Bottom Antireflection Coatings for High Numerical Aperture Imaging

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As we saw in the last edition of this column, bottom antireflective coatings (BARCs) are used extensively to reduce substrate reflectivity, helping to eliminate both standing waves and swing curves. Unfortunately, even a well designed single layer BARC may not be sufficient when a wide range of angles of light are traveling through the resist (see, for example, Figure 1). As a result, BARCs must be designed as a compromise, balancing the normally incident reflectivity against the reflectivity at larger angles and for different polarizations. But what is the best balance? In this column, we'll look at the impact of reflectivity on image formation, and decide on how best to optimize a BARC when printing small features.

Beginning with a very simple case, consider a plane wave traveling through a uniform, non-absorbing material and striking a partially reflective substrate at $z = 0$ (see Figure 2). The plane wave, described by its propagation vector $\vec{k}$, makes an angle θ with respect to the z-axis (which is also the normal to the reflecting surface). Any point in space (*x,z*) is described by its position vector $\vec{r}$. The electric field of the plane wave (before it reflects off the substrate) is then given by

$$E(x,z) = Ae^{-i\vec{k}\cdot\vec{r}} = Ae^{-ik(x\sin\theta + z\cos\theta)} \tag{1}$$

where *A* is the amplitude of the plane wave and the propagation constant *k* is given by $2\pi n/\lambda$ where *n* is the refractive index of the medium. This plane wave will reflect off the substrate with an angle- and polarization-dependent reflectivity $\rho(\theta)$. The total electric field to the left of the substrate is then the sum of the incident and reflected waves. This simple summation brings up the first interesting complication – the effect of polarization, the direction that the electric field is pointing. If the original electric field in equation (1) is *s*-polarized (also called TE polarized) so that the electric field vector points directly out of the plane of Figure 2, then both the incident and reflected electric fields will point in the same direction and the vector sum will equal the scalar (algebraic) sum of the incident and reflected fields.

$$s\text{-polarized:}\quad E(x,z) = Ae^{-ikx\sin\theta}\left(e^{-ikz\cos\theta} + \rho(\theta)e^{+ikz\cos\theta}\right)$$
$$I(x,z) = |E(x,z)|^2 = |A|^2\left(1 + |\rho(\theta)|^2 + 2|\rho(\theta)|\cos(2kz\cos\theta + \phi_\rho)\right) \tag{2}$$

where ϕ_ρ is the phase angle of the complex reflectivity ρ. The amplitude of the standing waves, given by the factor multiplying the cosine in the intensity expression above, is controlled by the magnitude of the electric field reflectivity. For *p*-polarized incident light, the standing wave amplitude is reduced by the factor cos2θ. If θ = 45º, the incident and reflected waves have no overlap of their electric fields and the resulting lack of interference means there will be no standing waves.

An aerial image is formed by the interference of plane waves called diffraction orders. One of the simplest cases to consider is the imaging of small lines and spaces so that only the zero and the two first orders travel through the lens. For coherent illumination, the zero order will be a plane wave traveling in the z-direction, with magnitude a_o. The two first orders will be plane waves each with magnitudes a_1 and traveling at angles given by

$$n\sin\theta = \pm\lambda / p \tag{3}$$

where p is the pitch of the line/space pattern. Ignoring for a moment the reflecting substrate, the image will be formed by the interference (sum) of these three plane waves. Assuming that the image is focused at $z = 0$ (the z position where all three of the plane waves have the same phase), the resulting electric field of the image will be, for s-polarization,

$$E(x,z) = a_o e^{-ikz} + a_1 e^{-ikx\sin\theta} e^{-ikz\cos\theta} + a_1 e^{+ikx\sin\theta} e^{-ikz\cos\theta} \tag{4}$$

This sum can be simplified into a more common and convenient form as

$$\begin{gathered} E(x,z) = e^{-ikz}\left(a_o + 2a_1\cos(2\pi x/p)e^{ikz(1-\cos\theta)}\right) \\ I(x,z) = a_o{}^2 + 4a_o a_1\cos(kz(1-\cos\theta))\cos(2\pi x/p) + 4a_1{}^2\cos^2(2\pi x/p) \end{gathered} \tag{5}$$

Equation (5) is the standard s-polarized three-beam image where z can be interpreted as the distance from best focus. A similar expression for p-polarized illumination can also be derived. If best focus is moved to $z = z_o$, equation (5) can be used by replacing z with $\delta = z - z_o$. To determine the aerial image in the presence of the reflecting substrate, the same procedure is followed as above, but including the reflected plane waves as well. The result is, for s-polarization,

$$E(x,z) = e^{-ikz}\left(a_o\left[1+\rho(0)e^{ik2z}\right] + 2a_1\cos(2\pi x/p)e^{ikz(1-\cos\theta)}\left[1+\rho(\theta)e^{ik2z\cos\theta}\right]\right) \tag{6}$$

In this equation, interference between plane waves causes a variation of the electric field in the x-direction (the image) and a variation in the z-direction (a combination of defocus and standing waves).

