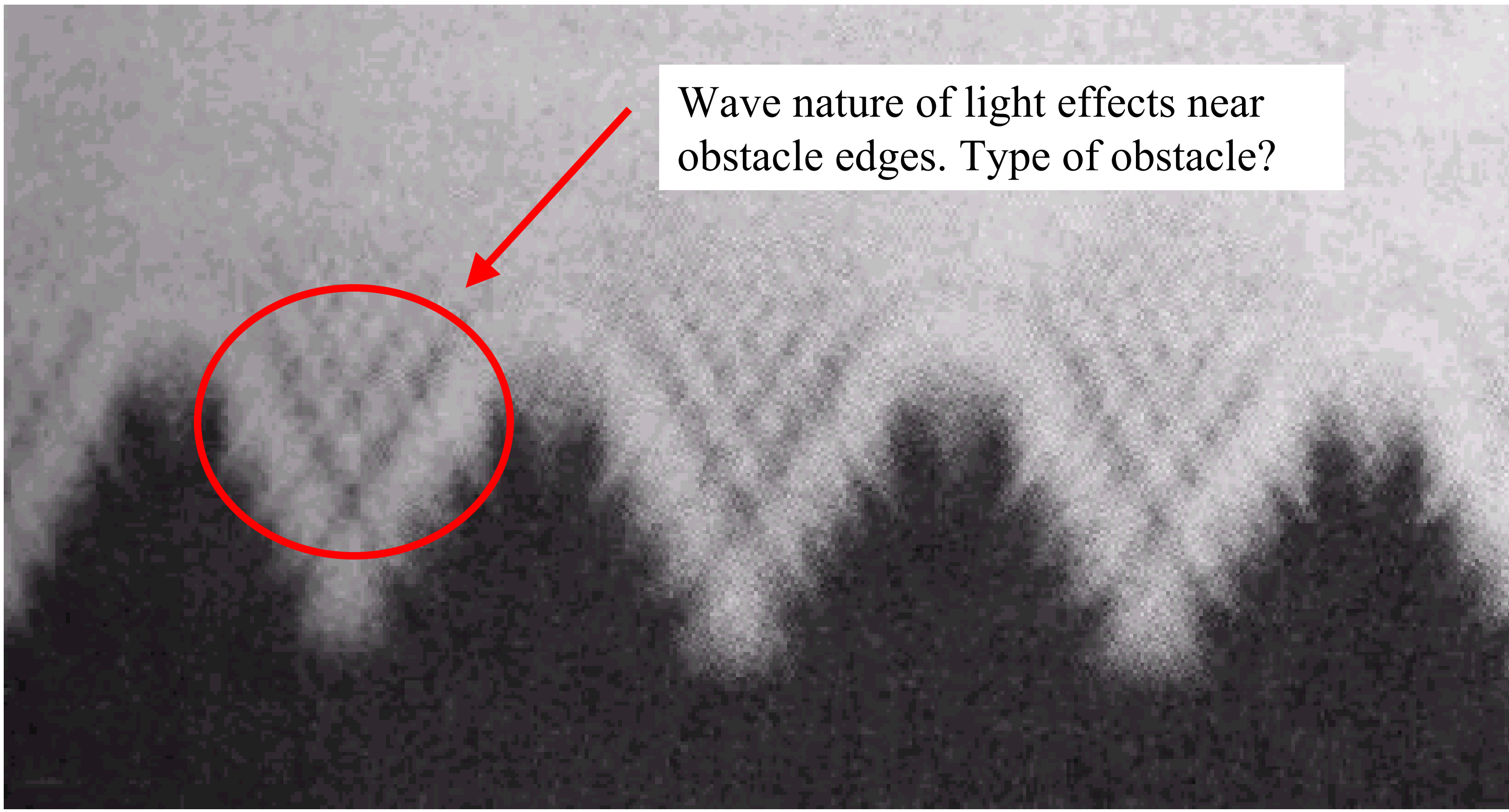
Basic Optics : Microlithography

5. Diffraction



Basic Optics : Microlithography

5. Diffraction

- **<u>Geometrical Optics:</u>** ray trace simplification for light propagation. Does not describe the propagation of diffracted waves.

- **<u>Physical Optics:</u>** Wave nature of light propagation

- **KEY IDEA: <u>Diffraction</u>** The effect of diffraction is the bending of light waves by an opaque obstacle

- **<u>Diffraction Theory</u>** describes how light propagates **.**

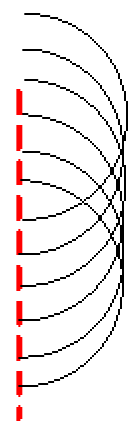
  – **Wave Optics: Huygens : extension of geometrical optics simplification. Wavefront idea: Plane or front of light with constant phase defined by many points of light creating wavelets.**

Basic Optics : Microlithography

5. Diffraction

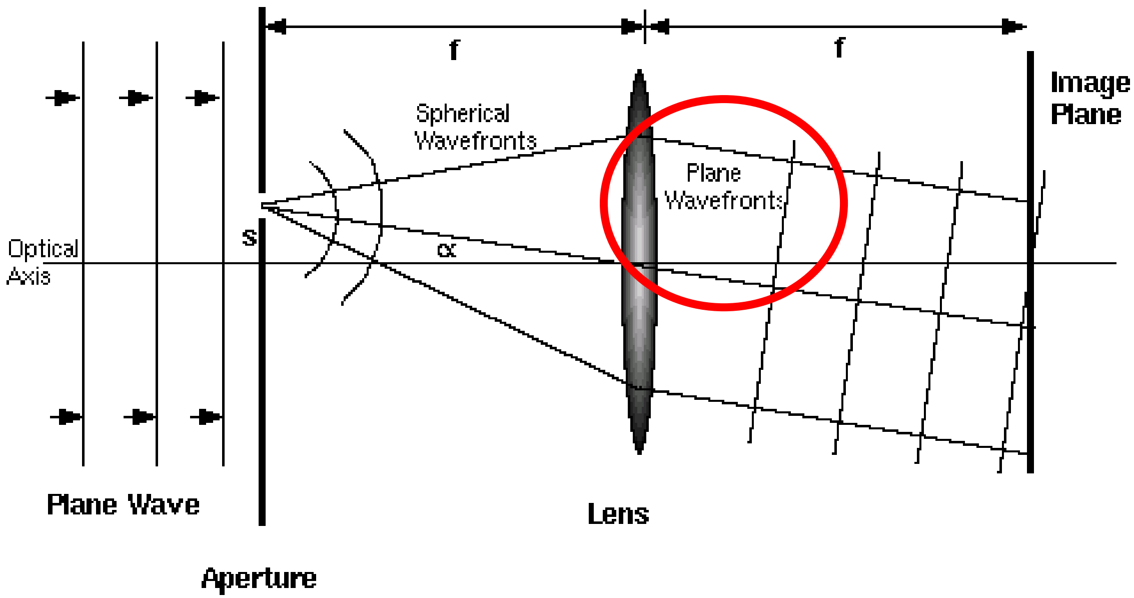
Huygens-Fresnel Principle

every unobstructed point of a wavefront, at a given instant, serves as a source of spherical secondary wavelets (same frequency as primary wave)



Basic Optics : Microlithography

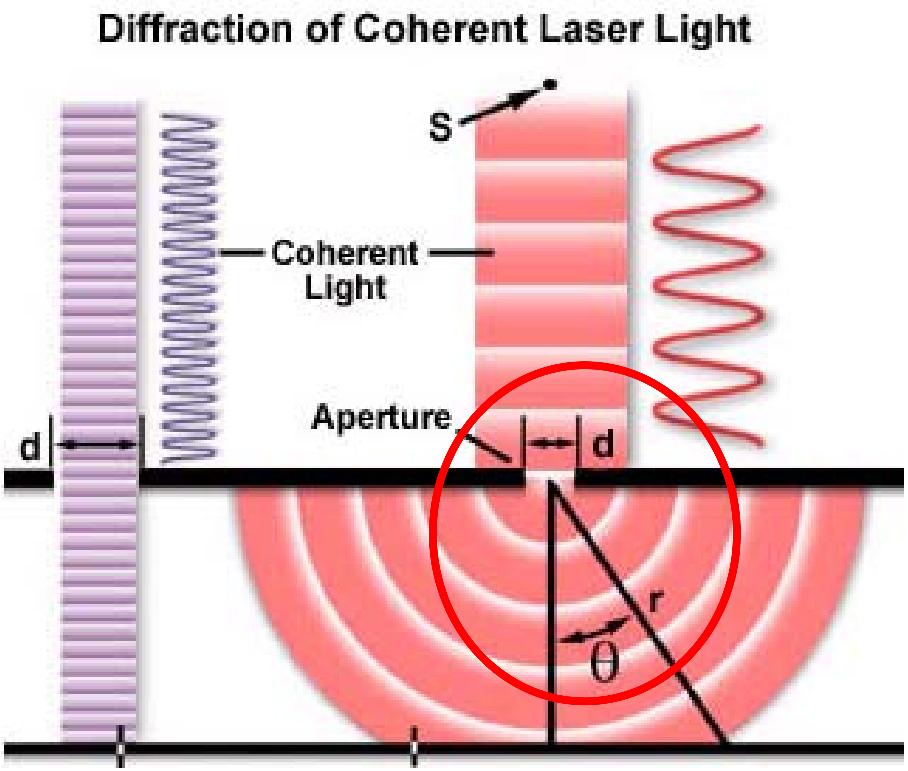
5. Diffraction: text page 112 -117 and 182-201

- **Wave optics:** The spherical wavefronts emitted by the small aperture tend towards plane wavefronts as they move further and further away from the aperture. The simple lens in this configuration directly (and exactly!) transforms the spherical waves into plane waves resulting in **Fraunhofer diffraction** at the image plane. For simplicity it is assumed that the incident light is monochromatic and that the scalar approximation is valid (ie ignore polarization effects).
- 

Basic Optics : Microlithography

5. Diffraction

- Key Ideas:
- Diffraction is bending of
- light waves when
- a barrier is encountered.
- The amount of diffraction
- (bending of the light waves
- is dependent upon the
- wavelength and the
- barriers opening size.



