Depth of Focus

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The effect of focus on a projection lithography system (such as a stepper) is a critical part of understanding and controlling a lithographic process. As feature sizes decrease, their sensitivity to focus errors increases dramatically. Many people would say that this focus sensitivity is the main limitation of the use of optical lithography for smaller and smaller features. This column will address the importance of focus by providing a definition of *depth of focus*.

Establishing a suitable definition for a commonly used concept such as depth of focus is not necessarily an easy task. Uses of the term vary widely, and there is no single definition which is commonly accepted as the "best" definition. In general, DOF can be thought of as the range of focus errors that a process can tolerate and still give acceptable lithographic results. Of course, the key to a good definition of DOF is in defining what is meant by tolerable. A change in focus results in two major changes to the final lithographic result: the photoresist profile changes and the sensitivity of the process to other processing errors is changed. The first of these effects, the photoresist profile change, is the most obvious and the most easily observed consequence of defocus. Typically, photoresist profiles are described (in an oversimplified way) using three parameters: the linewidth (also called the critical dimension, CD), the sidewall angle, and the resist thickness of the feature (which is useful for lines or islands, but not spaces or contacts). In effect, the resist profile is modeled as a trapezoid, as shown in Figure 1. Usually it is more convenient to talk about resist loss (the difference between the original resist thickness and the final resist thickness), possibly as a percentage of the original resist thickness.

The variation of linewidth, sidewall angle, or resist loss with focus can be readily determined for any given set of conditions. If these were the only responses of importance, specifications on these responses would lead to a simple definition of the depth of focus: the range of focus which keeps the linewidth, sidewall angle, and resist loss within their stated specifications. There is, however, a second affect of focus which is significantly harder to quantify and of great importance. As an image goes out of focus, the process becomes more sensitive to other processing errors such as exposure dose or develop time. Of these secondary process errors, the most important by far is exposure. To state the issue in another way, focus and exposure are coupled in their effect on the process.

Since the effect of focus is dependent on exposure, the only way to judge the response of the process to focus is to simultaneously vary both focus and exposure in what is known as a focus-exposure matrix. Figure 2 shows typical examples of the output of a focus-exposure matrix using linewidth, sidewall angle, and resist loss as the responses. The most common of these curves, Figure 2a, is called the Bossung plot [1] and shows linewidth versus focus for different exposures. (John Bossung was a field engineer with Perkin-Elmer when focus first become an issue of concern.)

Each plot in Figure 2 contains a large amount of data and interpretation can become a problem. Of course, one output as a function of two inputs can be plotted in several different ways. For example, the Bossung curves of Figure 2a could also be plotted as exposure latitude curves (linewidth versus exposure) for different focus settings (Figure 3a). This is very useful in showing how defocus causes a reduction in exposure latitude. Probably the most useful way to plot the two-dimensional data set of CD versus focus and exposure is a contour plot -- contours of constant linewidth versus focus and exposure (Figure 3b). Obviously, sidewall angle and resist loss could also be plotted in these alternate forms if desired.

The contour plot form of data visualization is especially useful for establishing the limits of exposure and focus which allow the final image to meet certain specifications. Rather than plotting all of the contours of constant CD for example, as was done in Figure 3b, one could plot only the two CDs corresponding to the outer limits of acceptability -- the CD specifications. Because of the nature of a contour plot, other variables can also be plotted on the same graph. Figure 4 shows an example of plotting contours of CD (nominal ±10%), 80° sidewall angle, and 10% resist loss all on the same graph. The result is a *process window* -- a region of focus and exposure which keeps the final resist profile within all three specs (shown as the shaded area of Figure 4).

