Analytic Approach to Understanding the Impact of Mask Errors on Optical Lithography

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Abstract

The characterization of the Mask Error Enhancement Factor (MEEF) for a variety of feature types under a variety of processing conditions is presented. Analytic expressions for the aerial image MEEF under simple incoherent and coherent illumination conditions are derived, including the effect of defocus. Errors in processing, such as focus and exposure errors, also affect the value of the MEEF. Thus, another approach to evaluating the impact of mask errors is to look at the reduction in the process window caused by these errors. Using simulation, a study of the impact of mask CD errors on the overlapping process windows is presented and used as the basis for realistic mask CD specifications.

I. Introduction

As optical lithography pushes to smaller and smaller dimensions, patterned features smaller than the wavelength of light are now routinely manufactured. In this regime mask errors take on an increasingly large share of the sources of critical dimension (CD) errors. The Mask Error Enhancement Factor (MEEF), first discussed by Wilhelm Maurer [1,2], serves to amplify reticle errors due to the highly non-linear nature of imaging near the resolution limit. Thus, CD control requirements on the mask are shrinking faster than the requirements on the wafer. An understanding of the MEEF, and what processing variables affect it, is essential if the CD control goals of future lithographic generations are to be met.

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,

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

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.

The MEEF is not a constant value for a given process. It is a strong function of feature size and type. Also, processing errors can affect MEEF, usually negatively. Focus errors, in particular, can make the MEEF significantly greater. It is important to characterize the MEEF for all feature types and sizes, and under a reasonable range of processing conditions, in order to properly specify the allowed reticle CD errors.

II. Theory

2.1 Image MEEF

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.

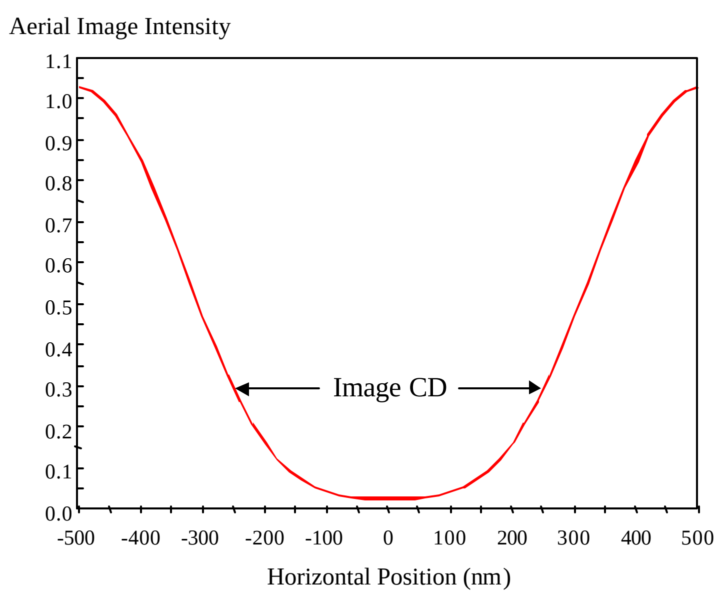

Figure 1. The *image CD* can be defined as the width of the aerial image measured using a predetermined aerial image threshold value.

For two simple cases of projection imaging, coherent and incoherent illumination, analytical expressions for the aerial image can be easily 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

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

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

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:

$$image\ MEEF = \frac{\partial CD_{image}}{\partial CD_{mask}} = \frac{\partial CD_{image}}{\partial w} \tag{4}$$

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

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

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. The partially coherent MEEF (the most important case) can be thought of as behaving somewhere in between the two extremes of coherent and incoherent illumination.

