

Swing Curves

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In the last edition of this column, we saw that exposing a photoresist involves the propagation of light through a thin film of partially absorbing material (the resist) coated on a substrate which is somewhat reflective. The result was *thin film interference effects* including standing waves. The existence and importance of standing waves in lithography were reported just as single wavelength projection printing was becoming viable [1-3]. Fortunately, most novolak based positive resists provided a simple way to eliminate the effects of standing waves on the shape of the photoresist profile: diffuse them away with a post-exposure bake [4]. Although the problem seemed to be solved, a less obvious but more important result of thin film interference was soon to be noticed: *swing curves* [5].

Generically, a swing curve is the sinusoidal variation of some lithographic parameter with resist thickness. There are several parameters which vary in this way, but the most important is the critical dimension (CD) of the photoresist feature being printed. Figure 1 shows a typical CD swing curve for *i*-line exposure of a 0.5 μm line on silicon. The change in linewidth is quite large (more than the typical 10% tolerance) for relatively small changes in resist thickness. Another swing curve is the E_0 swing curve, showing the same sinusoidal swing in the photoresist dose-to-clear (Figure 2). For a resist thickness which requires a higher dose-to-clear, the photoresist will, as a consequence, require a higher dose to achieve the desired line size. But if the exposure dose is fixed (as it was for the CD swing curve), the result will be an underexposed line which prints too large. Thus, it follows that the E_0 and CD swing curves result from the same effect. The final swing curve measures the reflectivity of the resist coated wafer as a function of resist thickness (Figure 3). Although reflectivity is further removed from lithographic metrics such as E_0 or CD, it is the reflectivity swing curve which provides the most insight as to the cause of the phenomenon.

The reflectivity swing curve shows that variations in resist thickness result in a sinusoidal variation in the reflectivity of the resist coated wafer. Since the definition of reflectivity is the total reflected light intensity divided by the total incident intensity, an increase in reflectivity results in more light which does not make it into the resist. Less light being coupled into the resist means that a higher dose is required to affect a certain chemical change in the resist, resulting in a larger E_0 . Thus, the E_0 and CD swing curves can both be explained by the reflectivity swing curve. (The interested reader can convince him/herself that the phases of Figures 1-3 make sense with respect to each other.)

What causes the reflectivity swing curve of Figure 3? Of course, the answer lies in the thin film interference effects that were discussed in the last edition of this column. Using the

same simple geometry shown in Figure 4a, a thin photoresist (layer 2) rests on a thick substrate (layer 3) in air (layer 1). Each material has optical properties governed by its complex index of refraction, $\mathbf{n} = n - i\kappa$. If we illuminate this film stack with a monochromatic plane wave normally incident on the resist, the analysis given before can be used to determine the standing wave intensity within the resist. However, our goal here is to determine the total light reflected by the film stack. As shown in Figure 4b, the total reflected light is made up of the incident beam reflecting off the air-resist interface and beams that have bounced off of the substrate and then were transmitted by the air-resist interface.

Let's begin by writing an expression for the electric field of the ray which is directly reflected by the air-resist interface. Recalling the definitions used in the last column,

$$E_{r0} = \rho_{12} E_I \quad (1)$$

where E_I is the incident electric field and ρ_{12} is the reflection coefficient of the air-resist interface. The next "reflected" beam is transmitted into the resist, reflected off the substrate, and transmitted into the air. The result, denoted as E_{r1} , is given by

$$E_{r1} = T_{12} E_I \rho_{23} \tau_D^2 \quad (2)$$

where T_{12} is the transmittance of the air-resist interface ($= \tau_{12} \tau_{21}$), ρ_{23} is the reflection coefficient of the substrate, and τ_D is the internal transmittance of the resist. The next reflected beam makes two bounces inside the resist before being transmitted out, resulting in an additional $\rho_{21} \rho_{23} \tau_D^2$ term.

The total reflection coefficient can be computed by totaling up all the reflected electric fields and then dividing by the incident field.

$$\rho_{total} = \frac{E_{ri}}{E_I} = \rho_{12} + \frac{T_{12} \rho_{23} \tau_D^2}{1 + \rho_{12} \rho_{23} \tau_D^2} = \frac{\rho_{12} + \rho_{23} \tau_D^2}{1 + \rho_{12} \rho_{23} \tau_D^2} \quad (3)$$