The focus-exposure process window is one of the most important plots in lithography since it shows how exposure and focus work together to affect linewidth, sidewall angle and resist loss. The process window can be thought of as a *process capability* -- how the process responds to changes in focus and exposure. How can we determine if a given process capability is good enough? An analysis of the error sources for focus and exposure in a given process will give a *process requirement* [2]. If the process capability exceeds the process requirements, yield will be high. If, however, the process requirement is too large to fit inside the process capability, yield will suffer. A thorough analysis of the effects of exposure and focus on yield can be accomplished with yield modeling [3], but a simpler analysis can be used to derive a number for depth of focus.

What is the maximum range of focus and exposure (that is, the maximum process requirement) that can fit inside the process window? A simple way to investigate this question is to graphically represent errors in focus and exposure as a rectangle on the same plot as the process window. The width of the rectangle represents the built-in focus errors of the processes, and the height represents the built-in dose errors. The problem then becomes one of finding the maximum rectangle which fits inside the process window. However, there is no one answer to this question. As Figure 5a shows, there are many possible rectangles of different widths and heights which are "maximum", i.e., cannot be made larger in either direction without extending beyond the process window. (Note that the concept of a "maximum area" is meaningless here.) Each maximum rectangle represents one possible trade-off between tolerance to focus errors and tolerance to exposure errors. Larger depth of focus can be obtained if exposure errors can be minimized. Likewise, exposure latitude can be improved if focus errors are small. The result is a very important trade-off between exposure latitude and DOF. Figure 5b shows an analysis of the process window where every maximum rectangle is determined and their height (the exposure latitude) is plotted versus their width (depth of focus).

The process window leads to a clear depiction of the trade-off between exposure latitude and depth of focus. In the next edition of this column we will further refine our analysis of the process window and provide an unambiguous definition of DOF which accurately reflects the needs of a manufacturing process.

References

1. J. W. Bossung, “Projection Printing Characterization,” *Developments in Semiconductor Microlithography II, Proc.*, SPIE Vol. 100 (1977) pp. 80-84.

2. C. A. Mack, “Understanding Focus Effects in Submicron Optical Lithography: a Review,” *Optical Engineering*, Vol. 32, No. 10 (Oct. 1993) pp. 2350-2362.

3. E. W. Charrier and C. A. Mack, “Yield Modeling and Enhancement for Optical Lithography,” *Optical/Laser Microlithography VIII, Proc.*, SPIE Vol. 2440 (1995)

List of Figures

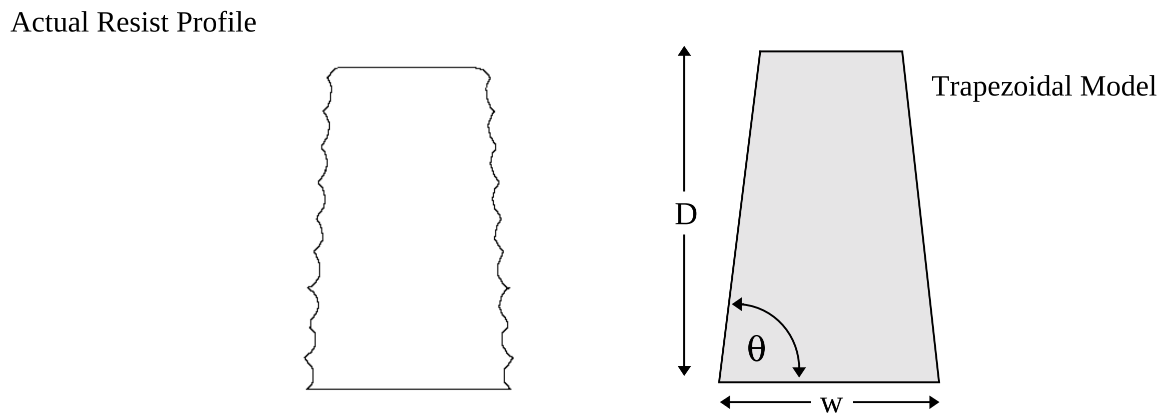


Figure 1. Comparison of an actual, complex photoresist profile with its trapezoidal model used to determine linewidth, sidewall angle, and resist loss.

