The Lithography Tutor *(April 1993)*

The Formation of an Aerial Image, part 2

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In the last issue, we began to described how a projection system forms an image of a mask. The basic principle which governs the behavior of an imaging system is diffraction. Diffraction describes the propagation of light and can include the effects of various boundaries (such as the chrome edges of a mask). As we saw last time, diffraction of light by a lithographic mask can be described by Fraunhofer diffraction and the Fraunhofer diffraction integral is essentially identical to the *Fourier Transform* integral. Thus, we arrived at the very important conclusion that the diffraction pattern of a mask is the Fourier transform of the mask pattern. Given a mask in the x-y plane described by its electric field transmission $m(x,y)$, the electric field M as it enters the objective lens (the x'-y' plane) is given by

$$M(f_x, f_y) = \mathcal{F}\{m(x,y)\}$$

where the symbol $\mathcal{F}$ represents the Fourier transform and f_x and f_y are the spatial frequencies and are simply scaled coordinates in the x'-y' plane.

We are now ready to describe what happens next and follow the diffracted light as it enters the objective lens. In general, the diffraction pattern extends throughout the x'-y' plane. However, the objective lens, being only of finite size, cannot collect all of the light in the diffraction pattern. Typically, lenses used in microlithography are circularly symmetric and the entrance to the objective lens can be thought of as a circular aperture. Only those portions of the mask diffraction pattern which fall inside the aperture of the objective lens go on to form the image. Of course we can describe the size of the lens aperture by its radius, but a more common and useful description is to define the maximum angle of diffracted light which can enter the lens. Consider the geometry shown in Figure 1. Light passing through the mask is diffracted at various angles. Given a lens of a certain size placed a certain distance from the mask, there is some maximum angle of diffraction, α, which just lets the diffracted light make it into the lens. Light emerging from the mask at larger angles misses the lens and is not used in forming the image. The most convenient way to describe the size of the lens aperture is by its *numerical aperture,* defined as the sine of the maximum half-angle of diffracted light which can enter the lens times the index of refraction of the surrounding medium. In our case, all of our lenses are in air and the numerical aperture is given by $NA = \sin\alpha$. (Note that the spatial frequency is the sine of the diffracted angle divided by the wavelength of light. Thus, the maximum spatial frequency which can enter the objective lens is given by NA/λ.)

Obviously, the numerical aperture is going to be quite important. A large numerical aperture means that a larger portion of the diffraction pattern is captured by the objective lens. For a small numerical aperture, much more of the diffracted light is lost. We can examine the relationship between *NA* and the diffraction pattern by graphing the diffraction pattern (as we did in the last issue) along with a picture of the aperture. Figure 2 shows quite readily which portions of the diffraction pattern enter the lens (in this case, for a series of equal lines and spaces of pitch *p*).

To proceed further, we must now describe how the lens affects the light entering it. Obviously, we would like the image to resemble the mask pattern. Since diffraction gives the Fourier transform of the mask, if the lens could give the inverse Fourier transform of the diffraction pattern, the resulting image would resemble the mask pattern. In fact, spherical lenses do behave in this way. We can define an ideal imaging lens as one which produces an image which is identically equal to the Fourier transform of the light distribution entering the lens. It is the goal of lens designers and manufacturers to create lenses as close as possible to this ideal. Does an ideal lens produce a perfect image? No. Because of the finite size of the numerical aperture, only a portion of the diffraction pattern enters the lens. Thus, even an ideal lens cannot produce a perfect image unless the lens is infinitely big. Since in the case of an ideal lens the image is limited only by the diffracted light which does not make it through the lens, we call such an ideal system *diffraction limited*.

In order to write our final equation for the formation of an image, let us define the objective lens *pupil function P* (a pupil is just another name for an aperture). The pupil function of an ideal lens simply describes what portion of light enters the lens and is one inside the aperture and zero outside:

$$P(f_x, f_y) = \begin{cases} 1, & \sqrt{f_x^2 + f_y^2} < NA/l \\ 0, & \sqrt{f_x^2 + f_y^2} > NA/l \end{cases}$$

Thus, the product of the pupil function and the diffraction pattern describes the light entering the objective lens. Combining this with our description of how a lens behaves gives us our final expression for the electric field at the image plane (that is, at the wafer):

$$E(x,y) = \mathcal{F}^{-1}\{M(f_x, f_y)P(f_x, f_y)\}$$

The *aerial image* is defined as the intensity distribution at the wafer and is simply the square of the magnitude of the electric field.

