Chapter 1

Photomask Technology

1.0 Introduction:

The modern age is the age of electronics. Electronics as we know would not exist without semiconductor devices. Semiconductor devices make it possible to perform the basic functions of switching and amplification.

Development of chips and microelectronics has revolutionized the whole world. Major part of this development has taken place since 1970s. Development of integrated circuits was a major milestone in history of mankind and electronics, which paved the way for current advancements. Smart Electronics and chips are replacing bulky electronics systems, and this trend will continue. The functional capabilities of all of today’s electronic devices, depends on key internal semiconductor components or ICs used in them. The ICs are manufactured through a pattern transferring process called Photolithography, which uses precision master templates called photomasks. The ability to provide IC manufacturers with sets of perfect photomasks for each device they produce is the determining factor in keeping pace with the electronics industry’s quest to shrink ICs and other related products ever smaller. Photomasks are defect-free optical templates that serve as printing masters for the fabrication of all ICs. Since invention of integrated circuit in 1959 at Texas Instruments, photomask fabrication has become an integral part of semiconductor wafer production. Starting out as simple 1X-magnification optical stencils, photomask fabrication technology has continued to advance with the needs of high-end semiconductor wafer production. Photomask fabrication was relatively straightforward, till IC features were larger than the wafer exposure tool’s source wavelength; however, when IC feature sizes fell below the exposure tool’s source wavelength, photomask fabrication moved into middle of the critical path of future IC business success. Global photomask production is a moderate-scale industry by annual revenue measures. Mask fabrication equipment is expensive and specialized and the market for new equipment is very small. It is not easy for manufacturers of mask fabrication systems to justify economically the large development effort to make significant changes in their technology. Masks are generated from an electronically
stored original pattern. Direct writing lithographic technique is used to create the pattern on mask blank coated with photoresist. Both, Electron beam and LASER beam mask writers are commonly used for fabricating photomasks.

1.1 Global scenario:

The revenue of the global semiconductor industry has reached from US$ 244 billion in 2005 to US$ 350 billion in 2014, making it one of the largest manufacturing industries in the world. The cost of materials used in chip fabrication is high. In 2005 global semiconductor market was US$ 215 billion, semiconductor equipment market was US$ 24 billion, Photolithography tools/Mask equipment/Resist materials/Masks/RET software market was 12.7 billion US$ and the mask market was 2.5 billion US$ [1]. The value of fabrication (wafer fab) materials was US$ 14 billion. Among them, microlithography formed 30% of the total materials expenses: photoresists cost US$ 1.5 billion and photomasks US$2.7 billion. As per SEMI, the worldwide semiconductor photomask market will grow modestly from $3.1 billion in 2013 to $3.3 billion in 2015 [2]. With $3.1 billion in revenue in 2013, photomasks represent 14 percent of the total wafer fabrication materials market, behind silicon and semiconductor gases. In addition, captive mask shops, which have gained market share at merchant suppliers’ expense, accounted for 49 percent of the total photomask market in 2013, up from 42 percent in 2012.

1.2 Microlithography:

Microlithography, also called photolithography is a critical process which transfers integrated circuits or device patterns onto wafers for fabricating the requisite devices/chips. Conventional microlithography has three important parts: (a) photomasks which have the patterns for various circuits; (b) photoresists that are sensitive to certain kind of radiation, such as laser, electron etc., that can faithfully replicate the photomask patterns and act as etching masks in subsequent etching processes; and (c) exposure tools, such as steppers and mask aligners. Microlithography is the key technology in micromachining and micro fabrication, because it is repeated in a process sequence that depends on the IC and device designs. It determines the device dimensions, the production yield and the manufacturing cost. Fig. 1.1 presents a schematic of a photolithographic process sequence.
Microlithography

The fabrication of an integrated circuit (IC) requires a variety of physical and chemical processes performed on a semiconductor (e.g., silicon) substrate. In general, the various processes to make an IC fall into three categories: film deposition, patterning, and semiconductor doping. Films of both conductors (such as polysilicon, aluminum, and more recently copper) and insulators (various forms of silicon dioxide, silicon nitride, and others) are used to connect and isolate transistors and their components. Selective doping of various regions of silicon allows the change in conductivity of silicon with application of voltage. By creating structures of these various components millions of transistors are fabricated and wired together to form the complex circuitry of a modern microelectronic device. Fundamental to all of these processes is lithography, i.e., the formation of three-dimensional relief images on the substrate for subsequent transfer of the pattern to the substrate.

The word lithography came from the Greek *lithos*, meaning stones, and *graphia*, meaning to write. It means quite literally writing on stones. In the case of semiconductor lithography (also called photolithography) our stones are silicon wafers (and other substrates) and our patterns are written with a light sensitive polymer called photoresist. To build the complex structures that make up a transistor and the many wires that connect the millions of transistors of a circuit, lithography and etch pattern transfer steps are repeated at least 10 times, but more typically are done 20 to 30 times to make one circuit. Each pattern being printed on the wafer is aligned to the previously formed patterns and slowly the conductors, insulators, and selectively doped regions are built up in planar fashion to fabricate the final device.
The importance of lithography can be appreciated in two ways. First, due to the large number of lithography steps needed in IC manufacturing, lithography typically accounts for about 30 percent of the cost of manufacturing. Second, lithography tends to be the technical limiter for further advances in feature size reduction and thus transistor speed and silicon/device area. Obviously, one must carefully understand the trade-offs between cost and capability when developing a lithography process. Although lithography is certainly not the only technically important and challenging process in the IC manufacturing flow, historically, advances in lithography have accelerated advances in IC performance and cost.

