The Formation of an Aerial Image

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Welcome to The Lithography Tutor, a new regular feature of *Microlithography World*. As the name implies, the purpose of this column is to present lithography information in a tutorial format. Each issue of *Microlithography World* will carry a two to three page edition of this continuing series on the basic principles of optical lithography. To give you a brief outline of what is to come in the next several issues, we'll begin by studying optics. How is an image formed by a projection optical system (stepper or scanner)? What is the influence of wavelength, numerical aperture, coherence, illumination? Then, we will examine how this image propagates through the photoresist (including absorption and standing waves) and exposes the resist. Finally, the properties of development will be discussed. From here, we can begin discussing lithography as a system, define what is meant by lithographic quality, and look for ways to optimize our lithography system to maximize its quality. All this in two to three pages per issue! I'm not sure how long it will take to get through all of these topics, but I'll certainly have fun writing this column. I hope you will enjoy reading it.

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Since 1973, when Perkin-Elmer first introduced their scanning projection system for lithography, optical projection of a mask pattern onto a photoresist coated wafer has become the standard method of lithographic imaging in the semiconductor industry. Today's projection tools, both steppers and the step-and-scan, are multi-million dollar systems of incredible complexity and technological achievement. The sophistication of a state-of-the-art lithographic lens today would have been unimaginable when the first stepper (from GCA) was introduced to the semiconductor industry in 1978. Is it possible for an average lithographer to understand how such systems work? Certainly! The principles of operation of a lithographic projection system have not changed in twenty years, only their implementation has.

Consider the generic projection system shown in Fig. 1. It consists of a *light source*, a *condenser lens*, the *mask*, the *objective lens*, and finally the resist-coated wafer. The combination of the light source and the condenser lens is called the *illumination system*. I will use the term "lens" the way an optical designer would: a lens is a system of (possibly many) lens elements. Each lens element is an individual piece of glass (refractive element) or a mirror (reflective element).

The purpose of the illumination system is to deliver light to the mask (and eventually into the objective lens) with sufficient intensity, the proper directionality and spectral characteristics, and adequate uniformity across the field (more on illumination systems later). The light then passes through the clear areas of the mask and diffracts on its way to the objective lens. The purpose of the objective lens is to pick up a portion of the diffraction pattern and project an image onto the wafer which, one hopes, will resemble the mask pattern.

The first and most basic phenomenon occurring here is the diffraction of light. Most of us think of diffraction as the bending of light as it passes through an aperture, which is certainly an appropriate description for diffraction by a lithographic mask. But more correctly, diffraction theory simply describes how light propagates. This propagation includes the effects of the surroundings (boundaries). Maxwell's equations describe how electromagnetic waves propagate, but using partial differential equations of vector quantities which are extremely difficult to solve without the aid of a powerful computer. A simpler approach is to artificially decouple the electric and magnetic field *vectors* and describe light as a *scalar* quantity. Under most conditions scalar diffraction theory is surprisingly accurate and shows that electric and magnetic fields do not significantly interact in typical optical situations. Scalar diffraction theory was first rigorously used by Kirchoff in 1882, and involves performing one numerical integration (much simpler than solving partial differential equations!). Kirchoff diffraction was further simplified by Fresnel for the case when the distance away from the diffracting plane (that is, the distance from the mask to the objective lens) is much greater than the wavelength of light. Finally, if the mask is illuminated by a spherical wave which converges to a point at the entrance to the objective lens, Fresnel diffraction simplifies to *Fraunhofer diffraction*.