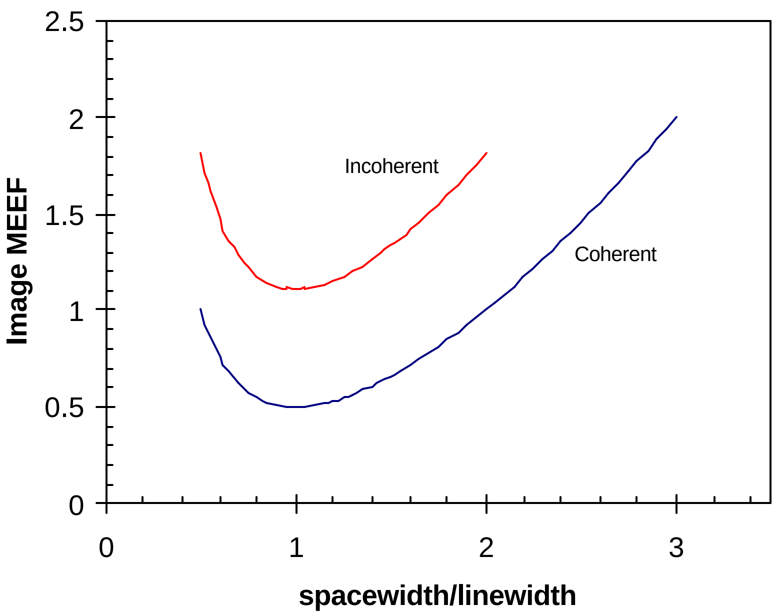

Figure 2. The impact of duty cycle (represented here as the ratio of spacewidth to linewidth for an array of line/space patterns) on the image CD based MEEF for both coherent and incoherent illumination. For the incoherent case, an MTF_1 of 0.45 was used.

2.2 Effect of Defocus

The effect of defocus on the image MEEF can also be derived analytically for the simple cases of coherent and incoherent illumination. For incoherent illumination, the effect of defocus is simply to decrease the value of the MTF for the first orders. Thus, equation (6) above is still correct and shows that increasing defocus, which gives a lower MTF, will give a higher value of the image MEEF. For the coherent illumination case, defocus by a distance δ produces the following aerial image (again assuming only the 0 and ±1 diffraction orders pass through the lens):

$$I(x) = \left[\frac{w}{p} + \Delta\frac{2\sin(p\,w/p)}{p}\cos(2p\,x/p)\right]^2 \tag{7}$$

where $$\Delta = \cos\left(p\, l d / p^2\right)$$

Note that Δ is 1.0 when in-focus and decreases as the amount of defocus increases. From this image expression, the image MEEF can be derived as before.

$$image\, MEEF = \frac{\frac{1}{\Delta} + 1 + \cos(2p\, w/\, p)}{1 - \cos(2p\, w/\, p)} \qquad (8)$$

Thus, as expected, increasing defocus causes the MEEF to increase. Figure 3 shows two examples of the effect of defocus on the coherent image MEEF.

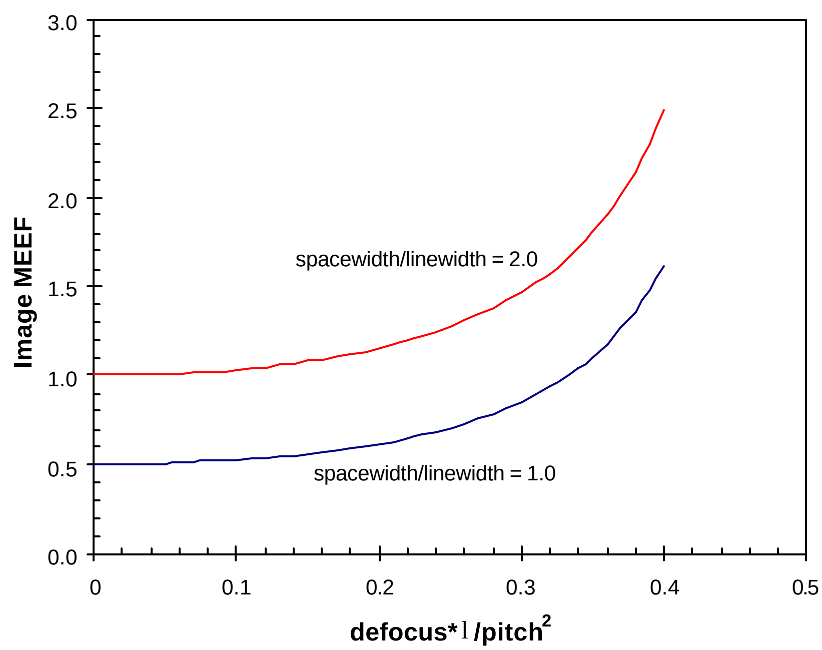

Figure 3. The effect of defocus is to increase the MEEF (coherent illumination, as calculated using equation (8)).

