More on the Mask Error Enhancement Factor

Chris A. Mack, *FINLE Technologies, Austin, Texas*

In a previous edition of this column (*Winter, 1999*) I described the importance of the Mask Error Enhancement Factor (MEEF), based on the observation that errors in the width of a feature on the mask are not linearly transferred by the imaging process into errors on the wafer. In a perfect world there would be no errors in the feature widths of the mask patterns, so that understanding their impact on the wafer would be moot. Unfortunately, we are far from this ideal. For the 180nm lithographic processes currently being ramped up into production, mask errors are often one of the largest sources of across-chip linewidth variations.

The MEEF (also called MEF by some authors) can be defined quite simply as the ratio of the change in resist feature width to the change in mask feature width assuming everything else in the process remains constant. In mathematical terms,

$$MEEF = \frac{\partial CD_{resist}}{\partial CD_{mask}} \qquad (1)$$

where the mask CD is in wafer dimensions (that is, already scaled by the magnification of the imaging tool). One way to define the MEEF of an array of line/space patterns is to assume a CD error for all the lines (dark features) keeping the pitch constant, then measure the resulting resist CD. A MEEF of 1.0 is the definition of a linear imaging result. Although a MEEF less than one can have some desirable consequences for specific features, in general a MEEF of 1.0 is best.

Fundamentally, what is the cause of MEEF values other than one? Anything that causes the overall imaging process to be non-linear will lead to a non-unit valued MEEF. In lithography, every aspect of the imaging process is non-linear to some degree, with the degree of non-linearity increasing as the dimensions of the features approach the resolution limits. Consider the first step in the imaging process, the formation of an aerial image. One might judge the linearity of this first step by approximating the resist CD with an image CD, defined to be the width of the aerial image at some image threshold intensity value (Figure 1). It is important to note that the image CD is only an approximate indicator of the resist CD. For an infinite contrast resist, proper selection of the image threshold intensity value will give an image CD exactly equal to the resist CD for all aerial images. For real, finite contrast resists, however, the differences between these two quantities can be substantial.

Nonetheless, the image CD will be used here to elucidate some general principles about imaging and the MEEF.

For two simple cases of projection imaging, coherent and incoherent illumination, analytical expressions for the aerial image can be defined. Assuming a pattern of many long lines and spaces with a spacewidth w and pitch p such that only the 0 and ±1 diffraction orders pass through the lens, the coherent and incoherent in-focus aerial images would be

$$Coherent\ Illumination: \quad I(x) = \left[\frac{w}{p} + \frac{2\sin(\pi w/p)}{\pi}\cos(2\pi x/p)\right]^2 \qquad (2)$$

$$Incoherent\ Illumination: \quad I(x) = \frac{w}{p} + \frac{2\sin(\pi w/p)}{\pi}(MTF_1)\cos(2\pi x/p) \qquad (3)$$

where MTF_1 is the value of the incoherent Modulation Transfer Function at the spatial frequency corresponding to the first diffraction order. The requirement that no orders higher than the first diffraction order be used to form the image means that the coherent image equation is valid for a limited range of pitches such that $1 < pNA/\lambda < 2$ (where NA is the objective lens numerical aperture and λ is the wavelength), and the incoherent expression is valid for $0.5 < pNA/\lambda < 1$.

Using these expressions to define the image CD, exact expressions for the *image MEEF* can be derived for these repeating line/space patterns under the conditions given above [1]:

$$image\ MEEF = \frac{\partial CD_{image}}{\partial CD_{mask}} = \frac{\partial CD_{image}}{\partial w} \qquad (4)$$

$$Coherent\ Illumination: \quad image\ MEEF = \frac{2 + \cos(2\pi w/p)}{1 - \cos(2\pi w/p)} \qquad (5)$$

$$Incoherent\ Illumination: \quad image\ MEEF = \frac{\frac{1}{MTF_1} + 1 + \cos(2\pi w/p)}{1 - \cos(2\pi w/p)} \qquad (6)$$

An interesting observation can be made immediately. Over the range of valid pitches, the coherent image MEEF is only dependent upon the duty cycle (w/p), not on the pitch itself. The incoherent image MEEF, on the other had, has a direct pitch dependence through the value of the MTF (which is approximately equal to $1 - \lambda/\{2NAp\}$). Figure 2 shows how both image MEEFs vary with spacewidth to linewidth ratio.

