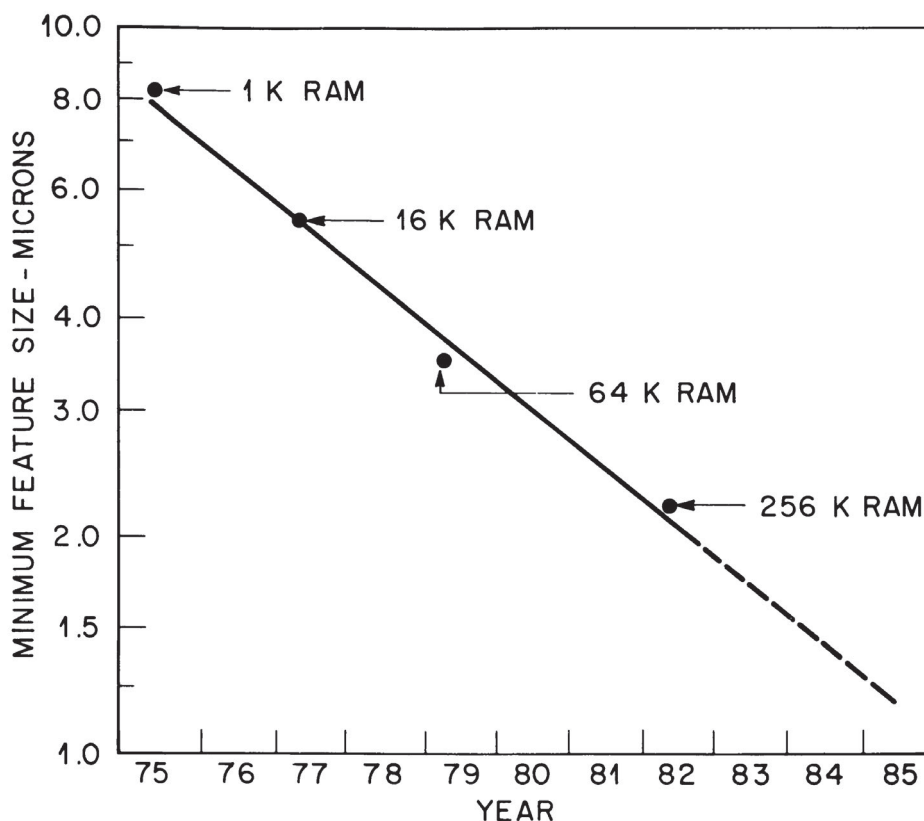


*Figure 1. Minimum feature size on a MOS random access memory device as a function of the year the devices were first commercially available.*

subsequently transferred, via techniques such as etching, ion implantation and/or diffusion, to the underlying substrate. This process is shown schematically in Figure 2. The purposes of this book are: (a) to review the lithographic strategies currently being used and under development, and (b) to emphasize in particular, the importance of resists and resist processing in achieving each individual lithographic technology goal.

*1.1.a Solid State Devices.* Many *designs* and *strategies* for device design and fabrication have intervened between the point contact transistor and the planar technology to which we alluded earlier, including grown junction transistors, alloyed junction transistors, and many variations of the planar technology. An understanding of the definition of integrated circuits, together with the details of the physics involved in their operation, is an