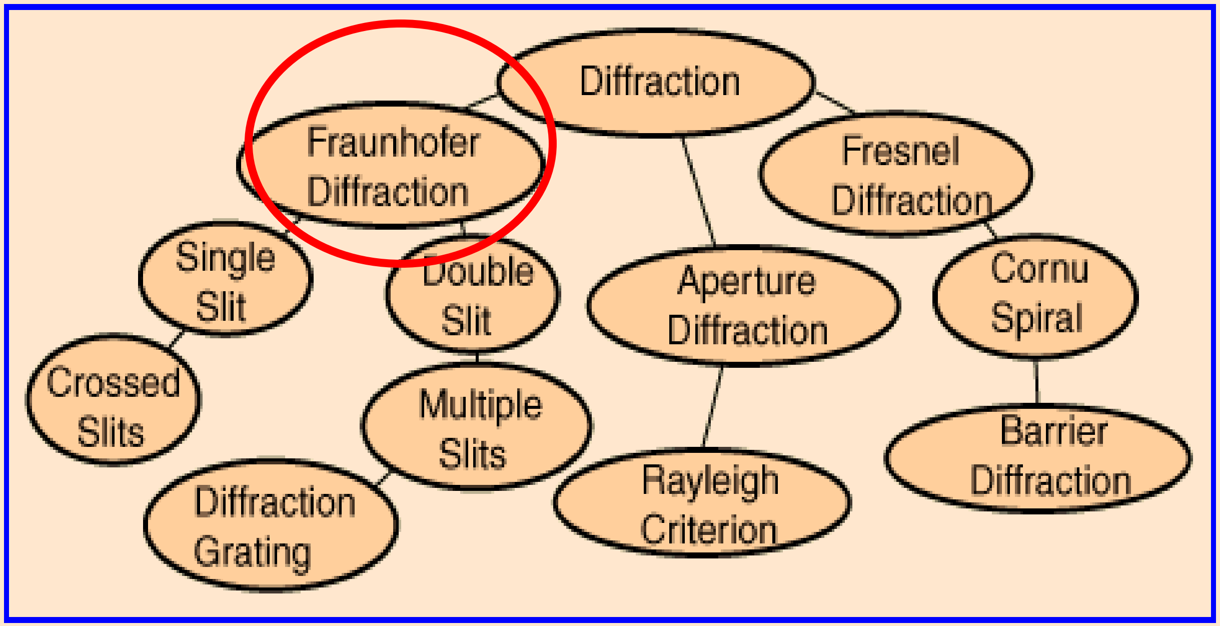
Intensity of light

Basic Optics : Microlithography

http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/diffracon.html#c1

- **5. Diffraction**

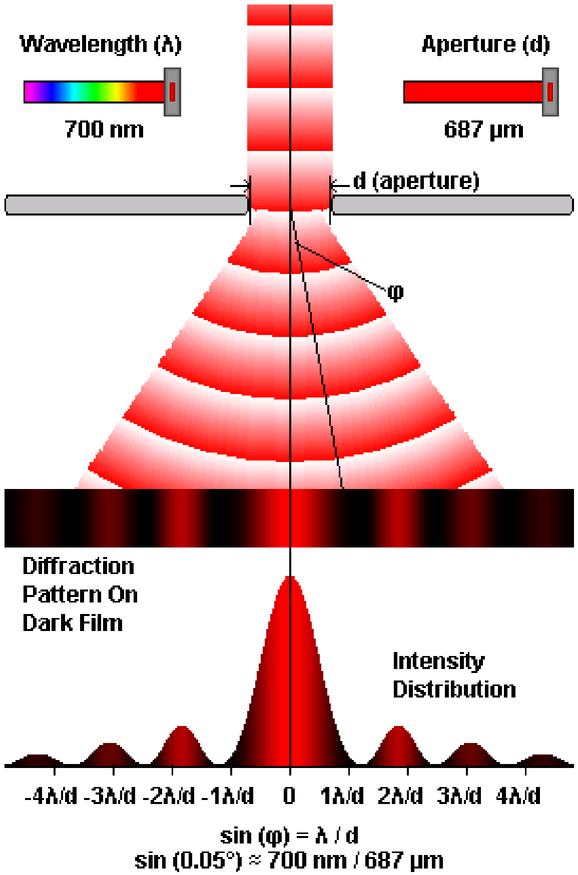
Diffraction manifests itself in the apparent bending of waves around small obstacles and the spreading out of waves past small openings.

