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Designing a Bottom Antireflection Coating

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As we've seen before in this column (Summer, 1997), antireflective coatings are used extensively to reduce substrate reflectivity, helping to eliminate both standing waves and swing curves. Recapping the basic thin film reflectivity theory, 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

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

where each complex index of refraction has real and imaginary parts ($\boldsymbol{n}_j = n_j - i\kappa_j$) and the intensity reflectivity is the square of the magnitude of this reflection coefficient. For the case of a bottom antireflection coefficient (BARC), assume the BARC (layer 2) is sandwiched between a resist (layer 1) and a very thick substrate (layer 3). The total reflectivity looking down on layer 2 includes reflections from both the top and bottom of the BARC film. The resulting reflectivity, taking into account all possible reflections, is

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

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

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

for a layer thickness of *D*.

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,

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

When designing a BARC material, there are only three variables that can be adjusted: the real and imaginary parts of the refractive index of the BARC, and its thickness. One classic solution to equation (4) works perfectly when the materials 1 and 3 are non-absorbing: let $\tau_D^2 = -1$ and $\rho_{12} = \rho_{23}$. This is equivalent to saying that the BARC thickness is a "quarter wave" ($D = \lambda/4n_2$), and the non-absorbing BARC has a refractive index of $\boldsymbol{n}_2 = \sqrt{\boldsymbol{n}_1\boldsymbol{n}_3}$. While this BARC solution is ideal for applications like antireflective coatings on lens surfaces, it is not particularly useful for common lithography substrates, which are invariably absorbing.

Will a solution to equation (4) always exist, even when the resist and substrate have complex refractive indices? Since all the terms in equation (4) are complex, zero reflectivity occurs when both the real part and the imaginary part of equation (4) are true. This can be made true but adjusting only two of the three BARC parameters (n, κ, and D). In other words, there is not just one solution but a family of solutions to the optimum BARC problem. Expressing each reflection coefficient in terms of magnitude and phase,

$$\rho_{ij} = \left|\rho_{ij}\right| e^{i\theta_{ij}} \tag{5}$$

equation (4) can be expressed as two equalities.

$$D = \frac{\lambda}{4\pi\kappa_2} \ln\left|\frac{\rho_{23}}{\rho_{21}}\right| = \frac{\lambda}{4\pi n_2}\left(\theta_{23} - \theta_{21}\right) \tag{6}$$

Unfortunately, the seemingly simple forms of equations (4) and (6) are deceptive – solving for the unknown complex refractive index of the BARC is exceedingly messy. As a consequence, numerical solutions to equation (4) are almost always used.

Consider a common case of a BARC for 193nm exposure of resist on silicon. The ideal BARC is the family of solutions as shown in Figure 1, which gives the ideal BARC n and κ values as a function of BARC thickness. Each solution produces exactly zero reflectivity for normally incident monochromatic light.

Things become a bit more complicated for the more general case of light traveling at an angle with respect to the film stack normal. In lithographic terms, high numerical apertures allow large ranges of angles to pass through the lens and arrive at the wafer. Off-axis illumination of small pitch patterns produces images made of light concentrated at large angles. Small isolated features with large σ partially coherent illumination create light reaching the wafer over a wide range of angles. And of course, low numerical apertures result in limited ranges of angles reaching the wafer.

How does non-normal incidence affect equation (2)? Each reflection coefficient ρ_{ij} is a function of the angle of light, and a function of polarization. Unpolarized light (the kind most commonly employed in lithographic tools) can be considered as the incoherent sum of two linear and orthogonal polarizations. If θ_i is the incident (and reflected) angle inside the resist and θ_t is the transmitted angle in the BARC, then the electric field reflection and transmission coefficients are given by the Fresnel formulae.