Optical lithography is the photographic process by which a light sensitive polymer, a photoresist, is exposed and developed to form three-dimensional relief images on the substrate. In general, the ideal photoresist image has the exact shape of the designed or intended pattern in the plane of the substrate, with vertical walls through the thickness of the resist. Thus, the final resist pattern is binary: parts of the substrate are covered with resist while other parts are completely uncovered. This binary pattern is needed for pattern transfer since the parts of the substrate covered with resist will be protected from etching, ion implantation, or other pattern transfer mechanism.

The general sequence of processing steps for a typical photolithography process [3] is as follows: substrate preparation, photoresist spin coating, prebaking, exposure, post-exposure baking, development, and post-baking. Stripping (removal of photoresist) is the final operation in the lithographic process, after the pattern has been transferred.

1.2.1 Photomask: the backbone of Lithography

The photomasks are essentially the design of chips or electronic circuits/devices on a glass plate. These are fabricated using photolithography technique. However, the illumination mechanism is different. The photomasks are used in the Lithography equipment to transfer the pattern from mask to the wafer. These are basic requirements for fabricating electronic devices or integrated circuits. The pattern transferring process involves use of photoresist, the solubility of which changes after exposure in a developer. In the case of the standard diazonaphthoquinone (DNQ) positive photoresist, the photoactive compound (PAC), which is not soluble in the
aqueous base developer, gets converted to indene carboxylic acid on exposure to UV light. The carboxylic acid product is soluble in the basic developer. Thus, a spatial variation in light energy incident on the photoresist causes a spatial variation in solubility of the resist in developer.

Contact and proximity lithography are the simplest methods of exposing a photoresist through a master pattern called photomask (Figure 1.2). Contact lithography offers high resolution (down to about the wavelength of the radiation), but practical problems such as mask damage and resulting low yield make this process unusable in most production environments. Proximity printing reduces mask damage by keeping the mask a set distance above the wafer (e.g., 20 µm). Unfortunately, the resolution limit is increased to greater than 2 to 4 µm, making proximity printing insufficient for today’s technology. By far the most common method of exposure is projection printing.

Figure 1.2 shows the basic Lithographic printing in semiconductor manufacturing.

In Projection lithography an image of the mask is projected onto the wafer. Projection lithography became a viable alternative to contact/proximity printing in the mid-1970s when the advent of computer-aided lens design and improved optical materials allowed the production of lens elements of sufficient quality to meet the requirements of the semiconductor industry. In fact, these lenses have become so perfect that lens defects, called aberrations, play only a small role in determining the quality of the image. Such an optical system is said to be diffraction-limited, since it is diffraction effects and not lens aberrations which, for the most part, determine the shape of the image.

There are two major classes of projection lithography tools – scanning and step-and-repeat systems. Scanning projection printing, pioneered by the Perkin-Elmer company, employs reflective optics (i.e., mirrors rather than lenses) to project a slit of light from the mask onto the wafer as the mask and wafer are moved simultaneously by the slit. Exposure dose is determined by the intensity of the light, the slit width,
and the speed at which the wafer is scanned. These early scanning systems, which use polychromatic light from a mercury arc lamp, are 1:1, i.e., the mask and image sizes are equal. Step-and-repeat cameras (called steppers for short) expose the wafer one rectangular section (called the image field) at a time and can be 1:1 or reduction. These systems employ refractive optics (i.e., lenses) and are usually quasi-monochromatic. Both types of systems are capable of high-resolution imaging, although reduction imaging is required for the highest resolutions.

Scanners replaced proximity printing by the mid-seventies for device geometries below 4 µm. By the early 1980s, steppers began to dominate as device designs pushed below 2 µm. Steppers have continued to dominate lithographic patterning throughout the 1990s as minimum feature sizes reached the 250 nm levels. However, by the early 1990s a hybrid step-and-scan approach was introduced by SVG Lithography, the successor to Perkin-Elmer. The step-and-scan approach uses a fraction of a normal stepper field (for example, 25mm x 8mm), then scans this field in one direction to expose the entire 4 x reduction mask. The wafer is then stepped to a new location and the scan is repeated. The smaller imaging field simplifies the design and manufacture of the lens, but at the expense of a more complicated reticle and wafer stage. Step-and-scan technology is the technology of choice today for below 250 nm manufacturing. Various Scanners and steppers use different techniques for exposing a large wafer with a small image field as shown in Fig. 1.3.

Resolution, the smallest feature that can be printed with adequate control, has two basic limits: the smallest image that can be projected onto the wafer, and the resolving capability of the photoresist to make use of that image. From the projection imaging side, resolution is determined by the wavelength of the imaging light (\(\lambda\)) and the numerical aperture (NA) of the projection lens according to the Rayleigh criterion:

\[
R \propto \frac{\lambda}{NA}
\]
Lithography systems have progressed from blue wavelengths (436 nm) to UV (365 nm) to deep-UV (248 nm) to mainstream high resolution wavelength of 193 nm which is commonly used today. In the meantime, projection tool numerical apertures have risen from 0.16 for the first scanners to amazingly high 0.93 NA systems which are used today to produce features well under 100 nm in size.