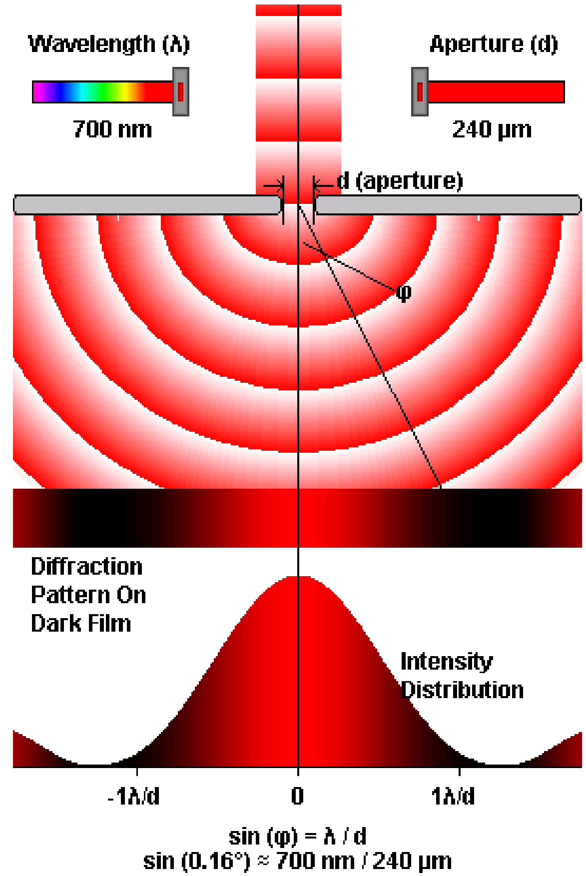


Basic Optics : Microlithography

http://micro.magnet.fsu.edu/primer/java/diffraction/index.html

- **5. Diffraction: dependence on aperture and wavelength: 700nm**

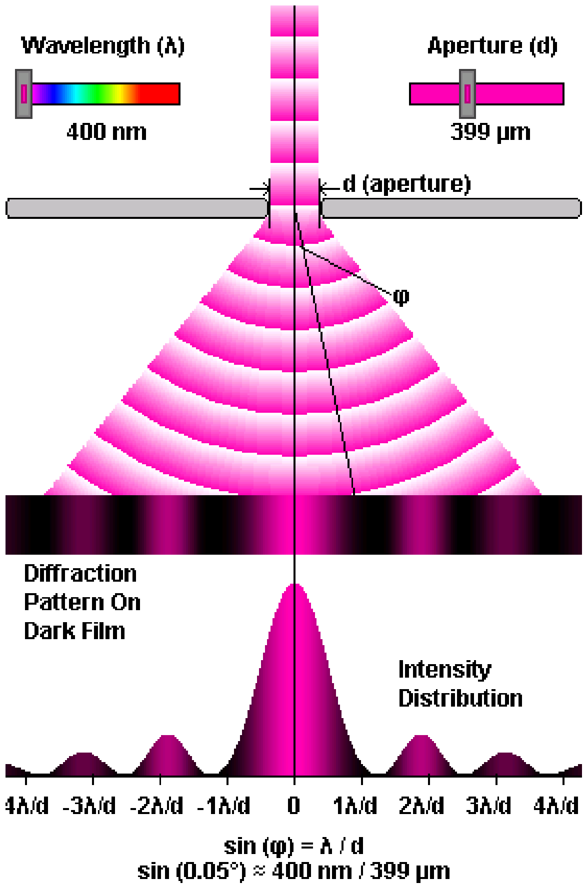


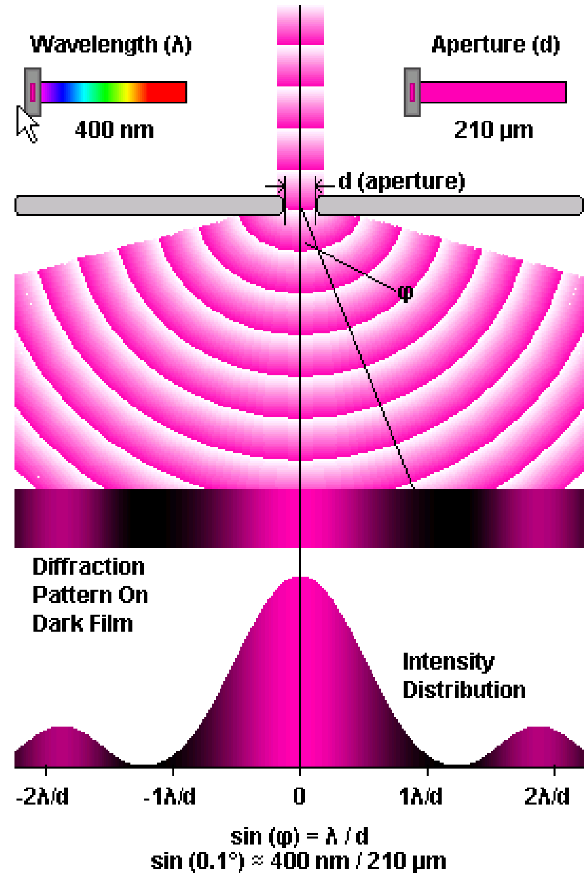


Basic Optics : Microlithography

http://micro.magnet.fsu.edu/primer/java/diffraction/index.html

- **5. Diffraction: dependence on <u>aperture and wavelength:</u> 400nm**

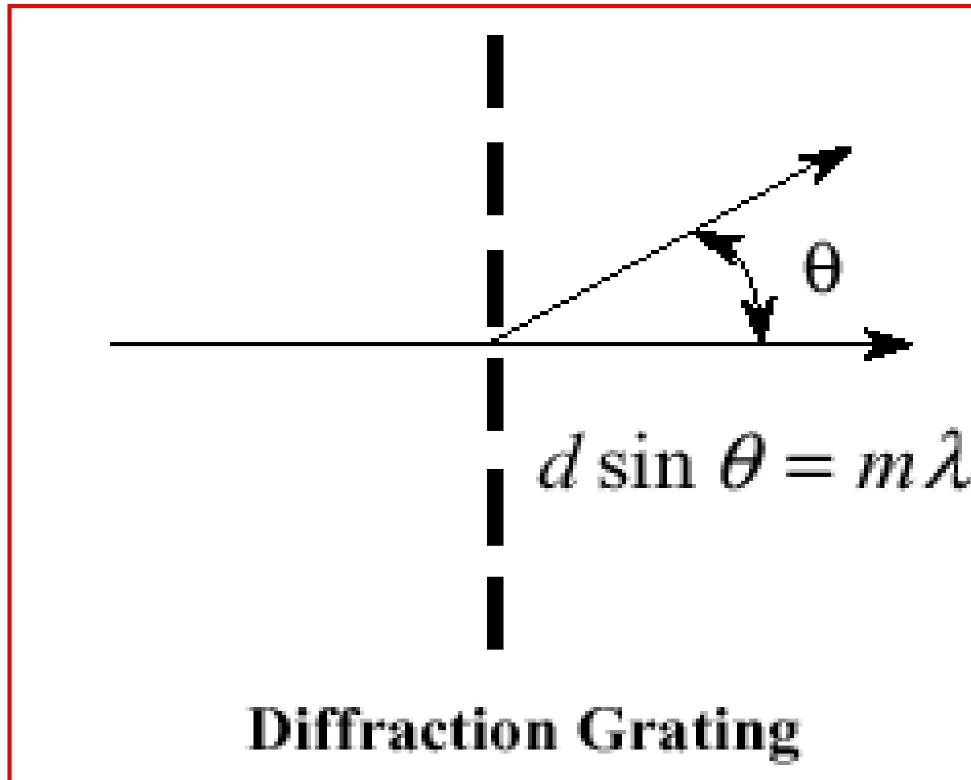




Basic Optics : Microlithography

5. Diffraction

The relationship between wavelength and slit width effect on the amount of bending



Basic Optics : Microlithography

5. Diffraction

- **Kirchoff 1882: Scalar theory : Close to object (diffracting plane). Numerical calculation**
- **<u>Fresnel Diffraction (near) </u>: Moving away from diffracting plane. This applies to Proximity printing. Numerical calculation.**
- **<u>Fraunhofer Diffraction (far)</u>: Moving away from diffracting plane. This applies to <u>Projection printing</u>. Integral calculation.**

Mask transmission function

$$t(x_1,y_1) = \begin{cases} 1 \text{ in clear areas} \\ 0 \text{ in opaque areas} \end{cases}$$

- **<u>Fraunhofer</u>**
- **<u>Diffraction</u>**
- **<u> Integral:</u>**

$$\mathcal{E}(x',y') = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} t(x_1,y_1)\, e^{-2\pi j(f_x x + f_y y)}\, dx\,dy$$

Electric Field

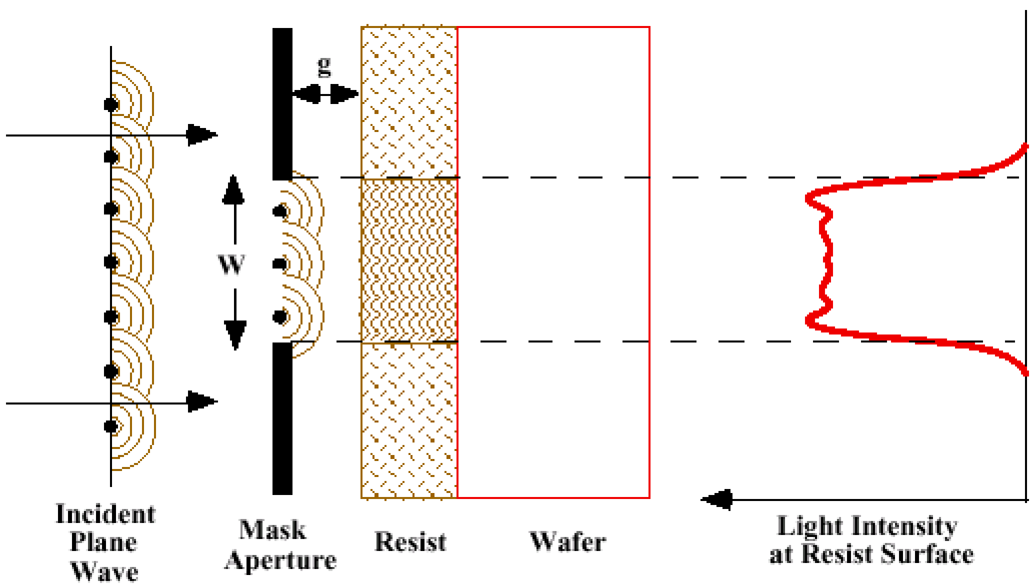
Spatial frequencies of diffraction pattern

$$f_x = \frac{x'}{z\lambda} \quad \text{and} \quad f_y = \frac{y'}{z\lambda}.$$

Basic Optics : Microlithography

5. Diffraction

- **Wave Optics: Huygens : Extension of geometrical optics simplification. Wavefront idea: Plane or front of light with constant phase defined by many points of light creating wavelets.**



Basic Optics : Microlithography

5. Diffraction

- **Diffraction Regions**
- **Slit width w illuminated by wavelength lamda λ and g is distance from mask (object) to image plane (image).**
- **Kirchoff Region: $g > \lambda/2$; $w > \lambda$**
- **<u>Fresnel Diffraction Region (near)</u> : $g >> w$**
- **<u>Fraunhofer Diffraction Region (far)</u>: $g >> \pi * w^2/\lambda$**

Basic Optics : Microlithography

5. Diffraction

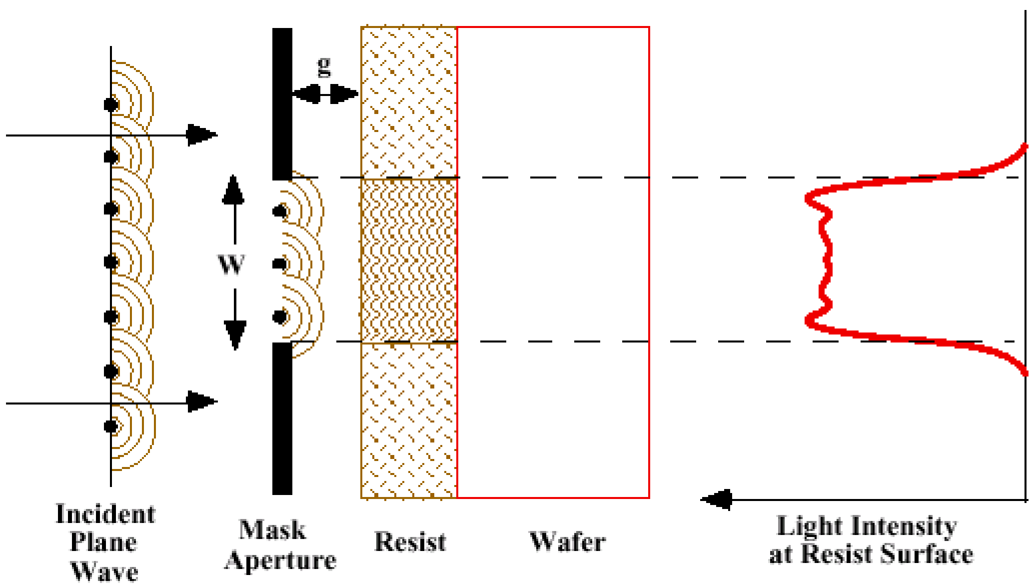
- **<u>Fresnel Diffraction (near)</u> : Moving away from diffracting plane. This applies to Proximity printing. Numerical calculation.**
- Fresnel diffraction: Light can also occur as spherical waves, which is analogous to the circular waves expanding from where we just dropped a pebble in water. A point source of light produces spherical waves. After these spherical waves pass by an obstruction, they will produce a Fresnel diffraction pattern at the screen or wall where they arrive. In general, the distance between the source and obstruction and the distance between the obstruction and the screen can be arbitrarily close, but the interesting distances are on the order of centimeters to 1 meter from a millimeter sized obstruction. Because these distances are not too far, this phenomenon is also called "near-field"

  diffraction.

Basic Optics : Microlithography

5. Fresnel Diffraction

- **Fresnel Diffraction is "near field diffraction" and applies to contact/proximity printing. i.e. z > > w (slit width)**



Basic Optics : Microlithography

5. Fresnel Diffraction

- **Fresnel Diffraction : contact or proximity printing**

  - **Fresnel diffraction applies when**

$$\lambda < g < \frac{W^2}{\lambda} \qquad (9)$$

  - **Within this range, the minimum resolvable feature size is**

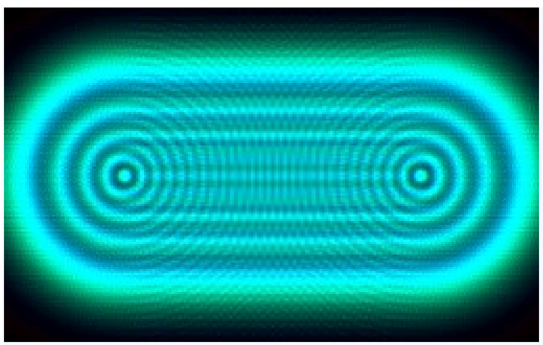
$$W_{min} \approx \sqrt{\lambda g} \qquad (10)$$

  - **Thus if $g = 10\ \mu m$ and an i-line light source is used, $W_{min} \approx 2\ \mu m$.**

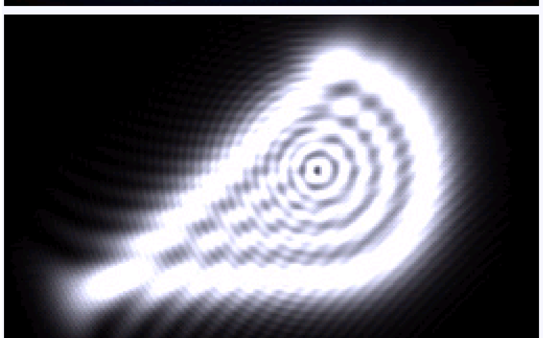
Basic Optics : Microlithography

5. Fresnel Diffraction Contact Printing

- **<u>Fresnel Diffraction (near)</u>: Patterns This happens at all edges and will cause image/photoresist artifacts!**



This was created using a racetrack-shaped hole 4 mm high, 2 m from the wall, and 20 cm from a 2441.4 nm source. The view is 8 cm wide.



