1. Introduction

Optical lithography is the process of creating specific patterns on semiconductor wafers using photosensitive material (known as photoresist, PR) and an ultraviolet light exposure system to transfer the patterns on the mask to the wafer. Processes with direct patterning on the wafers are also possible, such as directly writing on the wafer with an electron beam or a laser beam, but at this time none are in use for high-volume semiconductor manufacturing.

Optical lithography technology determines the smallest transistor dimensions which can be manufactured on a semiconductor chip. As such, it has been the primary driver for the remarkable improvements in performance and reduction in cost per function, the hallmark of the microelectronics industry. Optical microlithography involves the practice of multiple disciplines: physics, chemistry, and engineering specialties [1]. During this module, students will learn the basic principles of optical microlithography, chemistry of the photoresists, and pattern replicator instruments.

2. Photolithography Theory

2.1. Photoresist Composition

Photoresist (PR) is a radiation – sensitive compound that can be classified as positive or negative, depending on how it responds to radiation. For positive resists, the exposed regions become more soluble and are thus more easily removed in the development process. The net result is that the patterns formed (also called images) in the positive resist are the same as those on the mask. For negative resist, the exposed regions become less soluble, and the patterns formed in the negative resist are the reverse of the mask patterns [2] as shown in Figure 1.

Figure 1: Negative and positive photoresist [3].
Positive photoresists consist of three components: a photoactive compound (PAC), a base resin, and an organic solvent. Prior to exposure, it is insoluble in the developer solution; after development, the exposed areas are removed. Negative PRs are polymers combined with a photosensitive compound. After exposure, the photosensitive compound absorbs the optical energy and converts it into chemical energy to initiate a polymer cross-linking reaction as in Figure 2. This reaction causes cross-linking of the polymer molecules. The cross-linked polymer has a higher molecular weight and becomes insoluble in the developer solution. After development, the unexposed areas are removed. One major drawback of a negative PR is that in the development process, the whole resist mass swells by absorbing the developer solvent. This swelling action limits the resolution of negative PRs [2].

![Image reversal process and related chemistry of a negative photoresist](image)

**Figure 2: Image reversal process and related chemistry of a negative photoresist [4].**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion to Silicon</td>
<td>Fair</td>
<td>Excellent</td>
</tr>
<tr>
<td>Relative Cost</td>
<td>More Expensive</td>
<td>Less Expensive</td>
</tr>
<tr>
<td>Developer Base</td>
<td>Aqueous</td>
<td>Organic</td>
</tr>
<tr>
<td>Solubility in the developer</td>
<td>Exposed region is soluble</td>
<td>Exposed region is insoluble</td>
</tr>
<tr>
<td>Minimum Feature</td>
<td>0.5 μm and below</td>
<td>2 μm</td>
</tr>
<tr>
<td>Step Coverage</td>
<td>Better</td>
<td>Lower</td>
</tr>
<tr>
<td>Wet Chemical Resistance</td>
<td>Fair</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

Table 1 Comparison of positive and negative photoresists [13]

The polymer is the backbone of the PR. The most common polymers used in the semiconductor and MEMS industries are:

- Poly(methyl methacrylate) (PMMA),
- Poly(methyl glutarimide) (PMGI)
- Phenol formaldehyde resin (DNQ/Novolac),
- SU-8 (epoxy).
Note that every PR has its own instruction manual (datasheet or recipe) generally provided by its manufacturer. However, it is necessary for every laboratory to test the recipe offered by the manufacturer and create its own recipe adapted to the specific laboratory conditions (i.e. temperature, humidity, particular process interests and equipment characteristics). A general flow chart of the microlithography process can be seen in Figure 3. The students are encouraged to review some websites of PR manufacturers and vendors, such as the ones suggested in Section 8 of this module.

![Flowchart of the photolithographic process](image)

*Figure 3: Flowchart of the photolithographic process. The post-exposure and hard-bake steps can be omitted, depending on the process [1].*

Prebake/Soft Baking is done to remove excess solvents from the photoresist coatings. It is a crucial step in photolithography and the photoresist coatings become photosensitive only after this step. Prebaking for too long will degrade the photosensitivity by reducing solubility in developer. Exposure of positive photoresists is incomplete when considerable solvent remains.

Post-exposure bakes are carried out to enhance performance of the process. This is done to chemically amplify resists, crosslink negative resists, for highly reflective substrates, and for mechanical relaxation.

