Proximity Distance

Optical proximity effects are a well know problem in optical lithography – the printed size of a given feature is a function of other features in its proximity. This problem has a well know solution as well – optical proximity correction (OPC), the modification of the mask layout to compensate for these proximity effects. The most popular and accurate method of OPC is to use a model to predict proximity effects. Obviously, accurate OPC requires accurate modeling of the proximity effects. While there are many contributors to proximity effects, the main one is the optical imaging itself. Considering just this phenomenon, an important question to ask is how far do these proximity effects extend?

The answer has more than just academic significance. OPC models break the mask up into computationally manageable segments that are then simulated and stitched back together again. But because of proximity effects, the actual simulation area has to be made larger than the segment that will be used for OPC so that an accurate result can be had within the area being corrected. The amount of buffer distance that must be added to each side of the correction area should equal the *proximity distance*, *i.e.*, the distance over which proximity effects are expected to be of significance. If too small a buffer is chosen, the results will not be sufficiently accurate. If too large a buffer is chosen, simulation times will be unnecessarily long. What determines this proximity distance, and how should the operator of an OPC tool determine the correct buffer distance for the simulations?

To answer these questions, let us assume a very simple process model: an ideal threshold resist that puts the edge of the final printed feature at the point where the image reaches a certain threshold intensity. (While more accurate resist models are used in real OPC applications, this simple model will suffice for our purposes and will not significantly affect our analysis and resulting conclusions.) Also, to make a picture of our problem that is as straightforward as possible, consider an isolated space surrounded by chrome on the mask. If no other features are around this space, it will print at the desired critical dimension (CD_{nom}). Now suppose that a second feature is placed to the right of this space. How close can this second feature come before it starts to affect the dimension of our target space?

The optical interaction of the two features depends on the spatial coherence of the illumination. For incoherent illumination, the small intensity coming from the second feature (I_2) will overlap and add to the intensity of the first feature (I_1) at its edge, changing its size. Using our threshold model, a small change in the right edge position (Δx) can be estimated to be

$$\Delta x = \frac{I_2}{dI_1 / dx} \tag{1}$$

Putting this in terms of the normalized image log-slope (*NILS*),

$$\frac{\Delta x}{CD_{nom}} = \left(\frac{I_2}{I_1}\right)\frac{1}{NILS} \quad \text{where} \quad NILS = CD_{nom}\frac{d\ln I_1}{dx} \tag{2}$$

For our threshold model, I_1 must equal the threshold intensity. Let's assign some typical values to equation (2). A typical value for such a threshold intensity is about 0.25, and high resolution features often have a NILS of 2 or less. If we want our OPC model to notice a change in CD caused by the proximity of this second feature as small as 1%, then the minimum detectable edge change should be 0.5%. Thus, the minimum value if I_2 that we need to worry about is 0.0025. If the second feature is far enough away that its contribution to the edge intensity of the first feature is less than this amount, it can be ignored.

But lithography tools do not employ incoherent illumination. Let's examine what happens at the opposite extreme – using coherent illumination. Here, electric fields overlap and add together, not intensities. Assuming that the amount of light coming from the second feature is small and that the phases of the two electric fields are at their worst case (that is, in phase), the resulting total intensity at the right edge of feature 1 is

$$I_{total} = (E_1 + E_2)^2 \approx I_1 + 2E_1E_2 = I_1 + 2\sqrt{I_1}E_2 \tag{3}$$

where electric fields are represented by E. The change in edge position for this case becomes

$$\frac{\Delta x}{CD} = \left(\frac{2E_2}{\sqrt{I_1}}\right)\frac{1}{NILS} \tag{4}$$

Using the same typical values as before, we find now that the minimum electric field we must worry about is 0.0025. But since this results in an intensity of about 6×10^{-6}, we must keep track of much smaller intensities, and thus features that are farther away.

Before tackling the more interesting but difficult problem of partially coherent illumination, let's pick a specific feature to be in proximity to our target space. The worst feature that we could bring near our "isolated" space would be a large open area. Thus, the image of the second feature is that of an isolated edge between chrome and glass. Figure 1 shows the images of an isolated edge under conditions of coherent and incoherent illumination. For incoherent imaging, the isolated edge has quite a long tail of light, dropping down to an intensity of 0.0025 only after a distance of $10\lambda/NA$. For coherent illumination, the electric field oscillates, and the peaks drop off to a magnitude of 0.0025 at a distance of about $20\lambda/NA$.

One might expect, then, that partially coherent illumination would give results between these two extremes and have proximity distances between $10\lambda/NA$ and $20\lambda/NA$. Fortunately, this is not necessarily the case. When a mask is illuminated with partially coherent illumination, very close features will interact coherently while far away features interact incoherently. The point of transition between these regions is called the *spatial coherence length* ($l_{coherence}$). Distances much below the spatial coherence length will result in coherent interaction of images, while distances much larger than the spatial coherence length produces images that interact incoherently. This coherence length is given by

