The Lithography Expert *(November 2005)*

Horizontal-Vertical (H-V) Bias

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A nanometer here, a nanometer there. Before long, you've got a serious linewidth error. That's the way many lithographers feel about assessing the sources of critical dimension (CD) errors affecting sub-100nm processes. While just a few years ago an error source that contributed one nanometer to the CD error budget would be swamped by other 10nm error sources of the process, today the total CD error budget for a 65nm gate process can be ±4nm. At this level, a one nanometer CD error is significant, especially if it is systematic.

One of the systematic sources of CD errors receiving renewed scrutiny in recent years is called horizontal-vertical (H-V) bias. Quite simply, H-V bias is the systematic difference in linewidth between closely located horizontally and vertically oriented resist features that, other than orientation, should be identical. H-V bias has always been a concern in optical lithography, but it has tended to be one of the "second order" errors that rarely limits overall lithographic capability. It's not clear, however, whether H-V bias will retain its second tier status in the 65nm and 45nm generations, or graduate to a first tier concern.

There are two main causes of H-V bias. The first and most well known cause is astigmatism and related aberrations. The aberration of astigmatism results in a difference in best focus as a function of the orientation of the feature. Using the Zernike polynomial description of aberrations, 3rd order 90º astigmatism (which affects horizontally and vertically oriented lines) takes the form

$$phase\ error = 2\pi\, Z_{astig} R^2 \cos 2\theta \qquad (1)$$

where (R,θ) are polar coordinates in the pupil plane (R being defined relative to the numerical aperture and ranging from zero to one) and Z_{astig} is the Zernike coefficient in units of fractions of a wavelength. A picture of this phase error across the pupil is shown in Figure 1.

Consider a vertically, y-oriented pattern of lines and spaces. The diffraction pattern will spread across the x-axis of the pupil, corresponding to θ = 0º and 180º. Thus, the phase error will be $2\pi Z_{astig}R^2$ for this feature. Recalling the description of defocus as an aberration (this column, July 1993), the phase error due to defocus is

$$phase\ error \approx \frac{\pi\delta NA^2}{\lambda} R^2 \qquad (2)$$

where δ is the defocus distance, λ is the wavelength, and NA is the numerical aperture. (Equation (2) is approximate because it retains only the first term in a Taylor series. While this approximation is progressively less accurate for higher numerical apertures, it will be good enough for our purposes.) Immediately, one sees that 3rd order astigmatism looks just like the approximate effect of defocus. Thus, astigmatism will cause the vertically oriented lines to shift best focus by an amount

$$\Delta\delta_{vert} \approx \frac{2Z_{astig}\lambda}{NA^2} \tag{3}$$

For horizontally oriented lines, the diffraction pattern will be along the *y*-axis of the pupil (θ = ±90º) and the astigmatism will cause a phase error of $-2\pi Z_{astig}R^2$. Thus, the focus shift for the horizontal lines will be the same magnitude as given by equation (3), but in the opposite direction.

To see how astigmatism causes H-V bias, we need to understand how a shift in focus might affect the resist feature CD. To first order, CD has a quadratic dependence on focus.

$$CD \approx CD_{best\ focus} + a\delta^2 \tag{4}$$

where *a* is the dose-dependent curvature of the CD through focus curve. Recalling the typical shapes of Bossung curves, *a* can vary from positive to negative values as a function of dose. If best focus is shifted due to astigmatism, we can calculate the CD of the vertical and horizontal features by adding the focus shift of equation (3) to equation (4).

$$\begin{aligned} CD_{vert} &\approx CD_{best\ focus} + a\left(\delta - \frac{2Z_{astig}\lambda}{NA^2}\right)^2 \\ CD_{horiz} &\approx CD_{best\ focus} + a\left(\delta + \frac{2Z_{astig}\lambda}{NA^2}\right)^2 \end{aligned} \tag{5}$$