This was created using a racetrack-shaped hole 4 mm high with a razor blade at 45 degrees on top, 2 m from the wall, and 20 cm from a 2247.3 nm source. The view is 8 cm wide.

Basic Optics : Microlithography

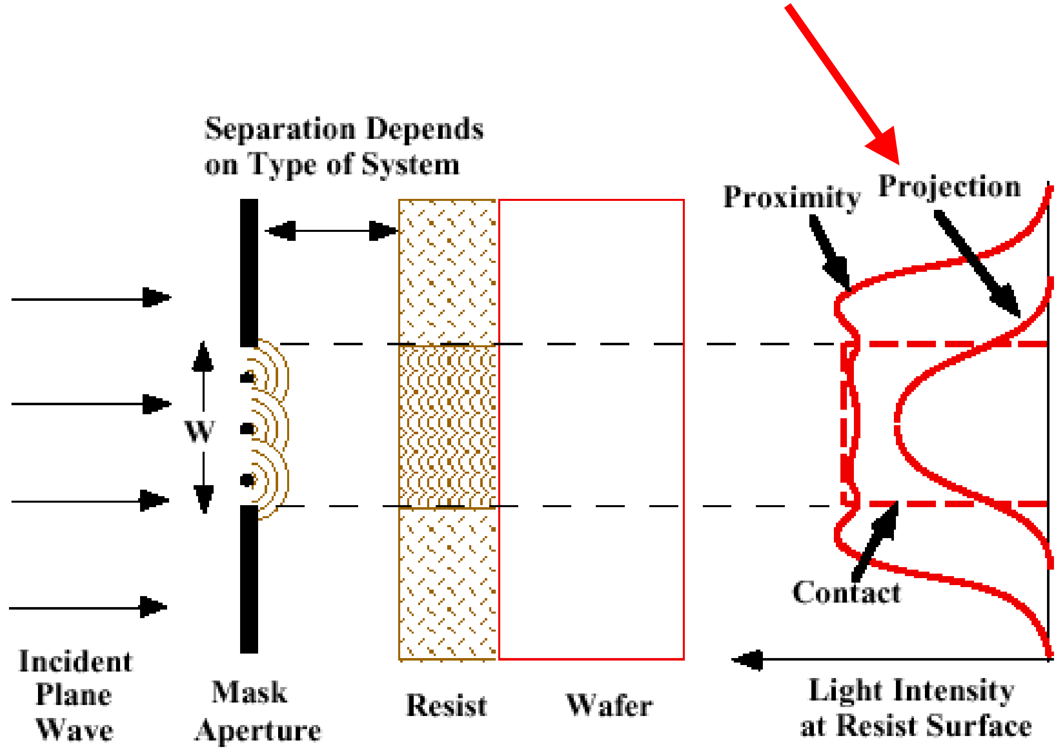
5. Fraunhofer Diffraction

- **<u>Fraunhofer Diffraction (far)</u>: Moving away from diffracting plane. This applies to Projection printing. Integral calculation.**
- Fraunhofer diffraction: Light can occur as plane waves, which we can imagine as the waves that come rolling in over the ocean. These plane waves can hit an obstruction, like when ocean waves hit a dock, and travel on in a very different pattern. At a large (compared to the size of the obstruction) distance away from the obstruction, there will be an illumination pattern of light and dark depending on the direction from the obstruction. This pattern is a Fraunhofer diffraction pattern. The (effective) source of light and the place where you're receiving the light must be relatively **_far_ from the obstruction (e.g. >1 meter from a 0.1 millimeter slit or hole),** hence the alternate name of "far-field" diffraction. These distances must be large enough so that the light that arrives and leaves the obstruction and reaches the wall or screen are nearly **<u>plane waves.</u>**

Basic Optics : Microlithography

5. Fraunhofer Diffraction

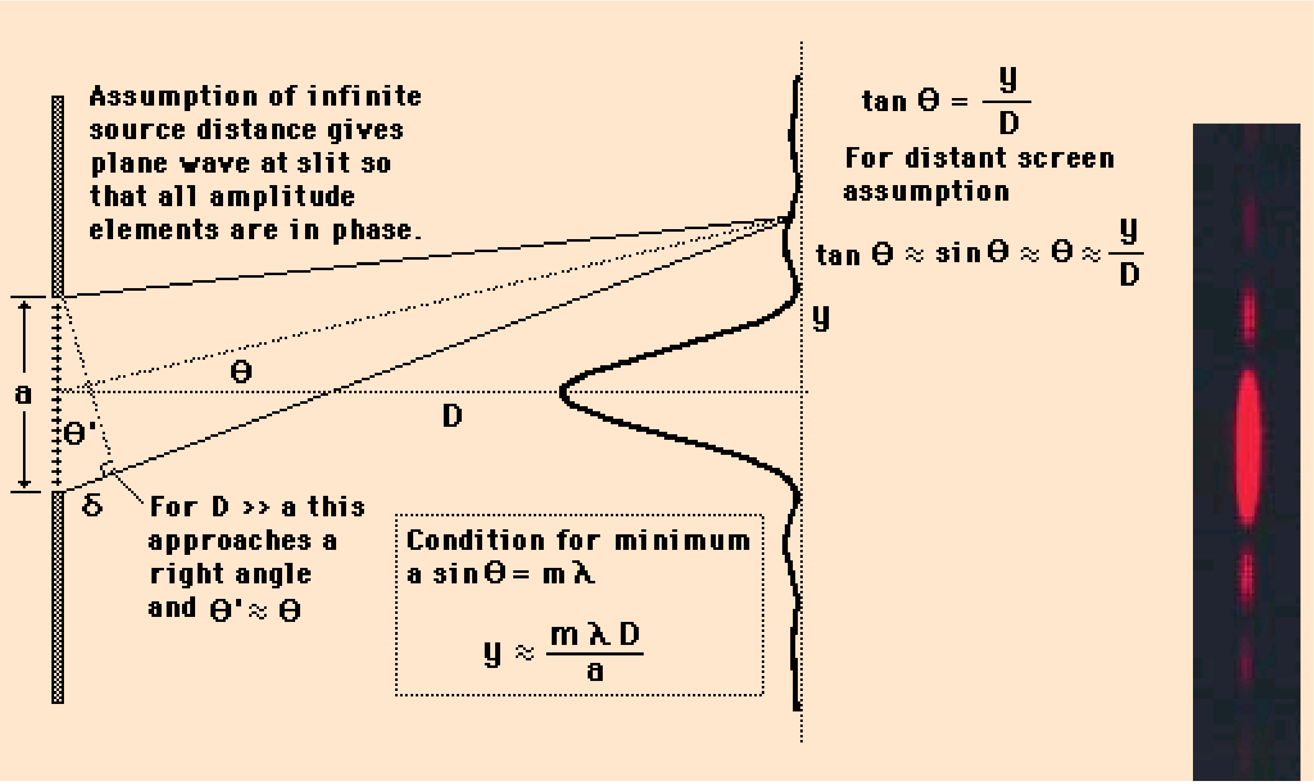
- **<u>Fraunhofer Diffraction (far)</u>: Moving away from diffracting plane.**



Basic Optics : Microlithography

5. Fraunhofer Diffraction

- **<u>Fraunhofer Diffraction (far)</u>: Note pattern!**

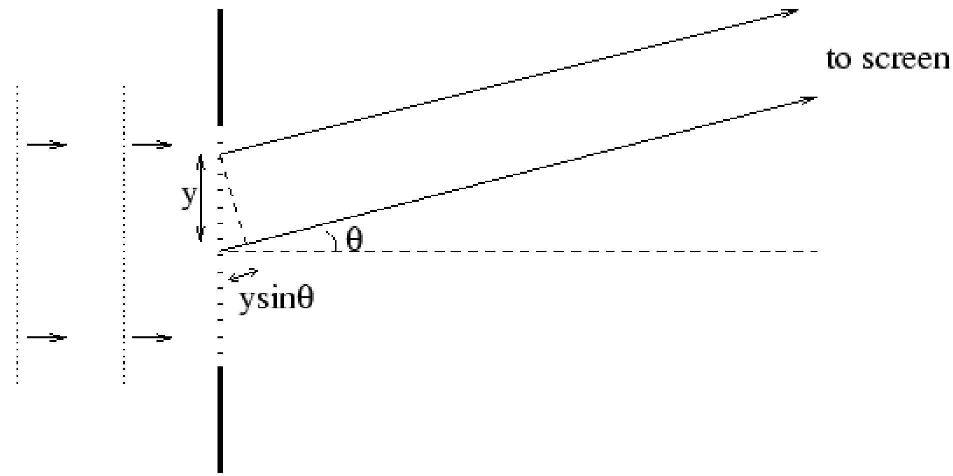


Basic Optics : Microlithography

5. Fraunhofer Diffraction

- **Fraunhofer Diffraction (far)**

- **mλ = d sinθ**
- **m = diffraction order**
- **λ = coherent illumination**
- **d = 2y = slit width**
- **θ = diffraction angle**



Basic Optics : Microlithography

5. Diffraction: Coherent illumination

An optical path length difference exists between waves traveling from the top and bottom of the aperture opening. One wave travels **D/2sinθ** farther than the other. Thus the waves from the top and bottom interfere destructively when **Dsinθ =mλ (m=+/-1, +/-2, +/-3, ….)**

