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Line End Shortening

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Historically, lithography engineering has focused on two key, complimentary aspects of lithographic quality: overlay and linewidth control. Linewidth control generally means ensuring that the widths of certain critical features, measured at specific points on those features, fall with acceptable bounds. However, as lithography pushes to smaller and smaller features, single number metrics such as the critical dimension (CD) of a feature may not be adequate. The three-dimensional shapes of the final printed photoresist features can, in fact, affect the performance of the final electrical devices in ways that cannot be described by variations in a single width parameter of those features. In such cases, increasingly common today, more information about the shape of a photoresist pattern must be measured in order to characterize its quality. One very simple example is known as “line end shortening”.

Consider a single, isolated line with width near the resolution limit of a lithographic process. Considerable effort is usually required to develop a process that provides adequate CD control over a range of processing errors (focus, exposure, mask errors, etc.). Although such a feature is generally considered to be one-dimensional (with CD, measured perpendicular to the long line, as the only important dimension), it must, by necessity, have a two-dimensional character at the line end. An important question then arises: for a process where control of the linewidth is adequate, will the shape of the line end also behave acceptably? Often, the answer to this question is *no* due to line end shortening.

Figure 1 illustrates the problem. When the process is adjusted to give the correct CD along the length of the line, the result at the line end will be a pull-back of the resist to produce a foreshortened end. The degree of line end shortening is a strong function of the line width, with effects becoming noticeable for k_1 (= width * numerical aperture / wavelength) less than about 0.8. At first glance, it may seem that a solution to this problem is straightforward. If the printed image of a line end is shorter than the drawn pattern on the mask, simply extending the mask by the amount of line end shortening would solve the problem. Of course, since the degree of line end shortening is feature size dependent, proper characterization would be required. Most commercial optical proximity correction or design rule checking software today can automatically perform such corrections on the design before the photomask is made. This solution ignores two very import problems, however. First, what happens when the end of the line is in proximity to another feature, as in Figure 1, and second, how does the degree of line end shortening vary with processing errors? For the first problem, a simple extension of the line may not work. Thus, more complicated corrections (such as increasing the width of the line near the end) are required. For the second problem, a more complete characterization of line end shortening is needed.

In order to characterize line end shortening, the first step is to find a way to measure it. Since line end shortening is fundamentally an error of the resist pattern relative to the design, it cannot be independently measured. Instead, it must be measured as the difference between two measurements, such as a measure of the line end position relative to another feature. A very simple approach is to use a test structure such as that shown in Figure 1 where the line end shortening is considered to be proportional to the width of the gap between the end of the line and the edge of the nearby perpendicular line. But this gap alone does not tell the whole story. Changes in the process (such as focus and exposure) will affect the gap width as well as the width of the isolated line.

Hollman and Mack [1] proposed an interesting approach to normalizing the relationship between linewidth and line end shortening by plotting the gap width from a structure like that in Figure 1 as a function of the resist linewidth over a range of processing conditions. Based on the simple behavior of a pattern of lines and spaces where the resist linewidth plus the spacewidth will always be equal to the pitch, one can establish the ideal, linear imaging result here. For the pattern in Figure 1, the ideal result should be a straight line with equation *linewidth* + *gapwidth* = 500nm, where the designed linewidth and gap width are both 250nm. As an example, the data from a focus-exposure matrix are plotted in Figure 2 using this technique. Interestingly, all of the data essentially follows a straight line which is offset from the ideal, no line end shortening result. The vertical offset between the ideal line and a parallel line going through the data can be considered the effective line end shortening over the range of processing conditions considered. Although not perfect, this result shows that the variables of focus and exposure do not influence the effective line end shortening to first order. The fact that the data forms a line which is not exactly parallel to the ideal line simply indicates that, to second order, the line end shortening does not exhibit the same process response to these variable as does the line width.