Hardbaking step is carried out after development to improve thermal stability of relief pattern. Chemical and physical stability of developed resist structures are also improved.
2.2. Optical Lithography

Photolithography is the process of transferring patterns of geometric shapes on a mask (or reticle) to a thin layer of PR covering the surface of a semiconductor wafer. The resist patterns defined by the lithography process are not permanent elements of the final device, but only replicas of circuit features [2]. The pattern transfer process is accomplished by using two kinds of lithography exposure tools: Pattern Generators and Pattern Replicators.

A pattern generator is an exposure tool that accepts pattern input data from a database and directly creates a physical image on a wafer using beams of either charged particles or photons. These tools are used extensively to create photomasks and reticles for pattern replicators. They are also used in limited volume for direct patterning on semiconductor wafers.

The main disadvantage in using pattern generators for general purpose high-volume lithography is the slow imaging on the wafer. The required patterning density is on the order of $10^{13}/\text{cm}^2$ discrete pixels for 65 nm. The achievable speeds for electron or photon pattern generators are less than 1010 pixels/s, leading to imaging rates of no more than one 200 mm wafer per hour. The general rule for economical semiconductor production requires a wafer patterning tool to process on the order of 100 wafers per hour or higher, and existing direct pattern generators simply cannot come close to achieving this speed [1].

![Typical high-pressure mercury-arc lamp spectrum](image)

*Figure 4: Typical high-pressure mercury-arc lamp spectrum.*
The solution to the throughput limitation of pattern generators is to create a master pattern image in the form of a photomask or reticle and then replicate the pattern in a massive parallel fashion onto wafers. Photomasks consist of a fused-silica substrate covered with a chromium layer [2]. Photomask fabrication is performed with electron beam and photon beam tools, while repair of mask pattern defects is performed with ion beam and photon beam tools.

Pattern replicators use a variety of image transfer techniques, including photons and charged particles. The most common pattern transfer agent is a well-conditioned beam of monochromatic photons in the wavelength range from 193 to 436 nm. The first practical step-and-repeat imaging tools used the so-called G-line of mercury, at 436 nm wavelength. Second generation stepper tools used the I-line of mercury, at 365 nm (see figure 4). In our lab, we also use the I-line. More recently, as the need for higher resolution drove the requirement for wavelength down, mercury arc lamps were replaced by excimer lasers. The lasers provide both very high intensity and very narrow bandwidth. The most common laser in use today is the KrF laser at 248 nm wavelength. The most advanced exposure tools in semiconductor manufacturing employ an even shorter wavelength, 193 nm, from the ArF excimer laser [1].

2.3. Image Resolution and Depth of Focus

The relationship of wavelength to image resolution and depth of focus in a projection optical system has been understood for more than 100 years. The simple relationship defined by the so-called Rayleigh equations is:

\[ l_m = k_1 \frac{\lambda}{NA} \]

Where \( \lambda \) is the exposure wavelength, \( k_1 \) is a process-dependent factor, and \( NA \) is the numerical aperture, which is given by:

\[ NA = \bar{n} \sin \theta \]

Where \( \bar{n} \) is the index of refraction in the image medium (usually air, where \( \bar{n} = 1 \)), and \( \theta \) is the half-angle if the cone of light is converging to a point image at the wafer, as shown in figure 5. Also shown in the figure is the Depth of Focus (DoF), which can be expressed as:

\[ DoF = \pm \frac{l_m}{2 \tan \theta} \approx \pm \frac{l_m}{2 \sin \theta} = k_2 \frac{\lambda}{NA^2} \]

Where \( k_2 \) is another process-dependent factor [2].
2.4. Exposure Methods.

Pattern Replicators can be classified by two exposure methods: shadow printing and projection printing. Shadow printing may have the mask and wafer in direct contact with one another (contact printing) or in close proximity (proximity printing), as illustrated in Figure 6. In this module, we will use the contact printing method. As shown in Figure 6a, in contact printing a resist-coated wafer is brought into physical contact with a mask. Resist is then exposed with a nearly collimated beam of ultraviolet light through the back of the mask for a fixed time.

The intimate contact between resist and mask provides a resolution of approximately 1µm. It is important to realize that the contact printing suffers a major drawback caused by dust particles. The imbedded particles cause permanent damage to the mask and result in
increasing defects in the wafer with each succeeding exposure [2].

3. References


8. Recommended Websites