Depth of Focus and the Alternating Phase Shift Mask

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One of the biggest advantages of the use of a strong phase shifting mask, such as the alternating PSM, is the increased depth of focus of fine pitch patterns (see the May, 2003 edition of this column). Here we will numerically evaluate the depth of focus for an alternating PSM, and show its dependence on partial coherence.

A conventional, binary chrome on glass mask of lines and spaces will produce a diffraction pattern of discrete diffraction orders at spatial frequencies that are multiples of the inverse pitch, $1/p$. For a high resolution (fine pitch) pattern, only the zero and the plus and minus first diffraction orders pass through the lens, as seen in Figure 1a. An alternating phase shift mask, as depicted in Figure 1b, adds "shifters" over every other space to shift the phase of the light by 180°. This mask then uses the destructive interference of light passing through adjacent spaces to completely eliminate the zero order. The image is obtained from the interference of the two first diffraction orders, now located at the spatial frequencies $f = \pm 1/(2p)$. Often, the binary mask imaging shown in Figure 1a is referred to as three beam imaging (due to the interference of the three diffraction orders) while the phase shift case, with two diffraction orders passing through the lens, is called two beam imaging.

The plane of best focus is determined by the phase of the interfering beams that combine to form the image. At best focus all of the interfering beams have the same phase. For the case of three beam imaging, propagation of the beams past this plane of best focus creates a phase difference between the beams. Since a path difference results in a phase difference (light changes phase 360° for every wavelength of distance traveled), the beams have an increasing phase error as a function of defocus, resulting in degraded image formation. For the two beam imaging case, if the two beams arrive at the wafer from the same angle (on opposite sides of the optical axis) a displacement of the wafer from the focal plane gives the same phase change to each beam. Thus, the phase difference between the beams remains zero and a perfect, in-focus image results. Translating this discussion to the diffraction plane, improved depth of focus (DOF) results from image formation with two beams when those two beams are equally spaced about the center of the lens. For line space patterns made with alternating phase shift masks, this arrangement of two equally spaced diffraction orders occurs naturally for all reasonably small pitches. Thus, an ideal alternating phase shifting mask, when illuminated with coherent, normally incident illumination, will exhibit infinite depth of focus for fine pitch patterns!

As one might expect, achieving the ideal conditions that create an infinite depth of focus is not easy. In fact, real lithographic projection tools cannot provide pure, coherent illumination. Partially coherent illumination, with partial coherence σ that can be varied down to about 0.3, is the closest that practical lithography tools can come ($\sigma = 0$ is coherent illumination). How does partial coherence affect depth of focus for an alternating PSM? How close to "infinite" DOF can a real exposure tool get?

The effect of partial coherence is to spread the diffraction order points into larger spots, the shape of each order's spot being determined by the shape of the source. Each point on the source is independent, i.e., incoherent, with no fixed phase relationship to any other source point. Each source point produces a coherent aerial image, the total image being the (incoherent) sum of all the intensity images from each source point. Since only the exact center source point produces an image with infinite depth of focus, all of the other source points contribute to a loss of DOF. To evaluate how much the DOF is affected by the partial coherence, we can analytically calculate the aerial image given some simple assumptions.

First, consider the case where only the first diffraction orders make it through the lens and that these orders are completely inside the lens (not clipped by the aperture), as shown in Figure 2. This occurs, for a given wavelength λ and numerical aperture *NA*, when

$$\frac{\lambda}{2NA(1-\sigma)} < p < \frac{3\lambda}{2NA(1+\sigma)} \qquad (1)$$

A quick look at this constraint shows that it can possibly be true only when $\sigma < 0.5$. Since, as we shall see, good DOF is obtained when σ is small, this constraint will be reasonable. Second, we shall use the paraxial approximation for the effects of focus, so that the optical path difference (OPD) due to a defocus error δ will be a quadratic function of the sine of the incidence angle θ, or the spatial frequency, f.

$$OPD = \delta(1-\cos\theta) = \tfrac{1}{2}\delta\left(\sin^2\theta + \frac{\sin^4\theta}{4} + \frac{\sin^6\theta}{8} + \ldots\right) \approx \tfrac{1}{2}\delta\sin^2\theta = \tfrac{1}{2}\delta\lambda^2 f^2 \qquad (2)$$

Now the aerial image in the presence of defocus can be calculated analytically by integrating over the source. Considering only equal lines and spaces for the sake of simplicity,

$$I(x) = \frac{4}{\pi^2}\left(1 + D\cos(2\pi x/p)\right) \qquad (3)$$

where

$$D = \frac{J_1(2\pi\,\delta\,\sigma\,NA/p)}{\pi\,\delta\,\sigma\,NA/p}$$

and J_1 is the Bessel function of the first kind, order one. This defocus function *D* is plotted in Figure 3 and has the familiar Airy disk form.

