Tutor41.doc; Version 12/9/03

Resolution Enhancement Technologies

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Classically speaking, optical lithography should have died long ago. The classical resolution and depth of focus limits of conventional optical imaging would never allow the kind of performance that has become routine in advanced semiconductor manufacturing today. How could this be? While the laws of physics have not changed in the last 15 years, our understanding of them has sharpened and our ability to commit this improved understanding into practice has been remarkable. The classical "limits" turned out to be limits of our knowledge and of our assumptions. Three major advances have combined to scale our perception of the ultimate resolution by a factor of two and have stretched the attainable depth of focus even further. These three advances, collectively known as resolution enhancement technologies (RET), are phase shift masks (PSM), off-axis illumination (OAI), and optical proximity correction (OPC). This triumvirate of three letter acronyms has over the last decade enabled the continued cost-effective progression of Moore's Law and the further delay of NGL (next generation lithography).

What are these resolution enhancements and how do they work? In essence, both PSM and OAI work in the same way to increase depth of focus as feature size is pushed remarkably smaller. OPC then makes these RETs work in practice by rendering a chip design compatible with the non-linearities inherent in working at the limits of imaging technology. Let's begin with a review of how a phase shift mask works.

A conventional, binary chrome on glass mask of lines and spaces will produce a diffraction pattern of discrete diffraction orders at spatial frequencies that are multiples of one over the pitch (see the very first edition of this column, January 1993). For a high resolution pattern, only the zero and the plus and minus first diffraction orders pass through the lens (which has a spatial frequency cut-off of NA/λ, where NA is the numerical aperture of the objective lens and λ is the wavelength), as seen in Figure 1a. In fact, it is the interference of the zero order light with the first orders that produces the bright and dark image of the proper pitch. If the pitch is made too small, the first order light diffracts at an angle too large to fit through the objective lens and no image is produced. The resolution limit, then, occurs when the first diffracted order (spatial frequency of 1/pitch) lands exactly at the edge of the aperture (spatial frequency of NA/λ) so that the minimum resolvable pitch is equal to λ/NA. Additionally, the use of partially coherent illumination can extend this classical resolution limit, but only at the expense of reduced image quality.

An alternating phase shift mask, as depicted in Figure 1b, adds "shifters" over every other space to shift the phase of the light by 180°. This mask then uses the destructive interference of light passing through adjacent spaces to completely eliminate the zero order. The image is obtained from the interference of the two first diffraction orders, now located at the spatial frequencies of $\pm 1/2p$. The resolution limit is again obtained when these first diffracted orders just barely pass through the edge of the lens, making the minimum resolvable pitch equal to 0.5λ/NA. Thus, the use of an alternating phase shift mask can double the resolution of a line/space pattern. Often, the binary mask imaging shown in Figure 1a is referred to as three beam imaging (due to the interference of the three diffraction orders) while the phase shift case, with two diffraction orders passing through the lens, is called two beam imaging. As we shall see, two beam imaging leads to enhanced depth of focus.

Off-axis illumination can be used to mimic the two beam imaging found in phase shifting masks (Figure 2). By tilting the illumination, the diffraction pattern of a conventional binary mask is shifted within the objective lens. With the proper tilt, one of the first diffraction order will fall outside of the lens so that only two of the orders (the zero and the remaining first order) are used to form the image. Like the alternating phase shift mask, the proper use of off-axis illumination can double the resolution limit of a line/space pattern.

Although the increase in resolution afforded by these RETs is certainly desirable, their real benefit comes from the enhanced depth of focus that accompanies the smaller dimensions. Again considering just a pattern of lines and spaces, the plane of best focus is determined by the phase of the interfering beams that combine to form the image. At best focus all of the interfering beams have the same phase. For the case of three beam imaging, propagation of the beams past this plane of best focus creates a phase difference between the beams. As seen in Figure 3a, beams that arrive at the image plane from different angles must travel different distances as they propagate, with the larger angle beams traveling farther than the smaller angle beams to reach a wafer that is displaced from best focus. Since a path difference results in a phase difference (light changes phase 360° for every wavelength of distance traveled), the beams have an increasing phase error as a function defocus, resulting in degraded image formation. For the two beam imaging case (Figure 3b), if the two beams arrive at the wafer from the same angle (on opposite sides of the optical axis) a displacement of the wafer from the focal plane gives the same phase change to each beam. Thus, the phase difference between the beams remains zero and a perfect, in-focus image results.

