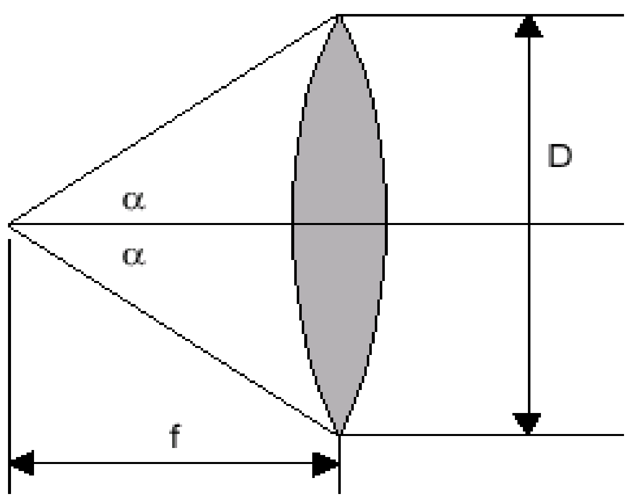
Basic Optics : Microlithography Optics Part 3

- **Numerical Aperture**
- **Resolution, Depth of Focus, and Depth of field (Text pp208-213)**
- **Partial Coherence (sigma or fill factor) (Text pp196-202)**
- **Off Axis illumination (Text pp 96-100) (Text pp235-244)**
- **MTF and Contrast (Text pp202-205) (Text pp 535)**
- **Image Formation (Text pp112-117)**
- **Optical Designs (Text pp261-268)**

Basic Optics : Microlithography

Numerical Aperture

- The f-number of a lens (f/#) is the focal length divided by the diameter. It is a measure of the light gathering ability.
- The numerical aperture (NA) of a lens is n*sin α, where α is the half-angle of the largest cone of light entering the lens.



$$f/\# = \frac{f}{D}$$

$$NA = n \sin \alpha$$

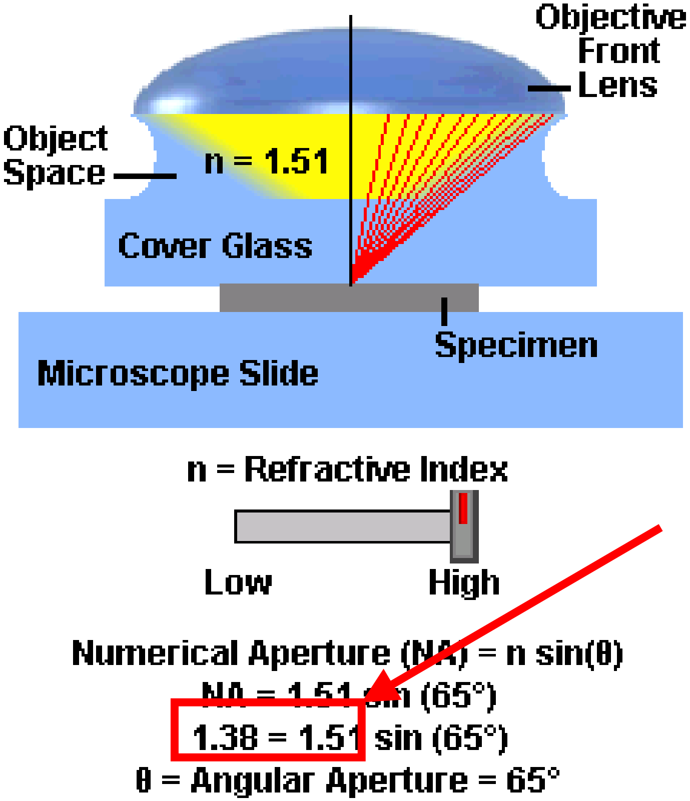
$$NA = \frac{\frac{1}{2}D}{\sqrt{\frac{1}{4}D^2 + f^2}} \approx \frac{D}{2f} = \frac{1}{2 \cdot f/\#}$$

Basic Optics : Microlithography

Numerical Aperture

http://www.microscopyu.com/tutorials/java/objectives/immersion/

- **NA = n$\sin\theta$**
- Typically n = 1.00 for air
- But you could use a higher refractive index medium to increase the effective NA!!
- This increase in NA allows one to capture higher diffracted order rays.
- This has not been done on exposure tools yet



High Refractive index medium effect:

NA is greater than 1.00!!

Basic Optics : Microlithography

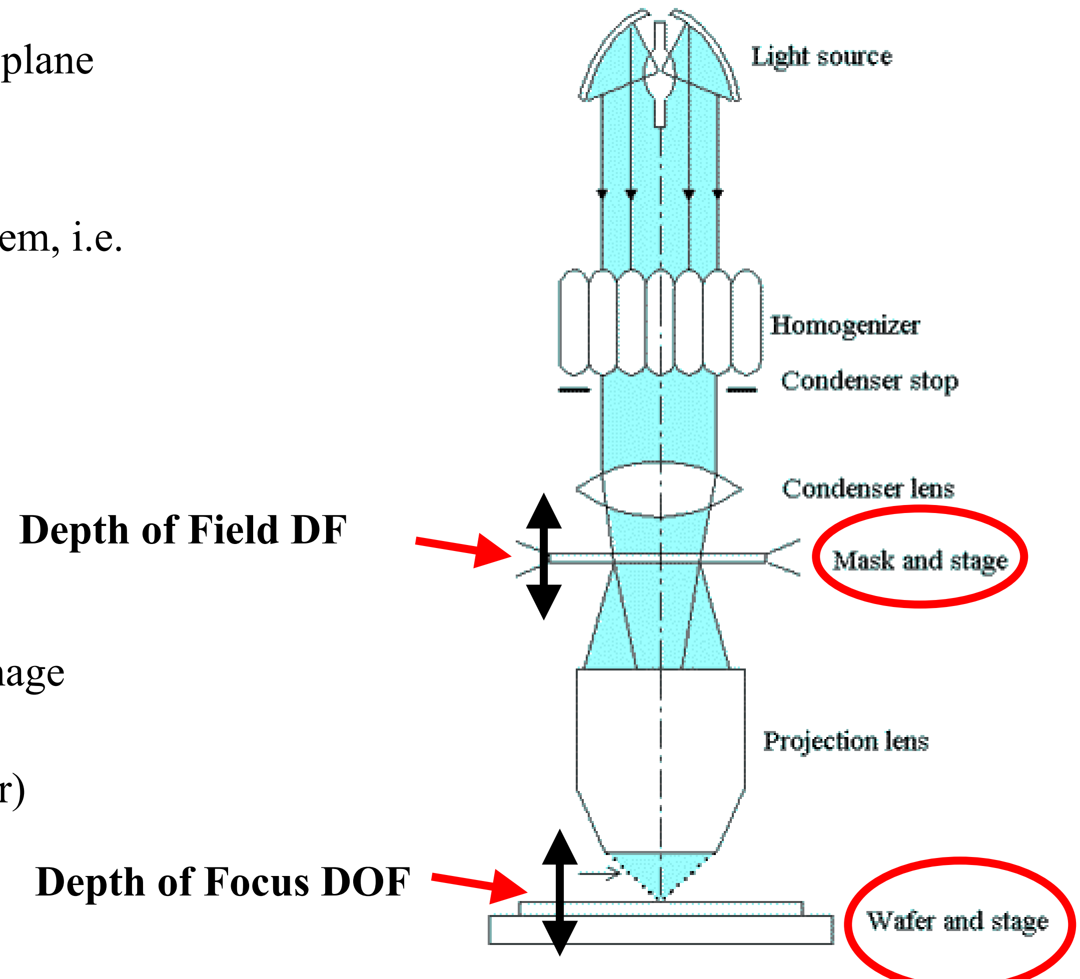
Resolution, Depth of Focus, and Depth of field

- Resolution for coherent illumination:
- $\mathbf{R = k_1\lambda/NA}$
- R measured as minimum usage feature size in microns
- $\mathbf{k_1}$ process factor; λ = exposure wavelength; **NA** numerical aperture
- Resolution for partially coherent system
- $\mathbf{R = k_1\lambda/NA(1+\sigma)}$ σ = partial coherence factor
- Resolution for Off axis ilumination system
- $\mathbf{R = k_1\lambda/(NA + NA^*\sigma + \sin\theta)}$ **;** $\mathbf{\sin}\,\theta$ = off axis illumination incident angle on ret.
- Depth of Focus (DOF) at image plane (wafer):
- $\mathbf{DOF = k_2\lambda/NA^2}$ ($\mathbf{k_2}$ process factor)
- Depth of field (DF) at object plane (reticle):
- $\mathbf{DF = DOF/m^2}$ (**m** = magnification of optical system, i.e. 5X = 0.2)

Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

- **<u>Depth of field (DF)</u>** at object plane (reticle):
- **DF = DOF/m^2**
- (**m** = magnification of optical system, i.e. 5X = 0.2)

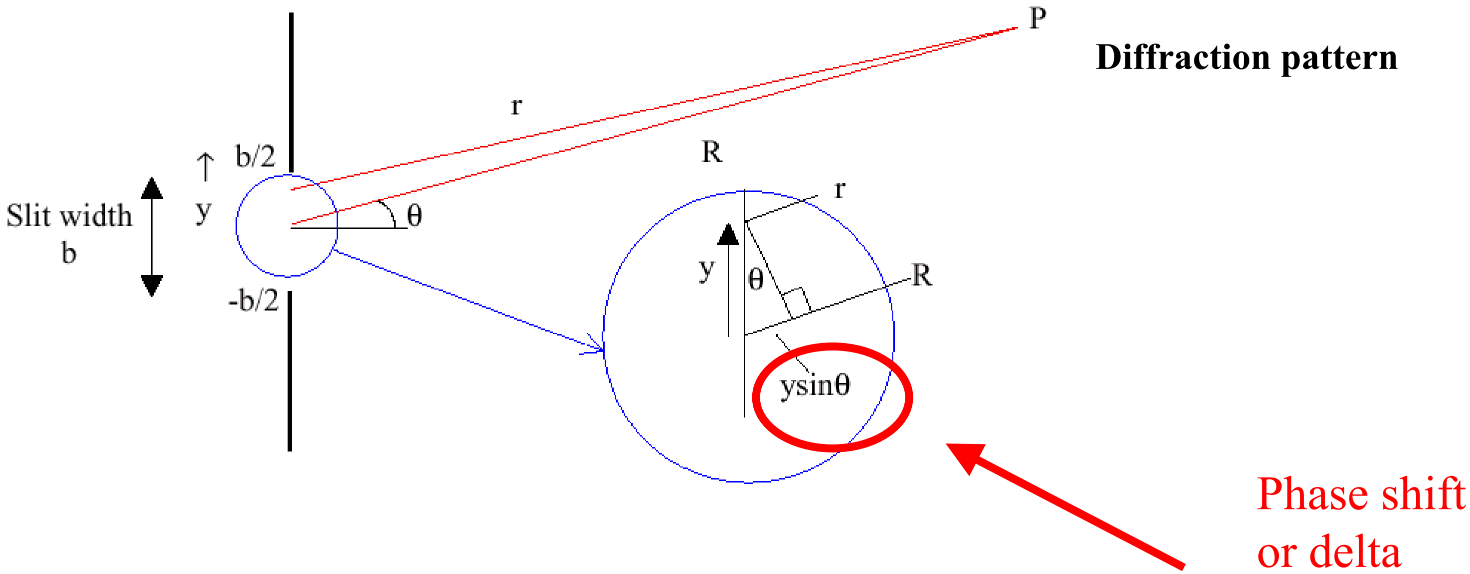


- **<u>Depth of Focus (DOF)</u>** at image plane (wafer):
- **DOF = k$_2\lambda$/NA^2** (**k$_2$** process factor)

Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

- Special Case: Single slit diffraction: Approximation > Phase of a wave from a point in the slit or aperture varies linearly across the slit!
- Slit width = b; y is position across slit;

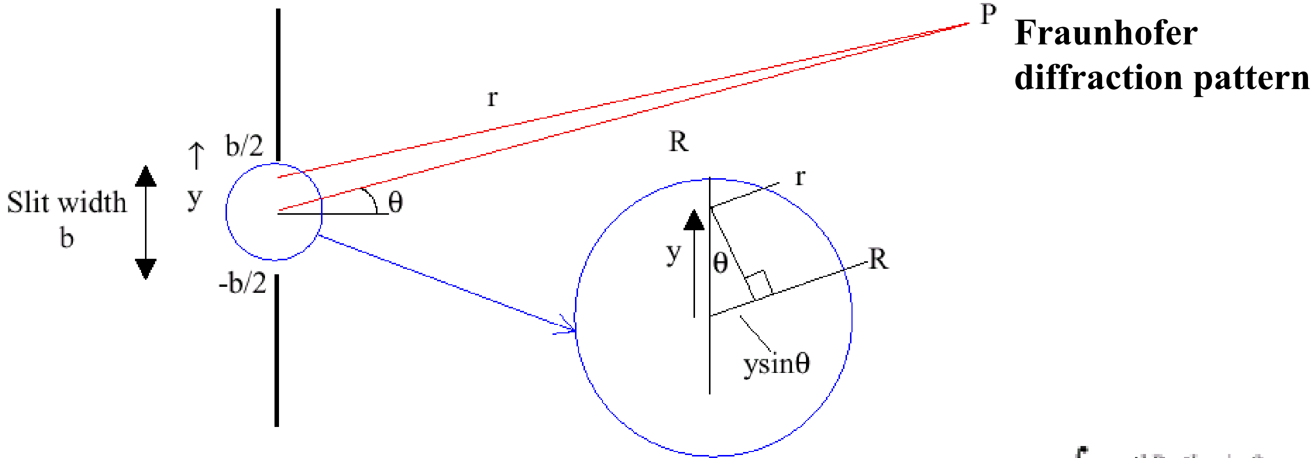


The phase of the wave reaching P varies across the slit because (in the linear approximation for Fraunhofer diffraction)

$$r = R - y\sin\theta \quad .$$

Resolution, Depth of Focus, and Depth of field

Special Case: Single slit diffraction:



$$E \propto \int_{aperture} e^{-ikR+iky\sin\theta}\,dy$$

$$= e^{-ikR}\int_{-b/2}^{+b/2} e^{iky\sin\theta}\,dy$$

$$= e^{-ikR}\,\frac{e^{ik\frac{b}{2}\sin\theta} - e^{-ik\frac{b}{2}\sin\theta}}{ik\sin\theta}$$

$$= e^{-ikR}\,b\,\frac{\sin\beta}{\beta}\,,\quad \text{where } \beta = k\frac{b}{2}\sin\theta \quad .$$

Fraunhofer diffraction Intergal across the slit. E = electric field

Resolution, Depth of Focus, and Depth of field

Special Case: Single slit diffraction:

$$E \propto \int_{aperture} e^{-ikR+iky\sin\theta}\,dy$$

Fraunhofer Diffraction pattern integral for electric field

$$= e^{-ikR}\int_{-b/2}^{+b/2} e^{iky\sin\theta}\,dy$$

$$= e^{-ikR}\,\frac{e^{ik\frac{b}{2}\sin\theta} - e^{-ik\frac{b}{2}\sin\theta}}{ik\sin\theta}$$

$$= e^{-ikR}\,b\,\frac{\sin\beta}{\beta}\,,\ \text{where}\ \beta = k\frac{b}{2}\sin\theta \quad .$$

The sincβ^2 function

Terms:

b = slit width; θ = diffraction angle; k = 2π /λ phase term

The intensity I is not influenced by the leading term e^{-ikR} and hence only the term sinβ/β = sincβ (pronounced "sink beta") gives the change in diffraction pattern with θ.

$$I = I(0)\left(\frac{\sin\beta}{\beta}\right)^2$$

Intensity of diffraction pattern for slit : sincβ^2 function

Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

Special Case: Single slit diffraction:

$$I = I(0)\left(\frac{\sin\beta}{\beta}\right)^2$$

Intensity of diffraction pattern for slit : sincβ^2 function

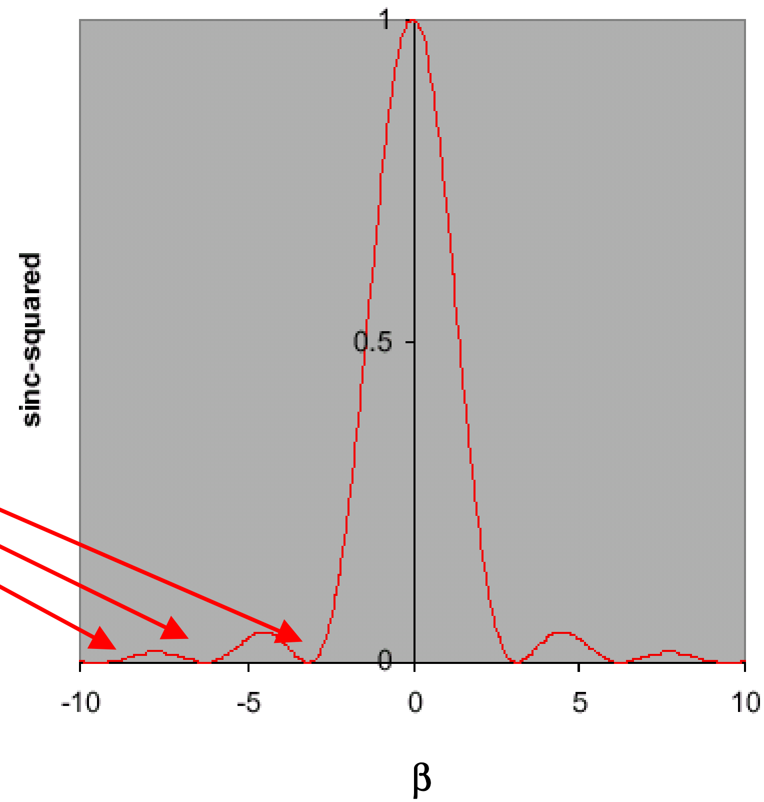
The sincβ^2 function has equally spaced zeros when b = nπ (n not equal to 0)

Hence the *zeros of the diffraction pattern occur when*

$n\pi = \beta$
$= (kb\sin\theta)/2$
$= \pi b\sin\theta/\lambda$

i.e.

$$\boxed{b\sin\theta = n\lambda}\quad .$$

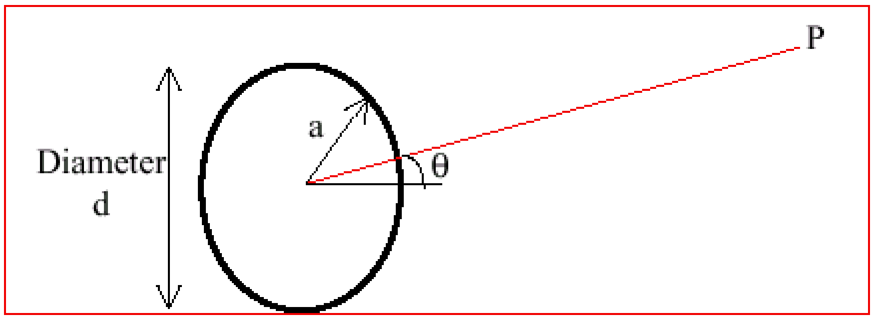


This is the same as the first equation we introduced mλ = bsinθ

b = slit width; θ = diffraction angle; k = 2π /λ phase term

Resolution, Depth of Focus, and Depth of field

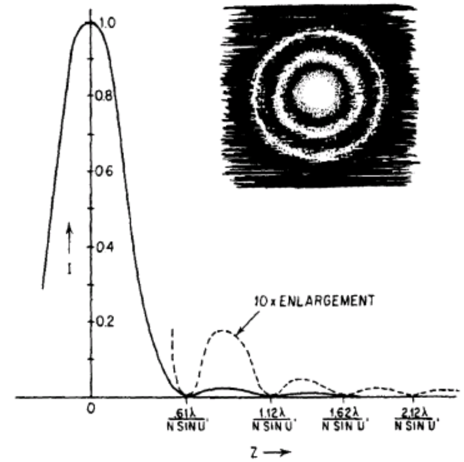
<u>Circular aperture diffraction:</u> diameter d and radius a



Diffraction pattern is given in terms of a Bessel function J_1 of the first kind (order1)

$$I = I(0)\left(2\frac{J_1(ka\sin\theta)}{ka\sin\theta}\right)^2$$

$$= I(0)\left(2\frac{J_1(\beta)}{\beta}\right)^2, \text{ where } \beta = ka\sin\theta$$

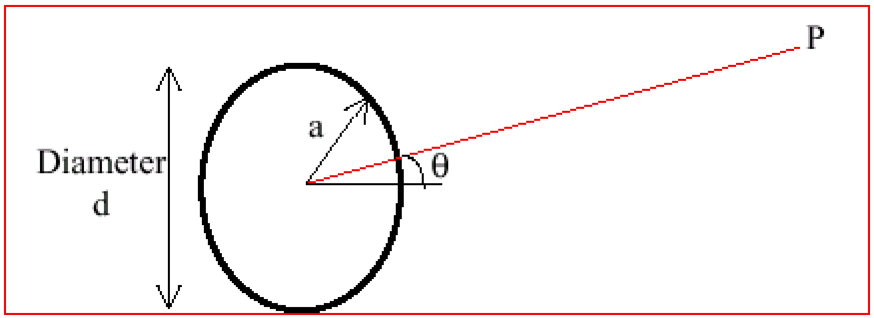


Diffraction pattern is given the name "airy" disk after George Airy an English Astronomer in the 1800's who worked out the math.

