Nanometer Scale Patterning and Processing

Spring 2016

Lecture 7

Optical Lithography – Lithography System

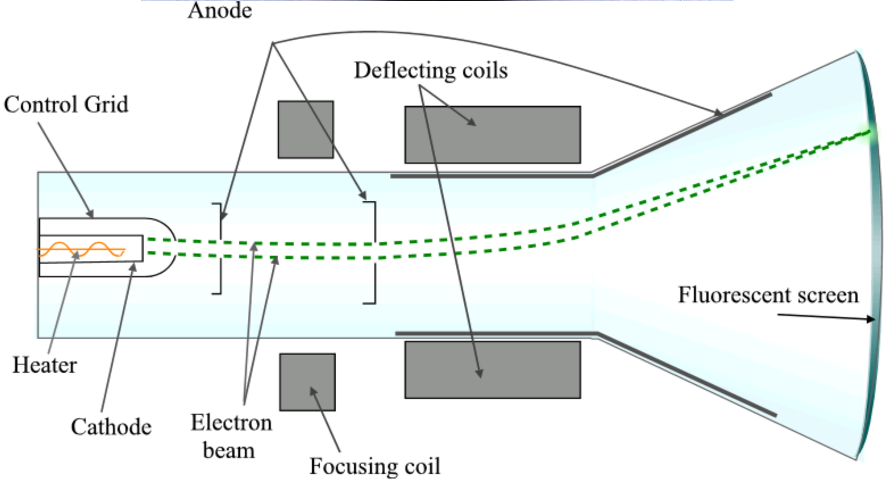
Importance of Lithography

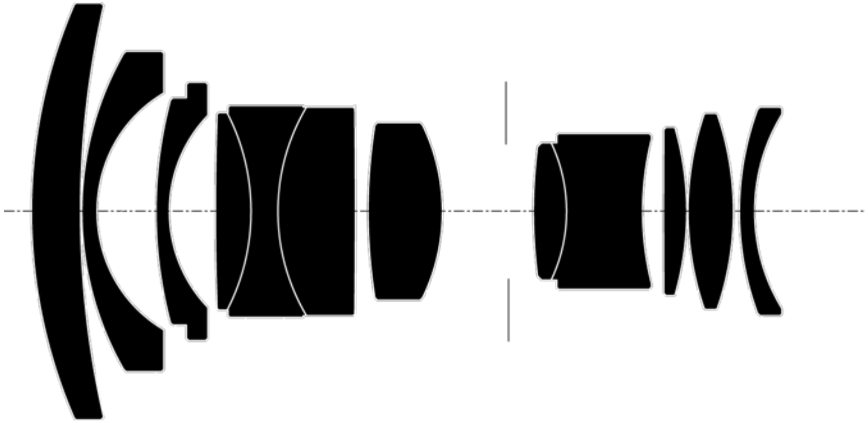
- It is the most critical process in the Integrated Circuit manufacturing
  - It defines technology generation
  - It determines the throughput
- *It encodes information, or human engineering effort, to the substrate*
- It will play an important role in the emerging nanotechnology

Two Aspects of Lithography:

Pattern Generation

Pattern Replication



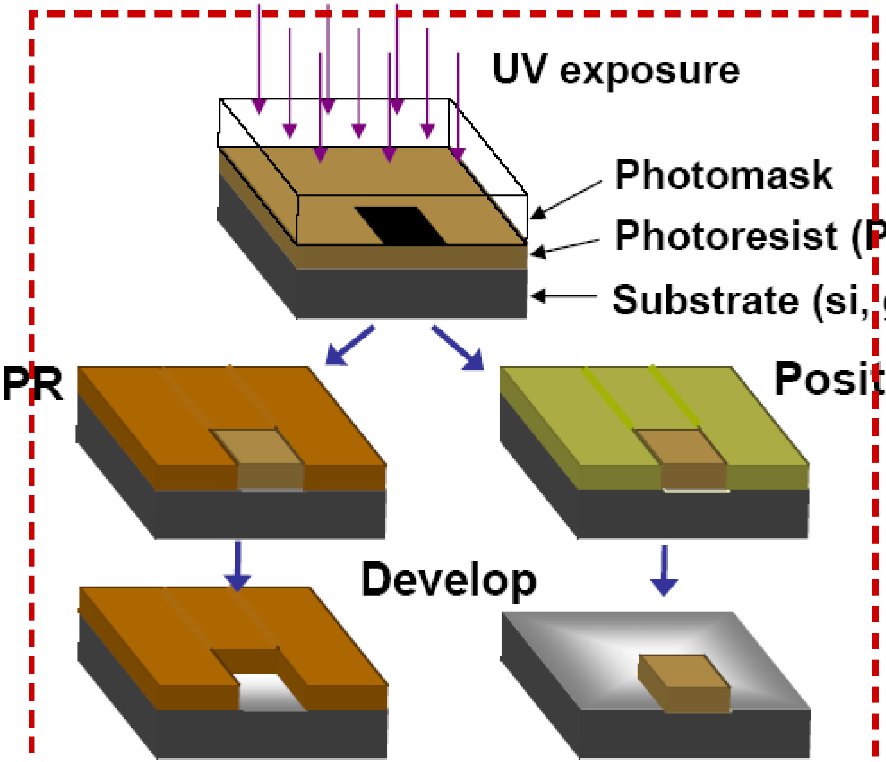


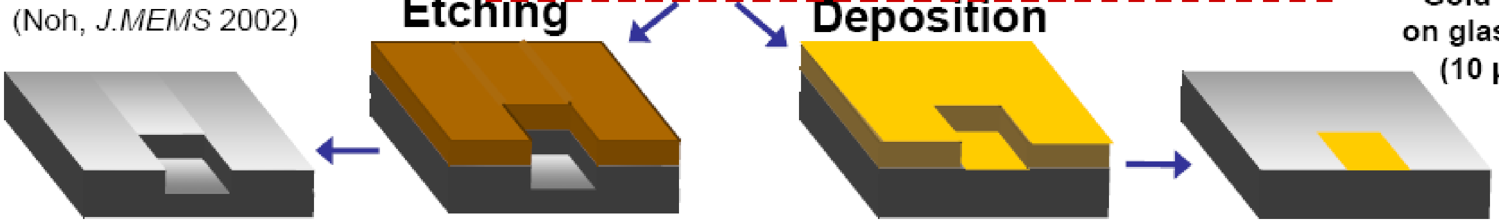
Resolution, uniformity, overlay, throughput

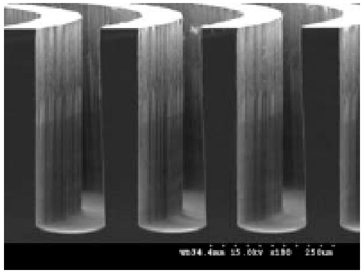
- **Photolithography:** Optical pattern transfer technique in which micro-pattern is transferred from a **photomask** to a **UV**-sensitive polymer layer (**photoresist**) coated on a substrate.

E-beam lithography
X-ray lithography
Soft lithography
Stereolithography

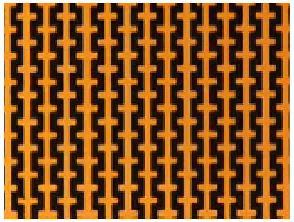
Photochemical reaction







Si microchannel
(Noh, *J.MEMS* 2002)

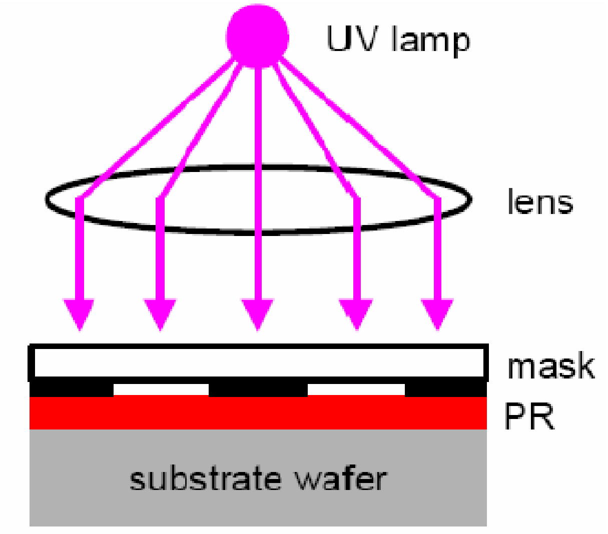


Gold electrodes on glass substrate (10 µm width)

Patterned PR is used as a masking material in the following process.
Pattern may be transferred to a coating layer instead of the substrate.