The gap width versus linewidth approach to characterizing the effective line end shortening still ignores the three-dimensional nature of line end effects. As is well known, processing changes, especially focus, can alter the shape as well as the size of a photoresist feature. For the case of a resist line cross-section, the sidewall angle of the resist pattern is reduced when out of focus. What is less obvious is that the end of a line is even more sensitive to focus errors than the line itself. Figure 3 shows how errors in focus can change the three-dimensional shape of a line end. Obviously, any metrology designed to measure line end shortening will almost certainly be affected by the shape changes depicted in Figure 3.

This column has tried to address some of the basics of line end shortening, including its measurement and characterization. In the next edition of the *Lithography Expert* we'll explore the fundamentals of why line end shortening occurs by examining the related issue of corner rounding.

References

1. R. F. Hollman and C. A. Mack, "3-D Optical Lithography Simulation Accuracy for Advanced Reticles," *17th Annual BACUS Symposium on Photomask Technology and Management*, SPIE Vol. 3236 (1997) pp. 424-429.

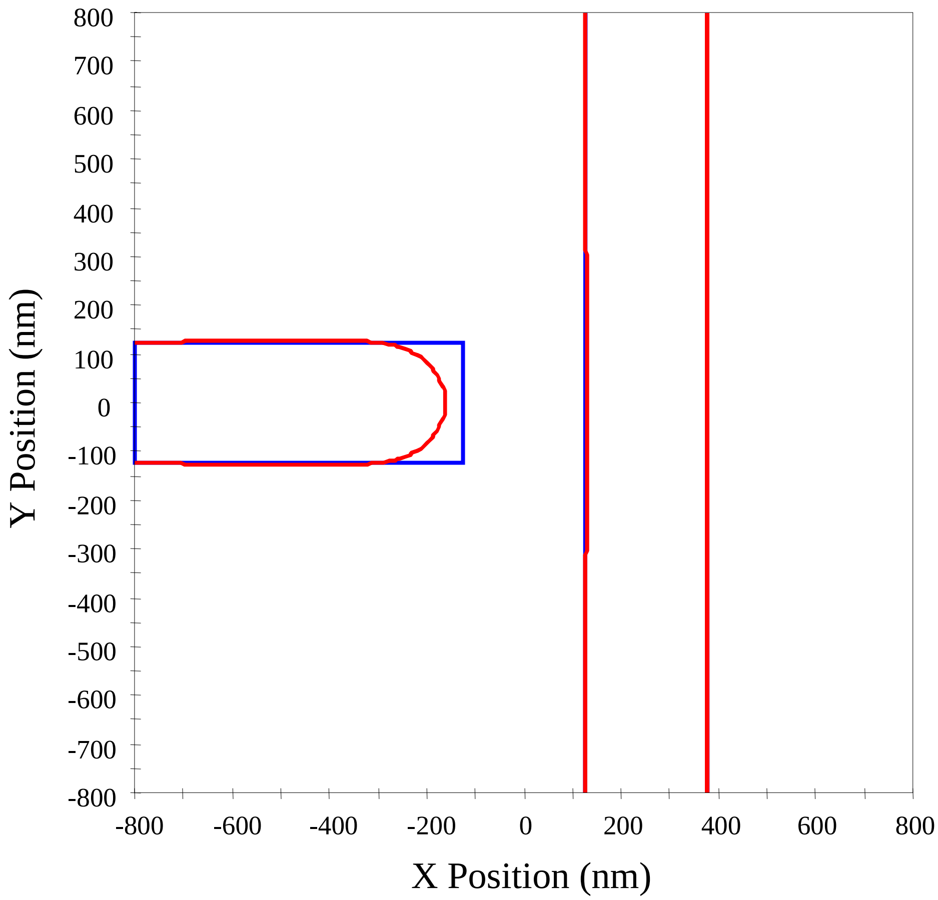

Figure 1. Outline of the printed photoresist pattern (red) superimposed on an outline of the mask (blue) shows an example of line end shortening (k_1 = 0.6).