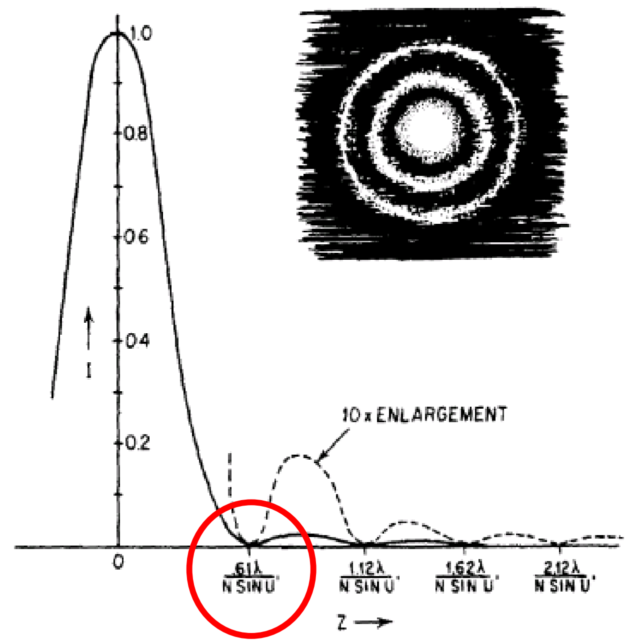
Looks very similar to the sincβ^2 function for the single slit diffraction case

Resolution, Depth of Focus, and Depth of field

<u>Circular aperture diffraction:</u> diameter d and radius a



Intensity of diffraction pattern for circular aperture : sincβ^2 function



Looks very similar to the sincβ^2 function. The first minimum of the Airy pattern occurs when

$$ka\sin\theta = 1.22\pi$$

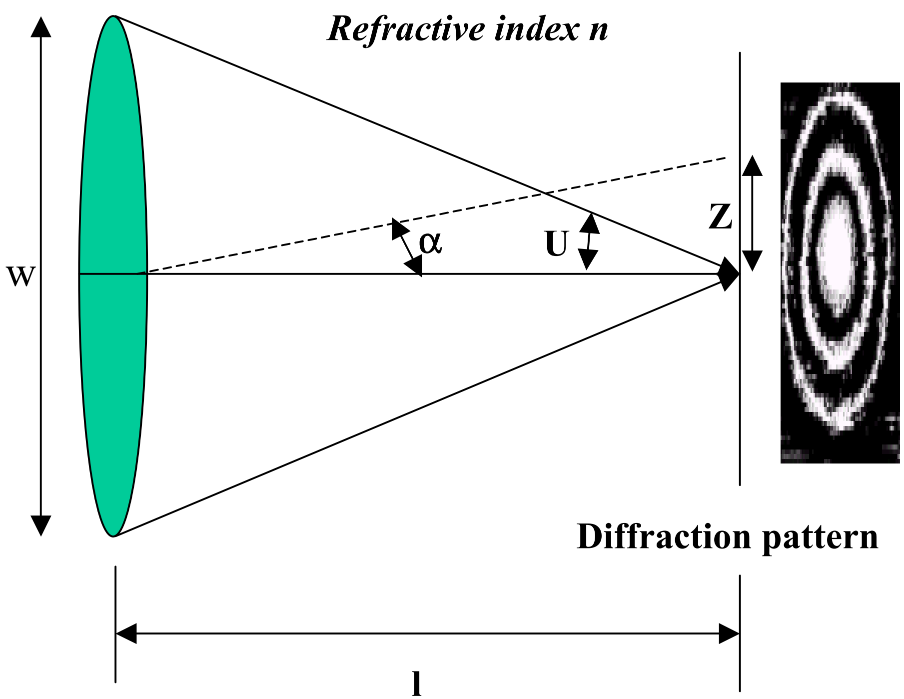
i.e. at $\sin\theta = 1.22\lambda/2a = 1.22\lambda/d$ (d = diameter of aperture

d = aperture diameter; θ = diffraction angle; k = $2\pi/\lambda$ phase term

Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

- Image of point source with diffraction = Airy disk (sinc function)
- Assume optical system is perfect and aberration free!



Z: Radial distance from center of pattern

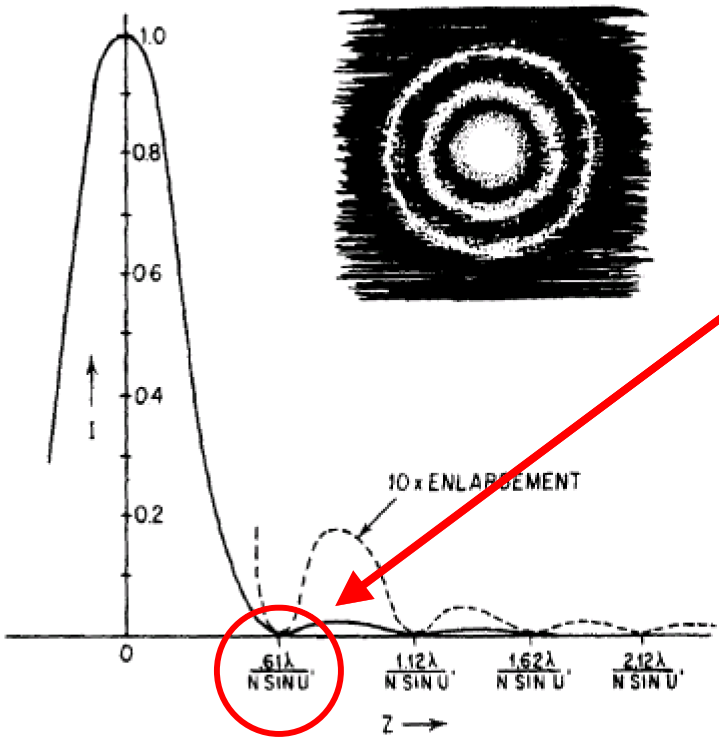
$l = -w/2\sin U$

Small angle α:

$$\mathbf{Z = l\alpha/n = \alpha w/2n\sin U}$$

Basic Optics : Microlithography
Resolution, Depth of Focus, and Depth of field

- Image of point source with diffraction = Airy disk (sinc function)
- Assume optical system is perfect!



Diffraction ring	Z circular aperture	units	Energy in Ring %	Z slit
0 central Maximum	**0**	λ/NA	83.9	**0**
1st dark	**0.61**	**λ/NA**		0.5
1st bright	0.82	λ/NA	7.1	0.72
2nd dark	1.12	λ/NA		1
2nd bright	1.33	λ/NA	2.8	1.23
3rd dark	1.62	λ/NA		1.5
3rd bright	1.85	λ/NA	1.5	1.74
4th dark	2.12	λ/NA		2
4th bright	2.36	λ/NA	1	2.24

Z values: radial distance from center of pattern and small angle

Z values in table above derived from:

Circular aperture

$$I = I(0)\left(2\frac{J_1(\beta)}{\beta}\right)^2 \text{, where } \beta = ka\sin\theta$$

Rectangular slit

$$I = I(0)\left(\frac{\sin\beta}{\beta}\right)^2$$

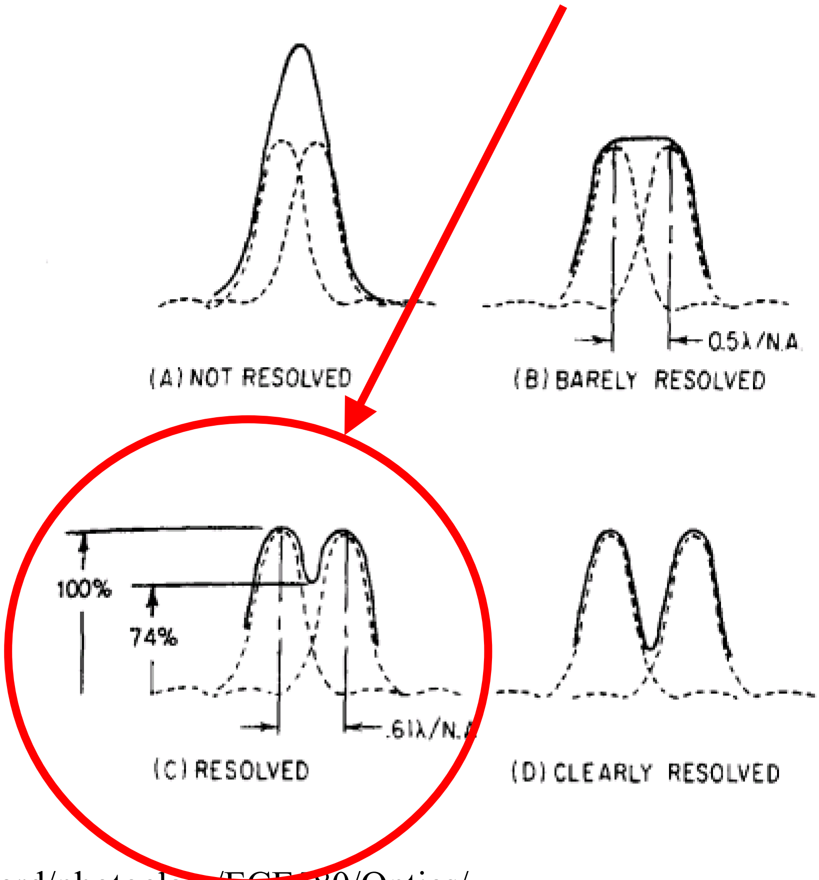
Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

- Resolution Criteria: b = Sparrows; c = Rayleighs

<u>Definition:</u> ***Lord Rayeigh's Criterion*** for limiting resolution of an optical system:

When the image separation Z reaches 0.61λ/NA, the maximum of one image coincides with the first minimum (dark ring) of the other pattern.



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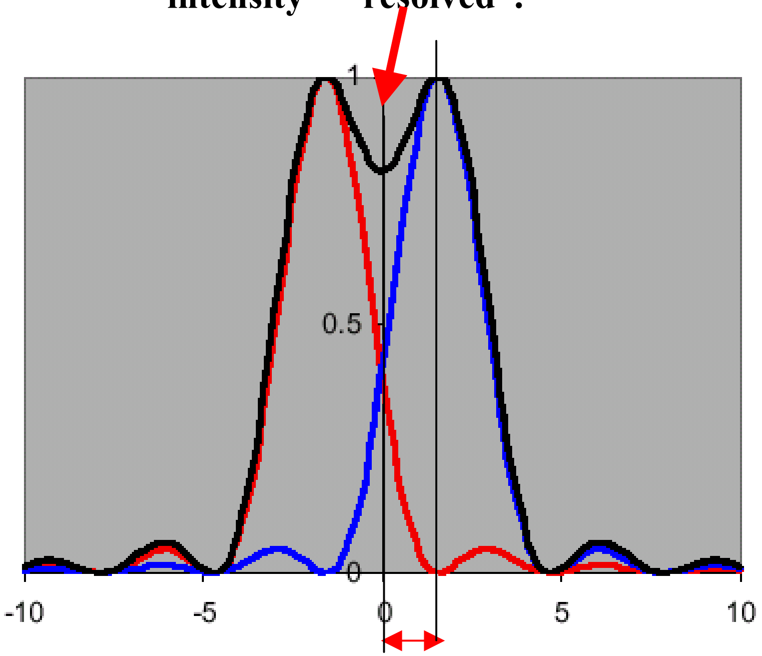
Resolution, Depth of Focus, and Depth of field

- Rayleigh resolution Criteria:
- Two overlapping sinc functions (red and blue) the black is their summation. The maximum of one image coincides with the first minimum (dark ring) of the other pattern.

- The limit in the angular separation of two adjacent objects (stars) in terms of lens diameter w is given by:

  $\alpha = 1.22\lambda/w$

Definition: Distinguishable dip in intensity = "resolved".



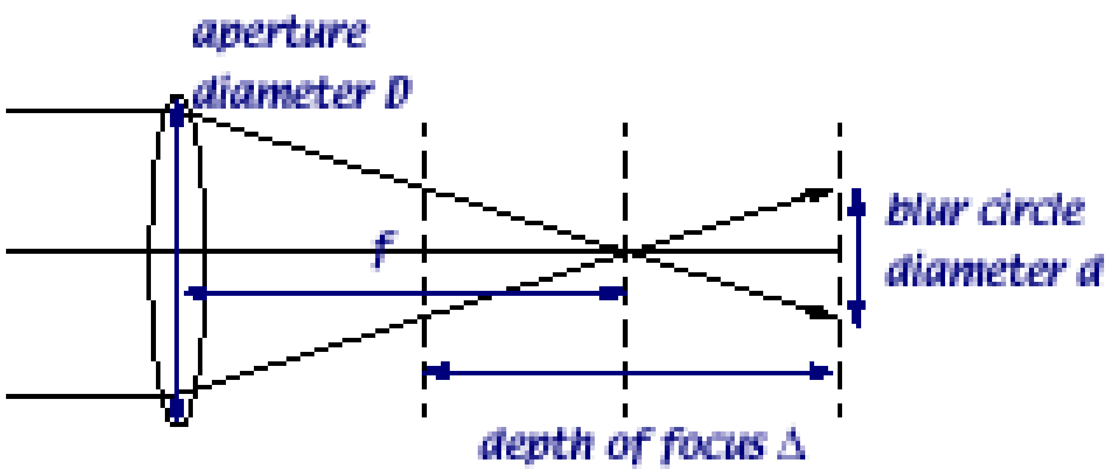
$Z = 0.61\lambda/NA$

For example, the entrance pupil of a telescope limits the resolution observable in object space. 'd' will then be d_o, the diameter of the objective. E.g. a 100mm diameter objective will define a diffraction-limited resolution at a wavelength of 500 nm of $\Delta\theta = 1.22\times5\times10^{-7}/1\times10^{-1} = 6.1\times10^{-6}$ radians = 1.26" arc.

Basic Optics : Microlithography

8. Resolution and DOF

- Depth of Focus (DOF) at image plane (wafer):
- **DOF = $k_2\lambda/NA^2$** (**k_2** process factor) Criteria based on CD and sidewall angle specifcations!



Basic Optics : Microlithography

Resolution KLA-Tencor Chris Mack Answers

Q The Rayleigh equation says depth of focus decreases with shorter wavelengths. I've also heard the opposite, that shorter wavelengths give more depth of focus. Which is correct?

A Both answers are correct, depending on the details of the specific question. The Rayleigh equation says depth of focus (DOF) is directly proportional to wavelength. This equation, however, is derived for a very specific case: when the feature being printed is at the resolution limit of the imaging tool. Rayleigh's resolution equation (the other Rayleigh equation) says the resolution limit is also directly proportional to wavelength. Thus, when the wavelength is reduced, the Rayleigh DOF equation says the DOF of the smaller feature is less. This is not an astounding conclusion – small features have less DOF.

Suppose the question were asked in a different way: for a given feature to be printed (say, 130 nm lines and spaces), how does wavelength affect DOF, all other things being equal? Is there a difference in DOF using 193 nm exposure tools versus 248 nm? The Rayleigh DOF equation by itself cannot answer this question. In fact, the lower wavelength will always give more depth of focus for a given feature size.

Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

http://www.ph.ed.ac.uk/~wjh/teaching/mo/slides/lens/lens.pdf

Consider point source imaged by a lens

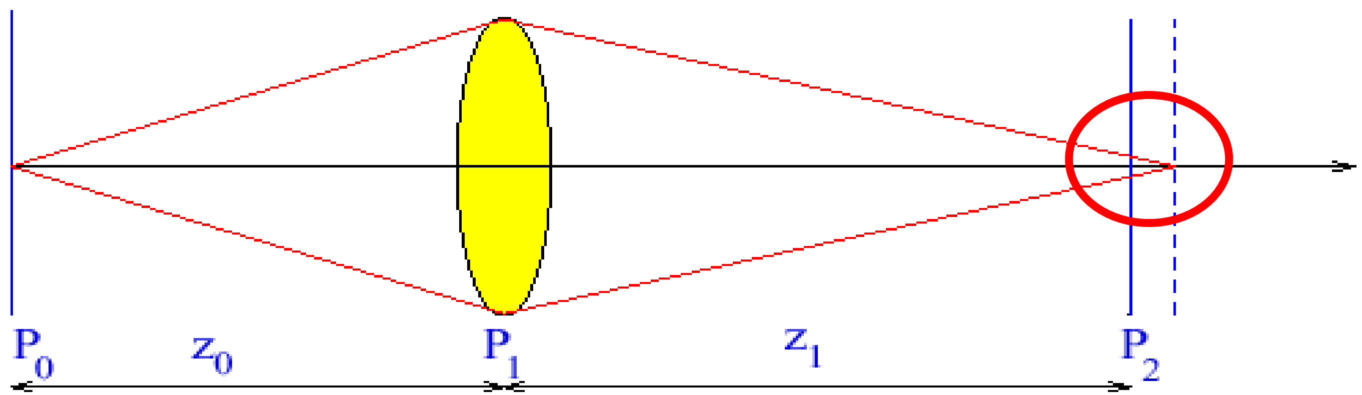


Image is "In Focus" if

$$\frac{1}{z_0} + \frac{1}{z_1} = \frac{1}{f}$$

Move P_2 system is "Defocused".

Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

http://www.ph.ed.ac.uk/~wjh/teaching/mo/slides/lens/lens.pdf

Define Defocus Parameter, D as:

$$D = \frac{1}{z_0} + \frac{1}{z_1} - \frac{1}{f}$$

Then if

$$\begin{array}{lll} D & < & 0 \end{array}$$ Negative Defocus, (z_1 too large)

$$\begin{array}{lll} D & > & 0 \end{array}$$ Positive Defocus, (z_1 too small)

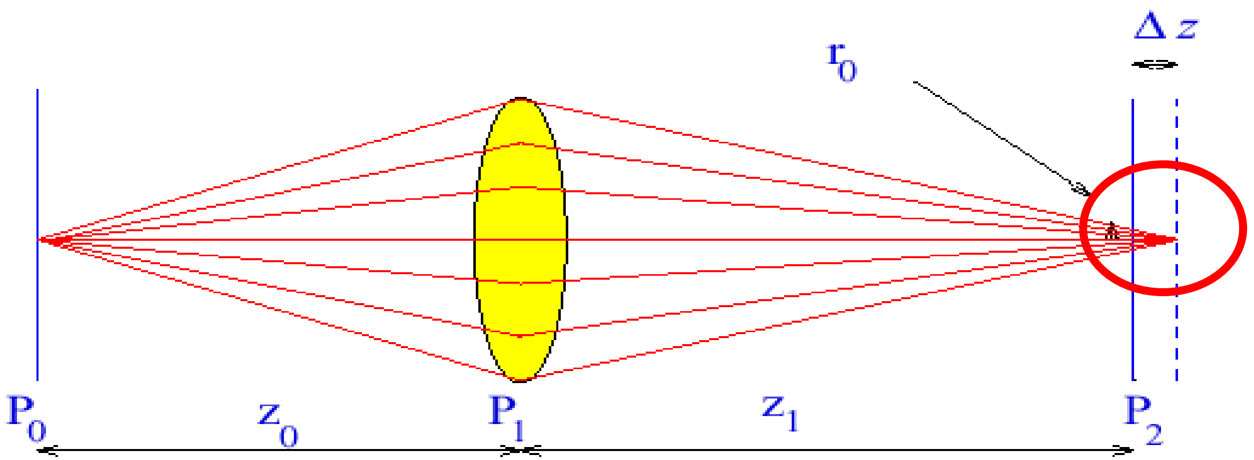
Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

http://www.ph.ed.ac.uk/~wjh/teaching/mo/slides/lens/lens.pdf

Ray Optics: Defocus system by Δz

Focus



Radius of the spot is given by similar triangles to be

$$r_0 = \frac{\Delta z d}{2 z_1}$$

where the lens is of diameter d. So larger defocus, large PSF. OK for

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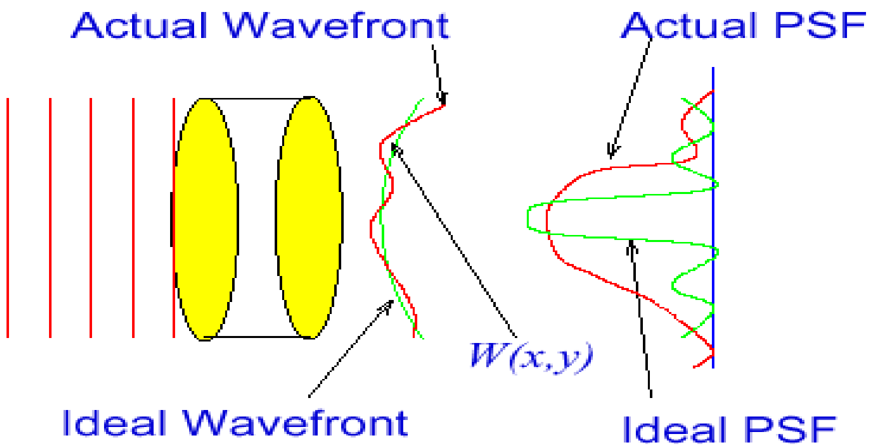
Resolution, Depth of Focus, and Depth of field

http://www.ph.ed.ac.uk/~wjh/teaching/mo/slides/lens/lens.pdf

Defocus Wavefront approach: Defocus is an aberration:
Zernike coefficient# Z3

To get ideal PSF (sharp focus), we need Parabolic Wave front behind the lens.