Three Major types of Optical Lithography

Contact Printing

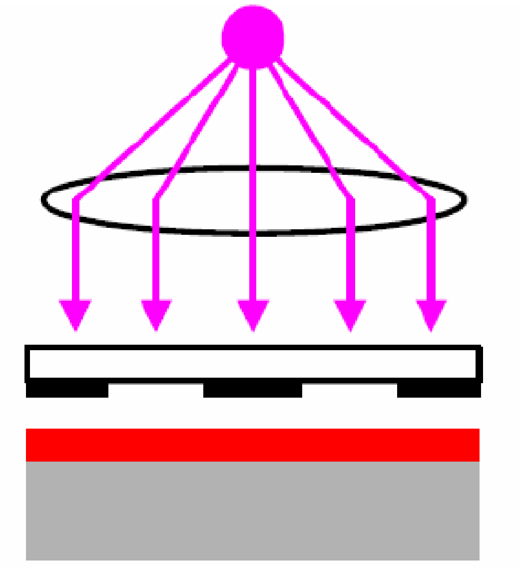


- Good resolution
- Degradation of mask
- Particulate contamination
- Standard mask aligners

Resolution: $\frac{3}{2}\sqrt{\lambda\left(g + t/2\right)}$

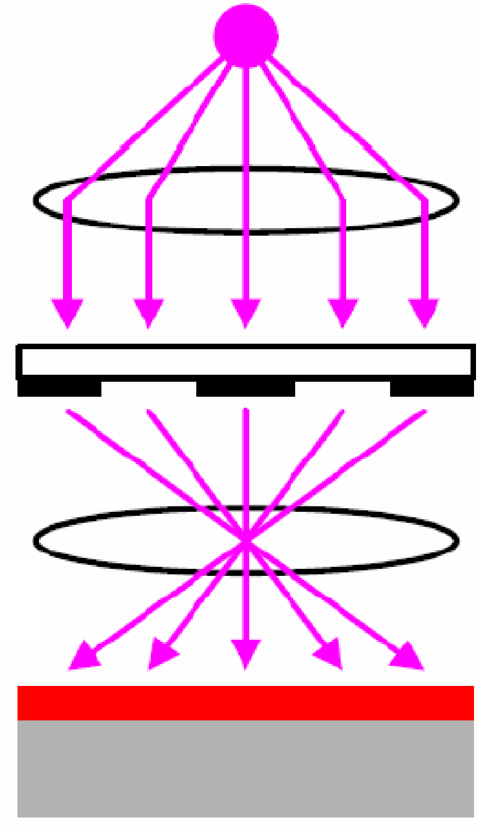
(g=gap, t=resist thickness)

Proximity Printing



- Eliminate mask damage and contamination
- Poor resolution due to light diffraction
- Standard mask aligners

Projection Printing



- Feature reduction
- Fast and expensive
- Pattern generators
- Used in IC industry

Some Contact Lithography Tools

MJB3 Mask Aligner

Karlsuss MA6 Mask Aligner

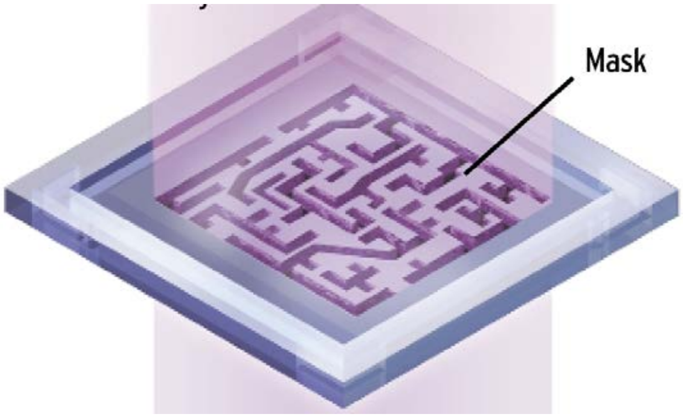
Exposure dose control

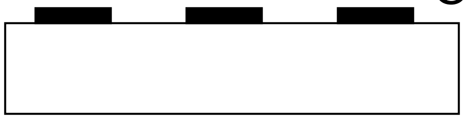
Dominant Player for Pattern Replication: Optical projection lithography (stepper/scanner)

- High cost: ~$50M
- High throughput (~90 300mm wafers per hour)
- Pattern is reduced by a factor of 4
- Mask not in contact with wafer

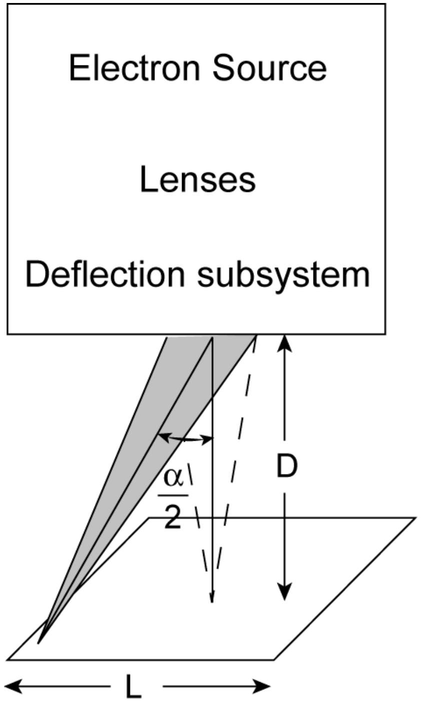
Resolution limited by the wavelength of the exposing light

Masks and Mask-making





Wet etch
or
Dry etch



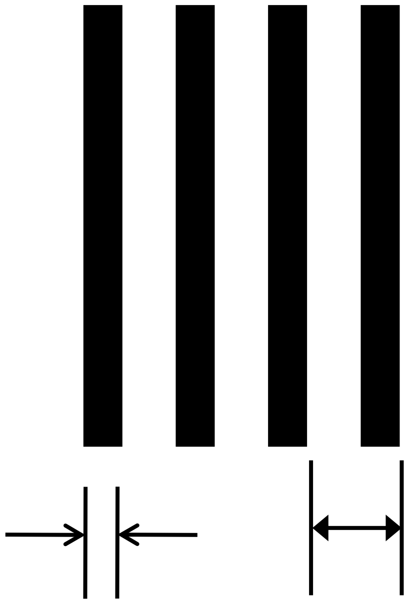
- Enables high-throughput replication
- Long turn-around time
- High-cost
- Placement accuracy
  - Environmental control
  - Frequent calibration
  - Spatial Phase-Locked E-beam litho
- Mask-writing:
  - Verification
  - Defect inspection
  - Repair

More on Photomasks

- **Types:**
  - Cr on soda lime glass (most common)
  - Cr on quartz glass (transparent to deep UV, expensive)
  - Photographic emulsion on soda lime glass (less expensive)
  - Fe_2O_3 on soda lime glass (semi-transparent to visible light)
  - High resolution laser printing on transparency
- Dimensions: 4” x 4” for 3 inch wafers, 5” x 5” for 4 inch wafers
- Polarity:
  - “light-field” = mostly clear, drawn feature = opaque
  - “dark-field” = mostly opaque, drawn feature = clear

Definition of Lithography Resolution

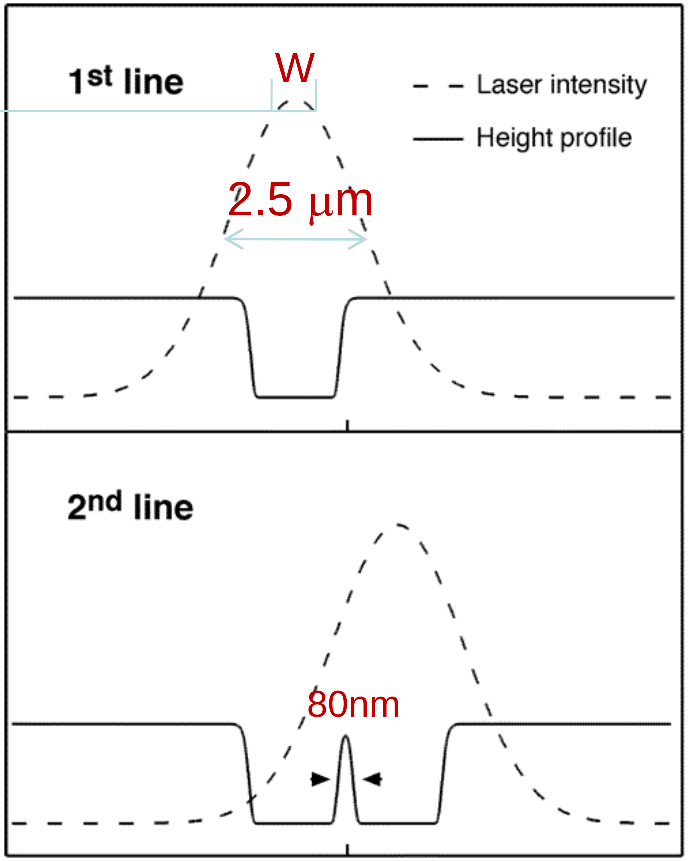
- To put a lot of transistors on a chip, they need to be close to each other.
- Pitches are limited by physics – minimum line-widths are not!
- The IC term for lithography is “half pitch”, though “resolution” is still used.



