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Optical Proximity Effects, part 2

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In the last edition of the *Lithography Expert*, we examined one type of optical proximity effect, the iso-dense print bias. This difference between the size of an isolated line and a line in a dense array of equal lines and spaces is the most commonly observed proximity effect in optical lithography. The magnitude of this print bias is strongly affected by the optical parameters of the stepper (as we saw last time) and the contrast of the photoresist. If these things remain constant, the print bias can be characterized and corrected by biasing the mask (i.e., changing the actual chrome width on the mask to be different from the desired resist width) [1,2]. This type of geometry-dependent mask biasing is commonly referred to as *optical proximity correction* (OPC), although a more descriptive name might be mask shaping.

In general, how does one determine the optimum mask shape to get the desired resist shape? This simple question is more complicated than it appears. As with most such questions, the answer depends on what is meant by “optimum.” Consider first the simple case of printing long lines. What is the optimum width of the mask line to get the desired resist line for many different linewidths and proximity of other lines? One simple definition of optimum could be just obtaining the right linewidth at the nominal exposure dose and focus. For a 0.4 µm resolution process, let us use the 0.4 µm equal line/space pattern as the baseline. Without any bias on the mask for this feature, we determine the exposure dose to properly size this feature. Our simple requirement, then, is that all other mask features must properly print at their correct size at this dose as well. As we saw in the last edition of this column, proximity effects prevent this from occurring naturally. As a result, we can only obtain this result by changing the feature sizes on the mask to correct for these proximity effects.

Figure 1 shows one example of what the mask bias solution might look like. The mask bias is defined as the actual chrome width minus the nominal (unbiased) chrome width. Thus, a positive bias means the chrome has been made bigger. Each curve shows the amount of bias needed as a function of the nominal feature width. The three different curves show different proximity to other features. As expected, the smaller features need more bias than the larger ones and are much more sensitive to proximity effects. Note that all of the features above 0.7 µm ($k_1 = wNA/l = 1.0$) need about the same mask bias. For this example we have defined our starting point as zero bias for the most difficult feature, the 0.4 µm lines and spaces. An alternate approach would be to set zero bias for the large features and adjust the bias of the smaller features to match the dose to size of the larger features.

Our definition of the “optimum” mask bias so far is a simple one -- the bias which gives the proper printed linewidth at the nominal process conditions. Other definitions may include the tolerance to variations in process conditions (for example, the maximum overlap of the focus-exposure process windows of the various features). Ultimately, the best solution is that which gives the tightest distribution of linewidths for all of the features in the presence of typical process variations.

Properly correcting for proximity effects for one-dimensional mask features such as lines and spaces is relatively straightforward. Correcting more realistic two-dimensional mask patterns is much more challenging. First of all, the 1-D case provides a simple metric for the proximity effect: the critical dimension error (CDE). The optimum mask bias is that which drives the CDE to zero. How do you judge the error in the shape of a 2-D pattern? For this we must define a critical shape error (CSE), the two-dimensional analog to the critical dimension error. Figure 2a shows a very simple elbow-shaped mask pattern and its corresponding printed shape (a top-down view of the photoresist, Figure 2b). To describe the error in the actual resist image from a target or desired resist image, one must first define this target image. Although it would be easy to assume that the original mask pattern is the target for the resist pattern, this is not actually the case. The mask is composed of elementary shapes such as rectangles, which necessarily have sharp corners. When printed in photoresist, these corners are always rounded to some extent. A certain amount of corner rounding is perfectly acceptable. Although there is no reason to round the corners of the designed mask layout, there is also no reason to insist that the final printed pattern match the square corners of the design. Thus, the actual *desired* pattern deviates from the *designed* pattern due to an acceptable amount of corner rounding. Figure 2c shows the desired pattern shape, which is simply the designed pattern of Figure 2a with a small amount of corner rounding. Defining the maximum acceptable rounding radius is an important part of determining a realistic target image shape, and thus a realistic value for the CSE.