Given the aerial image of equation (3), what is the depth of focus? A convenient way of estimating DOF is through the use of the normalized image log slope (NILS). For a nominal feature size of $p/2$, the NILS will be:

$$NILS = \pi D\,. \tag{4}$$

Feature sizes that have duty factors other than 1:1 will give different coefficients. When the NILS goes to zero, obviously the aerial image will have degraded beyond any usability. At this extreme,

$$DOF = 2\delta < \frac{1.22\,p}{\sigma\, NA}\,. \tag{5}$$

Perhaps a more reasonable estimate would be the range of focus that keeps the NILS within one half of its in-focus value (conservative) to one third of its in-focus value (aggressive). For these criterion,

$$\frac{0.7\,p}{\sigma\, NA} < DOF < \frac{0.85\,p}{\sigma\, NA} \tag{6}$$

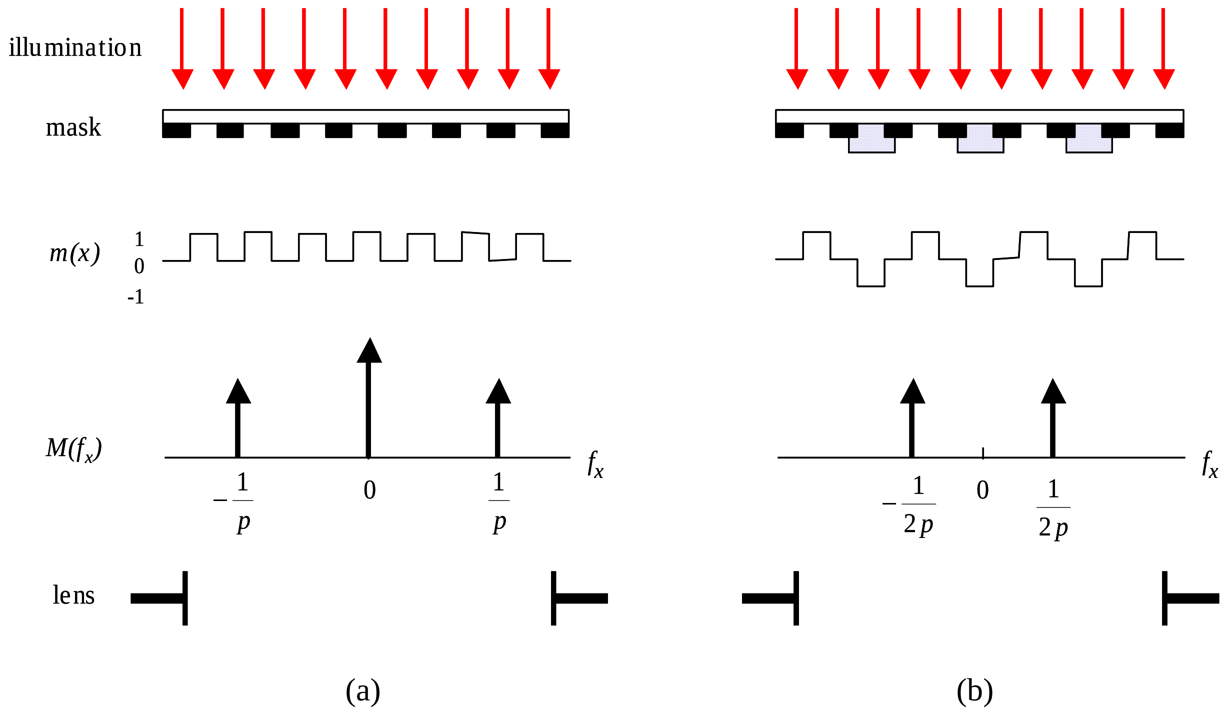
As equation (6) shows, the depth of focus for an alternating PSM mask improves as the partial coherence factor is reduced, approaching the theoretically possible infinite DOF as σ goes to zero. Note that the wavelength does not appear explicitly in equation (6), but only in the assumptions leading to it. Although the derivation of equation (6) has some constraints on pitch, uses an approximate defocus expression, assumes an ideal resist (only the aerial image was taken into account) and ignores flare, the trends are still accurate. This equation can be useful in understanding the basic effects of partial coherence on alternating PSM depth of focus. An analogous expression can be derived for other two-beam imaging cases.

Figure Captions:

Figure 1. A mask pattern of lines and spaces of pitch *p* has an idealized amplitude transmittance function *m(x)* that produces a diffraction pattern $M(f_x)$ where f_x is the spatial frequency. A binary chrome on glass mask is shown in (a), and an alternating phase shift mask is shown in (b).

Figure 2. The diffraction pattern, spread out by a partially coherent source, for an alternating phase shift mask.

Figure 3. The Airy disk function D (which is linearly proportional to NILS) as it falls off with defocus.