Linewidth + spacewidth = pitch

HP: half pitch

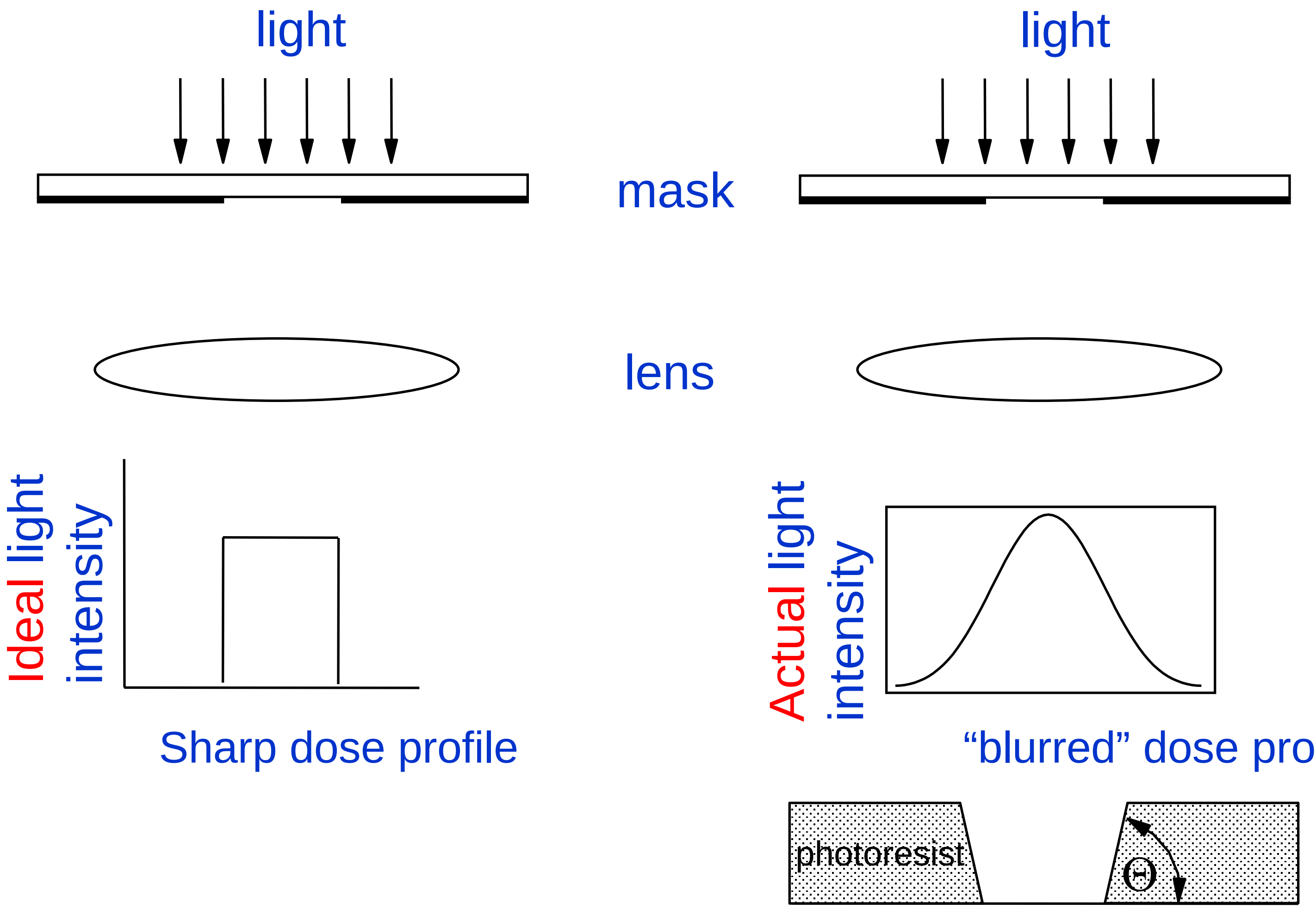
Threshold intensity here will give W<<2.5μm



Nano. Lett. 6(10), 2358(2006)

2.5μm laser beam can pattern 80nm line-width!
But it won’t be able to pattern a grating with pitch <2.5 μm.

