Mask Linearity and the Mask Error Enhancement Factor

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In the last two editions of this column, several aspects of resolution were discussed in some detail. The basic definition of resolution is *the smallest feature of a given type which can be printed with a specified depth of focus*. Likewise, the *pitch resolution* defines the smallest pitch that can be printed, and is often simply related to fundamental optical parameters. The *point spread function* and the *natural linewidth* of a phase edge were also shown to be "natural" metrics of imaging resolution. Another very practical metric of lithographic resolution is defined using a concept called *mask linearity.*

An important constraint placed on any lithographic imaging task is that *every* feature on the mask must be faithfully imaged onto the wafer within predetermined tolerances. Most typical integrated circuit device layers consist of a myriad of different pattern types, shapes, and sizes. It is a common assumption that since the resolution defines the smallest pattern that can be acceptably imaged, all features larger than this limit will also be acceptably imaged. Unfortunately, this assumption may not always be true. For imaging systems designed to maximize the printability of a given small feature (e.g., using off-axis illumination), often some larger features will be more difficult to print. One way to insure that larger features print well at the same time as the minimum feature is to build this requirement into the definition of resolution: *the smallest feature of a given type such that it and all larger features of the same type can be printed simultaneously with a specified depth of focus*. This resolution is called the *linear resolution* of the imaging system.

The linear resolution is typically assessed using the mask linearity plot. Consider a mask with many feature sizes of a given type, for example, equal lines and spaces, isolated lines, or contact holes. By plotting the resulting resist feature width versus the mask width, the mask linearity plot is generated. Shown in Figure 1 are examples of linearity plots for equal line/space patterns and isolated lines, both imaged at best focus and at the dose to size for the 350 nm features. Perfect, linear behavior would be a line through the origin with a slope of 1. By defining specifications for any deviation from perfect linearity (±5%, for example), the minimum feature that stays within the specification would be the linear resolution. Qualitatively, Figure 1 shows that the equal line/space patterns have a linear resolution down to about 350 nm, whereas the isolated lines are linear down to about 300 nm.

Of course, to be truly practical one should include variations in exposure and focus as well. The most rigorous approach would begin with the focus-exposure process window for the largest feature size. The process window from each smaller feature is then overlapped with the larger features and the depth of focus calculated. Smaller and smaller features are added until the overlapped depth of focus drops below the specified limit, indicating the linear resolution limit. Thus, although mask linearity plots do not provide a rigorous, general method for determining the linear resolution, they are qualitatively useful.

As lithography for manufacturing continues to push towards its ultimate resolution limits, linearity is playing a decidedly different role in defining the capabilities of low k_1 imaging. Consider, using Figure 1 as an example, manufacturing at the linear resolution limits: 350 nm lines and spaces and 300 nm isolated lines. Although these features may be "resolvable" by the definitions provided above, critical dimension (CD) control may be limited by a new factor: how do errors in the dimensions of the feature on the mask translate into errors in resist CD on the wafer?

For "linear" imaging, mask CD errors would translate directly into wafer CD errors (taking into account the reduction factor of the imaging tool, of course). Thus, a 10 nm CD error on the mask (all CDs on the mask will be expressed here in wafer dimensions) would result in a 10 nm CD error on the final resist feature. If, however, the features of interest are at the very edge of the linear resolution limit, or even beyond it, the assumption of linear imaging falls apart. How then do mask CD errors translate into resist CD errors?

Consider the examples shown in Figure 1. If an isolated line is being imaged near its resolution limit, about 300 nm, a 10 nm mask CD error would give a 14 nm resist CD error. Thus, at this feature width, isolated line mask errors are amplified by a factor of 1.4! This amplification of mask errors is called the *mask error enhancement factor* (MEEF). First discussed by Wilhelm Maurer [1], the MEEF is defined as the change in resist CD per unit change in mask CD:

$$MEEF = \frac{\partial CD_{resist}}{\partial CD_{mask}} \tag{1}$$

where again the mask CD is in wafer dimensions. Figure 2 shows how the MEEF varies with feature size for the mask linearity data of Figure 1. Regions where the MEEF is significantly greater than 1 are regions where mask error may come to dominate CD control on the wafer.