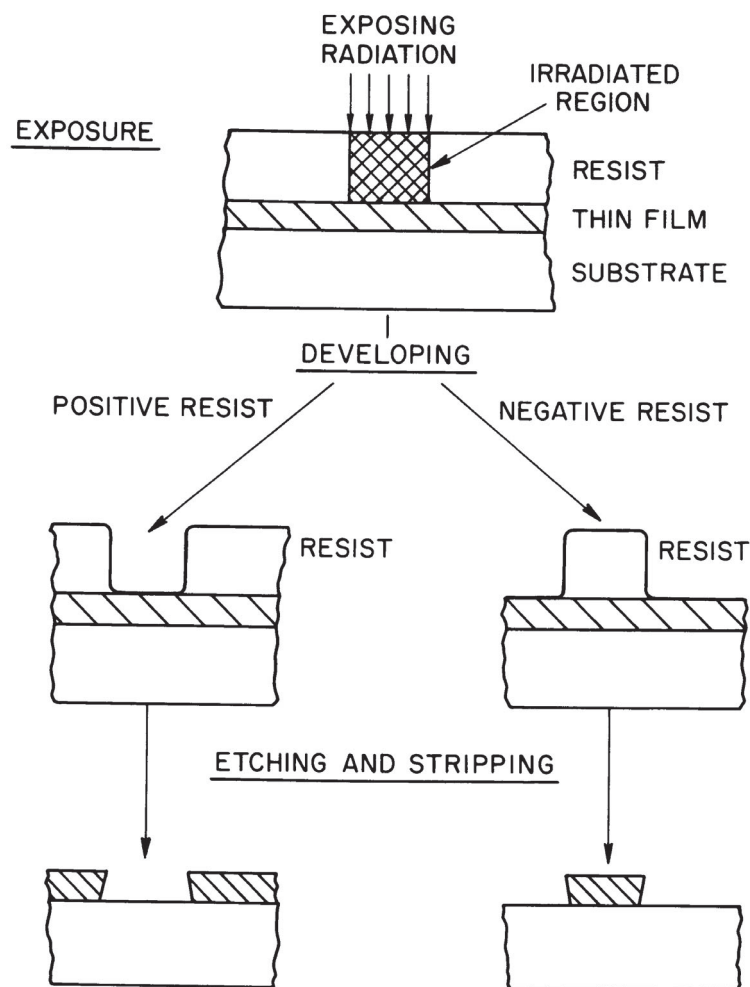


*Figure 2. The schematic diagram showing the formation of a polymeric relief image using lithography. The resist pattern is used to subsequently modify the underlying substrate.*

interesting story in itself, but beyond the scope of this book whose objective is limited to the lithographic process involved in circuit manufacturing (6). A single transistor is essentially a junction between two types of semiconducting materials (denoted p and n) and metal connections to the outside world. A large-scale integrated circuit contains tens of thousands of these individual transistor elements that are interconnected in complex ways by conductors such as aluminum or highly doped polycrystalline silicon. A simple transistor element of an integrated circuit is depicted in Figure 3.

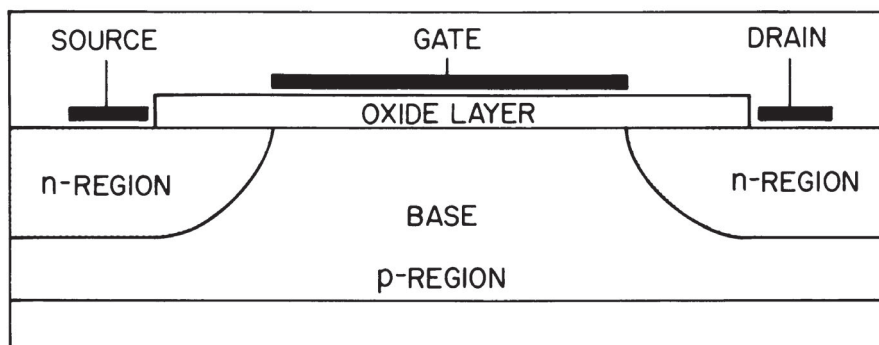


*Figure 3. Schematic representation of a single transistor similar to those used in a MOS memory device.*

Silicon is the dominant material for microelectronic circuits, primarily because of the ease with which it oxidizes to form insulating barriers for the subsequent implanting of tiny amounts of dopants into selected regions to achieve the requisite electrical properties. The silicon dioxide insulator and other dielectric films that are commonly encountered such as silicon nitride films are patterned by a process known as photolithography. Photolithography is probably *the* key process in microelectronic fabrication technology, because it is repeated 5 – 12 times before the three-dimensional circuit geometries necessary for a completed metal oxide semiconductor (MOS) or bipolar device are achieved. Figure 4 is an outline of the manufacturing sequence of a large-scale integrated circuit and illustrates the importance of understanding the lithographic technology used to delineate the patterns of thin-film dielectrics and conductors. The structure of an integrated circuit is complex both in the topography of its surface and in its internal composition. Each element of such a device has an intricate three-dimensional architecture that must be reproduced exactly in every circuit. The structure is made up of many layers, each of which is a detailed pattern. Some of the layers lie within the silicon wafer and others are stacked on the top. The manufacturing process consists in forming this sequence of layers precisely in accordance with the plan of the circuit designer.