From, here a straightforward subtraction gives us the H-V bias:

$$H - V\ bias \approx \frac{8a\delta Z_{astig}\lambda}{NA^2} \tag{5}$$

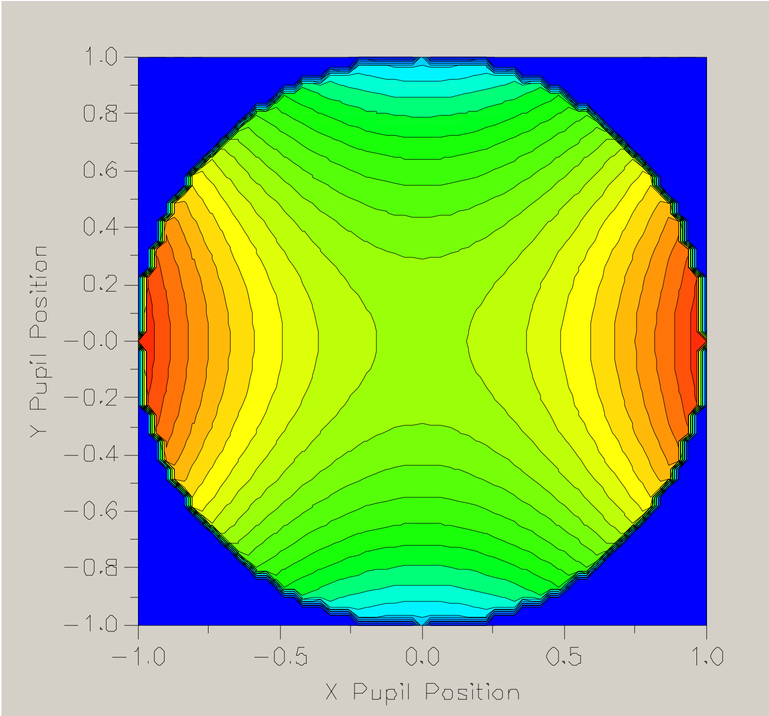
The H-V bias is directly proportional to the amount of astigmatism in the lens (Z_{astig}) and to the curvature of the CD-through-focus curve (*a*). But it is also directly proportional to the amount of defocus. In fact, a plot of H-V bias through focus is a sure way to identify astigmatism (so long as you don't use the isofocal dose, where $a \approx 0$, for the experiment). Figure 2 shows some typical results (using simulation to mimic the experiment). Note that the isolated lines show a steeper slope than the dense lines due to a larger value of the CD through focus curvature. In fact, if *a* is determined by fitting equation (4) to CD through focus data, a reasonable estimate of Z_{astig} can be made using an experimentally measured H-V bias through focus curve. Note also that the true shape of the curves in Figure 2 is only approximately linear, since both equations (3) and (4) ignore higher order terms.

Do we think that H-V bias due to astigmatism will be a major concern now or in the near future? We can use equation (5) to help answer that question. Let the maximum possible value of the defocus be one-half of the depth of focus (DOF). At this defocus, equation (4) would tell us that at the worst case dose the term $a\delta^2$ will be about 10% of the nominal CD (by definition of the process window with a ±10% CD specification). Thus, we can say that within the process window the worst case H-V bias due to astigmatism will be

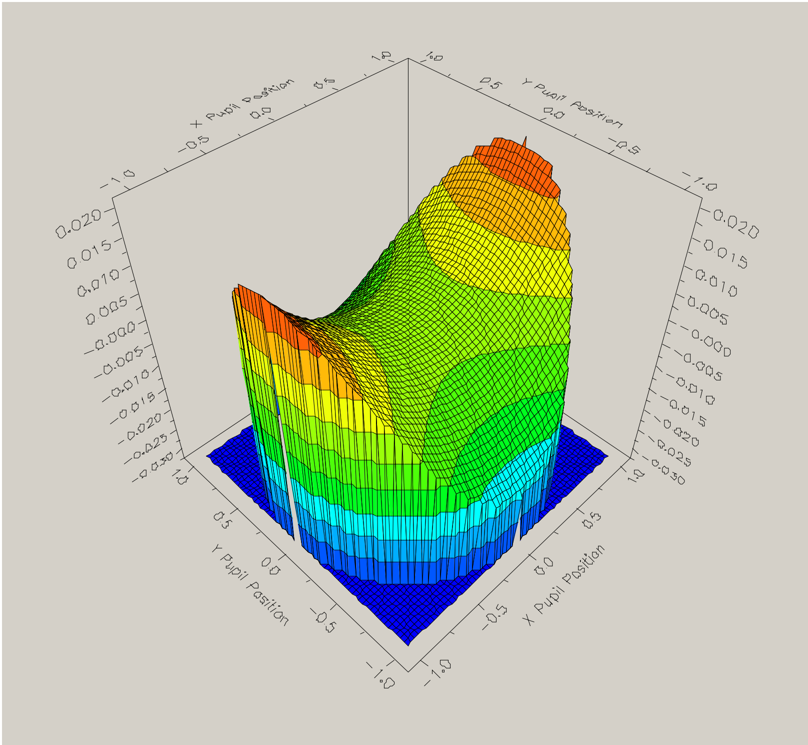
$$\left.\frac{H-V\ bias}{CD_{\text{nominal}}}\right|_{\max} \approx \frac{1.6\,Z_{astig}\,\lambda}{DOF\ \ NA^2} \qquad (6)$$