Our goal is now to understand how reflectivity, and the variation of reflectivity with angle, affects standing waves in the image. To begin, we'll define a metric I'll call the standing wave amplitude ratio (SWAR), given by

$$SWAR = \frac{I_{\max} - I_{\min}}{4I(\rho = 0)} = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}} \tag{7}$$

where the maximum electric field E_{max} (the peak of the standing wave looking in the z direction) corresponds to the maximum intensity I_{max}, and similarly for the minimum of the standing wave. I(ρ=0) denotes the intensity that would be present if there were no reflecting substrate. Note that the 4 in the denominator allows the metric to range from zero to one. For a single plane wave, such as equation (2), the SWAR is equal to the substrate amplitude reflection coefficient ρ(θ), and would be zero if the BARC were perfect. In fact, the main goal of BARC design is to make the SWAR as close to zero as possible.

For the imaging case, pulling the maximum and minimum values out of equation (6) is complicated by the defocus dependence of the image. If, however, the variation of the image intensity with z caused by defocus is small compared to the standing wave variation (i.e., if the depth of focus is much larger than one standing wave half-period), then an approximate value for the SWAR can be obtained for this three-beam imaging case.

$$SWAR \approx \frac{a_o|\rho(0)| + 2a_1 \cos(2\pi x / p)|\rho(\theta)|}{a_o + 2a_1 \cos(2\pi x / p)} \tag{8}$$

It is very interesting to note that the standing wave amplitude ratio is a function of x. Consider x = 0, the center of the space of the line/space pattern. Here, the SWAR is an average of the zero and first order reflectivities, weighted by the amplitudes of the diffracted orders.

$$SWAR(x = 0) \approx \frac{a_o|\rho(0)| + 2a_1|\rho(\theta)|}{a_o + 2a_1} \tag{9}$$

At $x = p/4$, corresponding to the nominal edge of the feature, the SWAR takes on a very different value.

$$SWAR(x = p/4) \approx |\rho(0)| \tag{10}$$

In other words, the standing waves at the edge of the feature are controlled only by the reflectivity of the zero order! Figure 3 shows an example of how the standing wave amplitude ratio varies with position along the line/space features. Note that equations (8) – (10) and Figure 3 all assume a non-absorbing media. A real resist, with its reasonably high absorption, will reduce the actual SWAR significantly.

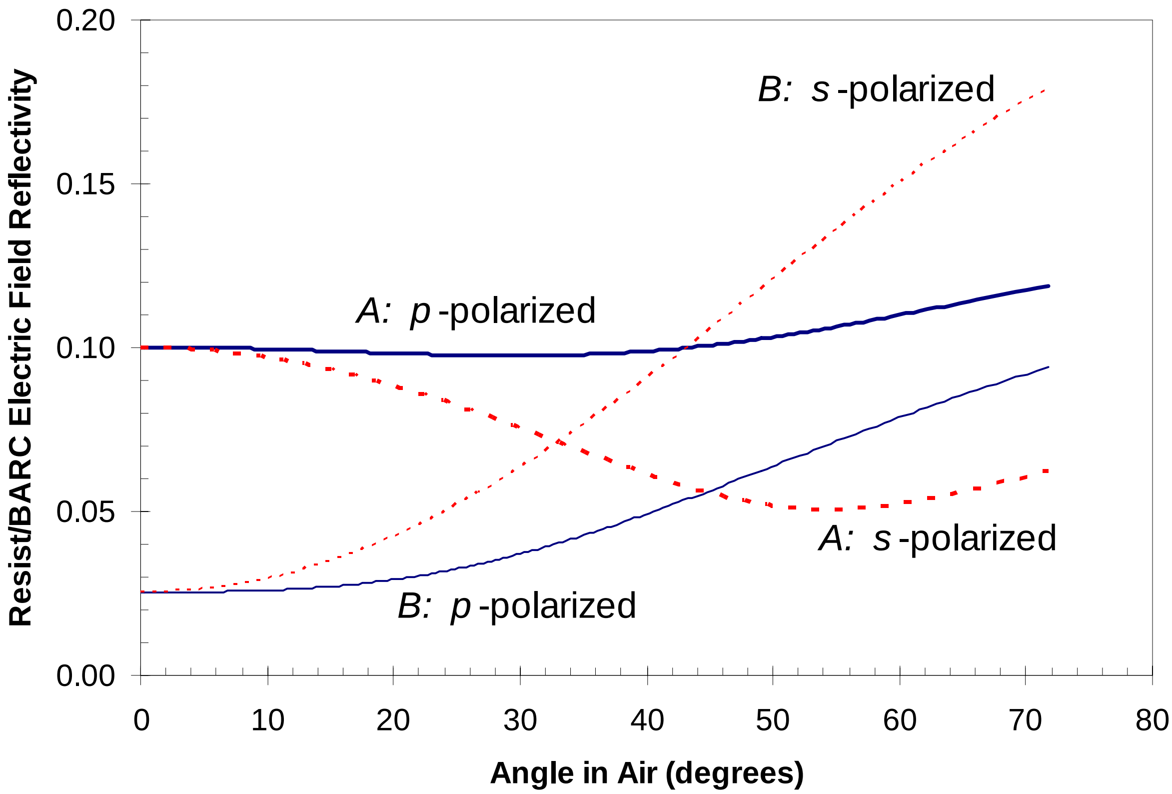
While the mathematics derived above apply to a fairly simple case, the results are appropriate for considering the approach towards optimizing a bottom antireflection coating for three-beam, high numerical aperture imaging (for two beam imaging there is no ambiguity, since there is only one angle to optimize for). Equation (9) shows that standing waves in the middle of the space are controlled by a weighted average of the reflectivities of the zero and first orders (i.e., at zero angle and at the angle of the first orders). However, when considering the more important standing waves at the edge of the feature, only the zero order reflectivity matters. While equation (10) applies to both s- and p-polarized illumination, equation (9) can be modified to approximate p-polarization by replacing a_1 with $a_1\cos\theta$ (to account for reduced interference creating the image) and by adding a cos2θ term to the weighting of the high angle reflectivity (to account for reduced interference in the standing wave formation). Thus, for p-polarization, even the SWAR in the center of the space becomes more heavily weighted to the normally incident reflectivity due to the reduced interference of the large angle first diffracted orders. It seems that designing a BARC by reducing the normally incident reflectivity provides a very good starting point for obtaining the best standing wave control. Beyond this initial design, full lithographic simulation will be required.