1.3 Photomask: definition and types:

According to the type of image transferred to the substrate, photomasks can be categorized into two groups: binary and grayscale photomasks. The image transferred from a binary mask to the substrate is a 2-dimensional (2D) structure, while the image from a grayscale mask is 3-dimensional (3D). In this thesis, the context is limited to Binary masks only. Binary photomasks consist of two types of image regions: opaque and transparent areas. Opaque and transparent, both areas have spatially constant transmission so that the light intensity does not change after shining through them: light is either completely blocked or transmitted. Binary photomasks are normally used to expose substrates which are in focus. This kind of photomask has been and will still be widely used in micromachining and microfabrication, and the importance of photomasks in both industries is growing. For example, binary photomasks have been widely used together with mask aligners for the past four decades to produce integrated circuits/chips.

Definition: A mask/photomask is essentially design of an electronic circuit on a glass plate. A photomask is the pattern transferring artifact [4]. As per another definition [5], “these are precision glass plates having microscopic images of electronic circuits”. These are of different types as enumerated below.

1.3.1 Photomask types:

Masters and reticles

The photomasks are either Masters or reticles. The Masters are the masks (1X), which are used without reduction. The Reticles are used with reduction. These are generally 4X. The pattern printed on wafer in Reticles is 4 time reduced, while in Masters, the pattern printed on wafer is as the size of mask [5].
Based on pattern type (bright field / dark field) A mask basically contains geometries or features of different geometrical shapes. There can be lines, rectangles, circles etc. A mask is either bright field or dark field. In bright field mask, the background is bright (transparent); it means the features are opaque. The CD in case of a bright field is opaque (dark). In dark field mask, the background is dark (opaque); it means the features are transparent. The CD is bright (transparent) in case of a dark field mask.

BF and DF patterns are illustrated in Fig.1.4.

Based on technology (emulsion, LASER and e-beam)

Masks/photomasks can be classified based on technology of fabrication. Emulsion masks are produced by a photographic process. The resolution is 5 micron and these masks are prone to scratch, so life is limited. LASER pattern generators can also be used for fabricating Chrome-on-glass (COG) masks. These have resolutions upto 0.25 µm and good life. E-beam writers can also be used for fabricating masks. These have high resolution and good life as these are also fabricated on COG blanks.

Based on resolution (high, medium, low)

The masks can also be classified based on resolution. E-beam masks have high resolution (few nm), LASER pattern generator masks have intermediate resolution (upto 0.25 µ and emulsion masks have low resolution (upto 5 µm).

New generation masks : The Phase shift masks

In an effort to extend the lives of expensive wafer exposure tools, resolution enhancements came in the form of a phase-shift mask (PSM). The term phase shift applies to the incident radiation in a wafer exposure tool relative to the radiation that has undergone a change in phase due to either the lack of, or addition of the photomask material. An unaltered phase area where an incident wave travels is
called a “0° phase” region, and an area of a photomask that has been \( p \)-phase shifted is called a “180° phase” region. There are two major categories of PSMs—alternating aperture phase-shift masks (AAPSM) and embedded attenuated phase-shift masks (EAPSM).

From a material’s standpoint, the alternating aperture class of PSM is built from a standard chrome-on-glass (COG), or binary photomask blank. No special materials are used since the action of phase shifting is accomplished by removing portions of the fused silica substrate by means of a wet or dry etch. So in the AAPSM case, phase shifting the incident exposure radiation is accomplished by removing material (glass) in strategically selected areas in order to enhance feature resolution. Conversely, EAPSM masks rely on the properties of an added film to accomplish the desired phase shift. These films allow a small percentage of the incident exposure radiation to “leak” through so as to enhance the resolution capabilities of the exposure tool beyond what was possible with binary photomasks. The actual transmission percentage of films varied during development phases in the i-line (365-nm) stepper era, but became standardized at 6.0 percent with its widespread adoption during the KrF (248-nm) scanner era. In all cases, the phase-shifting film needed to be designed such that it inverted the phase of the radiation it passed 180° relative to the radiation traveling through the transparent substrate nearby. The film of choice for both the KrF and ArF (193-nm) eras is molybdenum silicide oxinitride (MoSiON). Overall stoichiometry of MoSiON EAPSM films varies by the blank supplier and needs to be changed globally if the film is deposited in a homogeneous manner, or individually if a bilayer approach is used. The requirement, regardless of film composition, is to achieve the 6.0 percent transmission target while simultaneously causing a 180° phase shift in the leaked or transmitted radiation relative to the incident wave. Experimental EAPSM absorber materials have been created to provide transmissions much greater than 6.0 percent while still maintaining 180° phase-shifting properties.

1.4 An overview of Photomask technology:

Jack Kilby invented the first integrated circuit in 1958 at Texas Instruments, USA. Bell Labs also developed the oxidation, photomasking, etching and diffusion processes that underline IC production to this day. Planar technology set the stage for complex integrated circuits and is the process used today [6]. Masks are precision
glass plates having microscopic images of chips or electronic devices. These are the pattern transferring artifacts. Masks are the backbone of modern lithography and IC/Chip fabrication processes.