Let's plug in some typical numbers for a 65nm process. For a wavelength of 193nm, an *NA* of 0.9, and assuming a depth of focus of 200nm, the fractional H-V bias will be about $2Z_{astig}$. If we are willing to give 1% CD error to H-V bias, our astigmatism must be kept below 5 milliwaves. In general, equation (6) shows that as new, higher resolution scanners are designed and built, the astigmatism in the lens must shrink as fast or faster than the depth of focus of the smallest features to be put into production. So far, lens makers have been successful at achieving this kind of aberration scaling. Let's hope they can continue to do so.

The second major cause of H-V bias is illumination aberrations (that is, source shape asymmetries). This source of H-V bias could prove more troublesome than astigmatism, but that is the topic of the next edition of this column.



(a)



(b)

Figure 1. Plot of the phase error across the objective lens pupil for 0.02 waves of 90º astigmatism: a) contour plot, and b) 3D plot.

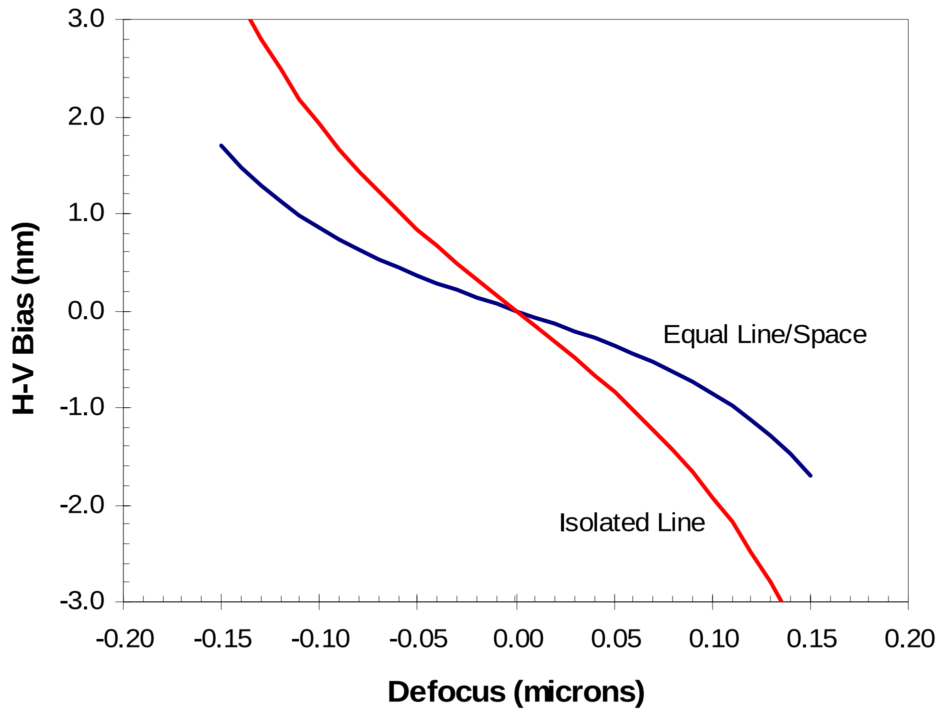


Figure 2. PROLITH simulations of H-V bias through focus showing approximately linear behavior (λ = 193nm, NA = 0.75, σ = 0.6, 150nm binary features, 20 milliwaves of astigmatism). Simulations of CD through focus and fits to equation (4) gave the CD curvature parameter a = -184μm^{-2} for the dense features and -403 μm^{-2} for the isolated lines.