The reflectivity of the film stack is the square of the magnitude of the reflection coefficient. At first glance, the sinusoidal dependence of reflectivity with resist thickness is not obvious from equation (3). The dependence is contained in the internal transmittance:

$$\tau_D = e^{-i2\pi n_2 D / \lambda} \quad (4)$$

where n_2 is the complex index of refraction of the resist, λ is the wavelength, and D is the resist thickness. Carrying out the calculation of reflectivity is simplified for the case when ρ_{12} and ρ_{23} are real, giving

$$R = \frac{|\rho_{12}|^2 + |\rho_{23}|^2 e^{-\alpha 2D} + 2|\rho_{12}\rho_{23}|e^{-\alpha D} \cos(4\pi n_2 D / \lambda)}{1 + |\rho_{12}\rho_{23}|^2 e^{-\alpha 2D} + 2|\rho_{12}\rho_{23}|e^{-\alpha D} \cos(4\pi n_2 D / \lambda)} \quad (5)$$

The discussion so far has been mostly mathematical. Equation (3) gives a rigorous result which, when expressed as equation (5), leads to an understanding of the reflectivity swing curve. Physically, the reflectance swing curve is the result of interference among the reflected rays. As pictured in Figure 4b, the total reflected field is the sum of the various rays. How the initially reflected ray E_{ro} adds to the first transmitted and reflected ray E_{r1} depends on the phase of E_{r1} , which in turn depends on the resist thickness. At some thickness E_{r1} will be in phase with E_{ro} , resulting in a maximum reflectivity. At another thickness E_{r1} will be out of phase with E_{ro} , resulting in a minimum reflectivity.

Equation (5) can also lead to a better understanding of swing curves. The period of all of the swing curves can be easily obtained from equation (5) and is the same as the period of the standing waves in the photoresist:

$$Period = \lambda / 2n_2 \quad (6)$$

Likewise, the effects of increasing or reducing the reflectivities can be seen. If the substrate is non-reflective ($\rho_{23} = 0$), the film stack reflectivity becomes constant. Thus, a bottom antireflection coating can reduce or eliminate the swing curve. Less obviously, if $\rho_{12} = 0$ the reflectivity will also become constant, eliminating the swing curve. This can be achieved by using a top antireflection coating. Physically, if the swing curve results from interference between E_{ro} and E_{r1} , eliminating E_{ro} will eliminate the interference and the swing. Finally, absorption in the resist will reduce the coefficients of the cosines in equation (5), reducing the swing curve as well.

Swing curves are extremely important in lithography for one simple reason: topography on the wafer leads to variations in resist thickness on the order of a period in the swing curve or more. In many leading edge fabs, these effects are the leading cause of CD errors on some critical mask levels. In the next edition of the *Lithography Tutor*, we'll look at the development step for conventional positive resists.

References

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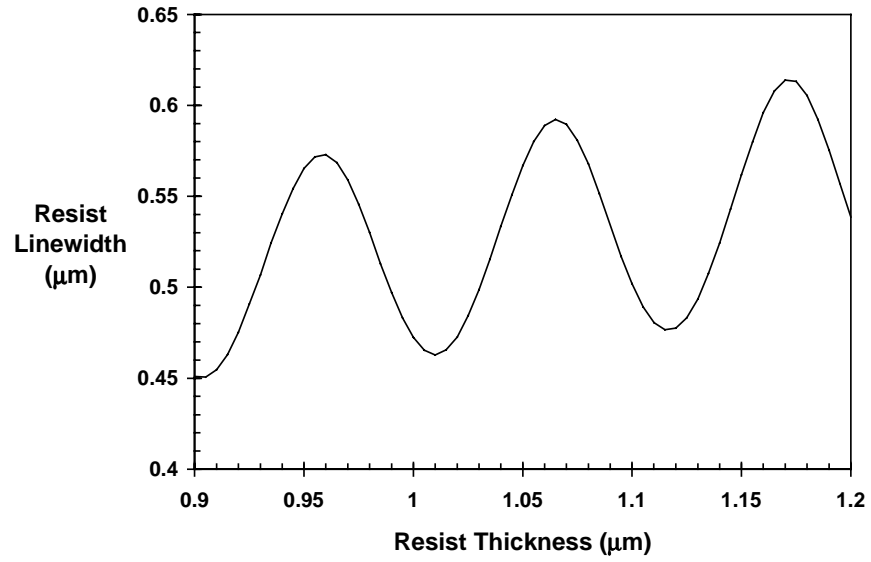


Figure 1. CD swing curve showing a sinusoidal variation in the resist linewidth with resist thickness.