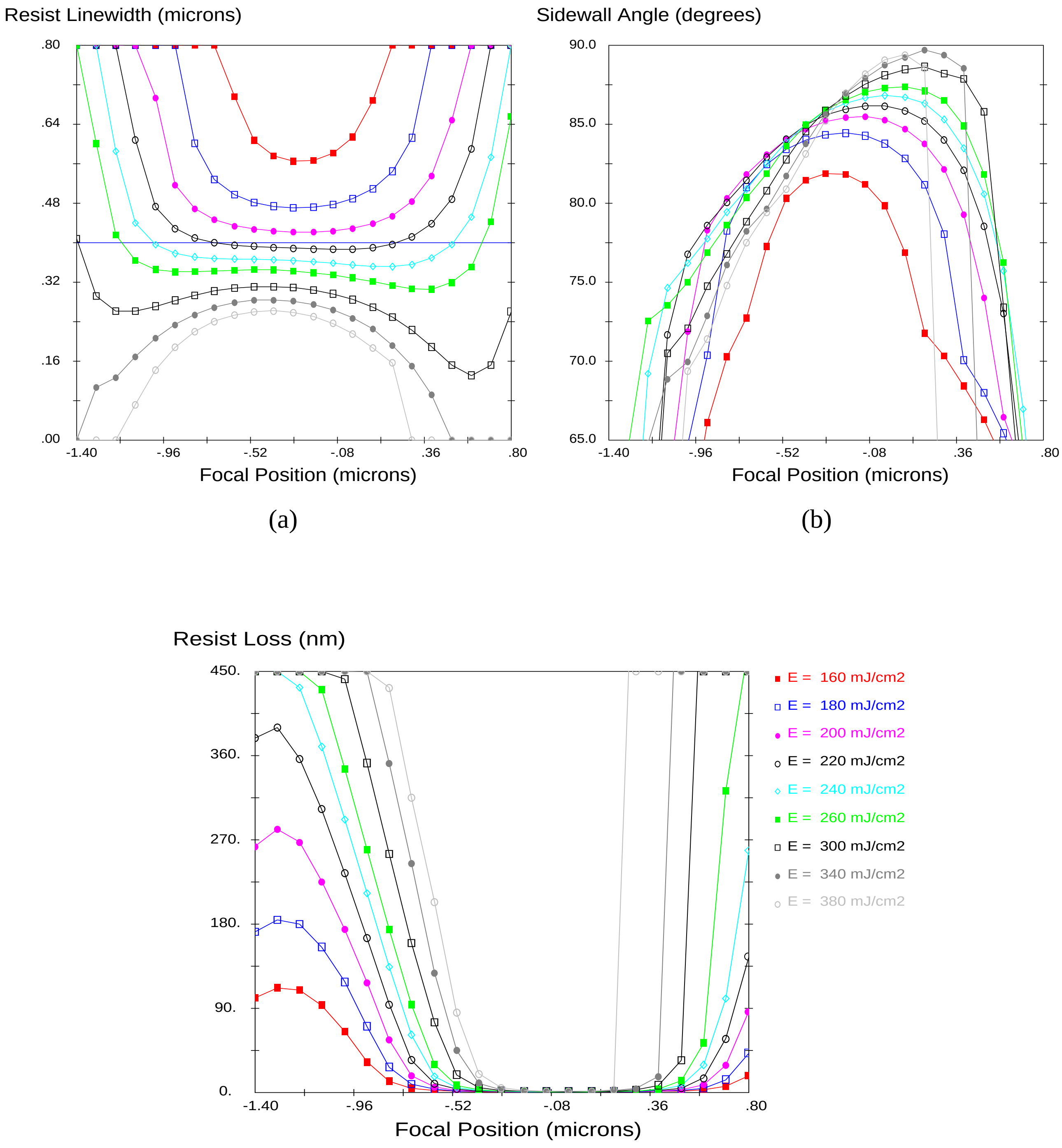
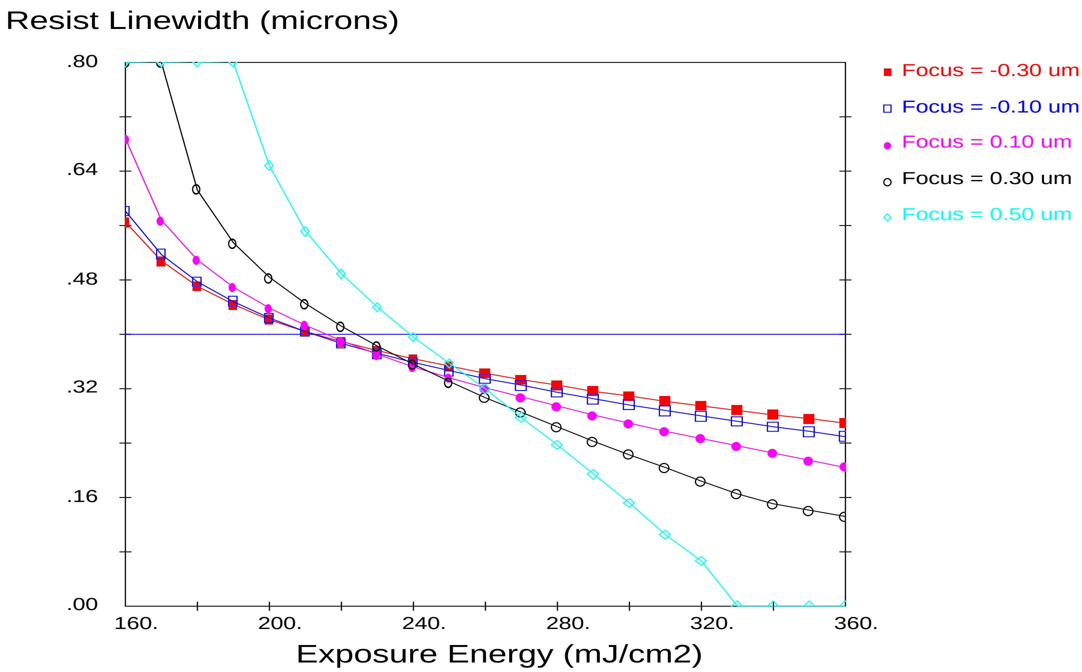
