Lithography:
the process, and the effects of
diffraction, interference, and numerical aperture

Group Activity #2
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February 17, 2004
Introduction

Lithography is a process used to create integrated circuits (ICs). ICs are commonly made using optical lithography (also called photolithography), which uses ultraviolet light to expose the desired IC patterns onto a semiconductor wafer. Though other types of IC lithography exist, such as ion beam, electron beam, and x-ray lithography, their basic principles and processes are similar.

The physical laws of light and optics determine the precision and accuracy of a lithographic device; and the device’s precision and accuracy determine the minimum feature size of the IC. Therefore, the effects of diffraction and interference of light waves, and the numerical aperture of lenses are critical factors in creating more dense integrated circuits.

The Lithographic Process

Figure 1. A lithography device [International Society of Optical Engineering]

The basic components of an optical lithography device are a prepared silicon wafer, a light source, an illuminator, a mask, and a lens. Figure 1 shows an optical lithography device. First, the silicon wafer is cleaned and covered with a barrier layer, usually of silicon dioxide (SiO₂), and a photoresist layer. The silicon wafer is the substrate on which the IC is built, and photoresist is a photosensitive polymer that becomes soluble when exposed to light. The prepared wafer is then soft baked to set the layers and remove solvents.

The lithographic tool’s light source provides wavelength-limited light to the illuminator. The illuminator is composed of mirrors and light pipes which shape the light to the necessary spatial uniformity and intensity across the
surface of the mask. The mask is a plate, usually quartz, with the pattern of a desired layer of IC sketched in chrome, like a stencil. Several masks are used to create the different layers and features of the IC. The light is changed into patterns of lighter and darker areas as it passes through to mask to the lens. The mask must be carefully aligned with the silicon wafer for proper transfer of the pattern to the silicon wafer.

The lens focuses and resolves the patterned light image into a smaller image, usually one-quarter the size of the mask. This smaller image is reflected on the photoresist surface of the silicon wafer. The parts of the photoresist exposed to light are washed away, leaving exposed and unexposed regions that match the pattern on the mask. The wafer is then hard baked to set the remaining photoresist. The unexposed regions are protected from the next step, in which the SiO₂ layer is removed by etching from the exposed regions. Then the remaining photoresist is removed. This entire process, from preparing the silicon wafer to etching and photoresist removal, is repeated with several masks to create the different layers of an IC. Figure 2 shows a flowchart of the lithographic process.

Figure 2. Flowchart of the lithographic process [Jaeger, p. 18]
Optics, Light, and Technological Limits of Lithographic Tools

The physical laws of optics and light play a critical role in determining the precision and accuracy of lithographic devices, and hence sets the limits to minimum feature size of an IC. By adjusting the lithographic technology to counteract or take advantage of the effects of diffraction, interference, and numerical aperture, lithographic device creators aim to create smaller IC feature sizes.

**Diffraction**

Diffraction is the property of light that is best demonstrated using the pinhole experiment. When light is directed towards a surface with a pinhole cutout, the light that emerges from the other side is not focused into a beam the size of the pinhole. Instead, the light spreads into an image that becomes larger and more diffuse as the distance from the pinhole increases. Figure 3 shows this experiment.

![Diffraction Experiment Diagram](image)

**Figure 3. Diffraction experiment** [Delpierre & Sewell]

Diffraction is a concern in photolithography, because the mask, with its stencil pattern of lines and holes, becomes a diffraction grating. So, the light image that passes through the mask diffracts into a larger image. This is a problem since minimizing feature size is a goal for IC fabrication.

To minimize feature size, we need a minimum size mask. However, smaller apertures result in an increase in diffusion. To counteract this, the wavelength of light used is minimized. This relationship is called the diffraction limit. In effect, the minimum feature size is directly proportional to the wavelength of light. Over time, semiconductor equipment makers have steadily decreased the light wavelengths used in lithographic systems from 365 nm in the...
1980s to 193 nm today. Using resolution enhancement techniques (RETs), these systems produce ICs with feature sizes of 100 nm.

**Interference**

Interference is another property of light that presents a challenge to lithography. Interference is best demonstrated by a similar experiment in which light is directed toward a surface with two pinhole cutouts. The two light beams that emerge from the pinholes each spread out into larger images which overlap each other. Because light has wave properties, the two light waves form constructive and destructive interference patterns. See Figure 4.

![Figure 4. Interference experiment.](image)

Again, the mask serves as a diffraction grating. So, the light that passes through the mask is split into many separate light beams which interfere with each other, creating a pattern on the wafer surface that differs from the pattern on the mask. Because interference increases as the pattern of holes and lines on the mask shrinks, interference restricts feature size.

The mask can be adjusted to nullify some of the interference or its negative effects. Sophisticated software exists that changes IC designs to minimize interference effects. The negative interference effects can also be reduced by using phase shifting. By changing the phase of the light coming from two adjacent lines on the mask, the out-of-phase light waves will cancel each other out in regions where no light is wanted. This is accomplished by etching the mask to different thicknesses in different regions. Phase shifting actually takes advantage of the increased contrast between constructive and destructive interference to create sharper lines and edges on the photoresist.
Numerical Aperture

The numerical aperture (NA) of the lens used is a key aspect in determining IC feature size. NA is defined as:

\[ \sin \theta \]

where \( \theta \) is the largest angle incident on the wafer. The critical relationship between numerical aperture, light source wavelength, and feature size for optical lithography systems is summarized in the following equation:

\[ R = k\lambda/NA. \]

R is the resolution or feature size. \( k \) is a proportionality constant that is determined by several factors, including antireflective coatings above or below the photoresist, the resist’s own parameters, and the coherence of the illumination. \( \lambda \) is the light source wavelength. NA is the numerical aperture. As NA increases, the resolution decreases, decreasing the feature size; feature size is inversely proportional to numerical aperture.

To increase the NA, lens designers have created larger diameter lenses and lens elements that collect more light from the light source. In 1977, reduction-system lenses had an NA of 0.2. Currently, 0.63 is common, and 0.95 may soon by achieved in commercial systems. An ideal NA of 1 requires an impossible infinitely large lens, so researchers are experimenting with a technique already used with microscopic lenses: filling the space between the lens and wafer with a high refraction index fluid. This simulates an air-immersed lens with NA even greater than 1, creating even greater improvements in resolution.

Unfortunately, increased NA also results in reduced depth of focus. Depth of focus is the range of distances from the lens for which the image is in focus on the wafer. The variations in surface heights of the silicon wafer must be less than the depth of focus for proper treatment. Therefore, for high resolution lithography, the surface must be as flat as possible.

Summary

Moore’s Law in the electronics industry dictates that the amount of transistors that can be put on an IC will double every couple of years. By continually refining lithographic equipment technology to compensate for or take advantage of the physical properties of light and optics, semiconductor equipment companies manage to keep pace with Moore’s Law’s demands.
References


