Pitch: The Other Resolution

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In past editions of this column (Spring and Summer, 1995), we defined quite carefully what is meant by depth of focus (DOF): *the range of focus which keeps the resist profile of a given feature within all specifications (linewidth, sidewall angle, and resist loss) over a specified exposure range*. DOF was measured for a given feature using a focus-exposure matrix and a specific methodology for analyzing the resulting data. Likewise, a careful definition of resolution resulted in an adequate description of the smallest manufacturable feature size: *the smallest feature of a given type which can be printed with a specified depth of focus* (*MLW*, Winter 1997).

Although the above definition of resolution is perfectly general, there is a class of features where a slightly different approach is more appropriate. Consider a simple repeating mask pattern of equal lines and spaces. One could determine the resolution of this pattern type using the above definition, with the condition that the resist features must be equal lines and spaces as well (i.e., the desired linewidth equals the desired spacewidth). However, if we were to concentrate only on the line feature, we could easily overexposure our positive resist to produce a smaller linewidth and, most likely, a smaller "resolution." That is, keeping the pitch of the pattern (linewidth plus spacewidth) constant, we could improve the line feature resolution by a simple processing change, but only at the expense of the space feature resolution. Is this truly an improvement in resolution?

The answer depends on the application. If only the width of the line is critical, then resolution should be based only on the line feature. The electric performance of a device, for example, may be critically dependent on the linewidth of a given device structure, but only marginally affected by the accompanying space feature size. In most cases, however, the space feature is also critical. In fact, the ability to decrease both linewidth and spacewidth simultaneously allows manufacturers to shrink chip sizes, putting more chips on a wafer and providing a huge economic driver for the quest for better resolution. For such applications, where linewidth and spacewidth are both critical, one can modify the above definition of *feature* resolution to produce a definition for *pitch* resolution: *the smallest pitch of a given duty cycle which can be printed with a specified depth of focus*, where duty cycle is defined as the ratio of spacewidth to linewidth.

At first glance the difference between the feature resolution and the pitch resolution seems almost trivial – hardly worth the effort to propose a separate definition. However, use of these two different types of resolutions reveals that the physical limits to resolution can be quite different for each. Consider the simple case of forming an image of an equal line/space mask pattern illuminated with a single wavelength, normally incident plane wave (i.e., coherent illumination). For such a case there will be a hard cut-off for the pitch resolution (Figure 1):

when the pitch drops below λ/NA (where λ is the wavelength and NA is the objective lens numerical aperture) no image whatsoever is formed for any duty cycle. Regardless of the profile, exposure latitude and DOF specifications, no pitch below this limit can be imaged. For the case of an isolated line, there is no equivalent "hard cut-off" of the feature resolution, which instead exhibits a gradual reduction in profile control as the feature size is decreased.

In general terms, the feature resolution is limited by photoresist profile control and is a complicated function of wavelength and numerical aperture (see this column, Winter 1997). Ultimately, the pitch resolution is limited by the cut-off of discrete diffraction information passing through the objective lens and is a relatively simple function of wavelength and numerical aperture. To understand this simple functionality, one must understand that a single diffraction order passing through the objective lens produces a single plane wave of light striking the wafer. Two plane waves at the wafer (coming from two separate diffraction orders) will interfere with each other to produce a sinusoidal pattern of light and dark (giving spaces and lines). If the two plane waves strike the image plane (i.e., the wafer plane) with angles θ_1 and θ_2 with respect to the optical axis (that is, a normal to the image plane), then the period of the resulting image will be

$$period = \frac{\lambda}{\sin\theta_1 - \sin\theta_2} \tag{1}$$

This general expression can be used to understand a variety of imaging situations. For the coherent illumination case described above, $\theta_2 = 0$ for the zero order and $\sin\theta_1$ is at its maximum value of NA. For the special case of two symmetrical beams, $\theta_1 = -\theta_2 = \theta$ and the period becomes (Figure 2)

$$period = \frac{\lambda}{2\sin\theta} \tag{2}$$

The angles of light exiting from the objective lens of a projection imaging system are limited by the numerical aperture of that lens. Thus, the ultimate pitch resolution of an imaging tool is obtained when $\sin\theta$ in equation (2) becomes its maximum value, the NA:

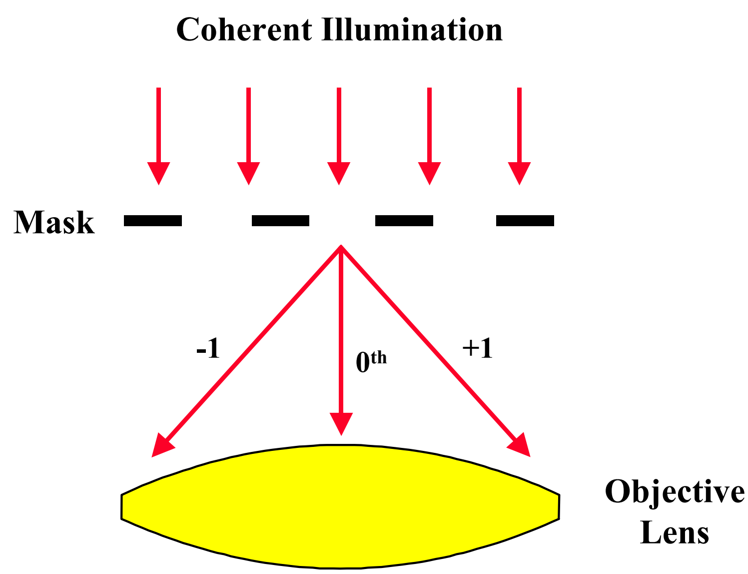
$$ultimate\ \ pitch\ \ resolution = \frac{\lambda}{2NA} \tag{3}$$

for all duty cycles. This ultimate pitch resolution can be obtained using an alternating phase shifting mask or an optimized off-axis illumination scheme. However, the actual pitch resolution may not be this good if the resulting printed image does not meet the required DOF specifications.