Mask linearity plots have been used for years to evaluate the linear resolution of a lithography process. However, as optical lithography pushes to lower and lower k_1 factors, we continue to push the limits of linearity and find ourselves working in the realm of high MEEF. Even worse, optical proximity correction techniques allow us to lower the linear resolution, but without improving the MEEF. As a result, the mask may begin to take on a much larger portion of the total CD error budget if significant improvements in mask CD control are not made.

References

1. W. Maurer, "Mask Specifications for 193 nm Lithography," SPIE Vol. 2884 (1996) pp. 562-571.

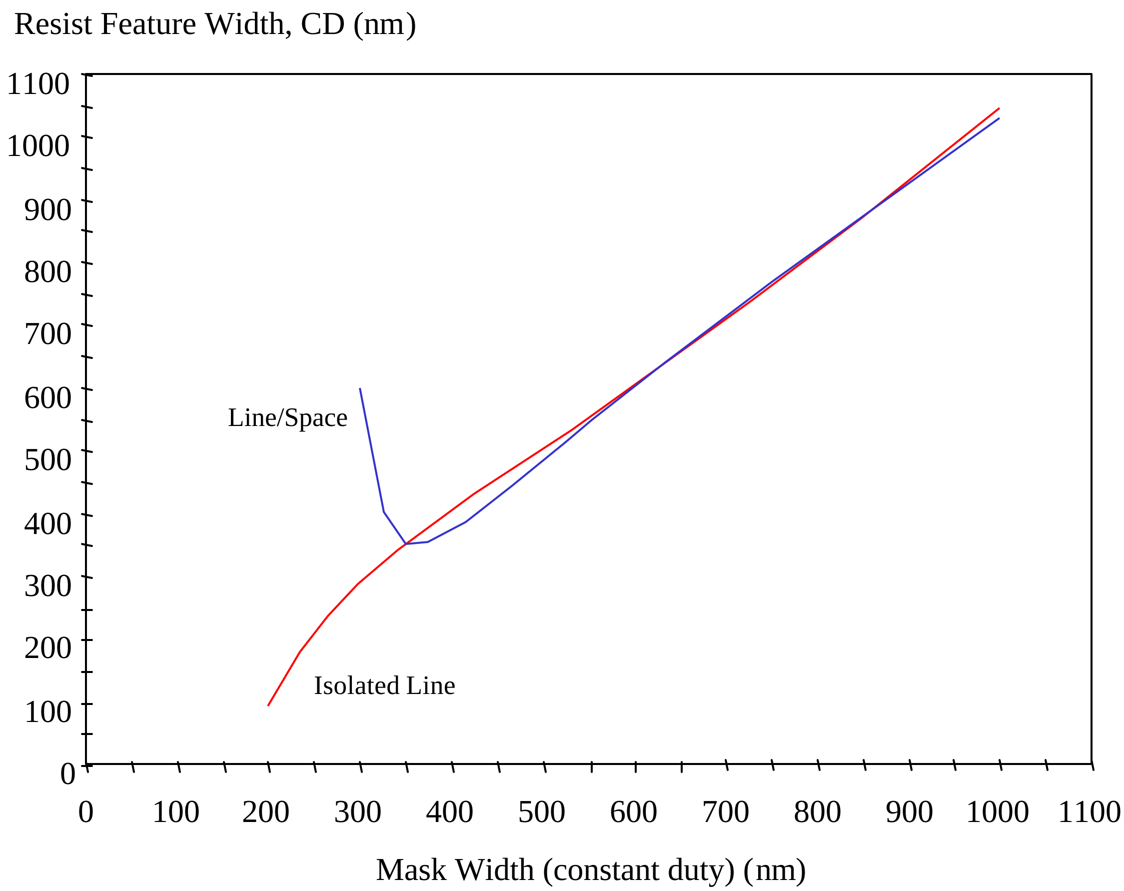

Figure 1. Typical mask linearity plot for isolated lines and equal lines and spaces (i-line, NA = 0.56, σ = 0.5).