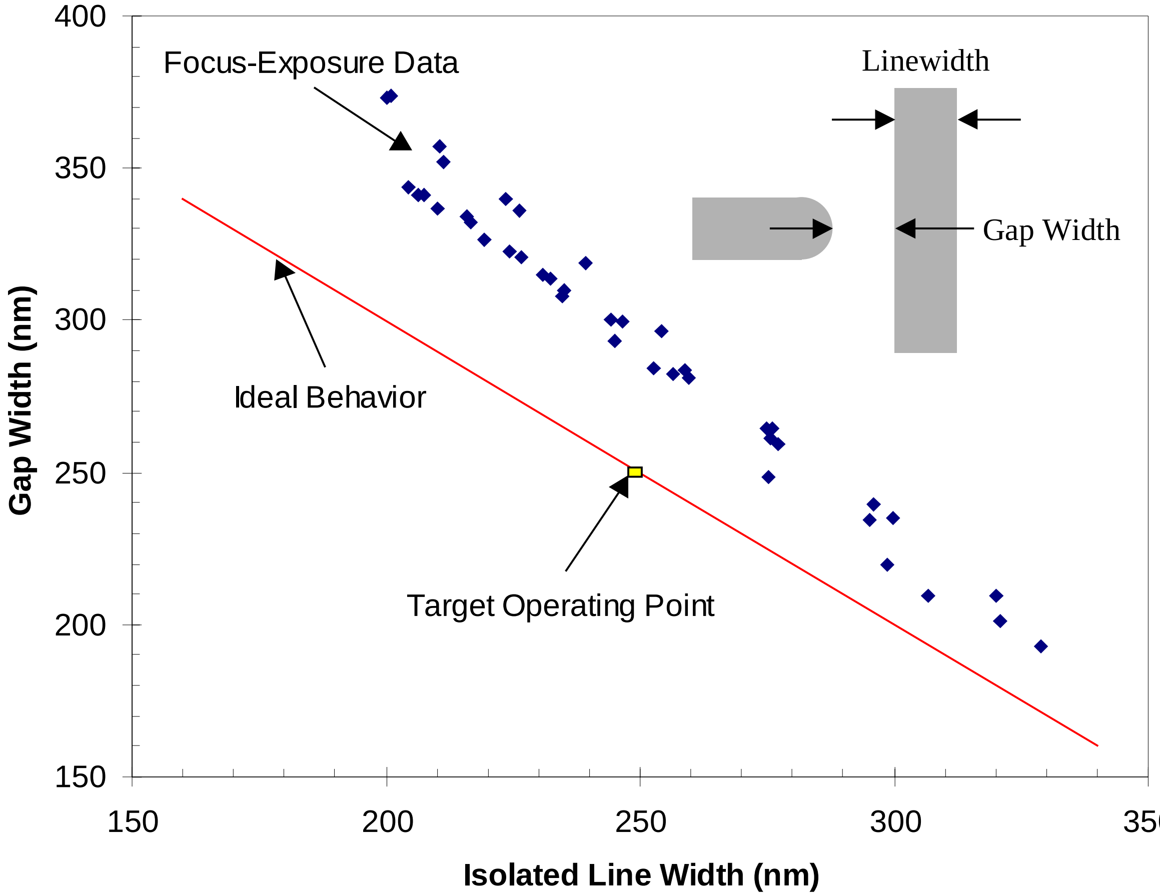

Figure 2. Line end shortening can be characterized by plotting the gap width of a structure like that in the insert as a function of the isolated linewidth under a variety of conditions. As shown here, changes in focus and exposure produce a linear gap width versus linewidth behavior.

