The Lithography Expert *(Summer 1997)*

Antireflective Coatings

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As we saw in the last edition of *The Lithography Expert*, reflections from the substrate can cause unwanted variations in the resist profile and swing curve effects (see also *MLW*, Summer 1994). Reflections are caused by a difference in the complex index of refraction of two materials. Since lithography takes place on a variety of substrates with film stacks of many materials and thicknesses, each interface in the film stack can contribute to the overall reflectivity back into the photoresist. This complicated situation is made worse by the inevitable variations in the thicknesses, and sometimes the refractive indices, of the films. One possible solution to reflectivity problems is the bottom antireflection coating (also called bottom ARC or just BARC). Also, swing curves can be improved by the use of a top ARC (or TARC). These types of anti-reflection coatings have somewhat different goals, but their basic behavior is the same.

Consider Figure 1 in which a thin antireflective layer (layer 2) is placed between two thick layers (1 and 3). As we saw in the last *Lithography Expert*, the electric field reflection coefficient (the ratio of reflected to incident electric fields) at the interface between two materials is a function of the complex indices of refraction for the two layers. For normal incidence, the reflection coefficient of light traveling through layer *i* and striking layer *j* is

$$\rho_{ij} = \frac{\mathbf{n}_i - \mathbf{n}_j}{\mathbf{n}_i + \mathbf{n}_j} \qquad (1)$$

where each complex index of refraction has real and imaginary parts ($\mathbf{n}_j = n_j - i\kappa_j$) and the intensity reflectivity is the square of the magnitude of this reflection coefficient. For the film stack of Figure 1, the total reflectivity looking down on layer 2 includes reflections from both the top and bottom of the film. The resulting reflectivity, taking into account all possible reflections, becomes

$$R_{total} = \left|\rho_{total}\right|^2 = \left|\frac{\rho_{12} + \rho_{23}\tau_D^2}{1 + \rho_{12}\rho_{23}\tau_D^2}\right|^2 \qquad (2)$$

where the internal transmittance, τ_D, is the change in the electric field as it travels from the top to the bottom of layer 2, given by

$$\tau_D = e^{-i2\pi \mathbf{n}_2 D/\lambda} \qquad (3)$$

for a layer thickness of *D*. The internal transmittance term adds a sinusoidal dependence of the reflectivity on the thickness of layer 2 due to thin film interference effects.

If the role of layer 2 is to serve as an anti-reflection coating between materials 1 and 3, one obvious requirement might be to minimize the total reflectivity given by equation (2). If the light reflecting off the top of layer 2 (ρ_{12}) can cancel out the light which travels down through layer 2, reflects off layer 3, and then travels back up through layer 2 ($\rho_{23}\tau_D^2$), then the reflectivity can become exactly zero. In other words,

$$R_{total} = 0 \quad when \quad \rho_{12} + \rho_{23}\tau_D^2 = 0 \tag{4}$$

When designing an ARC material, there are only three variables that can be adjusted: the real and imaginary parts of the refractive index of the ARC, and its thickness. One classic solution to equation (4) works very well when the materials 1 and 3 are not very absorbing. It is clear that equation (4) is satisfied when $\tau_D^2 = -1$ and $\rho_{12} = \rho_{23}$. The requirement that $\tau_D^2 = -1$ means that two passes of the light through the ARC causes a 180° phase change with no absorption (since the magnitude is still one). From the definition of the internal transmittance, this means that the ARC thickness must be adjusted to a "quarter wave":

$$D = \frac{\lambda}{4n_2} \tag{5}$$

The requirement that $\rho_{12} = \rho_{23}$ will be satisfied when the index of refraction of the ARC is made to be

$$\boldsymbol{n}_2 = \sqrt{\boldsymbol{n}_1\boldsymbol{n}_3} \tag{6}$$

Further, since the ARC does not absorb (a consequence of $\tau_D^2 = -1$), the imaginary part of its index is zero. Thus, equation (6) can only be true of both materials 1 and 3 have no imaginary parts to their indices of refraction. This classic ARC formulation works perfectly only when the materials in question are transparent.

An antireflection layer defined by equations (5) and (6) will have zero reflectivity. Also, due to the lack of absorption, 100% of the light striking the ARC will be transmitted into layer 3. Thus, this type of ARC is commonly used for coating optical components (such as camera or stepper lenses) where the goal is not so much reducing the reflectivity as it is maximizing the transmittance. The "maximum transmittance" type of ARC is also used for top antireflection coatings, whose job it is to reduce swing curves. This perfect ARC solution, however, is only available for the special case when both layers 1 and 3 are transparent (or nearly so). This is rarely the case when layer 1 is a photoresist and layer 3 is the substrate, such as silicon or some other reflective material. For such a case, the ARC should be made absorbing.

Consider a typical case of resist on ARC on silicon. If the ARC has an index of 1.8 - *i*0.2, the dependence of reflectivity on ARC thickness is given in Figure 2. There are two distinct trends evident in Figure 2. First, absorption in the film causes the reflectivity to decrease as the ARC thickness increases. This bulk absorption roughly follows

$$R \propto e^{-\alpha 2D} \qquad where \qquad \alpha = \frac{4\pi\kappa}{\lambda} \tag{7}$$

Superimposed on this bulk effect is a sinusoidal variation with ARC thickness due to thin film interference with a period of about 102nm ($\lambda/2n$). The amplitude of the oscillations is roughly proportional to $|\rho_{23}|e^{-\alpha D}$.

