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Off-Axis Illumination

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Off-axis illumination (OAI) is one of the three major resolution enhancement technologies that have enabled optical lithography to push practical resolution limits far beyond what was once thought possible (the others being phase shifting masks and optical proximity corrections). In order to effectively use off-axis illumination, the shape and size of the illumination must be optimized for the specific mask pattern being printed. In this column I'll describe how to optimize the most popular types of off-axis illumination, annular and quadrupole, to maximize depth of focus for a given pitch.

Off-axis illumination refers to any illumination shape that significantly reduces or eliminates the "on-axis" component of the illumination, that is, the light striking the mask at near normal incidence (Figure 1). By tilting the illumination away from normal incidence, the diffraction pattern of the mask is shifted within the objective lens. For the case of a repeating pattern, the diffraction pattern is made up of discrete points of light called diffraction orders. If the pitch of the repeating pattern is small, only a few diffraction orders can actually make it through the finite size lens. As discussed in the last edition of this column, placing those diffraction orders that make it through the lens evenly about the center of the lens leads to improved depth of focus (DOF). Thus, the main advantage of off-axis illumination is an increase in depth of focus for small pitch patterns.

Using Figure 1 as a guide, how much should the illumination be tilted to achieve maximum depth of focus? In spatial frequency terms, the distance between the zero and first diffracted orders is $1/p$, where p is the pitch. Let's begin by converting this spatial frequency distance to "sigma space", the spatial frequency normalized by λ/NA, where λ is the wavelength and NA is the numerical aperture of the objective lens. In this normalized coordinate system the maximum spatial frequency passing through the lens is 1.0. Thus, the distance between diffraction orders in sigma space is $\lambda/(pNA)$. To center the zero and first orders about the center of the lens, the zero order (found at the exact center of the lens for normally incident light) must by shifted by $\lambda/(2pNA)$ in sigma space. Thus, this becomes the optimum illumination tilt to give maximum depth of focus. Of course, tilting in the opposite direction (a $-\lambda/(2pNA)$ shift in sigma space) will produce the same effect. Combining both tilts into one illumination shape produces an illumination called "dipole" that adds the desirable effect of reducing sensitivity to lens aberrations such as image placement error. Note that the optimum illumination tilt is pitch dependent.

Real lithography, however, adds a significant complication to this otherwise simple picture. The line/space pattern shown in Figure 1 has a specific orientation (the lines are running into and out of the page) that results in an optimum tilt as shown in the figure. A perspective plot of the same diffraction situation may make this point clearer, as shown in Figure 2. Now, what if the mask pattern was rotated by 90°? Most integrated circuit designs will contain many line and space-like features that are oriented both vertically and horizontally. If the illumination is tilted by the amount discussed above, that tilt, in a specific direction, will only help the lines and spaces that are properly oriented with respect to that tilt. The other orientation of lines will not only not be improved by the illumination tilt, they are likely to be significantly degraded in imaging performance. What to do? If both vertical and horizontal lines are to be imaged together on the same mask, an illumination shape must be used that provides optimum tilts for both geometries. The simplest shape that provides this optimum tilt for both horizontal and vertical line/space patterns is called quadrupole illumination.

Quadrupole illumination takes the optimum dipole generated for one orientation of lines and spaces, then shifts it back and forth in the other direction to create the proper angles for the other orientation of lines. The result is four poles evenly spaced about the center of the lens, as shown in Figure 3. In sigma space, the radial position of the center of each pole with respect to the center of the lens that gives optimum DOF is $\sqrt{2}\lambda/(2pNA)$. Note that this positioning of the quadrupoles gives the same horizontal and vertical spacing between poles as in the dipole case, but places them closer to the edge of the lens aperture.

While the quadrupole shape provides optimum performance for vertical and horizontal lines, other orientations (such as a line/space array oriented at 45°) will not be optimum. For any orientation of lines, the optimum dipole for that pattern will be spread in a direction perpendicular to the line orientation, and can be shifted parallel to the lines in any amount that keeps the dipoles within the lens. If the mask will contain arbitrary orientations of lines, many rotations of the dipoles will produce an annulus of illumination. The optimum center of the annular ring is the same as the optimum dipole position.