Non-ideality in Lithographic Image Transfer



light

light

mask

lens

Ideal light intensity

Actual light intensity

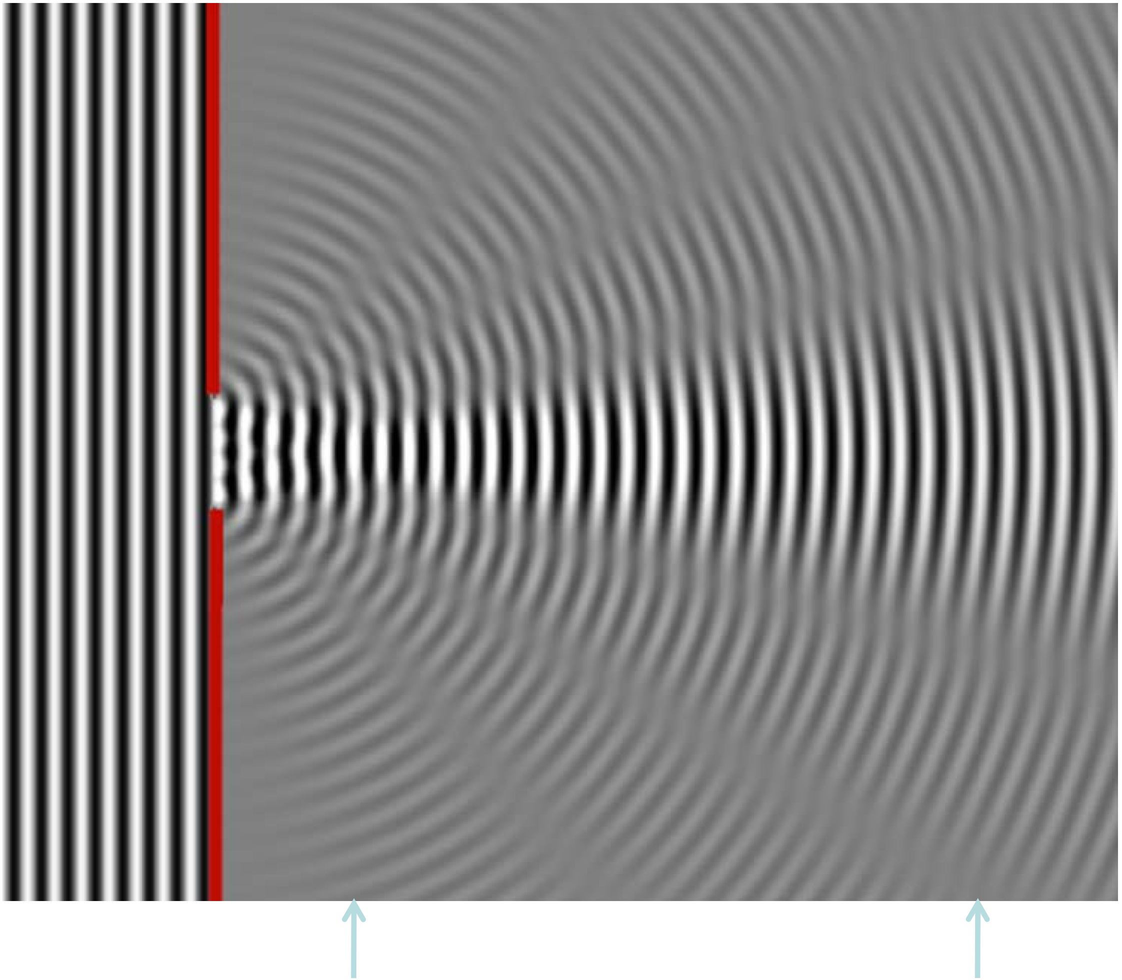
Sharp dose profile

“blurred” dose profile

photoresist

Θ

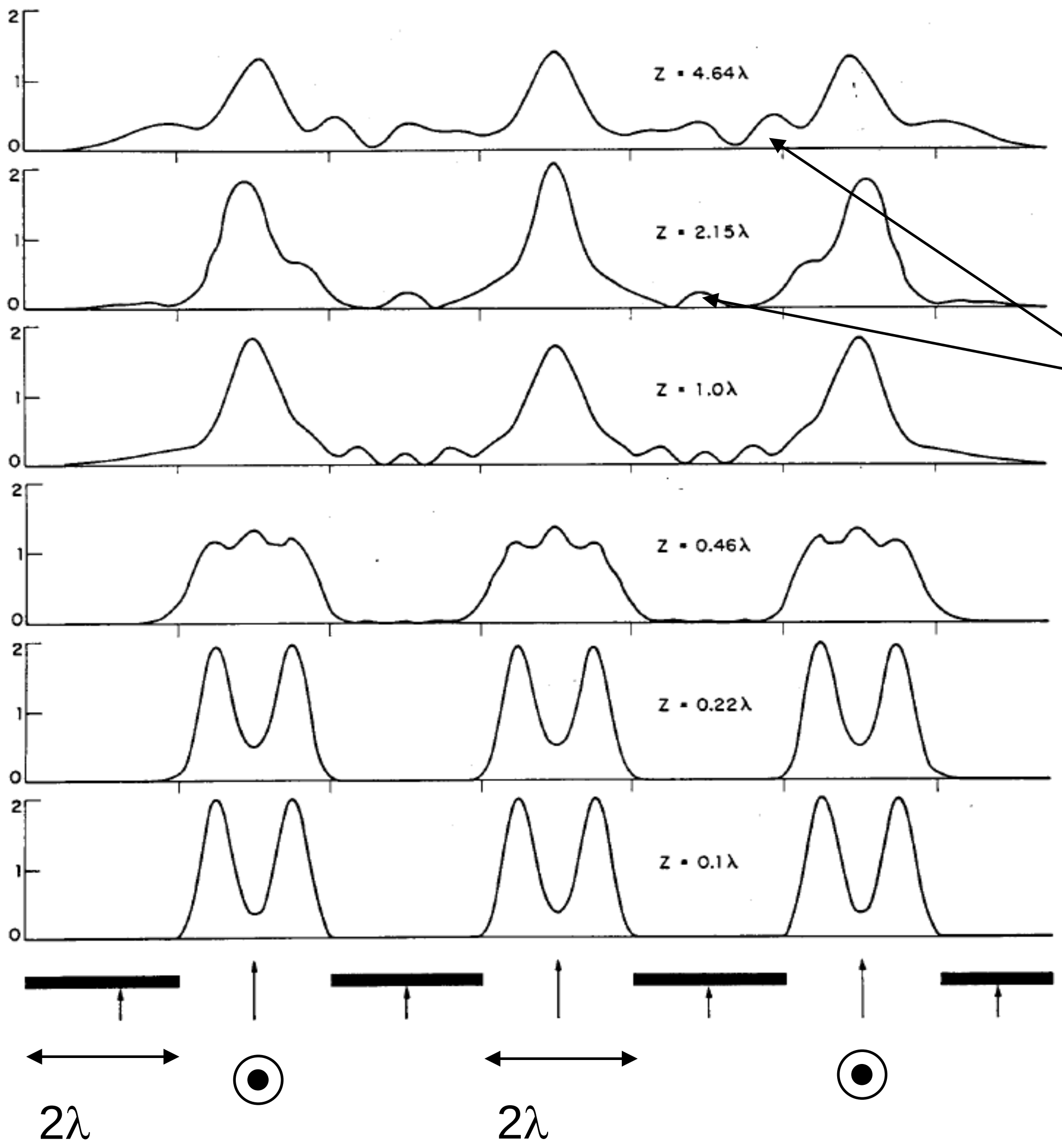
Fresnel & Fraunhofer diffraction (from an aperture)



Near field

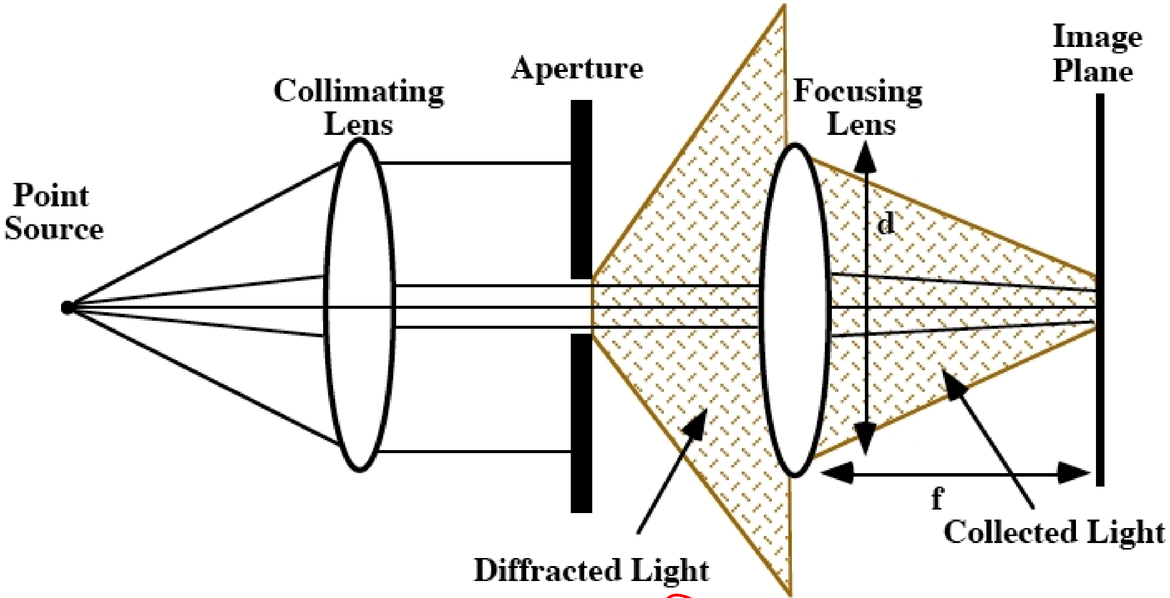
Far field

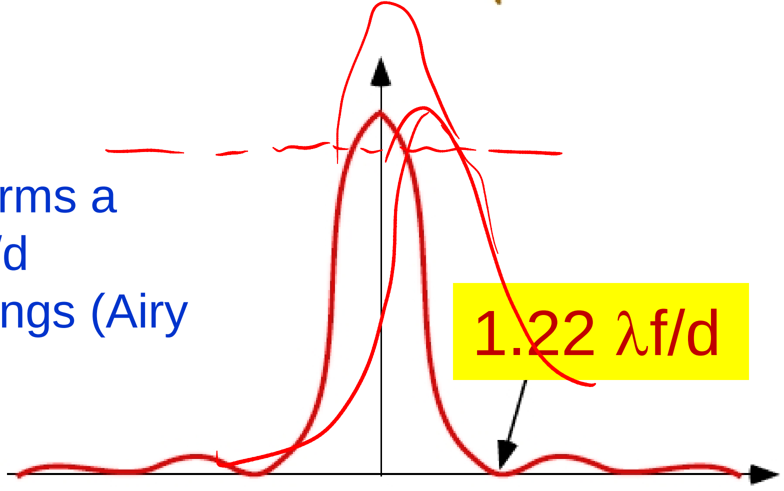
Diffraction effect in Grating Patterns



Optical fields in the shadowed areas

Light diffraction through a small circular aperture (Airy disk)





Airy pattern

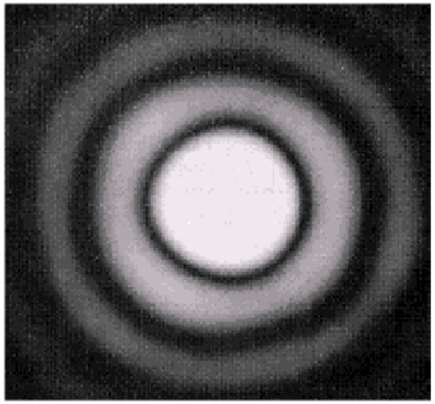
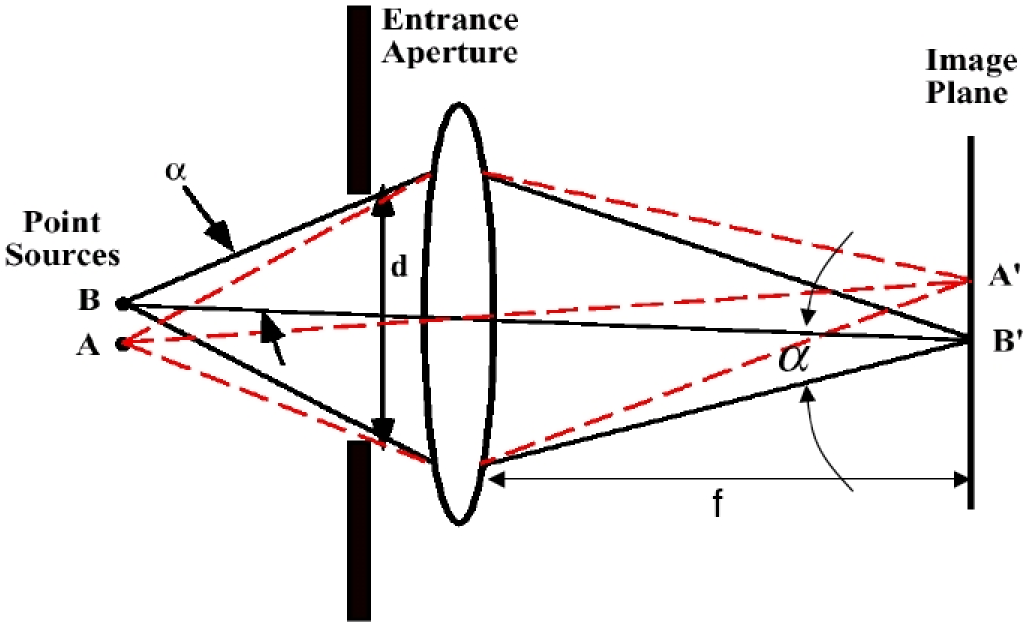
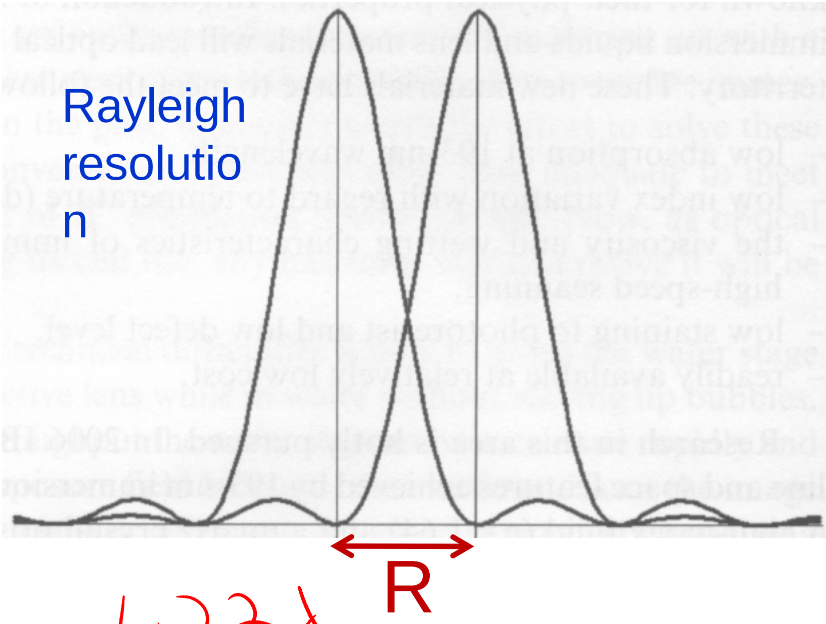


Image by a point source forms a circle with diameter 1.22λf/d surrounded by diffraction rings (Airy pattern).

