Isofocal Bias

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The variation of the width of a lithographic feature as a function of focus and exposure is a subject of great importance to the practicing lithographer. Errors in focus and exposure are an inevitable part of any manufacturing process, resulting in errors in the final feature width. Although exposure is used as a "dial" for the feature width (by turning the exposure dose up or down until the desired feature width is obtained), there is no benefit to linewidth change as a function of focus. Wouldn't it be nice if changes in focus had no effect on linewidth?

Since the effects of focus and exposure on the lithographic process are coupled, these effects are characterized together using a focus-exposure matrix (see, for example, this column in *MLW*, Spring and Autumn, 1995). The most common representation of this data is the Bossung plot [1], which shows the critical dimension (CD) as a function of focus for different exposures. Figure 1 shows a typical example. One can see that at the "nominal" conditions (best focus at about -0.4μm and an exposure to give the nominal 0.35μm linewidth), there is a strong curvature to the CD vs. focus curve. Going out of focus makes the linewidth smaller for this exposure.

Suppose, however, that the desired linewidth for the data in Figure 1 was not 0.35μm, but instead was about 0.5μm. In such a case, the exposure that yields this new "nominal" linewidth is also the exposure with the least sensitivity to focus. In other words, the "flattest" CD vs. focus curve produces a linewidth of about 0.5μm. The exposure that gives the flattest linewidth versus focus response is called the *isofocal exposure* for that particular mask pattern, exposure tool, and process. The resulting resist linewidth is called the *isofocal linewidth* (literally, the linewidth that stays the same through focus).

Unfortunately, the isofocal linewidth is quite often very different from the desired linewidth. In the case of Figure 1, the isofocal linewidth of 0.5μm is about 150nm larger than the nominal 0.35μm linewidth. The difference between the isofocal linewidth and the desired linewidth is called the *isofocal bias*. (The use of the term "bias" here may be somewhat confusing since it is not a bias of the mask, but rather a bias of the isofocal linewidth from the nominal linewidth.) Of course, it is quite desirable to have an isofocal bias of zero, but this is rarely the case. Many factors affect the isofocal bias, including the optical parameters of the imaging tool and the response of the photoresist (e.g., the resist contrast) [2].

Although the definition of isofocal bias given above seems quite obvious and intuitive, it is also somewhat vague. Just what do we mean by "flattest"? Can we define an algorithm that can extract the isofocal bias from actual data? How does this definition fit with our definition of depth of focus? Depth of focus is defined based on the focus-exposure process window, a contour of the resist profile specifications as a function of focus and exposure (see this column in *MLW*, Spring and Autumn, 1995). Figure 2 shows the linewidth process window for the data of Figure 1 (sidewall angle and resist loss specifications have been ignored here). The size of the window is a measure of the process's ability to tolerate errors in focus and exposure. The fact that the process window shape is not flat, but bends down at the extremes of focus, is an indication of the isofocal bias in the data.

The size of the process window can be measured by fitting rectangles (representing systematic errors in focus and exposure) or ellipses (representing random errors) inside the window, as in Figure 3. A plot of the height of each rectangle or ellipse versus its width shows the tradeoff between exposure latitude and depth of focus. By specifying a minimum acceptable exposure latitude (for example, 10%), a single depth of focus (DOF) can be established.

The definition of DOF can be used to determine the isofocal bias. If the desired linewidth is changed, a new process window can be calculated from the same set of focus-exposure data. Analyzing this process window leads to a measured DOF for this new desired feature size. This analysis process can be repeated for any number of desired feature sizes. The result is a plot of DOF versus bias (the difference between the desired feature size and the actual feature size on the mask). Figure 4 shows such a plot for the data of Figure 1 for both rectangle and ellipse analysis of the process window. The isofocal bias can be defined as that bias which gives the maximum depth of focus (in this case, resulting in a bias between 90 and 120nm, and an isofocal resist linewidth of 0.44 – 0.47µm for this 0.35µm mask feature). Note also that the isofocal bias, when defined in this way, is somewhat less than the 150nm estimate obtained by looking for the "flattest" CD vs. focus curve in the Bossung plot. The maximum DOF criteria for the isofocal bias means that we are searching for the set of CD vs. focus curves that are the flattest over a 10% exposure range (corresponding to the exposure latitude specification used in the DOF definition).

Once a useful definition is in place, the isofocal bias provides an important metric for the focus-exposure response of a lithographic imaging system and process. It is very important to note, however, that the magnitude of the isofocal bias does not give any indication as to how much bias, if any, should be applied to the mask in order to improve depth of focus. Rather, the isofocal bias is most useful for assessing the impact of imaging tool or resist process changes.