For each illumination shape discussed - dipole, quadrupole, and annular illumination - there is one size that maximizes the depth of focus for a given pitch. However, this illumination shape is only optimum for that one pitch. While pitches close to this optimum will get most of the benefit of the off-axis illumination, pitches sufficiently far away from the optimum will receive little or no benefit. In fact, the worst case pitch for any given off-axis configuration would put one of the diffracted orders dead center in the lens, the situation that off-axis illumination is designed to avoid. For each of the illuminations discussed here this worst case pitch occurs at exactly twice the pitch for which the illumination was optimized. Since this pitch receives none of the focus-enhancing benefits of the off-axis illumination, it is sometimes called a “forbidden” pitch, indicating the lithographer’s desire that this pitch be avoided during circuit design.

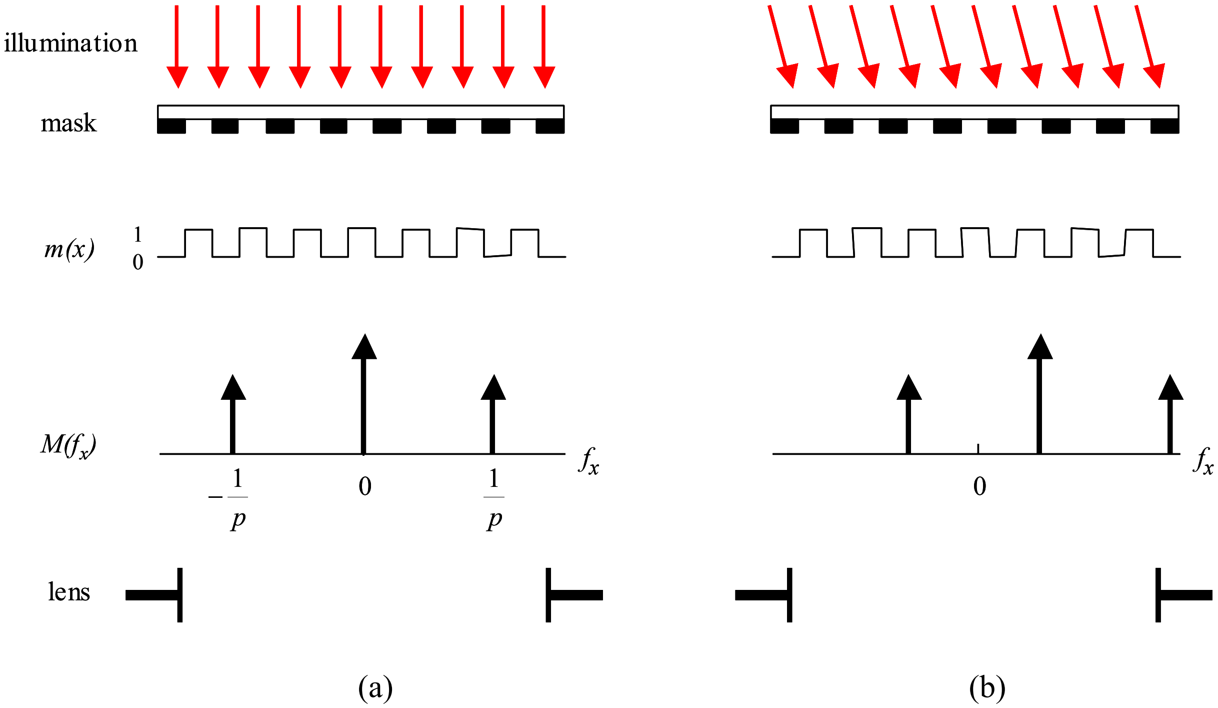

Figure 1. Off-axis illumination modifies the conventional imaging of a binary mask shown in (a) by tilting the illumination, causing a shift in the diffraction pattern as shown in (b). By positioning the shifted diffraction orders to be evenly spaced about the center of the lens, optimum depth of focus is obtained.

