THE LITHOGRAPHY TUTOR

Standing Waves in Photoresist

Chris A. Mack, *FINLE Technologies, Austin, Texas*

The energy that exposes a photoresist is not the energy incident on the top surface of the resist, but rather the energy that has propagated into the photoresist. Of course, exposure leads to chemical changes which modify the solubility of the resist in developer, 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.

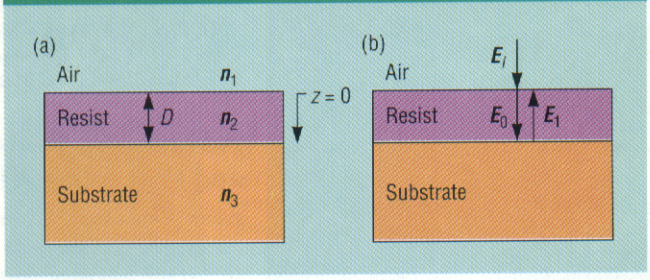
While previously this column has tried to describe various phenomena on a physical level, this time we will build up a mathematical description of standing waves in photoresist, and then glean physical insight from the equations that result. The purpose is to show that the equations are merely descriptions of physics and that the proper interpretation of an equation can be invaluable.

Let us begin with the simple geometry shown in Fig. 1a. A thin photoresist rests on a thick substrate in air. 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:

$$\alpha = \frac{4\pi\kappa}{\lambda} \tag{1}$$

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

Figure 1



Film stack showing geometry for standing wave derivation.

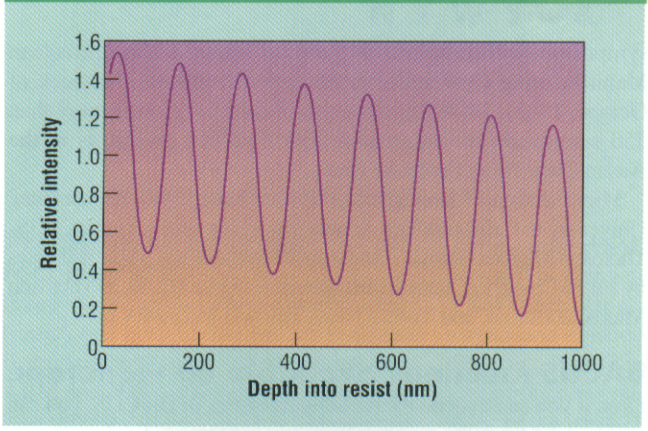
Consider now the propagation of light through this simple film stack. When the stack is illuminated by a monochromatic plane wave normally incident on the resist, some of the light will be transmitted and some will be reflected. The amount of each is determined by the transmission and reflection coefficients. 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

$$\tau_{ij} = \frac{2\mathbf{n}_i}{\mathbf{n}_i + \mathbf{n}_j} \tag{2}$$

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 from layer j back into layer i is given by the *reflection coefficient*, ρ_{ij}:

$$\rho_{ij} = \frac{\mathbf{n}_i - \mathbf{n}_j}{\mathbf{n}_i + \mathbf{n}_j} \tag{3}$$

Figure 2



Standing wave intensity in 1 μm of photoresist on a silicon substrate.

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

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:

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

where $E(z)$ represents a plane wave traveling in the +Z direction. Using the coordinates defined in Fig. 1a, the transmitted electric field propagating through the resist, $\boldsymbol{E}_0$, will be given by

$$E_0(z) = \tau_{12}E_I e^{-i2\pi n_2 z/\lambda} \tag{5}$$

Eventually, the wave will travel though the resist thickness, D, and strike the substrate, where it will be partially reflected. The reflected wave, $\boldsymbol{E}_1$, just after reflection will be

$$E_1(z = D) = \tau_{12}E_I\rho_{23}e^{-i2\pi n_2 D/\lambda} \tag{6}$$

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.

$$\tau_D = e^{-i2\pi n_2 D/\lambda} \tag{7}$$

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 Eqn. 4:

$$E_1(z) = \tau_{12}E_I\rho_{23}\tau_D e^{-i2\pi n_2(D-z)/\lambda} = \tau_{12}E_I\rho_{23}\tau_D^2 e^{i2\pi n_2 z/\lambda} \tag{8}$$

So far, our incident wave ($\boldsymbol{E}_I$) has been transmitted in the photoresist ($\boldsymbol{E}_0$) and then reflected off the substrate ($\boldsymbol{E}_1$), as pictured in Fig. 1b. The total electric field in the photoresist will be the sum of $\boldsymbol{E}_0$ and $\boldsymbol{E}_1$. 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

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

In reality, this sum is not the total electric field in the photoresist. The wave $\boldsymbol{E}_1$ will travel to the top of the resist where it will be reflected by the air-resist interface. The new wave, $\boldsymbol{E}_2$, will travel down through the resist where it will be reflected by the substrate, giving another wave, $\boldsymbol{E}_3$. 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 $\boldsymbol{E}_2$ and $\boldsymbol{E}_3$ have exactly the same form as the waves $\boldsymbol{E}_0$ and $\boldsymbol{E}_1$, 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]

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

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, Eqn. 10 needs only slight modification.

