The Lithography Tutor *(Autumn 1995)*

# Depth of Focus, part 2

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In the last column we began our search for a suitable definition for depth of focus (DOF). The effect of focus on a lithography process takes two forms: changes in the photoresist profile, and changes in the response of the process to other errors, most notably exposure. For this reason, we characterized focus effects with the focus-exposure matrix, a description of how the resist profile is changed with changes in both focus and exposure. One of the most useful ways of plotting these changes is with a contour plot. For example, one could plot contours of constant linewidth as a function of focus and exposure. By plotting only contours defined by the specification limits placed on acceptable linewidths, a window, called the focus-exposure process window, is generated. Specifications on other aspects of the photoresist profile, such as sidewall angle and resist loss, can also be plotted on the same contour plot. The result, shown in Fig. 1, is a process window which defines the values of focus and exposure which produce photoresist profiles which meet all of the profile specifications.

The size and shape of the process window provides a tremendous amount of information about the capability of the lithography process. Larger process windows will provide greater latitude for errors in focus and exposure. Can this be quantified? What are the maximum errors in focus and exposure that can be tolerated? Suppose that a given feature and process has the process window shown in Fig. 1. Suppose that there are known, systematic errors in focus and exposure that are built into the process (topography is a good example of a systematic focus error). These errors could be represented graphically as a rectangle in Fig. 1 whose width is the total range of systematic focus errors and whose height is the total range of systematic exposure errors. The rectangle would represent the requirements of the process. If the rectangle could be fit completely within the process window, then the process capability would exceed the process requirements and one would expect resist patterns on the wafer to be within specifications. If the rectangle was too big to fit inside the process window, then the process would not be capable of handling the excursions in focus and exposure and some resist patterns would be out of spec.

If all focus and exposure errors were systematic, then the proper graphical representation of those errors would be a rectangle. The width and height would represent the total ranges of the respective errors. If, however, the errors were randomly distributed, then a probability distribution function would be needed to describe them. For the completely random case, a gaussian distribution with standard deviations in exposure and focus, $\sigma_E$ and $\sigma_F$ respectively, is used to describe the probability of a given focus error.

$$p(\Delta E, \Delta F) = \frac{1}{2\pi\sigma_E\sigma_F} \exp\left(-\Delta E^2 / 2\sigma_E^2\right) \exp\left(-\Delta F^2 / 2\sigma_F^2\right) \qquad (1)$$

where focus errors and exposure errors are assumed to be independent. In order to graphically represent the errors of focus and exposure, one should describe a surface of constant probability of occurrence. All errors in focus and exposure inside the surface would have a probability of occurring which is greater than the established cut-off. What is the shape of such a surface? For fixed systematic errors, the shape is a rectangle. For a gaussian distribution, the surface can be derived by setting the probability of equation (1) to a constant, *p**.

$$p^* = \frac{1}{2\pi\sigma_E\sigma_F}\exp\left(-\Delta E^2 / 2\sigma_E^2\right)\exp\left(-\Delta F^2 / 2\sigma_F^2\right)$$

$$-\ln\left(2\pi\sigma_E\sigma_F p^*\right) = \frac{\Delta E^2}{2\sigma_E^2} + \frac{\Delta F^2}{2\sigma_F^2} \qquad (2)$$

Equation (2) is that of an ellipse. Suppose, for example, that one wishes to describe a "3-sigma" surface, where *p** corresponds to the probability of having an error equal to $3\sigma$ in one variable. The resulting surface would be an ellipse with major and minor axes equal to $3\sigma_E$ and $3\sigma_F$.

$$1 = \frac{\Delta E^2}{\left(3\sigma_E\right)^2} + \frac{\Delta F^2}{\left(3\sigma_F\right)^2} \qquad (3)$$

Using either a rectangle for systematic errors or an ellipse for random errors, the size of the errors which can be tolerated for a given process window can be determined. Taking the rectangle as an example, one could find the maximum rectangle which will fit inside the processes window. 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. 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. Fig. 2 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). Likewise, assuming random errors in focus and exposure, every maximum ellipse which fits inside the processes window could be determined. The horizontal width of the ellipse would represent a three-sigma error in focus, while the vertical height of the ellipse would give a three-sigma error in exposure. Plotting the height versus the width of all of the maximum ellipses gives the second curve of exposure latitude versus DOF in Fig. 2.

