

# The Impact of Phase Errors on Phase Shifting Masks, part 3

Chris A. Mack, KLA-Tencor, FINLE Division, Austin, Texas

In previous editions of this column (November 2002 and February 2003) we examined the impact of phase errors on the printing of alternating phase shifting masks (PSMs). While alternating aperture PSMs are important, the overwhelming majority of phase shift masks used today are attenuated PSMs (also called embedded phase shift masks, EPSM). EPSM blanks are composed of two or three layers making up the absorber, such as molybdenum/silicon (MoSi), that are then processed in much the same way as a standard chrome on glass mask. With the exception of some research and development applications, almost all EPSM blanks have about a 6% intensity transmittance (and of course a nominal 180° phase shift compared to the quartz substrate). The interference of the light transmitted by the EPSM material and that transmitted by the spaces (the quartz) produces a sharper transition from bright to dark at the edge in the resulting aerial image.

How does a small phase error affect the lithographic performance of an attenuated PSM? Consider a pattern of lines and spaces with spacewidth  $w_s$  and linewidth  $w_l$ . The electric field amplitude and phase transmittance of the line will be  $T$  and  $\phi$ , respectively. (Note that for a 6% EPSM,  $T \approx 0.25$ .) Because the mask is a repeating pattern of lines and spaces, the resulting diffraction pattern will be discrete diffraction orders. For high resolution patterns only the zero and first diffracted orders will pass through the lens and be used to generate the aerial image. Defining a coordinate system with  $x=0$  at the center of the space and letting  $p = w_s + w_l =$  the pitch, the amplitude of the zero and first diffraction orders will be given by

$$a_0 = \frac{w_s}{p} + \frac{w_l}{p} T e^{i\phi}$$

$$a_1 = a_{-1} = \frac{\sin(\pi w_s / p)}{\pi} - \frac{\sin(\pi w_l / p)}{\pi} T e^{i\phi} \quad (1)$$

For equal lines and spaces,

$$a_0 = \frac{1}{2} (1 + T e^{i\phi})$$

$$a_1 = a_{-1} = \frac{1}{\pi} (1 - T e^{i\phi}) \quad (2)$$

For an ideal attenuated PSM  $\phi = \pi$  (180°), giving

$$a_0 = \frac{1}{2}(1-T)$$

$$a_1 = a_{-1} = \frac{1}{\pi}(1+T) \quad (3)$$

Thus, equation (3) shows us that the effect of the attenuated PSM as compared to a chrome on glass mask is to reduce the magnitude of the zero order and increase the magnitude of the first order (which results in a higher contrast image).

For a mask with phase error, we can let  $\varphi = \pi + \Delta\varphi$ . Using this value in equation (2), and assuming that the phase error is small,

$$a_0 = \frac{1}{2}(1 - Te^{i\Delta\varphi}) = \frac{1}{2}(1 - T \cos(\Delta\varphi)) - i \frac{1}{2} T \sin(\Delta\varphi) \approx \frac{1}{2} \left( 1 - T + \frac{T\Delta\varphi^2}{2} \right) - i \frac{1}{2} T \Delta\varphi$$

$$a_1 = a_{-1} = \frac{1}{\pi}(1 + Te^{i\Delta\varphi}) \approx \frac{1}{\pi} \left( 1 + T - \frac{T\Delta\varphi^2}{2} \right) + i \frac{1}{\pi} T \Delta\varphi \quad (4)$$

Calculating the magnitude and the phase of each of each diffraction order,

$$|a_0| \approx |a_0|_{ideal} + \frac{\Delta\varphi^2}{4} \left( \frac{T}{1-T} \right)$$

$$\angle a_0 \approx -\Delta\varphi \left( \frac{T}{1-T} \right) \quad (5)$$

$$|a_1| \approx |a_1|_{ideal} - \frac{\Delta\varphi^2}{2\pi} \left( \frac{T}{1+T} \right)$$

$$\angle a_1 \approx \Delta\varphi \left( \frac{T}{1+T} \right) \quad (6)$$

Let's investigate the impact of the changes in the magnitude and phase of each diffracted order separately. As shown in equations (5) and (6), the magnitudes of the orders vary as the phase error squared (and so should be quite small for small errors). As an example, for a 6% EPSM with a 10° phase error the zero and first orders change by only +0.7% and -0.2% respectively. The resulting impact on the aerial image is quite small, less than 0.2% intensity difference in most cases.