$$\rho_{12\perp} = \frac{\boldsymbol{n}_1 \cos(\theta_i) - \boldsymbol{n}_2 \cos(\theta_t)}{\boldsymbol{n}_1 \cos(\theta_i) + \boldsymbol{n}_2 \cos(\theta_t)}$$

$$\rho_{12\|} = \frac{\boldsymbol{n}_1 \cos(\theta_t) - \boldsymbol{n}_2 \cos(\theta_i)}{\boldsymbol{n}_1 \cos(\theta_t) + \boldsymbol{n}_2 \cos(\theta_i)} \tag{7}$$

Here, $\|$ represents an electric field vector which lies parallel to the plane defined by the direction of the incident light and a normal to the material interface. Other names for $\|$ polarization include *p* polarization and TM (transverse magnetic) polarization. The polarization denoted by $\perp$ represents an electric field vector which lies in a plane perpendicular to that defined by the direction of the incident light and a normal to the surface. Other names for $\perp$ polarization include *s* polarization and TE (transverse electric) polarization. Note that for light normally incident on the resist surface, both *s* and *p* polarization result in electric fields which lie along the resist surface and the Fresnel formulae revert to the standard definition of normal incidence reflection coefficient given in equation (1). Of course, the relationship between incident and transmitted angle is given by Snell's law. The internal transmittance is also a function of angle. Equation (3) can still be used if the BARC thickness is replaced by $D\cos(\theta_t)$.

The requirements for zero reflectivity remain the same. Equation (4) must be satisfied for both *s* and *p* polarization. Since each equation has both real and imaginary parts, there are four constraints that must be satisfied in order to achieve exactly zero reflectivity for unpolarized illumination. However, the BARC film gives us only three degrees of freedom (n, κ, and D). In general, there can be no single BARC film that can make the reflectivity go to zero for a non-normal incident plane wave. Using PROLITH to calculate the unpolarized reflectivity (defined as the average of the individual reflectivities for *s* and *p* polarization), the best case optimum BARC parameters are given in Figure 2 as a function of incident angle (in air, before striking the resist).

Figure 3 shows the lowest possible reflectivity as a function of incident angle, using the optimum BARC parameters defined in Figure 2 for each angle. As can be seen, the best case reflectivity grows rapidly as the angle increases, and is worse for the thinner BARC film. Today's stringent CD control requirements demand reflectivities far below 1%, making BARC design difficult at high numerical apertures with extreme off-axis. One potential solution, though not pleasant from a cost and complexity perspective, is to increase the number of free variables available for optimization by using a two-layer BARC. This technique, a standard practice in antireflective coatings for lenses, would provide enough adjustable parameters to make the reflectivity go to zero at normal incidence and at one angle, thus providing low reflectivity over a wide range of angles. This approach may become necessary with the advent of immersion lithography and numerical apertures greater than 1.0.

