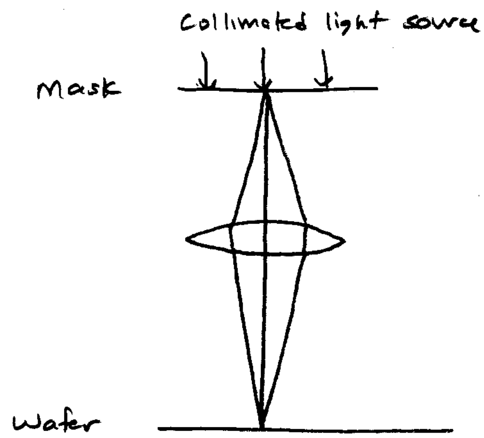
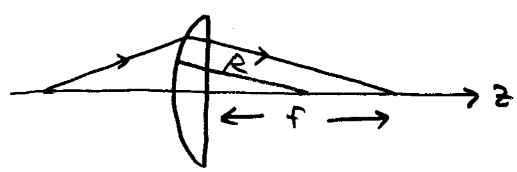
The most basic consideration in determining the resolution of a lithography system is the minimum spot size that can be produced on a wafer. The basic setup is



What is the actual intensity distribution of, say, a very small hole in the mask when projected onto the wafer?

We first need to understand how to model a lens. This can be done using Huygens' principle. For convenience, we will consider a half-spherical lens:



From basic ray optics, the focal length is

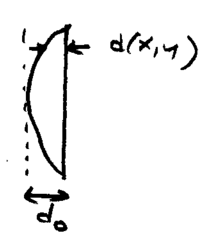
$$f = \frac{R}{n-1}$$

where $n = \sqrt{\epsilon_r}$ is the index of refraction of the lens and R is the radius of the spherical lens shape.

We want to get the aperture distribution of the fields at the exit side of the lens. The phase change across the lens is

$$e^{ik(\vec{r})z} \cong e^{ik_0(d_0 - d(x,y))}\, e^{ik_0 n d(x,y)}$$

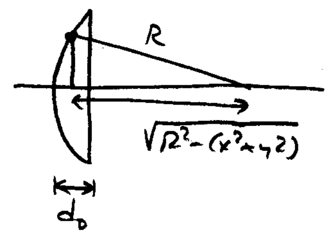
$$= e^{ik_0 d_0}\, \underbrace{e^{ik_0(n-1)d(x,y)}}$$



where we only care about the varying phase factor.

The lens thickness is

$$d(x,y) = d_o - \left(R - \sqrt{R^2-(x^2+y^2)}\right)$$
$$= d_o - R + R\sqrt{1 - \frac{(x^2+y^2)}{R^2}}$$
$$\simeq d_o - R + R - \frac{x^2+y^2}{2R}$$
$$= d_o - \frac{\rho^2}{2R}$$



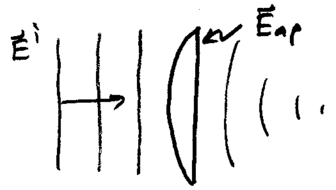
So, the phase is

$$e^{ik_o d_o}\, e^{ik_o(n-1)(d_o - \rho^2/2R)} = e^{ik_o n d}\, e^{-ik_o(n-1)\rho^2/2R}$$

$$= \underline{\underline{e^{-ik_o\rho^2/2f}}}\; e^{ik_o n d}$$

Now, we use Huygens' principle with the Fresnel approximation to get the fields radiated by the lens aperture. Let's assume that a nonuniform plane wave arrives at the lens at normal incidence:

$$\bar{E}^i = \hat{x}\, E_o(x,y)\, e^{ik_o z}$$
$$\bar{E}^a = \hat{x} E_o(x,y)\; e^{-ik_o\rho^2/2f}$$



Choosing the equivalent $\vec{J}_s = \hat{n}\times\vec{H}_{ap} = -\frac{2E_o}{\eta}\, e^{-ik_o\rho^2/2f}\,\hat{x}$, the radiated field is

$$\vec{E} = i\omega\mu \oint \bar{\bar{G}}(\vec{r},\vec{r}')\cdot\vec{J}_s(\vec{r}')\; d\vec{r}'$$

$$= i\omega\mu \int_{ap}\left[\bar{\bar{I}} + \frac{1}{k_o^2}\nabla\nabla\right]\cdot\frac{e^{ik_o|\vec{r}-\vec{r}'|}}{4\pi|\vec{r}-\vec{r}'|}\left(-\frac{2E_o}{\eta}\right) e^{-ik_o\rho'^2/2f}\,\hat{x}\; d\vec{r}'$$

$$= -2ik\int_{ap}\left[\hat{x} + \frac{1}{k_o^2}\nabla\frac{\partial}{\partial x}\right]\frac{e^{ik_o|\vec{r}-\vec{r}'|}}{4\pi|\vec{r}-\vec{r}'|}\, e^{-ik_o\rho'^2/2f}\, E_o\, d\vec{r}'$$