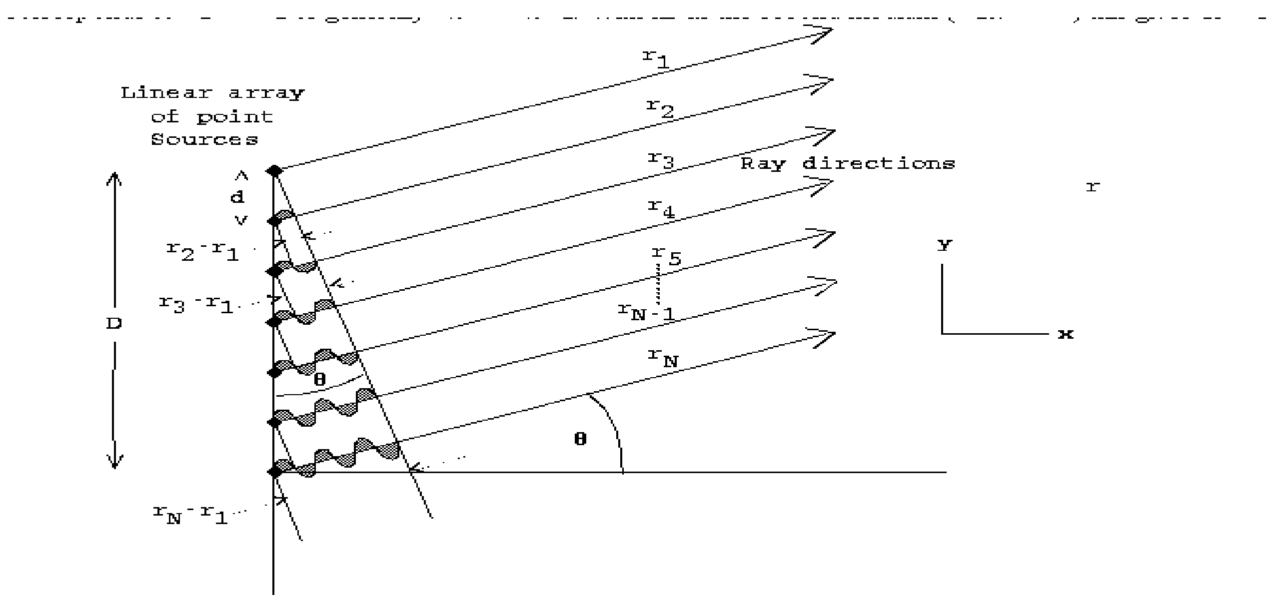


Figure 2.11: N-point sources forming a linear array of oscillators. Each oscillator emits waves which superimpose to form a diffraction pattern.

Basic Optics : Microlithography

5. Fraunhofer Diffraction

If the light from a single slit is observed very far away or at infinity something like the pattern in singleslit is seen.

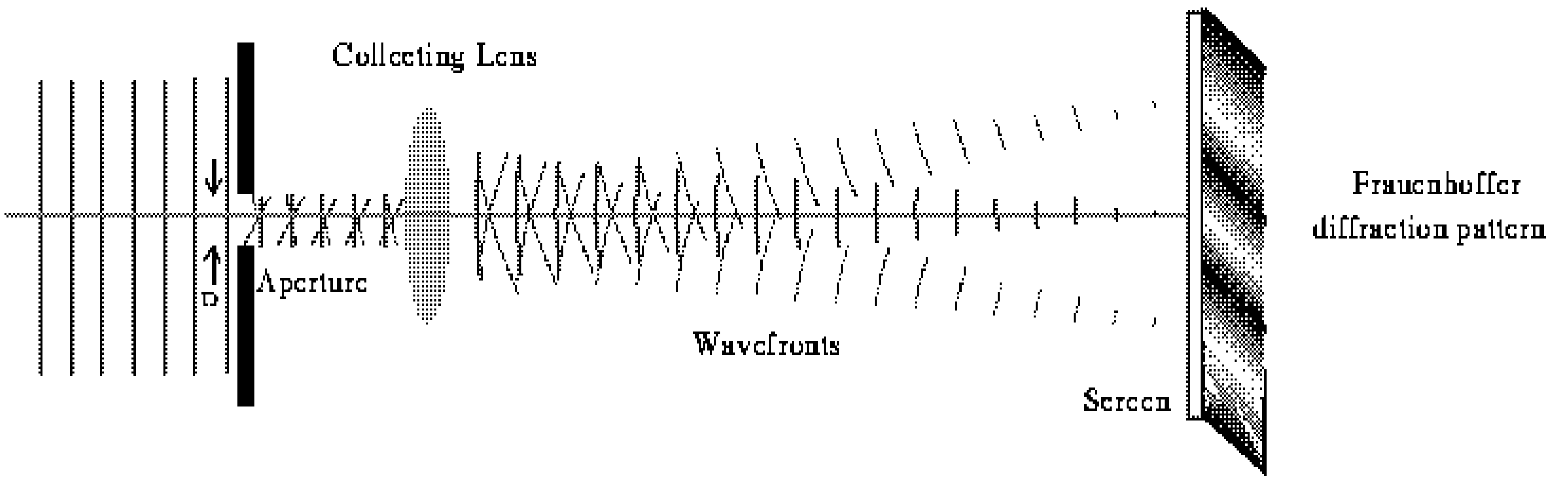
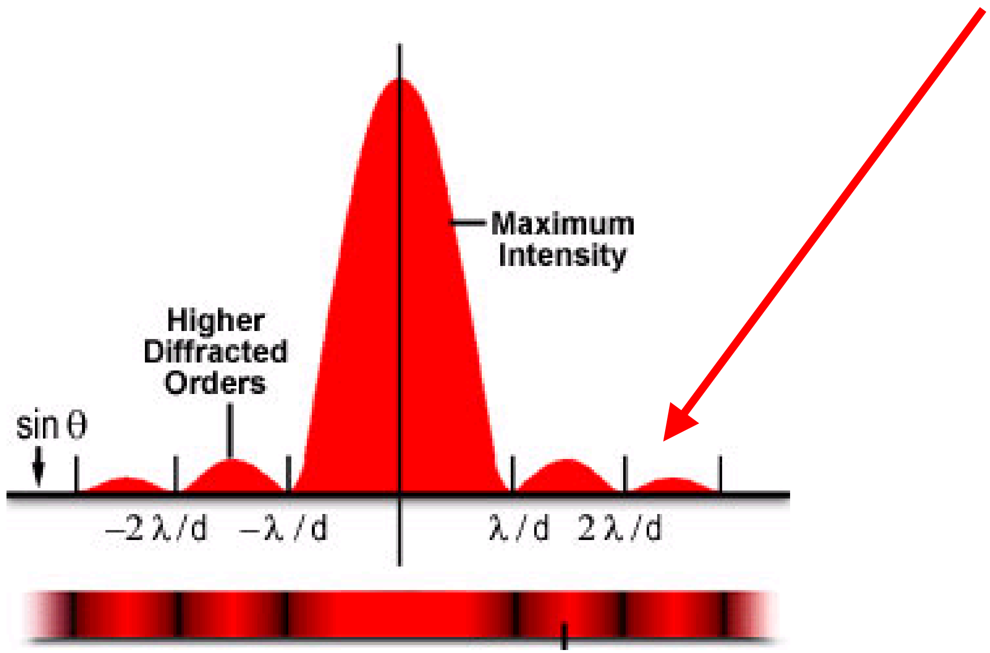


Figure 2.10: When plane waves passing through a small opening they spread out and a pattern of bright and dark lines are formed. This is the Frauenhofer diffraction pattern. The collecting lens are added to make the observation easier.

Basic Optics : Microlithography

5. Fraunhofer Diffraction

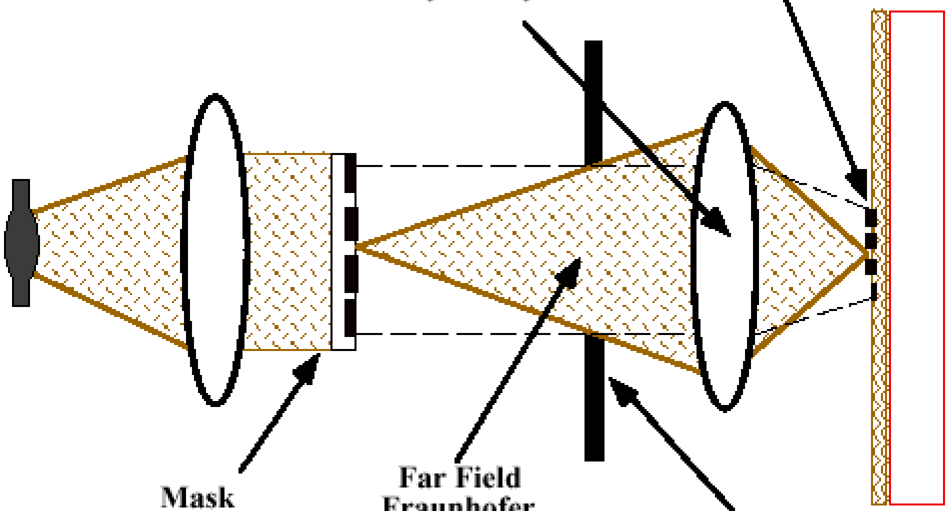
- **Fraunhofer Diffraction (far) Projection printing: diffraction pattern caused by interference of different diffracted orders.**
- **KEY Idea is that these orders will have different OPL, which means they arrive at the screen out of phase and hence "interfere".**