With Fraunhofer diffraction, we have simplified the problem to the point where it may be safe to show an equation. Let us assume we know our mask pattern, and that we can describe its electric field transmittance as $m(x,y)$, where the mask is in the x,y-plane and $m(x,y)$ has in general both magnitude and phase. For a simple chrome-glass mask, the mask pattern becomes binary: $m(x,y)$ is 1 under the glass and 0 under the chrome. Let the x',y'-plane be the diffraction plane, that is, the entrance to the objective lens, and let z be the distance from the mask to the objective lens. Finally, we will assume monochromatic light of wavelength λ and that the entire system is in air (so we can drop the index of refraction). Then, the electric field of our diffraction pattern, $E(x',y')$, is given by the Fraunhofer diffraction integral:

$$E(x',y') = \int_{-\infty}^{\infty} m(x,y)\, e^{-2\pi i (f_x x + f_y y)}\, dx\, dy$$

where $f_x = x'/z\lambda$ and $f_y = y'/z\lambda$ and are called the *spatial frequencies* of the diffraction pattern.

So why show an equation in a tutorial? For many scientists and engineers (and especially electrical engineers), this equation should be quite familiar: it is simply a *Fourier transform*. Thus, the diffraction pattern (i.e., the electric field distribution as it enters the objective lens) is just the Fourier transform of the mask pattern. This is the principle behind an entire field of science called Fourier Optics (for more information, consult Goodman's classic textbook *Introduction to Fourier Optics*, McGraw-Hill). Is this Fourier transform relationship useful?

Absolutely! Fourier transforms are relatively easy to calculate, often using pencil and paper. What is more, you can usually find your answer in a table of Fourier transforms. Let's look at two examples. Fig. 2 shows two mask patterns, one an isolated space, the other a series of equal lines and spaces, both infinitely long in the *y*-direction. The resulting mask pattern functions, *m(x)*, look like a square pulse and a square wave, respectively. The Fourier transforms are easily found in tables or textbooks and are also shown in Fig. 2. The isolated space gives rise to a *sinc* function diffraction pattern, and the equal lines and spaces yield discrete *diffraction orders*.

Let's take a closer look at the diffraction pattern for equal lines and spaces. Notice that the graphs of the diffraction patterns in Fig. 2 use spatial frequency as its *x*-axis. Since z and λ are fixed for a given stepper, the spatial frequency is simply a scaled x'-coordinate. At the center of the objective lens entrance ($f_x = 0$) the diffraction pattern has a bright spot called the *zero order*. The zero order is the light which passes through the mask and is not diffracted. You can think of it as D.C. light, providing power but no information as to the size of the features on the mask. To either side of the zero order are two peaks called the *first diffraction orders*. These peaks occur at spatial frequencies of $\pm 1/p$ where p is the pitch of the mask pattern (linewidth plus spacewidth). Since the position of these diffraction orders depends on the mask pitch, their position contains information about the pitch. It is this information that the objective lens will use to reproduce the image of the mask (we'll talk more about this in the next column). In fact, in order for the objective lens to form a true image of the mask it must have the zero order and at least one higher order. In addition to the first order, there can be many higher orders, with the n^{th} order occurring at a spatial frequency of n/p.

Diffraction patterns may seem a bit esoteric if your interest lies in images printed in photoresist. However, using our knowledge of diffraction patterns, we can understand how the numerical aperture affects resolution, describe partial coherence, determine why off-axis illumination works, and understand the fundamental advantages of phase-shifting masks. But I am getting ahead of myself. In the next issue we'll propagate our diffraction patterns through the objective lens to see how an image is formed.

