Optical Proximity Effects

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

Proximity effects are the variations in the linewidth of a feature (or the shape for a 2-D pattern) as a function of the proximity of other nearby features. The concept of proximity effects became prominent many years ago when it was observed that electron beam lithography can exhibit extreme proximity effects (backscattered electrons can travel many microns, exposing photoresist at nearby features). Optical proximity effects refer to those proximity effects that occur during optical lithography (even though they may not be caused by optical phenomenon!). The simplest example of an optical proximity effect is the difference in printed linewidth between an isolated line and a line in a dense array of equal lines and spaces, called the *iso-dense print bias*.

Although many factors may affect the iso-dense print bias, such as developer flow, PEB diffusion or proximity dependent surface inhibition effects, in general this bias is the result of optics -- the aerial images for dense and isolated lines are different. For high resolution features, the diffraction patterns from isolated and dense lines are significantly different (see the *Lithography Tutor*, January 1993). The result is different aerial images, as shown in Figure 1. In this case, the isolated line will print wider than the dense line (assuming a positive photoresist), giving a positive iso-dense print bias. It is important to note that this result is not a "failing" of the optical system, but a natural consequence of the physics of imaging. Also, aberrations in the optical system can change the magnitude of the bias, sometimes significantly.

The proximity effect is very feature size dependent. For large features, the diffraction patterns for isolated and dense lines are similar, giving very little differences in the aerial images. As feature size shrinks, the differences grow. Figure 2 gives an example of how the iso-dense print bias increases dramatically as the feature size approaches the resolution limit of the exposure tool (in this case, with a partial coherence of $\sigma = 0.5$). The iso-dense bias is quite small for feature sizes above $k_1 = wNA/l = 1.0$, and increases as k_1 goes down to 0.6.

Since the iso-dense print bias is predominantly an optical effect, one would expect that the optical parameters of the stepper would affect the magnitude of the bias. In the last *Lithography Tutor* we saw that partial coherence strongly influenced this bias. Figure 3 emphasizes this point by showing fairly dramatic differences among the different partial coherence values. A partial coherence of 0.5 gives the best results for larger features ($k_1 \geq 1$), $\sigma = 0.7$ shows less feature size dependence, while smaller partial coherences show more feature size dependence. One can see that for any feature size there will be at least one value of the partial coherence which drives the iso-dense print bias to zero. Unfortunately, zero bias at one feature size does not give zero bias at other sizes.

Modern steppers allow the variation of both numerical aperture (*NA*) and partial coherence over certain ranges. In the last *Lithography Tutor* we saw how these optical parameters could be used to maximize the depth of focus. They can also be used to minimize the iso-dense print bias. Figure 4 shows a contour plot of iso-dense print bias as both NA and σ are varied for 0.5 µm (k_1 = 0.71) and 0.7 µm (k_1 = 1.0) feature sizes. The shaded areas show the ranges of NA and σ that keep the bias within ±10 nm (an arbitrary specification). The larger feature has a wide range of numerical apertures and partial coherences which produce a small iso-dense bias. Note that for this feature a partial coherence of 0.9 provides small bias over the full range of numerical aperture, but a partial coherence of 0.8 produces a larger bias over the full range of numerical aperture. Small σ at high numerical apertures also give small iso-dense print bias. The rule of thumb that larger σ means less proximity effects is quite inaccurate. The smaller 0.5 µm feature has a much smaller "window" of acceptable stepper settings. Typical partial coherence values of 0.5 - 0.7 in particular provide poor performance. Either higher or lower σ is needed, as well as a high numerical aperture. Note that there is some overlap between the two feature sizes. It is possible to find a single stepper setting that will produce small iso-dense print bias for both of these features.

Although the iso-dense print bias is a reasonable measure of the magnitude of the proximity effects of one-dimensional lines and spaces, even these simple structures show more complicated behavior. In Figure 5 we show the effect of pitch on the printed linewidth of a nominally 0.5 µm line. A large pitch provides an essentially isolated line. In this case, the iso-dense print bias of about 35 nm is not the maximum proximity effect. At a pitch of 1.4 µm the linewidth is 40 nm larger than the equal lines and spaces. Full characterization of the proximity effect may require the study of many different pitches, not just dense and isolated.

