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The Death of the Aerial Image

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The aerial image is, quite literally, the image in air. In the world of semiconductor lithography, it is the image of a photomask projected onto the plane of the wafer, but assuming that only air occupies this space rather than the resist coated wafer. Although aerial images do not really exist in lithography, for many years our industry has used the aerial image, which is reasonably easy to calculate though very difficult to measure, as a proxy for the final resist image. By picking an exposure-dose dependent intensity threshold, an estimate of the final resist CD is obtained (this essentially assumes that the resist is ideal – infinite contrast). A somewhat more sophisticated approach varies this threshold as a function of the slope of the image, or the maximum or minimum intensity values. Such variable threshold resist models are commonly used for optical proximity correction. All of these uses are based on the idea that an aerial image is a good predictor of what the resist image will look like. While this assumption was reasonable in the past, is it still good in today's super-high numerical aperture world?

Over the last several years, many authors have explored the effects of high numerical apertures on imaging (e.g., reference [1]). In particular, the vector nature of light affects the formation of an image as a function of the polarization of the light and the angles of the various diffraction orders that add together to form the image. Two planes waves, approaching a wafer at different angles, will interfere to form fringe patterns of light and dark making the simplest of lithographic patterns – an array of lines and spaces. This phenomenon of interference is the key to pattern formation. Without it, light hitting the wafer from different directions would simply add up to give a uniform intensity. We can see mathematically the effect of interference by examining how two electric fields combine to form a resultant electric field (magnitude and intensity). Ignoring a few details, the intensity of light I is the square of the magnitude of the electric field E. If two electric fields are combined, what is the intensity of the combination? If the two electric fields do not interfere, the total intensity is the sum of the individual intensities (i.e., it is a constant).

$$I = |E_1|^2 + |E_2|^2 \qquad (1)$$

If, however, the two electric fields interfere completely, the total intensity will be

$$I = |E_1 + E_2|^2 \qquad (2)$$

Here, the variation in the phase of E_1 relative to E_2 produces a spatial variation in intensity that is our image. (Note that $E_1$and E_2 represent the scalar values of the electric fields – the impact of their vector nature will be described below.)

Two electric fields interfere with each only to the extent that their electric fields oscillate in the same direction. If the electric fields are at right angles to each other, there will be no interference. Thus, to determine the amount of interference between two electric fields one must first determine the amount of directional overlap between them. Standard vector mathematics gives us some simple tools to calculate directional overlap and thus the amount of interference. When thinking of light as a scalar rather than a vector quantity, we ignore the subtleties discussed above. Essentially, a scalar description of light always assumes that the electric fields are 100% overlapped and all electric fields add together as in equation (2). Since interference is what gives us the patterns we want, a scalar view of light is generally too optimistic. The vector description of light says that there is usually some fraction of the electric fields of our two vectors that don't overlap and thus don't contribute to interference. The non-interfering light is still there, but it adds as a uniform intensity that degrades the contrast of the image.

Consider the interference of two plane waves approaching the wafer at fairly large angles, as in Figure 1. How will the two electric fields interfere? The electric field can point in any direction perpendicular to the direction of propagation. This arbitrary direction can in turn be expressed as the sum of any two orthogonal (basis) directions. The most convenient basis directions are called transverse electric or TE (the electric field pointing out of the page of the drawing) and transverse magnetic or TM (the electric field pointing in the page of the drawing). As Figure 1 shows, the TE case means that the electric fields of the two planes wave are always 100% overlapped regardless of the angle between the plane waves. For the TM case, however, the extent of overlap between the two vectors grows smaller as the angle between the plane waves grows larger.

We can calculate how much the two electric fields for the TM case will interfere with each other. Suppose that the two rays in Figure 1 are traveling at an angle θ with respect to the vertical direction (i.e., the direction normal to the wafer). The electric fields E_1 and E_2 will have an angle between them of 2θ. The amount of the electric field vector E_2 that points in the same direction as E_1 is just the geometric projection, $E_2\cos(2\theta)$. Thus, the intensity will be given by the coherent (electric filed) sum of the parts that overlap plus the incoherent (intensity) sum of the parts that don't overlap.

$$I = \left|E_1 + E_2\cos(2\theta)\right|^2 + \left|E_2\sin(2\theta)\right|^2 \qquad (3)$$

