Lithography on Reflective Substrates

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In semiconductor lithography, our goal is to create a spatial variation in resist along the surface of a wafer, corresponding to the pattern being transferred into the wafer. Typically, we want the thickness of the resist to take on only two states: all of the resist is there or all of the resist is gone. This ideal binary pattern of resist thickness requires perfectly vertical resist sidewalls. Thus, the purpose of imaging, photoresist exposure, and development is to create a spatial variation in the plane of the wafer (the x and y directions), but the desire for vertical profiles means that we would like to have no spatial variation with depth into the resist (the z direction). Unfortunately, the physics of lithography rarely allows this ideal to be met.

There are two basic phenomena which introduce z-dependence to the lithography process: the propagation of light through the resist during imaging and exposure, and the propagation of developer through the resist during dissolution. Let's consider just the optical effects here. As light travels through the resist it is absorbed. As a result, the top of the resist receives a higher exposure dose than the bottom. For a positive resist this leads to "positive" sloped profiles (a resist line is narrower at the top than the bottom). For a negative resist, "retrograde" or "negative" profiles are produced (a resist line is wider at the top than the bottom). But absorption is rarely the only optical influence on the profile. As light reaches the bottom of the resist, it is reflected back up into the resist. This reflected ray then interferes with the light traveling down to produce standing waves (see the *Lithography Tutor*, *MLW Spring 1994*) and possibly swing curves (the *Lithography Tutor*, *MLW Summer 1994*). The reflected light often provides one of the dominant influences in determining the shape of the final resist profile.

What determines the properties of the light reflected back into the resist? For the simple case of resist on a very thick substrate, the reflection coefficient, defined as the ratio of reflected to incident electric fields, is determined by the indices of refraction of the resist and the substrate. For normal incidence, the reflection coefficient is

$$r = \frac{n_{resist} - n_{substrate}}{n_{resist} + n_{substrate}} \qquad (1)$$

Each refractive index is complex, the imaginary part being directly proportional to the absorption coefficient of the material. Thus, in general, the reflection coefficient is a complex number. The magnitude of r determines the magnitude of the reflected light while its phase gives a phase change upon reflection. Consider a typical resist on silicon at the i-line wavelength (365nm). The magnitude of the reflection coefficient is about 0.63 with a phase of 169º. For resist on aluminum, $r = 0.93\angle 138^\circ$. For more complicated layered substrates, both the magnitude and phase of the reflection coefficient will depend on the thicknesses of the various layers.

Consider a simple but common film stack: resist (1μm thick) on silicon nitride (100nm) on silicon dioxide (40nm) on silicon. The reflection coefficient between the resist and the underlying film stack is a function of the optical properties of all of the materials, but also of the thickness of the nitride and the oxide films. For example, variation of the nitride thickness leads to a moderate variation in the magnitude and a large variation in the phase of the reflection coefficient, as shown in Figure 1. Oxide thickness variations produce similar effects.

What will be the lithographic effects of this nitride thickness variation? The change in the magnitude of the reflection coefficient will have some subtle effects, but the large change in the phase of the reflection will cause two major problems. The resist swing curve is a function of the phase change of light that passes down and back up through the resist. Changes in resist thickness cause a change in this phase, giving rise to a sinusoidal variation in dose-to-clear (E_o) and linewidth. Any change in the phase upon reflection will produce the same effect. Figure 2 shows two resist swing curves corresponding to two nitride thickness (minimum and maximum thicknesses from Figure 1). The nitride thickness variation produces its own swing curve, resulting in linewidth variations of the same magnitude as for resist thickness variations. Control of the nitride thickness (and oxide thickness, for that matter) is just as critical as resist thickness control.

The second effect of this phase change upon reflection is on the shape of the resulting resist profile. When the reflected light is 180º out of phase with the incident light, destructive interference results in a minimum light intensity at the resist/substrate interface. When the reflected light is in phase with the incident light, constructive interference results in a maximum light intensity at the resist/substrate interface. Although standing waves are generally smoothed out by post-exposure bake diffusion, any asymmetry in the standing wave pattern inside the resist can lead to less than perfect reduction of the amplitude. When the phase change upon reflection is about +90º or -90º, the local region near the interface has an average intensity that is higher or lower, respectively, than the average through the bulk. The result is resist undercutting and resist footing. Figure 3 shows typical resist profile shapes at different nitride thicknesses.