The exposure latitude - DOF curves of Fig. 2 provide the most concise representation of the coupled effects of focus and exposure on the lithography process. Each point on the exposure latitude - DOF curve is one possible operating point for the process. The user must make the decision as to how to balance the tradeoff between DOF and exposure latitude. One approach is to define a minimum acceptable exposure latitude, and then operate at this point. This has the effect of maximizing the DOF of the process. In fact, this approach allows for the definition of a single value for the depth of focus of a given feature for a given process. The depth of focus of a feature can be defined as *the range of focus which keeps the resist profile of a given feature within all specifications (linewidth, sidewall angle, and resist loss) over a specified exposure range*. For the example given in Fig. 2, a minimum acceptable exposure latitude of 15%, in addition to the other profile specifications, would lead to the following depth of focus results:

DOF (rectangle) = 0.85 μm
DOF (ellipse) = 1.14 μm
DOF (average) = 1.00 μm

(Note: the days of quoting DOF as ± some distance are over. Focus behavior for small geometries is quite asymmetric so that only the total range has a useful meaning.)

As one might expect, systematic errors in focus and exposure are more problematic than random errors, leading to a smaller depth of focus. Most actual processes would have a combination of systematic and random errors. Thus, one might consider the rectangle analysis to give a pessimistic value for the DOF, while the ellipse method gives an optimistic view of DOF. The average value of the two will be a more realistic number in most cases.

Unfortunately, not everyone in industry uses the definition for DOF given above. The reason is quite simple -- collecting the data required to provide a full process window is quite time consuming. As a result, many people use “pseudo-DOF” metrics which, they hope, are related to the actual DOF of a process. The most common of these metrics is the constant exposure DOF. The constant exposure DOF is the range of focus which produces acceptable photoresist profiles at a single exposure. It is a special case of the full definition of DOF, corresponding to an exposure latitude specification of 0. Obviously, the constant exposure DOF requires far less data collection and analysis. Similarly, a constant focus exposure latitude can be defined as the exposure latitude at best focus. These two numbers give the “best case” values for exposure latitude and DOF and can be very misleading if not properly labeled as such.

Which brings up an important issue -- communication and the role of standards. When communicating information about the depth of focus of a process, there are two choices. First, the lithographer could provide all of the details of the data and an exact definition of the DOF used. Alternatively, the person could use a standard definition of DOF that is readily known and accepted, so that reporting a value of DOF involves only a reference to the standard. I propose the definition of DOF given here as the standard and encourage lithographers to explicitly state what definition of DOF they have used when reporting values.

In the next issue of the Lithography Tutor we will use our new definition of depth of focus to see how the process affects DOF. In particular, we’ll learn how to optimize the numerical aperture and partial coherence of a stepper.