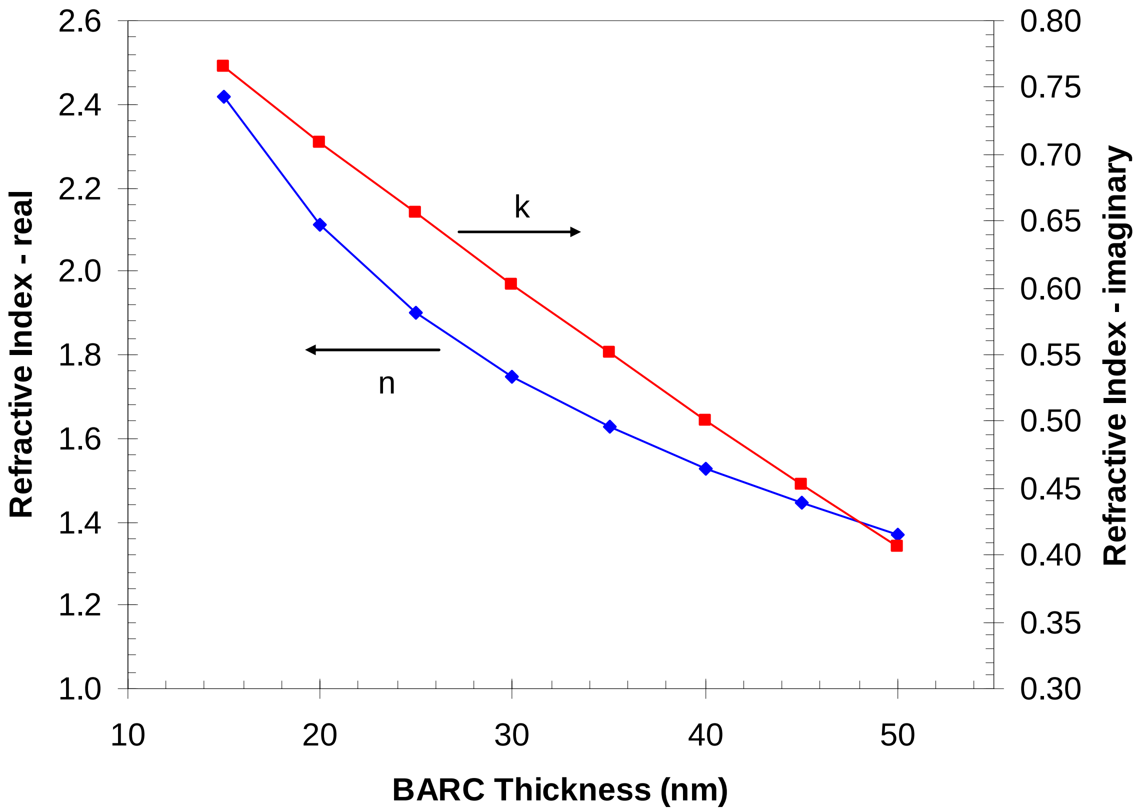
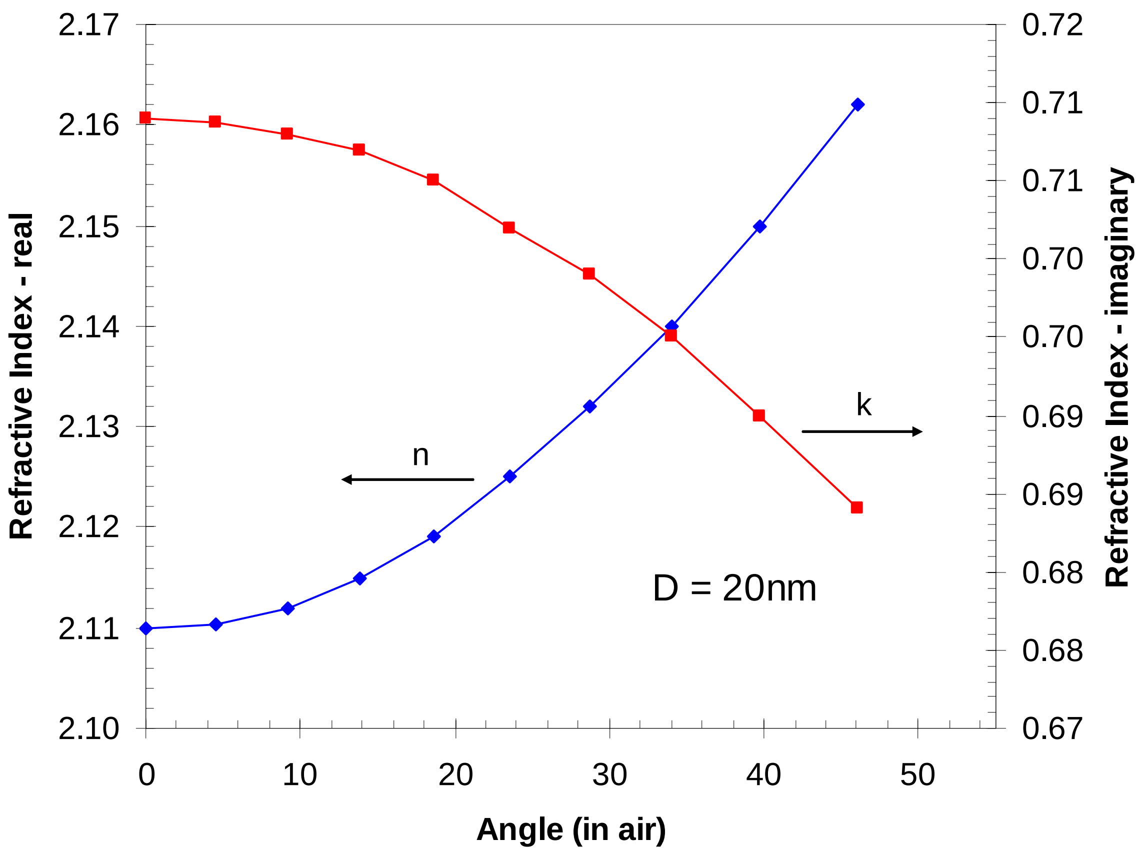