Prior to the 1960s, electronic devices were manufactured by soldering discrete components together to form the desired electrical circuits and, ultimately, the desired electronic components or products [7]. The result was the creation of a working device, albeit primitive by today’s standards, regarding number of functions, physical size, amount of power consumed, quantity of heat generated, ergonomics, and degree of control via user interface, to name a few categories. During this time period, the ubiquitous vacuum tube had also recently been replaced by the transistor, the adoption of which resulted in a huge reduction in electronic device size and heat load. Moreover, governmental and consumer populations were demonstrating their desire for even better, smaller, faster devices by funding the research and then buying the resulting products at an ever-growing rate. The semiconductor industry had begun. Even though transistors were a vast improvement over vacuum tubes, electrical devices still comprised discrete components, until the invention of the integrated circuit in 1959. With this invention, the need for a multistep microlithographic process that had the ability to transfer an entire circuit pattern onto a semiconductor substrate was evident. Leveraging the ability to design and build all components (such as resistors, capacitors, and transistors) on a single piece of semiconductor material (such as silicon and gallium arsenide) using common process steps allowed for the manufacture of much smaller and less expensive devices. So, shortly after semiconductor device physicists came up with clever ways to ion-dope silicon and to connect and insulate p and n regions to form unique electrical components, another group of individuals created a process for producing high-quality optical patterns used to transfer circuit pattern layers onto these semiconductor materials. Without these master circuit layer patterns, called photomasks, no microchip could be built using a microlithographic process, and the electronics industry as we know it would not exist. In the beginning, photomasks were not much more than optical stencils used to transfer patterns for single layers of semiconductor devices onto the semiconductor substrate material. Today, the resolution and image placement specifications required of photomasks have essentially turned them into removable transmissive elements in the wafer exposure tool’s optical path. This is an enormous change from 40 years ago, and has spawned
new fields of study such as design for manufacturability (DFM), new technologies such as complex resolution enhancement techniques, and countless feature CD uniformity and linearity improvement programs. To make matters worse, the photomask defect tolerance is zero at printable severity since it serves as the master from which all device patterns are printed in the lithographic process. A single defect on what is called a single-die photomask could result in printing nothing but zero-yielding devices. So, not only must all of the pattern features be of the correct size, position, transmission, and phase, but there must also be absolutely no printable contamination or flaws in the pattern plane either, such as dirt particles, stains, smudges, and scratches. Optical element specifications and the requirement for zero printable defects make building photomasks very different from building the actual electrical devices.

In the early 1960s, all companies wishing to produce semiconductor devices (later called microchips) needed to start from scratch. Managers in each manufacturing company assigned a small group of people to create a process line to produce its very first photomasks. The term “mask shop” was coined as these small, separate groups within each larger semiconductor manufacturing company were leveraged to supply the master patterns for all integrated circuits (ICs) being built. To establish these processes, early mask shop pioneers were challenged to select the most suitable substrate and absorber materials and then select or even build the requisite equipment that could produce these photomasks. Following the stencil analogy, the absorber material needed to block exposure radiation while the substrate material needed to allow 100 percent of it to pass.

At this early stage, photomask manufacturing was a manual process performed by a skilled few. The masking material, called Rubylith, was the principle design medium used to transfer the circuit pattern to the photomask itself. Rubylith was made up of two thin sheets of plastic adhered to each other. The base layer was a stiff, scratch-resistant plastic that was transparent to the green light used in the subsequent photomask exposure process.
The absorber layer was a red-colored plastic that absorbed green light, rendering it opaque under exposure. So the first “advanced” design work station consisted of a light table, masking tape to hold the Rubylith in place, a hobby knife, and a straight edge. Designs were trace cut by hand using the hobby knife and straight edge, and then the red plastic was peeled off leaving the red-on-clear circuit pattern (Fig. 1.5).

The Rubylith pattern was then reduced and replicated via a photoemulsion coating (sensitive to green light) on a thin piece of glass by photoreduction camera. This piece of glass was called a reticle and was an intermediate component toward making the final photomask. The remaining steps were accomplished by reducing and replicating the high-magnification image from the reticle to an emulsion layer on another glass plate. After photoemulsion development, the final product was the photomask (Fig. 1.6). The reduction ratio was such that whatever scale the design was cut originally was reduced via intermediate process steps to the desired semiconductor device size (1X). Once the photomask was built, the Rubylith and reticles were no longer needed technically. They were stored in case of irreparable photomask damage so another copy could be made. This damage did come occasionally from careless blunders of course, where the photomask was inadvertently scratched or even broken into pieces, but it also occurred from normal use on high-running IC devices. The reason was that early photomasks were used in a contact printing process. The mask was placed in a contact printing exposure tool, photoemulsion side down, and then pressed against the photoresist coating of a semiconductor wafer for exposure. After exposure, the photomask was lifted off the wafer, ready for another wafer exposure. Since the photoemulsion material was not very durable for this type of process, multiple copies of the photomask had to be made from the reticle to avoid excessive yield degradation from wafer to wafer.

Making multiple photomasks proved costly, so stronger materials were sought out to replace the photoemulsion layer. Ultimately, chromium was selected for its durability to physical contact and for its optical density to exposure radiation. To
further reduce costs, direct writing of the photomask via electron beam exposure tools came into existence in the late 1970s. Laser tools were also introduced in the 1980s as an alternate photomask writing method to e-beams. By writing the photomask in one step, all the other costly intermediate steps were eliminated. The need to store RubyLith and glass reticles was replaced with electronic file backups, and photomask fabrication cycle time decreased due to the fewer number of process steps. These masks had severe limitation of minimum dimension that could be fabricated on it. Moreover, these had limited shelf life and were prone to scratches and damages.