As the last edition of this column showed, a judicious choice of numerical aperture and partial coherence is needed to obtain the best depth of focus. What if the optimum settings for good depth of focus do not coincide with the optimum settings for small iso-dense print bias? As is often the case, good focus performance may be required for both dense and isolated lines at the same time. In this case, one approach is to evaluate the depth of focus as an *overlapping* of two focus-exposure process windows, one for the isolated line and one for the dense line. The optimum NA and σ will give the maximum depth of focus calculated from the overlapped process window.

The iso-dense print bias is one example of an optical proximity effect. As our discussion has shown, the magnitude of this effect is a strong function of the optical parameters of the stepper. But there are many other proximity effects that relate to more complicated two-dimensional mask shapes. In the next issue of this column will discuss other proximity effects and how to correct for them.

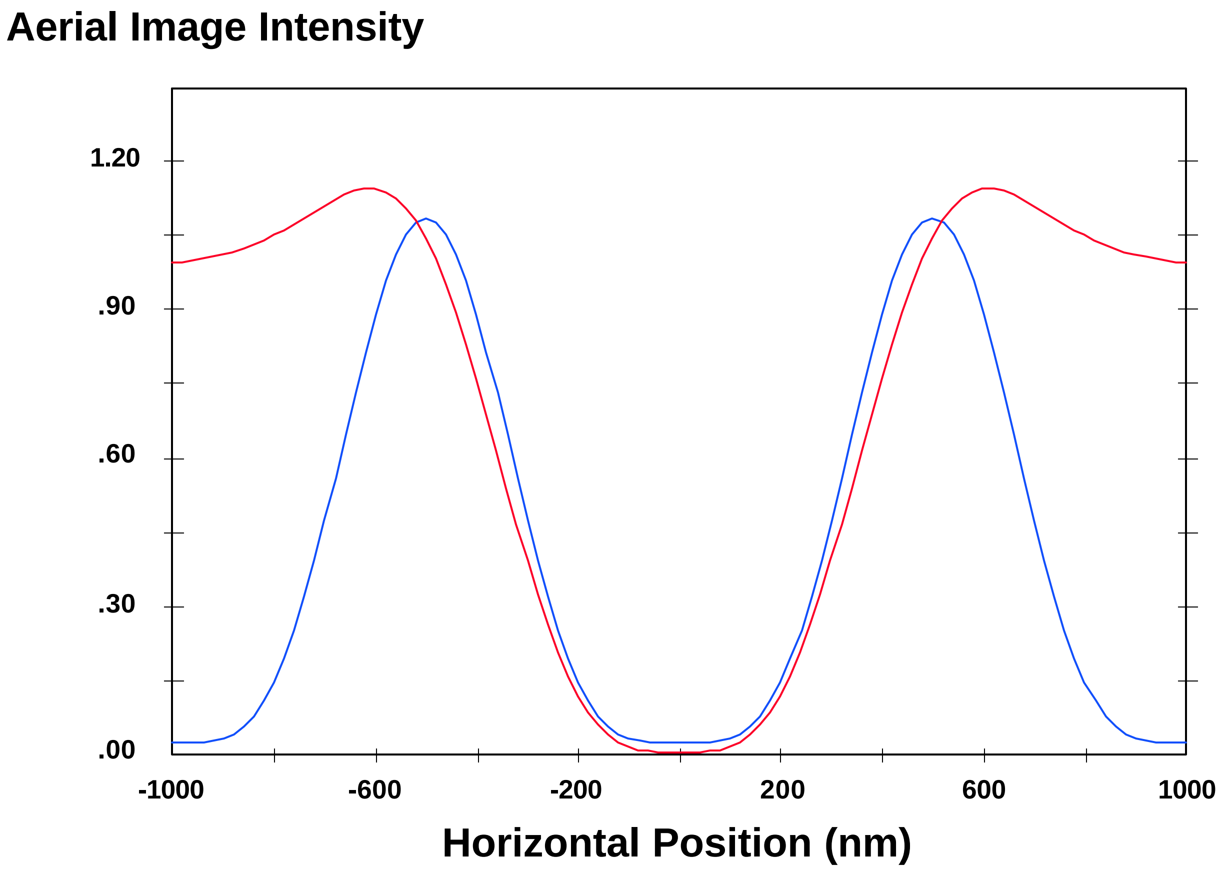


Figure 1. The iso-dense print bias is fundamentally a result of the difference in the aerial images between isolated and dense lines. In this case, the isolated line is wider than the line in a dense array of equal lines and spaces (0.5 micron features, λ = 365nm, NA = 0.52, σ = 0.5).

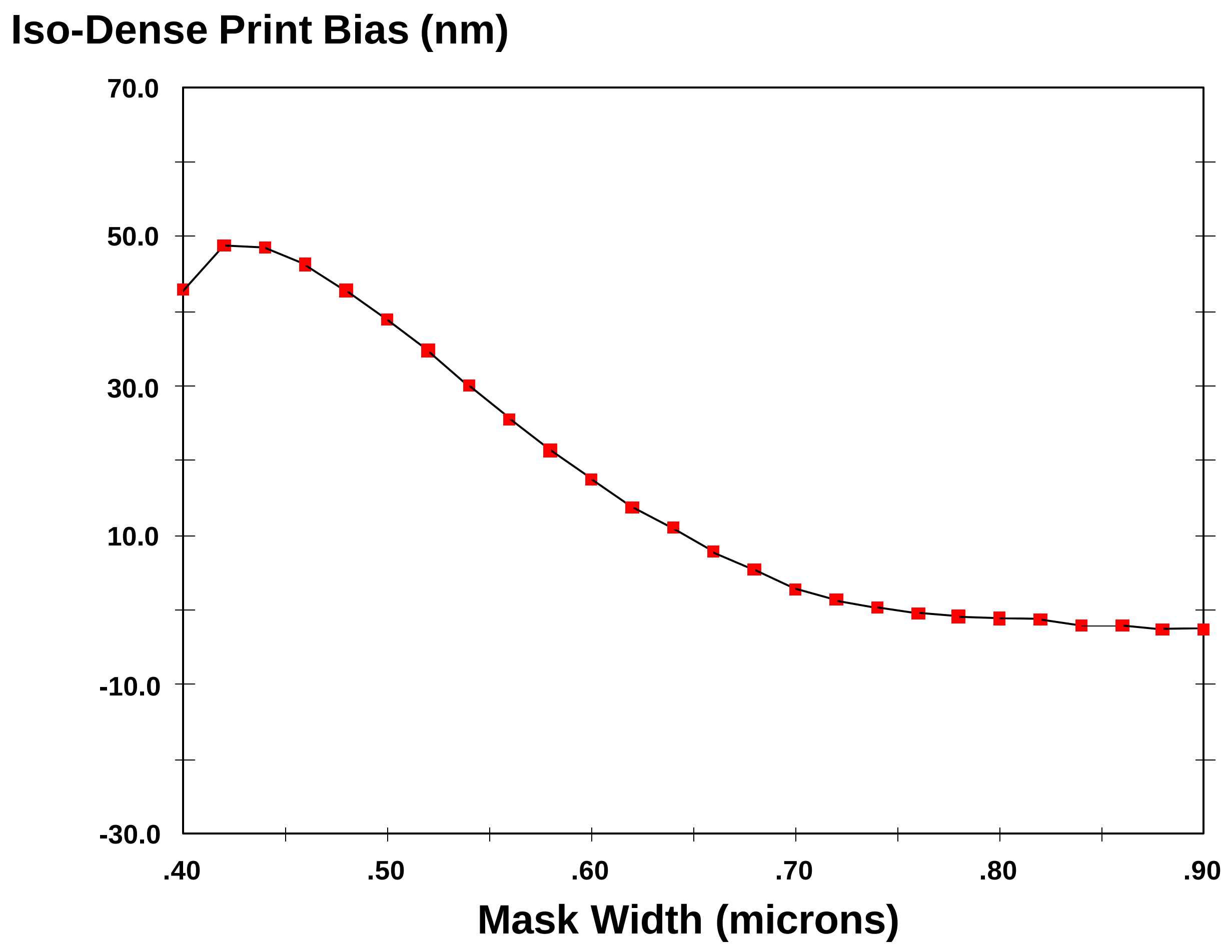


Figure 2. Feature sizes below 0.7µm ($k_1 = wNA/ l = 1.0$) show increasing proximity effects (λ = 365nm, NA = 0.52, σ = 0.5).