Note that for θ = 0, this equation reverts to the perfectly coherent (interfering) sum of equation (2). For θ = 45º, the two electric fields are perpendicular to each other and equation (3) becomes the perfectly incoherent (non-interfering) sum of equation (1). If we consider the simplest case of two unit amplitude plane waves,

$$E_1 = e^{-i2\pi(z\cos\theta + x\sin\theta)/\lambda}, \quad E_2 = e^{-i2\pi(z\cos\theta - x\sin\theta)/\lambda}$$
$$I_{TE}(x) = 2 + 2\cos(4\pi x\sin\theta/\lambda)$$
$$I_{TM}(x) = 2 + 2\cos(2\theta)\cos(4\pi x\sin\theta/\lambda) \qquad (4)$$

The visibility (or contrast) of the resulting fringes is the difference over the sum of the maximum and minimum intensities of the interference pattern. For the TE polarization case, the contrast is always exactly 1. For the TM case, the contrast depends on the angle between the two waves and is equal to $\cos(2\theta)$. Thus, as the angle between the plane waves increases, the contrast of the resulting image decreases. One can see why the TM polarization is often called the "bad" polarization – it provides less interference and a reduced quality image.

But why is the aerial image a bad judge of the final resist image for high numerical aperture imaging? The resist is not exposed by an aerial image, but by the image in resist. The plane waves that interfere to form the image first propagate into the resist. Once in the resist, they can interfere to form an image in the resist. This image will be different than the aerial image due to refraction. As each plane wave travels from air to resist, refraction lowers the angle of the light according to Snell's law. Letting *n* be the refractive index of the resist (and assuming the air above the resist has an index of refraction of 1.0), the angle of one of the plane waves inside the resist will be

$$\sin(\theta_{resist}) = \frac{1}{n}\sin(\theta_{air}) \qquad (5)$$

For the TE light, the interference will be the same and the two plane waves will produce a sinusoidal image of contrast 1. For the TM light, the contrast will be

$$TM\ Contrast = \cos(2\theta_{resist}) = 1 - 2\sin^2(\theta_{resist}) = 1 - \frac{2}{n^2}\sin^2(\theta_{air}) \qquad (6)$$

Figure 2 illustrates the difference between the contrast in air and the contrast in resist as a function of angle for TM light when the resist refractive index is 1.7. For an angle of 30º (corresponding to two beam imaging at the resolution limit of a lens of a modest NA = 0.5), the aerial image for TM illumination has a contrast of 0.5, while the image in resist has a much more acceptable contrast of 0.83. Unpolarized light, which produces an average of the TE and TM images, produces a contrast that is also the average between 1 and the value given by equation (6) (ignoring the difference in transmission of the two polarizations into the resist).

$$Unpolarized\ Contrast \approx 1 - \frac{1}{n^2}\sin^2(\theta_{air}) \qquad (7)$$

For the case of unpolarized two beam imaging at the resolution limit of an NA = 0.9 lens, the aerial image would show a contrast of 0.19 (obviously unacceptable) while the image in resist would have a more reasonable contrast of 0.72.

What does all of this mean? When calculating aerial images, vector effects can dramatically alter the resulting image compared to an approximate scalar calculation. The resist, however, mitigates some of these vector effects and the image in resist can be dramatically different from the aerial image. When trying to approximate a resist feature by a calculated intensity image, only the image in resist (calculated correctly using the vector nature of light) can be expected to give reasonable results. While the aerial image has served the industry well, it is time to put this image to rest (may it rest in peace), and turn to the image in resist as our new proxy for the true resist feature.

References

1. T. A. Brunner, et al., “High NA Lithographic Imagery at Brewster’s Angle,” *Optical Microlithography XV, Proc.*, SPIE Vol. 4691 (2002) pp. 1 – 10.