So let's review what we have discovered so far. First, light passing through the mask is diffracted. The diffraction pattern can be described as the Fourier transform of the mask pattern. Since the objective lens is of finite size, only a portion of the diffraction pattern actually enters the lens. The numerical aperture describes the maximum angle of diffracted light which enters the lens and the pupil function is used to mathematically describe this behavior. Finally, the effect of the lens is to take the inverse Fourier transform of the light entering the lens to give an image which resembles the mask pattern. If the lens is ideal, the quality of the resulting image is only limited by how much of the diffraction pattern is collected. This type of imaging system is called diffraction limited. The bottom graph in Figure 2 shows such a diffraction limited aerial image for our example of equal lines and spaces when the zero and the ± first diffraction orders are used.

Although we have completely described the behavior of a simple ideal imaging system, we must add one more complication before we have described the operation of a projection system for lithography. So far, we have assumed that the mask is illuminated by *spatially coherent* light. Coherent illumination means simply that the light striking the mask arrives from only one direction. We have further assumed that the coherent illumination on the mask is normally incident. The result was a diffraction pattern which was centered in the entrance to the objective lens (Figure 3a). What would happen if we changed the direction of the illumination so that the light struck the mask at some angle θ? As shown in Figure 3b, the effect is simply to shift the diffraction pattern with respect to the lens aperture (in terms of spatial frequency, the amount shifted is $\sin\theta'/\lambda$). Recalling that only the portion of the diffraction pattern passing through the lens aperture is used to form the image, it is quite apparent that this shift in the position of the diffraction pattern can have a profound effect on the resulting image.

If the illumination of the mask is composed of light coming from a range of angles rather than just one angle, the illumination is called *partially coherent*. If one angle of illumination causes a shift in the diffraction pattern, a range of angles will cause a range of shifts, resulting in broadened diffraction orders, as seen in Figure 3c. One can characterize the range of angles used for the illumination in several ways, but the most common is the *partial coherence factor*, σ (also called the degree of partial coherence or the pupil filling function or just the partial coherence). The partial coherence is defined as the sine of the half-angle of the illumination cone divided by the objective lens numerical aperture. It is thus a measure of the angular range of the illumination relative to the angular acceptance of the lens. Finally, if the range of angles striking the mask extends from -90° to 90° (that is, all possible angles), the illumination is said to be *incoherent*.

In the next issue we will discuss how defocus affects the imaging process, and briefly describe how phase-shifting masks and off-axis illumination can be explained using our knowledge of imaging.