2.3 Relationship between MEEF and NILS

One might intuitively suspect that there is a direct relationship between image quality and the magnitude of the MEEF. Describing image quality with the normalized image log-slope (NILS) [3], an image with a high NILS (a steep transition from high to low intensity at the nominal mask edge) should be less sensitive to errors in mask width than an image with low NILS. This idea can be explored rigorously for the simple case of coherent illumination through defocus. From the aerial image in equation (7), an expression for the NILS can be derived.

$$NILS \;=\; w\frac{\partial \ln I}{\partial x}\bigg|_{x=w/2} \;=\; 4\Delta\left[\frac{1-\cos(2p\,w/p)}{1+\dfrac{p\Delta}{pw}\sin(2p\,w/p)}\right] \tag{9}$$

There is no obvious direct relationship between NILS and MEEF. In particular, the duty cycle (*w/p*) affects NILS differently than it does the MEEF. However, for a specific duty cycle the impact of defocus on both NILS and MEEF can be correlated. Consider just the case of equal lines and spaces (*w/p* = 0.5). The general expressions (8) and (9) simplify to MEEF = 1/2Δ and NILS = 8Δ. Thus, for equal lines and spaces

$$MEEF \;=\; \frac{4}{NILS} \tag{10}$$

through focus. Falling NILS results in increasing MEEF, as expected.

The relationship between MEEF and NILS shown in equation (10), though not specifically true for all feature types nor for the partially coherent illumination used in lithographic applications, provides a basic concept that is generally correct. Continued advances in resist quality and reductions in process errors over the years have allowed adequate imaging of features with lower and lower NILS. Today's state-of-the-art lithographic processes for 150nm imaging at 248nm wavelengths routinely make use of images with NILS values below 2.0. The drive to 100nm optical lithography will push NILS values close to 1.0. In such cases the use of low NILS will invariably and inevitably lead to high MEEF imaging. It seems certain that MEEF values of 2 to 4 will become commonplace for advanced lithographic applications.

2.4 Alternating Phase Shifting Mask

An interesting case that can also be investigated with coherent illumination is the alternating phase shifting mask. For a space width of *w* and a pitch (as printed on the wafer) of *p*, if every other space is phase shifted by 180° the aerial image will be

$$I(x) \;=\; \left[\frac{4\sin(p\,w/2p)}{p}\cos(p\,x/p)\right]^2 \tag{11}$$

where only the ±1st diffraction orders are used to form the image. From this image, the image MEEF can be derived.

$$image\;MEEF \;=\; \frac{1+\cos(p\,w/p)}{1-\cos(p\,w/p)} \tag{12}$$

For equal lines and spaces (w/p = 0.5), the image MEEF for an alternating PSM is 1.0. For spacewidths larger than the linewidth (w/p > 0.5), the image MEEF becomes less than one, whereas spaces smaller than the linewidth produce MEEF values greater than 1.

2.5 Image MEEF for Large Pitch Patterns

The image MEEF calculations presented above all assume that the pitch of the pattern is small enough to only allow up to the $\pm 1^{st}$ diffraction orders to pass through the lens. In fact, for the more general case of higher orders (larger pitch), image MEEF expressions can also be derived. For the cases of coherent and incoherent illumination, in focus, the image MEEF for line/space patterns of spacewidth w and pitch p are

$$CoherentIllumination: \quad image\,MEEF = \frac{1+\sum_{n=1}^{N}\left(1+\cos(2\pi nw/p)\right)}{\sum_{n=1}^{N}\left(1-\cos(2\pi nw/p)\right)} \tag{13}$$

$$IncoherentIllumination: \quad image\,MEEF = \frac{1+\sum_{n=1}^{N} MTF_n\left(1+\cos(2\pi nw/p)\right)}{\sum_{n=1}^{N} MTF_n\left(1-\cos(2\pi nw/p)\right)} \tag{14}$$

where N is the number of the maximum diffraction order that passes through the lens.

III. Examples of MEEF

Lithography simulation (in this case, using PROLITH/2 v6) can be useful for understanding MEEF. Consider the linearity curves shown in Figure 4 [4]. If an isolated line for this system is being imaged near its resolution limit, about 250 nm in this case, a 10 nm mask CD error would give a 15 nm resist CD error. Thus, at this feature width, isolated line mask errors are amplified by a factor of 1.5. Figure 5 shows how the MEEF varies with feature size for dense and isolated lines for a typical imaging application. Note that the MEEF of the isolated line can be derived directly from the linearity plot (the MEEF is just the slope of the linearity curve), but not so for the dense lines. Figures 6 and 7 show experimental results for isolated lines indicating the same trends [5]. Note that the etch process also impacts the final “post-etch” MEEF.