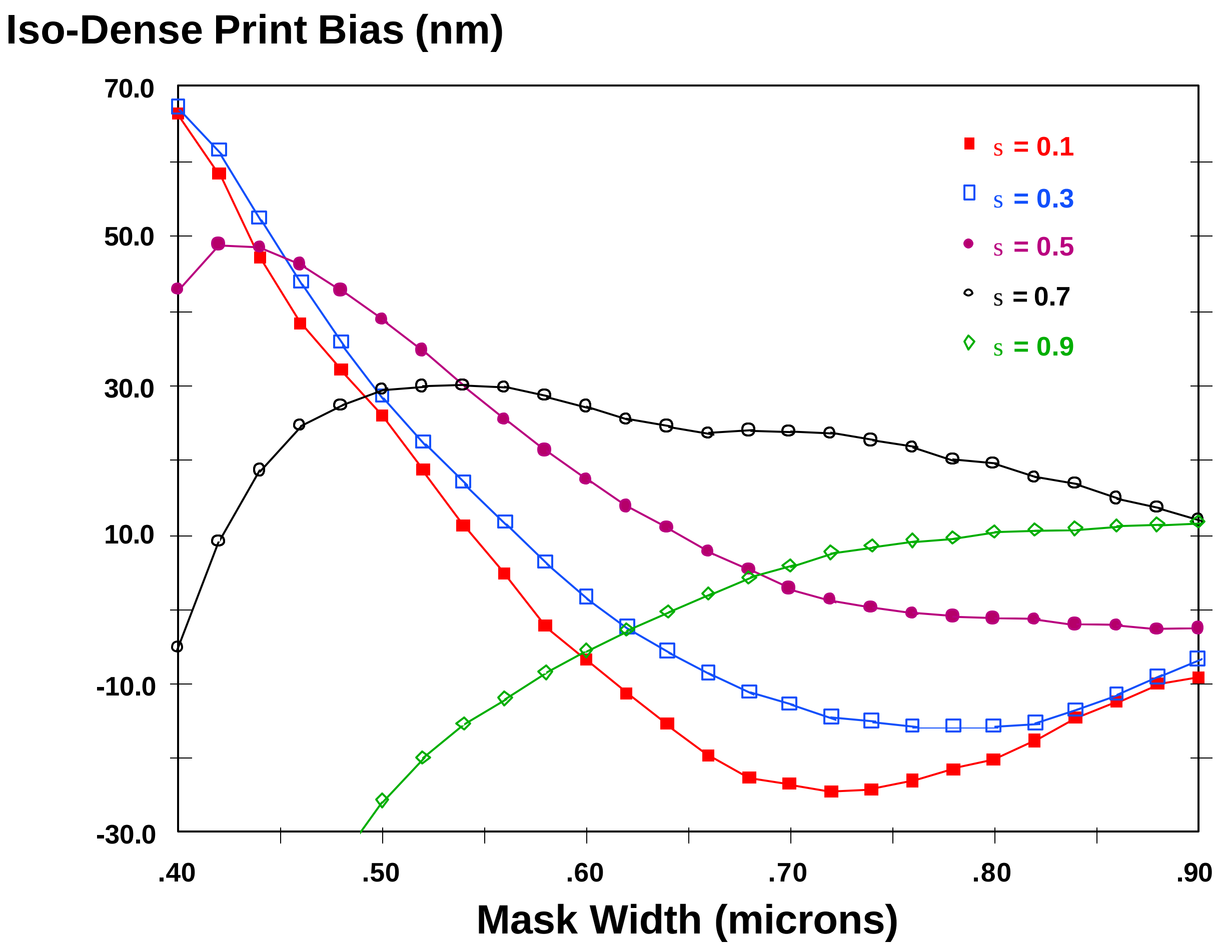