Translating the above discussion to the diffraction plane, improved depth of focus results from image formation with two beams when those two beams are equally spaced about the center of the lens. For line space patterns made with alternating phase shift masks, this arrangement of two equally spaced diffraction orders occurs naturally for all reasonably small pitches. For off-axis illumination, the angle of illumination tilt can be adjusted to put the zero and one of the first diffraction orders equally spaced about the center of the lens, but only for one pitch.

In the next edition of 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.

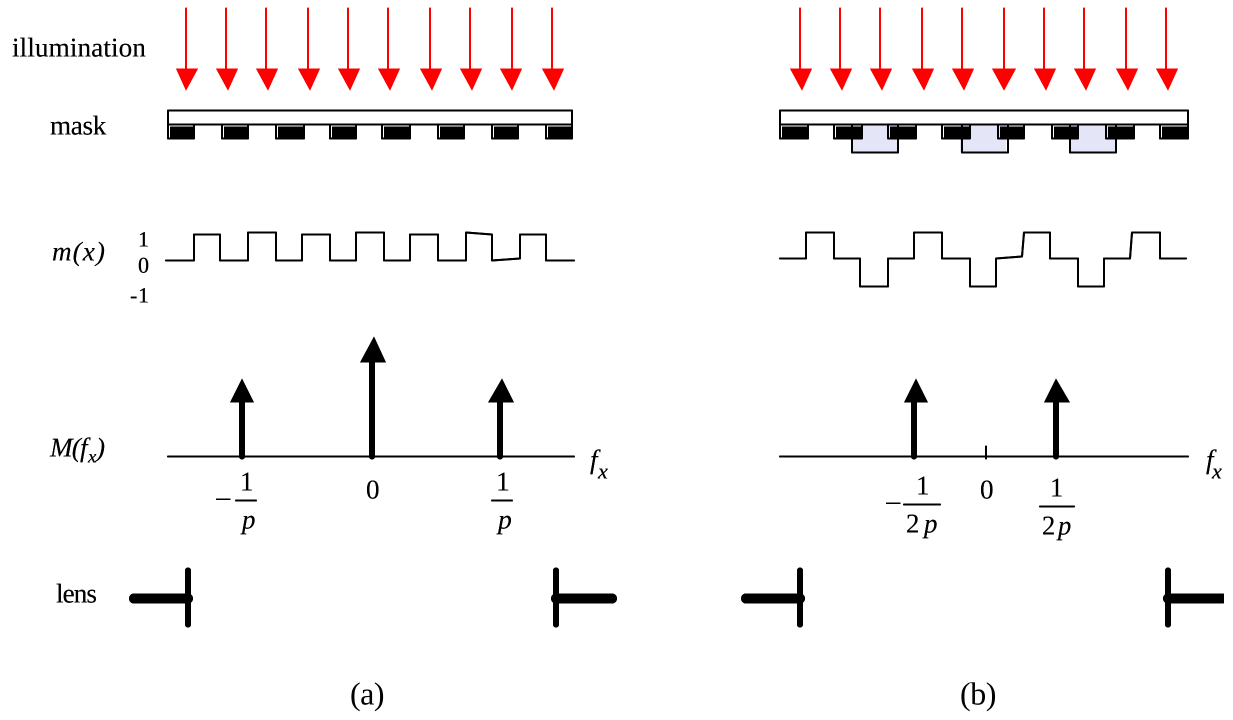

Figure 1. A mask pattern of lines and spaces of pitch *p* has an idealized amplitude transmittance function *m(x)* that produces a diffraction pattern $M(f_x)$ where f_x is the spatial frequency. A binary chrome on glass mask is shown in (a), and an alternating phase shift mask is shown in (b).