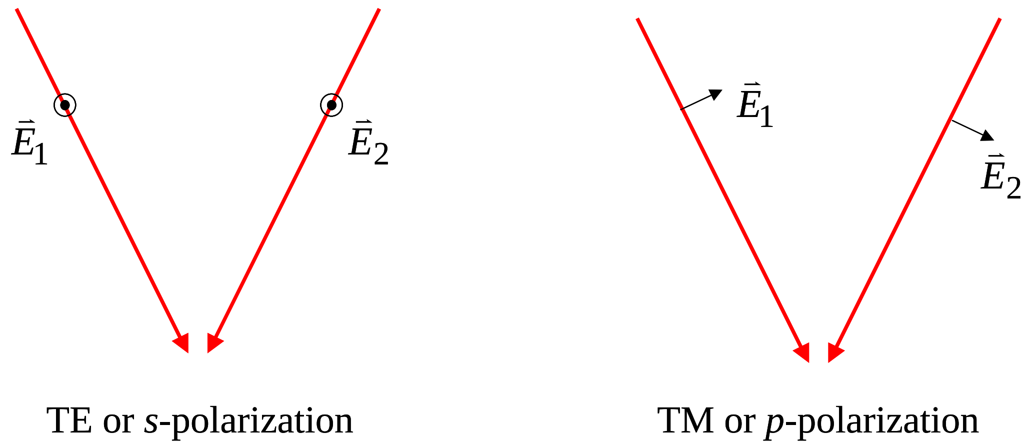

Figure 1. Two planes waves with different polarizations will interfere very differently. For transverse electric (TE) polarization (electric field vectors pointing out of the page), the electric fields of the two vectors overlap completely regardless of the angle between the interfering beams.

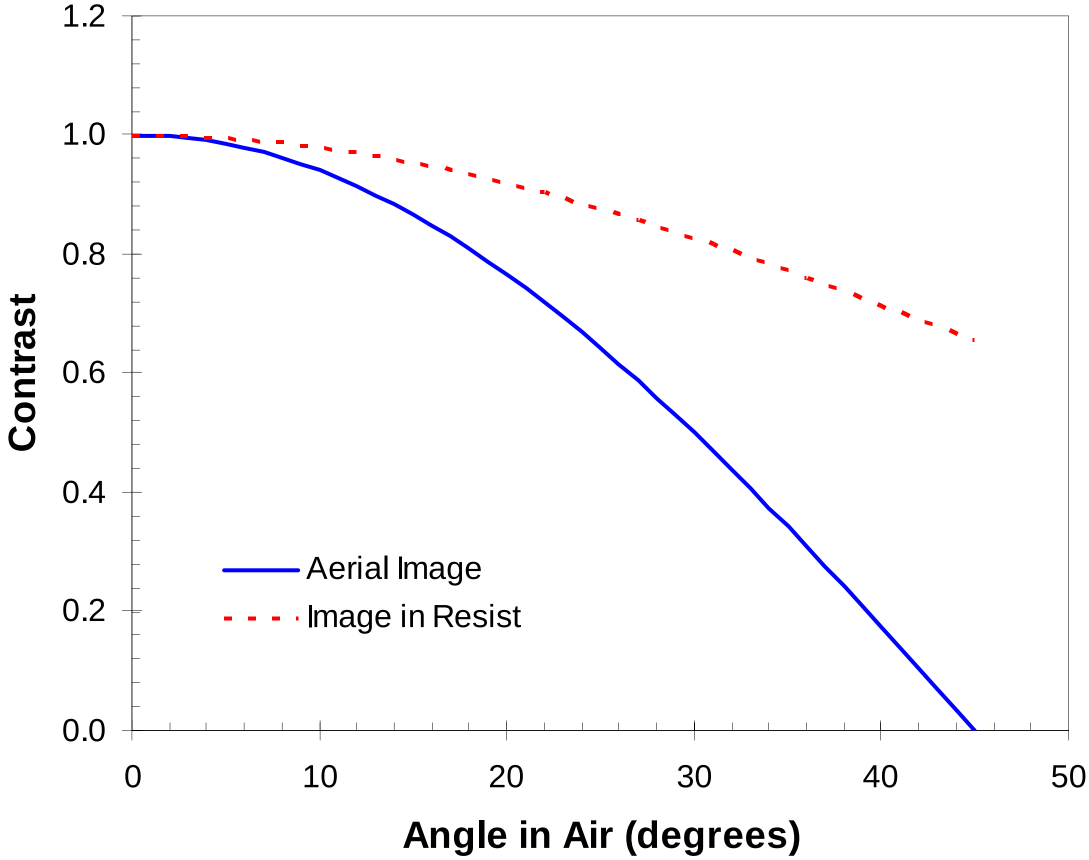

Figure 2. The interference between two TM polarized planes waves produces an image whose contrast depends on the angle. Since the angle in resist is reduced by refraction, the contrast of the image in resist is better than the aerial image.