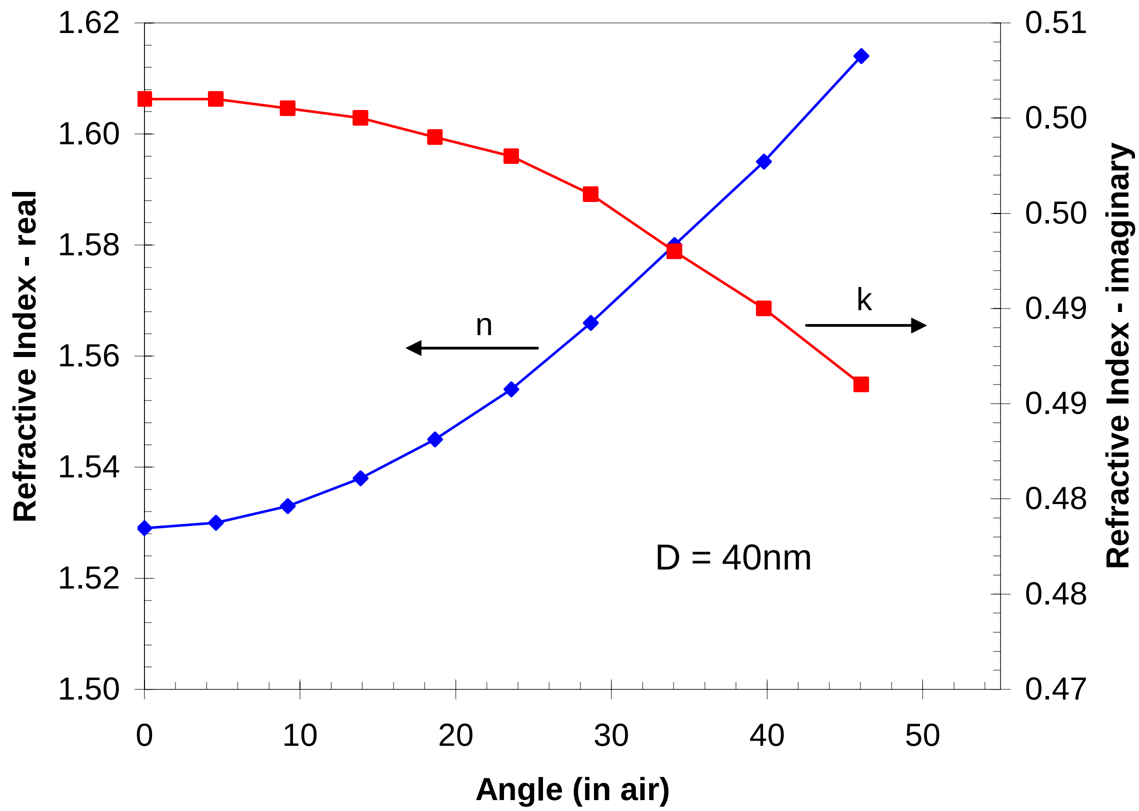


