Effect of Numerical Aperture and Partial Coherence on Swing Curves

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As we saw in the last two editions of *The Lithography Expert*, reflections from the substrate can cause unwanted variations in the resist profile and swing curve effects. Antireflective coatings, both top and bottom, are often used to reduce these undesirable reflectivity effects. And as we saw last time, the top or bottom antireflective coating (ARC) can be optimized by adjusting its optical properties (real and imaginary parts of its index of refraction) and thickness. However, the formulas given assumed that the light was normally incident on the film. If the light strikes the ARC at an angle (or a range of angles), the optimum ARC properties will change. In addition, the size and phase of a swing curve depends on the incident angles of the light. In lithography, the range of angles of the light striking the photoresist is determined by the numerical aperture and partial coherence of the stepper, and also by the feature size on the mask.

How does reflectivity vary with angle? When light strikes any sharp boundary between two materials, its reflection is governed by the requirement that Maxwell's equations for the light meet certain boundary conditions, namely that the electric and magnetic fields parallel to the surface are the same on either side of the boundary and the electric and magnetic flux densities perpendicular to the surface are the same on either side of the boundary. By combining these boundary conditions, the reflection (and the transmission) of the light can be determined for any incident angle, resulting in Snell's law and the Fresnel reflection and transmission formulae. In addition to the incident angle, the amount of light reflected will be a function of the polarization of the incident light. (The polarization describes the direction of the electric field relative to the direction of propagation of the light, and thus relative to the reflecting surface.) For example, if light traveling through air is incident on a photoresist film, the intensity reflectivity will vary with the angle of incidence (Figure 1). But the variation is quite different for different polarizations. For *s*-polarized light (with the its electric field parallel to the resist surface), the reflectivity increases as the angle of incidence increases. *P*-polarized light shows the opposite trend. Unpolarized light (with an equal but random amount of *s*- and *p*-polarizations) will become slightly polarized as it enters the photoresist at an angle other than zero (normal incidence).

However, the variation of the reflectivity with incident angle is not the primary cause of the variations in the thin film interference effects which give rise to swing curves. The main cause is the change in the path of the light as it travels through the film. Recall that thin film interference effects cause a sinusoidal variation of the reflectivity of the thin film as the thickness of that film varies. Light striking the top of a photoresist layer, for example, will be both reflected and transmitted. The transmitted light will pass through the resist, reflect off the substrate, and pass back up to the top of the resist. This light can then interfere with light that was originally reflected at the top of the resist. This interference will depend on the distance that the light traveled through the resist (see Figure 2). Changes in resist thickness, which change the path length that the light travels, produce a sinusoidal variation in the total amount of light that is reflected out of the resist. But changes in the angle of incidence of the light have the same effect on path length as changes in the resist thickness!

Consider a simple case. Light normally incident on a thin resist film coated on a reflective substrate is found to have a maximum of its swing curve at a certain thickness. This means that the path length traveled by the light through the resist is an integer multiple of the wavelength. If now the angle of incidence is increased, the path length through the resist will also increase. If the angle is large enough so that the path length increases by half a wavelength, this same resist thickness will correspond to a minimum of the swing curve. The angle inside the resist which causes this swing curve reversal is given by

$$\theta = \cos^{-1}\left| \frac{m}{m+0.5} \right|$$

where m is the multiple of wavelengths that the swing curve maximum represents. For $m = 9$ (typical for a 1.0μm film), $\theta \approx 18.7°$ inside the resist, corresponding to about a 32° angle incident on a typical photoresist.