The critical shape error is determined by finding the point-by-point difference between the actual printed resist shape and the desired shape [3,4]. The result is a frequency distribution of errors as shown in Figure 3. Once such a distribution is determined, some characterization of the distribution can be used to describe the overall shape error. For example, the average error could be used (CSE_{avg}) or the error which is greater than 90% of the point-by-point measurements (CSE_{90}), or some other percentage could also be used. For the distribution in Figure 3, some results are given below:

CSE_{avg} = 26.9 nm

CSE_{80} = 46 nm

CSE_{90} = 55 nm

CSE_{95} = 65 nm

$CSE_{99.7}$ = 91 nm

Once the critical shape error can be determined, the mask can be “corrected,” i.e., shaped, to minimize the CSE. As with the correction of 1-D mask patterns, there can be many criterion for the optimum mask shape, but the CSE allows these criterion to be applied systematically. The main advantage of using the critical shape error is its analogy to the one-dimensional critical dimension error. Much of the methodology of examining and optimizing a process to minimize critical dimension errors can be applied directly to the CSE. For example, one could plot a focus-exposure matrix of CSE, determine exposure latitude, generate a process window, even define the depth of focus of a complicated two-diemnsional pattern based on the CSE.

In the next edition of the Lithography Expert we will expand our discussion of proximity effects to look at the impact of resist properties.

References

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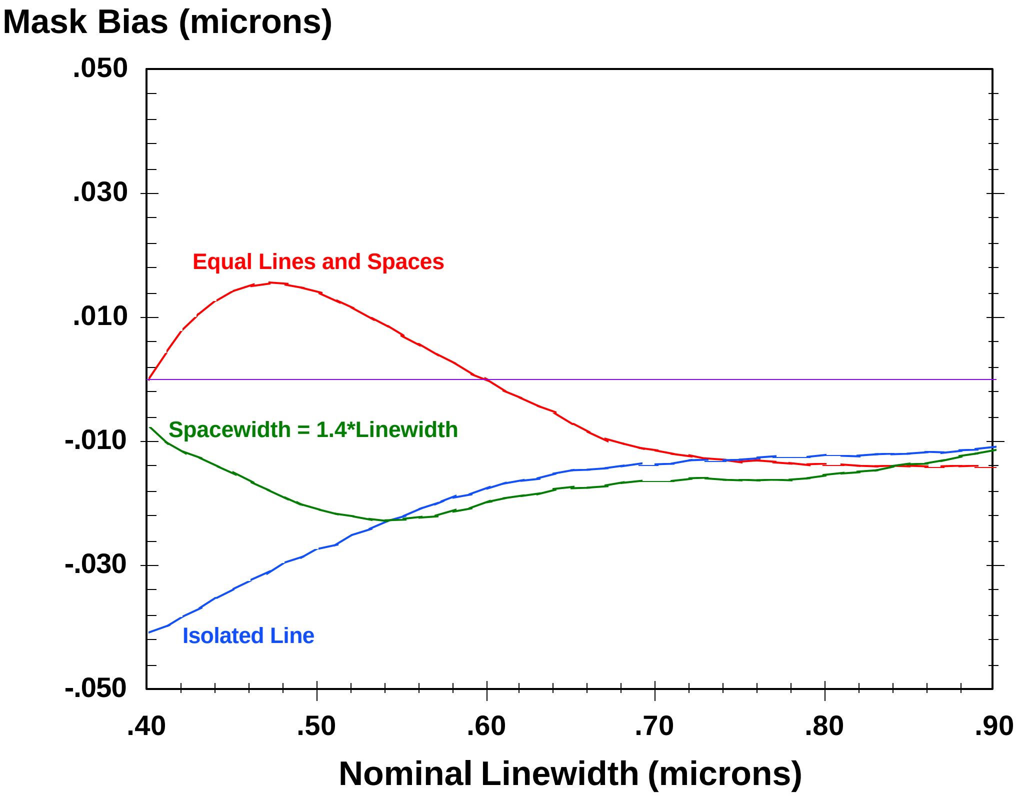


Figure 1. Design curves of the mask bias required to make all of these features print at the nominal linewidth (i-line, NA = 0.52, σ = 0.5, typical resist).