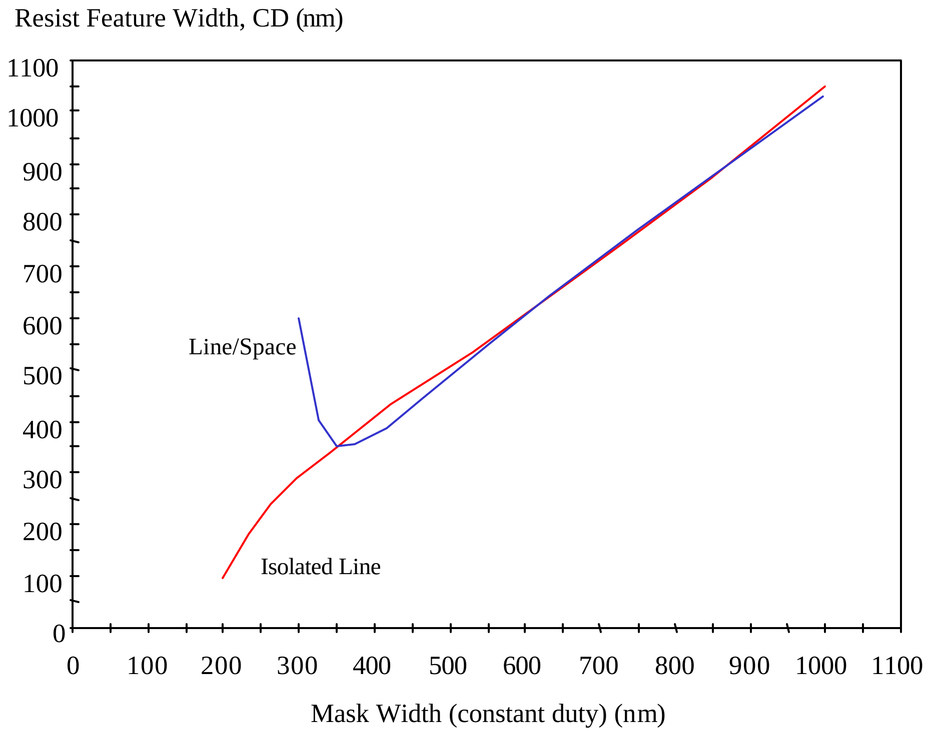

Figure 4. Typical mask linearity plot for isolated lines and equal lines and spaces (simulated for i-line, NA = 0.56, σ = 0.5).

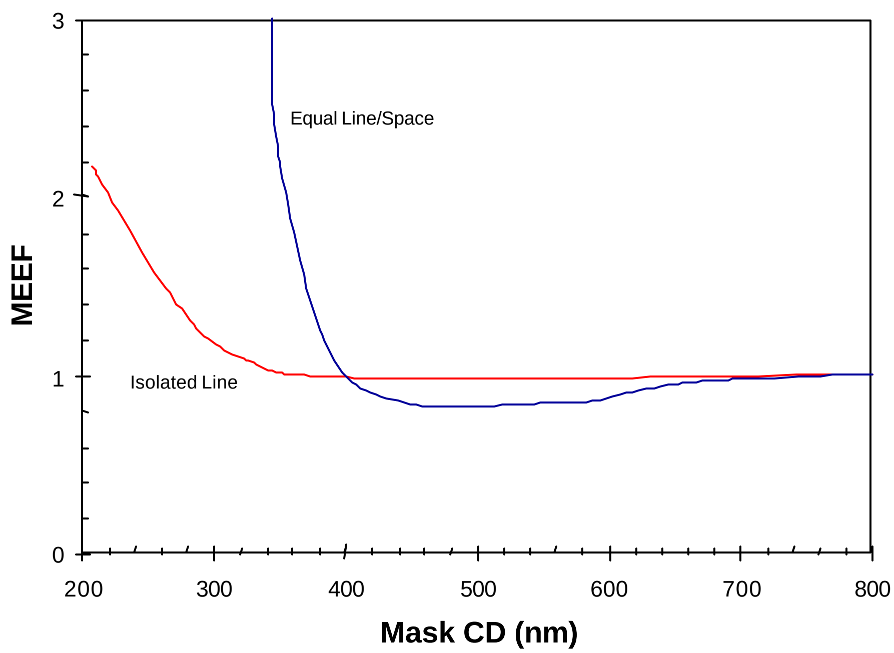

Figure 5. The mask error enhancement factor (MEEF) under the same conditions as Figure 4.