A concept for a new circuit is transformed into a circuit design by engineers who have a knowledge of both circuit electronics and processing. Circuit designers who conceive of the new product work at specifying the functional characteristics of the device and select the processing steps that will be required to manufacture it. The actual design of the device begins

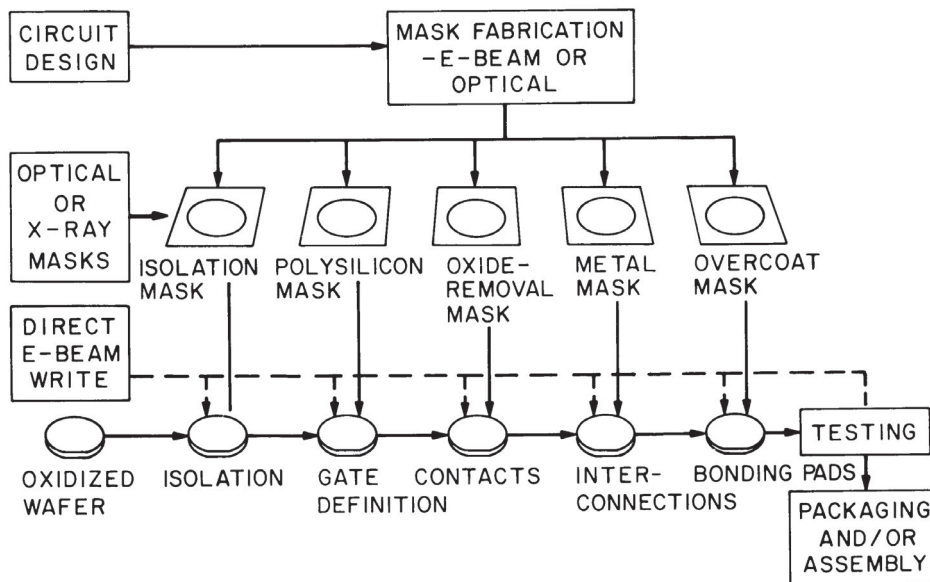


Figure 4. Outline of Manufacturing Sequences for a typical solid state device.

with an estimation of the size and approximate location of every circuit element. This preliminary design work is usually done with the aid of computers. Upon completion of the circuit design layout, a computer memory contains a list of the exact position of every element in the circuit. From data in the computer memory a set of plates, called photomasks, is prepared. Each mask contains the pattern for a single layer of the circuit. Since the circuits are so small, many can be fabricated side by side simultaneously on a single wafer of silicon. Thus each photomask, typically a glass plate about five inches on a side, has a single pattern repeated many times over its surface.

A complete set of correct masks is the culmination of the design phase of the development of the microelectronic circuit. The plates are delivered to the wafer-fabrication facility, where they will be used to produce the desired sequence of patterns in a physical structure.

As the complexity of integrated circuits increases and the dimensions of each circuit element decrease, greater demands are placed on the lithographic process, particularly with respect to resolution. Indeed, we are rapidly approaching the limits of photolithographic techniques for reproduc-

ing circuit geometries. We should also point out that in addition to the exposure technology, the resist itself is also an important factor limiting resolution and must be considered as we continue the trend of decreasing element size and increasing integration complexity. In subsequent chapters we will examine the various alternatives to photolithography, as well as the importance of processing and resists in this industry.

*1.1.b Lithography, the Art.* Lithography, often referred to as photoengraving, is the process of transferring a pattern into a reactive polymer film (termed a resist) which will subsequently be used to replicate that pattern into an underlying thin film or conductor. Photolithography, which uses ultraviolet radiation (360 — 410 nm), is the current "workhorse" technology in integrated circuit fabrication. It is interesting to note that the technology currently used has been in existence since the early days of planar transistor development (7). Many of the processing steps, which were worked out empirically with the use of phenomenological models and parametric studies, fall more into the realm of art rather than science.

The understanding of the physics and chemistry of resist materials and attendant processing has been largely neglected in the three decades of semiconductor device innovations. As the minimum feature size in a device approaches 1  $\mu\text{m}$  and new lithographic technologies develop rapidly, it is of paramount importance that we transform the important area of lithographic processing from an art to a science. Thus an understanding of the fundamental physics and chemistry of resist exposure, together with the compatibility of semiconductor processing steps with polymer films, is of crucial importance in extending semiconductor device geometries into the submicron region.

## 1.2 Lithographic Strategies

Integrated circuit fabrication requires a method for forming accurate and precise patterns on silicon substrates. These patterns delineate the area for subsequent doping and/or internal interconnection. As mentioned earlier, this is currently done by photolithography and is shown schematically in Figure 5. The photolithographic process consists of (a) producing a mask carrying the requisite integrated circuit pattern information for a given level and (b) subsequently transferring that pattern, using some optical technique into a photoactive polymer known as a resist. Typically, ultraviolet light in the wavelength region 350 — 430 nm is used with a variety of exposure techniques to be discussed later. Diffraction considerations limit the size of the individual elements to about 1  $\mu\text{m}$ , and new lithographic strategies will be required to achieve the dimensions and overlay accuracies required for future generations of devices. Several strategies are currently being pursued