Photomask substrate requirements include both physical and optical properties and must be tightly controlled since the photomask serves as the master copy for all subsequent pattern exposures. There is very little room for error regarding these physical and optical qualities. Optically, the material must be transparent at the wafer exposure tool's wavelength and must have minimal reflectivity as well. Many different glass and crystalline materials have been used over the years, such as soda lime glass, white crown, quartz, and various grades of fused silica. Today, the standard photomask substrate material used for advanced lithographic applications is amorphous fused silica. This material possesses high transmittance and low reflectance at the actinic (commercial exposure) wavelength, in addition to possessing superior physical properties. When the photomask was used as a proximity printing master in the 1980s, or even as a 5X reduction element in the 1990s, requirements for flatness and rigidity of glass substrate were fairly loose by today's standards. In these cases, the photomask substrate could be large but relatively thin (7.0 in. × 7.0 in. × 0.15 in., for example). When the exposure tool industry moved to a 4X reduction scenario at the same time when the wafer pattern features required to be printed were near the actinic wavelength size, the photomask substrate needed to maintain its shape without sagging. Sagging errors caused by the mounting arrangement in typical wafer exposure tools manifest themselves as pattern position errors on the wafer that can lead to unacceptable yield loss. By increasing the photomask substrate thickness to 0.25 inch in this example, the mask substrate became more rigid, meaning that there was less sag and therefore less pattern position error.
When designs pushed the limits of 1X lithographic capability, a decision was made to increase the magnification factor across the industry to 5X on the newly developed wafer stepper. At the same time, the photomask size was standardized at 5.0 in. × 5.0 in. × 0.09 in. Any size or placement error on the photomask was also reduced by the magnification factor. This was very beneficial to the photomask maker as many of the errors seen on the photomask were unresolvable after the image was reduced in size by five times. Specifications on the equipment needed to build 5X photomasks could also be relaxed. The period of time that 5X wafer exposure tools were used was called the “mask maker’s vacation.” The only downside to making the change from 1X to 5X was that chip designers would have to restrict their maximum design size to 5X compared to the space available on a photomask under 1X wafer lithography conditions.

When device design sizes became too large to fit on the 5-inch photomask substrate, and the need for a more rigid substrate was evident, the industry again made a move to accommodate data. Wafer exposure tool companies standardized on a new magnification and a larger photomask substrate size. The magnification went back from 5X down one step to 4X, and the substrate size went up in both side length and thickness to 6.0 in. × 6.0 in. × 0.25 in. These two factors, in addition to the ever-tightening pattern fidelity specifications ended the “vacation” enjoyed by the mask industry. Pattern errors were now reduced by only 4X instead of 5X—a 20 percent loss in margin. To add to that, the area covered by the patterns increased on the new larger substrate, which forced the requirement to maintain all pattern specifications over this larger area as well.

Early photomask pioneers used different types of opaque absorber materials to either paint or tape the first primitive patterns onto small thin pieces of glass, which were used as contact print templates for semiconductor devices. As the industry evolved, chromium (or chrome) was selected as the standard binary intensity mask (BIM) absorber material for its durability and optical properties. The chrome absorber layer went through several developmental morphologies where thickness and reflectivity were adjusted until it reached a form in the 1980s that held fairly constant through the end of the century. The chrome absorber is actually a stacked film comprised of roughly 20 percent chrome oxide antireflective (AR) layer on top of the remaining 80 percent pure chromium. The industry standard thickness became about
1050 Å, which meant that the stack component thicknesses were roughly 800 Å and 250 Å for the chrome and chrome oxide AR films, respectively.

The key technology breakthrough in mask fabrication during 1960 to early 1970s was migration to hard surface (COG) photomask. Other significant development of this period was a tool called ‘Optical pattern generator’, which produced 10X reticles directly on emulsion glass substrate. In mid 1970s, the need for mask with longer lifetime became apparent to the industry. Due to increase in device complexity, it became difficult for Optical pattern generators to fabricate the reticle. A faster method was required for writing reticles, and thus born was the e-beam writer called Manufacturing Electron Beam Exposure System (MEBES), which was developed at Bell Lab and commercialized by ETEC Corporation in late 1970s. The raster scan MEBES Systems remained the major mask-making tool for critical masks till end of 1990s. The throughput of e-beam writer was always an issue. To increase the throughput, LASER pattern generators were introduced in mid 1980s. LASER systems provided higher throughput, better reliability and lower cost of ownership as compared to e-beam system, while e-beam systems provide better resolution. The earliest LASER pattern generators exposed the mask with a single focused LASER beam that moved over the surface of photomask. Bell Labs and Micronic LASER Systems AB, made early developments in the 1970s. To increase the throughput, Heidelberg and ETEC Systems introduced the use of multiple beams writing different parts of the pattern in parallel. Raster scan pattern generators thus became the workhorses of the mask shops. This technology is mature, stable and fast. The systems presently in use are the ALTA series from ETEC Systems and Omega series from Micronic LASER Systems AB. The three major players manufacturing LASER Pattern generators presently are Micronic LASER Systems AB, Sweden, Heidelberg Instruments, Germany and Planar Concern, Minsk (Russia). The technology nodes have changed rapidly over the years as shown in Fig. 1.7.

Fig. 1.7: Change in technology nodes over the years
Photomasks are required to meet strict quality norms, as the yield of chips/devices are dependent on them [8, 9]. Systematic experiments over few trial runs do provide the valuable input for developing appropriate processes/technology. Suitable pattern features provide information regarding resolution, Critical Dimension (CD) and other parameters [10-12]. The characterization of resist is essential for fabricating desired size of geometries [13-14]. Adequate dose of exposing light is necessary to get the designed pattern on mask plate [15, 13]. Chrome etching is an important process that determines mask features. It is carried out by two methods-wet (chemical) and dry (plasma) processes. Depending on nature of photoresist and etch rate, a suitable chrome etchant is used for fabricating masks. Excellent process control is essential for fabricating masks.

