Swing Curves and the Process Window

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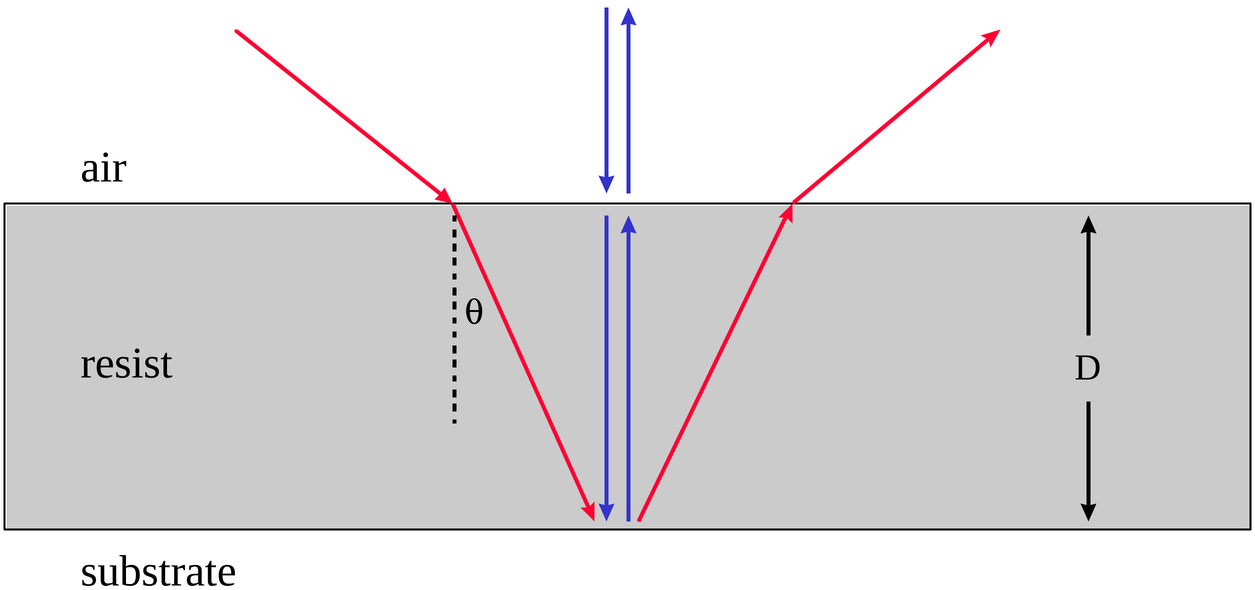
As we saw in the last edition of *The Lithography Expert*, numerical aperture and partial coherence can have a large effect on photoresist swing curves. Swing curves are caused by interference between light reflected off the top of the photoresist and light which travels through the resist, bounces off the substrate, and emerges back out from the top of the resist. The path length that the light travels through the resist determines its phase, and thus whether the interference will be constructive or destructive. Changes in resist thickness give rise to a sinusoidal variation in the amount of energy that actual makes it into the resist. But the path length that the light travels changes as the angle of the light striking the resist is changed (Figure 1). Thus, light traveling through the resist at one angle may produce a swing curve maximum, while the same resist thickness could be a swing curve minimum for a different angle of illumination. Both partial coherence (σ) and numerical aperture (*NA*) affect the angles of the light that expose the resist.

When imaging high resolution features, diffracted light can reach the maximum possible angle that can travel through the lens. In such a case, some of the light striking the resist will be at the maximum possible incident angle of $\sin^{-1}(NA)$. A numerical aperture of 0.6 means that diffracted light can strike the resist at angles up to about 37°. Consider a simple example of imaging small lines and spaces. For conventional illumination, the zero order will be centered around normal incidence at the resist surface with a range of angles determined by σNA. The $\pm 1^{st}$ diffraction orders will strike the resist at an angle of $\sin^{-1}(\lambda/p)$ where λ is the wavelength and p is the pitch of the line/space pattern. For 0.35µm features imaged with *i*-line, the center of the first order angular range will be about 31.4°. If the resist thickness were adjusted to give a maximum of the E_o swing curve (i.e., the zero order is at a maximum of the swing curve), the first orders would effectively be at a minimum of the swing curve! The zero order light would be maximally reflected *out* of the resist while the first order light would be maximally coupled *into* the resist. When these orders combine to form the image in resist, the result will be significantly different than the case of imaging on a non-reflecting substrate. On the other hand, if the resist thickness were at an E_o swing curve minimum, the first orders would be at a swing curve maximum. The lithographic response of these features (for example, the size of the focus-exposure process window) could be quite different when operating at an E_o swing curve minimum versus a maximum [1].

