

Standing Waves in Photoresist

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The energy which exposes a photoresist is not the energy incident on the top surface of the resist, but rather the energy which has propagated into the photoresist. Of course, exposure leads to chemical changes which modify the solubility of the resist in developer and so a knowledge of the exact exposure inside the resist is essential. The propagation of light through a thin film of partially absorbing material coated on a substrate which is somewhat reflective is a fairly well known problem and results in various *thin film interference effects* including standing waves.

In previous issues of this column, I have tended to avoid overly mathematical descriptions, trying instead to describe various phenomena on a more physical level. In this column I will use a different approach: we will build up a mathematical description of standing waves in photoresist and then glean physical insight from the equations which result. My purpose here is to show that equations are merely descriptions of physics, and that the proper interpretation of an equation can be invaluable.

Let us begin with the simple geometry shown in Figure 1a. 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, $\mathbf{n} = n - i\kappa$, where n is the real index of refraction and κ , the imaginary part, is called the extinction coefficient. This latter name comes from the relationship between the imaginary part of the refractive index and the absorption coefficient of the material:

$$\alpha = \frac{4\pi\kappa}{\lambda} \quad (1)$$

where α is the absorption coefficient and λ is the wavelength.

Consider now the propagation of light through this simple film stack. We will begin with simple illumination of the stack by a monochromatic plane wave normally incident on the resist. When this plane wave strikes the resist surface, some of the light will be transmitted and some will be reflected. The amount of each is determined by the transmission and reflection coefficients. Defined as the ratio of the transmitted to incident electric field, the *transmission coefficient* τ_{ij} for a normally incident plane wave transmitting from layer i to layer j is given by

$$\tau_{ij} = \frac{2n_i}{n_i + n_j} \quad (2)$$

In general, the transmission coefficient will be complex, indicating that when light is transmitted from one material to another, both the magnitude and the phase of the electric field will change. Similarly, the light reflected off layer j back into layer i is given by the *reflection coefficient* ρ_{ij} :

$$\rho_{ij} = \frac{\mathbf{n}_i - \mathbf{n}_j}{\mathbf{n}_i + \mathbf{n}_j} \quad (3)$$

If an electric field E_I is incident on the photoresist, the transmitted electric field will be given by $\tau_{12}E_I$.

The transmitted plane wave will now travel down through the photoresist. As it travels, the wave will change phase sinusoidally with distance and undergo absorption. Both of these effects are given by the standard description of a wave as a complex exponential:

$$E(z) = e^{-i2\pi z/\lambda} \quad (4)$$

where $E(z)$ represents a plane wave traveling in the $+z$ direction. Using the coordinates defined in Figure 1a, the transmitted electric field propagating through the resist, E_0 , will be given by

$$E_0(z) = \tau_{12}E_I e^{-i2\pi z/\lambda} \quad (5)$$

Eventually, the wave will travel through the resist thickness D and strike the substrate, where it will be partially reflected. The reflected wave, E_1 , just after reflection will be

$$E_1(z = D) = \tau_{12}E_I \rho_{23} e^{-i2\pi D/\lambda} \quad (6)$$

The complex exponential term in the above equation has some physical significance: it represents the electric field transmitted from the top to the bottom of the photoresist and is called the *internal transmittance* of the resist, τ_D .

$$\tau_D = e^{-i2\pi D/\lambda} \quad (7)$$

As the reflected wave travels back up through the resist, the distance traveled will be $(D-z)$ and the propagation will be similar to that described by equation (4):

$$E_1(z) = \tau_{12}E_I \rho_{23}\tau_D e^{-i2\pi(D-z)/\lambda} = \tau_{12}E_I \rho_{23}\tau_D^2 e^{i2\pi z/\lambda} \quad (8)$$

So far, our incident wave (E_I) has been transmitted in the photoresist (E_0) and then reflected off the substrate (E_1), as pictured in Figure 1b. The total electric field in the photoresist will be the sum of E_0 and E_1 . Before evaluating mathematically what this sum will be, consider the physical result. When two waves are added together, we say that the waves *interfere* with each other. If the waves are traveling in opposite directions, the result is a classical *standing wave*, a wave whose phase is fixed in space (as opposed to a traveling wave whose phase

changes). Of course, we would expect the mathematics to confirm this result. The sum of the two waves in the resist is

$$E_{sum}(z) = \tau_{12}E_I \left(e^{-i2\pi n_2 z/\lambda} + \rho_{23}\tau_D^2 e^{i2\pi n_2 z/\lambda} \right) \quad (9)$$

