The Natural Resolution

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In past editions of this column (Summer 1998, Winter 1997), the concept of resolution was discussed in some detail. Quite practically, resolution is defined as *the smallest feature of a given type which can be printed with a specified depth of focus*. Further, the *pitch resolution* defines the smallest pitch that can be printed, and ultimately is a fairly simple function of the optical parameters of the imaging tool. These very general definitions can be applied to any feature type. There are, however, two special purpose metrics of resolution that can also be used to define the ultimate capabilities of an imaging system. These special metrics, though defined for very specific mask features, have almost universal appeal as "natural" metrics of imaging resolution.

The first metric concerns the smallest possible contact hole that can be printed. Consider a mask pattern of an isolated contact hole in a chrome (totally dark) background. Now let that hole shrink to an infinitesimal pinhole. If this small pinhole could be imaged in a positive resist, how big would the resist hole be? Of course, there is a practical problem with experimentally determining this "resolution": as the pinhole shrinks, the intensity of light reaching the wafer becomes infinitesimally small, making the required exposure time for the resist grow to infinity. However, from a theoretical perspective we can avoid this problem by assuming we are very patient and calculating what we believe would be the printed result.

Thinking first of just the imaging tool, what would be the aerial image resulting from this infinitely small pinhole? As noted before, the amount of light actually going through the hole is infinitesimally small, but we can compensate for this with the proper normalization. We will normalize our aerial image coming from the pinhole to have a peak intensity of 1.0 when in-focus for an ideal, aberration free optical system. The aerial image of a pinhole, when normalized in this way, is called the *point spread function* (PSF) of the optical system. The PSF is a widely-used metric of imaging quality for optical system design and manufacture and is commonly calculated for lens designs and measured on fabricated lenses using special bench-top equipment. For classical imaging applications, the PSF can be calculated as the square of the magnitude of the Fourier transform of the imaging tool exit pupil. For an in-focus, aberration free system of wavelength λ, the pupil function is just a circle whose radius is given by the numerical aperture NA, and the PSF becomes

$$PSF_{ideal} = \left| \frac{J_1(2\pi\rho)}{\pi\rho} \right|^2 \qquad (1)$$

where J_1 is the Bessel function of the first kind, order one, and ρ is the radial distance from the center of the image normalized by multiplying by NA/λ. Figure 1 shows a graph of Equation (1).

How wide is the PSF? For large contact holes, the normalized intensity at a position corresponding to the mask edge (that is, at the desired contact hole width) is about 0.25 – 0.3. If we use this intensity range to measure the width of the PSF, the result is a contact hole between 0.66 and 0.70 λ/NA wide. Thus, this width represents the smallest possible contact hole that could be imaged with a conventional chrome on glass (i.e., not phase-shifted) mask. If the contact hole size on the mask approaches or is made 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. Thus, this width of the PSF, the ultimate resolution of a chrome on glass (COG) contact hole, is a natural resolution of the imaging system.

Another special mask feature which exhibits a similar natural resolution behavior is the 180° phase edge. Consider a chromeless mask with a large region shifted by 180° to produce a long, straight boundary between the 0° and the 180° regions. Since light transmitted to either side of this edge will have a 180° phase difference, the light that diffracts and interferes under the edge will cancel out producing a dark line centered under the phase edge. As a result, this isolated 180° phase edge will print as a narrow line in a positive photoresist. How wide will this line be?

A mathematical treatment of this imaging problem for coherent illumination allows for an analytical expression for the in-focus image of an isolated phase edge [1]:

$$I_{phase-edge}(x) = \frac{4}{\pi^2}\mathrm{Si}^2\left(\frac{2\pi NAx}{\lambda}\right) \tag{2}$$

where

$$\mathrm{Si}(\theta) = \int_0^\theta \frac{\sin z}{z}\,dz$$

$\mathrm{Si}(\theta)$ is called the sine integral and is tabulated in standard mathematical references or can be computed numerically. Figure 2 shows a graph of equation (2). The width of this image can be estimated in the same way as the PSF. Assuming an intensity level between 0.25 and 0.3, the width of the phase edge line is between 0.26 and 0.29 λ/NA. An isolated phase edge prints as a very narrow line indeed!

What controls the width of the image of an isolated phase edge? Obviously the edge itself does not have a "width". The width of the phase edge image is in fact an inherent property of the imaging system, controlled by its numerical aperture and wavelength. In fact, analogous to the PSF, the image of equation (2) could be called the *phase edge line spread function*. The size of this tiny line is the "natural" resolution of any 180° phase edge. But its importance goes beyond just the printing of small isolated lines. A phase shifted mask can be thought of as a collection of 0 - 180° phase transitions. Each transition has a tendency to print at its "natural linewidth" of about 0.26 λ/NA. Much insight can be gained by approaching phase shifting mask design with this natural linewidth in mind.

For the special types of mask features described above, the resolution of that feature becomes a function only of the properties of the imaging system and, strangely, becomes independent of the size of the feature on the mask. I call these resolution properties the "natural" resolutions of the imaging tool. For a contact hole in a standard COG mask, the point spread function determines the resolution. For an isolated 0 - 180° phase edge, the phase edge line spread function determines the resolution. In each case, the mask does not control the feature size (other than dictating the feature type). Considering these natural resolutions as ultimate resolving power limits for particular feature types,

$$\textit{Ultimate COG Contact Hole Resolution} = 0.66\frac{\lambda}{NA} \tag{3}$$

$$\textit{Ultimate Phase Edge Line Resolution} = 0.26\frac{\lambda}{NA} \tag{4}$$

The natural resolutions expressed in equations (3) and (4) make good rules of thumb for predicting the ultimate resolution of an imaging tool.