Inspection of masks for correct critical dimension (CD) and quality evaluation is an essential requirement in mask fabrication cycle [16, 17]. It is important to minimize variations in CD across a mask. The results of process variations are verified after inspection and analysis of results. Reduction of errors is a key component of whole fabrication process [18].

Photomasks are integral components in the lithographic process of Semiconductor manufacturing. Conventional photomasks are made of high-purity quartz or glass plates containing precision images of integrated circuits. They are used as masters to optically transfer these images onto substrates coated with photoresists. IC chips are manufactured layer by layer, and each layer requires a unique photomask. Fig 1.8 Shows the role of mask in IC fabrication process.

Steppers typically reduce the mask image by 10 or 5x, thus mask feature sizes are 5x larger than those on the wafers. As exposure wavelength has got reduced: from l-line (365 nm) to deep-UV KrF-excimer laser (248 nm), ArF-excimer laser (193 nm) and F2 laser (157 nm); mask magnification has been reduced from 5x to 4x to cope with increasing chip size. Six-inch-square, 0.25-inch-thick quartz plates are commonly used in steppers for both l-line and KrF exposure.

Fig. 1.8: The mask in IC fabrication process
A mask blank consists of an opaque film on a substrate. Sodalime and Quartz are generally used as substrate materials. Quartz is usually used as a substrate material due to its high transmission at wavelengths shorter than UV (Newport Crystal quartz has 85% transmission at 175 nm wavelength [19], its low thermal expansion coefficient (0.52x10^{-6}/K), and its chemical stability. The opaque film should have an optical density OD > 3 (less than 0.1% transmission). The optical density is defined as shown below:

\[ OD = -\log_{10}(T) \]

where, T is the transmission of the material. An optical density larger than 3 implies that the transmittance of the light is less than 0.1%. The opaque film is also required to have the following properties [20):

- High chemical stability
- High durability against irradiation
- Strong adhesion to the substrate
- Moderate electrical conductivity
- Ease of preparation and patterning

Of all the materials with these properties, chromium and its compounds are those most widely used [20-23]. Pure Cr has high reflectance on both the film side and the glass side of a photomask, which causes problem due to stray light. To solve this problem an anti-reflection coating (CrO_x) is used on one side of the Cr film, as shown in Figure 1.9.

The manufacturing process of conventional photomasks is similar to that of the microlithography and etching of silicon wafers shown in Figure 1.1, which involves many of the same steps such as resist coating, exposure, development, resist patterning etching, etc. The masks are generally fabricated in LASER Pattern Generator. Masks involving small dimensions are fabricated using Electron Beam Lithography System. In chip fabrication, the exposure is done using a Mask aligner...
(using visible or UV light), however, Mask fabrication is carried out using by using a LASER or Electron beam. The equipment are also modified form of wafer/chip fabrication equipment. The masks are required to be free from defects and should meet CD requirements, thus there are stringent quality requirements for masks. This is important as the mask may affect the yield.

Figure 1.10 shows a typical process flow for the fabrication of a photomask. The design data which is prepared in an Electronic Design Automation (EDA) software is checked, verified and augmented by adding features and converted/transformed to exposure machine readable format. This converted data is then transferred to exposure equipment and mask fabrication process is started. The Chrome blanks are loaded in exposure equipment and exposure is carried out. Post exposure, the mask plate is developed and subsequently the chrome is etched. Finally, the resist is removed by process called stripping. The inspection and measurement of critical dimension is carried out after each process step to ensure defect free masks. The finished mask is handed over to users for device fabrication by Lithography process.

The process (chemical processing) as shown in Fig above is shown in Fig.1.11. The resist coated Chrome blank is the basic raw material for mask fabrication. It has multilayered structure. On glass is a layer of Chromium which is patterned as per data. On top of it is a layer of Chrome oxide, which an anti-reflecting layer. At the top is a thin layer of photoresist. The mask plate is exposed as per data. After exposure, a latent image of pattern is created in photoresist. The next process step is development. The exposed resist gets dissolved in
developer in case of positive resists and now pattern becomes visible. The next step is etching of chromium. This is done either by wet etching (using a Chrome etchant solution) or dry etching (using chrome etchant gases). Once the chrome layer has been patterned, the remaining photoresist is removed by stripping by putting mask plate in stripper solution. The stripping can also be done by dry process. Finally, the mask is inspected for quality and cleaned if required.

The need for photomasks was born out of the semiconductor industry in which each photomask contained the pattern information for a single layer of a device. The end product produced by these photomasks was a microchip. Of course these microchips were then utilized by the entire electronics industry for computational, timing, data storage, and many other applications. These basic functions have now been applied to a host of products in both commercial and military applications. Basically, almost everything today that plugs into a wall or runs off battery power contains microchip technology, built by photoimaging the mask patterns onto silicon wafers. One can see then the importance of the role of the photomask in the history and continuance of the semiconductor industry itself.

Throughout the evolution of semiconductor industry, devices were invented or eventually shrunk to sizes beyond the capabilities of the macroprocessing techniques employed, and the photolithographic process was leveraged as the means by which to fabricate them. Wave guides, flat panel displays, optical gratings used in the photonics industry, thin-film heads for computer disk drives, microelectromechanical systems (MEMS), and now even biotechnological applications utilize photomasks for any photoimaging processes required in their fabrication. As long as optics is the means by which devices are patterned and mass produced, photomasks will have a place in their fabrication.