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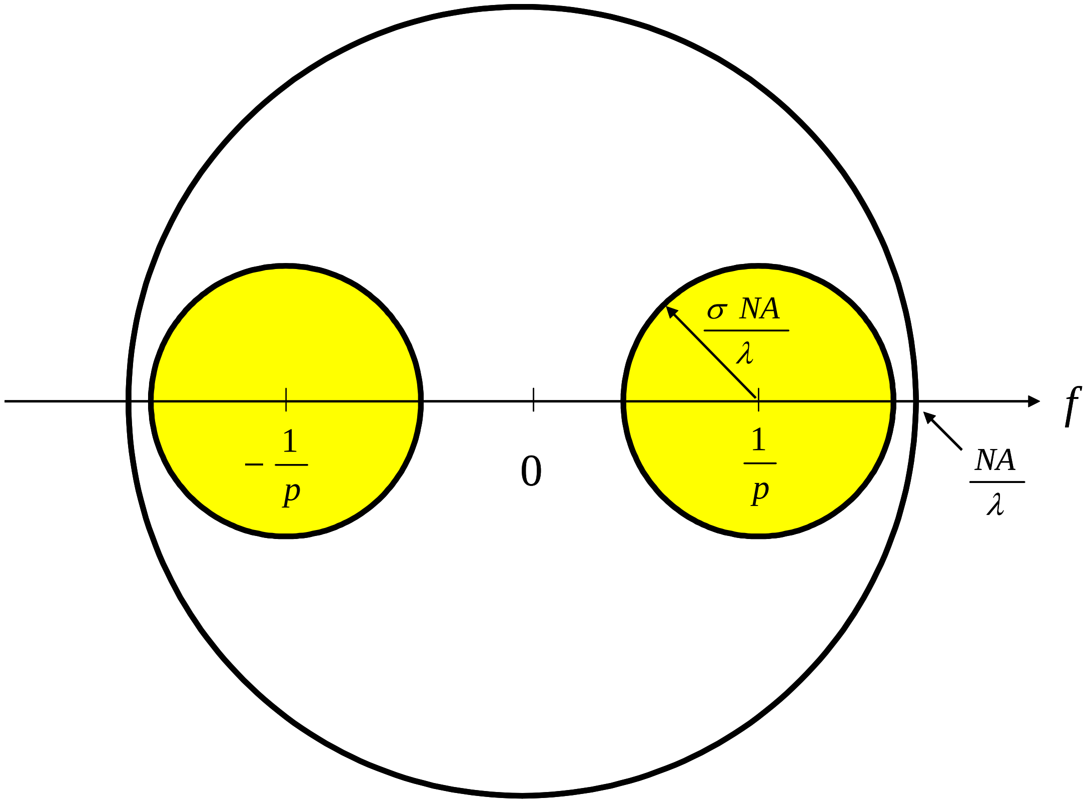

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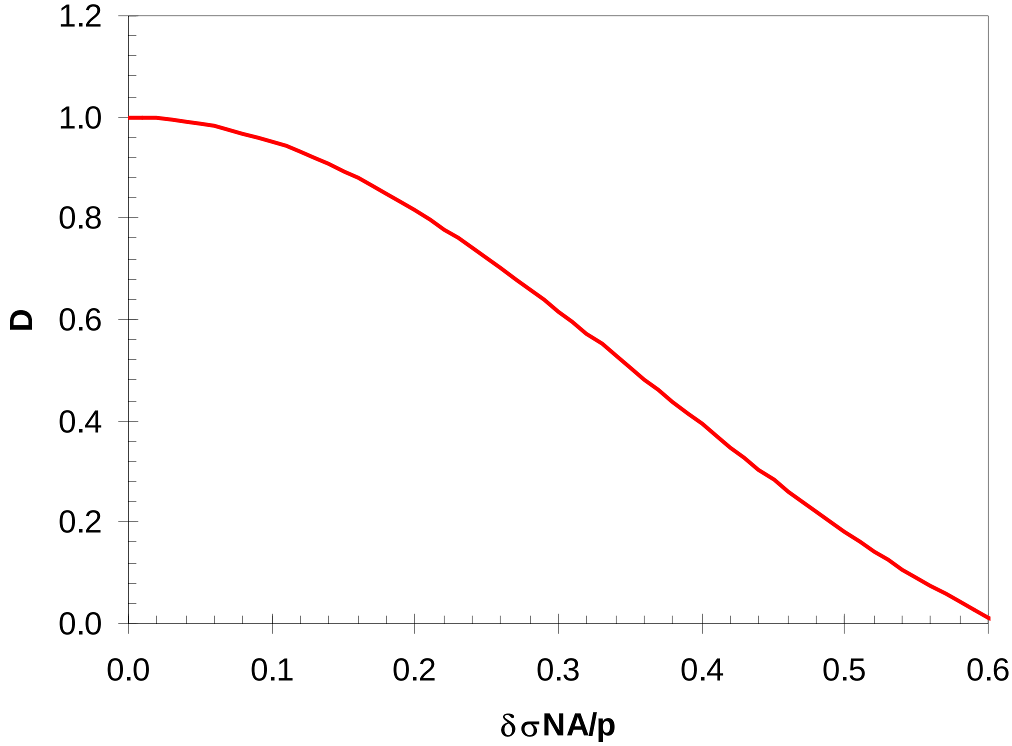

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