What does this mean for real swing curves in real lithographic situations? When measuring a dose-to-clear (E_o) swing curve, open frame (no mask) exposures of the resist are used to measure the minimum dose required to clear away the resist in the allotted development time as a function of resist thickness. The light striking the resist is made up of zero order light (that is, light which is not diffracted). If the illumination were coherent, the light would be normally incident on the resist. For partially coherent illumination the light is incident on the resist over a range of angles given by $\theta = \pm\sin^{-1}(\sigma NA)$ where NA is the numerical aperture of the objective lens and σ is the partial coherence factor. Each angle produces its own "swing curve" and the total result is the superposition of all the individual responses to each angle. Since any change in σ or NA will change the range of angles striking the photoresist, the swing curve will change as well. Figure 3 shows how E_o swing curves vary with σNA (affected by changing either the partial coherence or the numerical aperture). These effects are even more dramatic when off-axis illumination is used. Quite clearly, the positions of the swing curve maximums and minimums are dependent on the illumination conditions. Likewise, the optimum thickness of an antireflection coating will depend on the angles of the light striking the ARC.

Measurements of dose-to-clear use only zero order light. When imaging high resolution features, higher diffraction orders reach the maximum possible angle that can travel through the lens. In this 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°. This is very close to the angle given above for swing curve phase reversal! Thus, 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. We'll look at these differences in the next edition of this column.