Rayleigh resolution criteria (for circular aperture)





Rayleigh resolution

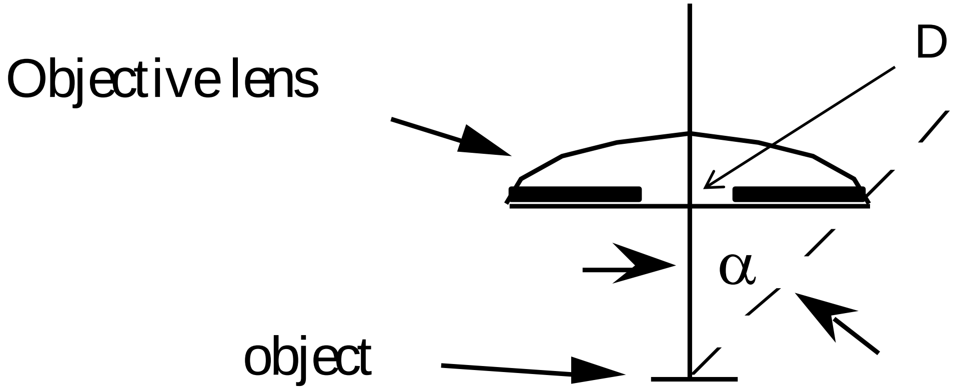
$$R= \frac{1.22\,\lambda f}{d} = \frac{1.22\,\lambda f}{n(2f\sin\alpha)} = \frac{0.61\,\lambda}{n\sin\alpha} = \boxed{\frac{0.61\,\lambda}{NA}}$$

$$= \frac{1.22\lambda}{2NA}$$

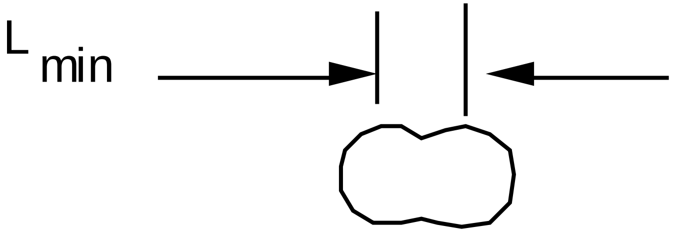
NA= n·sinα, numerical aperture

NA: the ability of the lens to collect diffracted light

Numerical aperture: NA = *n* sin α



s5



s6

f stop number: $N = \dfrac{f}{D}$

where D is the diameter of the pupil

f is the focal length

Aperture area $= \pi\left(\dfrac{f}{2N}\right)^2$

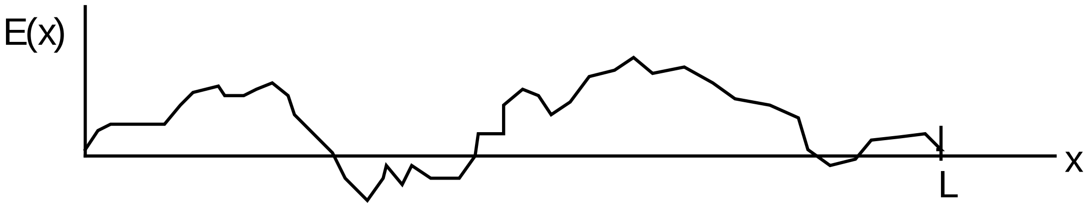
Determines resolution!

$$L_{\min} = \frac{1.22\lambda}{2n\sin\alpha} = \frac{1.22\lambda}{2\mathrm{NA}}$$

Rayleigh Criterion

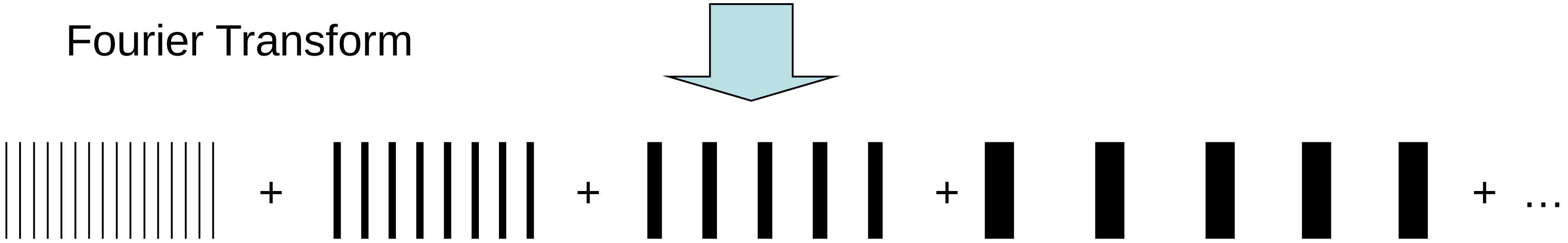
Use grating as the resolution standard

Electric field distribution on a sample (illustrated in 1D)



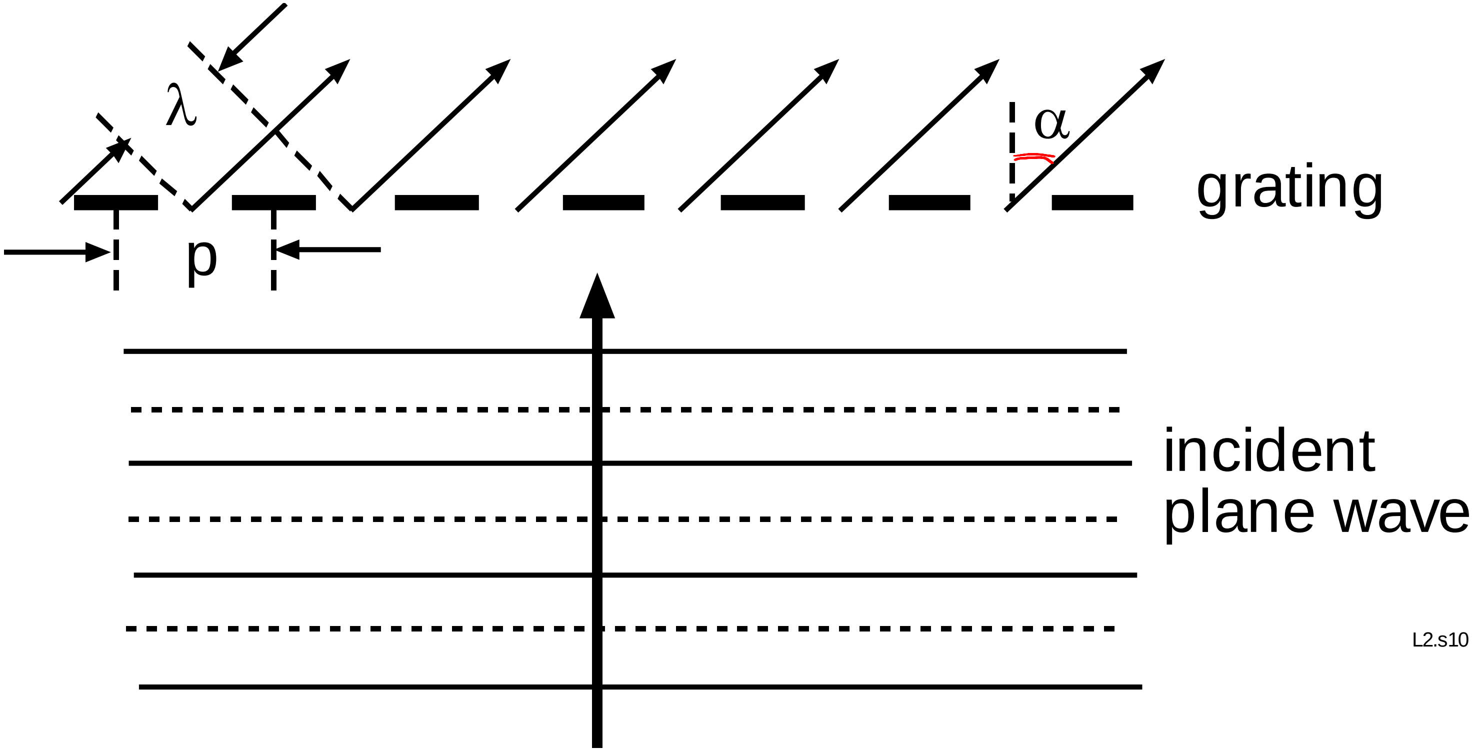
s15

Fourier Transform



- Must be able to resolve the smallest period of grating.

