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Corner Rounding and Round Contacts

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In the Fourier Optics view of imaging, light passing through a photomask propagates to form a diffraction pattern that is the Fourier transform of the mask transmittance. The diffraction pattern is made up of "spatial frequency" components, high frequencies corresponding to large diffracted angles. The objective lens then acts as a low pass filter, throwing away frequencies higher than the cut-off of the lens (the numerical aperture divided by the wavelength, NA/λ). Any feature on the mask can be broken up into its frequency components, knowing that the higher frequencies will inevitably be lost. A good example is a corner, a 90° junction of two edges of chrome. The sharp corner represents an infinite range of spatial frequencies. Once the diffraction pattern passes through the lens, however, the loss of the high frequency components results in an image with a rounded corner.

How much does the corner round? For an isolated corner imaged with coherent light, the radius of the corner of the aerial image is about $0.36\lambda/NA$. The use of partially coherent imaging changes the amount of corner rounding, but only slightly. The lithographic impact of this corner rounding often depends on the proximity of the corner to other features, in particular to other corners. Consider two corners next to each other, that is the end of a line. If the linewidth is more than twice the corner rounding radius (i.e., about $0.7\lambda/NA$), then each corner will have only a small influence on each other. If the linewidth is less than this amount, the rounding of the two corners will overlap, resulting in line end shortening (see the previous edition of this column). The actual effects are somewhat more complicated due to the coherent interaction of the aerial images from each corner.

A more extreme case is the interaction of four corners to make a small island or contact hole. The result is familiar to anyone who has ever printed such features: square contact hole mask patterns (less than about $1.0\lambda/NA$ in width) always print as round holes on the wafer [1]. Since the result is inevitable, this type of corner rounding is not considered a problem.

Since the printing of these inexorably round contact holes is well accepted, an interesting question arises: if the corners on the *mask* are rounded, how will this affect the final printed *wafer* results? At first thought, one might expect that any corner rounding on the mask less than the natural wafer corner rounding due to the diffraction cut-off will not significantly alter the printed results. This is not exactly true for one simple reason – the rounding of a corner on the mask will lower (for a space corner) or raise (for a line corner) the total amount of energy being transmitted through the mask. It is this total mask transmittance effect, rather than the impact of the mask shape change, that determines the influence of mask corner rounding on final printed wafer results.

To test out this hypothesis, consider the printing of a very small contact (150nm×150nm, λ = 248nm, NA = 0.7, σ = 0.4, resulting in k_1 = 0.423). If only the area of the contact hole on the mask matters, then a series of masks with various amounts of corner rounding should produce the same images if the area of each of the mask holes is kept constant. Simulated aerial images (Figure 1) show that very little change is seen when the mask contact hole area is held constant while the corner rounding radius is varied from 0 (a perfectly square mask) to 84.6nm (a perfectly circular mask) [2]. The shape (and the width) of the aerial image is constant, but the peak intensity increases slightly (about 1.4%) as the corner rounding radius increases. This small increase in aerial image center intensity will result in a small (a few percent) increase in the final printed wafer contact width. Interestingly, there is no change in the shape of the printed contact pattern: the wafer pattern is a circle regardless of whether the mask pattern is a circle or a square. Further studies have shown that the focus-exposure process window for these contacts is also unaffected by the amount of corner rounding on the mask [2].

From these results, one can draw several conclusions. First, although the impact of mask corner rounding radius on final resist CD is small, it is not negligible. For the contacts examined here, if the corner rounding radius on the mask varied by about 20nm across the mask plate, the result would be a 1% final wafer CD variation. Thus, the control of corner rounding uniformity should be considered in the mask making process. Second, the key conclusion is that the impact of mask corner rounding is completely dwarfed by the effect of the <u>area</u> of the contact hole on the mask. The peak intensity of the aerial image of a small contact hole is proportional to the area of the contact hole on the mask ("small" being defined as on the order of or smaller than the width of the point spread function of the imaging tool, 0.66λ/NA). To first order, the area of the mask contact hole pattern is the only variable of importance. In fact, for small contact holes, an *effective* mask critical dimension can be defined as the square root of the area of the mask pattern:

$$\text{effective mask contact CD} = \sqrt{\text{contact hole area}}$$

When making masks with small contact hole patterns, all efforts should focus on controlling the effective mask contact hole CD.

References

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2. C. A. Mack, C. Sauer, S. Weaver, and J. Chabala, "Lithography Performance of Contact Holes — Part II: Simulation of the Effects of Reticle Corner Rounding on Wafer Print Performance" *Photomask Japan, Proceedings* (2000), in press.

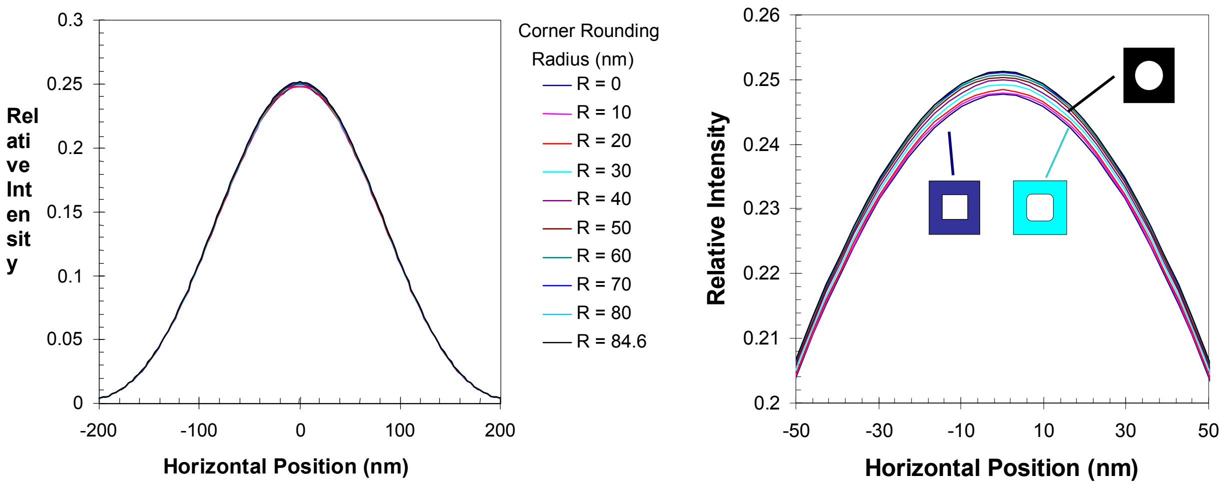

Figure 1. Aerial image results as a function of corner rounding radius (λ = 248nm, NA = 0.7, σ = 0.4, isolated 150nm contacts) shown at two different graph scales. For all masks, the area of the contact hole remained constant.