1.5 Devices:

The modern day society uses a variety of devices for various applications. In early days, the devices/chips were fabricated for computer memories and flash memory storage. The technology has made it possible to have a large number of devices on a single chip. The applications are from commercial mobile phones, communication systems to the strategic GaAs devices for Military and Space applications, RADAR components, Surface Acoustic Wave (SAW) devices for
sensing and communication applications. In the perspective of this thesis, the SAW devices are considered.

1.5.1 SAW devices:

Surface Acoustic Waves (SAW) based devices have wide range of Military and Civilian applications. These devices are mostly used as filters, oscillators and transformers, as they offer capabilities unattainable by any other technology. In civilian applications, SAW devices are used in TV receivers, Cellular and cordless phones, Cellular phone base stations and cable TV equipment. These devices are also used as sensors for automotive applications (torque and tire pressure sensor), medical applications (chemical and bio-sensors), industrial and commercial applications (vapor, humidity, temperature and mass sensors). Major military applications of SAW devices are the waveform generator and receiver modules, used in digital communication systems, ESM and RADAR systems and Satellite communication.

1.5.2 Advantages of SAW Devices:

SAW-based devices and systems have several excellent features [24], which are as follows:

- SAW devices can generally be designed to provide quite complex signal processing functions fabricated on a single piezoelectric substrate with input and output interdigital transducers within a single package.

- SAW devices can be mass produced using standard semiconductor photolithographic process. As a result, they can be made to be cost competitive in mass-volume applications.

- SAW devices exhibit outstanding reproducibility in performance, from device to device. This is especially desirable for various civil applications like channelized receiver & military applications like pulse compression radar.

- SAW devices can be packaged in small, rugged, light and power efficient modules. As a result they are finding ever-increasing application in mobile and space-borne communications systems.
• SAW devices are a link between analogue devices and digital technology. The IDT works on the principle of Transversal filter thus opening the gates for implementing digital design technology in SAW devices. As a result, these can be utilized in many digital communications systems.

• SAW filters can be made to operate very efficiently at high-harmonic modes. As a result, gigahertz frequency devices can be fabricated using relatively inexpensive photolithographic techniques, rather than the significantly more expensive processes involving electron-beam (E-beam) lithography.

1.5.3 Applications of SAW Devices:

SAW devices are designed as per the desired application. Substrate as well as the IDT design plays a major role in the device design. The IDT design accounts for signal processing and frequency response characteristics of a SAW device on a piezoelectric whereas the substrate properties govern the applications like sensors. The IDT geometries have evolved to cater for a multitude of signal processing functions. Despite the variety, transducers and device structures can be grouped under four general categories [24].

Surface-acoustic-wave signal processing is based on planar technology and the use of photolithography to define the structures. It shares this feature with semiconductor microelectronics, but differs in that it normally requires just a single photolithographic mask. The common use of masks has enabled surface-wave devices to benefit from the large advances in photomask technology made by the semiconductor industry.

Surface-acoustic-wave devices are also known for their sensitivity to various external physical factors such as, pressure, proximity of chemical substances and temperature, all of which are carefully considered in the design of filters and resonators to ensure that when exposed to the real world, they remain within specification. These characteristics of SAW devices makes them suitable to act as sensors, with applications for a wide range of sensing needs, one of the notable developing interest being the selective biosensors.

The need for superior device performance with increased stability in harsh environments like high temperatures and reliability at a reasonable cost has
compelled material researchers to investigate new materials and techniques for improving the performance of these devices.

1.5.4 SAW Principle:

The most effective SAW generator and the transducer to-date is the Interdigital Transducer referred to in the SAW literature as IDT. It consists of a series of parallel metal electrodes periodically spaced on the surface of a piezoelectric substrate (Fig. 1.12). These electrodes are usually made up of Gold (Au)/ Chromium (Cr) or Aluminium (Al). Since Au is highly inert and Cr serves as an adhesive, the Au/Cr combination is very advantageous. On the other hand, Al serves both as an inert metal as well as a good adhesive. This discovery of the IDT structure enabled relatively simple yet efficient generation and reception of SAWs and signalled a new interest in the application of acoustic waves.

IDTs made of two comb-like structures of metal electrodes photo deposited onto a precisely oriented piezoelectric substrate, act as both transmitters and receivers of acoustic waves in a SAW device. This device is bidirectional as SAWs are launched both to the left and to the right from the IDT. In its simplest form, a SAW device with IDTs and all external components (Fig. 1.12) can be modelled as one wherein, an alternating voltage $V_{in}$ applied to the input IDT facilitates the generation of mechanical waves (SAW) on the piezoelectric substrate.

SAW is launched by the input IDT and propagates to the output IDT through the free or metallized crystal surface. An output voltage $V_{out}$ is received at the output IDT due to a mechanical-to-electrical transformation (inverse piezoelectric effect) The physics and propagation of surface waves under the influence of metal IDT structures are available in the
The efficiency of an IDT transducer has been found to be maximum at the excitation frequency $f_0$. Fig. 1.13 depicts the most widely used IDT geometry configurations in a SAW device. Fig. 1.13 depicts the 'single' electrode type IDT structure. Fig. 1.13 (b) shows the 'double' or 'split' electrode type IDT structure. Fig. 1.13 shows the specialized 'split' electrode apodized IDT with dummy fingers. In these diagrams, $\lambda$ is the periodicity or the uniform electrode spacing of the IDT structure. It also corresponds to the IDT centre frequency of operation $'f_0'$ and is given by $\left(\lambda = \frac{v_0}{f_0}\right)$ where $v_0$ is the SAW velocity on a free piezoelectric surface.