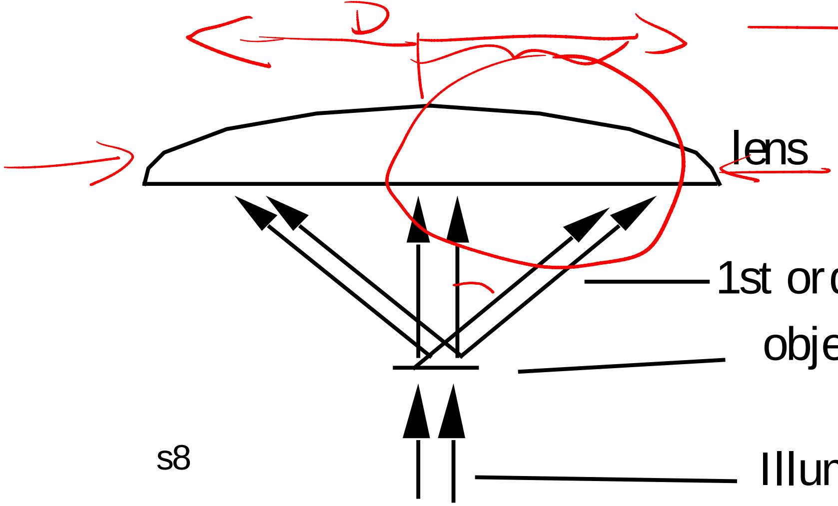
Diffraction of a grating pattern



$\sin \alpha = \lambda / p$, or $p = \lambda / \sin \alpha$

$p \downarrow$ $\alpha \uparrow$ lens size $\uparrow$

At least two orders of diffraction is required to form an image (Abbe's rule)



lens

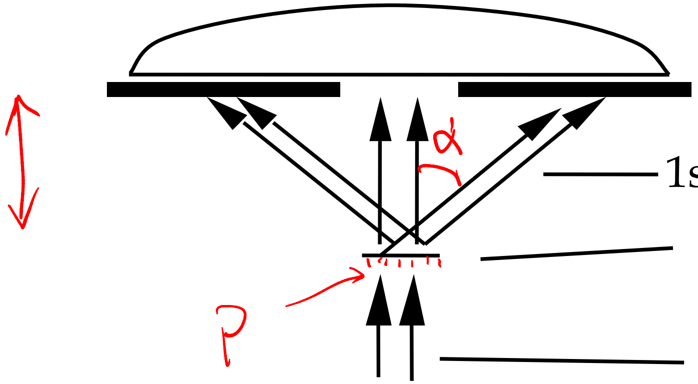
1st order

object (e.g., a grating)

Illuminating beam

s8

$NA = n\frac{D}{2f} = n\sin\alpha$



apertured lens, i.e., 1st order beams are not intercepted by the lens

1st order

object (e.g., a grating)

Illuminating beam

$\alpha = \sin^{-1}\frac{\lambda}{P}$

$P < \lambda$

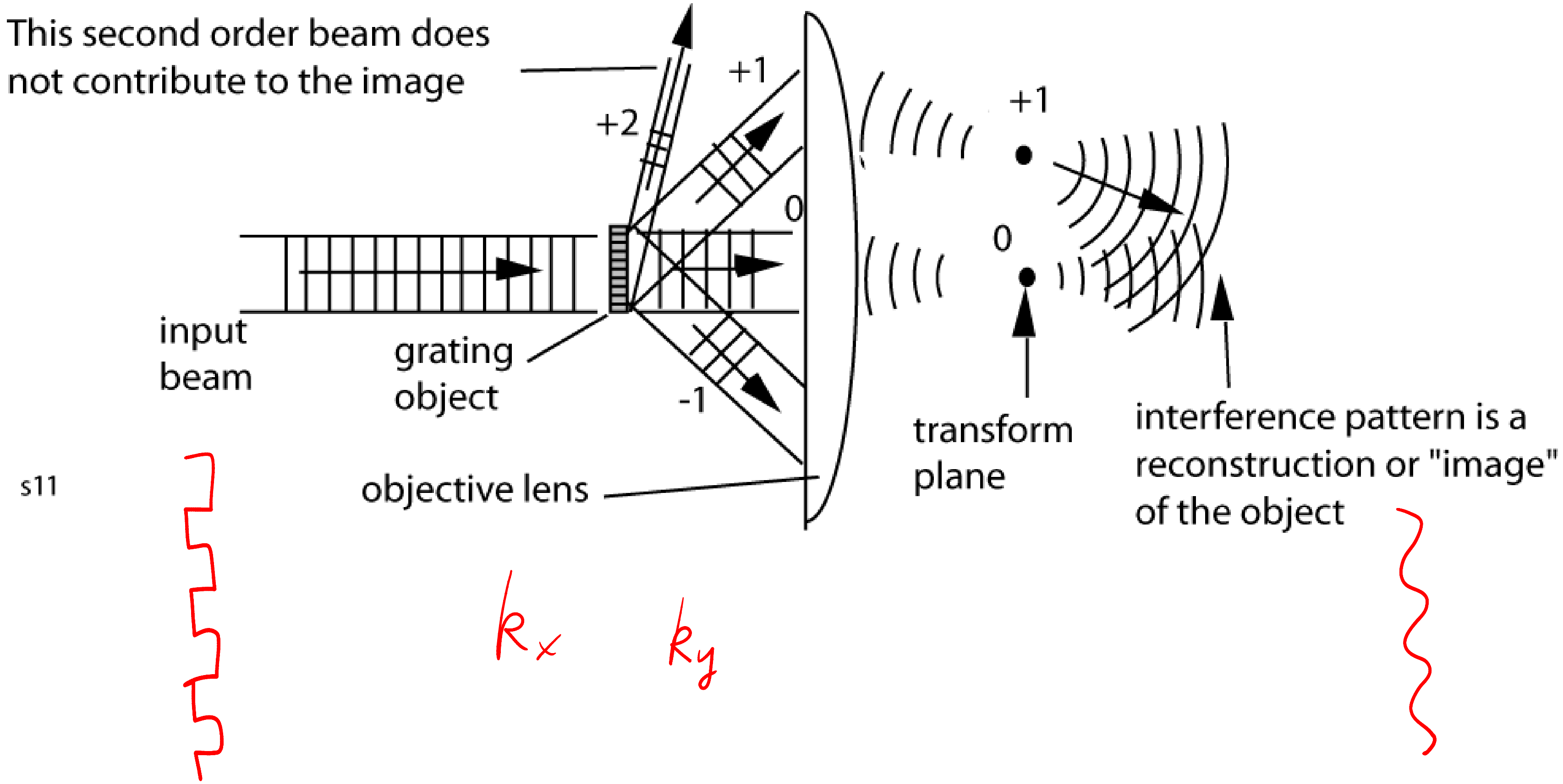
s9

$\alpha > 90^\circ$

Cannot tell if the bright spot at the focal plane is due to a true plane wave or the 0th order diffraction of a grating.

Diffraction Analysis of Imaging

Image contrast may be low

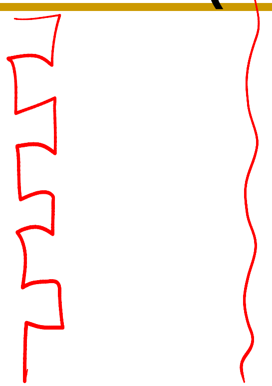


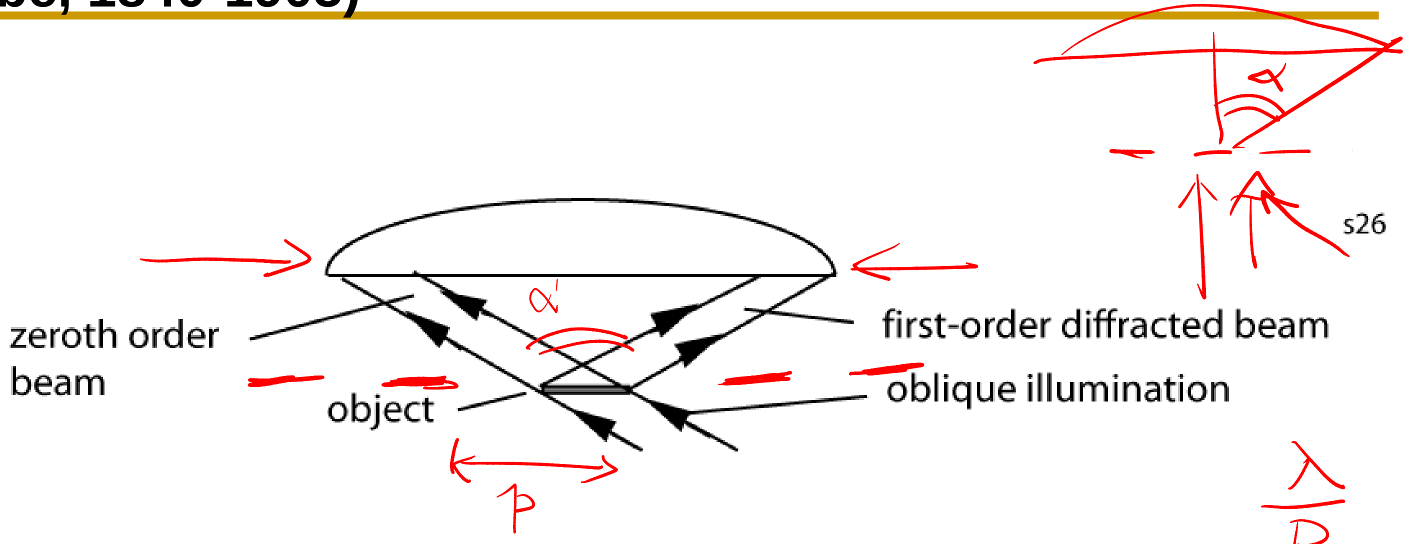
k_x k_y

The Abbé Formulation

(E. Abbé, 1840-1905)