Basic Optics : Microlithography

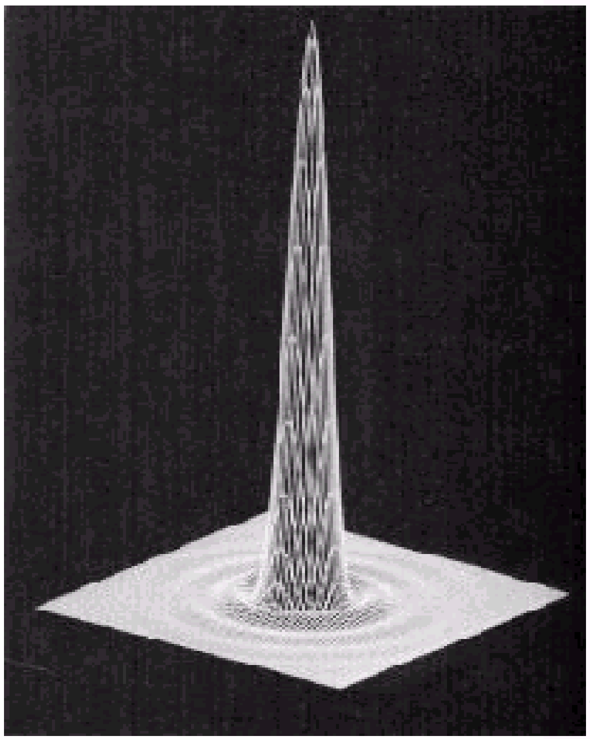
5. Fraunhofer Diffraction

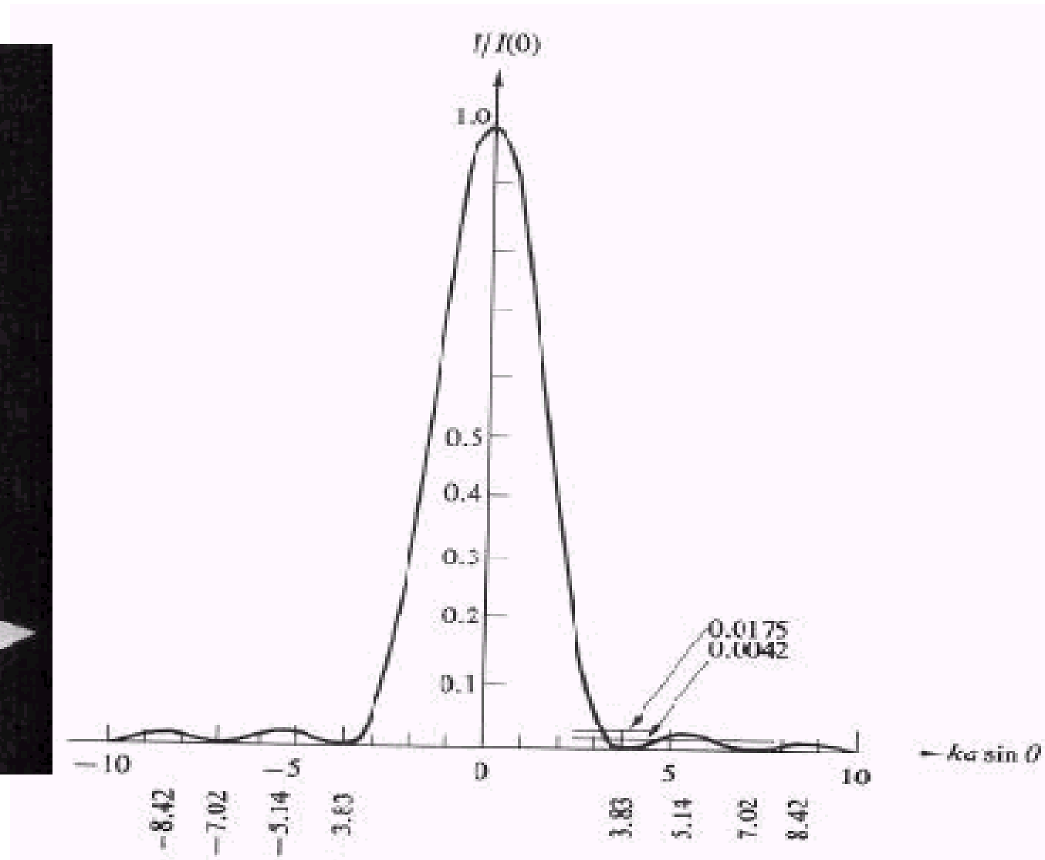
- **Fraunhofer Diffraction (far) Projection printing: Determines resolution**



Basic Optics : Microlithography

5. Diffraction: Airy Disk and NA



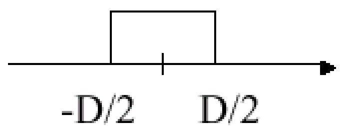


Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196

Example1: Diffraction by a slit

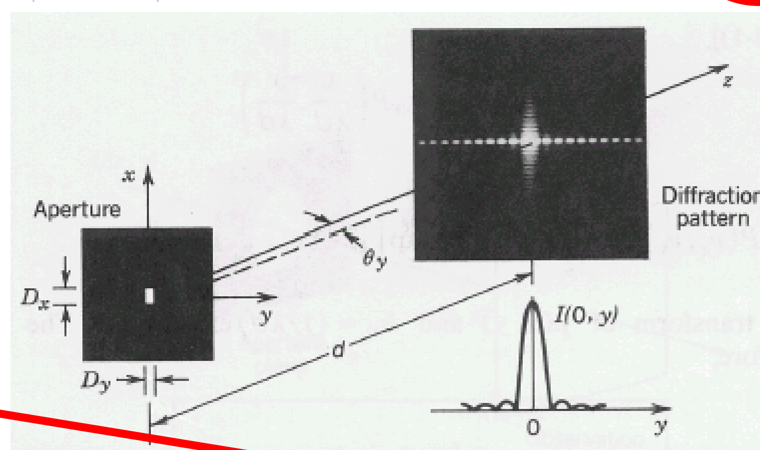
rectangular



sinc(KD/2)
= sin(KD/2)/ KD/2

Fraunhofer diffraction pattern = Fourier Transform of mask pattern

I = Aerial image intensity at image plane



$K=2\pi y/d\,\lambda \Rightarrow I = I_o \sin^2(\pi y D/d\lambda\,)/\,(\pi y D/d\lambda\,)^2$

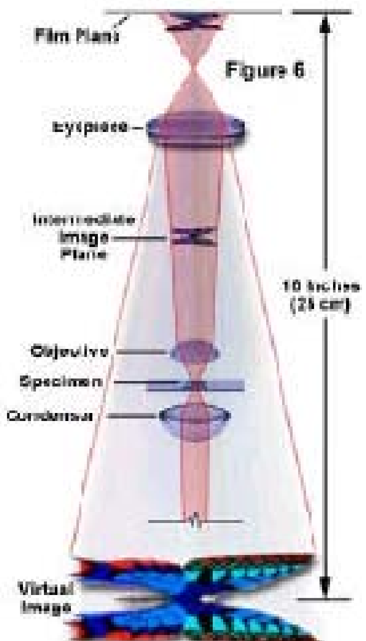
Basic Optics : Microlithography

5. Diffraction: Fourier Transform: TEXT page 188 - 196

Image formation

Image = 2D real function = $f(x,y) \propto \langle |E_o|^2(x,y) \rangle$

$E(x,y)$ = electric field = complex function



How is the information transferred ?

How can we modify the image ?

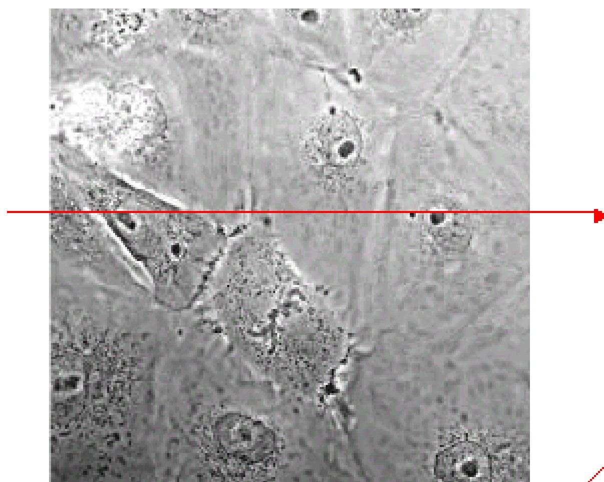
What are the limitations in the imaging process ?

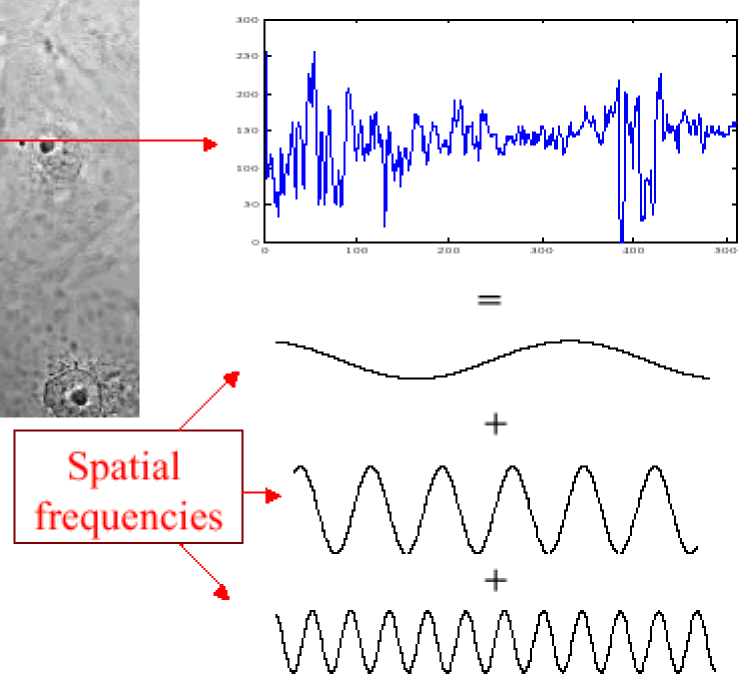
Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196

KEY IDEA: Diffracted light from any object is composed of many frequencies!

intensity profile = f(x)





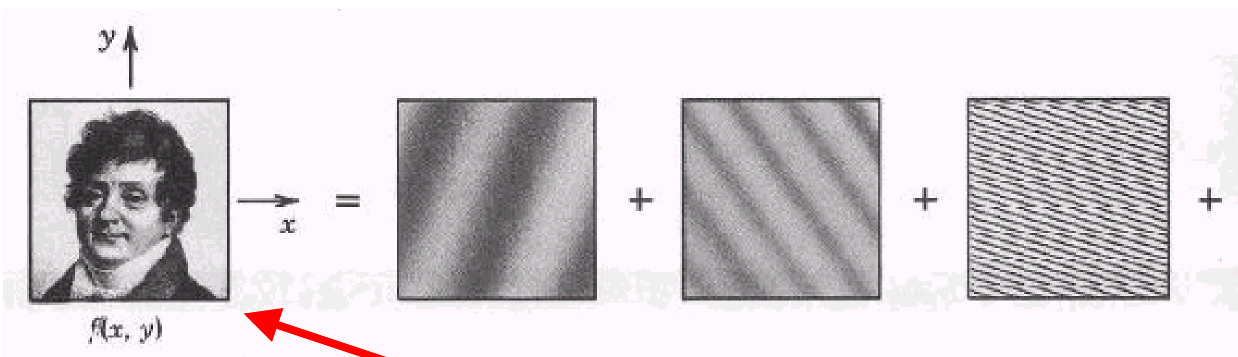
+ etc.

Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196

Fourier Transform translates dimensional (x,y) information into spatial frequency and phase information.

2D Fourier transform



Object function

Transform function

Spatial frequencies

$$F(K_x, K_y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x,y)\exp(i(K_x x + K_y y))dxdy$$

Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196 ***Image Formation***

Fraunhofer diffraction = Fourier transform of mask function

- **The mask is considered to have a digital transmission function**

$$t(x_1, y_1) = \begin{Bmatrix} 1 \text{ in clear areas} \\ 0 \text{ in opaque areas} \end{Bmatrix} \qquad (15)$$

- **After the light is diffracted, it is described by the Fraunhofer diffraction integral**

$$\mathcal{E}(x', y') = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} t(x_1, y_1) e^{-2\pi j\left(f_x x + f_y y\right)} dx dy \qquad (16)$$

where f_x and f_y are the spatial frequencies of the diffraction pattern, defined as

$$f_x = \frac{x'}{z\lambda} \quad \text{and} \quad f_y = \frac{y'}{z\lambda}.$$

Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196 ***Image Formation***

Fraunhofer diffraction = Fourier transform of mask function

- **$\mathcal{E}(x', y')$ is the Fourier transform of the mask pattern.**

$$\mathcal{E}(f_x, f_y) = F\{t(x_1, y_1)\} \qquad (17)$$

- **The light intensity is simply the square of the magnitude of the $\mathcal{E}$ field, so that**

$$I(f_x, f_y) = \left|\mathcal{E}(f_x, f_y)\right|^2 = \left|F\{t(x_1, y_1)\}\right|^2 \qquad (18)$$

Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196 ***Image Formation***

Fourier Transform: Rectangular feature Diffraction

- **The Fourier transform of t(x) is in standard texts and is the sin(x)/x function.**

- **After passing through the mask, the light is collected by the objective lens (x', y' plane).**

  - **But only a portion of the light is collected.**
  - **This is characterized by a pupil function:**

Cutoff frequency

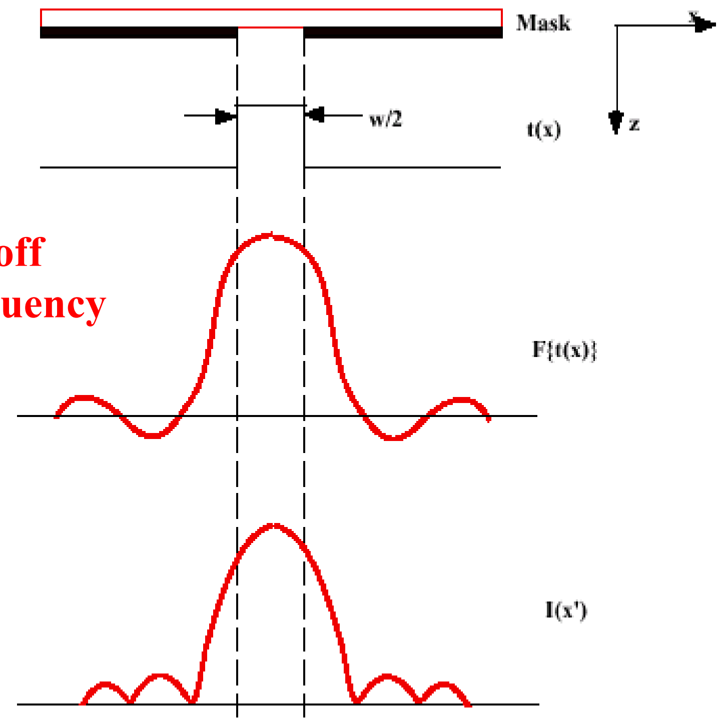
$$P(f_x, f_y) = \begin{cases} 1 \text{ if } \sqrt{f_x^2 + f_y^2} < \dfrac{NA}{\lambda} \\ 0 \text{ if } \sqrt{f_x^2 + f_y^2} > \dfrac{NA}{\lambda} \end{cases} \qquad (19)$$

  - **The objective lens now performs the inverse Fourier transform.**

$$\mathcal{E}(x,y) = F^{-1}\left\{\mathcal{E}(f_x,f_y)P(f_x,f_y)\right\} = F^{-1}\left\{F\{t(x_1,y_1)\}P(f_x,f_y)\right\} \qquad (20)$$

resulting in a light intensity at the resist surface (aerial image) given by

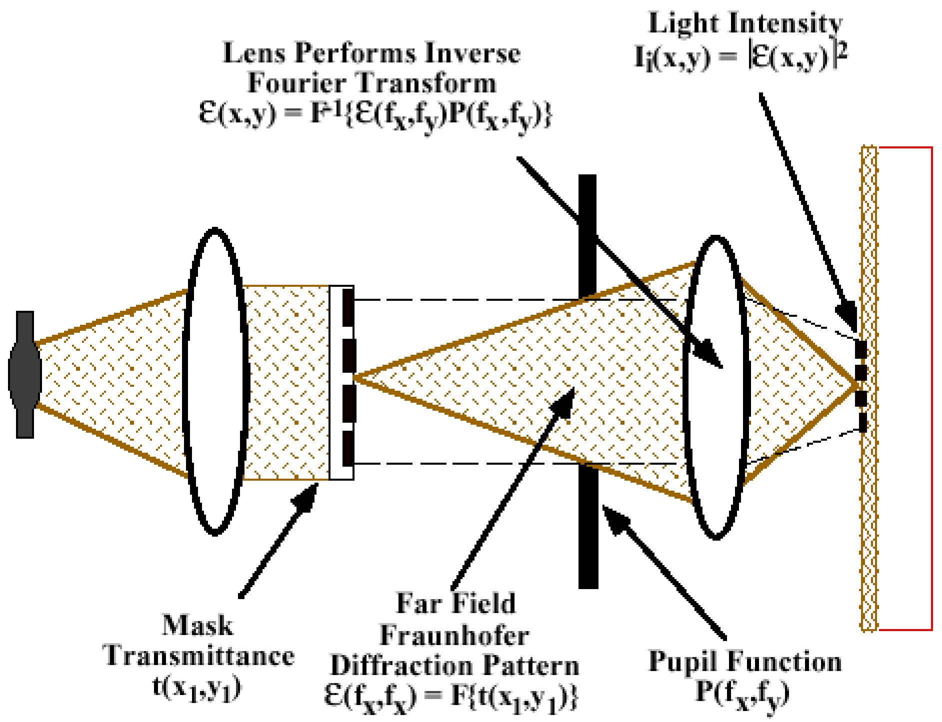
$$I_i(x,y) = |\mathcal{E}(x,y)|^2 \qquad (21)$$



Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196 ***Image Formation***

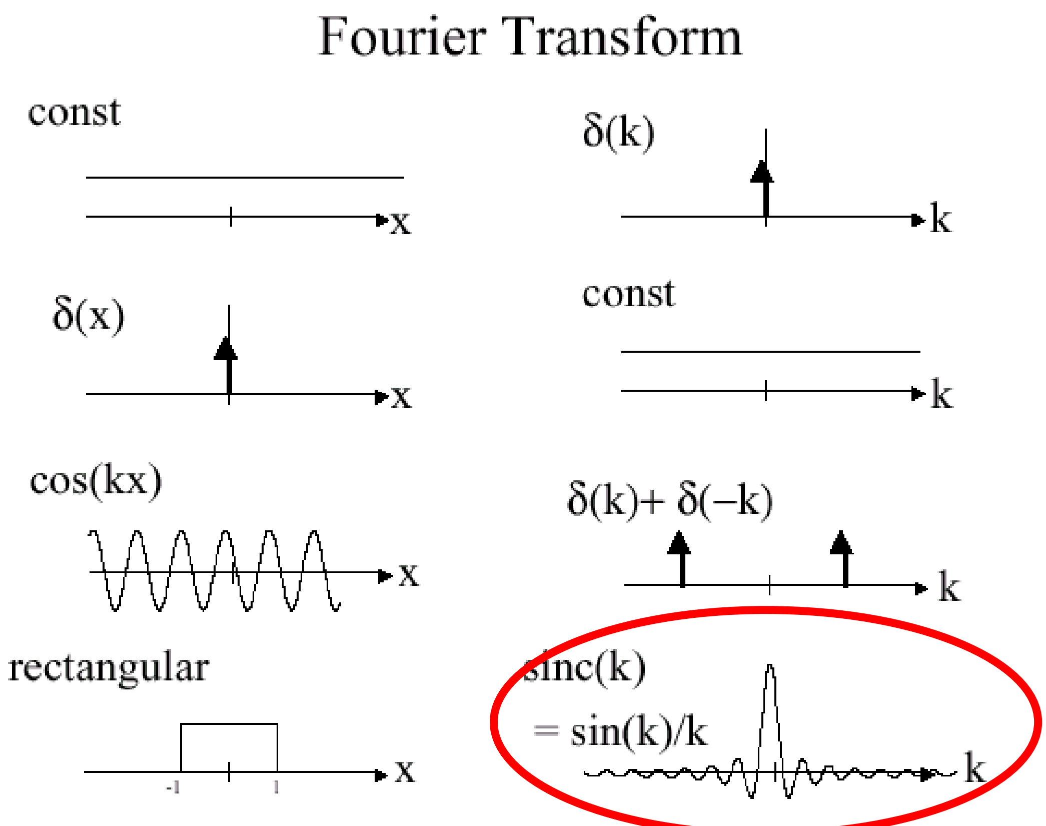
We are very fortunate to have Prolith simulator as it performs all these calculations to determine the aerial image intensity distribution!!



Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196

Some examples of Fourier Transforms



Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196

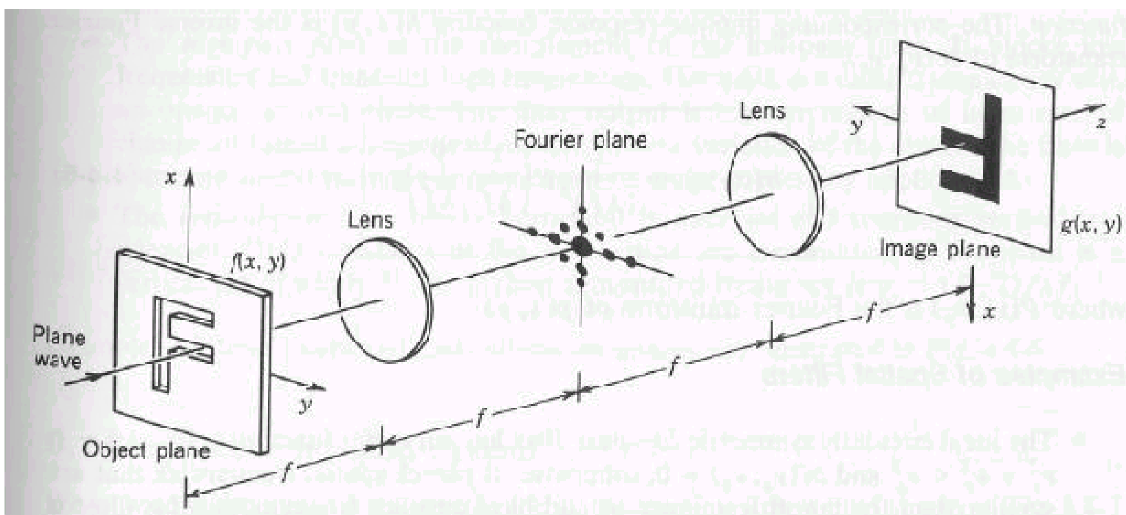
2D Fourier Transform Properties

Property	*Spatial Domain*	*Frequency Domain*
Addition theorem	$f(x, y) + g(x, y)$	$F(u, v) + G(u, v)$
Similarity theorem	$f(ax, by)$	$\frac{1}{\lvert ab \rvert} F\left(\frac{u}{a}, \frac{v}{b}\right)$
Shift theorem	$f(x - a, y - b)$	$e^{-j2\pi(au+bv)} F(u, v)$
Convolution theorem	$f(x, y) * g(x, y)$	$F(u, v) G(u, v)$
Separable product	$f(x) g(y)$	$F(u) G(v)$
Differentiation	$\left(\frac{\partial}{\partial x}\right)^m \left(\frac{\partial}{\partial y}\right)^n f(x, y)$	$(j2\pi u)^m (j2\pi v)^n F(u, v)$
Rotation	$f(x \cos\theta + y \sin\theta, -x \sin\theta + y \cos\theta)$	$F(u \cos\theta + v \sin\theta, -u \sin\theta + v \cos\theta)$
LaPlacian	$\nabla^2(x, y) = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) f(x, y)$	$-4\pi^2(u^2 + v^2) F(u, v)$
Rayleigh's theorem Parseval	$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \lvert f(x, y)\rvert^2 \, dx \, dy = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \lvert F(u, v)\rvert^2 \, du \, dv$	

Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196

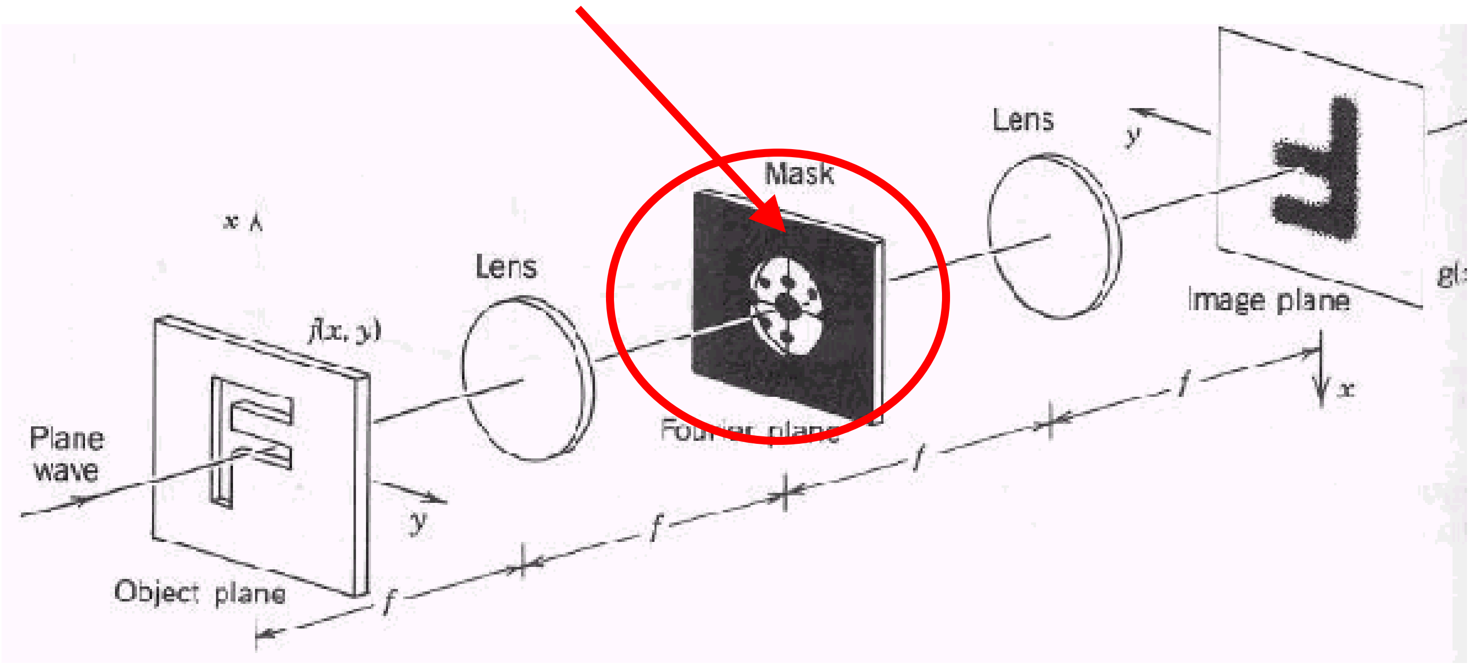
Typical setup in optical lithography projection lens: **Lens acts as band pass filter** by only accepting a portion of the diffracted light. Limited by the NA. The **Fraunhofer diffraction pattern of the mask is called the Fourier Transform** of the mask pattern. This Fourier Transform plane contains all object information: which is typically located at entrance pupil! **The lens then performs an inverse Fourier Transform on this diffraction pattern to form the image**!



Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196

Spatial filtering (filters located at the Fourier Transform plane can be used to increase image contrast! You may come across papers discussing this. We have not used this yet in main stream industry.



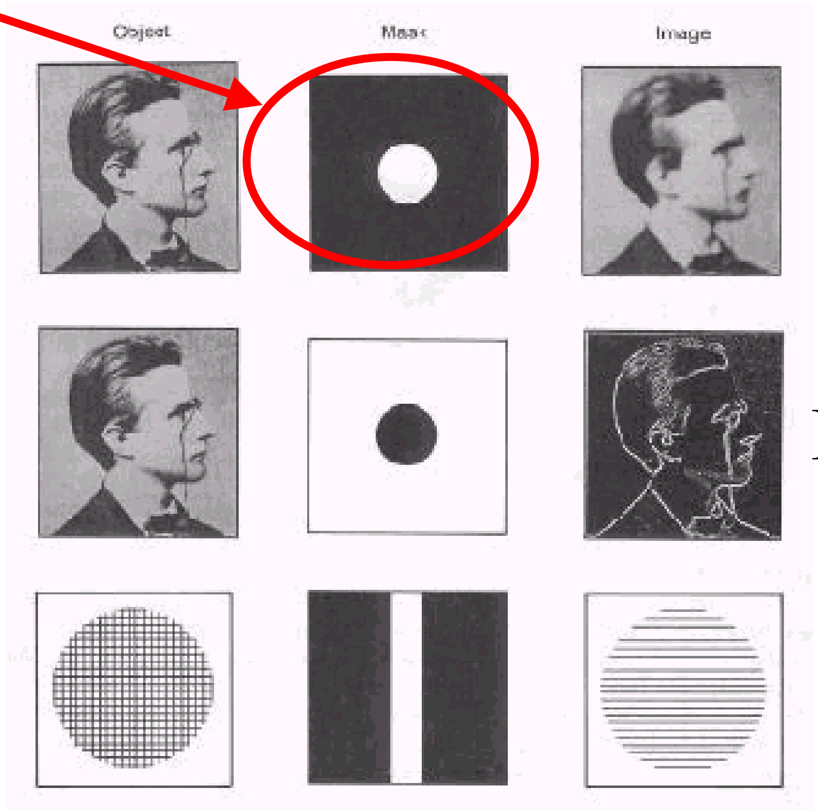
Basic Optics : Microlithography

5. Diffraction: Fourier Transform TEXT page 188-196

Classic Spatial filtering examples

Spatial filter or mask

Object



Image

Basic Optics : Microlithography

5. Diffraction:

KEY Diffraction Ideas for optical lithography

- Huygens-Fresnel Principle: every unobstructed point of a wavefront serves as a source of spherical secondary wavelets
- Diffraction is the result of the interference of these coherent wavelets
- Diffraction in the far field is the Fourier transform of the object
  - spatial frequencies $K = 2\pi \sin\theta/\lambda$

Basic Optics : Microlithography

5. Diffraction:

KEY Diffraction Ideas for optical lithography

- A lens acts as a Fourier transformer at its focal plane

Spatial filtering

- Filtering (optical image processing) can be performed in the Fourier plane
  - intensity and phase filters can be applied