Actual wavefront may vary from this ideal.



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Resolution, Depth of Focus, and Depth of field

http://www.ph.ed.ac.uk/~wjh/teaching/mo/slides/lens/lens.pdf

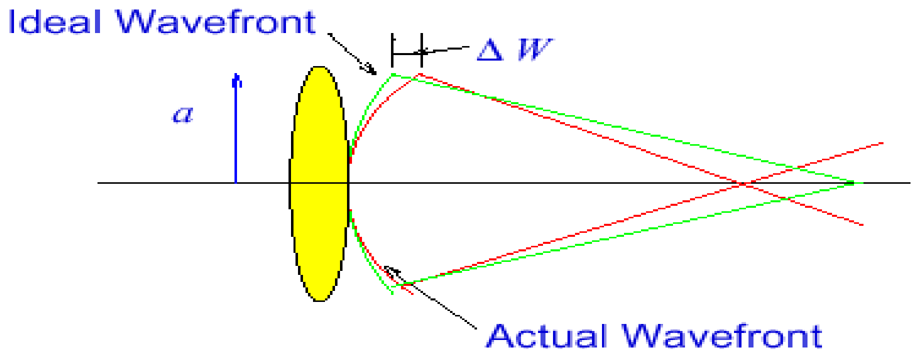
Wavefront aberration approach

Under defocus, the wavefront aberration is

$$W(x,y) = \frac{D}{2}(x^2 + y^2)$$

Measure the Defocus as the extent of the wavefront aberration at the edge of the lens, at

$$x^2 + y^2 = a^2$$



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Resolution, Depth of Focus, and Depth of field

http://www.ph.ed.ac.uk/~wjh/teaching/mo/slides/lens/lens.pdf

Wavefront aberration approach

Denote wavefront aberration at edge by ΔW, so wavefront aberration is:

$$W(x,y) = \Delta W \left(\frac{x^2 + y^2}{a^2} \right)$$

so

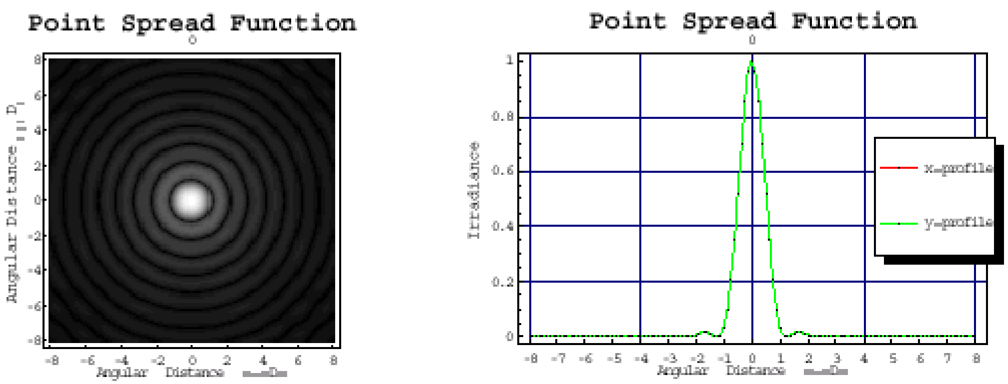
$$D = \frac{2\Delta W}{a^2}$$

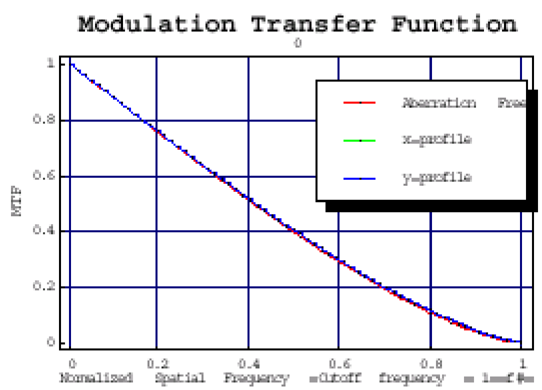
No easy solutions for PSF under defocus.

Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

- Focus: In focus no aberrations





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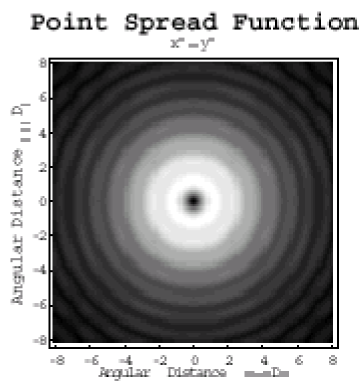
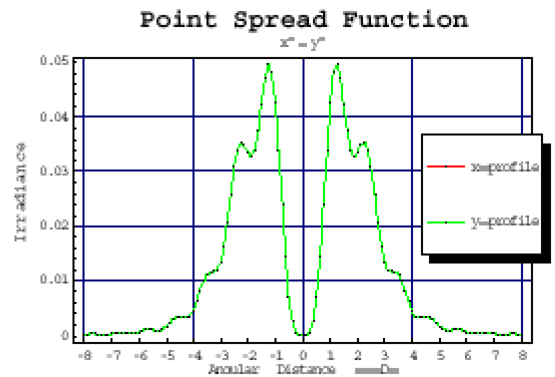
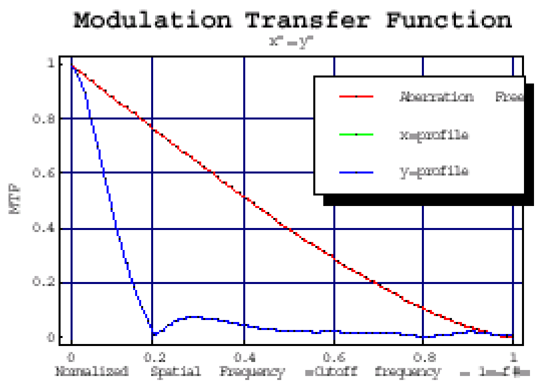
Resolution, Depth of Focus, and Depth of field

- Focus: Out of focus : Waves arrive out of phase (OPL difference)







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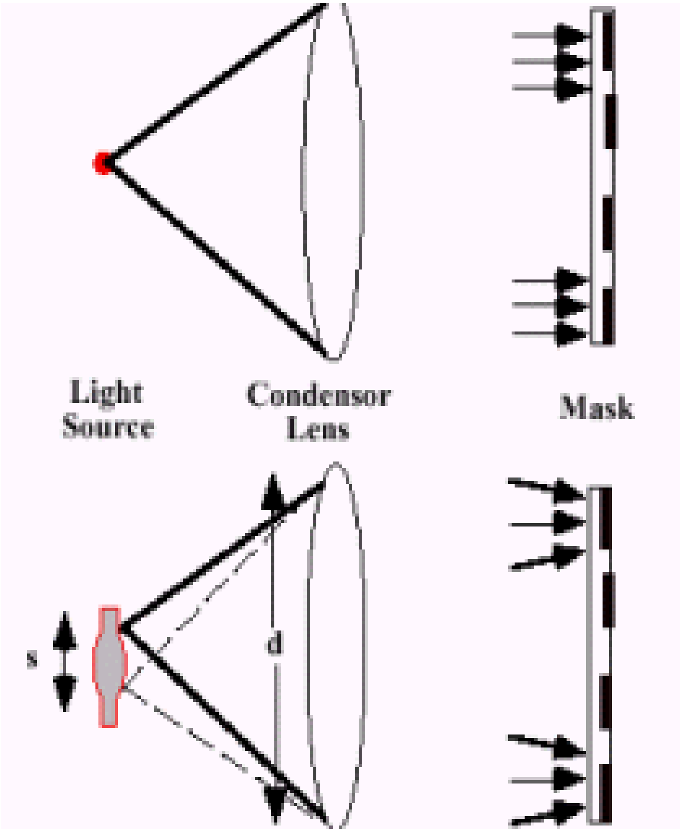
Partial ***Coherence (sigma or fill factor)***



- Practical light sources are not point sources.
- ∴ the light striking the mask will not be plane waves.
- The spatial coherence of the system is defined as

$$S = \frac{\text{light source diameter}}{\text{condenser lens diameter}} = \frac{s}{d}$$

or often as

$$S = \frac{NA_{\text{condenser}}}{NA_{\text{projection optics}}}$$

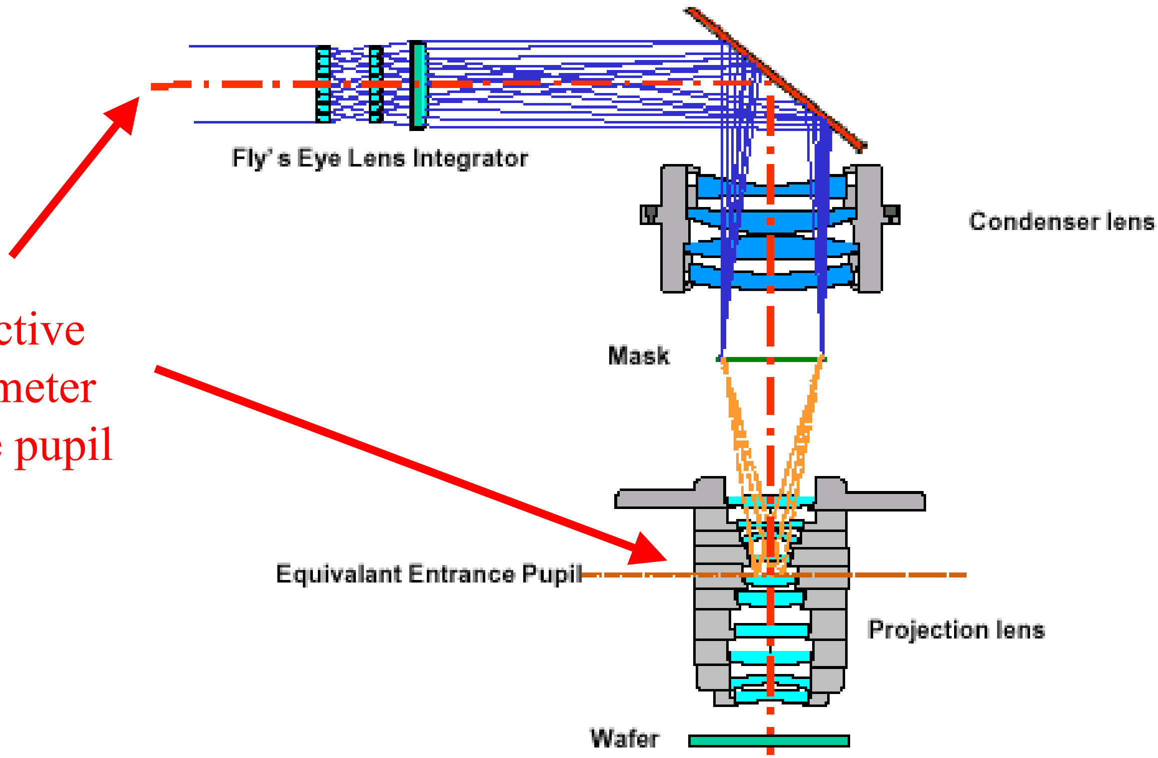
Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

Illumination Systems: Partially Coherent (On-Axis)

Kohler illumination **σ** (sigma) is the so-called *partial coherence factor or fill factor*.

Sigma = NA_c/NA_p



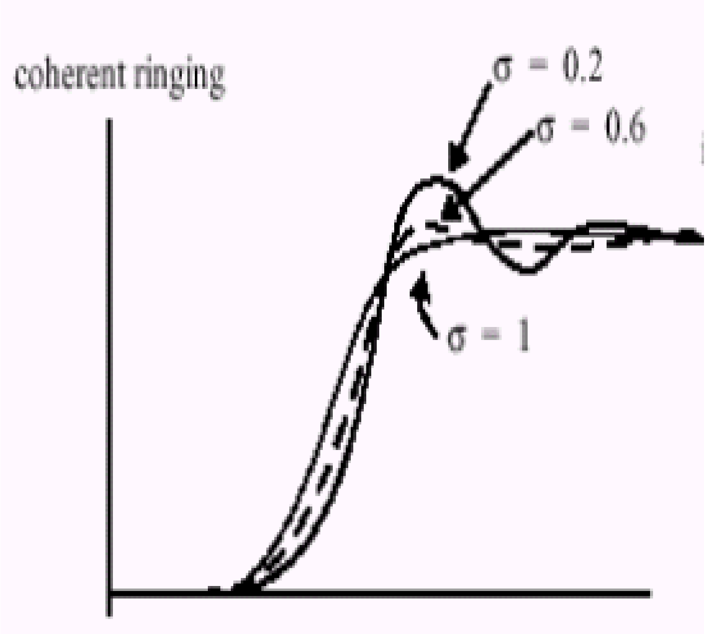
Focus effective source diameter in entrance pupil

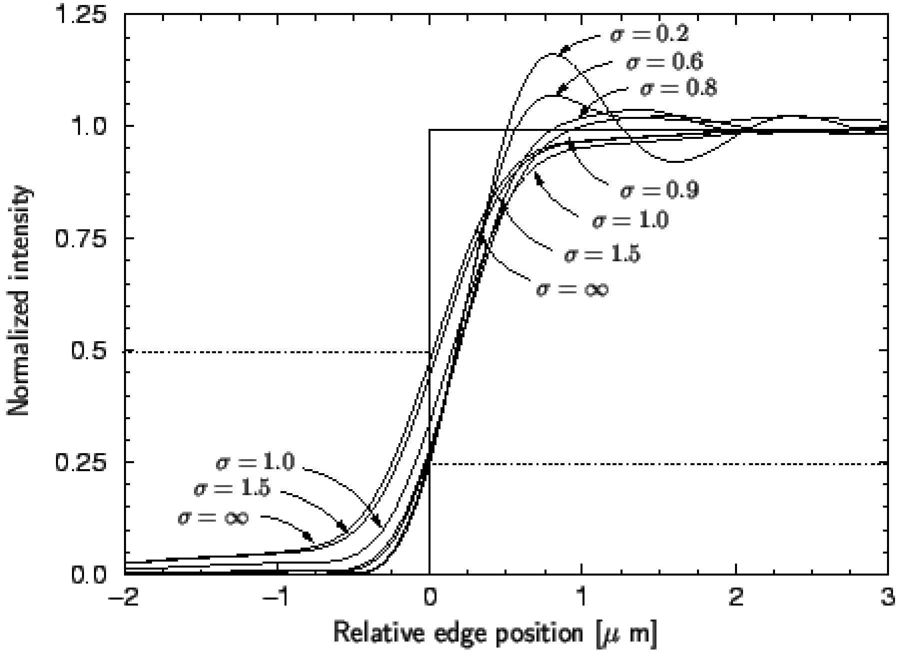
Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

σ (sigma) *partial coherence factor or fill factor*. The influence of is demonstrated in Figure by showing the image intensity near a simple knife-edge. **σ** = infinity = lowest contrast

- Decreasing **σ** increases the edge slope and contrast
- Intensity at edge





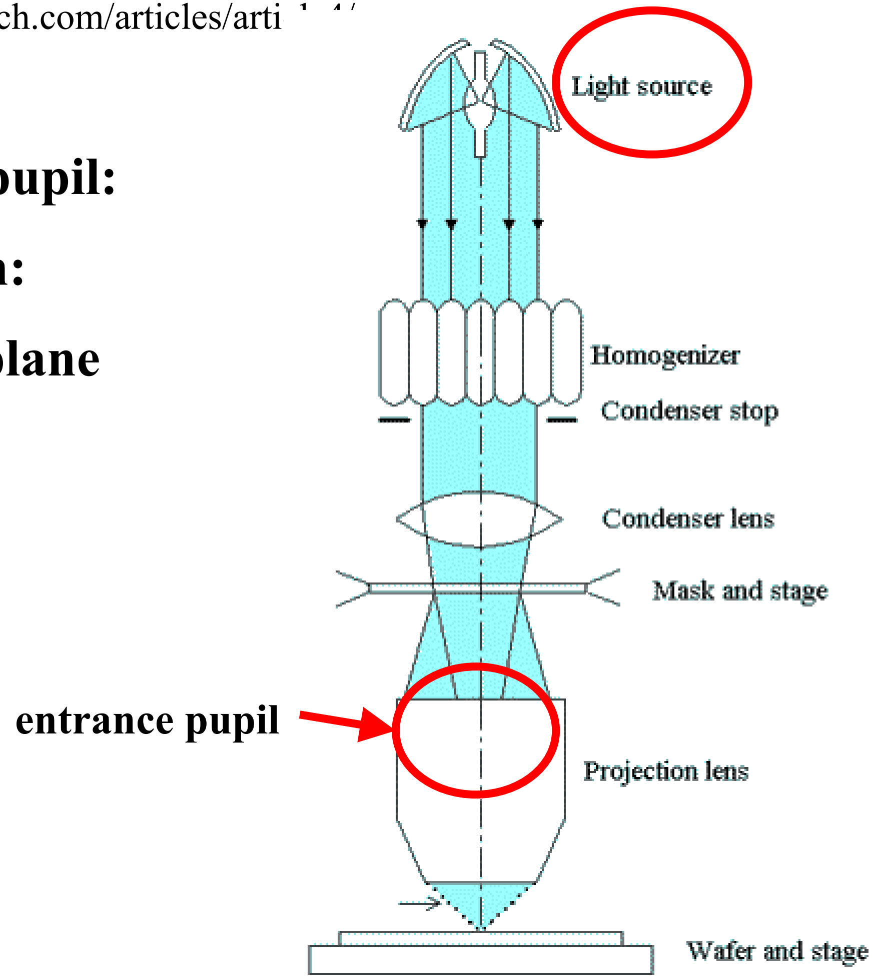
Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

http://www.mmresearch.com/articles/arti

- **Typical setup:**
- **Focus source in entrance pupil:**
- **Called Kohler Illumination:**
- **ie. At Fourier Transform plane**

$$\sigma = \frac{NA_c}{NA_p}$$



Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

• Partial Coherence and Advanced Apertures

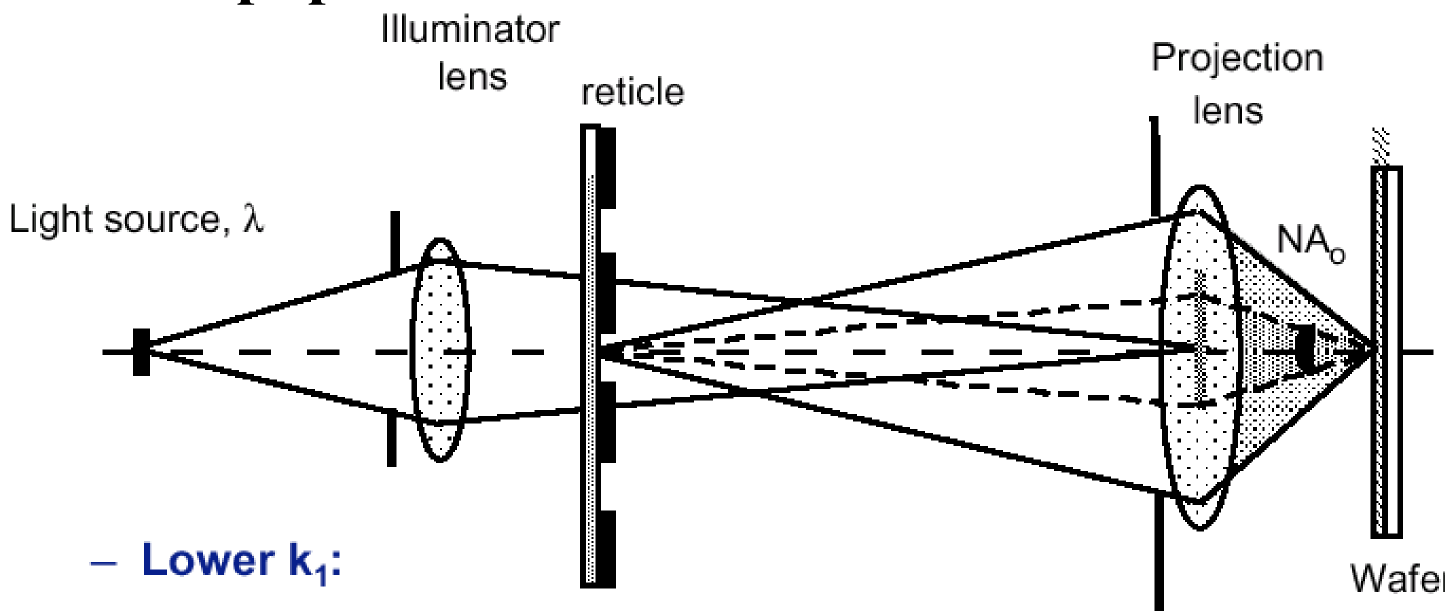
- Two aspects of coherence play an important role in lithography. Firstly, the light is strongly coherent in the ***time (temporal) domain (color)*** because of the required monochromaticity of the light source . The coherence in the ***spatial domain (phase)***, however, is an adjustable parameter that has great influence on the imaging performance. The illumination is said to be partially coherent, if a certain amount of spatial coherence exists. The amount of partial coherence is governed by the ratio of the numerical aperture of the condenser lens NA_c and projection lens NA_p
- $$\sigma = \frac{NA_c}{NA_p}$$

Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

- **Partial Coherence setup: Focus source in entrance pupil**

$$\sigma = \frac{NA_c}{NA_p}$$



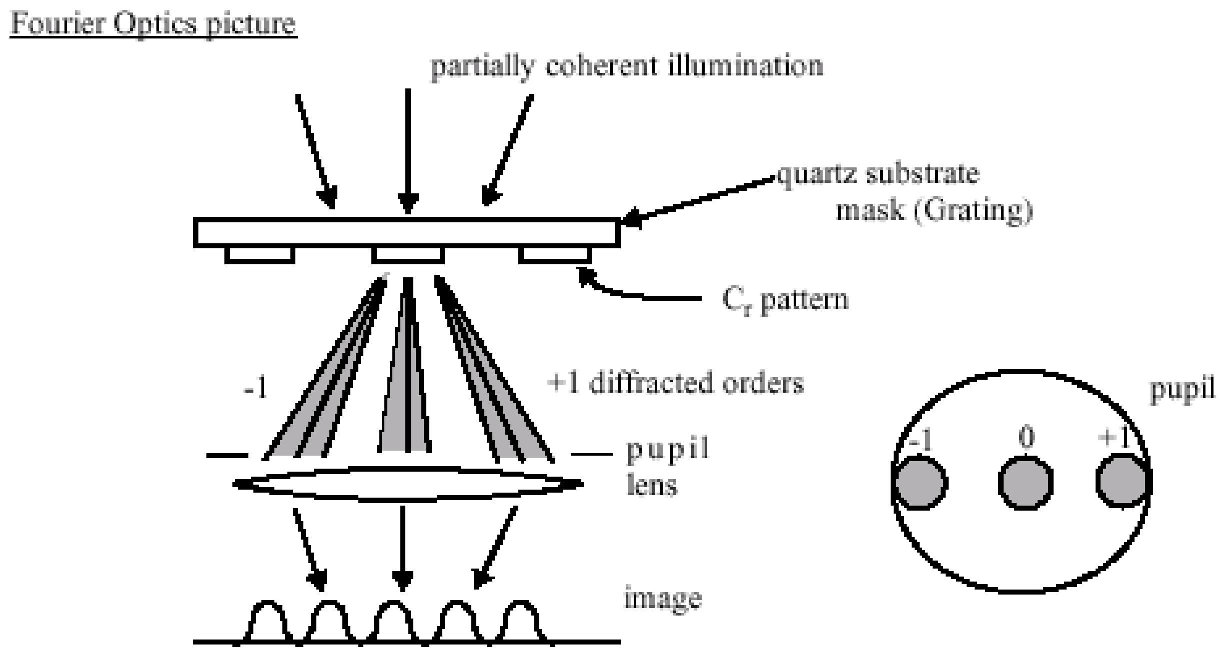
- **Lower k_1:**
  - Resolution enhancement techniques
  - Optics utilization improvement
  - Process improvement

Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

σ (sigma) *partial coherence factor or fill factor*. Sigma = NA_c/Na_p

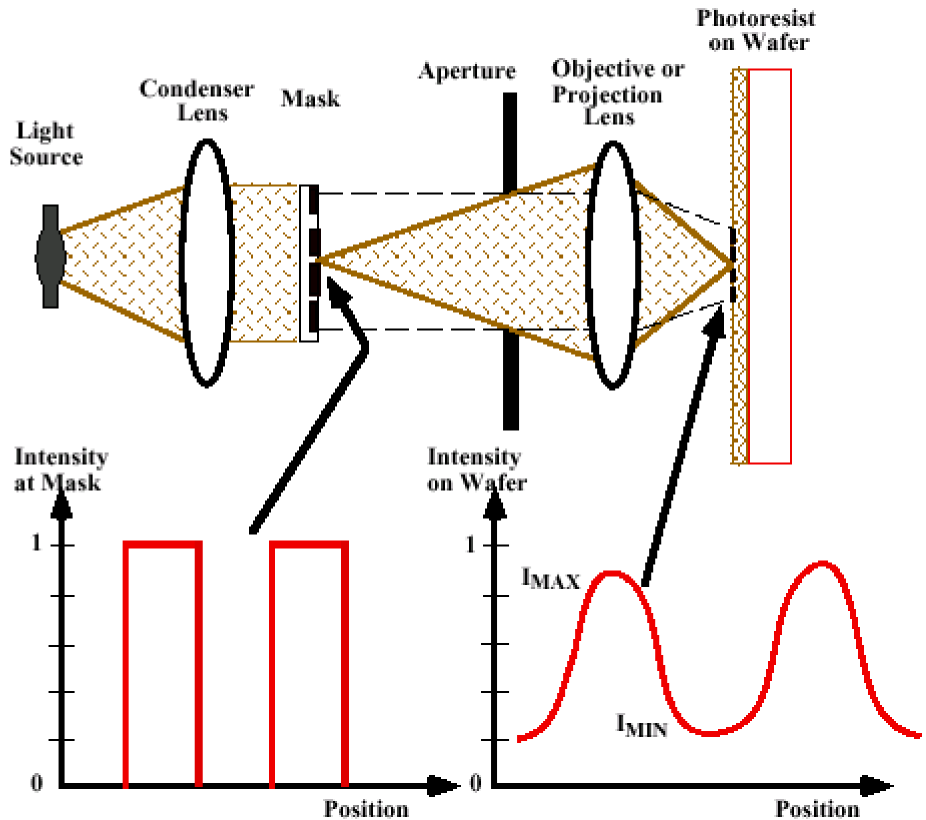
Partial coherence and and diffraction: Fourier transform plane



Basic Optics : Microlithography

MTF and Contrast

$$\mathrm{MTF} = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}} \qquad (6)$$



Basic Optics : Microlithography

MTF and Contrast

MTF : Modulation Transfer function: Ration of output to input as

$$\mathbf{MTF = M_i/M_o \text{ at specified frequency}}$$

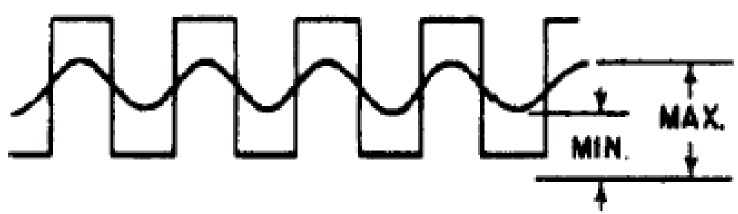
M_i = Modulation of image at specified frequency

M_o = Modulation of object at specified frequency

$M = [I_{max} - I_{min}]/[I_{max} + I_{min}]$ for periodic feature of specified frequency

I = intensity

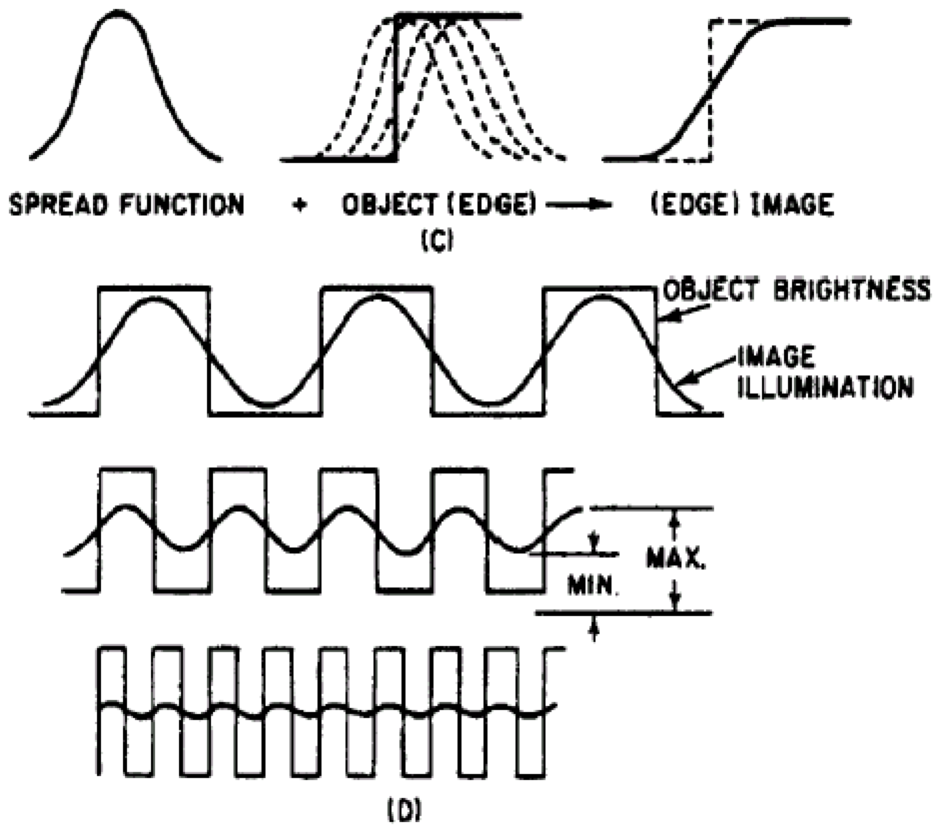
Frequency is measured in N lines/mm typically: period = 1/N



Basic Optics : Microlithography

MTF and Contrast

MTF : **MTF = M_i/M_o at specified frequency**



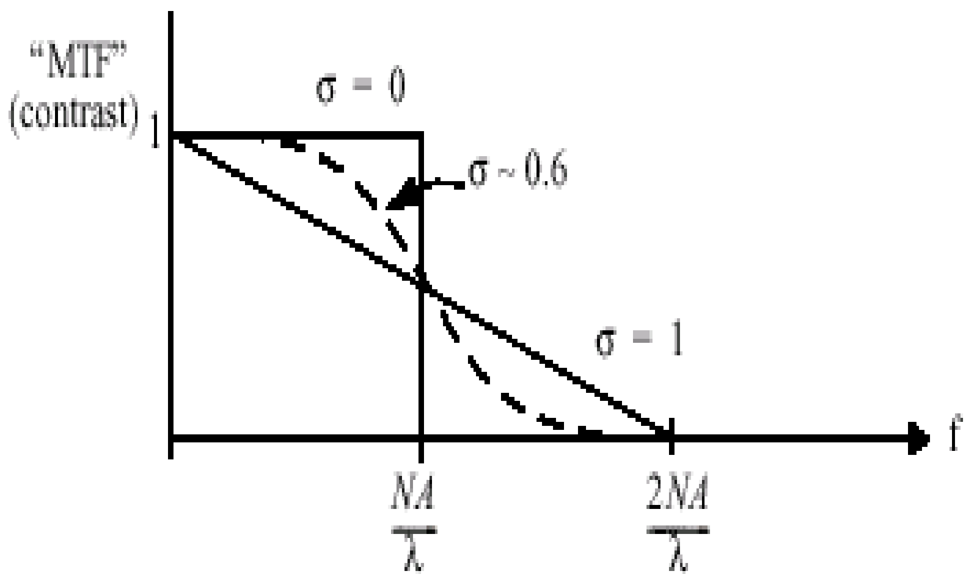
Basic Optics : Microlithography

MTF and Contrast

MTF Curve and cut off frequencies: **i.e diffraction limited frequency >> not captured by the lens!!**

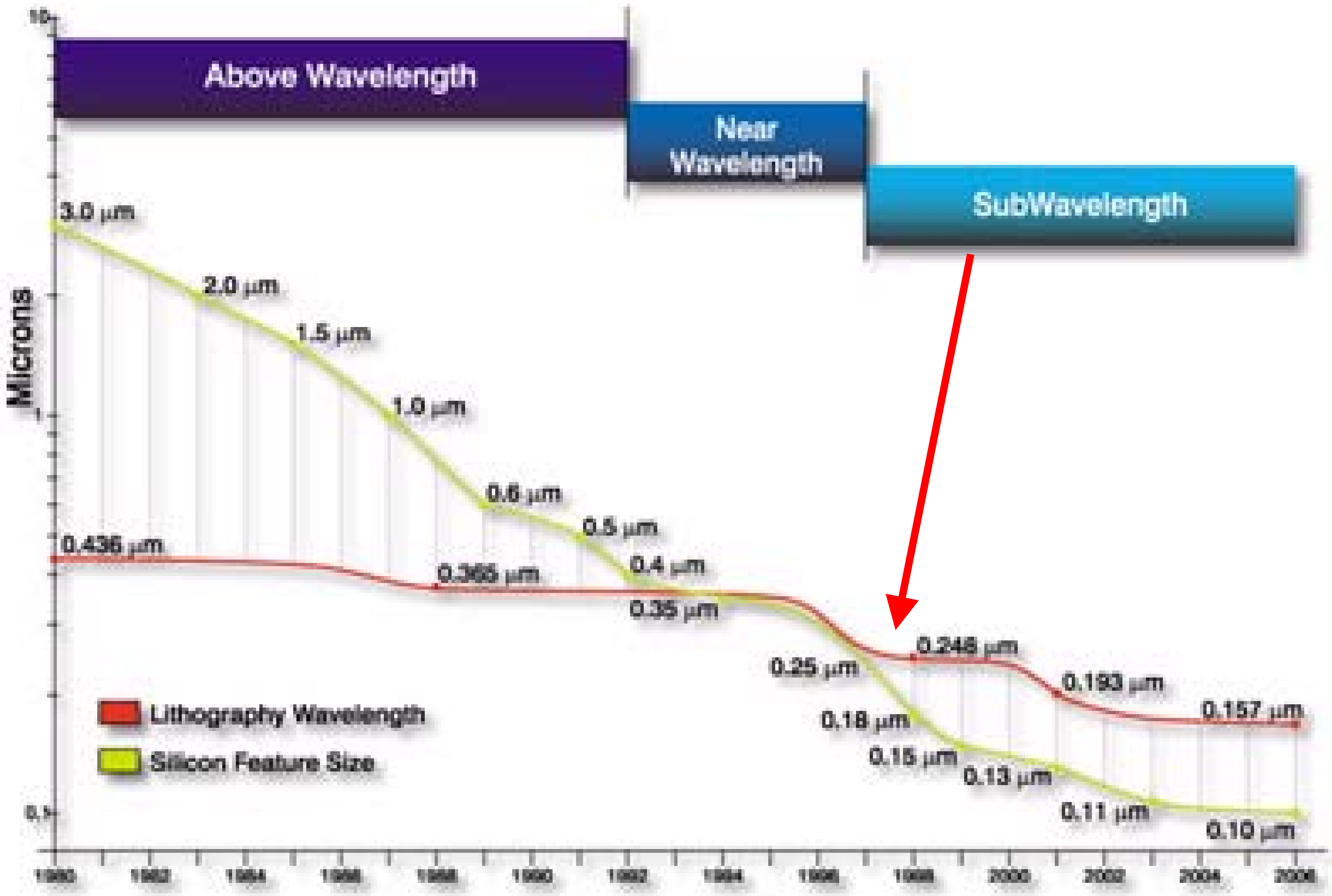
Coherent illumination $v_{cutoff} = NA/\lambda$;

Incoherent illumination $v_{cutoff} = 2NA/\lambda$;



Basic Optics : Microlithography

Resolution: Sub-resolution: How do we do that?



Basic Optics : Microlithography

Resolution: Sub-resolution: How do we do that?

How can you print a linewidth less than the wavelength of the exposing radiation?

Resolution equation for coherent light is: $\mathbf{R = k_1\lambda/NA}$

While for partially coherent it is: $\mathbf{R = k_1\lambda/NA(1+s)}$ **s** = partial coherence factor

The diffraction relationship we looked at before still is true, but for partially coherent illumination the **Fraunhofer Diffraction** pattern order pattern is spread out (not a point). These "spread" order patterns contain the transformed object information like before. If only part of these "spread" orders are captured by the lens, a image can be constructed. Part of the information is lost and the modulation (output/input) is less than 1!

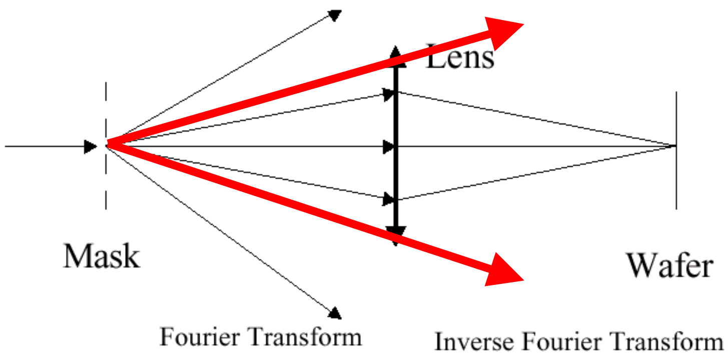
- $\mathbf{m\lambda = d \sin\theta}$ **;m = diffraction order; λ = coherent illumination**
- **d = 2y = slit width; θ = diffraction angle**

Basic Optics : Microlithography

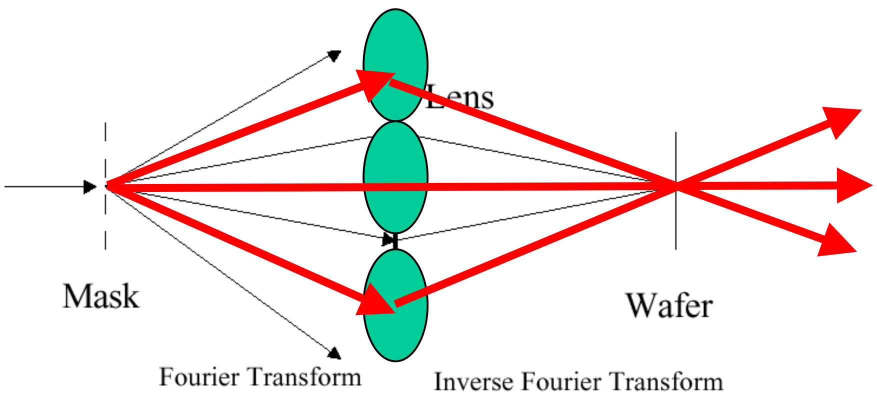
Resolution: Sub-resolution: How do we do that?

How can you print a linewidth less than the wavelength of the exposing radiation?

Partially coherent illumination Vs Coherent: Effectively higher diffraction angles are captured, but with less information. Hence resolution is increased!