In summary, it is often useful to define two separate resolutions: the smallest feature that can be adequately printed and the smallest pitch that can be adequately printed. Feature resolution is limited by profile control, which is a complicated function of almost every variable in the lithographic process. The pitch resolution is limited by the angles of light that can make it through the objective lens, and is ultimately determined only by the numerical aperture and wavelength of the imaging tool. It is interesting to note that the numerical aperture has a maximum possible value of 1.0, so that a pitch resolution of half of the imaging wavelength is the theoretical (though not too practical) limit [1].

References

1. S. R. J. Brueck, "Imaging Interferometric Lithography," *Microlithography World*, Vol. 7, No. 1(Winter, 1998) pp. 2 – 10.



1st diffraction order: $\sin\theta = \lambda / p$

$$p_{\min} = \frac{\lambda}{\sin\theta_{\max}} = \frac{\lambda}{NA}$$

Figure 1. The pitch resolution of an imaging tool can be clearly defined for coherent illumination, independent of the duty cycle.

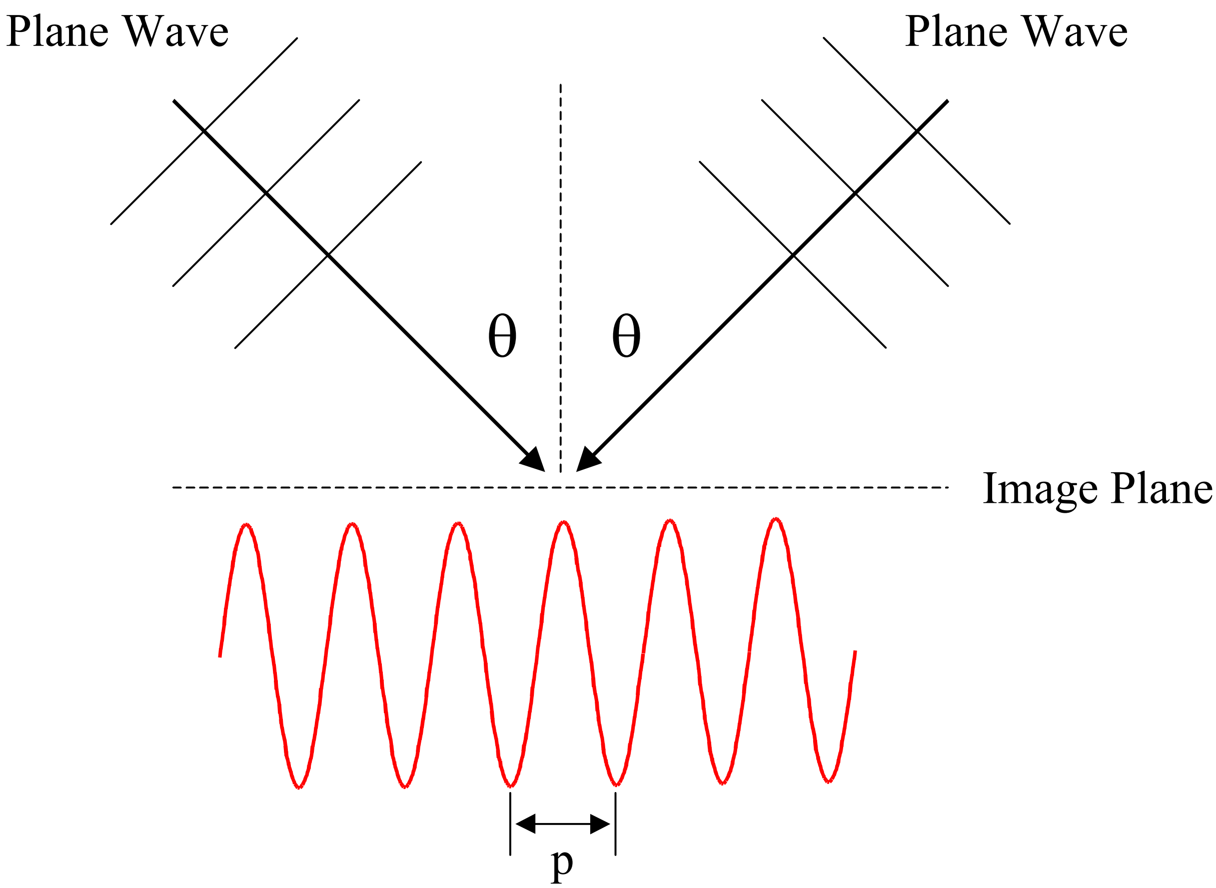


Figure 2. The interference of two plane waves produces a sinusoidal interference pattern. This intensity pattern is equivalent to the image of a repeating line/space pattern with a pitch given by $p = \lambda/2\sin\theta$.