The following figures show the results of different thin film interference effects for different diffraction orders. The effects are subtle, but significant. Figure 2 compares the focus-exposure process windows at resist thicknesses corresponding to the maximum and minimum of the E_o swing curve. As can be seen for this case, the E_{max} process window shows greater exposure latitude than the E_{min}. Figure 3 illustrates how isolated and dense lines can have different swing curve phases (and as a result, different optimum resist thicknesses). In addition, both of these curves show different maxima and minima than the E_o swing curve. It is also apparent that the iso-dense print bias (the difference in linewidth between isolated and dense lines printed in resist) varies with resist thickness. Because of the slight phase difference between the two swing curves, the iso-dense print bias is significantly less at the minimum of the swing curve than at the maximum.

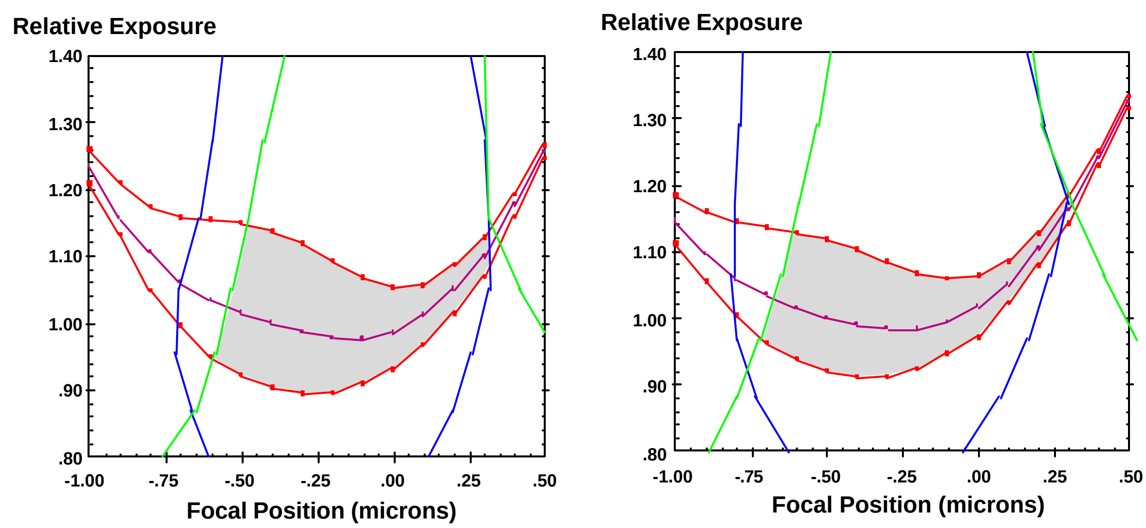
All of the effects described above are a function of any variable that might change the range of angles of the light striking the resist. In particular, the numerical aperture and the size and shape of the illumination source have a large effect, as does the feature size and type. These effects are more pronounced at higher *NAs* and are virtually undetectable at numerical apertures below about 0.5. In addition, all of these effects disappear when imaging on a non-reflective substrate.

1. R. A. Cirelli, J. Garofalo, E. L. Raab, J. Xiao, R. Socha, and S. Vaidya, "The Impact of Optical Thin Film Effects on CD Control in DUV Lithography," *Optical/Laser Microlithography VIII, Proc.*, SPIE Vol. 2440 (1995) pp. 594-608.