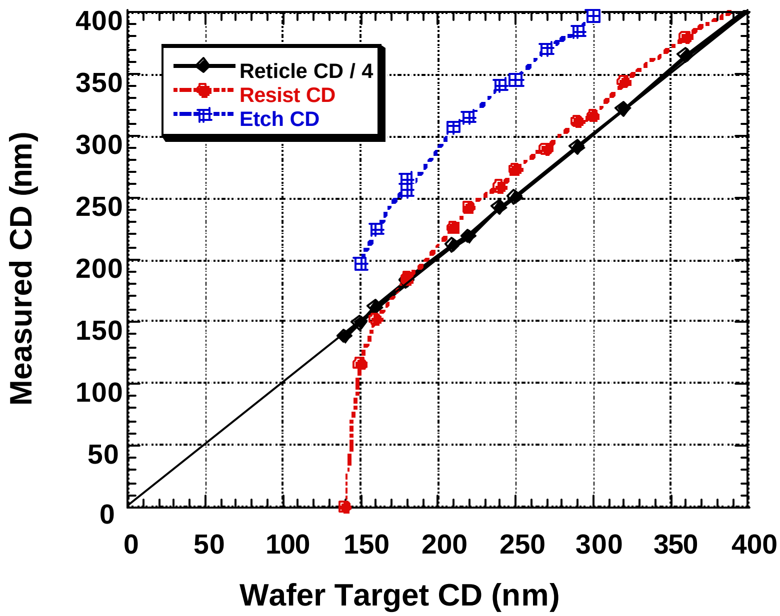

Figure 6. Experimental linearity data for isolated lines both before and after etch [5].

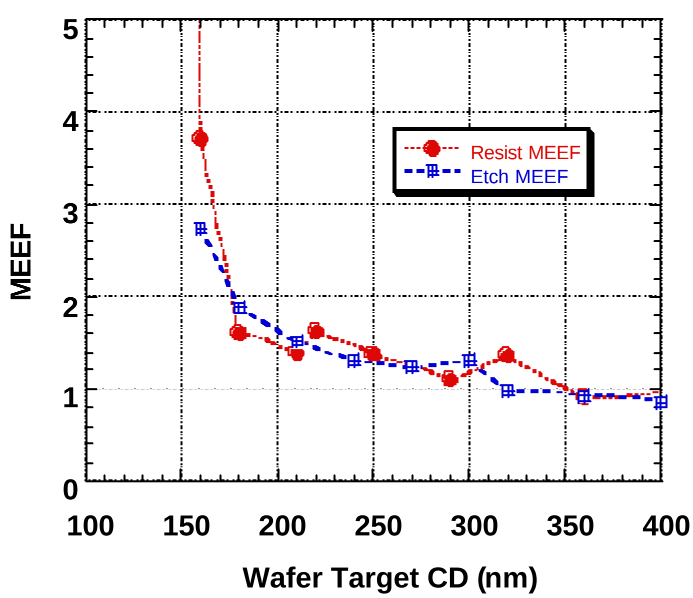

Figure 7. MEEF results for isolated lines both before and after etch (from the data in Figure 6).

Obviously, MEEF is a strong function of feature size. MEEF is also a function of feature type. Figure 8 shows both the image MEEF and the resist MEEF for dense and isolated lines and dense and isolated contact holes. As can be seen, dense lines have worse MEEF values than isolated lines, and contact holes are significantly worse than lines. It is also interesting to note that the image MEEF does a very good job of predicting the resist MEEF until the resolution limit is approached. The image MEEF underestimates the resist MEEF near the resolution limit, sometimes significantly. One exception to this general rule is the isolated line feature, where the image MEEF is actually worse (by a small amount) than the resist MEEF.