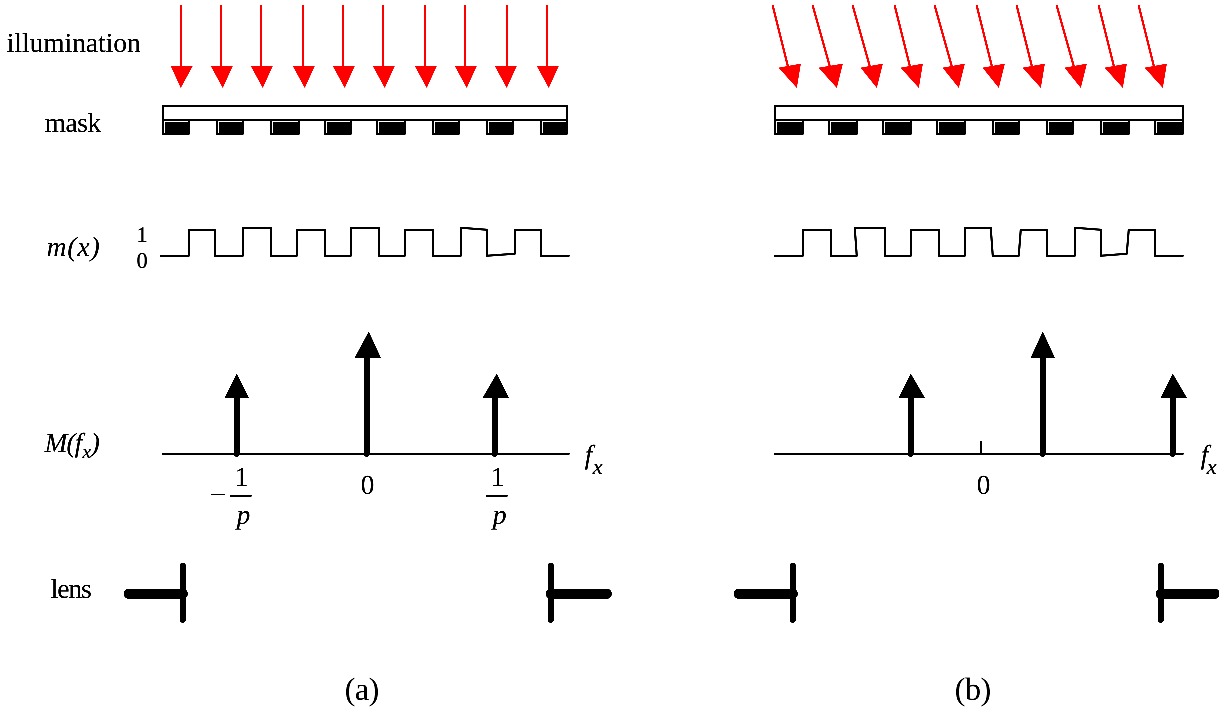

Figure 2. Off-axis illumination modifies the conventional imaging of a binary mask shown in (a) by tilting the illumination, causing a shift in the diffraction pattern as shown in (b).

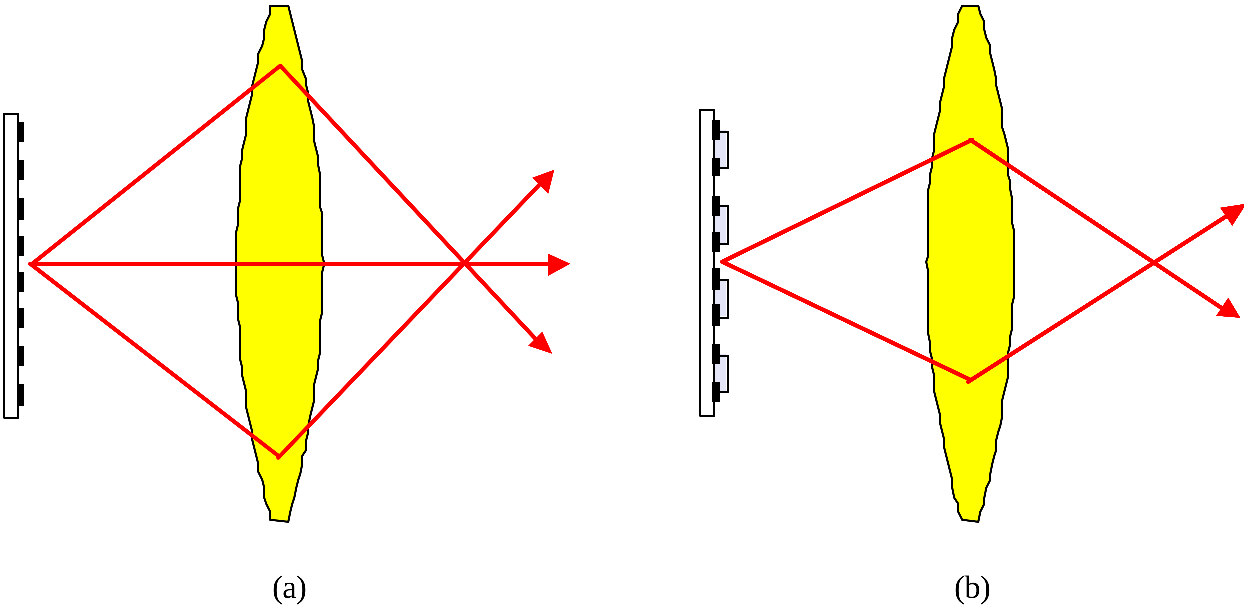
(a) (b)

Figure 3. For three beam imaging (a), propagation of the beams past the plane of best focus leads to phase differences and image degradation. For optimum two beam imaging (b), the phase difference between beams stays the same as the beams propagate, leading to extended depth of focus.