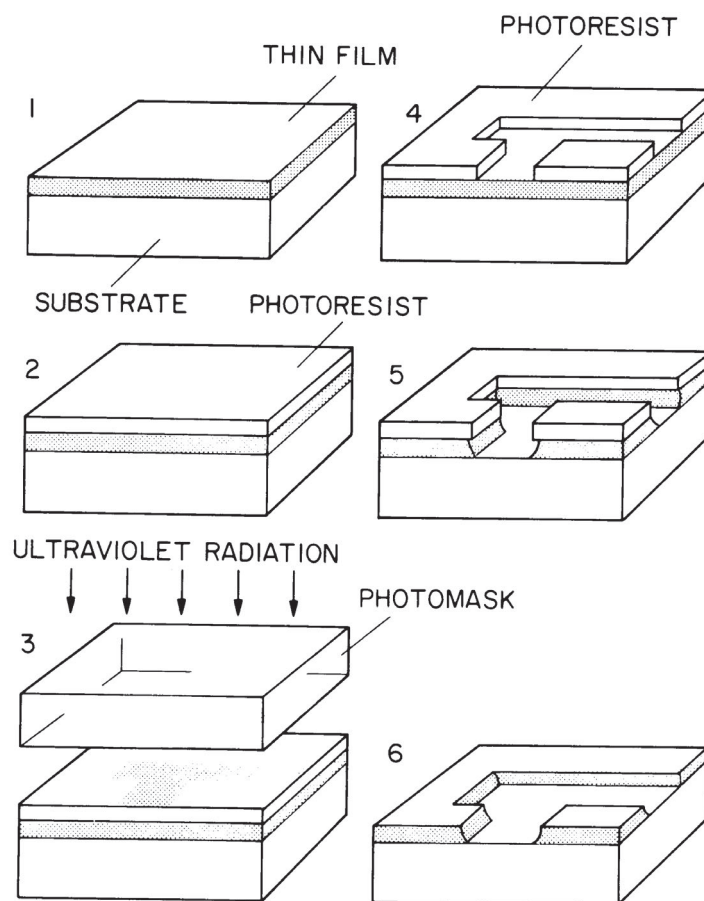


*Figure 5. A typical photolithography process*

to achieve this goal. These include: short wavelength photolithography (8-10), electron beam lithography (11-17), x-ray lithography (18-20) and ion beam lithography (27-30). The final choice as to which strategy will be adopted will depend not only on the capabilities in terms of performance, resolution and registration accuracy, but also on the cost effectiveness involved in manufacturing integrated circuits. At the present time, the lithographic process contributes only a small fraction (less than 10%) of the cost of a finished device. However, if a lithographic technology that requires large capital investments in exposure equipment with low throughput is chosen, the lithographic process could become a dominant fac-

tor in the cost of submicron devices. Each of the potential lithographic strategies has its own inherent limitations which must be evaluated; these include resolution, registration accuracy, throughput, capital investment in exposure hardware, and others.

*1.2.a Photolithography.* The most common photolithographic technique is contact printing (8). This involves holding a mask just off the wafer surface and visually aligning the mask to the previous pattern on the wafer. This process is known as registration or alignment. After alignment is achieved, the mask is pressed into hard contact with the resist coated wafer which is then exposed through the mask with a flood beam of ultraviolet light. A modification of this technique is to maintain a space between the mask and the wafer. This technique, known as soft contact printing or proximity printing (21-23), minimizes mask/wafer damage caused by contact, but at the expense of resolution. A recent development in photolithography is the technique known as projection alignment, in which the mask image is projected onto the wafer through a reflective optical system (8,24,26). This technique improves mask lifetime and decreases defect densities because intimate contact between the wafer and mask is not required. Because wafers are increasing in size every few years, a continuing problem is the task of designing optics that can form an accurate image over larger and larger areas. Another photolithographic technique which has been developed involves exposing a smaller area (on the order of 1 sq. cm.) and stepping this pattern over a large — diameter wafer. This technique (known as step-and-repeat photolithography) improves resolution and alignment accuracy.

The minute size of the features that can be formed using photolithography is ultimately limited by the *wavelength* of the exposing radiation. Current photolithographic techniques can routinely reproduce geometries a few microns across, and it is likely that dimensions as small as 1  $\mu\text{m}$  can be produced using step-and-repeat photolithography. The resolution achieved by these photolithographic techniques can be improved by using shorter wavelength UV light.