$P/2 = 32\,\text{nm}$ 64 $193\,\text{nm}$ λ



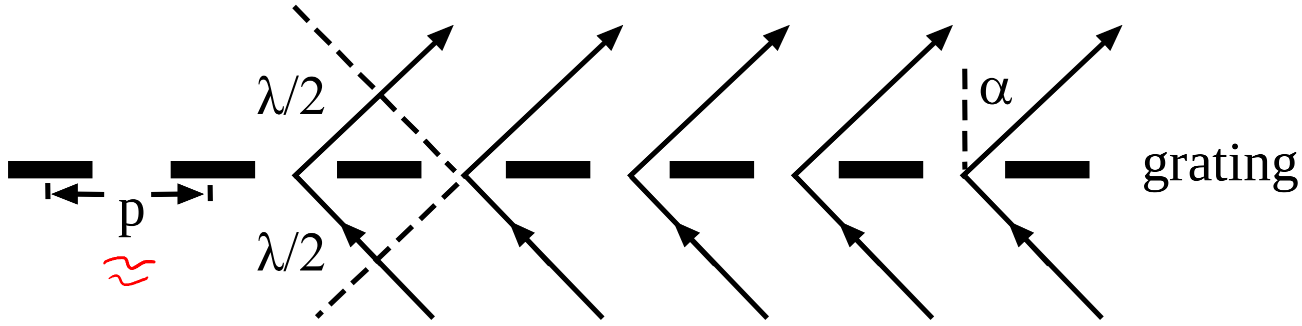


$$\sin\alpha = \frac{\lambda/2}{p}$$

$$\frac{\lambda}{P}$$

diffracted beam

$$\frac{\lambda/2}{P} < 1$$



L2.s27

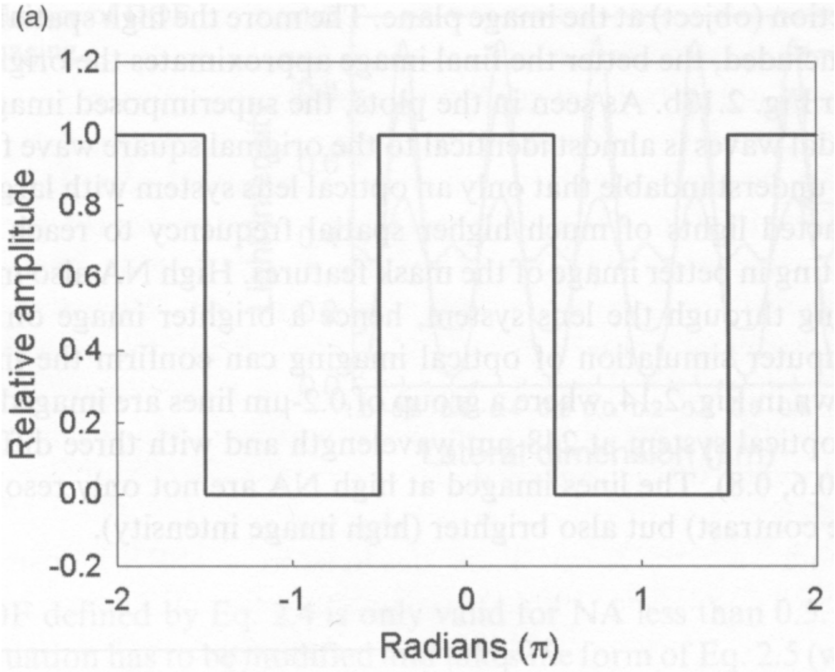
Oblique illumination

$$\boxed{\boxed{P_{\min}} = \frac{\lambda}{2n\sin\alpha} = \frac{\lambda}{2\text{NA}}}$$

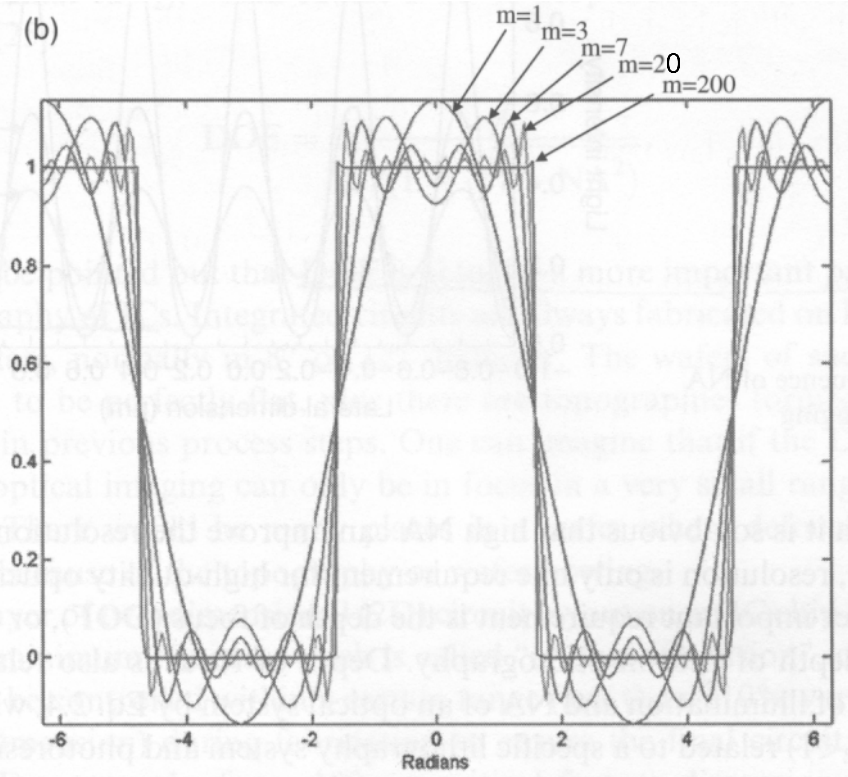
$$P_{\min} = \frac{\lambda}{2n}$$ for infinitely large lens

NA: effect of including increasing numbers of diffracted orders on the image of a slit

Mask image without diffraction

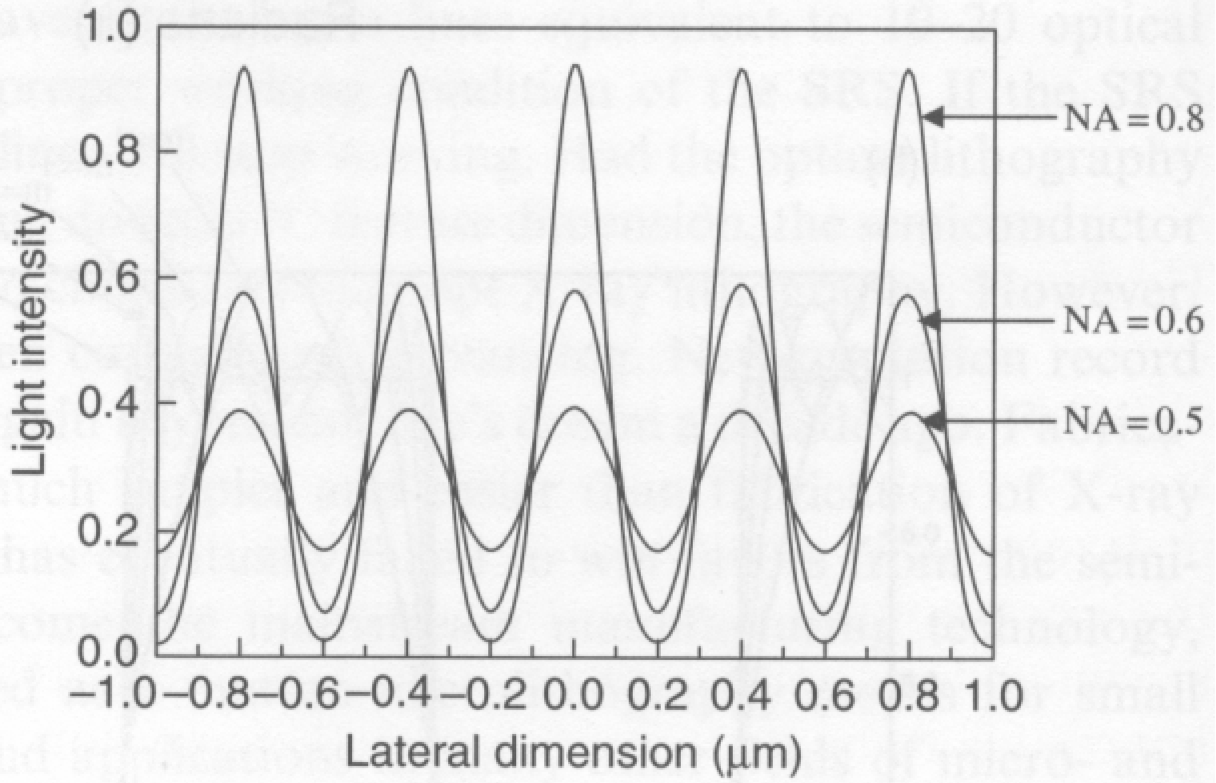


Mask image with diffraction



- With the help from photoresist, m=1 is sufficient to make good lithography!