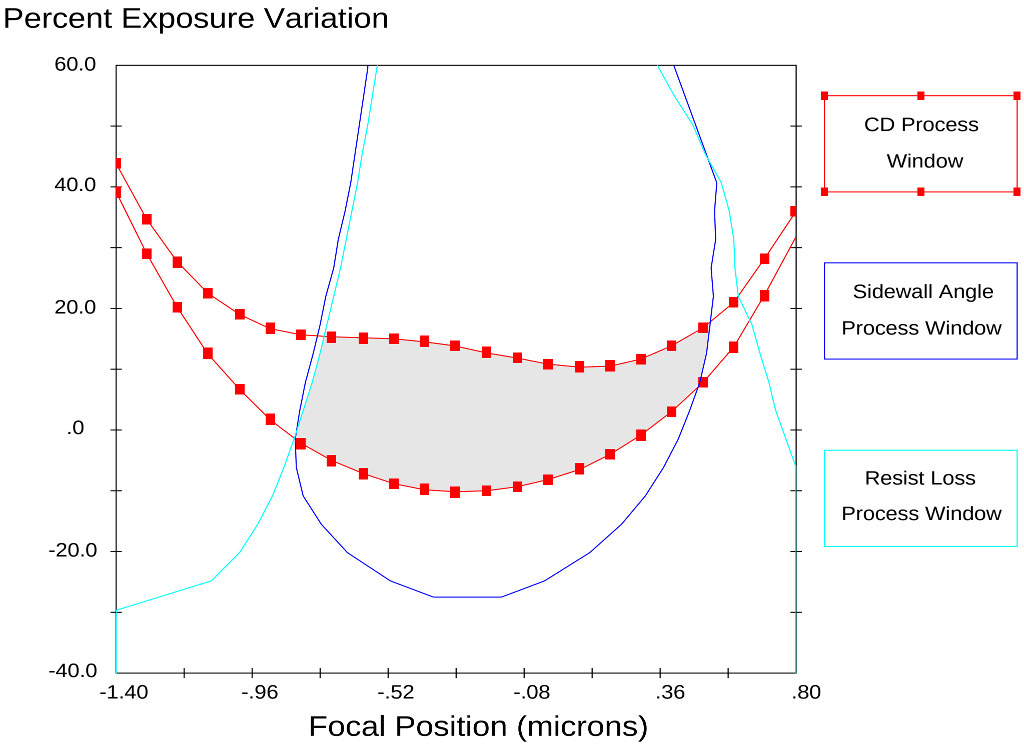

Figure 1. The focus-exposure process window constructed from contours of the specifications for linewidth, sidewall angle and resist loss. The shaded area shows the overall process window.

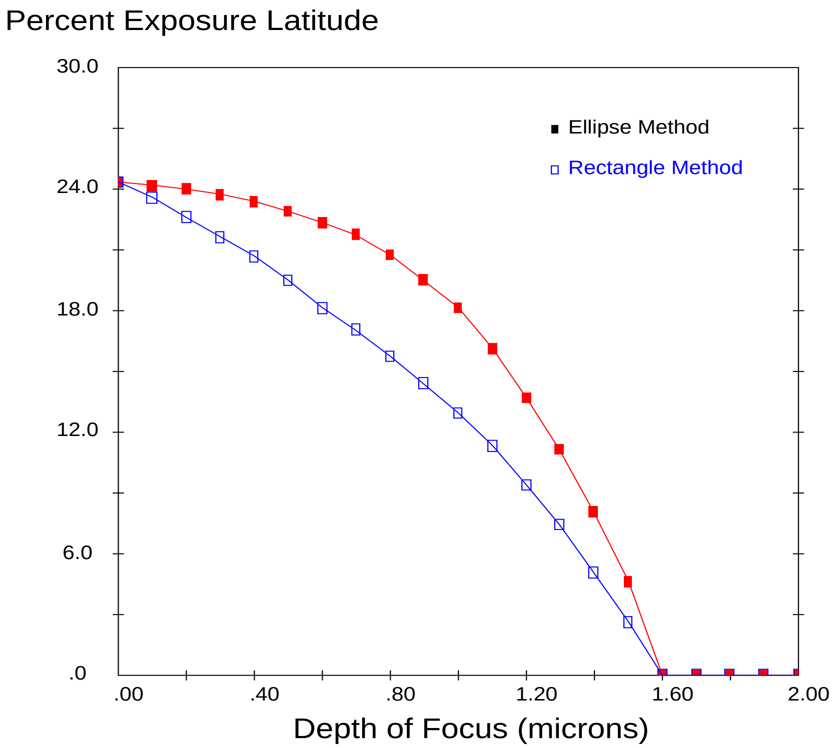

Figure 2. The process window of Fig. 1 is analyzed by fitting all of the maximum rectangles and all of the maximum ellipses, then plotting their height (exposure latitude) versus their width (depth of focus).