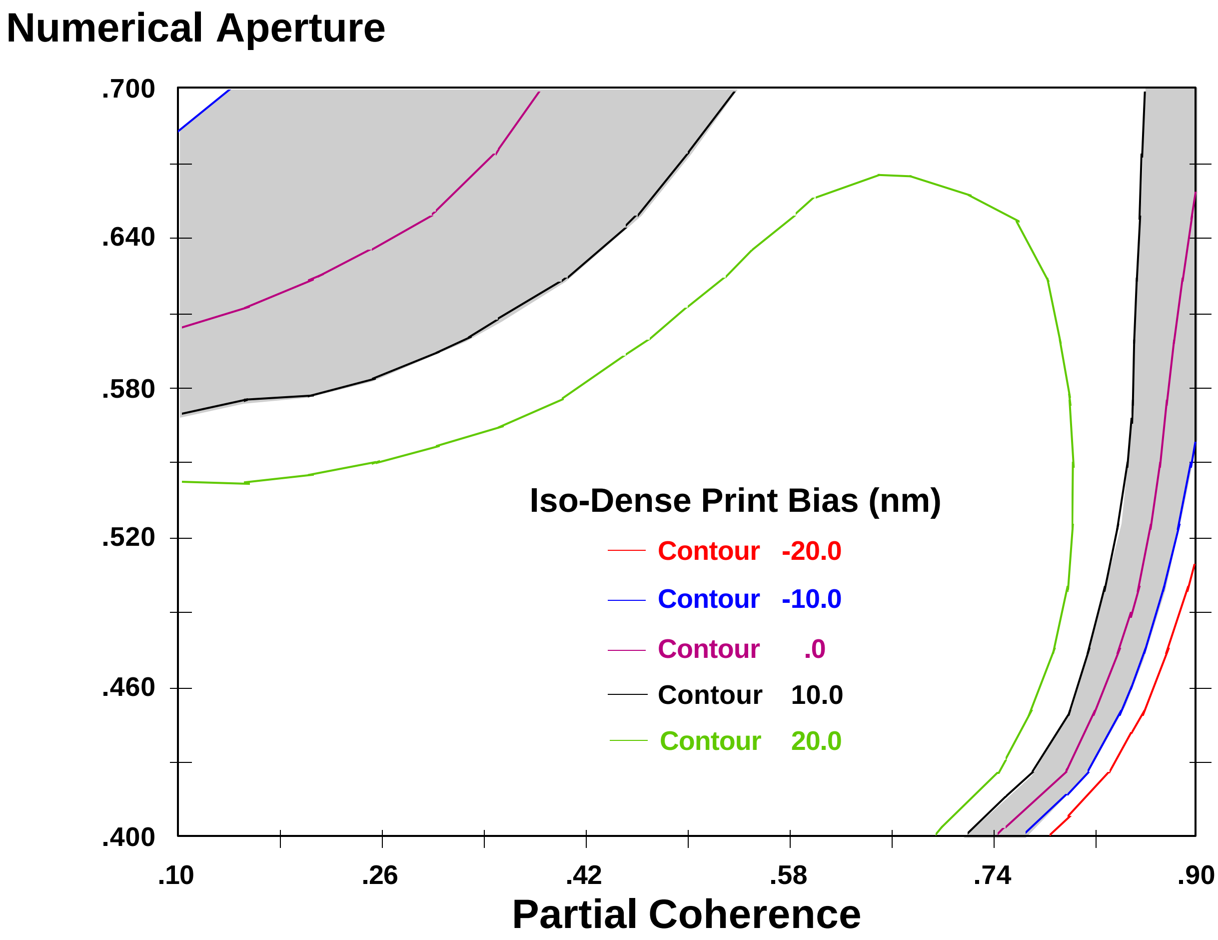
