

Module 11: Photolithography

Lecture11: Photolithography - I

11.0 Photolithography Fundamentals

We will all agree that incredible progress is happening in the field of electronics and computers. For example, only a few years back we had bulky and heavy laptops and few hundred GB memories was the state of art. In contrast, we now have slim, light weight devices such as i-pads and notebooks, we have Terabyte memory, Smart Phones that provide most of the functionalities of a personal computer etc., to name a few. Have you ever wondered what really makes this phenomenal progress happen? In fact you will be surprised to know that it is a patterning technique called Photolithography which is at the back of such phenomenal progress. The idea is very simple. A semi conducting chip in the simplest form is an array of P – N junctions, which can be realized from the animation shown in figure 10.1A. Consequently, it can also be understood that higher is the number of such junctions on a chip, faster will be its performance or higher will be the storage capacity. Now in case the width of each P and N type domain remains the same, the overall size of the chip would increase, which is not desired. Thus, the desired target is to pack more number of chips without altering the overall size of the chip, which becomes possible only when the individual domain size of each of the P and N type zones (known as “line width”) can be narrowed down. This is aptly reflected from the fact that line width diminished from $\sim 10 \mu\text{m}$ in 70’s to about 200 nm in early 2000. In fact for a intel I7 core processor, the line width now is down to approximately 32 nm. Till date, the development in this field has been at part with the Moore’s law, which defines a long-term trend in the progress of computing hardwires. It is worth highlighting that this stupendous progress in the field had only been possible due to progress in Photolithography. Therefore, it becomes important to have some what in depth idea about the method itself, particularly as this course talks about surface nano patterning in particular. Spread over the following five chapters, we discuss the essential concepts of photolithography in a very simple manner, which should be easily understandable for a student with undergraduate level knowledge in Chemical Engineering. As the name suggests (“Photo”), the technique uses “light”, which is achieved by using a special class of polymeric

material known as photo resist. We start our discussion with brief introduction about Photo Resists and follow it up with some what detailed, step by step discussion on the process of photolithography.

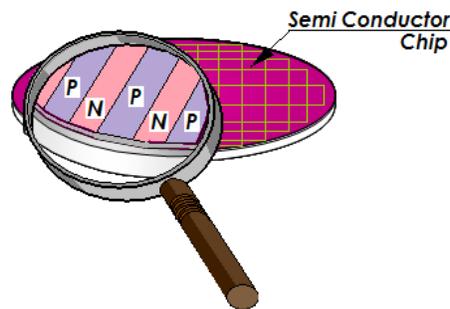


Figure 11.1: Simplified structure of a Integrated Circuit Chip.

11.1 Photo Resists

We get started with the general concept that in Photolithography, a surface is first covered with a layer of photo sensitive polymer called photo lithography. It is then exposed to “light”, which in most cases is UV light, using a photo mask. The Photo mask contains the desired final pattern drawn on it. In essence, the mask allows the light to pass over certain areas, while prevents it on other areas. This essentially results in some parts of the photo resist layer getting exposed to light, while other parts remain unexposed (figure 10.2). As we already understand that a photo resist layer undergoes changes in “property” (what exact property, we will discuss later) upon exposure to light, we understand that the UV light exposure leads to some sort of a chemical contrast between parts of the photo resist film over which light has fallen and areas over which light was prevented from falling by the mask. In essence, this contrast in property is exploited to generate the patterns. We would also like to highlight that the word Photoresist (PR) comes from the combination of photosensitive and acid resistant. Why acid resistance is necessary will become clear during the detailed discussion of the process.

Now the question that should come to your mind at this point is what type of contrast in chemical property gets generated between the exposed and unexposed parts of the photo resist film? The easiest way to think would be, whether the parts on which light falls become structurally harder

or weaker. As we have already mentioned that photo resists are essentially polymers, the easiest way to co-relate the two cases would be if there is possible cross linking between the long chain molecules or if there is chain scission due to exposure to light. In fact, both the situations are possible, and photo resists are classified in to two categories (Photo Resist Tones), based on how they respond to optical exposure. In the event a photo resist layer gets hardened (or insoluble) upon exposure, the resist is called a Negative Photo resist. The opposite happens for a Positive Photoresist, where the exposed resist becomes weaker (or soluble). With this much amount of understanding now let us try to learn some more basic aspects about Photo Resists.