References

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

2. J. S. Petersen, "An Experimental Determination of Optical Lithographic Requirements for Sub-Micron Projection Printing," *Optical/Laser Microlithography II, Proc.*, SPIE Vol. 1088 (1989) pp. 540-567.

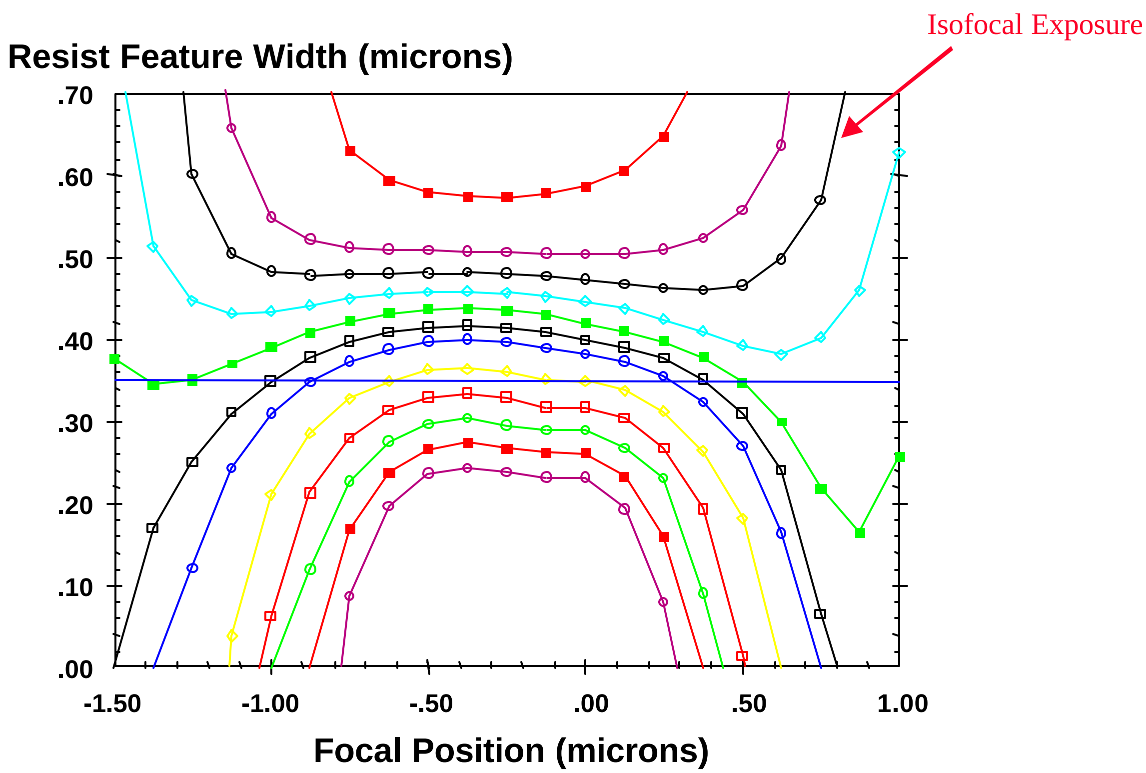


Figure 1. Bossung plot of linewidth versus focus for different exposure energies (0.35µm line, 0.65µm space, NA = 0.63, σ = 0.5, i-line). The isofocal exposure is the exposure energy which produces the "flattest" CD vs. focus curve.