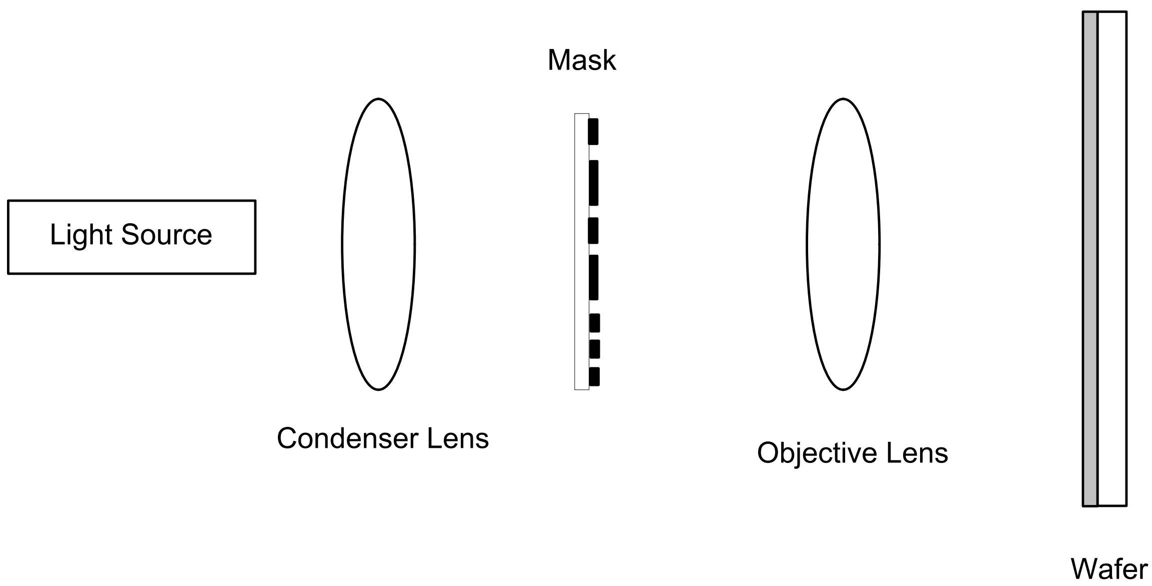

Figure 1. The basic components of a generic optical projection system.

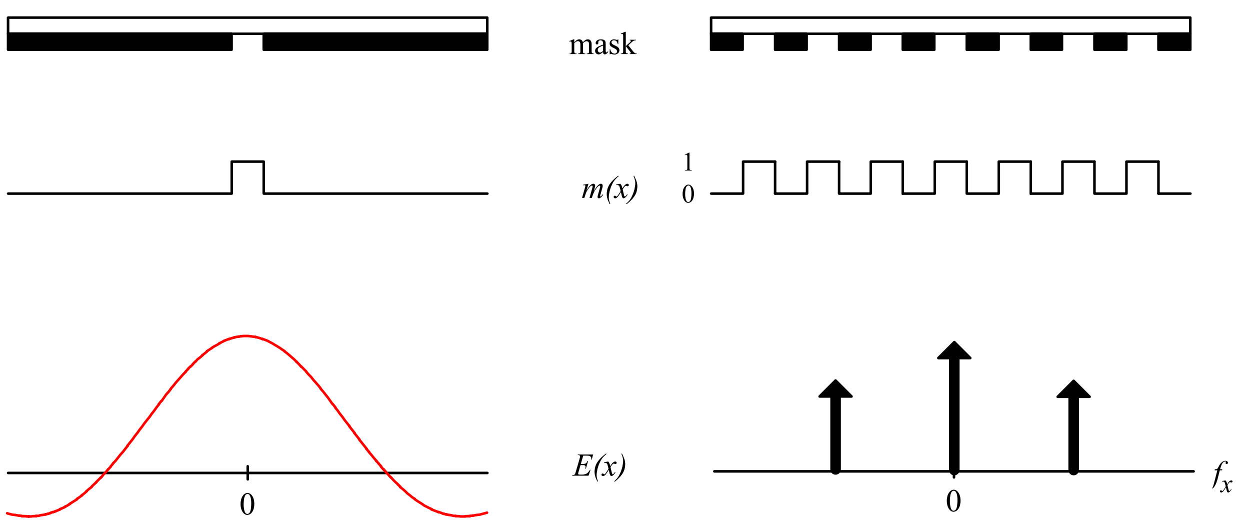

Figure 2. Two typical mask patterns, an isolated space and an array of equal lines and spaces, and the resulting Fraunhofer diffraction patterns.