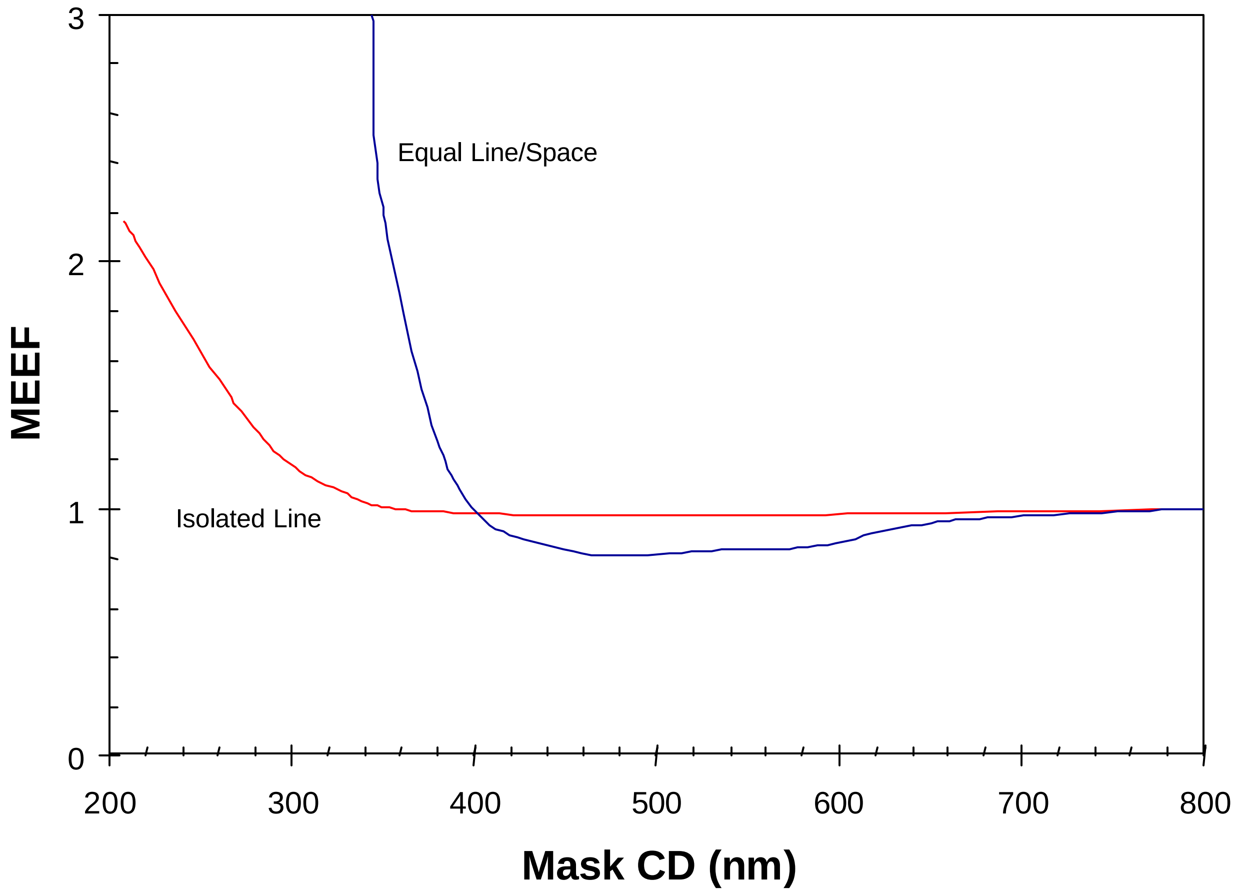

Figure 2. The mask error enhancement factor (MEEF) for the data of Figure 1.