Normal Incidence Path Length = 2D
Oblique Incidence Path Length = $2D/\cos\theta$

Figure 1. Oblique incidence of light on a thin film increases the path length that the light travels through the film.



(a) (b)

Figure 2. Focus-Exposure process windows at different resist thicknesses show that, in this case, the swing curve maximum (a) produces a greater exposure latitude than the swing curve minimum (b). (i-line, NA = 0.6, σ = 0.5, 0.35μm lines and spaces, about 0.9μm resist thickness on silicon). The shaded areas in each plot represent the overlap of the linewidth, sidewall angle, and resist loss process windows.

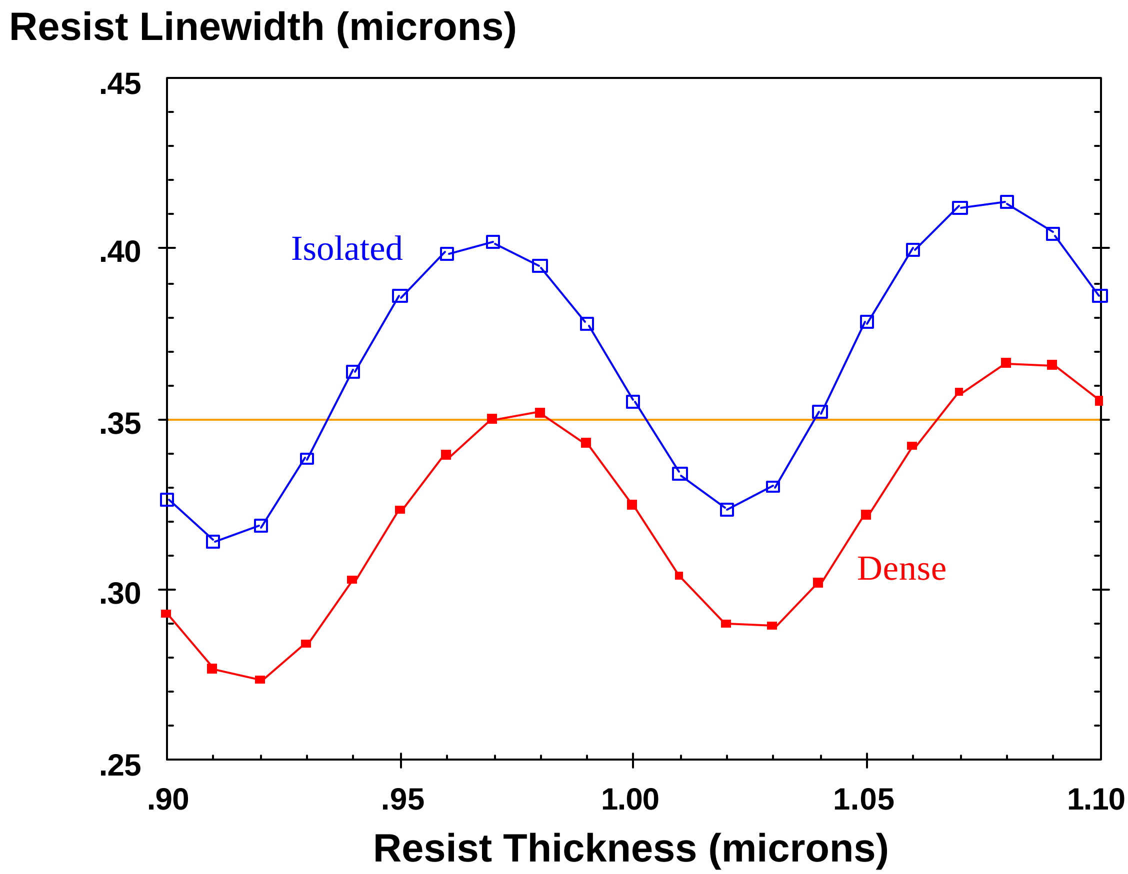


Figure 3. The different diffraction patterns of dense and isolated lines result in different angles of light hitting the photoresist, and thus different swing curve phases. (i-line, NA = 0.6, σ = 0.5, 0.35µm features, about 0.9µm resist thickness on silicon)