# The Formation of an Aerial Image, part 3

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In the last two issues, we described how a projection system forms an image of a mask: diffraction of light by the mask, collection of a portion of the diffracted light by the objective lens, and recombination of the diffracted light to form an image. Examining this process in more detail, the diffraction pattern is described by the Fourier Transform of the mask transmittance and is expressed in terms of spatial frequencies, which is just a scaled coordinate system in the plane of the diffraction pattern. In general, this diffraction pattern will extend throughout this plane in all directions. However, any lens of finite size will only collect a portion of this infinitely big diffraction pattern. Thinking of the entrance to the lens as an aperture which collects only the light that falls inside the aperture, light with too large a spatial frequency will not make it into the lens and thus will be lost. The radius of this lens aperture is described by its numerical aperture (*NA*), defined as the sine of the maximum half-angle of light that can pass through the aperture. Finally, the lens acts as a second Fourier Transform acting on the portion of the diffraction pattern entering the aperture. The result is an image of the mask, degraded due to the lost information of the high frequency portion of the diffraction pattern.

Although we have built up a basic knowledge of how an image is formed, there is one important piece still missing: how does defocus affect the aerial image? Over the last several years, depth-of-focus (DOF) has become a limiting factor in our ability to push optical lithography to smaller and smaller geometries. Why do smaller features have less DOF than larger features? Can we quantify the effects of defocus? What can be done about it? Before answering these and other questions, we must first gain a solid understanding of how defocus affects the imaging process.

Consider a perfect spherical wave converging (i.e., focusing) down to a point. An ideal projection system would create such a wave coming out of the lens aperture (called the *exit pupil*), as shown in Figure 1a. If the wafer to be printed were placed in the same plane as the focal point of this wave, we would say that the wafer was in focus. What happens if the wafer were removed from this plane by some distance $\delta$, called the defocus distance? Figure 1b shows such a situation. The spherical wave with the solid line represents the actual wave focused to a point a distance $\delta$ away from the wafer. If, however, the wave had a different shape, as given by the dotted curve, then the wafer would be in focus. Note that the only difference between these two different waves is the radius of curvature. Since the dotted curve is the wavefront we want for the given wafer position, we can say that the actual wavefront is in error because it does not focus where the wafer is located. (This is just a variation of "the customer is always right" attitude - the wafer is always right, it is the optical wavefront that is out of focus.)

By viewing the actual wavefront as having an error in curvature relative to the desired wavefront (i.e., the one that focuses on the wafer), we can quantify the effect of defocus. Looking at Figure 1b, it is apparent that the distance from the desired to the "defocused" wavefront goes from zero at the center of the exit pupil and increases as we approach the edge of the pupil. This distance between wavefronts is called the *optical path difference* (OPD). The OPD is a function of the defocus distance and the position within the pupil and can be obtained from the geometry shown in Figure 2. (The following description necessarily becomes a bit mathematical, but the results are worth the effort.) Describing the position within the exit pupil by an angle $\theta$, the optical path difference is given by

$$OPD = \delta(1 - \cos\theta)$$

As we have seen before, the spatial frequency and the numerical aperture define positions within the pupil as the sine of an angle. Thus, the above expression for optical path difference would be much more useful if expressed as a function of $\sin\theta$:

$$OPD = \delta(1 - \cos\theta) = \tfrac{1}{2}\delta\left(\sin^2\theta + \frac{\sin^4\theta}{4} + \frac{\sin^6\theta}{8} + \ldots\right) \approx \tfrac{1}{2}\delta\sin^2\theta$$

where the final approximation is true for relatively small angles.