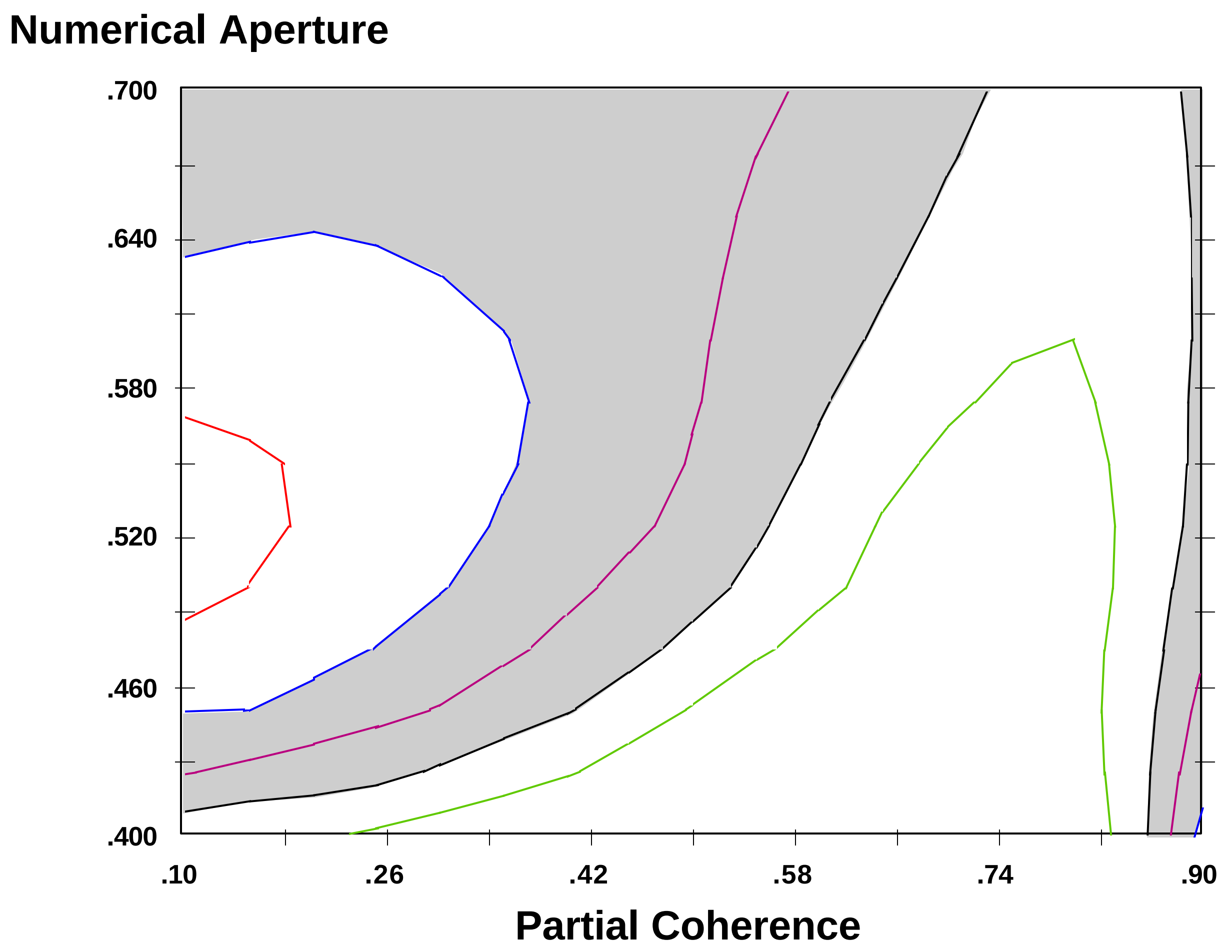