References

1. C. A. Mack, "Fundamental Issues in Phase-Shifting Mask Technology," *KTI Microlithography Seminar Interface '91, Proc.*, (1991) pp. 23-35.

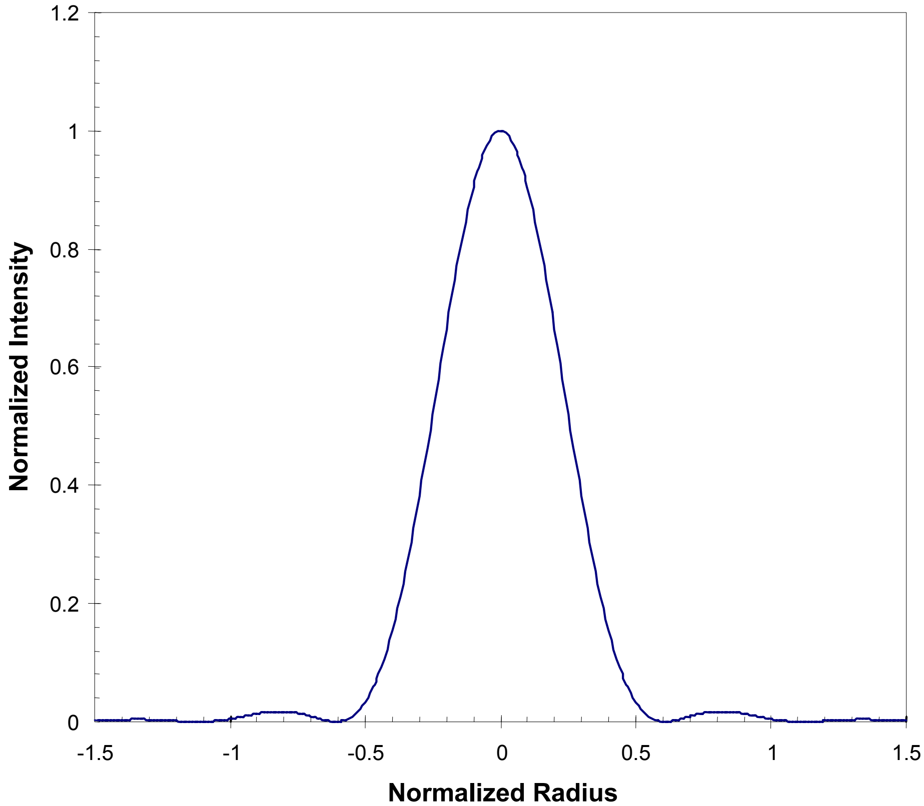

Figure 1. Ideal point spread function (PSF), the normalized image of an infinitely small contact hole. The radial position is normalized by multiplying by NA/λ.

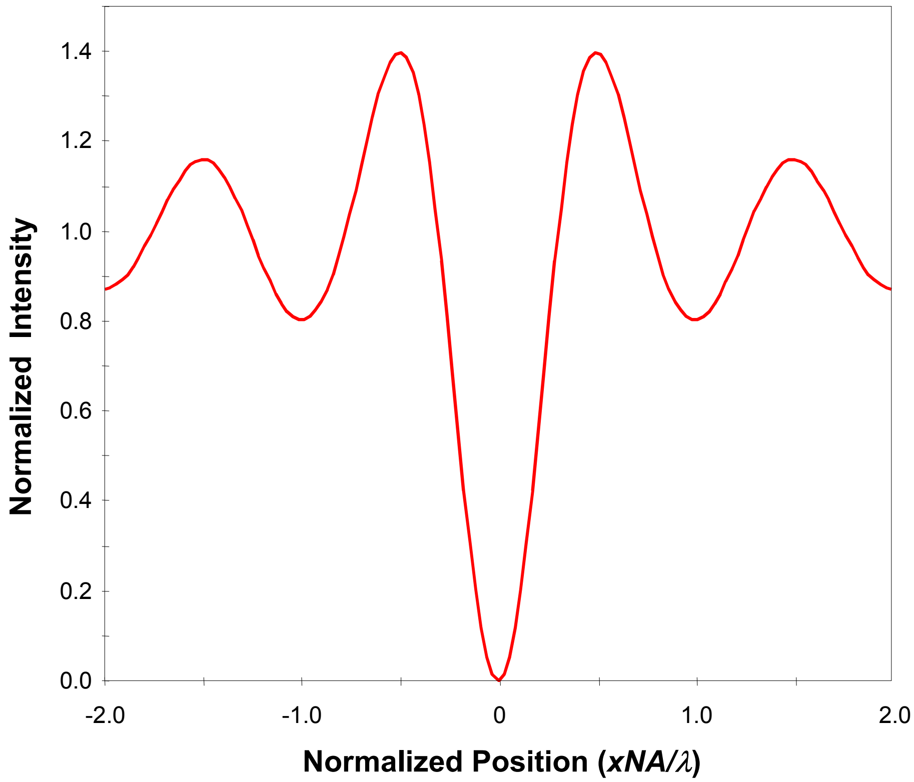

Figure 2. The aerial image of an isolated 180° phase edge (shown here using coherent illumination) will produce a narrow line in a positive resist.