In addition to photo sensitivity, several other properties are essential for a material to be used as a Photoresist for patterning. Some such essential properties are:

1. Possible to coat a surface with the materials, and the coating must be in the form of a thin, uniform, pinhole free film.
2. The coated film must exhibit superior adhesion to the underlying substrate and does not lift or peel off during subsequent processing.
3. The PR layer must exhibit high sensitivity to the wavelength of radiation utilized for exposure.
4. Developing – The PR film must exhibit a significant contrast in terms of solubility between the exposed and unexposed areas without pattern distortion, during the stage of development.
5. Should exhibit significant resistance towards subsequent processes such as plasma etch, high dose ion implantation, wet etching etc.
6. Finally, the PR layer should dissolve and can be removed before the doping stage.
7. The PR film should exhibit significant Thermal stability and must be able to withstand bake processes without pattern distortion.
8. The coated PR layer must be stable enough to be stored for reasonable periods of time.

From the stand point of chemistry, a photoresist typically consists of three major components.

They are:

1. **A Polymer base**, which is the backbone of the photoresist. During exposure and development the polymer is the major constituent of the patterned photoresist film.
2. **A Photo Active compound (PAC)**, which is the constituent of the photoresist that undergoes Structural modification when exposed to light. It is the PAC that gives the photo sensitive property to the photo resist.
3. **Solvent**: Typically this is added to the PR just before coating so that it can uniformly spread over the substrate.

Further, depending on how the Photo Resist Property changes upon exposure to light, Photoresist may be classified as negative or positive photoresist. These are called **Photo Resist Tones**.

Figure 10.2 clearly demonstrates the difference between these two tones.