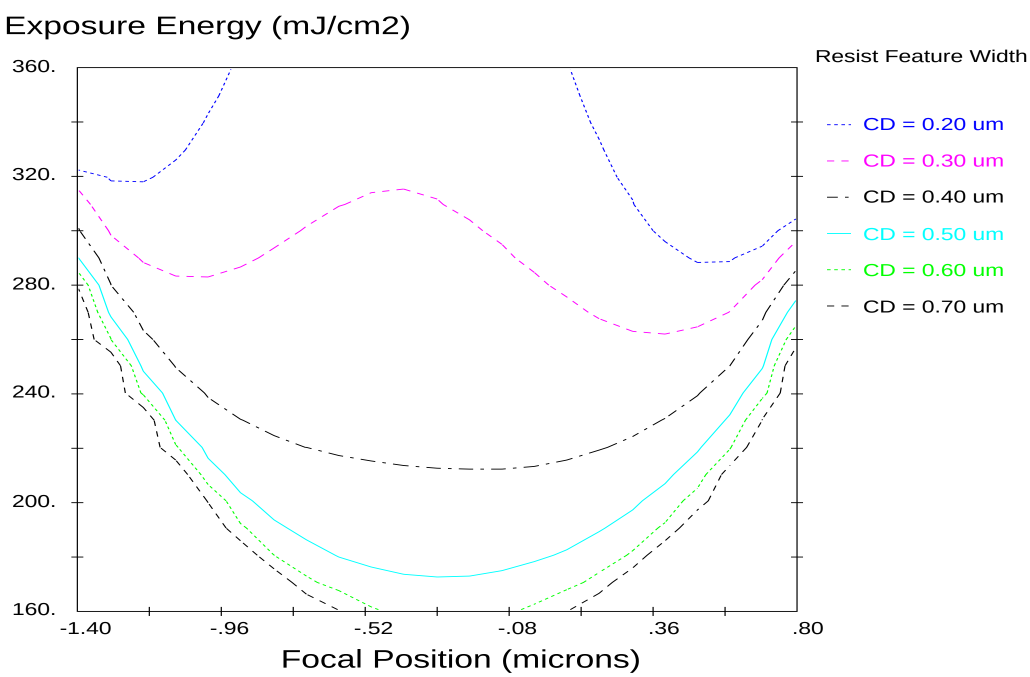