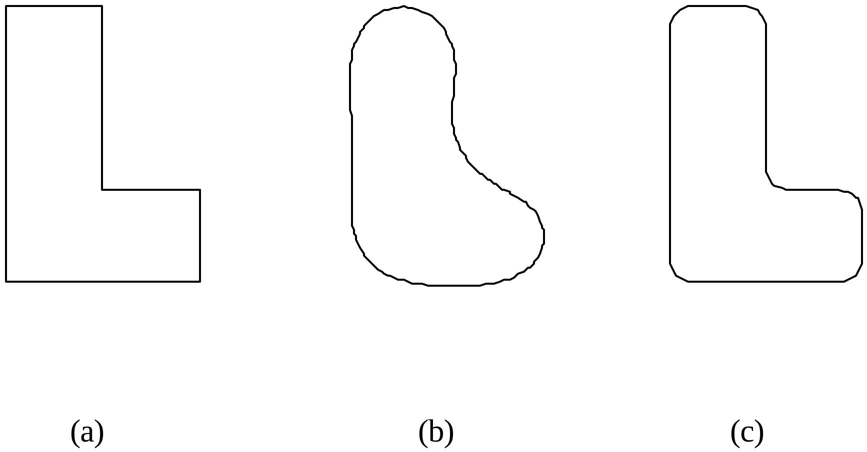
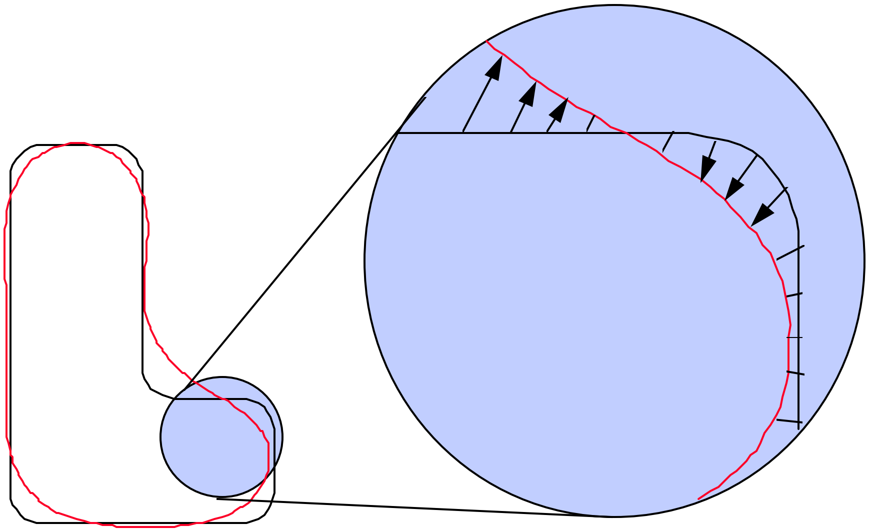
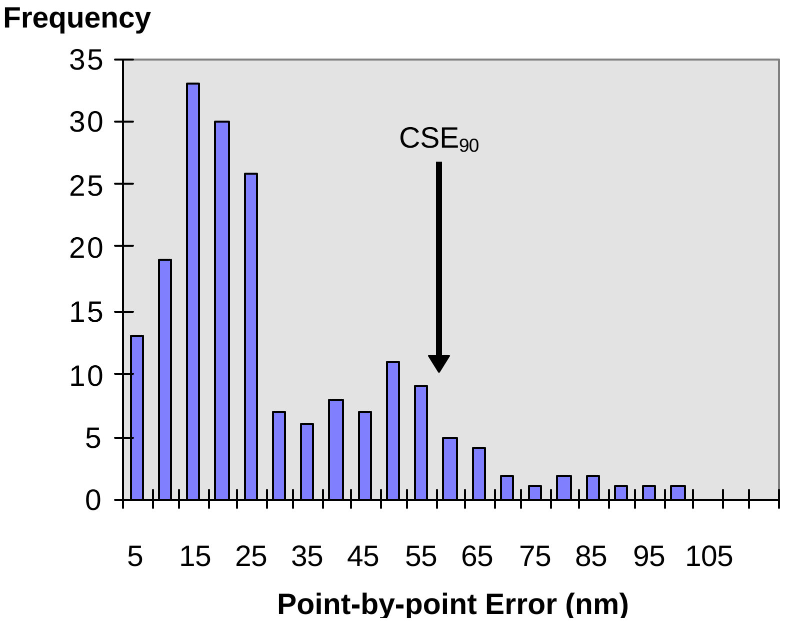


Figure 2. Printing of a two-dimensional pattern provides three distinct shapes: (a) the designed pattern (with 400nm minimum width), (b) the final printed pattern (top down view), and (c) the desired pattern (with 100nm corner rounding).



(a)



(b)

Figure 3. Making point-by-point measurements (a) comparing actual to desired shapes results in (b) a frequency distribution of errors, using a technique similar to that discussed by Tsudaka et al. [3]. One possible critical shape error (the CSE$_{90}$) is shown as an example of the analysis of this distribution.