The Formation of an Aerial Image, part 4

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In the last issue, we described how defocus affects the formation of an image. This information, combined with the basic imaging theory introduced in the first two parts of this series, has given us a fairly clear picture of how lithographic imaging systems work. We are now in a position to make a limited definition of *resolution*, the smallest feature which can be printed, and to describe, in a very limited way, how phase-shifting masks and off-axis illumination work.

From the limited perspective of image formation, a reasonably straightforward definition of resolution is possible. Consider the simple case of a mask pattern of equal lines and spaces. As we have seen, the resulting diffraction pattern is a series of discrete diffraction orders. In order to produce an image which even remotely resembles the original mask pattern it is necessary for the objective lens to capture the zero order (i.e., the undiffracted light) and at least one higher diffraction order. If the light illuminating the mask is a normally incident plane wave, the diffraction pattern will be centered in the objective lens. Since the position of the ±1 diffraction orders are given by $\pm\lambda/p$ where p is the pitch of the mask pattern, the requirement that a lens of a finite size must capture these diffraction orders to form an image puts a lower limit on the pitch which can be imaged. As Fig. 1a illustrates, the smallest pitch which still produces an image would put the first diffraction order at the outer edge of the objective lens. Thus,

$$\frac{\lambda}{p} = NA$$

If we let R represent the resolution element (the linewidth or the spacewidth) of our equal line/space pattern, the resolution will be given by

$$R = 0.5\frac{\lambda}{NA}$$

This classic equation is often called the *theoretical resolution* of an imaging system. Note that we made several very specific assumptions in deriving this resolution equation: a mask pattern of equal lines and spaces was used, and the illumination was a single wavelength normally incident plane wave (called

coherent illumination). For other features, for example an isolated line, there is no clear resolution cut-off. For other types of illumination, this cut-off will change.

Consider, for example, the effect of simply changing the incident angle of illumination on the mask, as in Fig. 1b. In fact, let us pick a very specific angle of illumination such that the zero order of light will enter the objective lens at one edge. Thus, one half of the diffraction pattern will always be lost. However, the other half will enter the lens and an image can still be formed. The smallest imagable pitch will put one of the first diffraction orders at the edge of the objective lens, as before. But now, the distance between the zero order and the first order is not the numerical aperture (the radius of the lens) but twice the numerical aperture (the diameter of the lens). Thus, the resolution in this case will be given by

$$R = 0.25\frac{\lambda}{NA}$$

The simple modification of changing the incident angle of illumination resulted in a doubling of the resolution! Of course, nothing has been said of the quality of the images produced at this feature size, only that an image can be produced.

The first resolution equation given above is often called the *coherent resolution limit* since most people assume that a coherent source will be centered on the optical axis resulting in a normally incident plane wave. The second resolution equation is also called the *incoherent resolution limit* since incoherent illumination, which contains all possible angles of illumination, will contain the one angle which maximizes the resolution. The ultimate resolution limit for partially coherent illumination is something between these two extremes:

$$R = 0.5\frac{\lambda}{NA(1+\sigma)}$$

where σ is the partial coherence (see Part 2 of this series for a definition of partial coherence).

It should be pointed out that these optical definitions of resolution do not address the issue of what features can be printed in photoresist. The above resolution limits should be considered the extremes of resolution - the result one would obtain using a perfect photoresist. Given this and the other limitations discussed above, these resolution expressions must be thought of as guidelines pointing out some major factors affecting resolution, but not as numerical predictors of resolution.

Obviously, the manipulation of the angle of illumination had a dramatic affect on the resolution (improvement by up to a factor of two). Thus, one would suspect that the use of off-axis illumination would be a clear path towards resolution enhancement. But it is not resolution which is driving the use of off-axis illumination, but depth-of-focus (DOF). As we saw last time, the effect of defocus is to cause a phase error on the diffraction order as a function of its radial position within the objective lens pupil. Different diffraction orders falling in different locations within the pupil will have different phase

errors, resulting in image degradation. If, however, the angle of illumination were chosen such that, for a given feature, the zero order and one of the first diffraction orders are spaced evenly about the center of the objective lens (Fig. 2), the phase change due to defocus will be the same for both orders, resulting in no phase difference and no degradation. Thus, the proper choice of an off-axis illumination angle for a given equal line/space pitch will result in a potentially dramatic increase in the DOF of that feature!

Phase shifting masks, in some applications, improve depth-of-focus by the same mechanism as off-axis illumination. For example, the use of alternating shifters on an equal line/space pattern (called the Levenson technique) produces a diffraction pattern with only two diffraction orders, both the same distance from the center of the lens aperture, thus maximizing the DOF.