Figure 2. Examples of the effect of focus and exposure on the resulting resist profile: (a) linewidth, (b) sidewall angle, and (c) resist loss. Focal position is defined as zero at the top of the resist with a negative focal position indicating that the plane of focus is inside the resist.



(a)



(b)

Figure 3. Displaying the data from a focus-exposure matrix in alternate forms: (a) decrease in exposure latitude resulting from defocus, and (b) contours of constant CD versus focus and exposure.

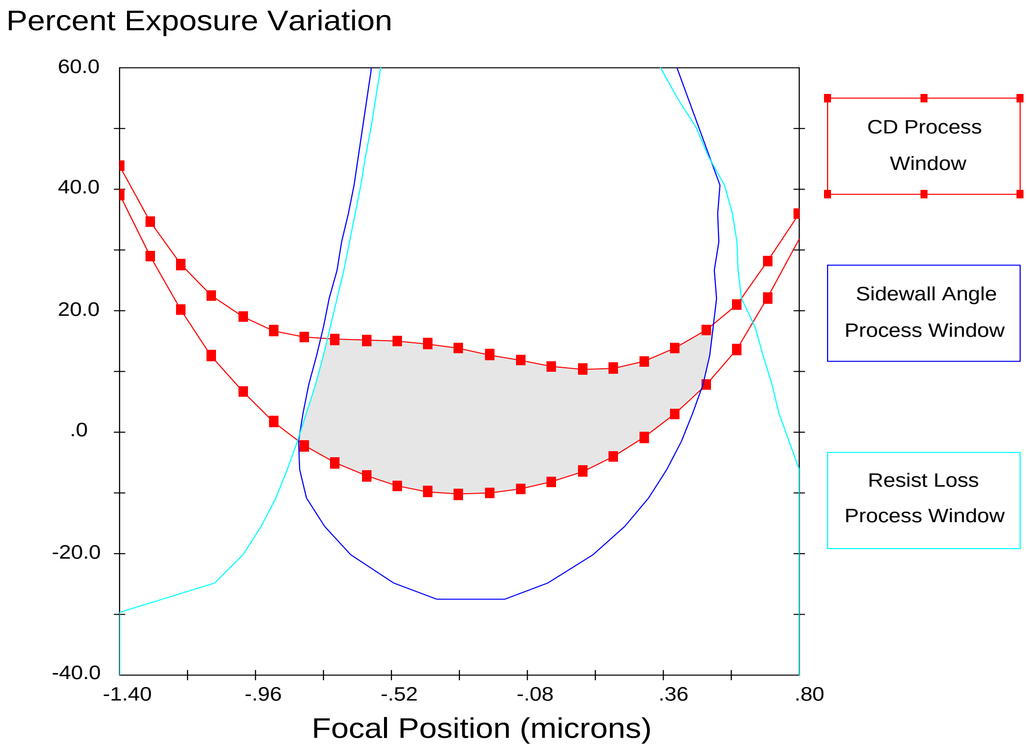
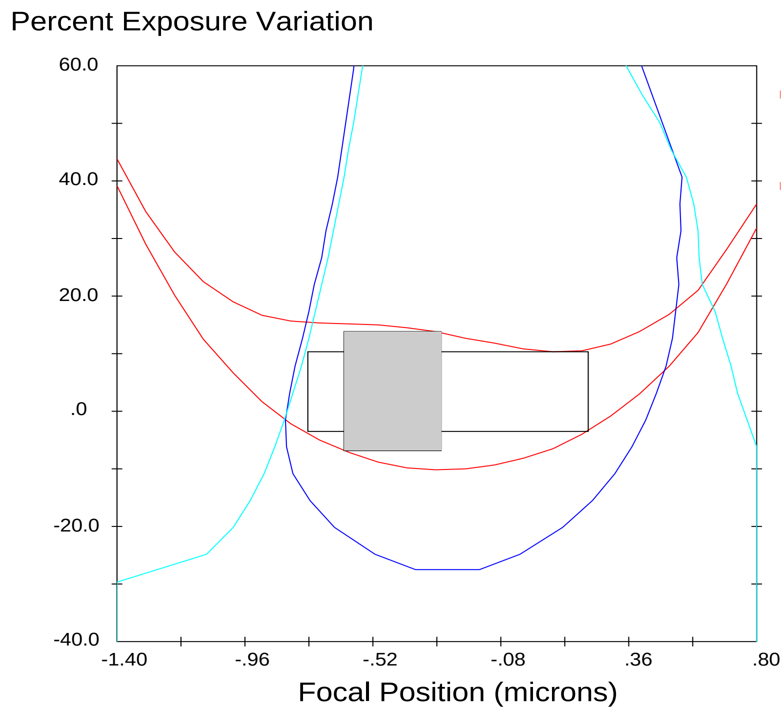
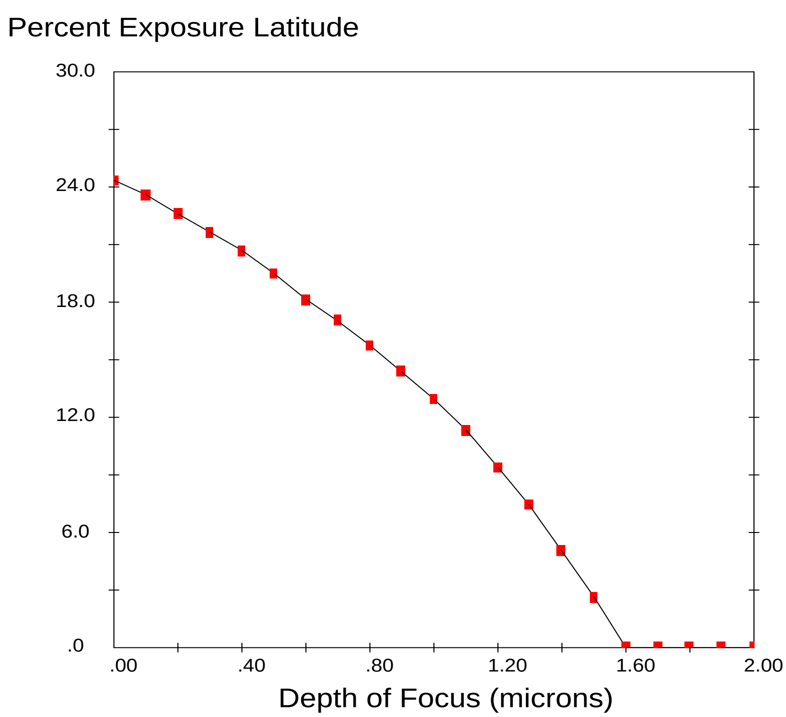


Figure 4. The focus-exposure process window constructed from contours of the specifications for linewidth, sidewall angle and resist loss. Shaded area shows overall process window.



(a)



(b)

Figure 5. The process window (a) is analyzed by fitting all of the maximum rectangles, then plotting their height (exposure latitude) versus their width (depth of focus) as in (b).