So how does this optical path difference affect the formation of an image? For light, the path length traveled is equivalent to a change in phase. Thus, the OPD can be expressed as a phase error, $\phi$, due to defocus:

$$\phi = k\,OPD = \pi\delta\sin^2\theta / \lambda$$

where $k = 2\pi/\lambda$ = the *propagation constant*. We are now ready to see how defocus affects the diffraction pattern and the resulting image. Our interpretation of defocus is that it causes a phase error as a function of radial position within the aperture. Light in the center of the aperture has no error, light at the edge of the aperture has the greatest phase error. This is very important when we remember what a diffraction pattern looks like as it enters the lens aperture. Figure 3 shows such a diffraction pattern for the simple case of equal lines and spaces. Recall that diffraction by periodic patterns results in discrete diffraction orders: the zero order is the undiffracted light passing through the center of the lens, higher orders contain information necessary to reconstruct the image. In this case, only the zero and the ±1 diffraction orders make it through the lens. *Thus, the effect of defocus is to add a phase error to the higher order diffracted light relative to the zero order.* When the lens recombines these orders to form an image, this phase error will result in a degraded image.

With this basic understanding of how defocus affects the diffraction pattern, we can now explore one of the most important aspects of high resolution imaging: how depth-of-focus changes with feature size. Recall that the position of the diffraction orders within the aperture varies inversely with the pitch of the pattern being printed. In fact, the diffraction angle $\theta$ for the first orders is given by

$$\sin\theta = \frac{\lambda}{p}$$

where $p$ is the pitch of the equal line/space pattern. As a result, the phase error can be expressed as a function of the mask feature:

$$\phi = \pi\delta\lambda / p^2$$

A smaller line/space pitch results in a greater phase error for a given amount of defocus. Since it is the phase error which degrades the image, one would expect there to be some maximum tolerable phase error ($\phi_{max}$) equivalent to the maximum tolerable defocus (called the depth-of-focus, DOF). Thus,

$$DOF = \frac{p^2\phi_{max}}{\pi\lambda} = K\frac{p^2}{\lambda}$$

where $K$ is just a constant for a given amount of image degradation.

This result is extremely important and is the main reason for our discussion. The DOF scales as the square of the feature size being printed. If we cut our minimum feature size in half, our DOF will be reduced by a factor of four! No wonder the industry is working so hard to improve DOF as we move to smaller production linewidths. Also notice that for a given feature size, reducing the wavelength *increases* the DOF. The motivation for moving to i-line ($\lambda$=365nm) and then deep-UV ($\lambda$=248nm) is obvious. I should make clear, however, that the above equation really only applies to coherent illumination when only the zero and first diffraction orders enter the lens. In any case, it does give us a good physical understanding of the relationship of feature size and wavelength to the effects of defocus.

Next time we'll briefly look at phase-shifting masks and off-axis illumination from the limited perspective of how they relate to this discussion on focus effects and to resolution.