Figure Captions:

Figure 1. An example of the variation of BARC reflectivity as a function of light angle and polarization for two different BARCs. The intensity reflectivity is the square of the electric field reflectivity plotted here, but interference makes the field reflectivity a better measure of the standing wave effects. (Resist index = 1.7 - i0.015358, silicon substrate index = 0.883143 - i2.777792, BARC A index = 1.80 - i0.48, BARC A thickness = 30nm, BARC B index = 1.53 - i0.54, BARC B thickness = 39nm.)

Figure 2. Geometry used for describing plane waves and standing waves.

Figure 3. The standing wave amplitude ratio (SWAR) at different positions on the feature for three-beam imaging and *s*-polarization. For this example of three-beam imaging of 100nm lines and spaces, a_o = 0.5, a_1 = 0.3183, $|\rho(0)| = 0.1$, and $|\rho(\theta)| = 0.15$.



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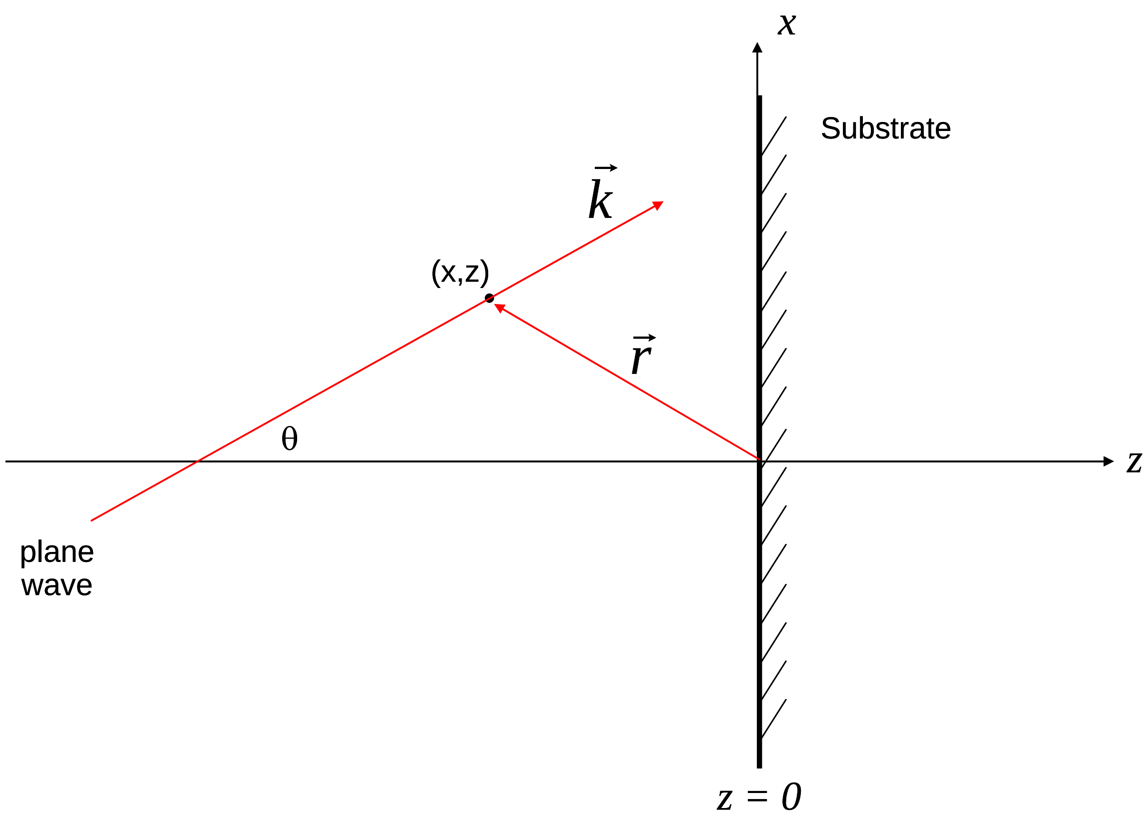