Coherent illumination (pt source): orders lost: no image formation

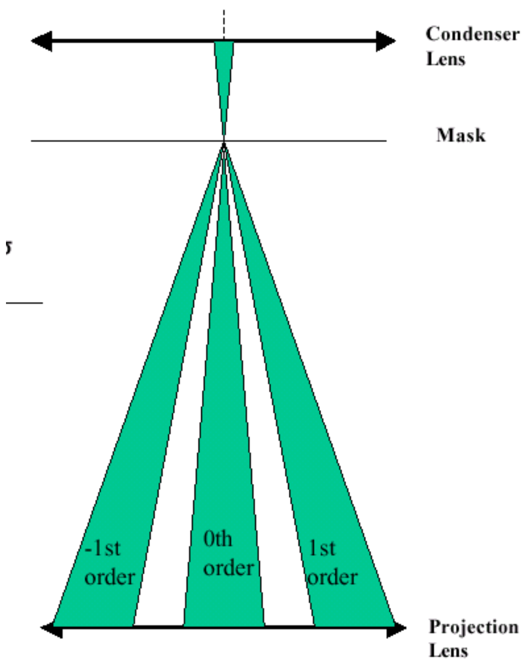


Partially Coherent illumination (extended source): : at same diffraction angle information captured = image formation

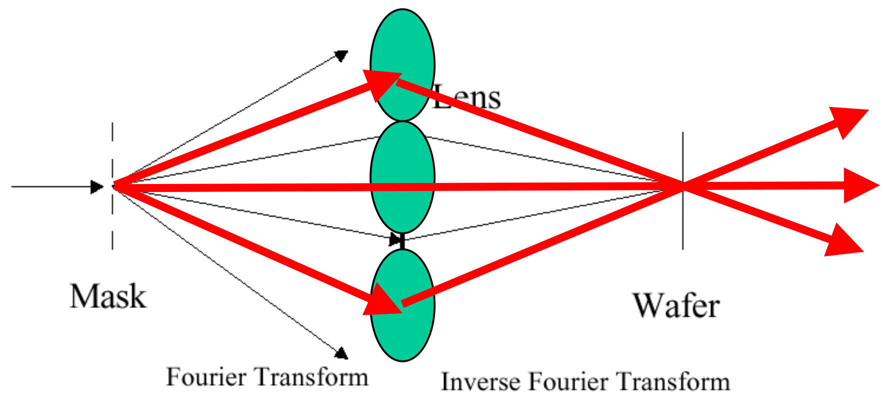
Basic Optics : Microlithography

Resolution: Sub-resolution: How do we do that?

Partially coherent illumination!



3 beam image formation

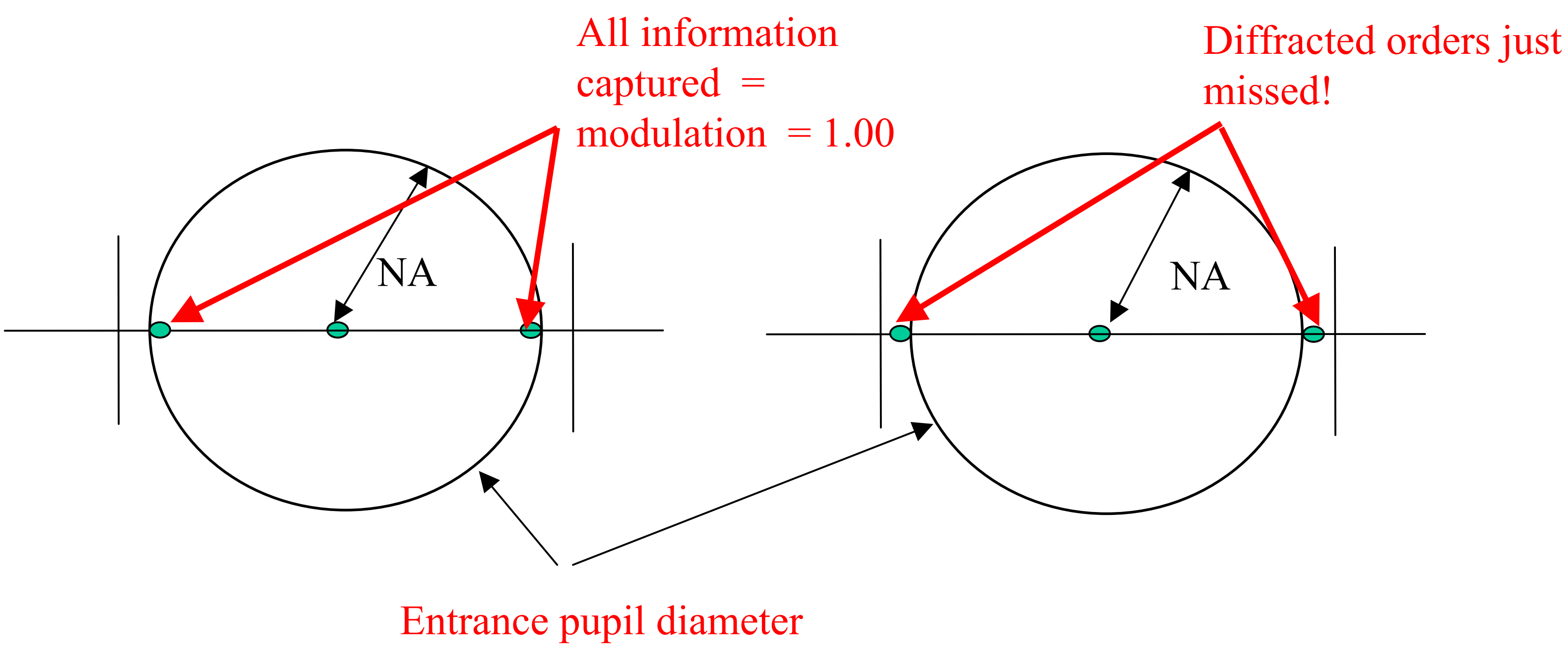


Partially Coherent illumination (extended source): : at same diffraction angle information captured = image formation

Basic Optics : Microlithography

Resolution: Sub-resolution: How do we do that?

<u>Coherent illumination</u> : Fraunhofer diffraction pattern in entrance pupil:



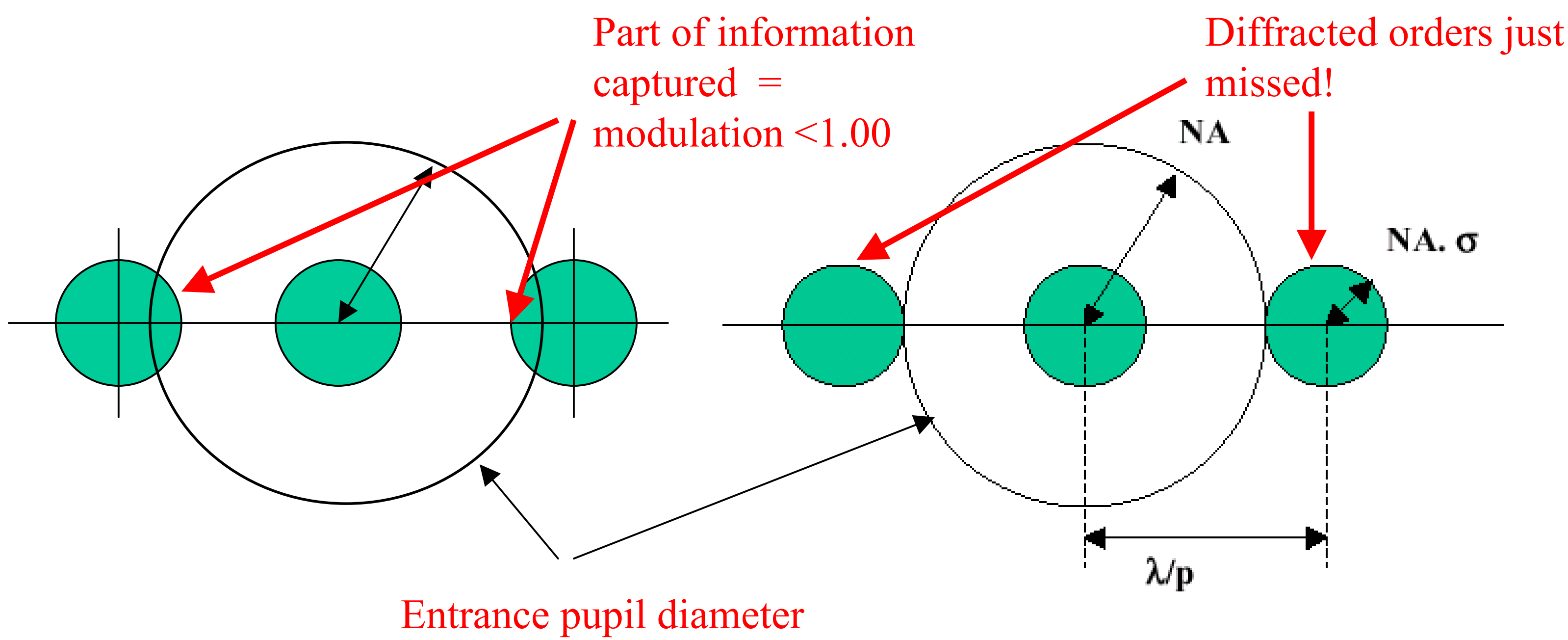
Coherent illumination Modulation = 1.00

Coherent illumination Modulation = 0.00 no image formation

Basic Optics : Microlithography

Resolution: Sub-resolution: How do we do that?

<u>Partially coherent illumination</u> : Effectively higher diffraction angles are captured . Fraunhofer diffraction pattern in entrance pupil:



Partially Coherent illumination
Extended source: Higher orders captured with lower modulation

In partially coherent imaging the resolution limit is achieved when **$\lambda/p = NA + NA.\sigma$**
p (pitch)= $\lambda / NA(1+\sigma)$

Basic Optics : Microlithography

Resolution: Sub-resolution: How do we do that?

<u>Definition:</u> ***Lord Rayeigh's Criterion*** for limiting resolution of an optical system:

$R = 0.61\lambda/NA$,

Our original resolution definitions

$R = k_1\lambda/NA$ coherent light: Coherent resolution cutoff limit is **λ/NA**

•**$R = k_1\lambda/NA(1+\sigma)$** σ = partial coherence fill factor

•Resolution for Off axis illumination system

•**$R = k_1\lambda/(NA + NA^*\sigma + \sin\theta)$;** **sin** θ = off axis illumination incident angle on ret.

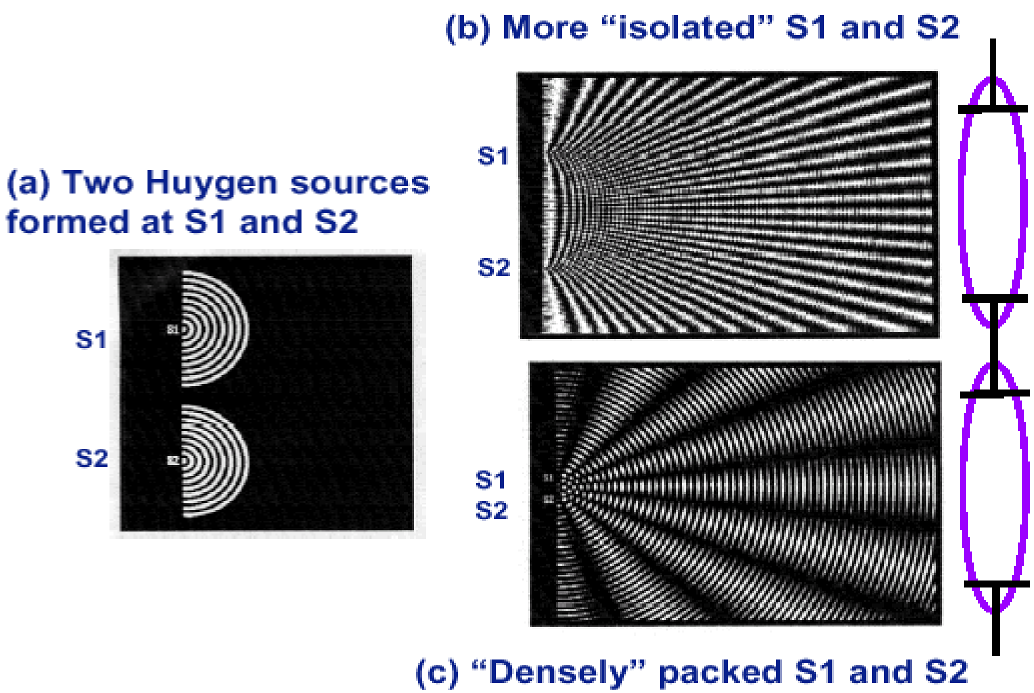
•**Now define in terms of pitch p for** partial coherent illumination as::

•**$P(\text{pitch}) = k_1\lambda/NA(1+\sigma)$;** Partially coherent resolution cutoff limit is **$\lambda/NA(1+\sigma)$**

Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

σ (sigma).



<u>**Observations:**</u>

1) Diffraction patterns are not the same from dense to isolated

2) Lens act as "low-pass" filter, only lower diffraction order light beams can get through lens

Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

from: Chris Mack "Optical Proximity Effects"

http://www.usa.canon.com/indtech/semicondeq/news_optical2.html

σ (sigma) *partial coherence factor or fill factor*. Sigma = NA_c/Na_p

Partial coherent has a large effect on optical proximity effects

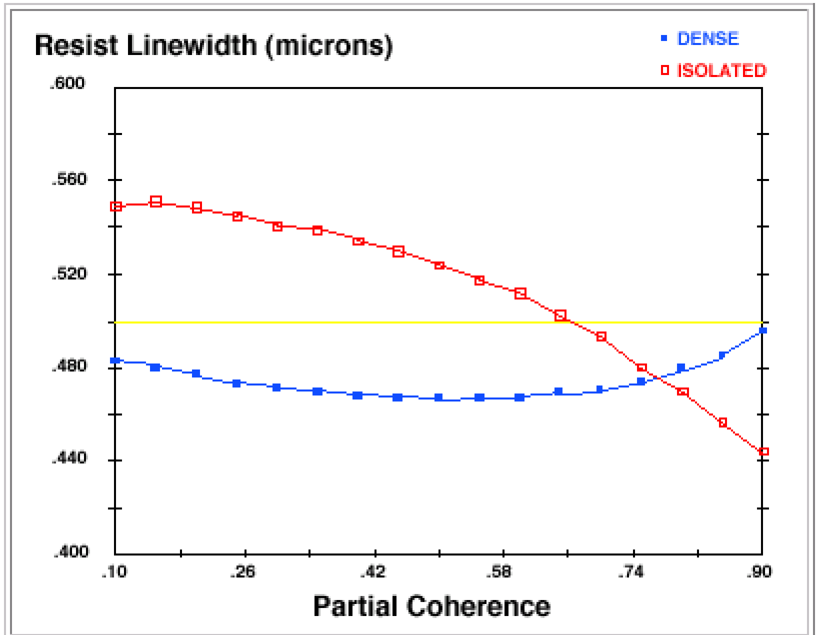
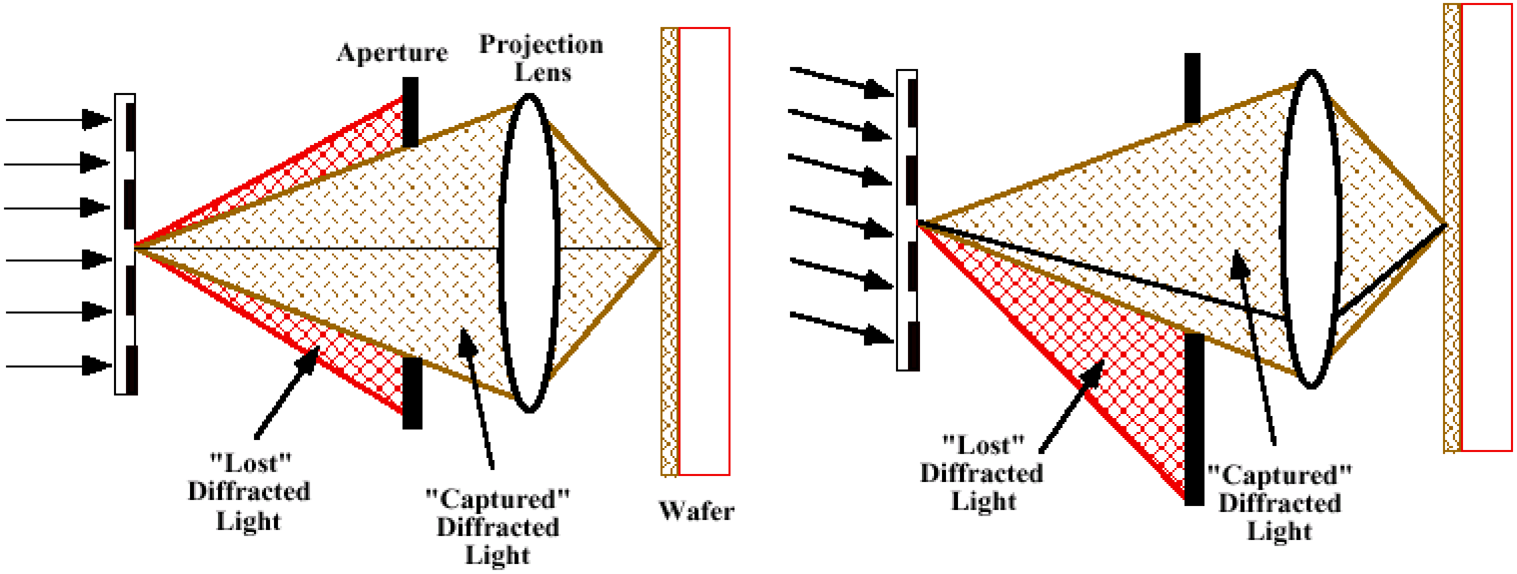


Figure 1. The impact of partial coherence on linewidth is very different for isolated and dense lines (in this case, *i*-line exposure with NA = 0.48 was used for nominal 0.5 μm lines).

Basic Optics : Microlithography

Off Axis illumination

- **Off Axis Illumination : Tilt the illuminator! Capture only 0 and +1 orders = 2 beam image formation! Effectively doubles the captured diffraction angle.**

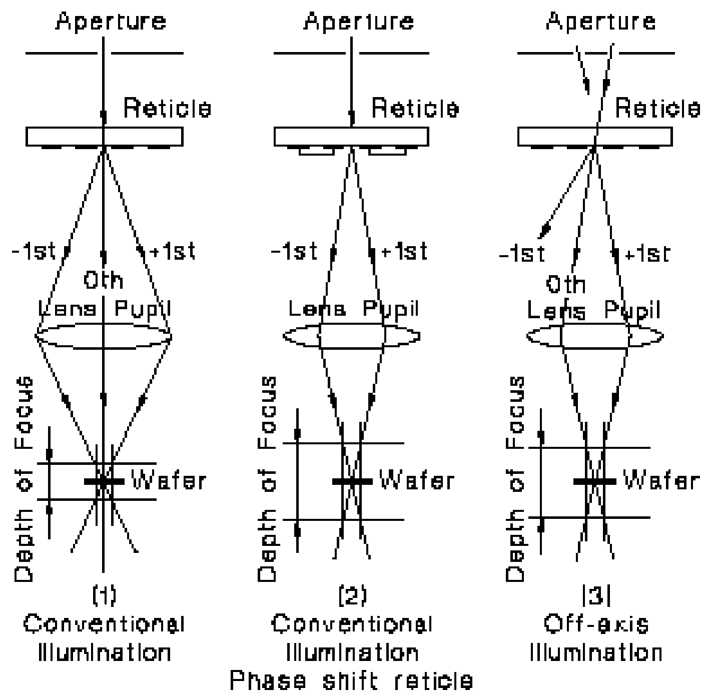


Basic Optics : Microlithography

Off Axis illumination

from ASML Richard Rogoff, "Photolithography using Aerial Illuminatyion in a Variable NA Wafer Stepper, SPIE March 1996

- **Three Beam Imaging conventional illumination(partially coherent) Vs Two beam Imaging Off axis.**
- **KEY RESULT: 2 beam = no phase shift when focal plane moves = increased DOF!**



Basic Optics : Microlithography

Off Axis illumination

- **Three Beam Imaging conventional illumination(partially coherent) Vs Two beam Imaging Off axis.**

Three-Wave Interference:

Plane wave: $E = E_0 \exp(i \vec{k}\,\vec{u}) = E_0 \exp(2i\pi/\lambda\ (x \sin\alpha + z \cos\alpha))$

Sum of 3 waves with angles 0, α and $-\alpha$:

$E = E_0 \exp((2i\pi/\lambda)\ z) + E_1 \exp((2i\pi/\lambda)\ (x \sin\alpha + z \cos\alpha)) + E_1 \exp((2i\pi/\lambda)\ (-x \sin\alpha + z \cos\alpha))$

$E = E_0 \exp((2i\pi/\lambda)\ z) + 2\ E_1 \exp((2i\pi/\lambda)\ z \cos\alpha)\ \cos((2\pi/\lambda)\ x \sin\alpha)$

$I = E\,E^* = E_0^{\ 2} + 4\ E_1^{\ 2} \cos^2((2\pi/\lambda)\ x \sin\alpha) + 2\ E_0 E_1 \cos((2\pi/\lambda)\ x \sin\alpha) \cos((2\pi/\lambda)\ z\ (1-\cos\alpha))$

z dependence (finite depth of focus)

Two-Wave Interference:

Sum of 2 waves with angles α and $-\alpha$:

$E = E_0 \exp((2i\pi/\lambda)\ (x \sin\alpha + z \cos\alpha)) + E_0 \exp((2i\pi/\lambda)\ (-x \sin\alpha + z \cos\alpha))$

$E = 2\ E_0 \exp((2i\pi/\lambda)\ z \cos\alpha)\ \cos((2\pi/\lambda)\ x \sin\alpha)$

$I = E\,E^* = 4\ E_0^{\ 2} \cos^2((2\pi/\lambda)\ x \sin\alpha)$

Pitch $= \lambda / (2 \sin\alpha)$, no z dependence (infinite depth of focus)

Two-Wave Interference: alternating aperture phase-shifting masks, off-axis illumination (when 0 and +/- 1 are symmetrical around the optical axis (α and $-\alpha$))

Three-Wave Interference: on-axis illumination

Off Axis illumination: Two beam Imaging

Incident Off axis illumination angle = θ

Diffraction angle = $2\theta = \lambda/p$

Maximum DOF requires:

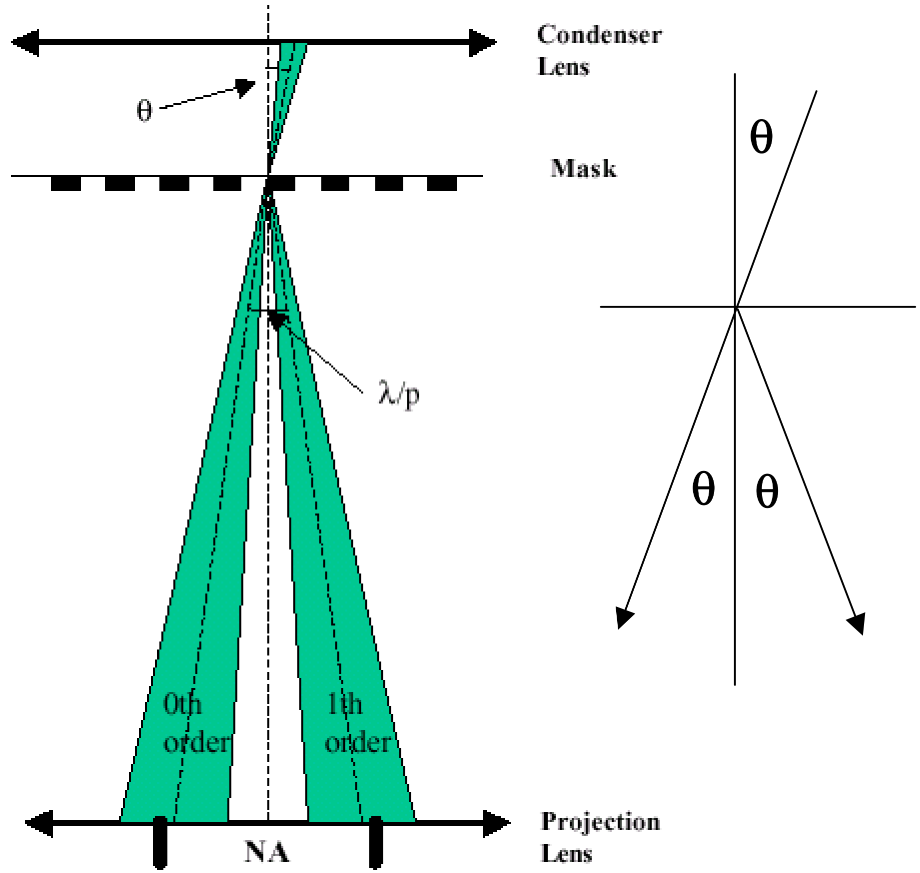
$$\mathbf{Sin\theta = \lambda/2p}$$

- Resolution (pitch p) limit for Off axis illumination system
- **$p = \lambda/NA\ (1 + \sin\theta/NA)$; sin** θ = off axis illumination incident angle on ret.

- Let **$\sin\theta/NA = \sigma_o$**

$$\sigma_o = \lambda/2pNA$$

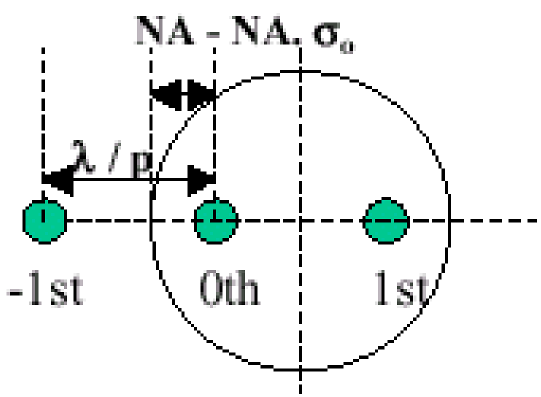
$$p = \lambda/NA\ (1 + \sigma_o)$$



Basic Optics : Microlithography

Off Axis illumination: Improved resolution and DOF

Resolution Improvement: in theory pitch down to $\lambda/2.NA$
Depth of Focus Improvement: Defocus creates a phase error for each diffraction order which is proportional to the square of the radial position within the pupil. For off-axis illumination the 0th and 1st order can have the same distance from the center of the pupil. The relative phase difference between the 0th and 1st orders due to defocus will be zero thus leading to less sensitivity through focus.



$\sigma_o = \lambda/2pNA$

$p = \lambda/NA\ (1 + \sigma_o)$

The maximum DOF requires only two beam 0 and +1 orders entering the lens E.P.

Means:

Max DOF: NA-(NA $\boldsymbol{\sigma_o}$)< $\boldsymbol{\lambda/p}$ or $1 - \boldsymbol{\sigma_o} < \boldsymbol{\lambda/2pNA}$

Worst case Pitch: $1 - \boldsymbol{\sigma_o} = \boldsymbol{\lambda/pNA}$ **or**

$\boldsymbol{\sigma_o} > 1 - \boldsymbol{\lambda/pNA}$ **and** $\boldsymbol{p_w = \lambda/NA\ (1 - \sigma_o)}$

Basic Optics : Microlithography

Partial Coherence (sigma or fill factor)

from ASML Richard Rogoff, "Photolithography using Aerial Illuminatyion in a Variable NA Wafer Stepper, SPIE March 1996

- **Imaging: projection optics and illumination impact on resolution**

The adapted Rayleigh's criterion for resolution is shown in equation 1. This describes the resolution limit of the lens (R_{limit}) and shows that the projection lens as well as the illumination optics play an important role in the imaging performance of a photolithographic system.

$$R_{limit} \propto \frac{\lambda}{NA\left(1+\sigma+\frac{\sin(\Theta)}{NA}\right)} \qquad (1)$$

Θ = angle of incident rays on the reticle. $\Theta > 0$ = Off axis ilumination (OAI)

$$Where \left(\sigma+\frac{\sin(\Theta)}{NA}\right)<1$$

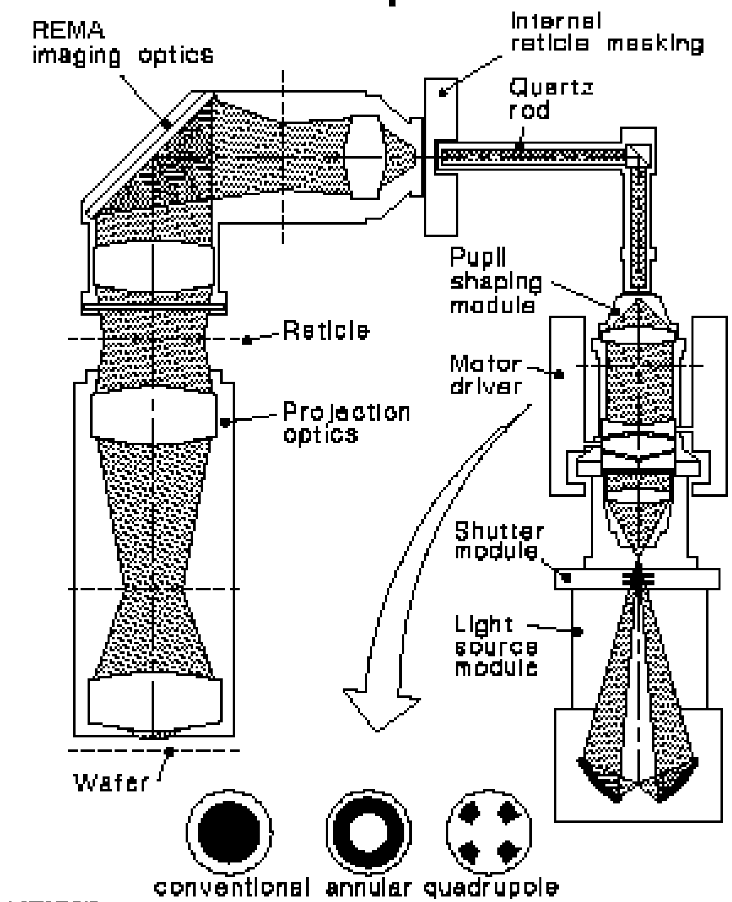
The main design parameter of the projection lens is Numerical Aperture (NA), while the illumination system determines the other parameters: λ (wavelength of the light source), σ (spatial partial coherence factor) and θ (angle of incidence of rays at the reticle as seen from the wafer level). Illumination sources with $\theta > 0$ are often described as "off-axis".

Basic Optics : Microlithography

Off Axis illumination

from ASML Richard Rogoff, “Photolithography using Aerial Illuminatyion in a Variable NA Wafer Stepper, SPIE March 1996

- **ASML Illuminator for both partial coherence and off axis!**

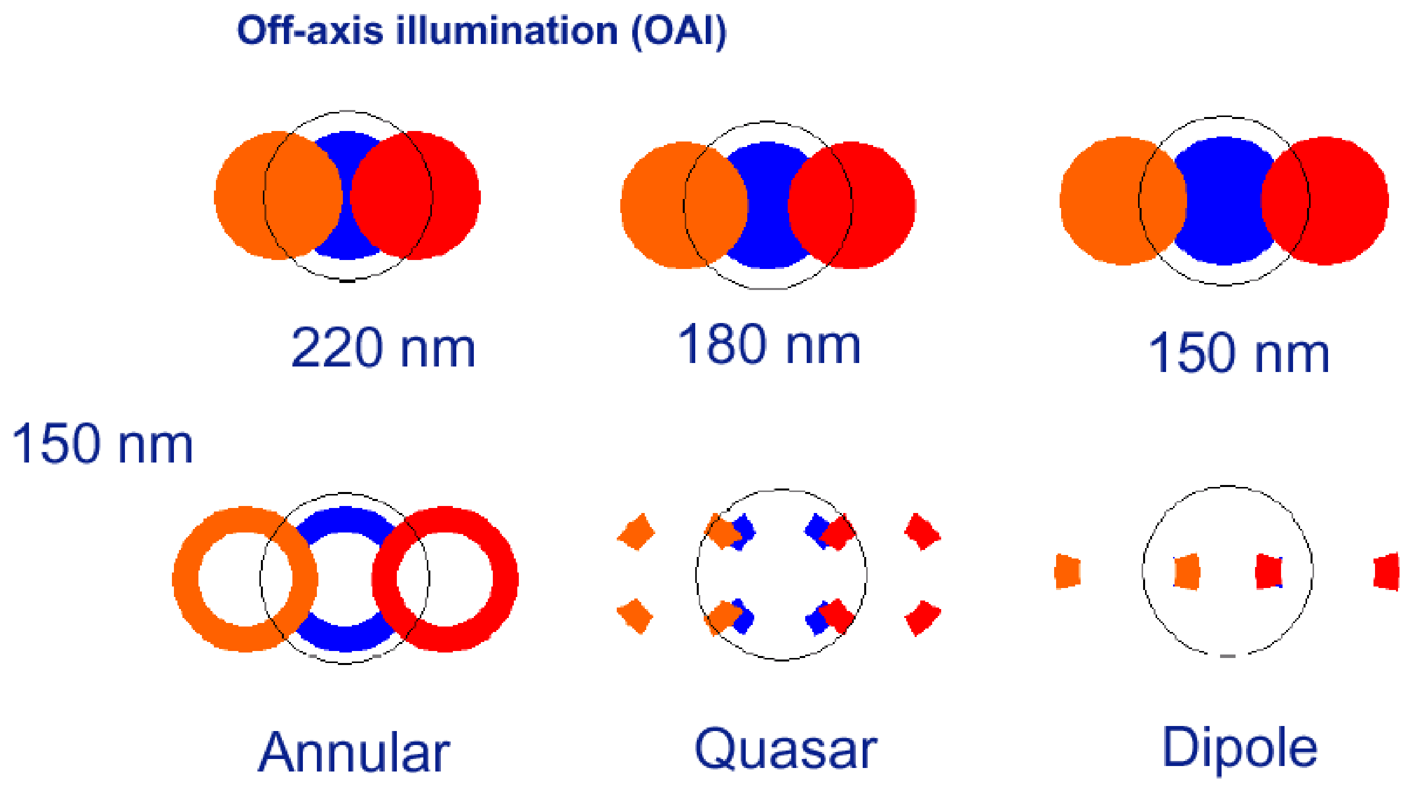


Basic Optics : Microlithography

Off Axis illumination

OAI : **annular good for all for features**

Quadrapole biggest benefit for vertical and horizontal dense linewidths



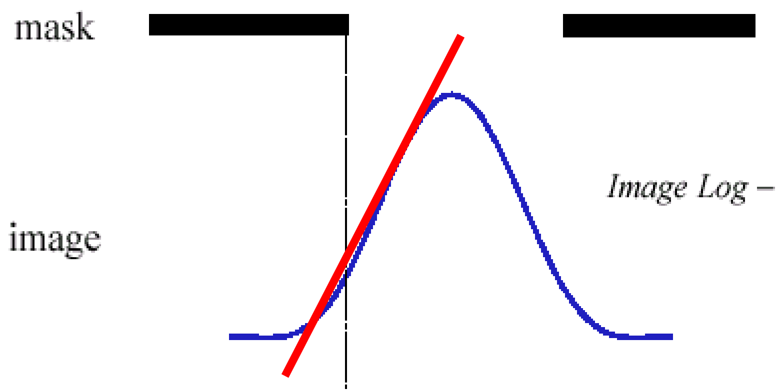
Basic Optics : Microlithography

Off Axis illumination :NILS

NILS : Normalized image log slope: slope of aerial image intensity (NILS) pattern multiplied by the feature width. This is a metric for the quality of the aerial image. Values between 6 – 8 are good! Can use in Prolith for quick Simulations

$$NILS = w\frac{d\ln(I)}{dx} \qquad (3)$$

The NILS is the best single metric to judge the lithographic usefulness of an aerial image.



$$Image\ Log-Slope = \frac{1}{I}\frac{dI}{dx} = \frac{d\ln(I)}{dx}$$

Figure 2. Image Log-Slope (or the Normalized Image Log-Slope, NILS) is the best single metric of image quality for lithographic applications.

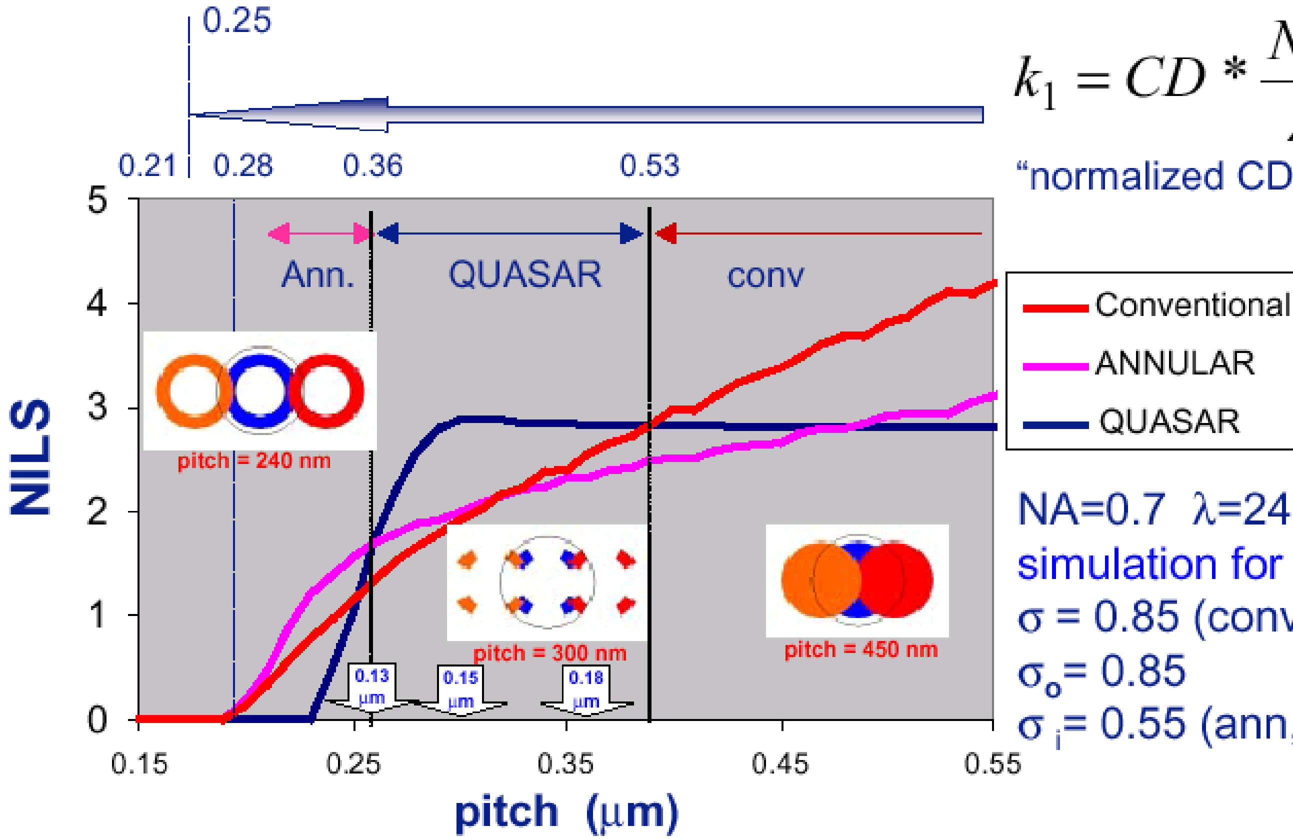
Basic Optics : Microlithography

Off Axis illumination

NILS

Illumination enhancement techniques

OAI and Normalized Image Log Slope



$$k_1 = CD * \frac{NA}{\lambda}$$

"normalized CD"

NA=0.7 λ=248 nm

simulation for L/S (1:1)

σ = 0.85 (conv.)

σ_o= 0.85

σ_i= 0.55 (ann, QUASAR

Basic Optics : Microlithography

MTF and Contrast

http://www.asml.com/support/pdf/94083.pdf

- MTF curves for incoherent, partially coherent, and off axis illumination..

OAI: 2 diffracted beams out of phase for low frequencies reduces image modulation.

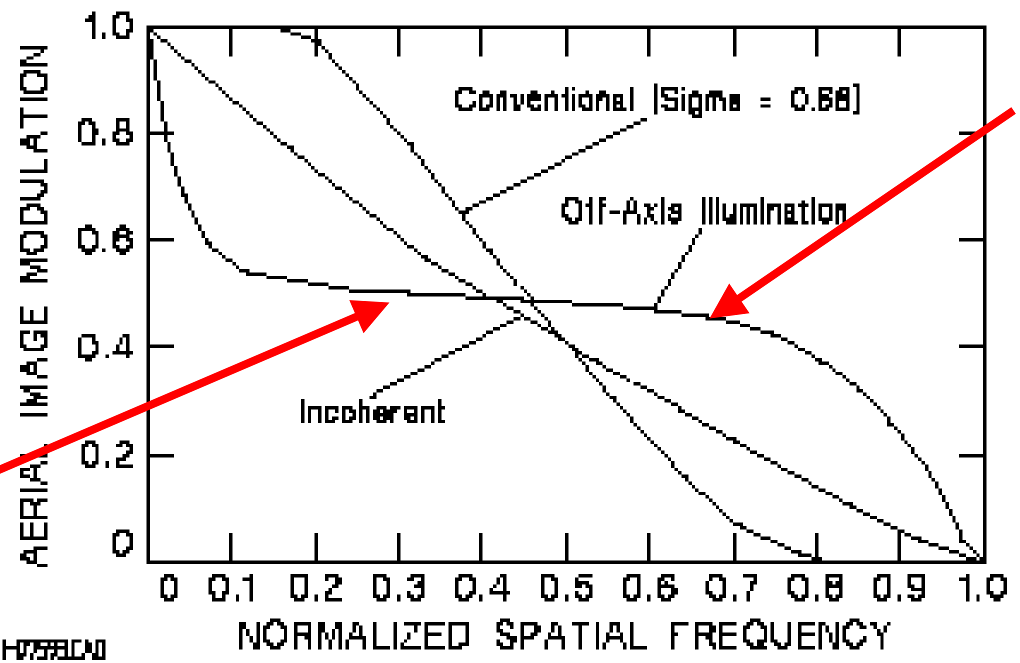


Figure 2 Contrast curves for different illumination conditions and spatial frequencies (image size).