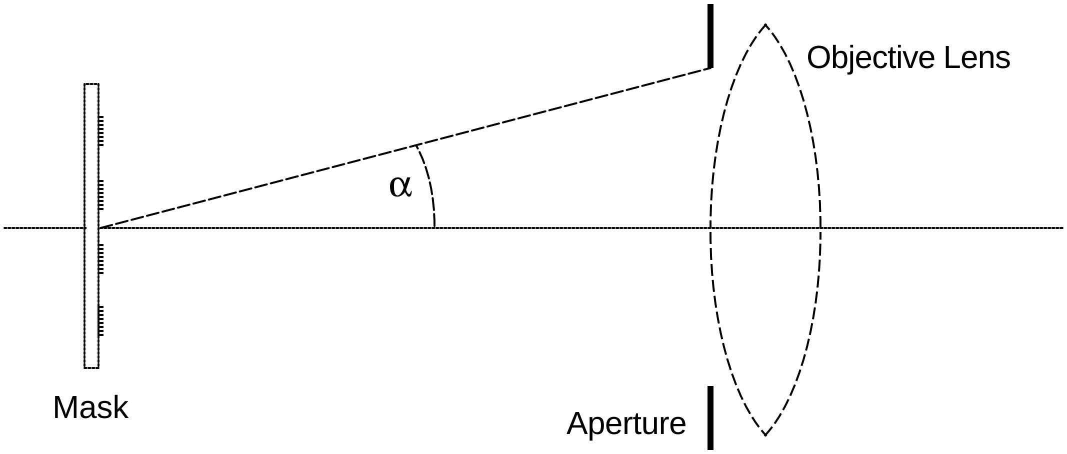
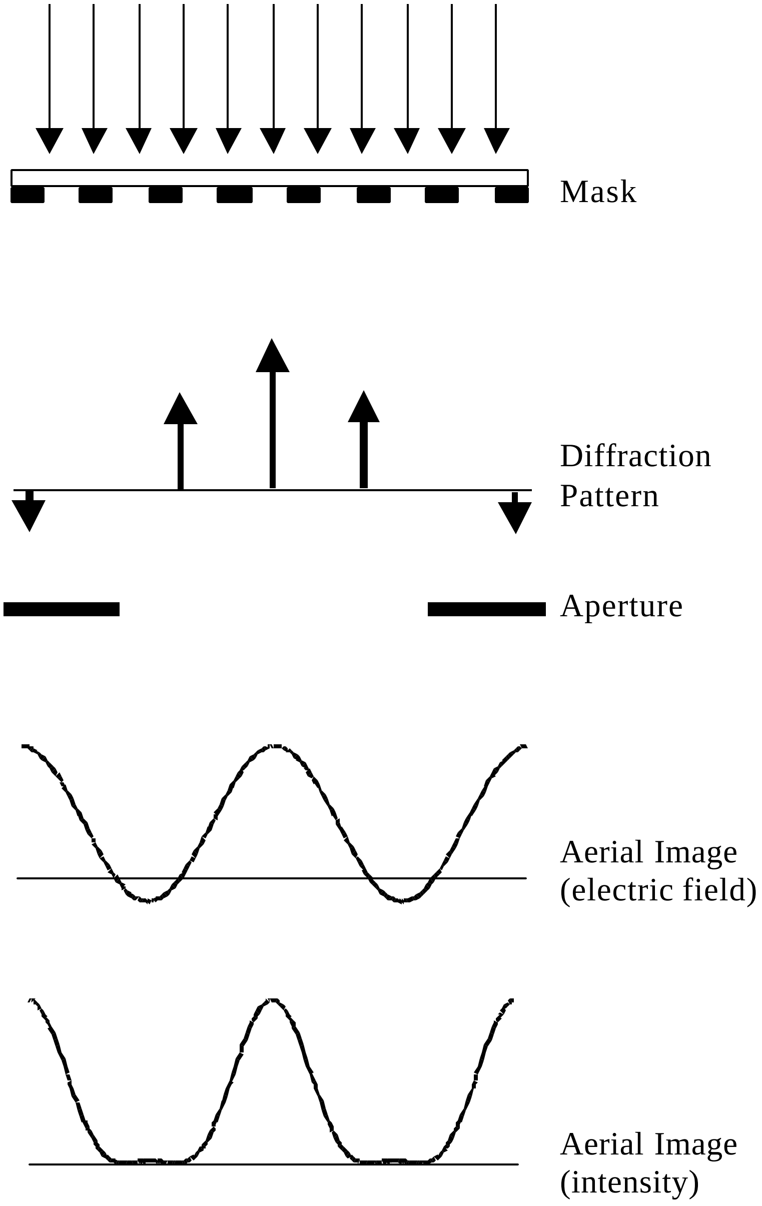


Figure 1. The numerical aperture is defined as $NA = sin\alpha$ where α is the maximum half-angle of the diffracted light which can enter the objective lens.