In reality, this sum is not the total electric field in the photoresist. The wave E_I will travel to the top of the resist where it will be reflected by the air-resist interface. The new wave, E_2 , will travel down through the resist where it will be reflected by the substrate, giving another wave E_3 . This process will continue infinitely, each reflected wave being smaller than the previous wave. The total electric field will be an infinite sum of the reflected waves bouncing up and down in the resist. Fortunately, this infinite sum is easy to evaluate. The pair of waves E_2 and E_3 have exactly the same form as the waves E_0 and E_I , differing only by a multiplicative constant. The infinite sum will become just a geometric series, which has a well-known limit. The total electric field in the resist will be [1]

$$E_{total}(z) = \frac{\tau_{12}E_I \left(e^{-i2\pi n_2 z/\lambda} + \rho_{23}\tau_D^2 e^{i2\pi n_2 z/\lambda} \right)}{1 + \rho_{12}\rho_{23}\tau_D^2} \quad (10)$$

Equation (10) is an exact expression for the electric field within the resist assuming a normally incident plane wave of illumination. Although we assumed the resist was on a single substrate, in fact any number of layers below the resist do not affect the form of the result. Equation (10) still applies if an effective reflection coefficient is used in place of ρ_{23} . This effective reflection coefficient can be easily determined for any film stack [1]. If the illumination is at an angle, or over a range of angles, equation (10) needs only slight modification.

Although we have determined an expression for the standing wave electric field, it is the intensity of the light which causes exposure. Calculation of intensity from equation (10) leads to a fairly messy result, but some simplifications allow for a reasonably useful form:

$$I(z) \approx \left(e^{-\alpha z} + |\rho_{23}|^2 e^{-\alpha(2D-z)} \right) - 2|\rho_{23}| e^{-\alpha D} \cos(4\pi n_2(D-z)/\lambda) \quad (11)$$

This equation is graphed in Figure 2 for a photoresist with typical properties on a silicon substrate. By comparing the equation to the graph, many important aspects of the standing wave effect become apparent. The most striking feature of the standing wave plot is its sinusoidal variation. The cosine term in equation (11) shows that the period of the standing wave is given by

$$Period = \lambda / 2n_2 \quad (12)$$

The amplitude of the standing waves is given by the multiplier of the cosine in equation (11). It is quite apparent that there are two ways to reduce the amplitude of the standing wave intensity. The first is to reduce the reflectivity of the substrate (reduce ρ_{23}). Of course, the use of an anti-reflection coating (ARC) is one of the most common methods of reducing standing waves. The

second method for reducing the standing wave intensity that equation (11) suggests is to increase absorption in the resist (reduce the $e^{-\alpha D}$ term). This is accomplished by adding a dye to the photoresist (increasing α).

The above discussion is an excellent example of how a purely mathematical analysis, which may seem dry and less than intuitive, can lead to important physical conclusions. In this case, the methods available to reduce standing waves become obvious after examining an analytical equation for the standing wave intensity. Other important effects can also be deduced, such as the influence of an ARC on bulk absorption (the first term in parentheses on the right hand side of equation (11)). In the next edition of the *Lithography Tutor*, the discussion of standing waves will be expanded to include the thin film interference effects which lead to swing curves.

References

1. C. A. Mack, "Analytical Expression for the Standing Wave Intensity in Photoresist", *Applied Optics*, Vol. 25, No. 12 (15 June 1986) pp. 1958-1961.