$'W'$ is the aperture of the device or the finger overlap in an IDT.

$\eta = \frac{a}{b}$ is called the metallization ratio and is a very important parameter in design. Here 'a' is the metal width of an IDT finger and 'b', the combined metal cum finger spacing. For single electrode geometry (Fig.1.13(a)) it is found that the finger spacing and width are equal to $\lambda/4$ whereas for the split electrode geometry (Fig. 1.13 (b)) the finger spacing and width is $\lambda/8$.

1.6 Types of SAW Devices:

Even though there exist scores of commercially available SAW devices that cater to multifarious needs and applications, the important guiding principle exploited in most of these devices is the slow speed of SAW on a piezoelectric substrate while propagating between IDTs, which being nearly $10^5$ times lesser than EM waves. The reduction in SAW velocity makes it easy to sample and perform signal processing operations in both the time and spatial domains. This ultimately leads to significant miniaturization in physical dimensions. Typically the surface area of a SAW device is only a few square millimeters. There are numerous SAW devices, but in this thesis, SAW devices that are relevant to research (delay lines and resonators) only are discussed. Fig. 1.14 shows schematics of a delay line.
1.6.1 Resonators:

A resonator is based on the principle of standing waves formed on the surface of piezoelectric material. A one-port SAW resonator consists of one IDT with reflective gratings on either side (Fig. 1.15). These reflective metallic gratings are placed in an array such that their spacing is \( \lambda/2 \). Even though the reflection coefficient of each line is small, the reflected waves are in phase leading to a large cumulative effect of the whole array.

Experience has shown that this principle of reflective gratings can be used to produce moderately high Q (Quality factor) resonators as these can be used to form a resonant cavity around an IDT source-receiver pair. Since the grating is sharply resonant compared to the IDT, it gives rise to a sharp resonant spike superimposed on the broad maximum IDT insertion loss curve. Moreover, as SAW devices are inherently small and rugged, high operating frequencies limited to the present day’s micro fabrication facilities, can be achieved.

A two-port SAW resonator consists of two IDTs with reflective gratings on either side (Fig.1.16).

1.7 SAW based sensors and gas sensors:

Acoustic wave devices have been in commercial use for a long time. Telecommunication industry is the largest consumer. Several applications of Surface acoustic waves (SAW) devices are for sensor application as torque and tyre pressure, chemical sensors, vapor, humidity, temperature and mass sensor [26]. Advantages of SAW sensors are their low cost, ruggedness, sensitivity, reliability. Some have the capability of being passive and wireless interrogation.

SAW devices can be used to monitor/sense gases and organic solvents, if these are coated with a material which selectively adsorbs molecules from air [27-
Use of SAW devices for detection/sensing of Chemicals/ explosives/chemical warfare agents (Sarin through DMMP) has been an active area of study [31-39]. In a SAW based chemical sensor, either a delay line or a resonator is inserted into feedback loop of a two port oscillator, whose frequency then depends on the number of molecules adsorbed. A delayline is the simplest structure made of two inter-digital transducers (IDT). For IDT, located sufficiently far apart, the free substrate surface between them offers uniform adhesion conditions for the chemically sensitive coating.

The resonators in contrast have small attenuation than most delay lines and do not need any matching. The oscillator design is simple as compared with delay line in terms of phase change.

The elements of SAW reflection gratings comprise of periodic discontinuities. These consist of open thin metal strips. The no. of strips required for near total reflectivity depends on reflection mechanism. In case of dominant piezoelectric shortening e.g. Lithium niobate substrate, total reflection is achieved by few metal strips. In case of dominant mass loading e.g. ST-quartz substrate of, a few thousand grating elements are required to achieve a reflection coefficient close to unity. To keep device size realistic, SAW resonator designs on quartz substrates are normally used for frequencies above 100 MHz.

SAW sensors operate at frequencies of MHz to low GHz range to measure physical, chemical or biological quantities. Their high sensitivity makes them attractive for chemical vapour detection and gas sensing. In many cases, the output of these sensors is a frequency, which can be measured simply with an electronic counter. With proper design, these sensors can be quite stable permitting a large dynamic range to be realized.

The basic structure of a SAW gas sensor consists of a SAW delay line connected in the feedback path of a suitable amplifier resulting in a delay line stabilized SAW oscillator. For use as a gas sensor, the propagation path of the delay line is coated with a thin film of a suitable material (the chemical interface or membrane), which can selectively sorb the gas of interest. Sorption of gas results in a change in the time delay of the delay line and thereby in the frequency of the oscillator. Thus, the sensor is essentially an oscillator whose frequency is modulated by the gas concentration. Attractive features of the SAW chemical sensor include high sensitivity, wide dynamic range, direct digital (frequency) output, and potentially
low cost due to fabrication compatibility with silicon microelectronic circuits. The delay line works on the principle of travelling surface waves.

The gas sensing can also be achieved by using a resonator. The resonator works on the principle of standing surface waves.

1.8 Conclusion:

The chapter introduces the masks/photomasks and global scenario. The principle of microlithography is explained specifying role on mask/photomask in it. Different types of masks are explained. An overview of evolution of photomask technology has been provided. The processes for photomask fabrication are explained. The introduction of Surface acoustic wave devices is given, along with advantages, principle and applications. Types of SAW devices (delay line and resonator) are described for gas sensing applications.
1.9 References:


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