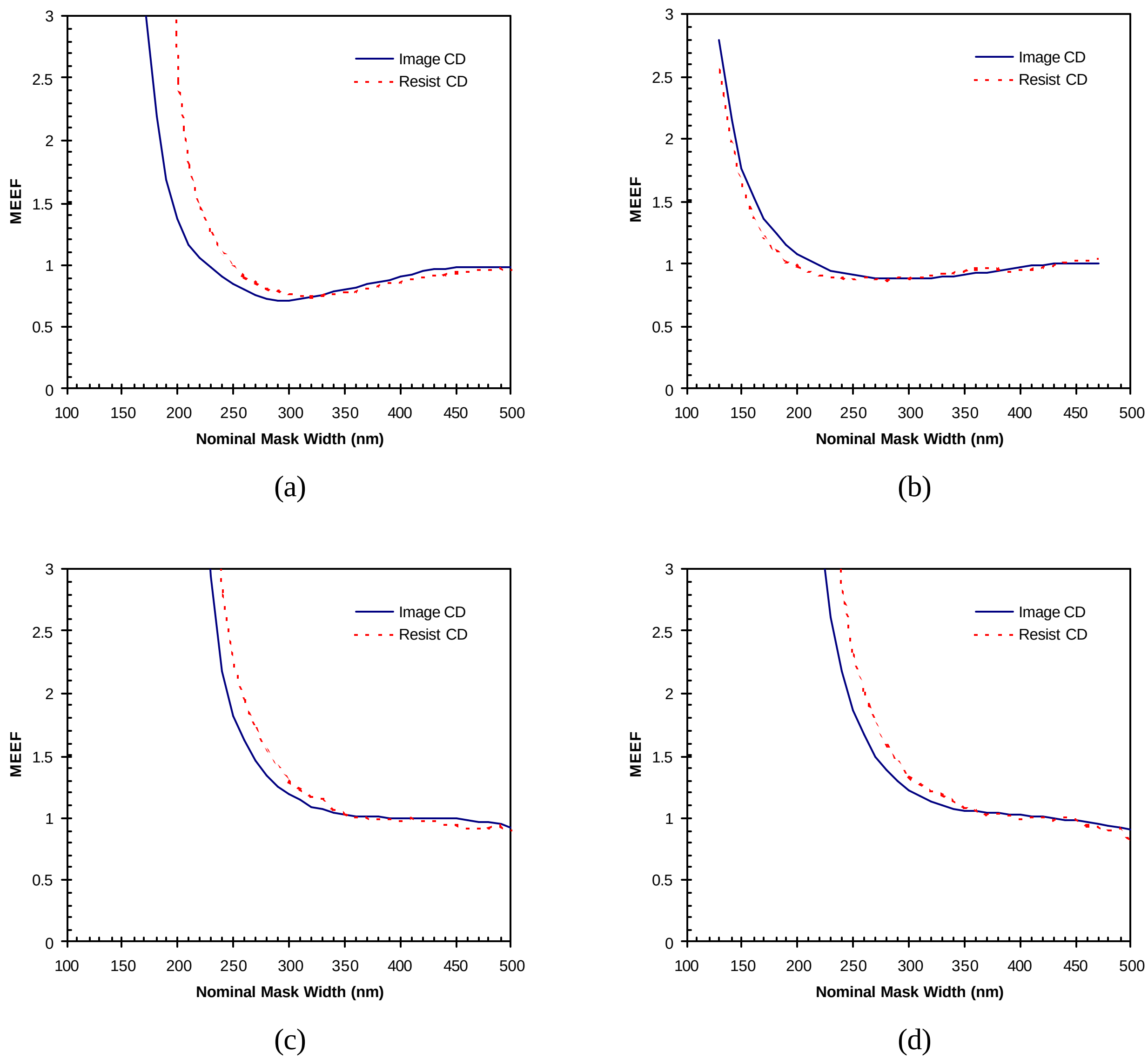

Figure 8. Comparison of simulated image and resist MEEF for (a) dense lines, (b) isolated lines, (c) dense contacts, and (d) isolated contacts. Deep UV exposure of UV6 on ARC with NA = 0.6 and σ = 0.5.

The impact of focus on the MEEF can be seen in Figure 9. Obviously, going out of focus (in this case, by 0.5 µm, still less than the limit of tolerance for this process) can dramatically increase the sensitivity of the process to errors in the mask CDs. This increased sensitivity to mask errors means that mask specifications, even when taking the MEEF into account, may not fully account for the impact of these errors on the total CD budget of a real process.