We will now assume a paraxial approximation:

$$|\vec{r}-\vec{r}'| = \sqrt{(x-x')^2+(y-y')^2+z^2}$$
$$= z\sqrt{1+\frac{(x-x')^2+(y-y')^2}{z^2}}$$

$$\simeq z\left(1+\frac{(x-x')^2+(y-y')^2}{2z^2}\right)$$

$$= z + \frac{(x-x')^2+(y-y')^2}{2z}$$

$$= z + \frac{x^2+y^2-2xx'-2yy'+x'^2+y'^2}{2z}$$

$$= z + \frac{\rho^2+\rho'^2-2xx'-2yy'}{2z}$$

$$= z + \frac{\rho^2}{2z} + \frac{\rho'^2}{2z} - \frac{xx'+yy'}{z}$$

So,

$$\vec{E} = \frac{-2ik}{4\pi}\int_{ap} dx'dy'\left[\hat{x}+\frac{1}{k_0^2}D\frac{\partial}{\partial x}\right]\frac{e^{ik_0z}}{z}\, e^{ik_0\rho^2/2z}\, \underbrace{e^{ik_0\rho'^2/2z}}_{\text{"Fresnel phase"}}\, e^{-ik_0(xx'+yy')/z} \times \underbrace{E_0(x,y)\, e^{-ik_0\rho'^2/2f}}_{\text{aperture phase}}$$

At the focal plane $z=f$, the aperture phase cancels the "Fresnel" term in the Green's function, and we are left with

$$\vec{E} = -2ik\int_{ap} dx'dy'\left[\hat{y}+\frac{1}{k_0^2}D\frac{\partial}{\partial x}\right]\frac{e^{ik_0z+k_0\rho^2/2z}}{z}\, e^{-ik_0(xx'+yy')/z}\, E_0(x,y)$$

$$= \frac{-2ik}{4\pi}\left[\hat{y}+\frac{1}{k_0^2}D\frac{\partial}{\partial x}\right]\frac{e^{ik_0z+k_0\rho^2/2z}}{z}\, \underbrace{\int_{ap} dx'dy'\, e^{-ik_0(xx'+yy')/z}\, E_0(x,y)}_{\text{determines radiated field distribution at } z=f}$$

This is a remarkable result. Although we only made the Fresnel (and not the Fraunhofer) approximation, the field distribution at $z=f$ is given by the Fourier transform of the distribution $E_0(x,y)$. Thus, a lens brings the far field from $r\to\infty$ to $z=f$!

Now, we can compute the distribution for a given incident field, say, $E_0(x,y)$ = constant:

$$U(x,y) = \int_{ap} dx'dy' \, e^{-ik_0(xx'+yy')/z} \quad (E_0 = 1)$$

$$= \int_0^{2\pi}\int_0^a \rho' d\rho' d\phi' \, e^{-ik_0(\rho\rho'\cos(\phi-\phi'))/z}$$

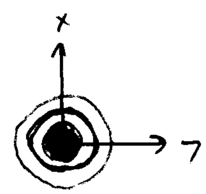
$$= \int_0^a \rho \, d\rho' \int_0^{2\pi} d\phi' \, e^{-ik_0\rho\rho'/z \, \cos\phi'}$$

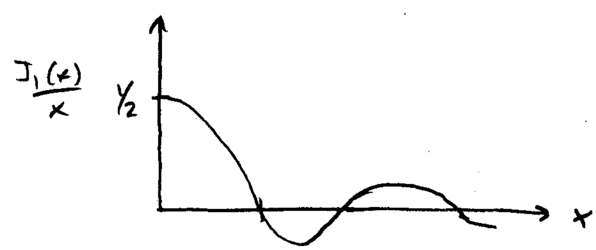
$$= \int_0^a \rho \, d\rho' \, 2\pi \, J_0(k_0\rho\rho'/z)$$

$$= 2\pi a \frac{J_1(k_0 a\rho/z)}{k_0\rho/z} \quad (z=f)$$

$$= 2\pi a \frac{J_1(k_0 a\rho/f)}{k_0\rho/f}$$

This is similar to a sinc function, but is circularly symmetric:





This distribution is called an Airy pattern.
The radius of the central lobe is at

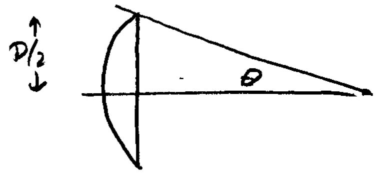
$$\frac{k_0 a \rho_s}{f} = 3.8317 \Rightarrow \rho_s = \frac{3.8317}{k_0 a} f$$

$$= \frac{3.8317 f\lambda}{2\pi a}$$

$$= \frac{3.8317}{\pi} \frac{f\lambda}{D} \quad (D = 2a)$$

$$\cong 1.22 \frac{f\lambda}{D}$$

We can rewrite this in terms of the angular extent of the lens,



$$\sin\theta = \frac{D/2}{f}$$

So that

$$\rho_s = 1.22 \frac{\frac{D/2}{\sin\theta}}{D}\lambda = \frac{1.22}{2}\frac{\lambda}{\sin\theta} = \underline{\underline{0.61\frac{\lambda}{\sin\theta}}}$$