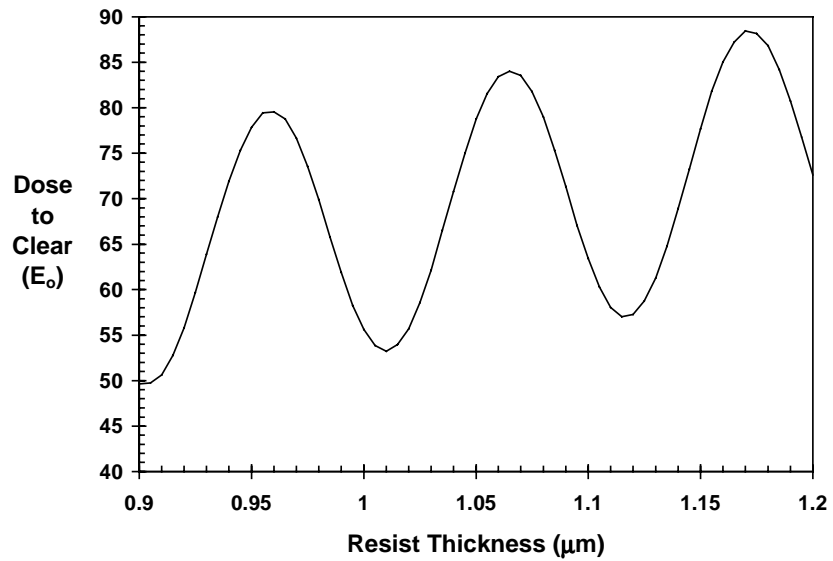


Figure 2. E₀ swing curve showing a sinusoidal variation in the resist dose-to-clear with resist thickness.

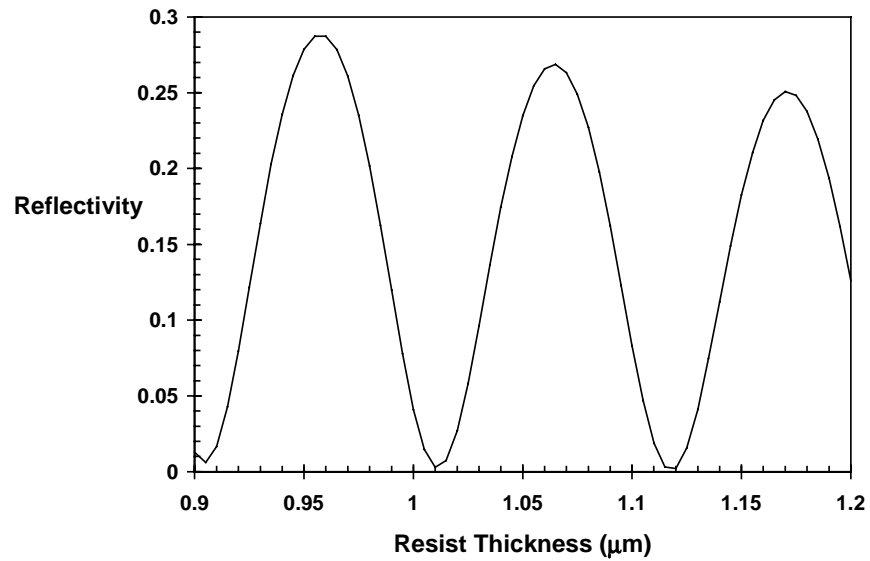


Figure 3. Reflectivity swing curve showing a sinusoidal variation in the resist coated wafer reflectivity with resist thickness.

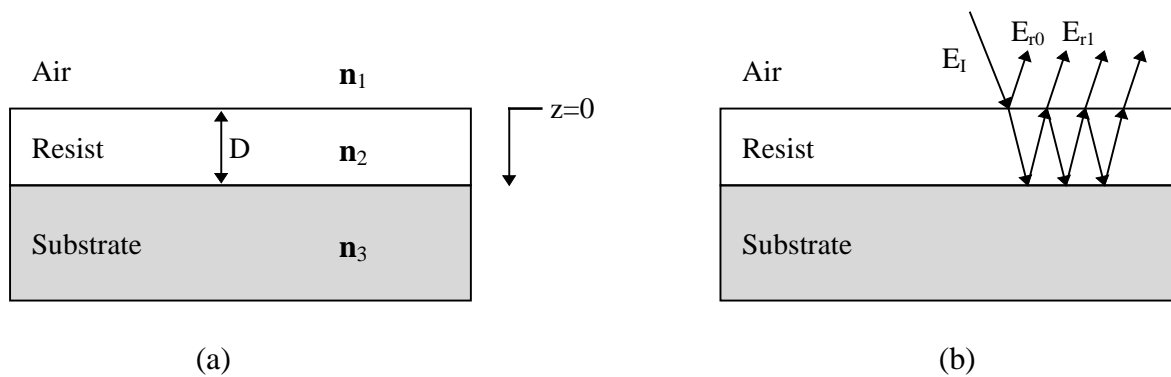


Figure 4. Film stack showing geometry for swing curve derivation (oblique angles in (b) are shown for diagrammatical purposes only).