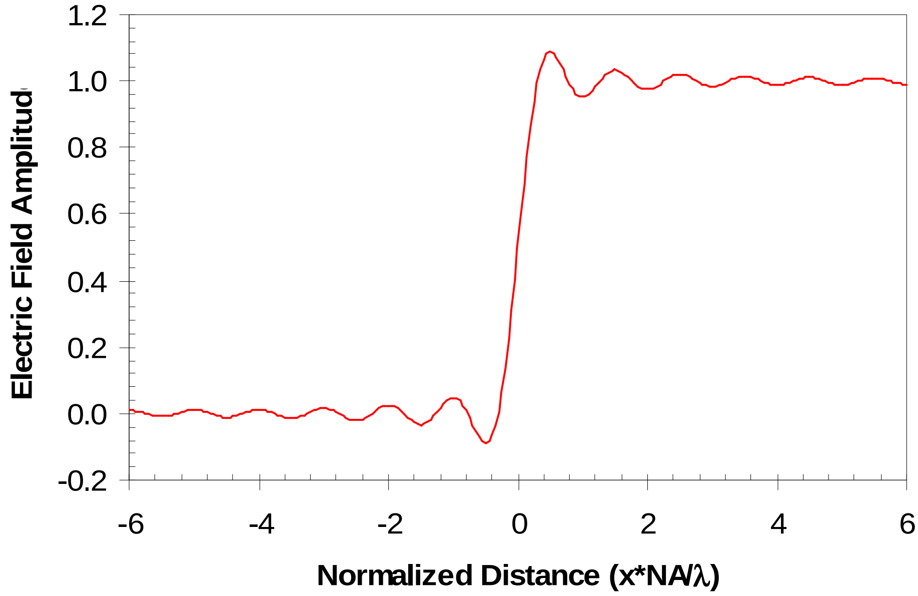
$$l_{coherence} = \frac{\lambda}{\sigma NA} \tag{5}$$

where σ is the partial coherence factor. For conventional illumination, σ is the radius of the illumination disk, whereas for off-axis illumination it is the radius or half-width of the off-axis pole or annulus. As σ goes to zero the illumination becomes fully coherent and the coherence length becomes infinite. Thus, all electric fields add coherently and something like the $20\lambda/NA$ proximity distance applies. For incoherent illumination, σ goes to infinity, the coherence length becomes zero, and intensities add incoherently everywhere.

Consider an intermediate case of $\sigma = 0.5$. The coherence length is about $2\lambda/NA$ so that features much further away than this will interact incoherently. But for distances near $2\lambda/NA$, the intensity from an isolated edge imaged with this partial coherence is already less than 0.0025, though greater than $6\text{X}10^{-6}$. Thus, the proximity distance is in the transition region between coherent and incoherent interactions, and is thus about equal to the coherence length (within a factor of 2–3 or so). For very high resolution processes using off-axis illumination, σ can be as small as 0.1. Here, the coherence length is $10\lambda/NA$ and the proximity distance is certainly greater than the coherence length. As a very rough rule of thumb, I often use twice the coherence length (up to a maximum of $20\lambda/NA$) as my estimate of the proximity distance.

In the end, the coherence length is often a reasonable estimate of the proximity distance, so long as getting it right to a factor of two or so is good enough. For better estimates, full lithographic simulation under the conditions of interest is invaluable, since the proximity distance will depend not only on the specifics of the illumination, but on the *NILS* and simulation accuracy requirements as well.

List of Figures.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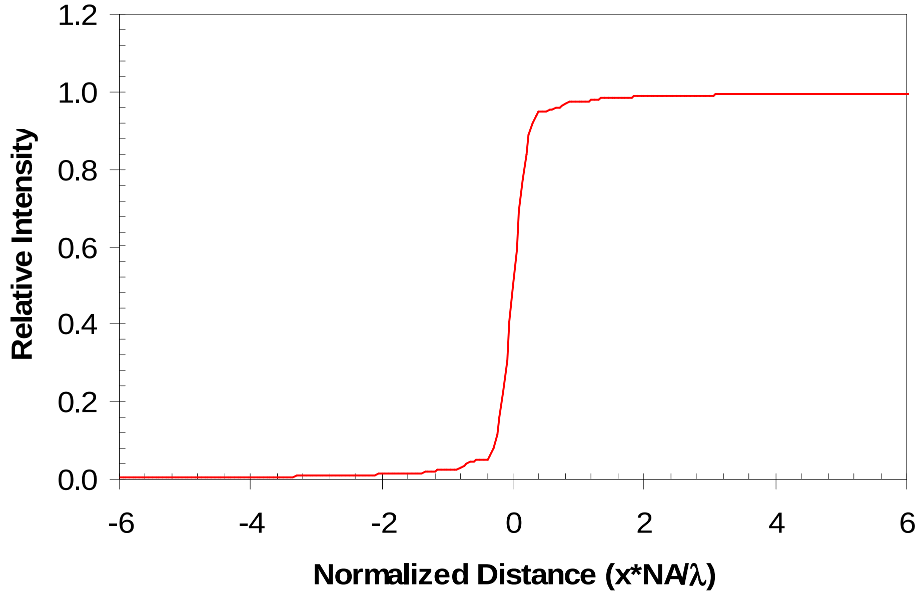
0.8
0.6
0.4
0.2
0.0
-0.2
Electric Field Amplitud
-6
-4
-2
0
2
4
6
Normalized Distance (x*NA/λ)

(a)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1.0
0.8
0.6
0.4
0.2
0.0
Relative Intensity
-6
-4
-2
0
2
4
6
Normalized Distance (x*NA/λ)

(b)

Figure 1.