One can see that nitride thickness variations of just ±20nm can have huge effects on both linewidth and resist profile shape. If oxide thickness can vary as well, these requirements become even tighter. In many cases, the lithographic requirements for thin film thickness uniformity and control far exceed other device-related requirements. Of course, the more reflective the substrate the more pronounced the standing wave and swing curve effects. But the more moderately reflective substrates (such as this nitride/oxide/silicon film stack) add sensitivity to film stack thicknesses. In some cases, the more moderately reflective film stacks can cause more problems with linewidth and profile shape control.

One approach to reducing the problems of lithography on reflective substrates is to use a bottom antireflection coating, the subject of the next edition of the *Lithography Expert*.

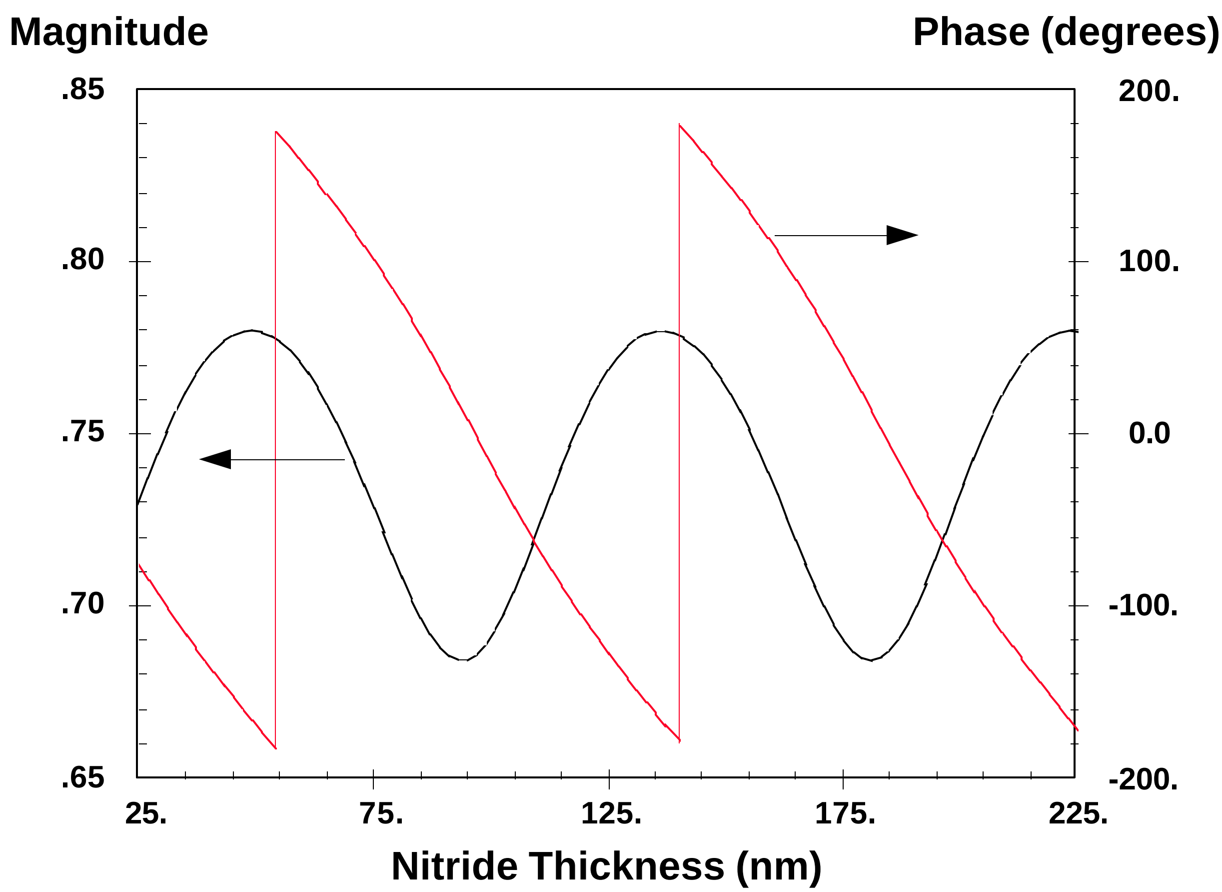

Figure 1. Variation of the magnitude and phase of the resist/substrate reflection coefficient as a function of silicon nitride thickness for a film stack of resist on nitride on 40nm of oxide on silicon.

