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Absorption and Reflectivity: Designing the Right Photoresist

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By their very nature, photoresists must absorb some portion of the exposing radiation in order to undergo a photochemical reaction. Thus, absorption of light is an indispensable part of photoresist design. However, absorption also means that light traveling through the thickness of the resist will attenuate as it travels. As a consequence, the bottom of the photoresist receives a smaller exposure dose than the top, leading to different feature sizes and process sensitivities for the top of the photoresist profile compared to the bottom. The most obvious result of this absorption is sloped photoresist profiles. Also, as we have seen in this column before (*MLW*, Summer, 1994), absorption has a strong effect on the magnitude of the swing curve for lithography on reflective substrates. In light of these many factors, what is the optimum absorption in a photoresist?

As we shall see, the optimum resist absorption is a strong function of the reflectivity of the substrate. Consider first, however, the simple case of a non-reflecting substrate so that light travels only downward through a resist film of thickness D. The absorption of light through the resist leads to an exposure dose error: a smaller dose at the bottom of the resist (E_{bottom}) compared to the top (E_{top}). The fraction of light making it to the bottom is given by

$$\frac{E_{bottom}}{E_{top}} = T_D = e^{-\alpha D} \qquad (1)$$

where α is the resist absorption coefficient, which is assumed to be constant through the resist film. As an example, for a resist with $\alpha = 0.5\mu m^{-1}$, a 1 micron thick film will absorb 40% of the light so that $T_D = 0.6$.

If the resist film is coated on a reflective substrate, reflected light traveling up through the film will also be absorbed. The reflected beam will be brighter at the bottom of the resist, so that the sum of the incident and reflected beams will have a smaller variation in dose from top to bottom than for the non-reflective substrate case. The amount can be quantified using an expression for the intensity distribution through the resist derived $I(z)$ in a previous edition of this column (*MLW*, Spring, 1994):

$$I(z) \approx \left[e^{-\alpha z} + |\rho_{23}|^2 e^{-\alpha(2D-z)} \right] - 2|\rho_{23}| e^{-\alpha D} \cos(4\pi n_2 (D-z)/\lambda) \qquad (2)$$

where z is the depth into the resist ($z = 0$ is the top of the resist), n_2 is the real part of the resist refractive index, λ is the vacuum wavelength of the exposing light, and ρ_{23} is the electric field reflection coefficient between the resist and the substrate (the intensity reflectivity is $\left|r_{23}\right|^2$). The cosine term describes the standing waves that inevitably result from the interference of incident and reflected beams. The period of the standing waves is $\lambda/4n_2$, which is typically much smaller than the thickness of the resist. For such a case, the "bulk" intensity variation can be thought of as the actual intensity given by equation (2) averaged over a period of the standing wave. Thus, this bulk variation would just be the term in the square brackets of equation (2). Normalizing this quantity to the intensity at the top gives a bulk intensity variation:

$$I_{bulk}(z) = e^{-a z}\left(\frac{1+\left|r_{23}\right|^2 e^{-a2D}\, e^{a2z}}{1+\left|r_{23}\right|^2 e^{-a2D}}\right) \tag{3}$$

The term $\left|r_{23}\right|^2 e^{-a2D}$ represents the fraction of light that makes it back to the top of the resist after traveling down through the resist, reflecting off the substrate, and traveling back up to the top. It can be thought of as a "round-trip" transmittance and is an important factor in determining the difference between equation (3) and simple bulk absorption.

For small amounts of absorption ($\alpha 2D < 1$, for example), the z dependent exponential term in the parentheses of equation (3) can be expanded as Taylor series and an approximate expression for the bulk effect can be derived:

$$I_{bulk}(z) \approx e^{-a_{eff}\, z} \tag{4}$$

where the effective absorption coefficient is given by

$$a_{eff} = a\left(\frac{1-\left|r_{23}\right|^2 e^{-a2D}}{1+\left|r_{23}\right|^2 e^{-a2D}}\right) \tag{5}$$

As discussed above, a more reflective substrate actually reduces the bulk intensity variation through the resist, which is expressed here as a lower effective absorption coefficient.

How can equation (5) be used when designing resists for different reflectivity applications? One simple design criterion might be to fix the effective absorption coefficient. Suppose that a 0.7 µm thick deep-UV resist with an absorption coefficient of 0.4 μm^{-1} is currently providing acceptable resist profile results on a silicon wafer ($\left|r_{23}\right|^2 = 0.5$). In other words, for the parameters given, the effective absorption provides an acceptably dose variation from the top to the bottom of the resist. From equation (5), the effective absorption coefficient is 0.22 μm^{-1}. Thus, for a resist to have approximately the same profile behavior on a perfectly non-reflecting substrate, its absorption coefficient would have to be lowered to this 0.22 μm^{-1} value. On the other hand, if you wanted to use an equivalent resist on an aluminum substrate with a reflectivity of 0.84 (not necessarily a good idea, given the swing curve effects), you could raise the absorption coefficient to 0.52 μm^{-1} and still exhibit the same effective absorption.

Of course, the impact of absorption and reflection on the photoresist profile is not the only lithographic effect to consider. The amplitude of the swing curve is approximately given by [1]

$$\textit{swing amplitude} \approx 4\left|r_{12}\, r_{23}\right| e^{-a D} \qquad (6)$$

where ρ_{12} is the electric field reflection coefficient for the air-resist interface. Combinations of substrate reflectivity and absorption that give the same effective absorption coefficient will not give the same swing amplitude, and vice versa. Only by adding the ability to vary ρ_{12} (with a top antireflection coating) is there enough flexibility to meet arbitrary effective absorption and swing amplitude criterion.

The choices in resists and antireflection coatings facing the lithography process designer are becoming increasingly varied, with “designer” resists geared toward specific making levels. The concept of the effective absorption adds a simple design variable to be considered.

References

1. T. A. Brunner, “Optimization of Optical Properties of Resist Processes,” *Advances in Resist Technology and Processing VIII, Proc.*, SPIE Vol. 1466 (1991) pp. 297-308.