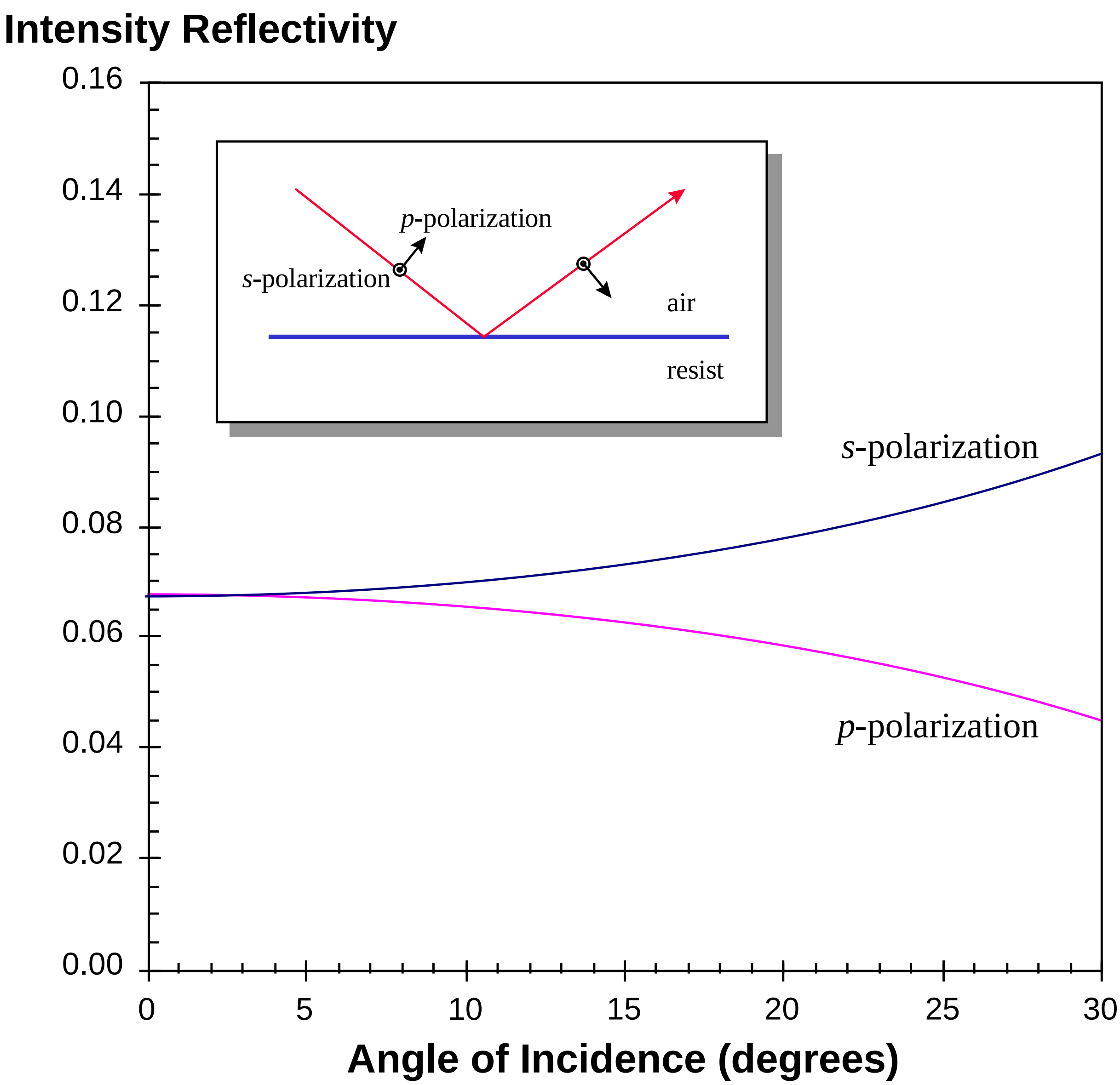
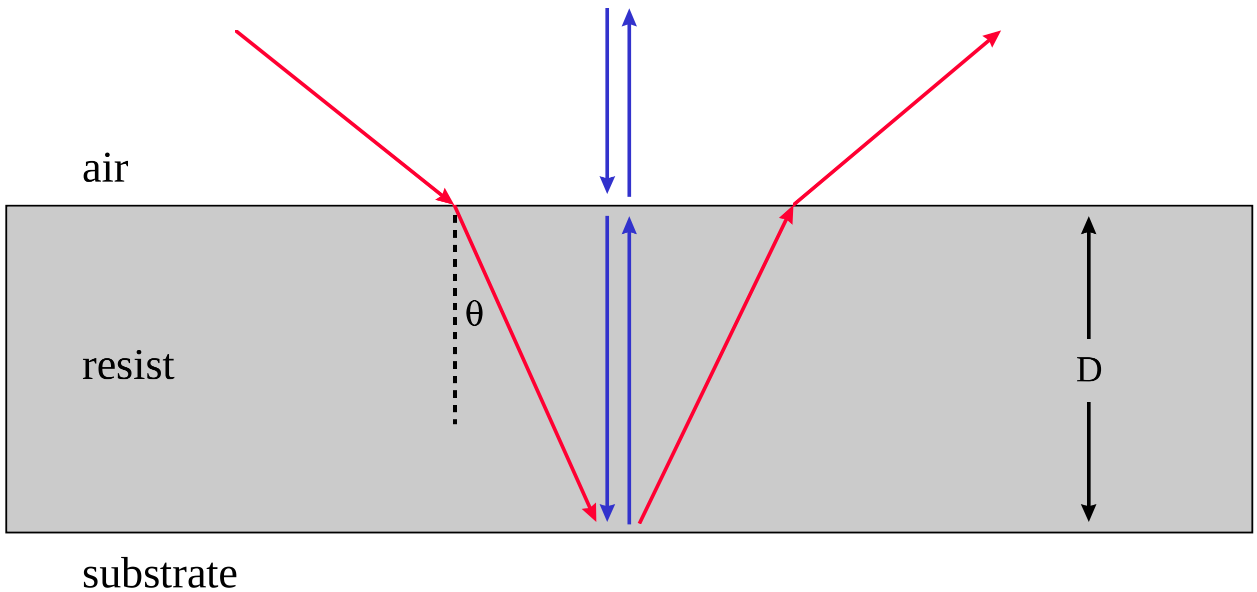


Figure 1. Intensity reflectivity (square of the electric field reflection coefficient) between air and resist (*n* = 1.7) as a function of the angle of incidence showing the difference between *s*- and *p*-polarizations.



Normal Incidence Path Length = 2D

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

Figure 2. Oblique incidence of light on a thin film increases the path length that the light travels through the film.