OAI: 2 diffracted beams in phase and larger diffraction angle captured for high frequencies increases image modulation.

Basic Optics : Microlithography

Resolution, Depth of Focus, and Depth of field

- Forbidden Pitch
  - **Understanding the Forbidden Pitch Phenomenon and Assist Feature Placement**

  - Xuelong Shi[1], Stephen Hsu[1], Fung Chen[1], Michael Hsu[1], Robert J. Socha[2], Micea Dusa[2]

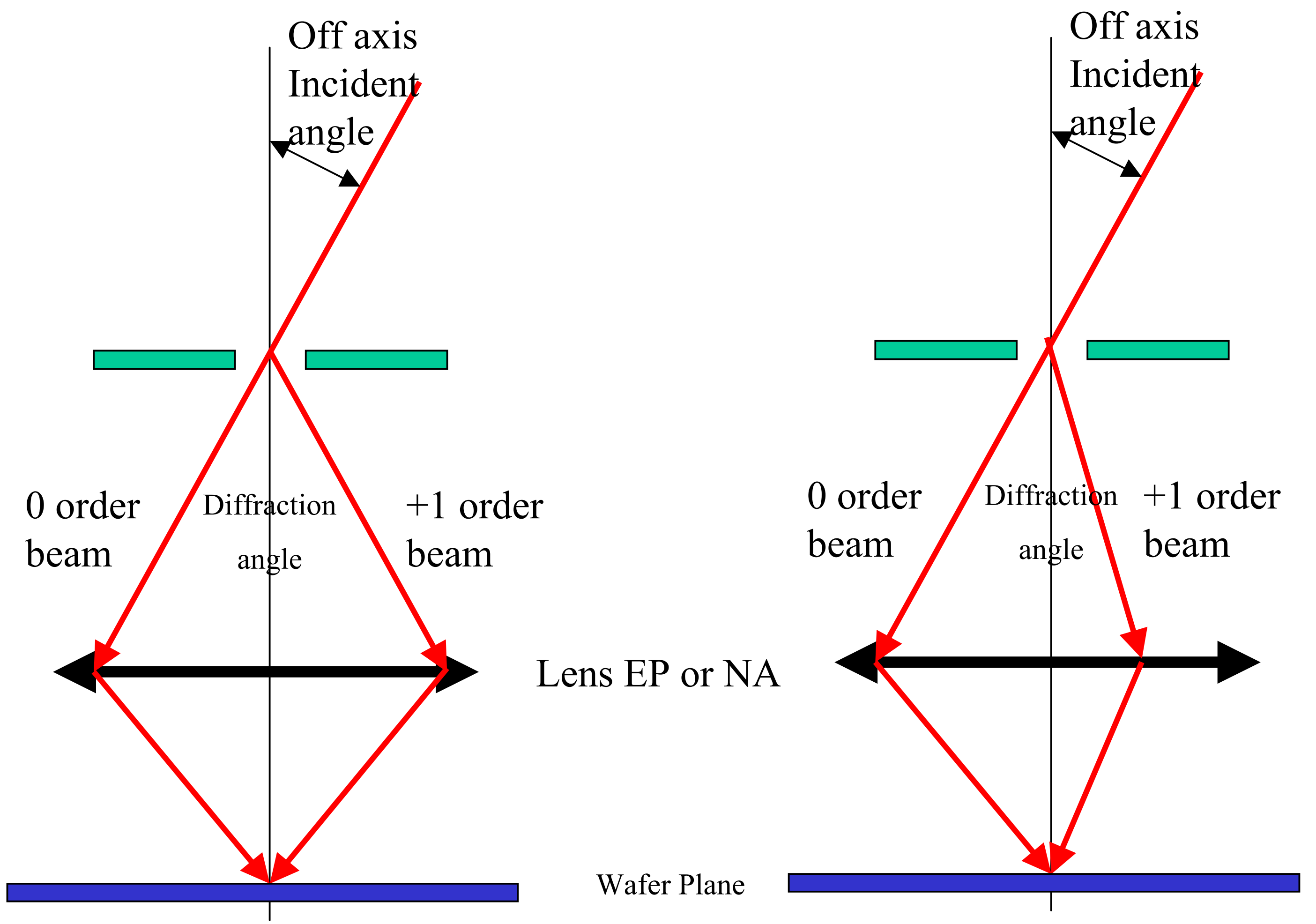
1. ASML MaskTools, Inc. 4800 Great America Parkway, Suite 400, Santa Clara, CA 95054
2. ASML, TDC Group 4800 Great America Parkway, Suite 400, Santa Clara, CA 95054

Presented at SPIE, 2002

- **Abstract**

- Optical proximity effect is a well-known phenomenon in photolithography. Such an effect results from the structural interaction between the main feature and the neighboring features. Recent observations have shown that such structural interactions not only affect the critical dimension of the main feature at the image plane, but also the exposure latitude of the main feature. In this paper, it has been shown that the variation of the critical dimension as well as the exposure latitude of the main feature is a direct consequence of light field interference between the main feature and the neighboring features. Depending on the phase of the field produced by the neighboring features, the main feature exposure latitude can be improved by constructive light field interference, or degraded by destructive light field interference.
- The phase of the field produced by the neighboring features can be shown to be dependent on the pitch as well as the illumination angle. For a given illumination, the forbidden pitch lies in the location where the field produced by the neighboring features interferes with the field of the main feature destructively. The theoretical analysis given here offers the tool to map out the forbidden pitch locations for any feature size and illumination conditions. More importantly, it provides the theoretical ground for illumination design in order to suppress the forbidden pitch phenomenon, and for scattering bar placement to achieve optimal performance as well.

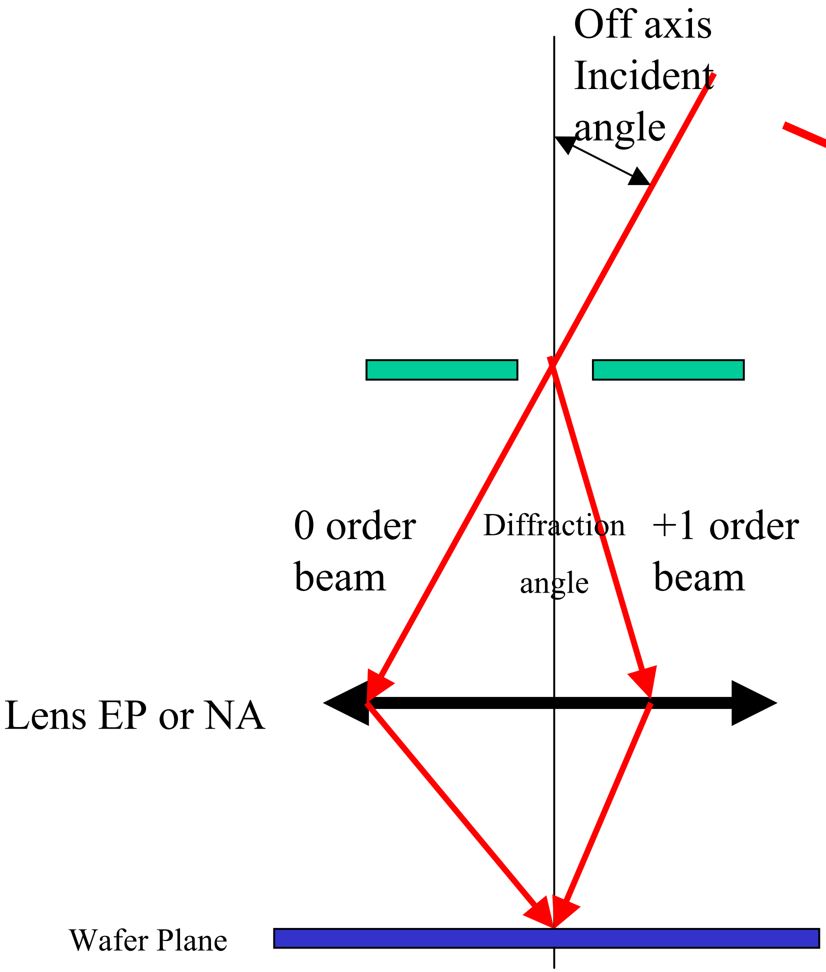
OAI Forbidden Pitch

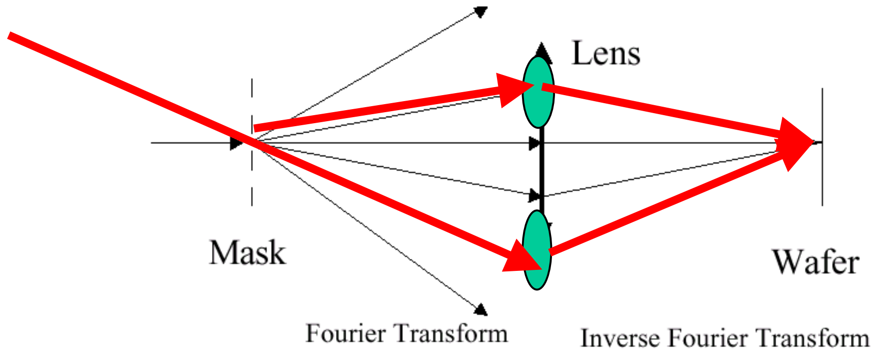


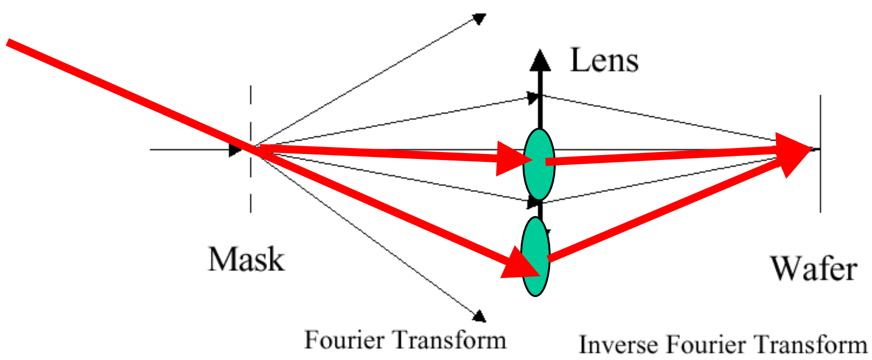
Equal path lengths = optimal mask pitch increased res & DOF

Unequal path lengths = bad or forbidden pitch = reduced image contrast and resolution

OAI Forbidden Pitch



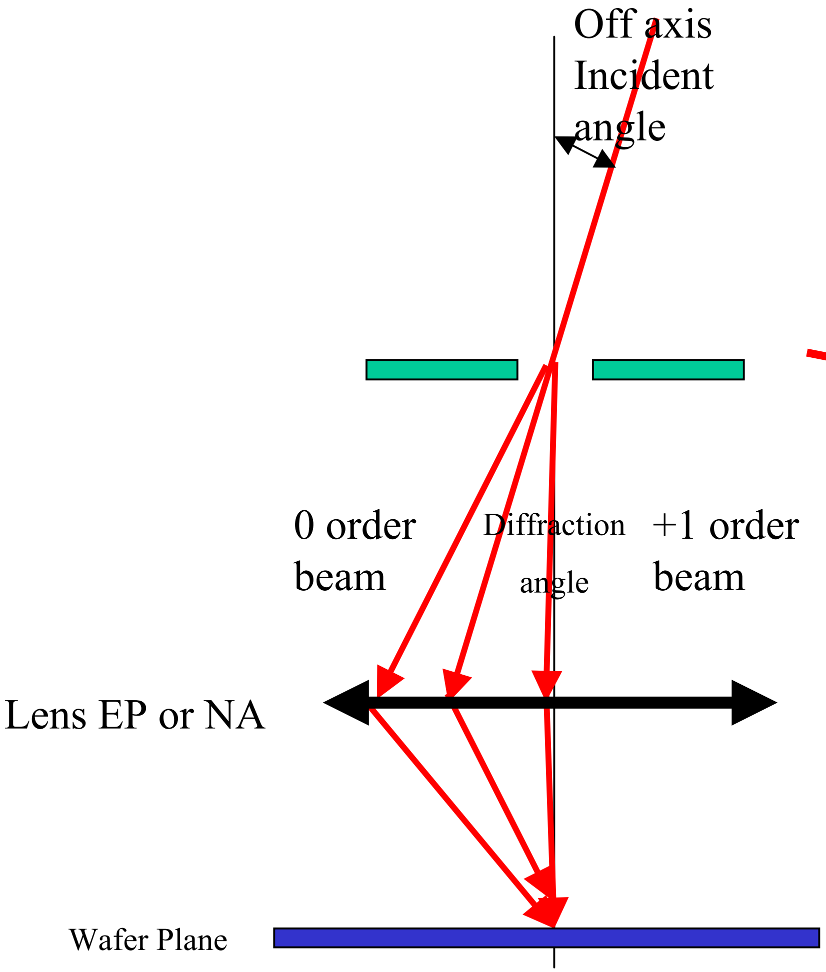


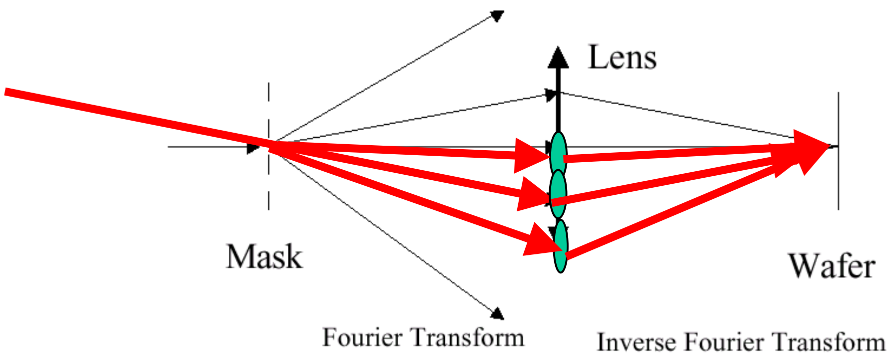


Unequal path lengths = bad or forbidden pitch = reduced image contrast and resolution

Unequal path lengths result in poor image contrast

OAI Forbidden Pitch





Unequal path lengths +1,0,-1 orders result in very poor image contrast and DOF

Unequal path lengths and +1,0,-1 orders entering lens = bad or forbidden pitch = reduced DOF and resolution

Basic Optics : Microlithography

Resolution KLA-Tencor Chris Mack Answers

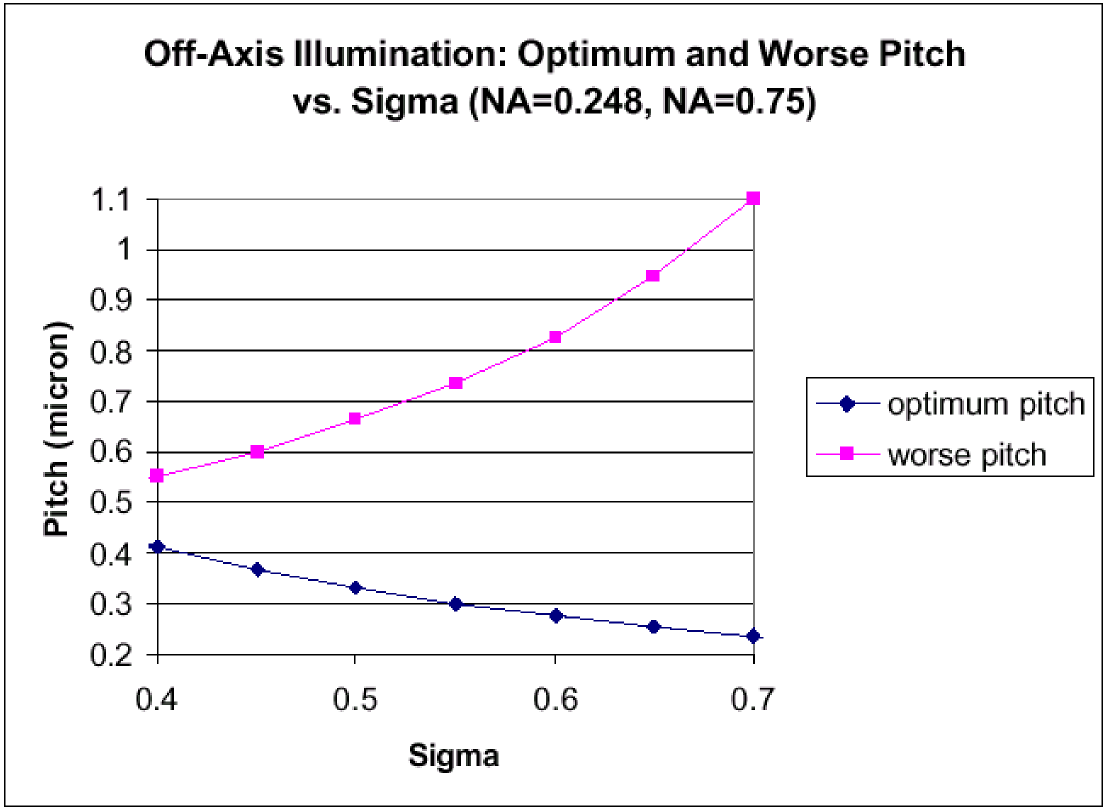
- Forbidden Pitch

Q I read a paper that talked about "forbidden pitches". What is a forbidden pitch and why can't I use them?

A The term "forbidden pitch" is frequently used when imaging with off-axis illumination, such as quadrupole or annular illumination. These illuminations bring light to the mask at an oblique angle. Diffraction of light from the patterns on the mask occurs at angles that depend on the pitch of the patterns. Off-axis illumination is optimized so that the angle of illumination striking the mask matches the angle of diffraction for a given pitch to give optimum performance (usually be spacing the diffraction orders evenly about the center of the stepper lens). This angle of illumination is only optimum at this one pitch. When the off-axis illumination is optimized for one pitch (usually the smallest pitch on the mask), there will always be some other pitch where the angle of the illumination works with the angle of diffraction to produce a very bad distribution of diffraction orders in the lens (one diffraction order in the middle of the lens and the others at the outer edges of the lens), resulting in poor depth of focus for that pitch. We call this pitch "forbidden" because of its poor lithographic response, and because we hope the chip designers will listen to us and avoid putting that pitch on the mask.

Basic Optics : Microlithography

***Off Axis illumination** Forbidden Pitch*
or Worse Pitch



For example:
for sigma=0.6,
optimum pitch=0.28 micron
worse pitch=0.83 micron

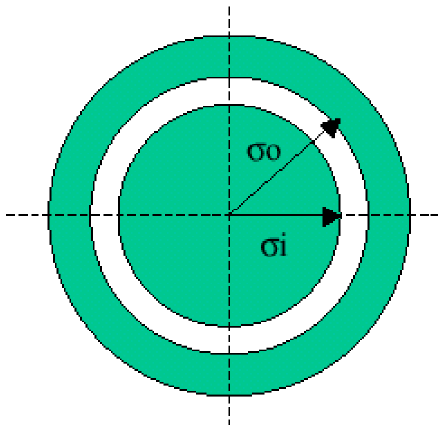
Optimum pitch $\mathbf{p_o = \lambda / (2. \sigma_o .NA)}$

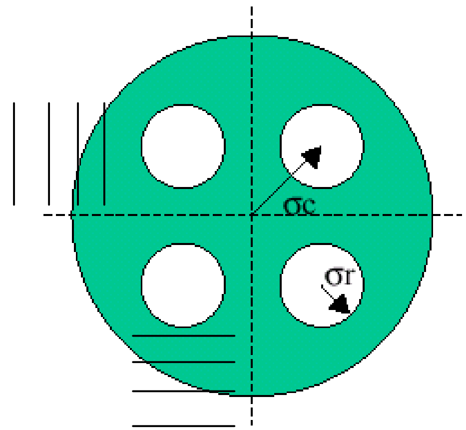
Worse pitch: $\mathbf{p_w = \lambda /((1 - \sigma_o).NA)}$

Ref: C. Mack, Proc. SPIE vol. 1927, 1993, pp. 125-136.