In this and the previous three editions of this column, I have presented a reasonably concise review of the theory of projection imaging. Of course, such a review is by its very nature quite limited in scope and there is certainly much more to discuss on this topic. However, lest I give the impression that only optics affects the quality of a lithographic process, next time we will begin to examine photoresists by looking at their interactions with light.

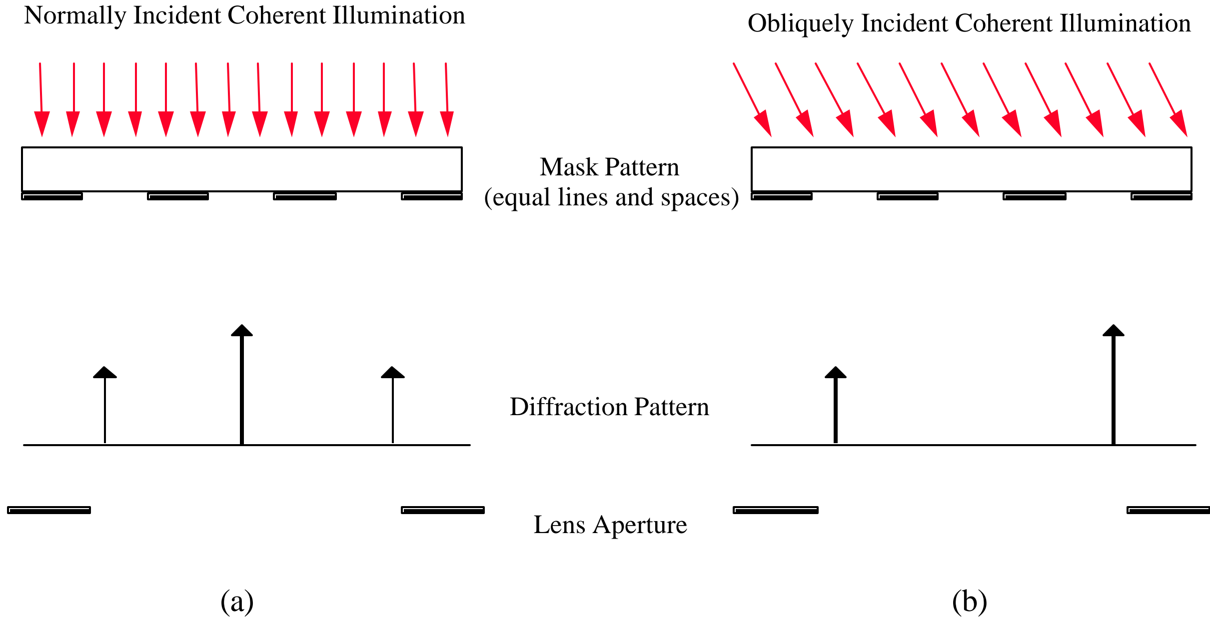

Figure 1. Resolution Limit for equal lines and spaces for (a) normally incident illumination and (b) oblique incidence.

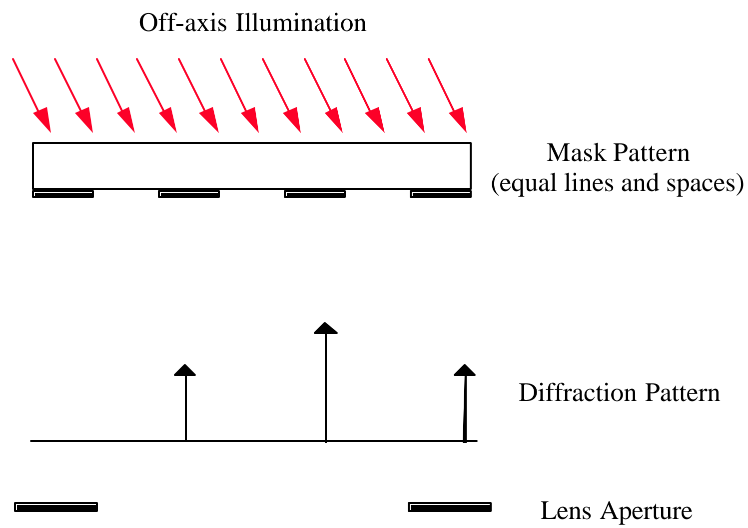

Figure 2. The goal of off-axis illumination is to place the diffraction orders (for a given mask pattern) an equal distance from the center of the aperture in order to minimize defocus effects.