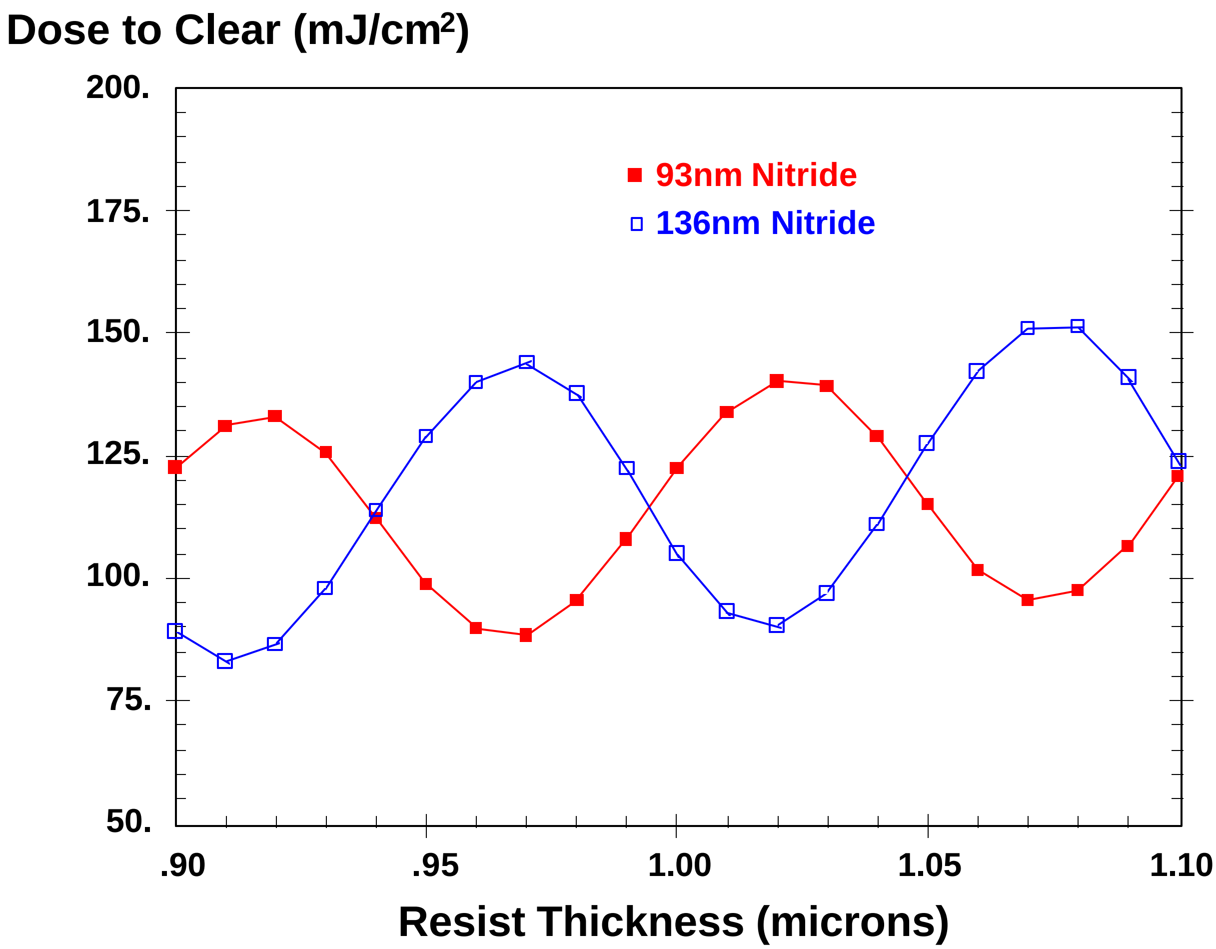

Figure 2. Changes in nitride thickness cause a shift in the phase of the resist swing curve, making nitride thickness control as critical as resist thickness control.