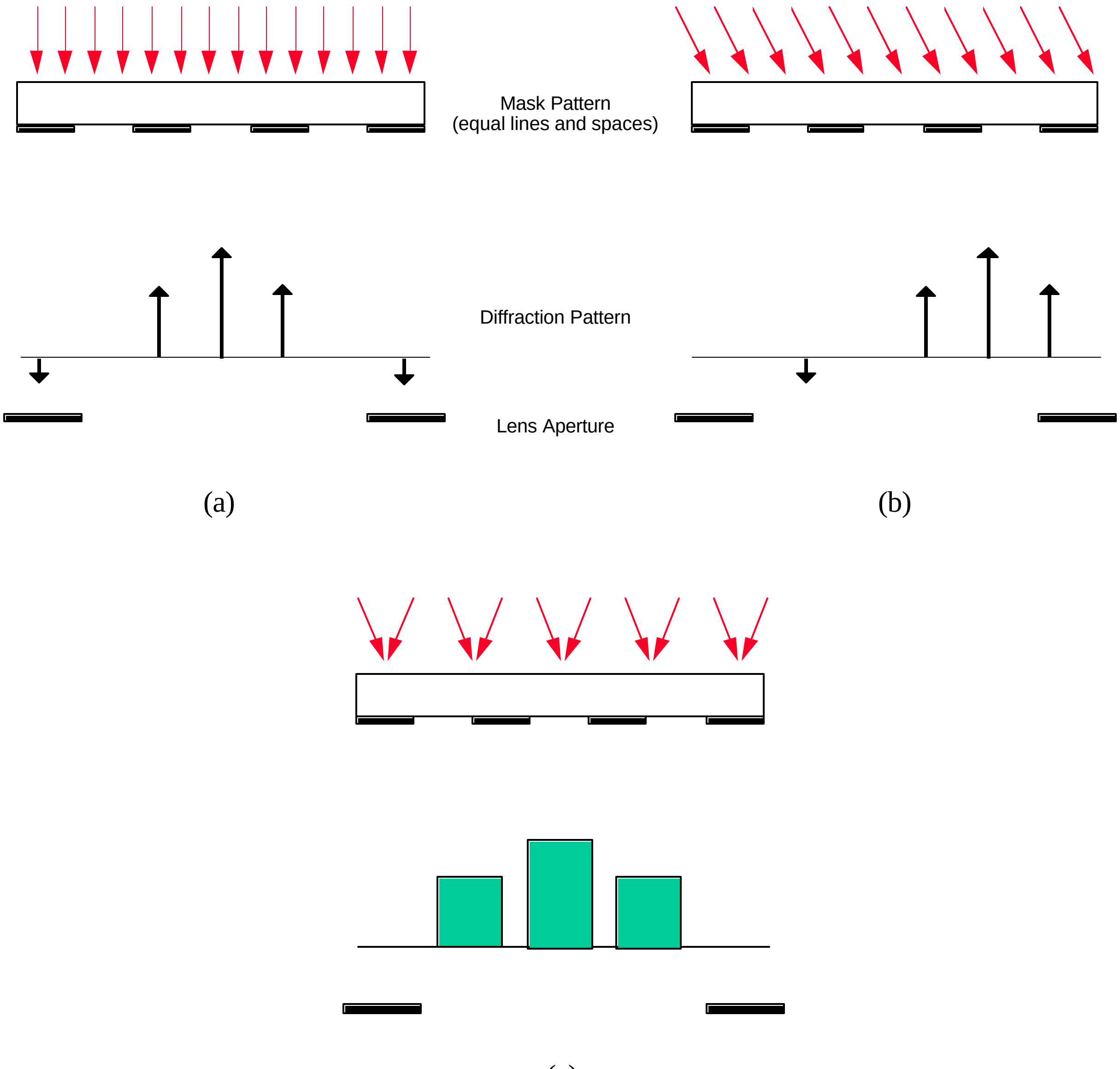


$$M(f_x) = \sum_{n=-\infty}^{\infty} \frac{\sin(pwf_x)}{pf_x} d\left(f_x - \frac{n}{p} \right)$$

$$E(x) = \frac{1}{2} + \frac{2}{p}\cos\left(2px/p\right)$$

$$I(x) = \left[\frac{1}{2} + \frac{2}{p}\cos\left(2px/p\right) \right]^2$$

Figure 2. The formation of an image for equal lines and spaces under coherent ilumination.



(a) (b)

(c)

Figure 3. Illuminating the mask at an angle shifts the diffraction pattern relative to the aperture of the objective lens.