*1.2.b X-ray Lithography.* In many laboratories x-ray lithography has been investigated as a possible replacement for photolithography. X-rays with a wavelength of a few angstroms used in an exposure format similar to contact or proximity photolithography have been used to fabricate features as small as 0.02  $\mu\text{m}$  (27,30). Since x-ray lithography allows exposure of the entire wafer, the process is potentially inexpensive. However, many problems still exist, including the fabrication of stable x-ray masks, alignment, and the availability of suitable, commercially available resist systems.

*1.2.c Electron Beam Lithography.* Electron beam lithography is a mature technology, which developed from scanning electron microscope developed in the early 1960's (31-36). Systems for electron beam exposure are very similar to scanning electron microscopes although the complexity of data transfer and computer-control systems needed for electron beam writing machines results in a cost of several million dollars per machine. Electron beam writing is capable of submicron pattern definition and is used currently by many companies to manufacture specialty, high-resolution devices. It is also used for the fabrication of photomasks that are used with one-to-one and step-and-repeat projection photolithographic systems. The principal drawback of electron beam lithography is low throughput coupled with high capital cost. However, progress in this field continues at a rapid pace, and no doubt less expensive, higher throughput machines will be developed in the next two decades. Two major advantages of electron beam lithography are (a) its ability to register accurately over small areas of a wafer and (b) lower defect densities. The latter advantage results from the lack of a need for intermediate masks.

*1.2.d Ion Beam Lithography.* Ion beam lithography has been investigated recently by several workers (18-20). Compared with electron beam lithography, it offers the advantage of improved resolution (ions are scattered much less than electrons during passage through the resist) as well as lower resist sensitivities. The hardware for this technique is similar to that of an electron beam exposure system, the major difference being the source. Before this technique can be competitive with electron beam lithography, however, advances must be made in the areas of high brightness sources and high speed deflection systems.

In subsequent chapters we will briefly review the limitations and advantages of each of these technologies, and we will relate the advantages and disadvantages specifically to the resist and subsequent processing that must be employed to utilize each of these technologies.

### 1.3 Resist Materials and Processes

Two families of photoactive and/or radiation-sensitive materials have been described in the literature: organic and inorganic. The inorganic materials, described several years ago by Yoshikawa and co-worker (37,38), are based on silver-sensitized chalcogenide glasses and are sensitive to almost all forms of actinic radiation. These materials offer considerable promise for photolithography and have been described in detail by Tai et al. (39). Organic materials are generally polymeric in nature, with properties tailored for a specific lithographic technology. This book will deal exclusively with organic-based radiation-sensitive materials that are used in lithographic processes.

Photoresist and photoengraving processes have been described and used in industry for well over 100 years. In 1826, W. H. F. Talbott received a British patent (No. 565) on a photoetching process used to

engrave copper. The resist material was gelatin, sensitized with a bichromate salt; ferric chloride was the etchant. In 1852, J. N. Niepce discovered that certain types of asphalt were sensitive to ultraviolet radiation, and he applied these materials successfully to the etching of pewter and other decorative metals. In the ensuing years, many natural products (including protein, shellac, starches, and carbohydrates) were sensitized with dichromate and bichromate salts. These materials were all negative-acting resists (7,40).

In 1958, P. J. Griess discovered that aromatic orthoquinone diazids would undergo reactions when exposed to ultraviolet light. Almost 100 years elapsed before these materials were used in positive acting resist systems. In the early 1920s, Kalle and Company, AG in Germany, and its American subsidiary Azoplate Corporation developed the first positive-acting photoresist based on novolac resins and quinone diazid photoactive dissolution inhibitors (41). Originally this work was aimed at the fabrication of lithographic plates, and only later were these systems applied to microcircuit manufacturing. It is interesting to note that the basic chemistry and formulations have undergone little change over the ensuing years and that these resist systems still constitute the "workhorse" materials of the semiconductor industry.

The first modern day negative photoresists were developed by the Eastman Kodak Company which utilized cyclized rubbers and cinnamic acid derivatives as photosensitive crosslinking agents (42). The first commercially important photoresist based on this chemistry was known as KPR, which was of a cinnamate ester of polyvinyl alcohol. It was introduced by Kodak in 1954.

Before the invention of the planar transistor, many photoresist processes were developed for the manufacture of circuit boards. Experience gained in this area was rapidly transferred to silicon processing, and much of the early work in integrated circuit lithography can be traced directly to circuit board manufacturing.

The basic concepts employed in early photolithography, both in materials and processing, have been extrapolated to modern lithographic technologies including x-ray and electron beam. In the remainder of this book we will discuss in detail the fundamental principles of chemistry and physics as they apply to the design and use of resist materials.

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