# Printing Small Contact Holes: Energy, Area, and CD

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Possibly the most challenging mask layer to print in high-end lithography processes today is the contact layer. These small features are sub-wavelength in two dimensions, making them exceptionally sensitive to everything that makes low $k_1$ lithography difficult. For example, it is well known that contact holes suffer from the largest mask error enhancement factors (MEEF) of any feature type. Why? The reason is quite simple, really. Assuming that the source of the mask error is uniform (that is, it affects both the height and width of the contact in the same way), then such an error is affecting two dimensions of the mask simultaneously. In other words, errors in the area of the mask feature go as errors in the CD squared. Let's examine this effect in a little more detail.

The MEEF of a feature is defined as

$$MEEF = \frac{\partial CD_{wafer}}{\partial CD_{mask}} \quad (1)$$

where the mask CD is scaled to wafer dimensions. If we assume a "zero bias" process (where the target CD on the wafer is the same as the mask CD), then the MEEF can also be expressed as

$$MEEF = \frac{\partial \ln CD_{wafer}}{\partial \ln CD_{mask}} \quad (2)$$

This form of the MEEF equation will be useful later.

When printing a small contact hole, the aerial image projected onto the wafer is essentially the same as the point spread function (PSF) of the optical system.[1] The point spread function is defined as the normalized aerial image of an infinitely small contact hole on the mask. For small contact holes (about $0.6\lambda/NA$ or smaller), the aerial image takes on the shape of the PSF. If the contact hole size on the mask is smaller than this value, the printed image is controlled by the PSF, not by the dimensions of the mask. Making the contact size on the mask smaller only reduces the intensity of the image peak. This results in a very interesting relationship: changes in the mask size of a small contact hole are essentially equivalent to a change in exposure dose.

It is the area of the contact hole that controls the printing of the contact.[2] The electric field amplitude transmittance of a small contact hole is proportional to the area of the contact, which is the CD squared. The intensity is then proportional to the area squared. Thus, the effect of a small change in the mask CD of a contact hole is to change the effective dose reaching the wafer ($E$) as the CD to the fourth power.

$$E \propto CD^4_{mask}$$

$$d\ln E \approx 4\, d\ln CD_{mask} \quad (3)$$

where the approximate sign is used because the fourth-power dependence is only approximately true for typically sized contact holes.

The above equation relates mask errors to dose errors. Combining this with the MEEF equation (2) allows us to relate MEEF to exposure latitude.

$$\mathrm{MEEF} = 4\frac{\partial \ln CD_{wafer}}{\partial \ln E} \quad (4)$$

The term $\partial \ln CD/\partial \ln E$ can be thought of as the percent change in CD for a 1% dose change and is the inverse of the common exposure latitude metric. Thus, anything that improves the exposure latitude of a contact hole will also reduce its MEEF. Anything that reduces exposure latitude (like going out of focus) will result in a proportional increase in the MEEF. The importance of exposure latitude as a metric of printability is even greater for contact holes due to this direct link with MEEF. Additionally, the above expression could be used to lump mask errors into effective exposure dose errors for the purpose of process window specifications. Mask errors could be thought of as consuming a portion of the exposure dose budget for a process.

As lithography continues to push towards lower $k_1$ imaging, the importance of controlling contact hole dimensions on the mask will only increase. The above analysis provides a concrete approach towards quantifying the need for mask dimensional control for advanced contact hole and via reticles.

## References


1. C. A. Mack, "The Natural Resolution," Microlithography World, Vol. 7, No. 4 (Autumn, 1998).
2. C. A. Mack, "Corner Rounding and Round Contacts," Microlithography World, Vol. 9, No. 3 (Summer, 2000) pp. 26 – 28.