If the goal of the ARC is to minimize the substrate reflectivity (as it usually is), proper choice of the ARC thickness is very important. Picking the thickness to be at a minimum of the reflectivity curve is an obvious choice. But which minimum? Minimums at greater thicknesses may have lower reflectivity, but the greater ARC thickness often has detrimental effects during ARC etch. The trade-off is application specific, but the second minimum (at about 170nm in this case) is a common choice. As we saw in the last issue of *The Lithography Expert*, the thickness of the ARC can also have a significant impact on the shape of the resist profile.

Improved ARC performance can also be obtained if its index of refraction can be optimized. Some inorganic films in particular can be adjusted in composition to give a wide range of n,κ values that, along with the film thickness, can be used to minimize the reflectivity.

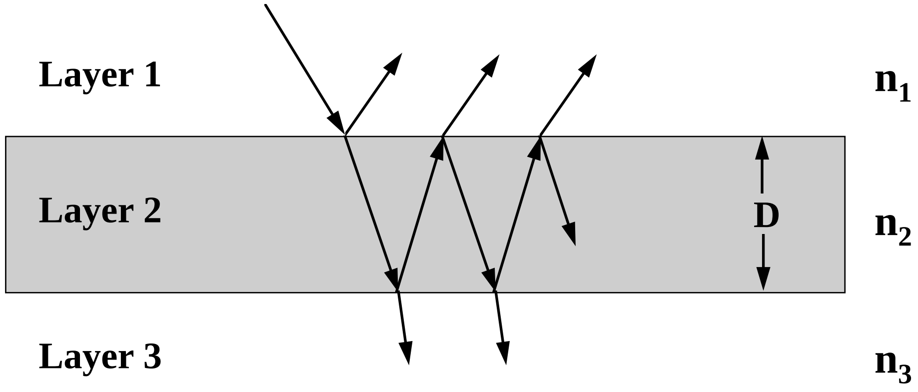

Figure 1. Geometry showing reflections on and within a thin layer (oblique angles shown for illustrative purposes only).

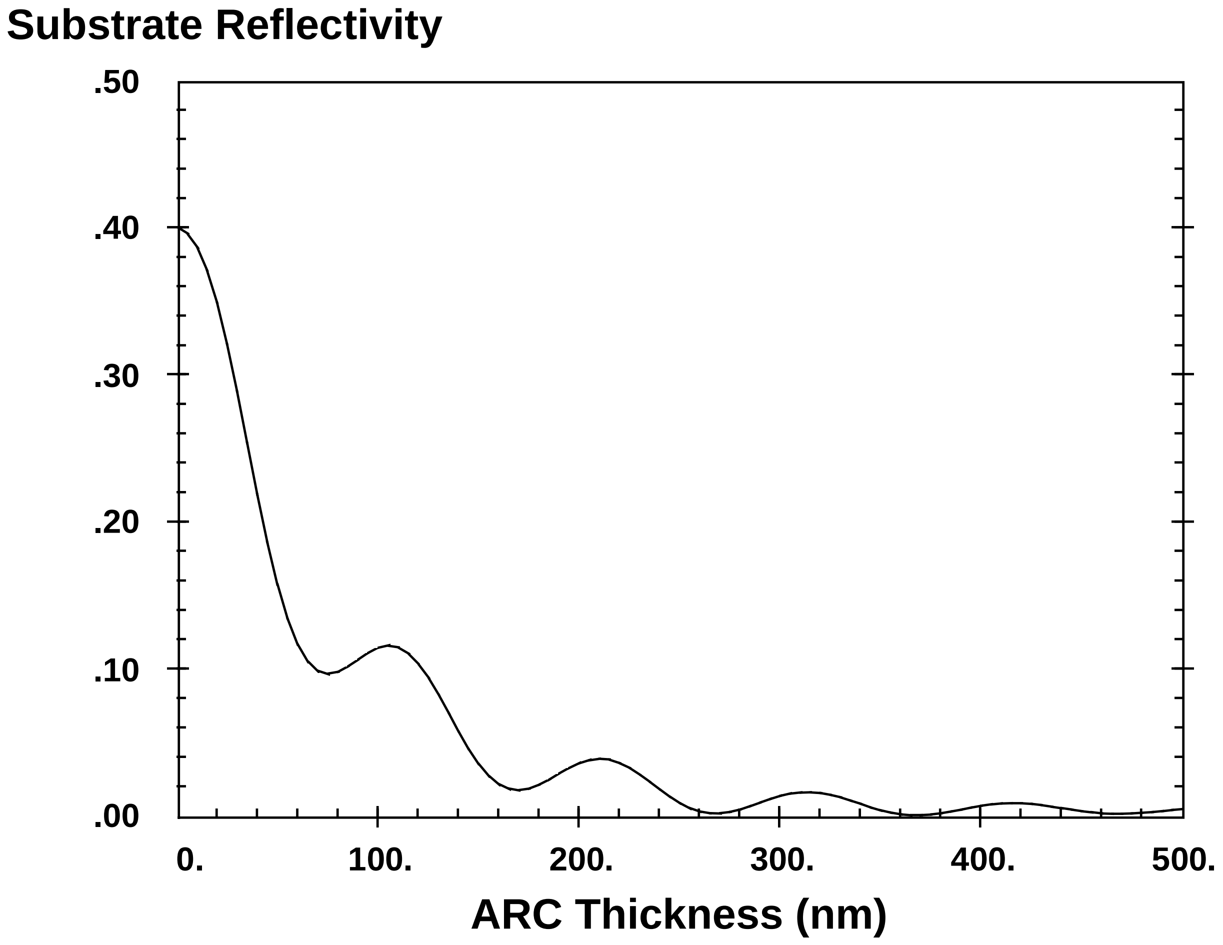

Figure 2. Variation of reflectivity with ARC thickness for resist on ARC (n = 1.8 - i0.2) on silicon.