The quantity $\sin\theta$ is called the numerical aperture (NA) of the lens. For an ideal, infinite lens, $\sin\theta = 1$, and the spot size ρ_s is minimized:

$$\rho_{s_{min}} = 0.61\,\lambda$$

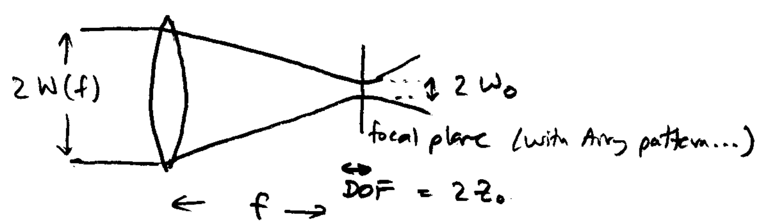
A real, finite size lens will have a spot size larger than this value.

This result, often expressed in the form

$$\rho_s = K_1 \frac{\lambda}{NA}$$

is one of the fundamental limitations on lithography. Essentially, every feature to be patterned on a wafer resist layer is convolved with an Airy pattern of central spot size given by ρ_s. This sets a resolution limit on the smallness of features.

The second fundamental limitation is depth of focus. The smaller the DOF, the more carefully alligned the mask must be:



We can estimate the DOF by modelling the wave as a Gaussian beam. If we put $z=0$ at the focal plane,

$$\frac{D}{2} = W(f) = W_0\sqrt{1+(f/z_0)^2}$$

So,

$$W_0 = \frac{D/2}{\sqrt{1+(f/z_0)^2}} \approx \frac{D/2}{f/z_0} = \frac{z_0 D}{2f}$$

The beam waist is

$$w_0 = \sqrt{\frac{\lambda z_0}{\pi}}$$

Solving for z_0,

$$z_0 = \frac{2f}{D} w_0 = \frac{2f}{D} \sqrt{\frac{\lambda}{\pi} z_0}$$

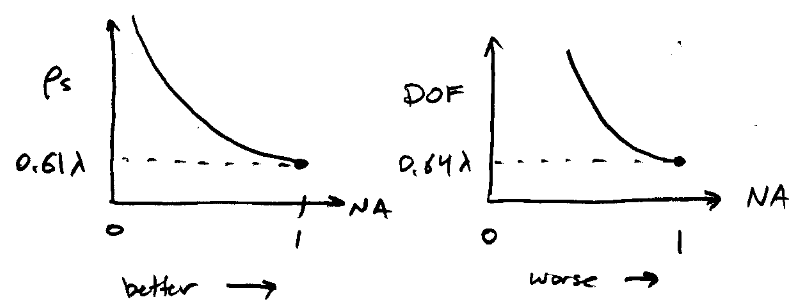
$$\sqrt{z_0} = \frac{2f}{D} \sqrt{\frac{\lambda}{\pi}}$$

$$z_0 = \frac{4f^2}{D^2} \frac{\lambda}{\pi}$$

Using $NA = D/2f$,

$$DOF = 2 z_0 = \frac{8 f^2}{4 f^2 NA^2} \frac{\lambda}{\pi} = \frac{2}{\pi} \frac{\lambda}{NA^2} \simeq 0.64 \frac{\lambda}{NA^2}$$

If we increase the lens aperture, resolution gets better, but the DOF decreases:



In practice, DOF limits the NA to be below, say, 0.85.

The basic approach to improving resolution is to increase the frequency of operation, so that λ becomes smaller. If this is done, ρ_s does decrease, but the DOF also gets smaller.

Some current and proposed methods for improving resolution are,

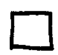
- Move to excimer lasers with $\lambda = 248$ nm, 193 nm, etc, or x-ray sources with ever smaller wavelength.

- High contrast resists with nonlinear response:

  Intensity:  threshold → resist response: 

  In this way, k_1 can be made effectively smaller.

- Change mask to account for diffraction

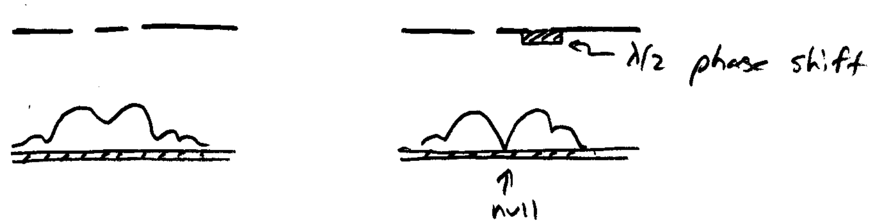
  Mask:  → image: 

   →  (sharper corners)

- off axis illumination:

  ∮ extra aperture w/o DOF penalty

- phase masks:



- Immersion: put lens and mask in a liquid to increase the index of refraction of the medium and decrease λ.