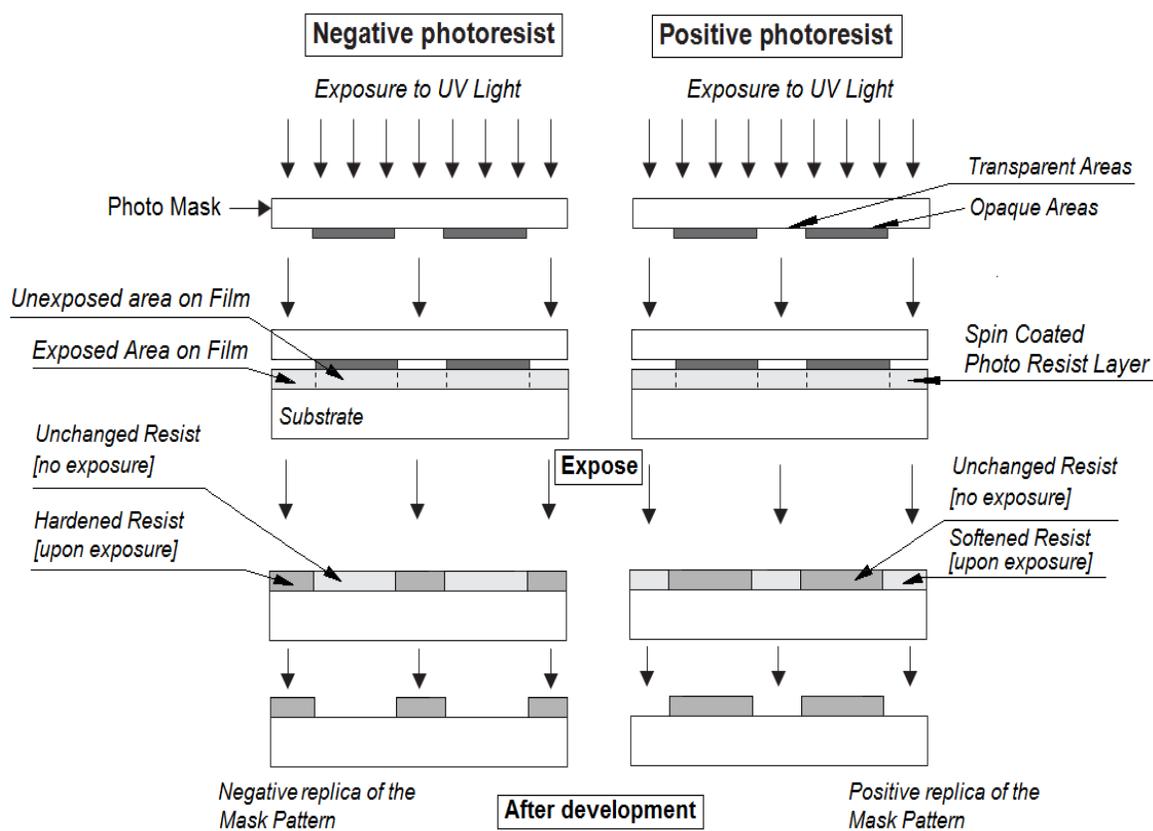


Figure 11.2: Schematic of the two different Photo Resist Tones

A Negative photoresist is inherently relatively developer soluble until exposed to light, when it becomes hardened and the exposed portion exhibits decreased developer solubility. In contrast, a Positive Photoresist is relatively developer insoluble until exposed to light at which point the exposed portion exhibits increased developer solubility. As can be clearly understood from figure 10.2, a negative replica of the mask pattern is obtained on a Negative photo resist layer. In contrast, a positive replica of the mask pattern is obtained on a layer of positive PR upon exposure to UV light. It is worth highlighting that the first commercial photoresist for semiconductor production was a negative photoresist - Kodak Thin Film Resist (KTFR). It was widely used in the semiconductor industry from 1957 until approximately 1972 when minimum dimensions reached approximately 2 μm . The base polymer in KTFR is a cyclized poly(cis-isoprene) of molecular weight of $\approx 150,000$. Photoresist properties such as photo-speed, adhesion and thermal behavior depend significantly on the cyclization process. High molecular weight cyclized rubber exhibits greater photo sensitivity but has poorer adhesion and is more difficult to develop. Cyclized rubber does not absorb light above 300 nm, which is a desirable property in a photo resist. Further, a photo resist should not undergo significant cross linking under ultraviolet (UV) exposure.

Historically, by 1972 the limitations of negative photoresist were reached. Subsequent developments were all based on positive photo resists. Majority of the commercial resists used are based on Diazonaphtho- quinone/novolac (DQN), which uses novolak based resin. Apart from the mere functionalities, there is some additional critical difference between a negative and a positive photo resist, particularly in terms of developing. This difference is in fact responsible for obtaining much finer features with a positive resists, which is elusive in a negative resist. A negative photo resist uses a solvent based development process, where the unexposed, weaker portions of the resist layer simply dissolve in the developer solution. However, this approach has several problems. One major problem is the polymer (both exposed and unexposed) swell when it comes in contact with the developer solution. Further, after developing, the photoresist is

rinsed with a solvent which is miscible with developer but not with the polymer. The rinsing step halts developing and reduces the photoresist swelling. However, the final photoresist pattern gets distorted by some extent during developing and ultimately this limits the resolution of negative photoresist. The problem of swelling induced distortion of pattern geometry can be understood from figure 10.3.

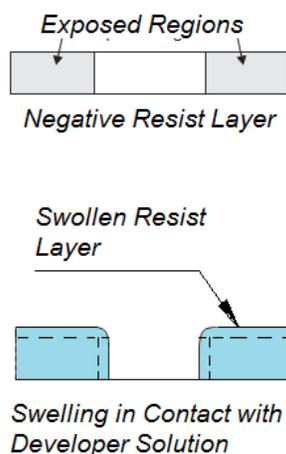


Figure 11.3: Swelling of a Negative Photo Resist in presence of a solvent

The development of a DQN based positive photoresist is fundamentally different from a negative photoresist. In contrast to a dissolution based mechanism in a negative photoresist, developing is a chemical etching reaction in a positive resist.

It is also important to note that a large number of additives are added in commercial photoresist formulations to achieve various functionalities. For example, dyes are added to mask discoloration of the resist during storage, surfactants are added to improve coating uniformity, and a variety of additives are used to improve adhesion, heat resistance, dry etch resistance, photo speed etc. Recent developments in the area of Photoresists include the development of a chemically amplified photoresist, which offer much higher sensitivity than the conventional ones. In a chemically amplified photoresist, a catalytic specie generated during exposure causes a cascade of subsequent chemical reactions to occur.

10.2 Some critical Photo Resist Parameters

There exist several important parameters that quantify the performance of a photoresist. Some of these parameters are:

Dose to clear (E_0): It is a measure of the sensitivity of the photoresist. The lower is the dose to clear, higher is the sensitivity of the photoresist for a given thickness and exposure wavelength. High sensitivity photoresists are advantageous for high productivity, as expose more rapidly for a given exposure source intensity.

Gamma (γ): It is a measure of how good the contrast is between the exposed and unexposed regions to produce an image. Higher γ results in sharper patterns.

Thickness loss: it is a measure of the change in photoresist thickness following develop in the unexposed regions of the photoresist.

Finally, the following table gives some comparison between a typical positive and a negative resist.

Table 11.1: Comparative properties of Positive and Negative Photo Resist

Property	Positive PR	Negative PR
Adhesion to Si	Fair	Excellent
Relative Cost	More	Less
Developer Base	Aqueous	Organic
Minimum Resolution	0.5 μm	2.0 μm
Step Coverage	High	Lower
Wet Chemical Resistance	Fair	Excellent

Reference:

1. Scotten W. Jones, "Photolithography", IC Knowledge LLC. 2008.