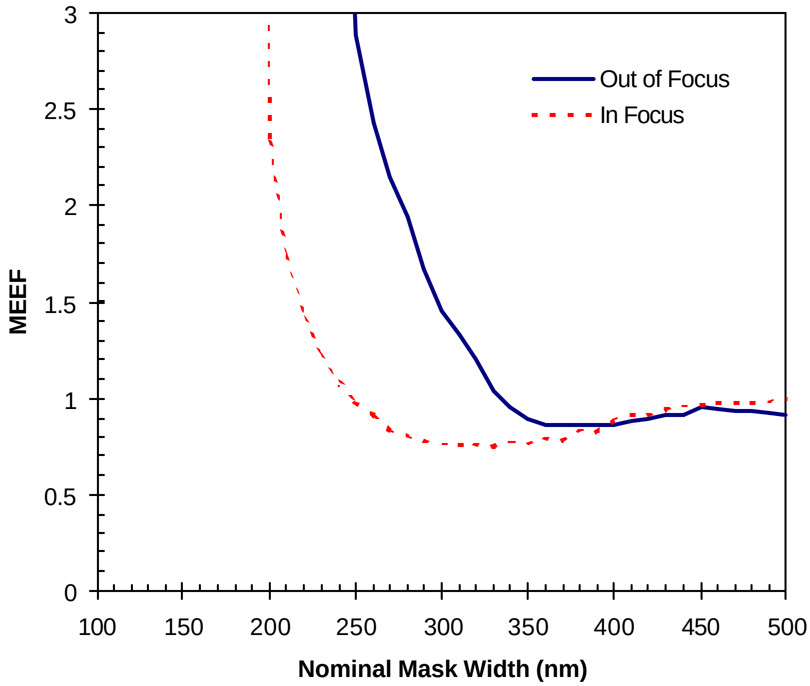

Figure 9. Focus errors can dramatically worsen the resist MEEF (simulated deep UV exposure of UV6 on ARC with NA = 0.6 and σ = 0.5, at both best focus and 0.5 µm out of focus).

In order to properly understand the impact of mask errors on a realistic process, the process window proves to be an exceptionally useful tool. Figure 10 shows a simulated process window for a baseline process (250nm dense lines and spaces imaged in UV6 photoresist on ARC with λ = 248nm, NA = 0.6, σ = 0.5). Sufficient process window exists to print these features with acceptable exposure latitude and depth of focus. What is the impact of a mask error on the process window? Figure 11 shows three process windows: the nominal process plus the imaging results for +10nm and –10nm reticle CD errors (wafer dimensions). The overlap of these three process windows, also shown on Figure 11, is significantly smaller than the baseline process. Figure 12 shows the analysis of these process windows to produce the exposure latitude versus depth of focus (DOF) curves (a measure of the size of the process window). It is quite obvious that these relatively small reticle CD errors are reducing the size of the process window by more than half! The DOF drops from a respectable 1.4 µm to an intolerably small 0.6 µm.

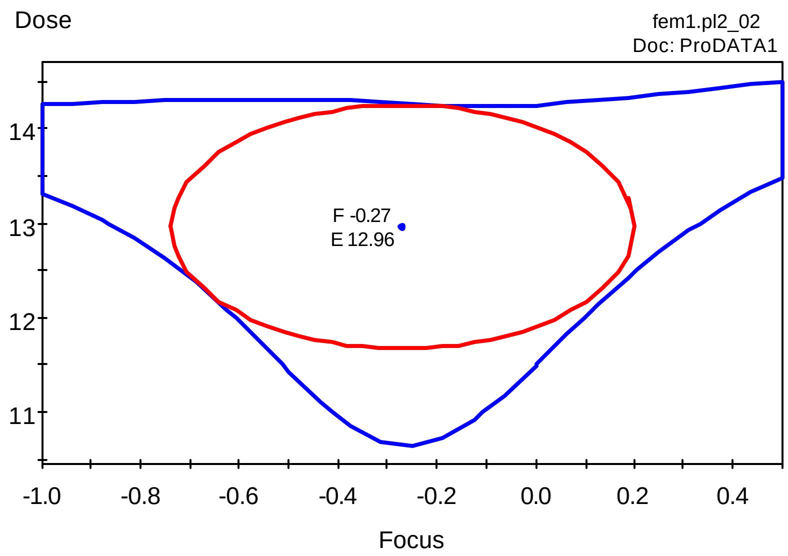

Figure 10. Baseline process (with no reticle errors) shows sufficient process window for imaging 250nm dense lines and spaces (simulated deep UV exposure of UV6 on ARC with NA = 0.6 and σ = 0.5, analyzed with ProDATA).