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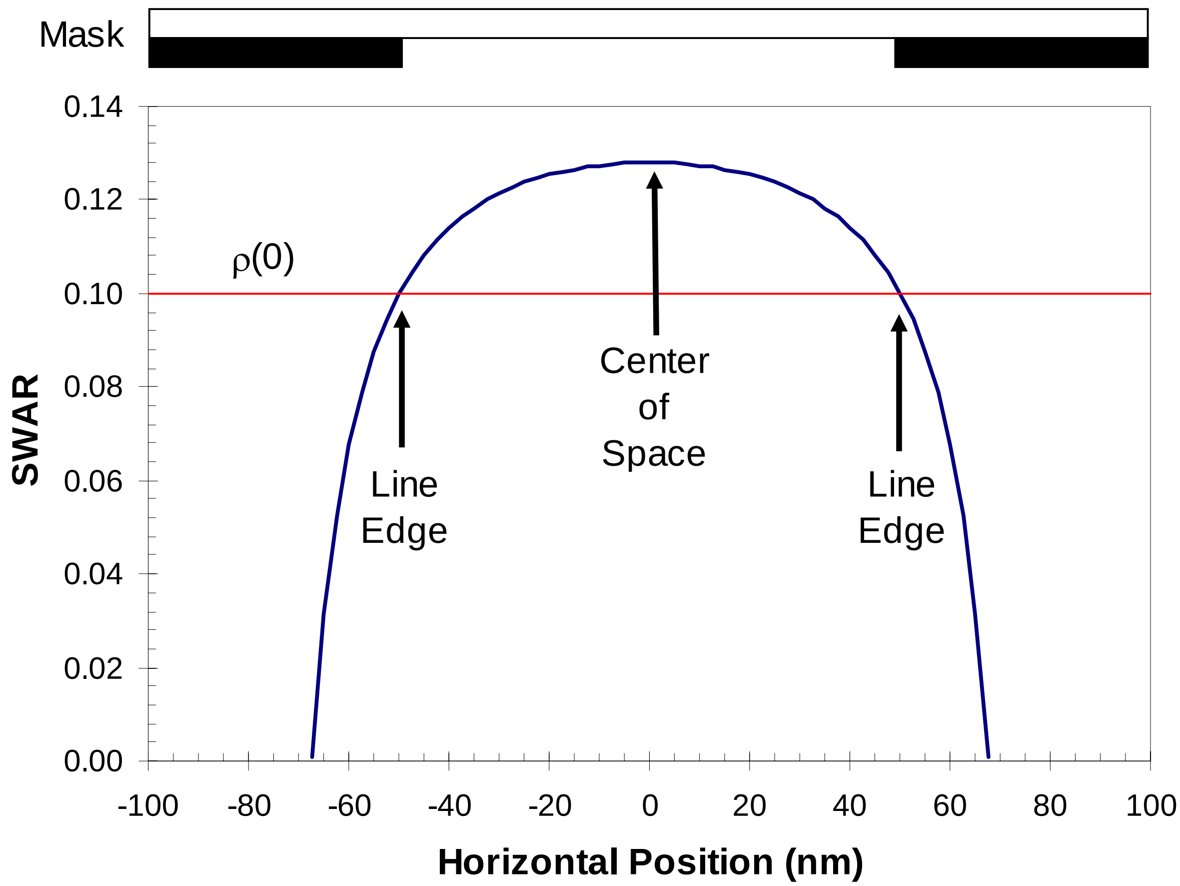

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