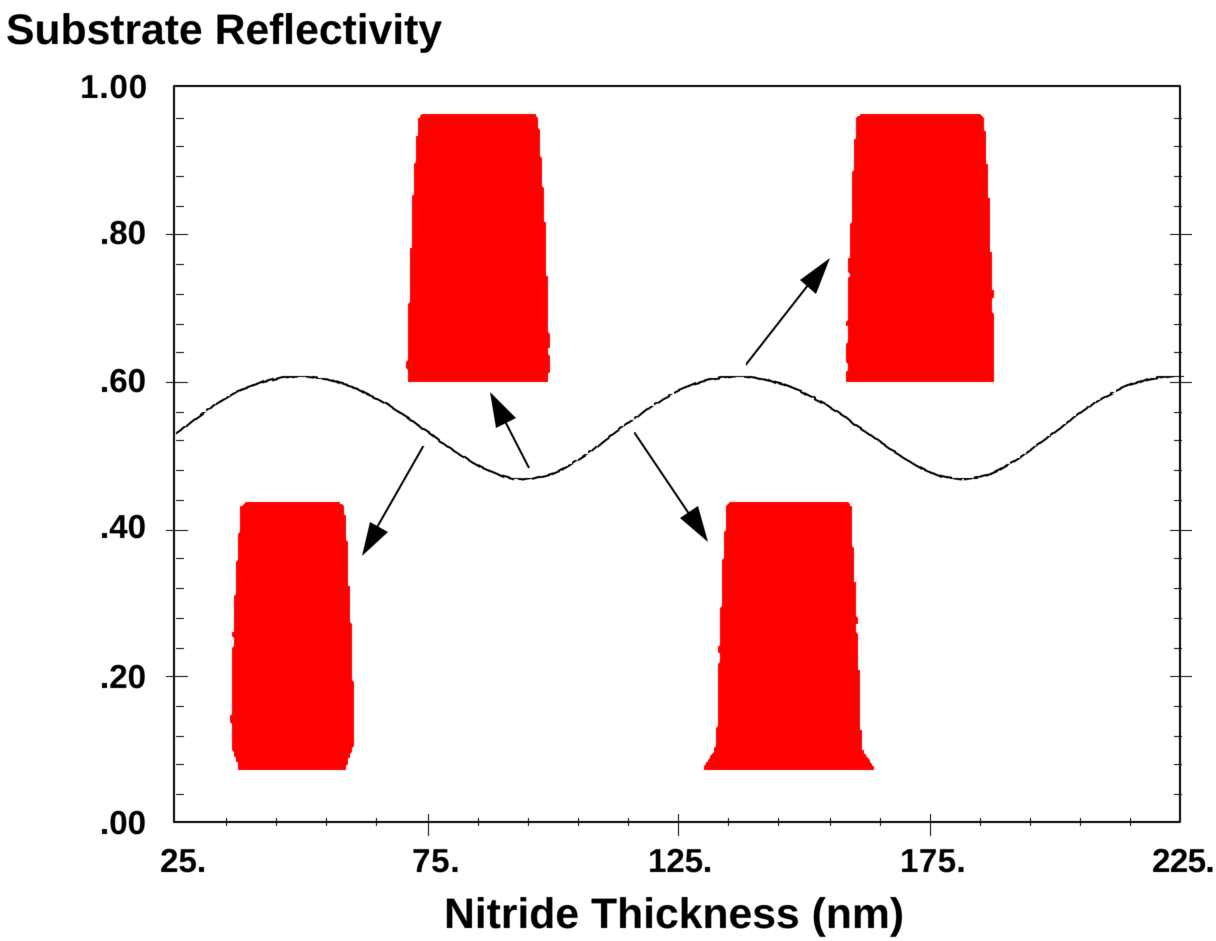

Figure 3. Nitride thickness also affects the shape of the resist profile, causing resist footing, undercuts, or vertical profiles. Substrate reflectivity (the square of the magnitude of the reflection coefficient) is shown for comparison.