Figure 3. Partial coherence significantly affects the iso-dense print bias (λ = 365nm, NA = 0.52).



Numerical Aperture
.700
.640
.580
.520
.460
.400
Iso-Dense Print Bias (nm)
Contour -20.0
Contour -10.0
Contour .0
Contour 10.0
Contour 20.0
.10
.26
.42
.58
.74
.90
Partial Coherence

(a)



(b)

Figure 4. Contours of constant iso-dense print bias for (a) 0.5 µm and (b) 0.7 µm lines. The shaded areas show regions where the print bias is less than ±10nm.

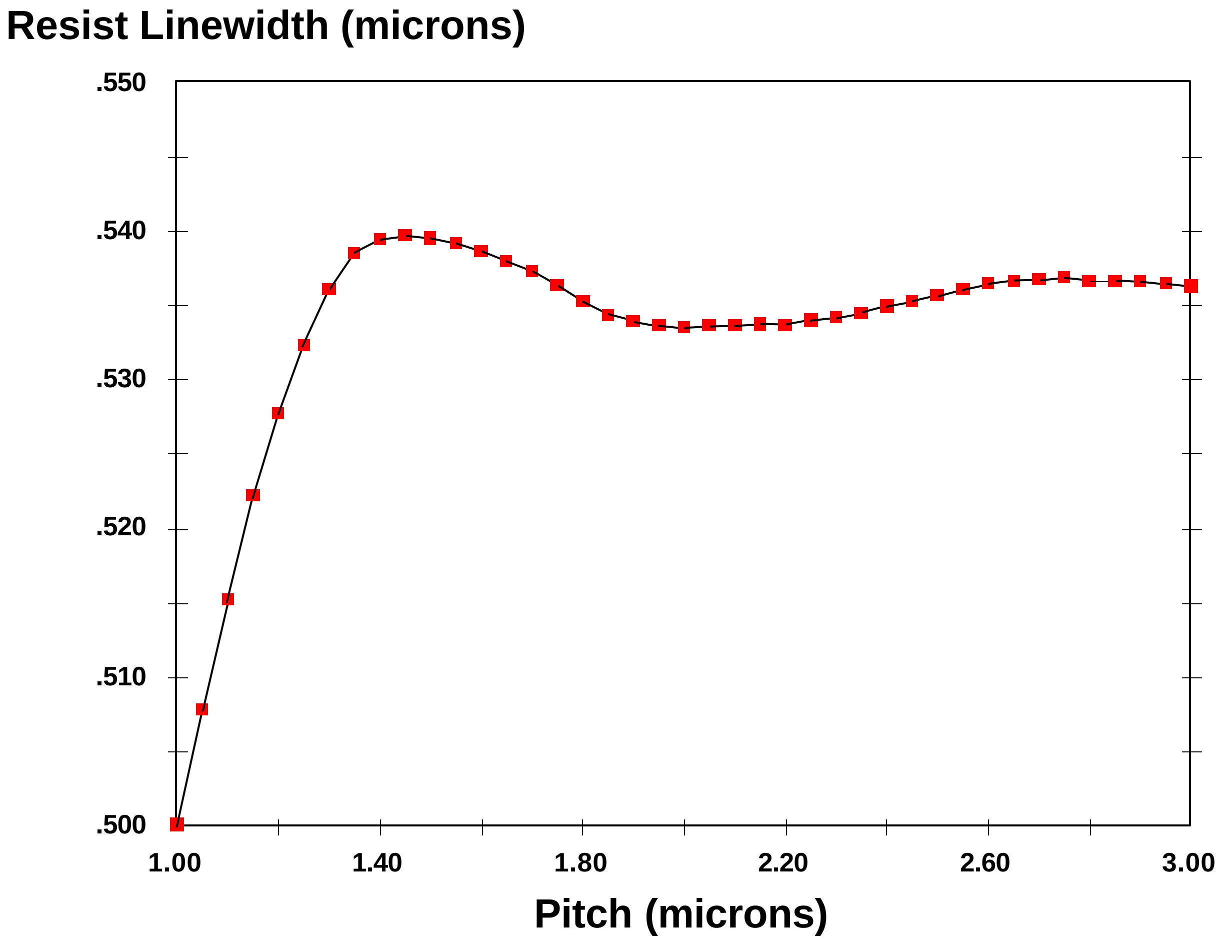


Figure 5. Variation of a feature linewidth as a function of the nearest neighbor distance reveals that the maximum proximity effect is often not the iso-dense print bias (i-line, NA = 0.52, σ = 0.5).