The extreme non-linearity of the imaging process is evident from the results shown in Figure 2. For coherent illumination, a pattern of equal lines and spaces will have an image MEEF of 0.5. A spacewidth twice the linewidth produces a MEEF of 1.0, and a spacewidth three times the linewidth results in a coherent image MEEF of 2.0! Obviously, different duty cycles can have wildly different sensitivities to mask errors. While the approximations used do not apply to truly isolated lines, it is clear that such features will also deviate from unit MEEF. A spacewidth/linewidth ratio less than unity also enhances the effect.

Although neither purely coherent nor purely incoherent illumination are ever used in real lithographic imaging, these two extremes tend to bound the behavior of typical partially coherent imaging tools. Thus, we would expect the image MEEF of a partially coherent imaging system to vary with both duty cycle and pitch, and to vary by about a factor of 2 as a function of the partial coherence. The effect of the resist on the final MEEF is not obvious from this discussion, but the resist will both reduce the variation of the MEEF for larger feature sizes and increase its variation as the resolution limit is approached.

References

1. Full derivations of these expressions will be published at a later date.

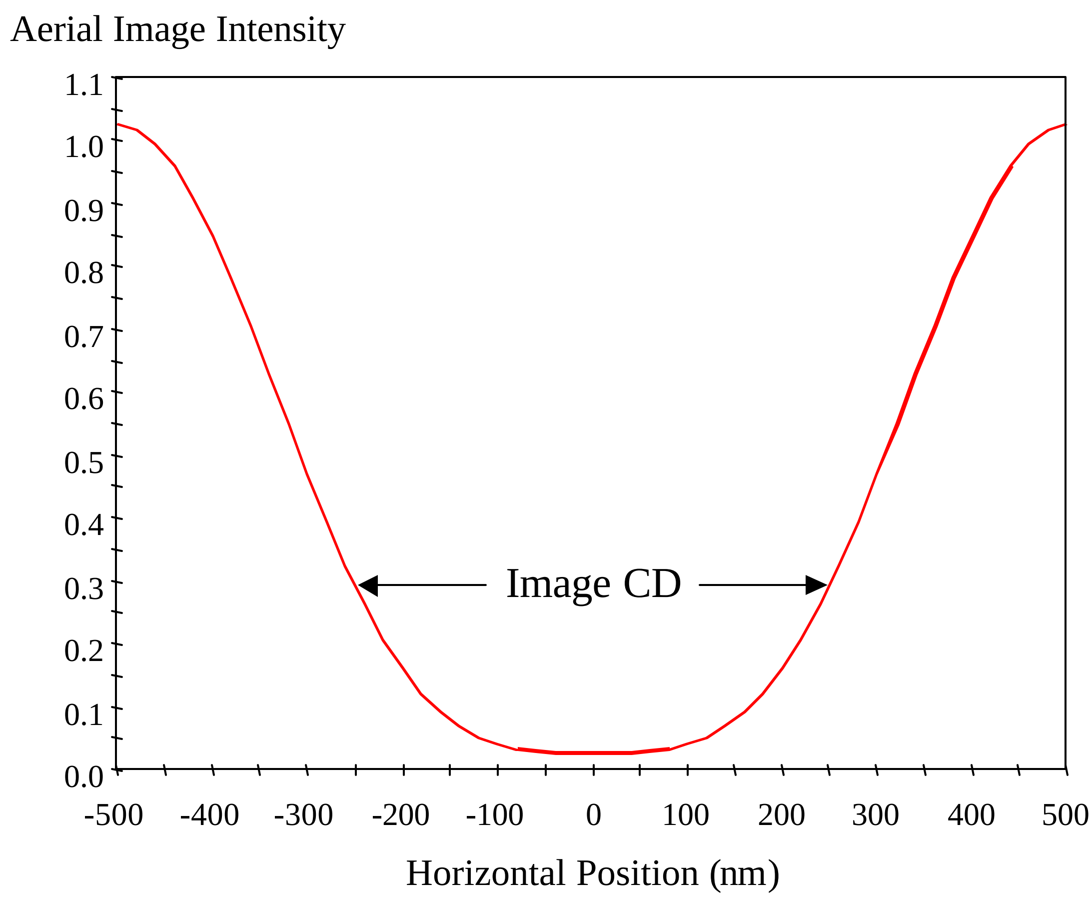

Figure 1. The *image CD* can be defined as the width of the aerial image measured using a predetermined aerial image threshold value.

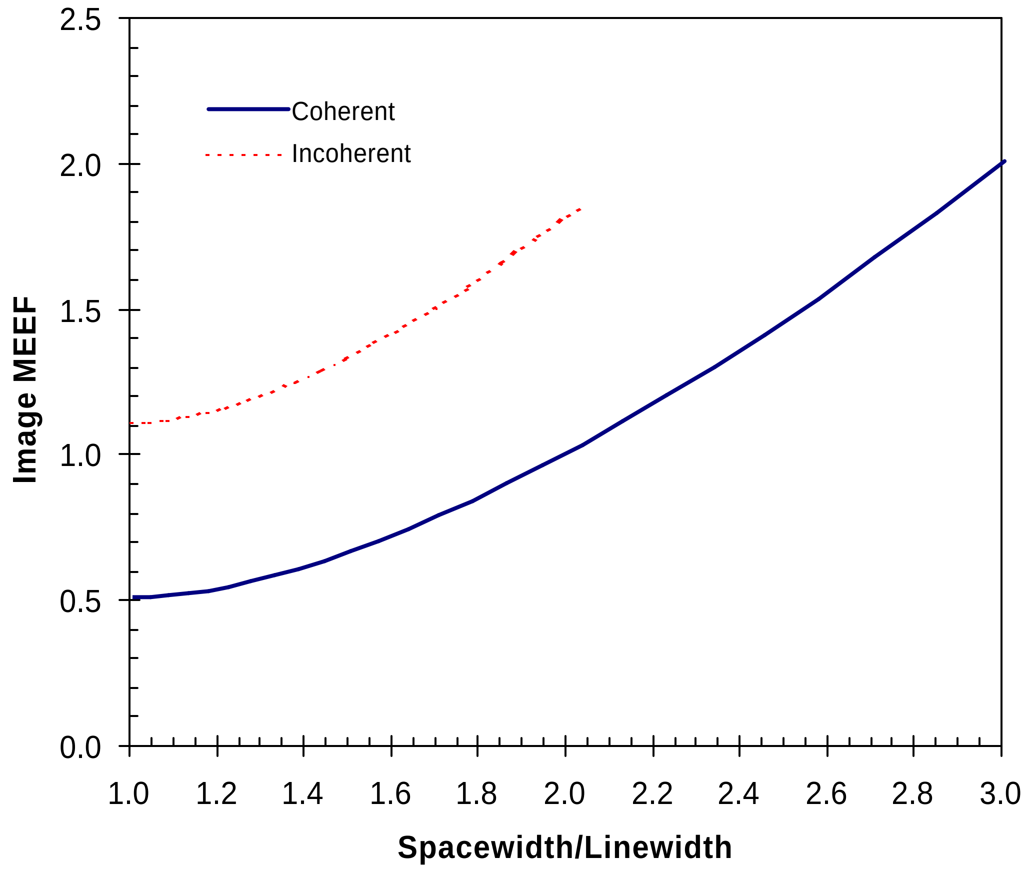

Figure 2. The impact of duty cycle (represented here as the ratio of spacewidth to linewidth for an array of line/space patterns) on the image CD based MEEF for both coherent and incoherent illumination. For the incoherent case, an MTF_1 of 0.45 was used.