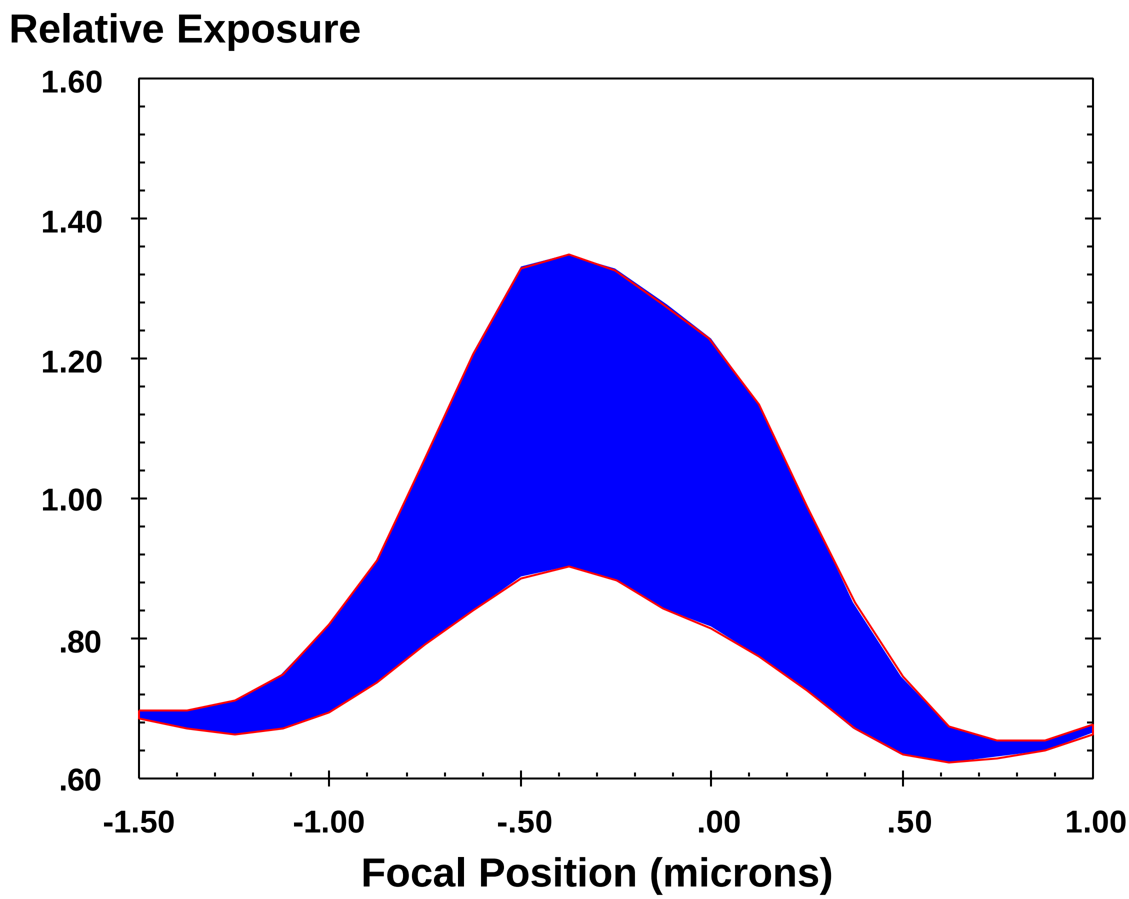
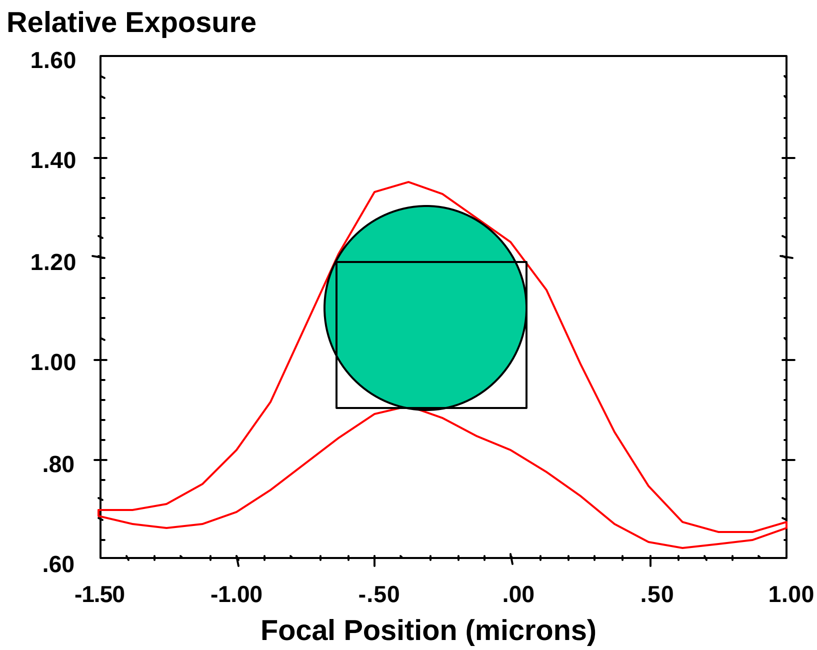
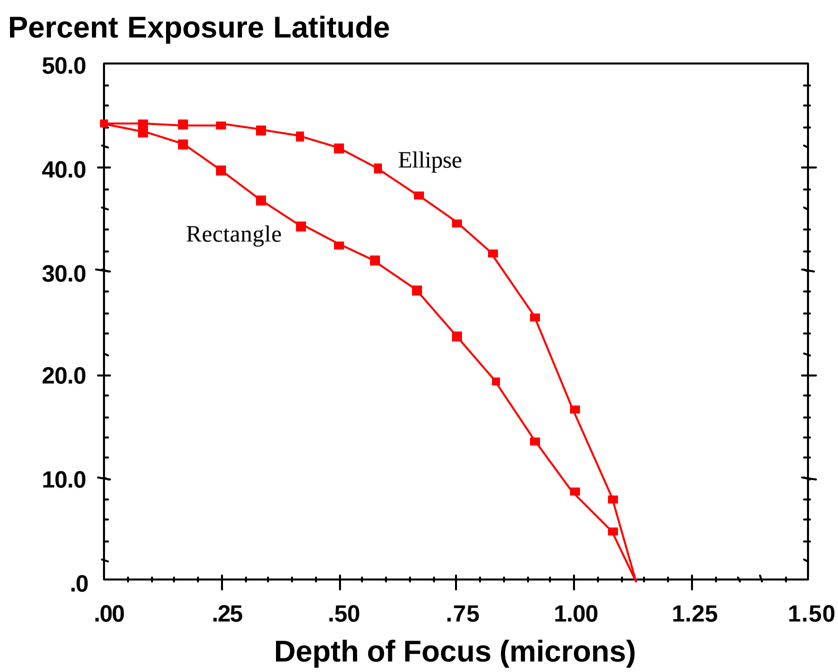