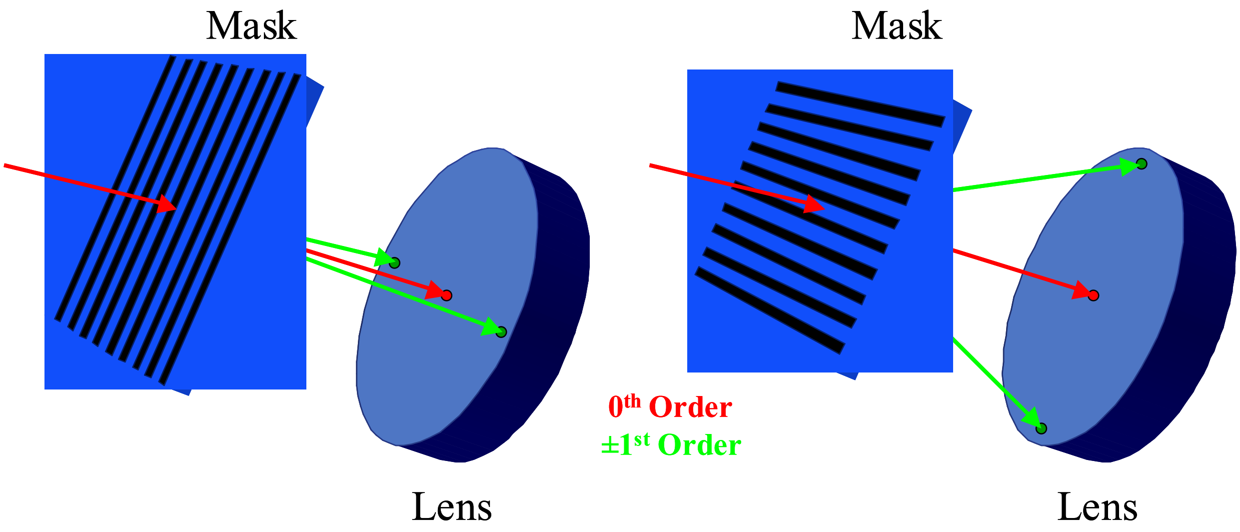

Figure 2. The position within the lens of the diffracted orders from a pattern of lines and spaces is a function of the orientation of the lines and spaces on the mask.

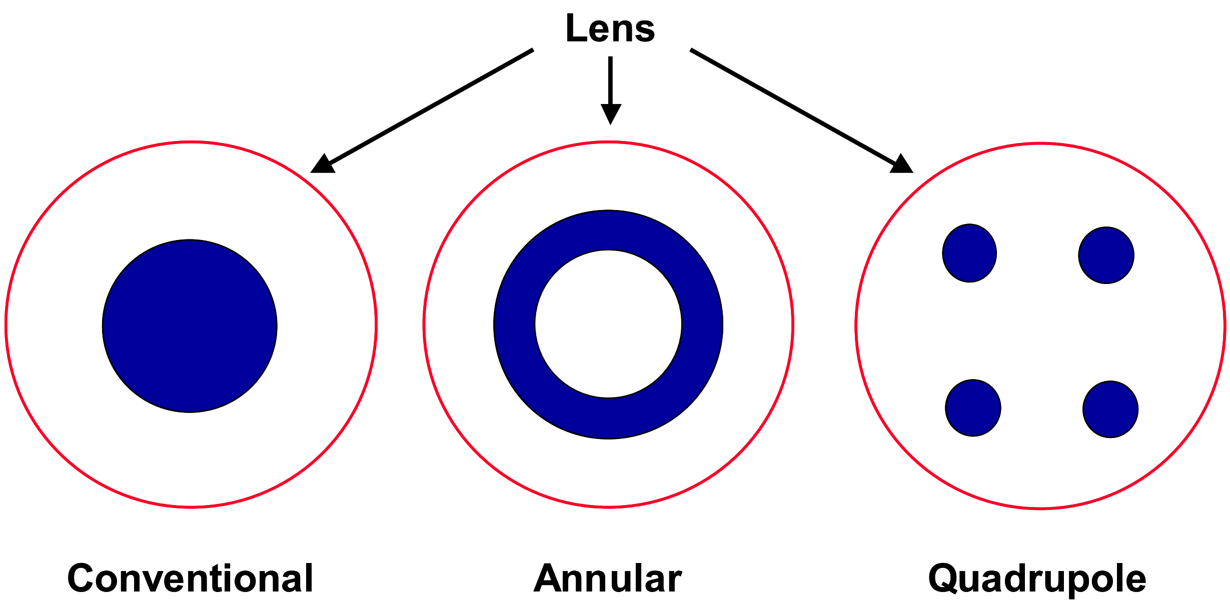

Figure 3. Various shapes for conventional and off-axis illumination.