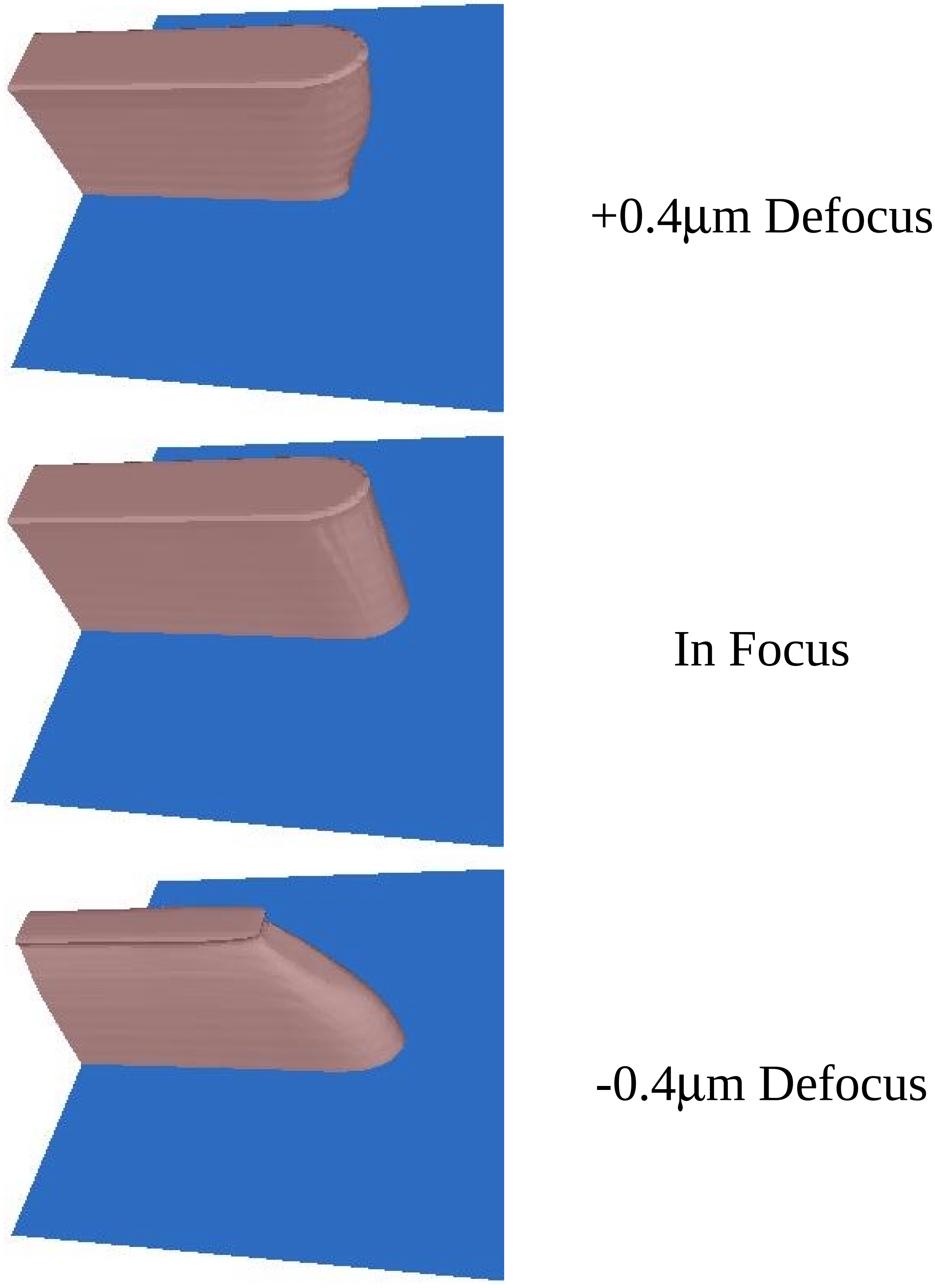

Figure 3. Simulated impact of focus on the shape of the end of an isolated line (250nm line, NA = 0.6, $\sigma = 0.5$, $\lambda = 248$, positive focus defined as shifting the focal plane up).