Figure 2. Linewidth process window for the focus-exposure data of Figure 1 (assuming a ±10% linewidth specification). Exposure is plotted relative to the nominal dose.



Relative Exposure
1.60
1.40
1.20
1.00
.80
.60
-1.50
-1.00
-.50
.00
.50
1.00
Focal Position (microns)

(a)



Percent Exposure Latitude
50.0
40.0
30.0
20.0
10.0
.0
Ellipse
Rectangle
.00
.25
.50
.75
1.00
1.25
1.50
Depth of Focus (microns)

(b)

Figure 3. The process window can be analyzed by (a) fitting all of the maximum ellipses and rectangles inside the window, and (b) plotting their heights (exposure latitude) versus their widths (depth of focus).

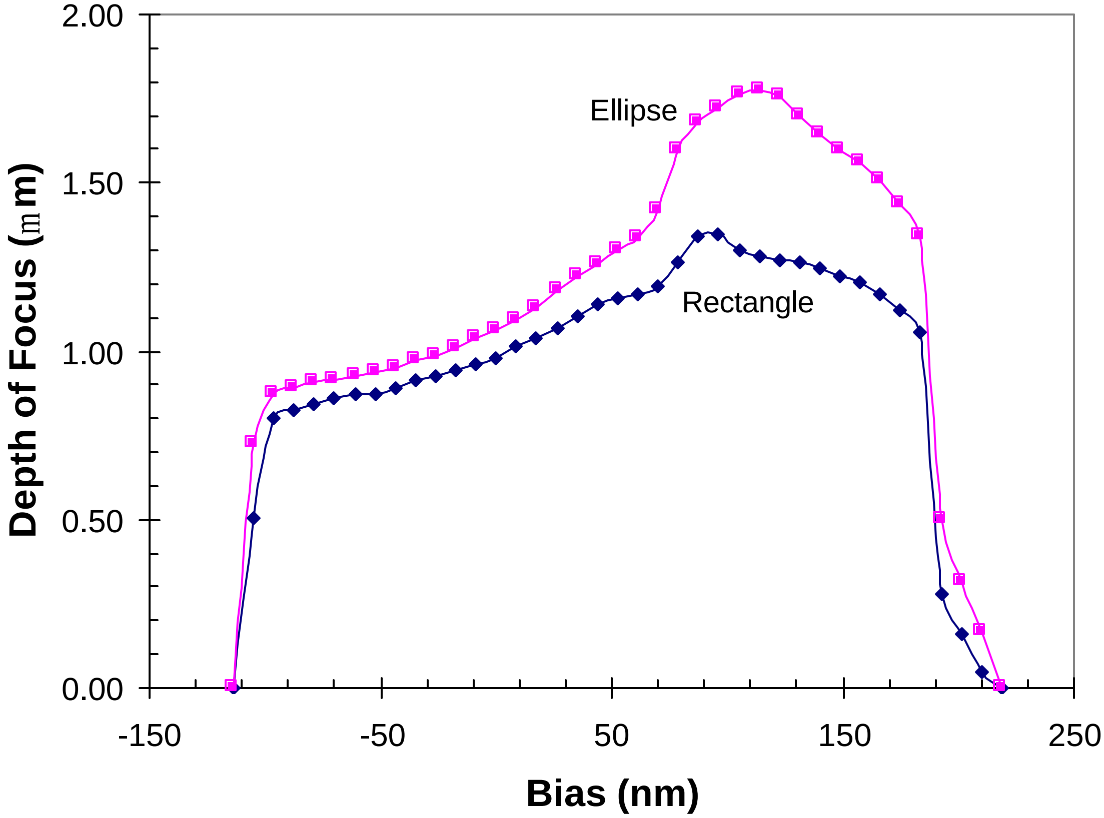


Figure 4. The isofocal bias can be defined as that bias (the difference between the desired feature width and the actual mask width) which gives the maximum depth of focus.