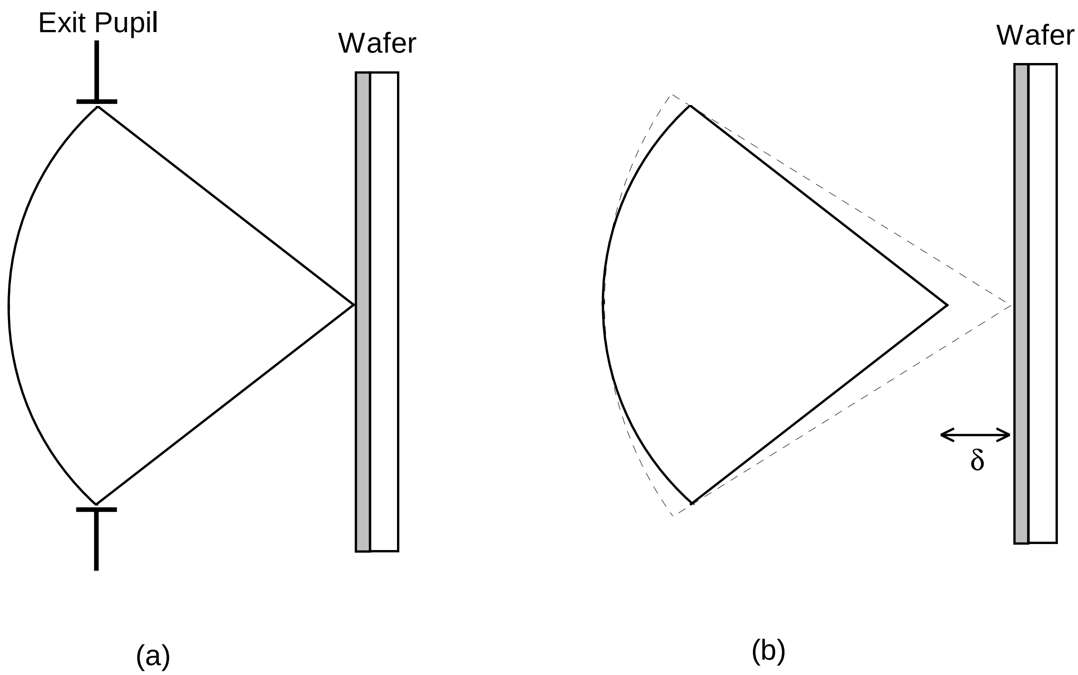


Figure 1. Focusing of light can be thought of as a converging spherical wave: a) in focus, and b) out of focus by a distance $\delta$.

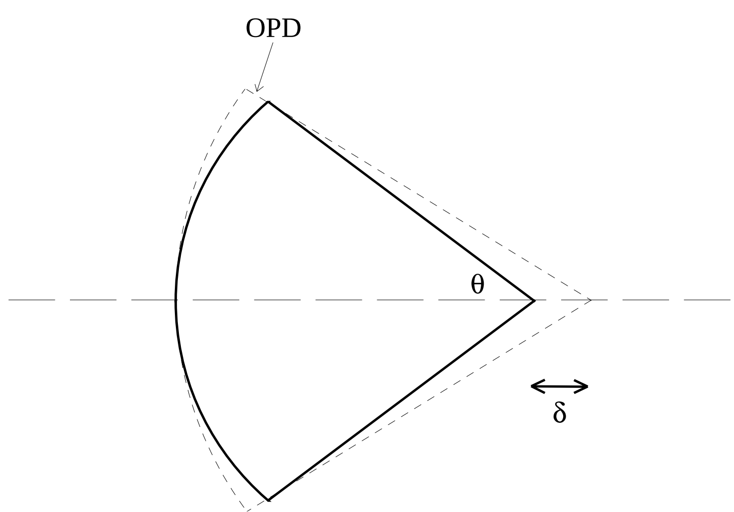


Figure 2. Geometry relating the optical path difference (OPD) to the defocus distance $\delta$ and the angle $\theta$.

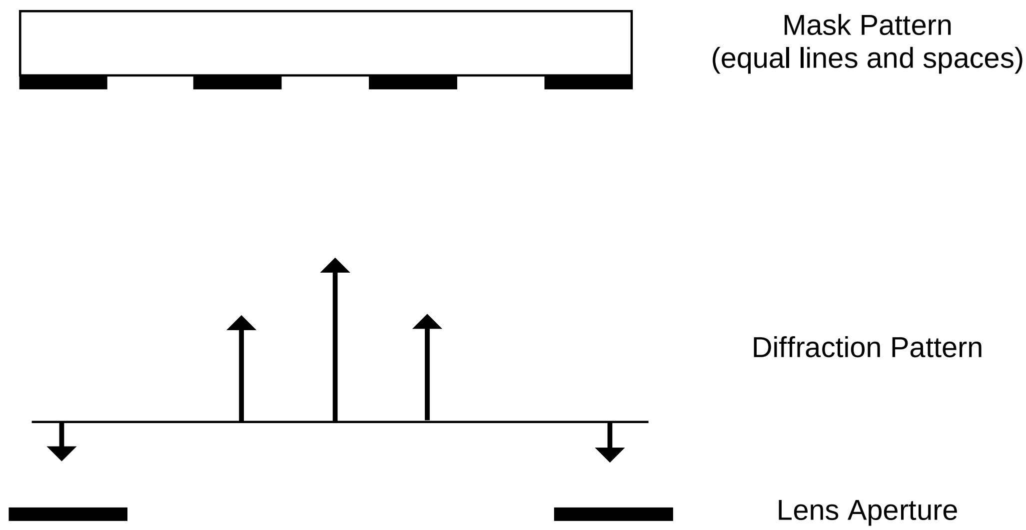


Figure 3. Typical diffraction pattern entering an objective lens aperture (assuming coherent illumination and a mask pattern of equal lines and spaces).