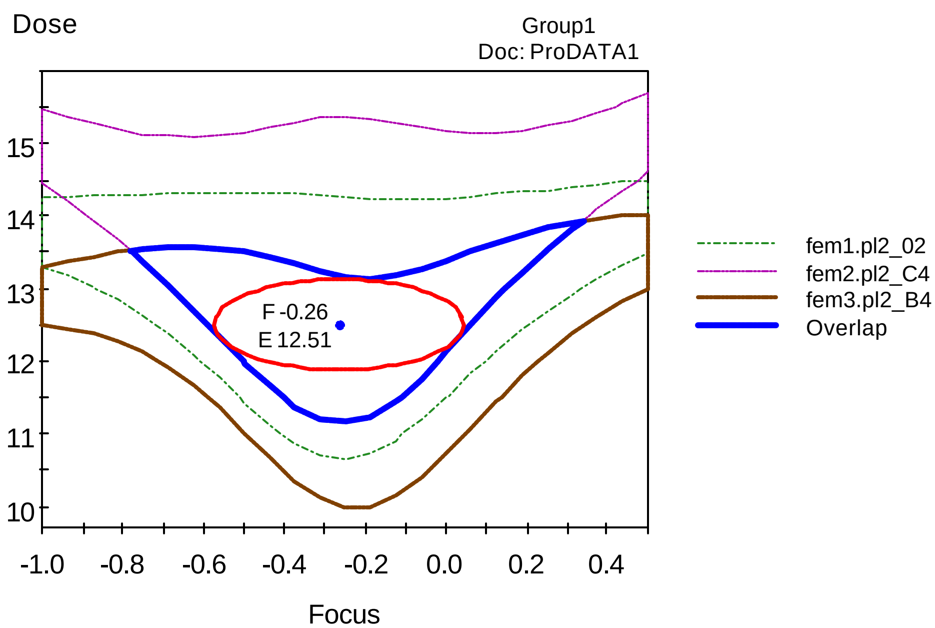

Figure 11. Overlapping process window includes the baseline process of Figure 8 plus cases where the reticle contains +10nm and –10nm CD errors (wafer dimensions).

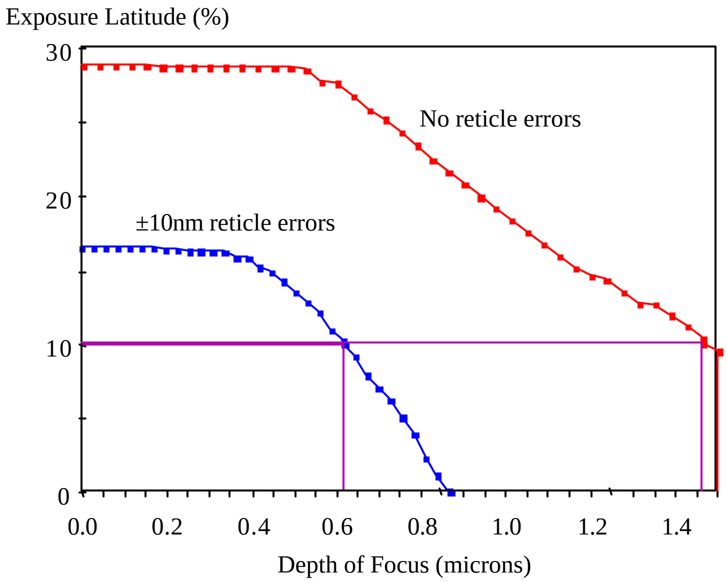

Figure 12. The impact of reticle errors is shown by comparing the exposure latitude/DOF analysis results from the process windows with and without reticle errors.

IV. Conclusions

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 will begin to take on a much larger portion of the total CD error budget if significant improvements in mask CD control are not made. The impact of mask errors on the final resist CD is also very dependent on normal variations in the process. The analytical expressions for image MEEF provided in this paper give some insight into how various mask duty cycles affect the MEEF, as well as the role of defocus and the normalized image log-slope. Overlapping process windows as a function of the magnitude of mask CD errors is the best approach to fully characterizing and specifying photomask CD errors.

References

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