Figure 1. Optimum BARC refractive index (real and imaginary parts, *n* and κ) as a function of BARC thickness for normal incidence illumination (resist index = 1.7 - *i*0.015358 and silicon substrate index = 0.883143 - *i*2.777792) at 193nm.



2.17
2.16
2.15
2.14
2.13
2.12
2.11
2.10
0.72
0.71
0.71
0.70
0.70
0.69
0.69
0.68
0.68
0.67
0
10
20
30
40
50
Refractive Index - real
Refractive Index - imaginary
Angle (in air)
n
k
D = 20nm

(a)



(b)

Figure 2. Optimum BARC parameters to achieve minimum substrate reflectivity as a function of incident angle (angle defined in air, before entering the photoresist) for two different BARC thicknesses.

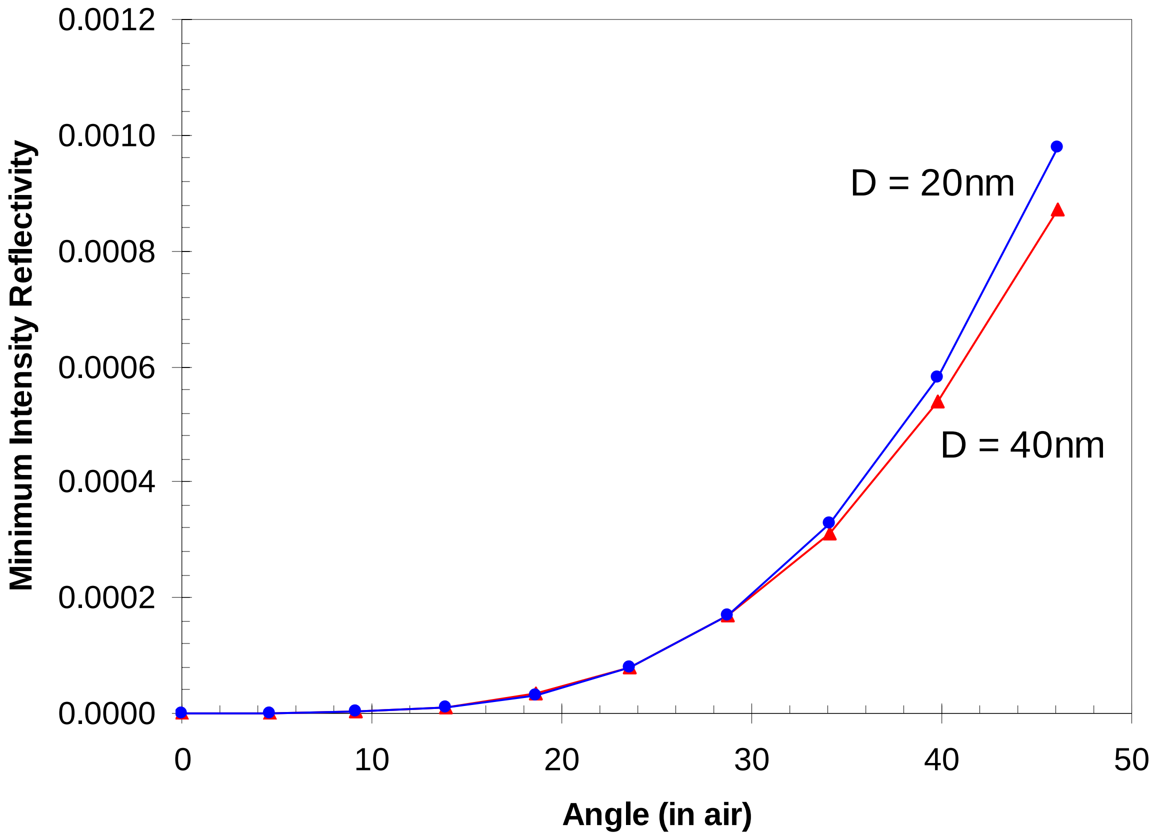


Figure 3. The best case (minimum) reflectivity (using the BARC parameters shown in Figure 2) of the substrate as a function of incident angle for 20nm and 40nm thick BARC films.