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

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

This equation is graphed in Fig. 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 Eqn. 11 shows that the period of the standing wave is given by

$$\text{Period} = \lambda/2n_2 \tag{12}$$

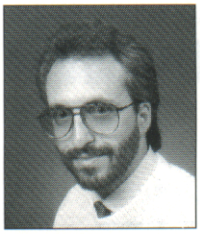
The amplitude of the standing waves is given by the multiplier of the cosine in Eqn. 11. It is quite apparent that there are two ways to reduce the amplitude of the standing wave intensity. The first is to reduce the reflectivity of the substrate (reduce ρ_{23}). Of course, the use of an antireflective coating (ARC) is one of the most common methods of reducing standing waves. The second method for reducing the standing wave intensity that Eqn. 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 foregoing discussion provides 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 Eqn. 11). In the next Lithography Tutor column, 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, pp. 1958–1961 (15 June 1986).



Chris A. Mack received B.S. degrees in Physics, Chemistry, Electrical Engineering, and Chemical Engineering from Rose-Hulman Institute of Technology, Terre-Haute, IN, in 1982 and an M.S. degree in Electrical Engineering from the Univ. of Maryland in 1989. He joined the Microelectronics Research Laboratory of the Dept. of Defense in 1983 and worked in optical lithography research. He has authored numerous papers about optical lithography, regularly teaches courses on this topic, and has developed the lithography simulation programs PROLITH and PROLITH/2. In 1990–1991, he was on assignment at SEMATECH, working in deep-UV photoresist characterization and phase-shifting mask optimization. Since January 1992, he has been vice president of R&D for FINLE Technologies. He also serves as an adjunct faculty member at the Univ. of Texas at Austin.

SPIE ACTIVITIES

continued from page 10

symposium will be held with the third annual SEMI Ultraclean Manufacturing Conference at SEMICON/Southwest the week of October 17–21, 1994. The SEMICON trade show gathers more than 550 semiconductor equipment and materials exhibitors at the Austin Convention Center in Texas.

Microelectronic Manufacturing 1994 is chaired by C. Kumar Patel, University of California/Los Angeles, and Hoang Huy Hoang, SGS-Thomson Microelectronics. The symposium features keynote addresses by Pallab Chatterjee, Texas Instruments Inc., Steve Tso, SGS-Thomson Microelectronics, and Yoshio Nishi, Hewlett-Packard Co.

BACUS meetings available on videotape

Even if you can't attend the monthly meetings of BACUS, you can still benefit from the presentations via videotape. Each tape presents two 30- to 45-min technical presentations on innovative aspects of photomask technology drawn from the BACUS meetings in Sunnyvale, CA. Presentations are followed by brief question and answer sessions.

Videotapes are available individually or as a yearly subscription. Current tapes include presentations at the April meeting by Sheldon Kugelmass, Lepton Corp., and Michael Rolle, Pattern Data Systems. February tapes contain discussions of photolithography trends for flat panel displays by Dave Kettering, Nikon, and Jim McKibben, Semiconductor Systems Inc. Tapes of the January meeting present approaches to reducing the cost of lithography and a two-dimensional self-calibration method for measuring tools. ■

Great Performance, No Compromises

Imagine getting everything you want. Newport's PM500 family of ultra-precision stages gives you true power of choice. You can choose the stage that's precisely right for your application without having to settle for one performance criterion over another. There is no trade-off between resolution and velocity or between acceleration and reliability.

PM500 linear stages are available with 0.1μm, 0.05μm or 0.025μm resolution and bidirectional repeatability without sacrificing velocity. These stages can move up to 100 mm/sec and still deliver desired resolution and repeatability over travels up to 8 inches.

Although high accelerations degrade the lifetimes of other motion devices, every PM500 can reliably deliver up to 1/4 g, with an industry-leading 20,000-hour MTBF.

If your application requires precision rotation, PM500 rotary stages deliver up to 0.5 arcsec incremental motion and bidirectional repeatability.

All of Newport's PM500 stages, including the new vertical stage, feature integral glass scale encoders for precise