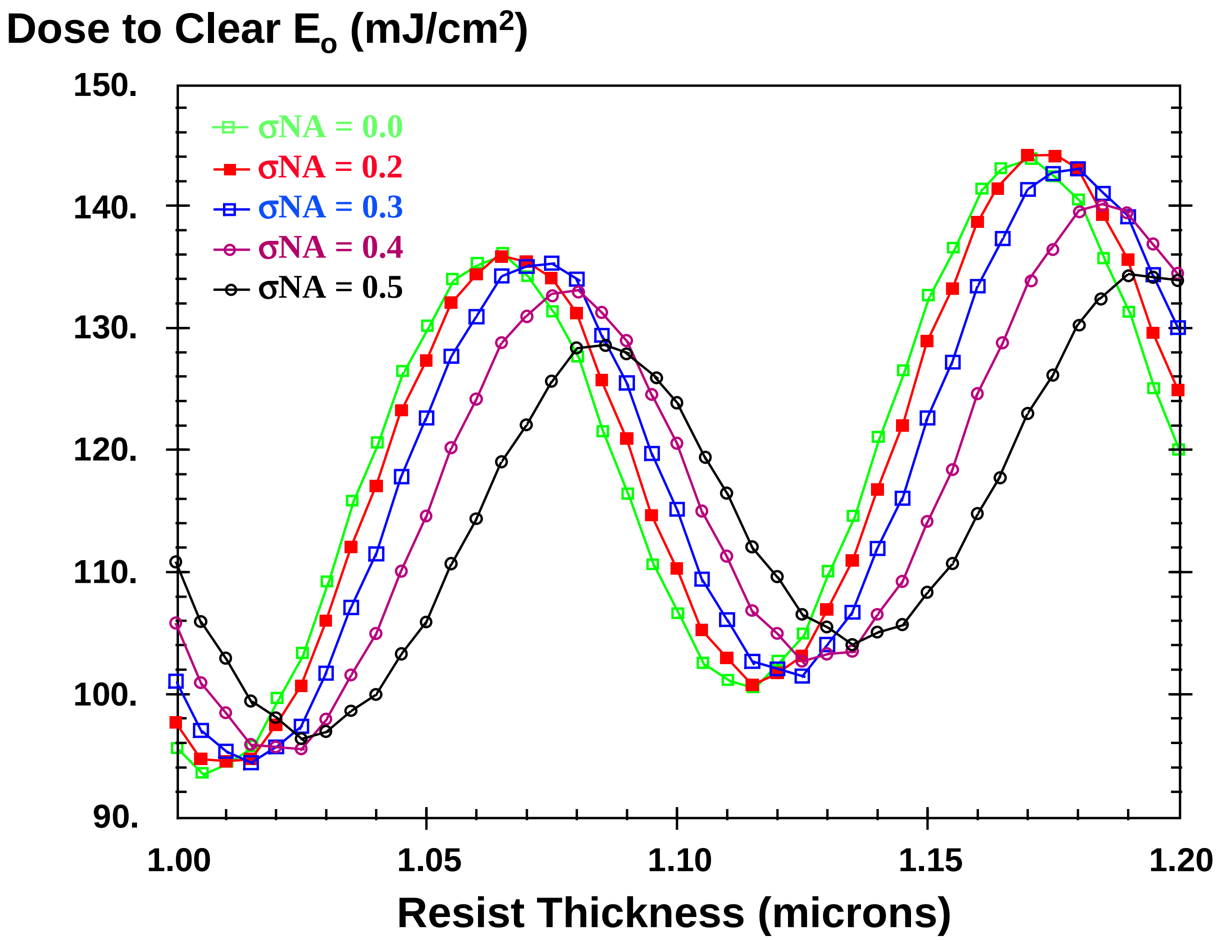


Figure 3. The phase and amplitude of a dose-to-clear swing curve are affected by the range of angles striking the resist, which is controlled by the product of the partial coherence and the numerical aperture (σNA).