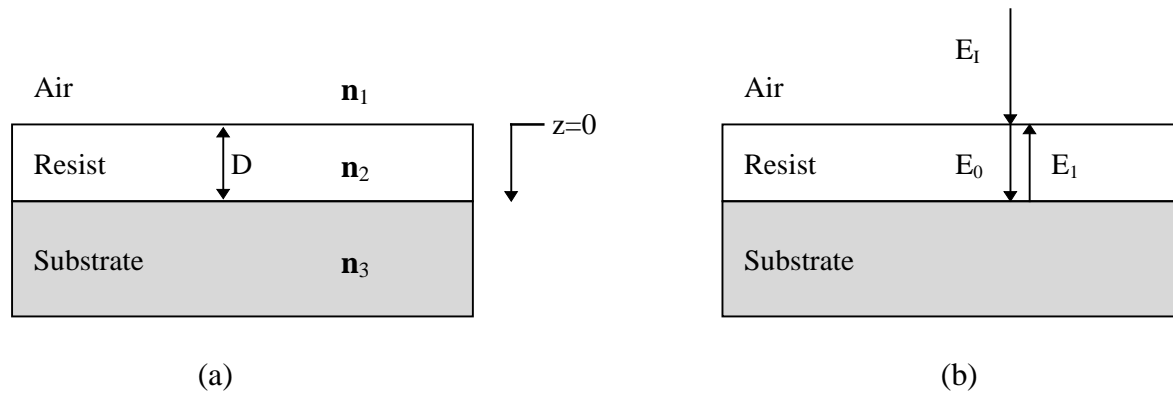


Figure 1. Film stack showing geometry for standing wave derivation.

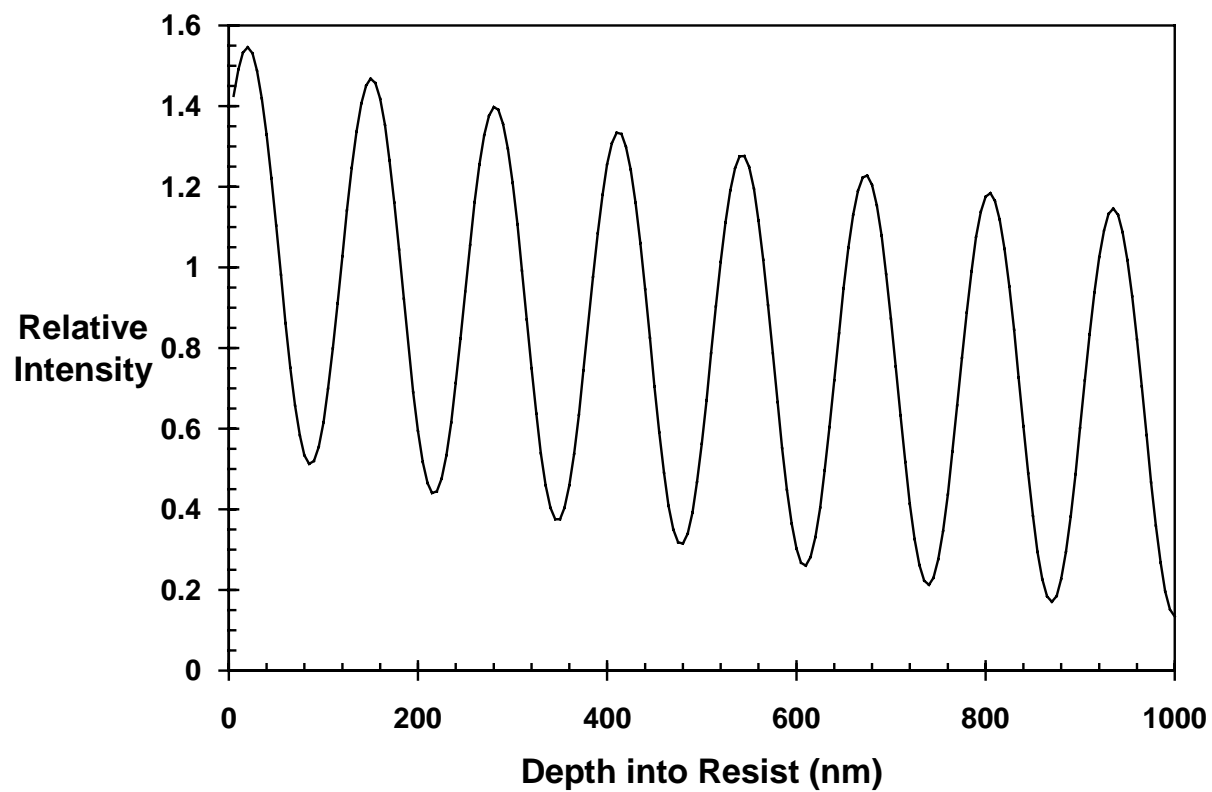


Figure 2. Standing wave intensity in one micron of photoresist on a silicon substrate.