The phase of the diffraction orders, on the other hand, vary directly as the EPSM phase error. In fact, the phase difference between the zero and first orders, which ideally would be zero, becomes in the presence of EPSM phase error

$$\angle a_1 - \angle a_0 \approx \frac{2\Delta\phi T}{1+T^2} \quad (7)$$

What is the impact of such a change in the phase difference between the diffraction orders? Focus also causes a phase difference between the zero and first orders. For the simple case of coherent illumination, a defocus of  $\delta$  causes a phase difference of

$$\angle a_1 - \angle a_0 \approx \frac{\pi \delta \lambda}{p^2} \quad (8)$$

Thus, the effect of the EPSM phase error will be to shift best focus by an amount given by

$$\delta_{shift} \approx \frac{2p^2 \Delta\phi T}{\pi \lambda (1+T^2)} \quad (9)$$

Fortunately, a quick look at the magnitude of this focus shift shows that it is reasonably small. For a 6% EPSM at 248nm wavelength, focus will shift between 1 and 3nm per degree of EPSM phase error, with the smallest shifts occurring for the smallest features. Remembering that equation (9) was derived under the simple assumption of coherent illumination, full image simulations show that the use of partial coherence can double or triple the focus shift compared to the coherent case. Off-axis illumination, however, tends to lower this effect since this illumination is specifically intended to minimize the impact of phase errors between the zero and first orders. Figure 1 illustrates this focus-shift effect, showing also that unlike alternating PSM, there is no pattern placement change through focus in the presence of an EPSM phase error.

In general, attenuated phase shift masks are much less sensitive to phase errors than alternating phase shift masks. The major impact of small phase errors is a focus shift, so the biggest worry would be a variation of EPSM phase across a reticle rather than a mean to target error. Since cleaning can cause phase errors in an EPSM mask, understanding the impact of these errors is quite important.

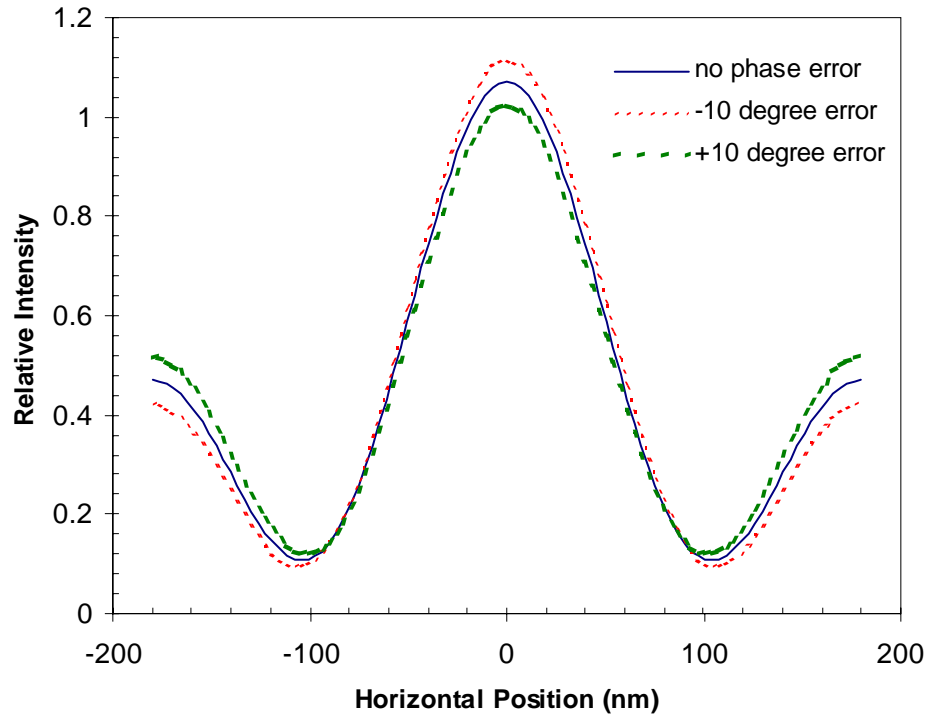


Figure 1. A small phase error in an EPSM mask changes the aerial image in the same way as a small shift in focus. Here,  $\pm 10^\circ$  phase error moves the image closer and farther away from best focus (wavelength = 248nm, NA = 0.8, 180nm lines/space pattern, coherent illumination, 150nm defocus). For this case, a  $10^\circ$  phase error shifts best focus by about 14nm.