Basic Optics : Microlithography

Off Axis illumination Forbidden Pitch





Like spatial filtering only vertical and horizontal diffracted orders get through

First pass approximation: $\boldsymbol{\sigma}_{op} = (\boldsymbol{\sigma}_o + \boldsymbol{\sigma}_i)/2$
Optimum sigma $\boldsymbol{\sigma}_{op} = \lambda / 2.\ p_o.NA$
Minimum sigma $\boldsymbol{\sigma}_{op} = 1 - \lambda / p_o.NA$
Worse pitch: $p_w = \lambda /(1 - \sigma_o).NA$

First pass approximation: $\boldsymbol{\sigma}_{op} = \boldsymbol{\sigma}_c /\mathrm{sqrt}(2)$
Optimum sigma $\boldsymbol{\sigma}_{op} = \lambda / 2.\ p_o.NA$
Minimum sigma $\boldsymbol{\sigma}_{op} = 1 - \lambda / p_o.NA$
Worse pitch: $p_w = \lambda /(1 - \sigma_o).NA$

More accurate optimization requires simulation and experimental work

Ref: C. Mack, Proc. SPIE vol. 1927, 1993, pp. 125-136.

Basic Optics : Microlithography

Projection printing: Telecentric system

- Telecentricity: Source is focused in entrance pupil:
- Image side: Image size (magnification) is invariant with wafer defocus!
- Object side: Image size (magnification) is invariant with object position.

Basic Optics : Microlithography

Projection printing: Telecentric system

- The source in focused in the Entrance pupil. The chief ray from this properly focused condenser emerges from parallel to optical axis! This causes the Exit Pupil to be focused at infinity.

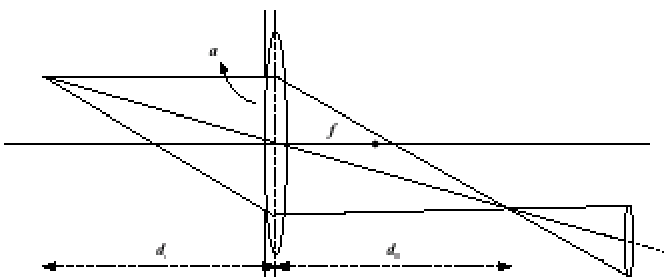


Figure 1. In a conventional imaging system, each scene point produces a light-cone. The orientation as well as the half-angle of the light-cone varies with the location of the scene point.

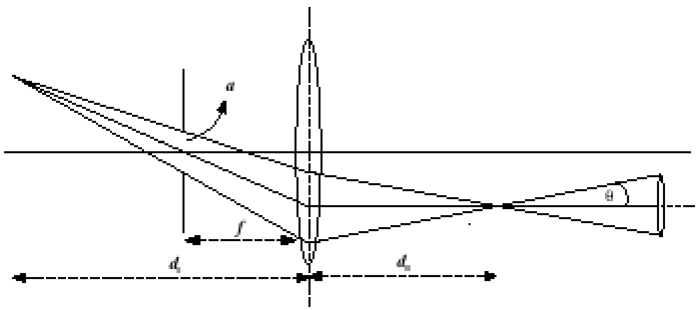


Figure 2. A telecentric system is obtained by placing a small aperture at the front focal plane. In this case, the axis of the light-cone is parallel to the optical axis for any scene point. The half-angle θ of the cone, is a system constant determined by the f-number of the system, $f_\sigma = \frac{f}{a}$.

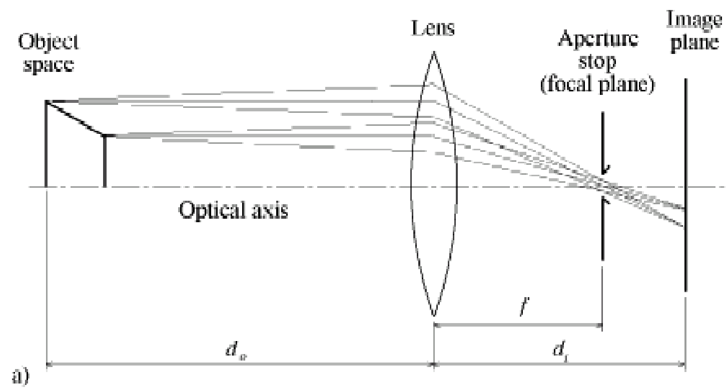
Basic Optics : Microlithography
Projection printing: Telecentric system

- The condenser lens is used to focus the source in the entrance pupil.
- **PROPER CONDENSER FOCUS:** Source focused in Entrance pupil: chief ray emerges from parallel to optical axis! This causes the Exit Pupil to be focused at infinity. Image location (I.e. defocused) does not change image size (magnification).
- **POSITIVE CONDENSER FOCUS:** Source focused before entrance pupil: chief ray emerges converging! Image location (I.e. defocused) causes change in image size (magnification). Image is smaller as the image plane moves away from the optical best focus.
- **NEGATIVE CONDENSER FOCUS:** Source focused behind entrance pupil: chief ray emerges diverging! Image location (I.e. defocused) causes change in image size (magnification). Image is larger as the image plane moves away from the optical best focus.

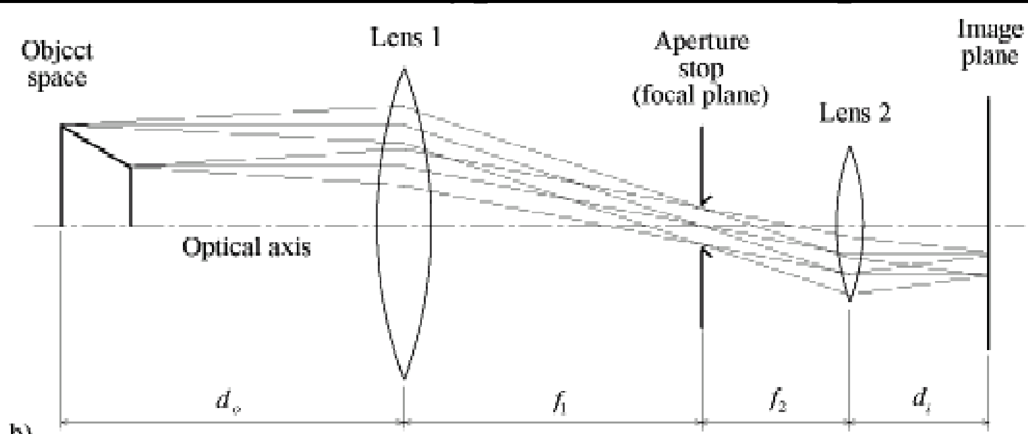
Basic Optics : Microlithography

Projection printing: Telecentric system

- **Single side telecentric (object): This is how older ASML's adjusted magnification**



- **Double side telecentric (typical modern exposure tool)**



Basic Optics : Microlithography

Projection printing: Telecentric system

- Nikon stepper : telecentric lens

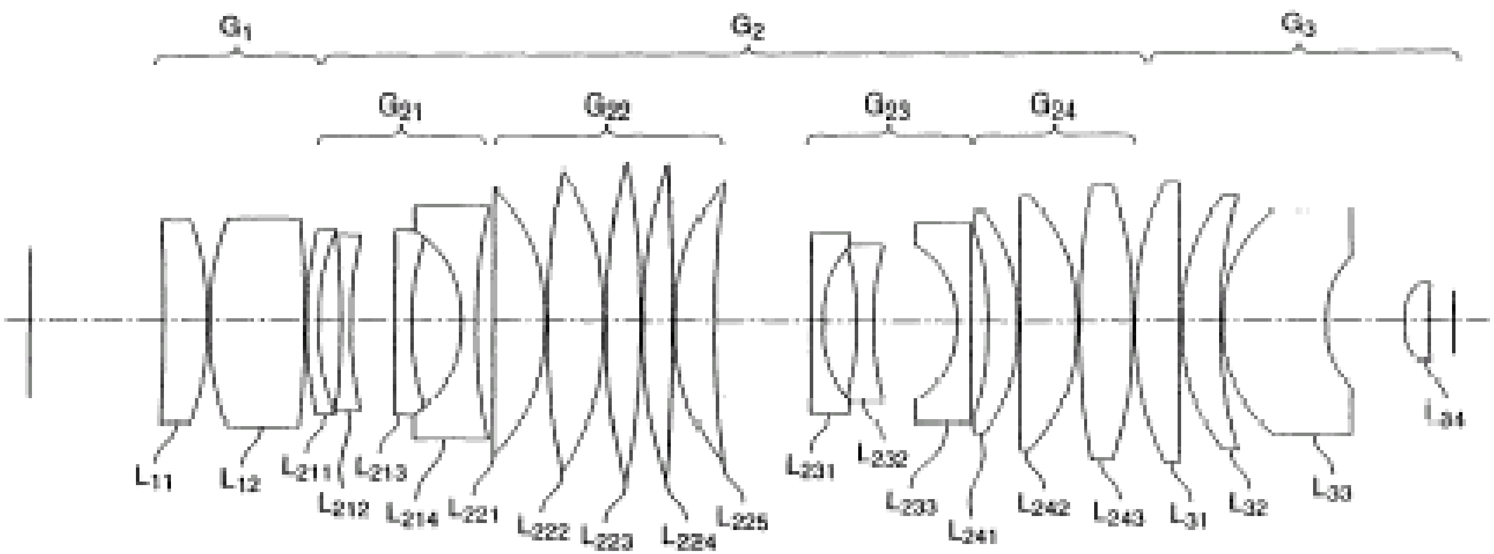
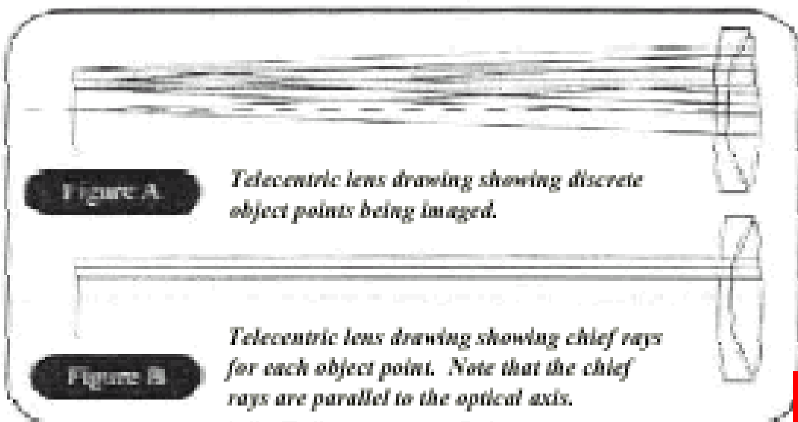


FIG. 9

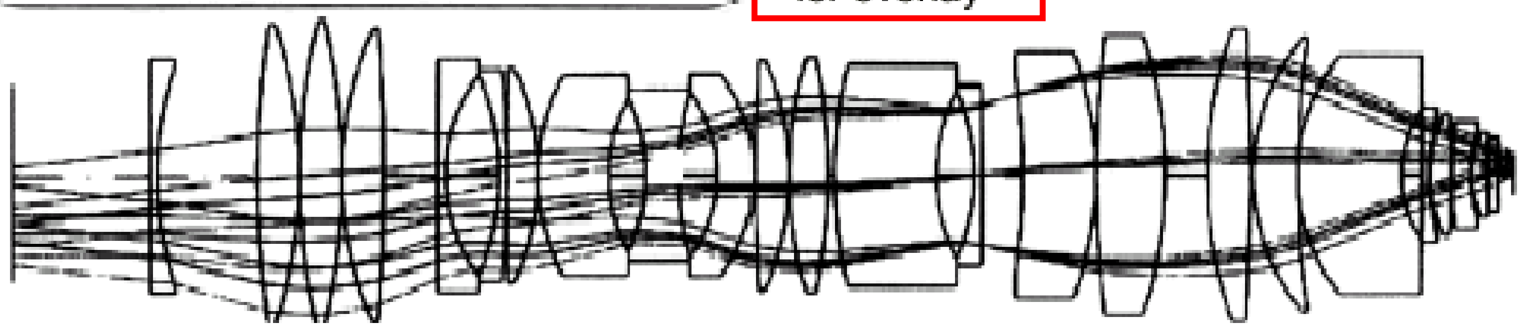
Basic Optics : Microlithography
Projection printing: Telecentric system

Telecentricity -1



Scanner / stepper lenses are doubly telecentric -- telecentric in both mask illumination plane and at object wafer plane

Doubly telecentric design ensures a constant magnification over the working distance -- very important for overlay



Basic Optics : Microlithography

Optical Designs

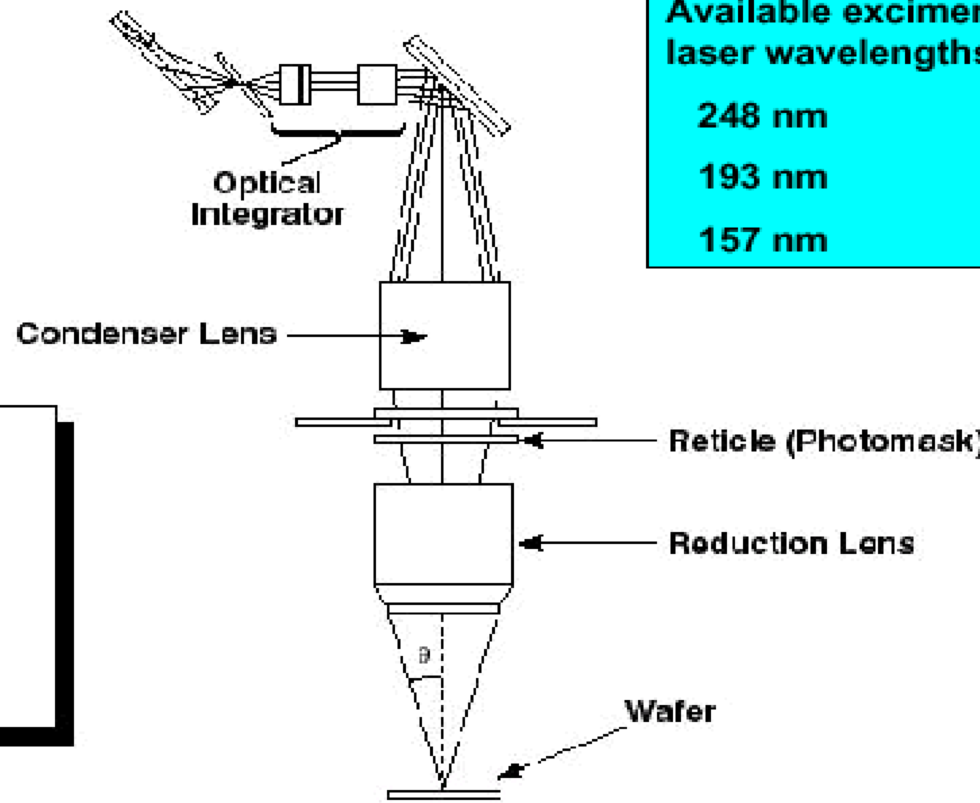
- Basic microlithographic exposure tool Optical designs:
- Dioptric: All refractive optics (lens): most common
- Catoptric: All Reflective optics (Mirrors): Micralign
- Catadioptric : Combination of refractive and reflective optics: SVGL scanner, Ultratech 1 X

Basic Optics : Microlithography

Optical Designs: Dioptric

Available excimer laser wavelengths:

- 248 nm
- 193 nm
- 157 nm



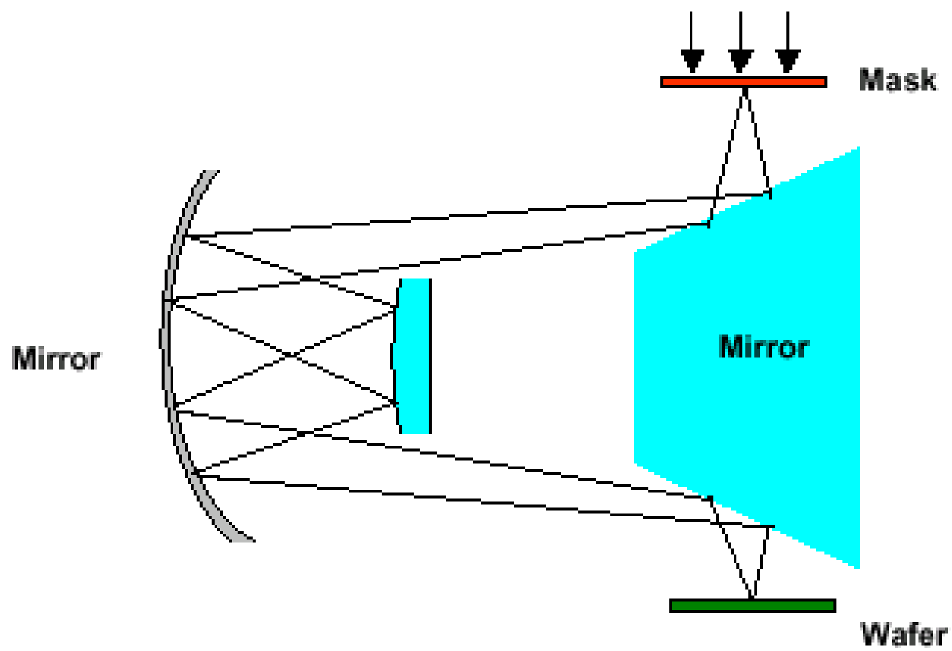
$$\text{Feature Size} = k_1 \frac{\lambda}{NA}$$

$$NA = \sin\theta \approx \frac{1}{2f\#}$$

Basic Optics : Microlithography

Optical Designs: Catoptric

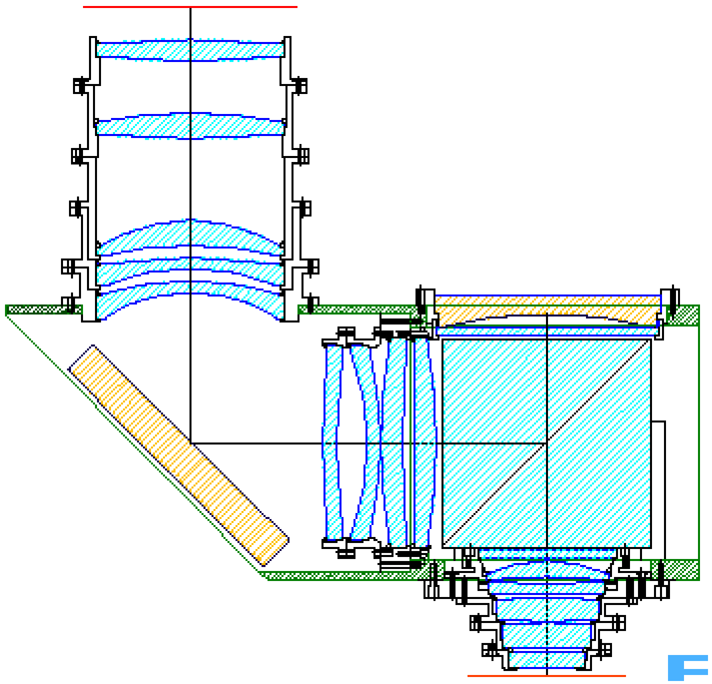
- Offner design: **Old Perkin Elmer 1X scanner**



Basic Optics : Microlithography

Optical Designs: Catadioptric

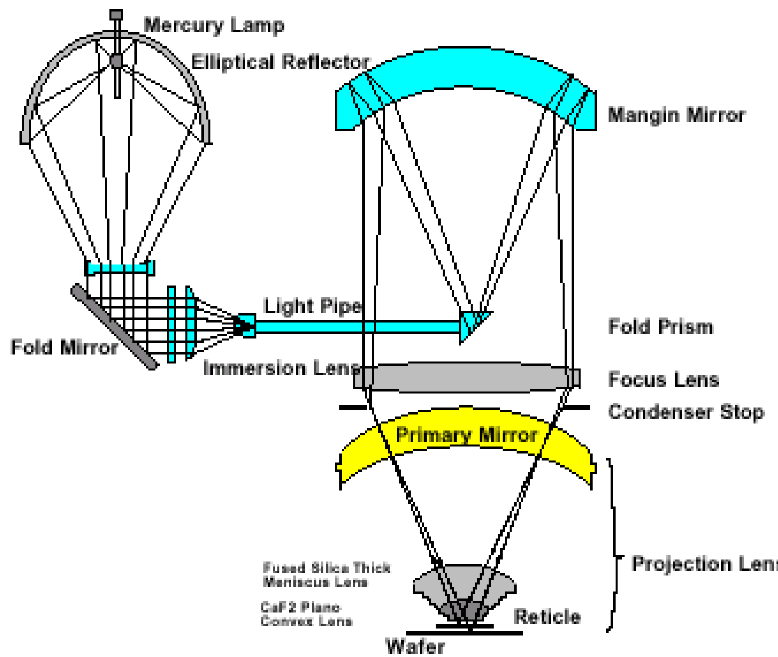
- SVGL: design beamsplitter (ArF)



Basic Optics : Microlithography

Optical Designs: Catadioptric

- Ultratech: Wynne-Dyson Design (1959)



NA : 0.7
Image field Ø 58 mm (25.6 x25.6 or 20.3 x 40.6)
Light source : mercury arc lamp