NA: its influence on optical imaging by numerical simulation

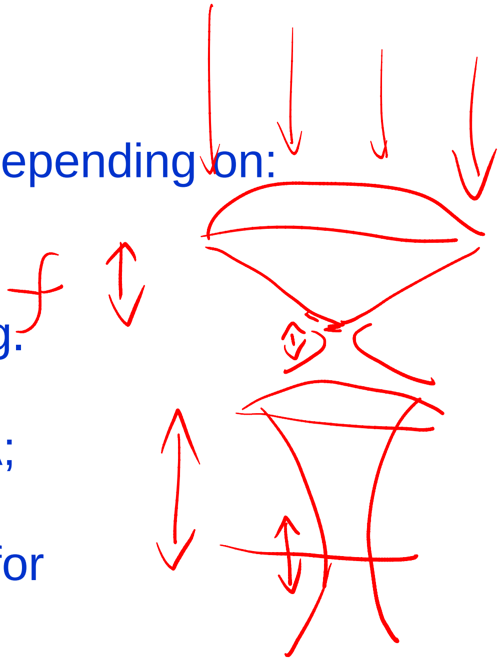


0.2μm pitch grating imaged through a projection optical system at λ=248nm.

Increase NA:
- Resolve better the line image (higher image contrast)
- Gives brighter image (higher image intensity).

Generalized resolution (half pitch)

$$R = k_1 \frac{\lambda}{NA}$$



k_1 represents the ability to approach physical limits depending on:

- Lenses: aberrations.
- Resists: contrast.
- Equipment and process control in manufacturing.

To increase resolution: reduce λ and k_1, increase NA;

But this also reduces depth of focus (a bigger issue for lithography).

Depth of Focus or Depth of Field (DOF):

$$DOF = k_2 \frac{\lambda}{(NA)^2}$$ For NA ≤ 0.5

$$DOF = k_3 \frac{\lambda}{2\left(1-\sqrt{1-NA^2}\right)}$$ For NA > 0.5

Resolution of high NA lenses

NA	Theory, p = $\lambda/2NA$		Experimental Result (nm)
	@λ = 400 nm	@λ = 550 nm	
0.9	222 nm	306 nm	258
0.95	211 nm	289 nm	258
1.4	143 nm	196 nm	155

Lines down to 85 nm can be experimentally resolved with 400 nm light!

Is NA=1.4 relevant to lithography?
Yes! Immersion projection lithography at 193 nm

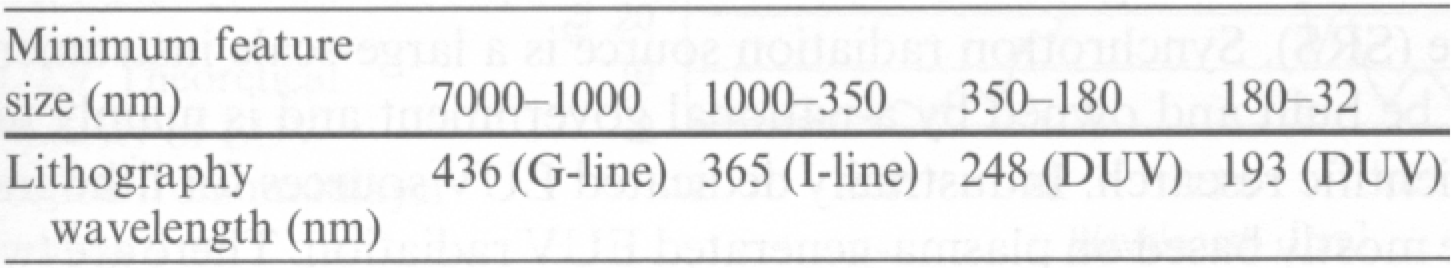
Increase resolution by reducing λ

Mercury arc lamps — Excimer lasers (nanosecond pulse)

g-line → i-line → KrF → ArF → F_2

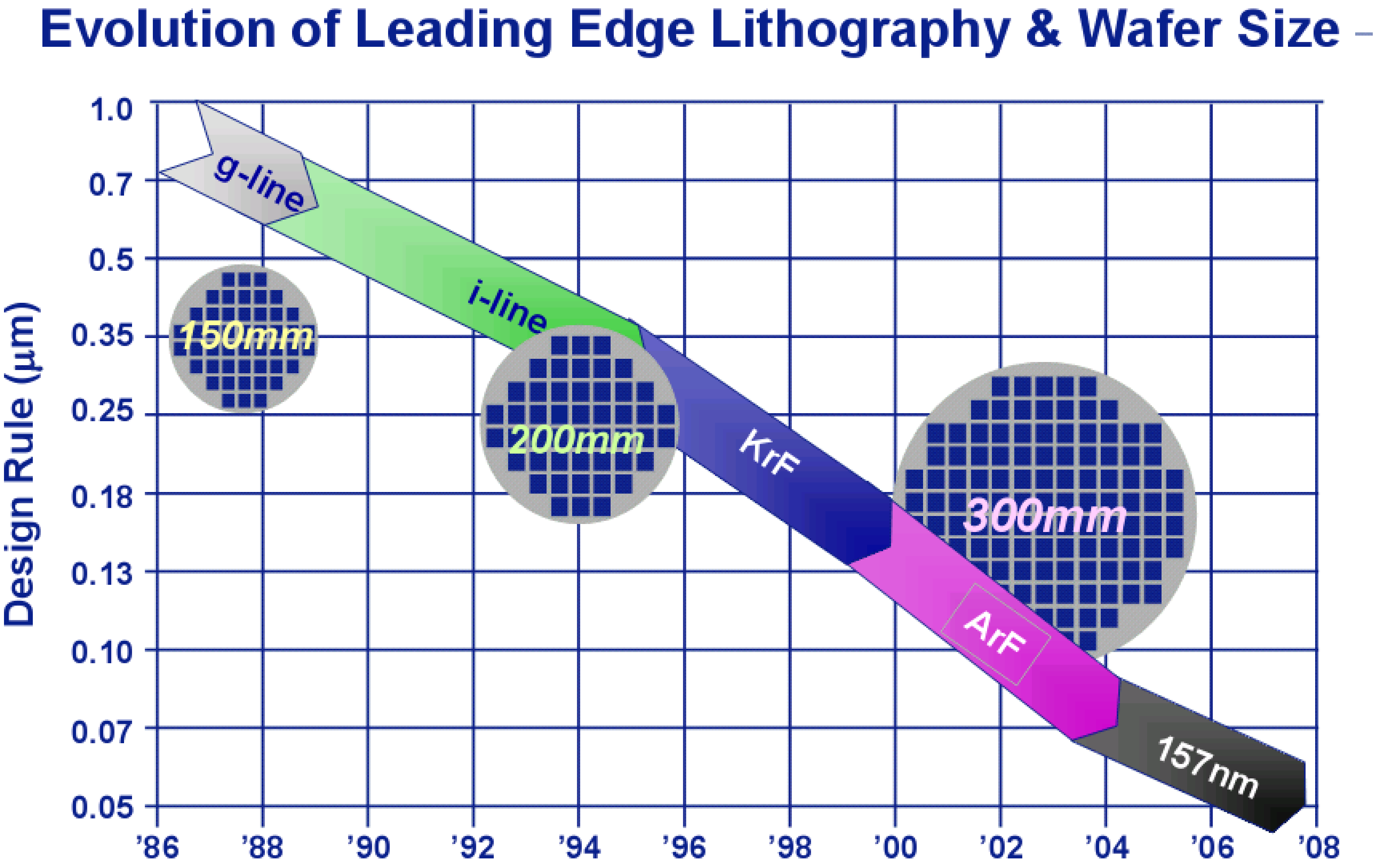
436 nm → 365 nm → 248 nm → 193 nm → 157 nm (damaging the mask)

1 → 0.44×



	$R \gg \lambda$	$R > \lambda$	$R \sim \lambda$	$R \ll \lambda$
Minimum feature size (nm)	7000–1000	1000–350	350–180	180–32
Lithography wavelength (nm)	436 (G-line)	365 (I-line)	248 (DUV)	193 (DUV)

Wavelength Reduction is Slow

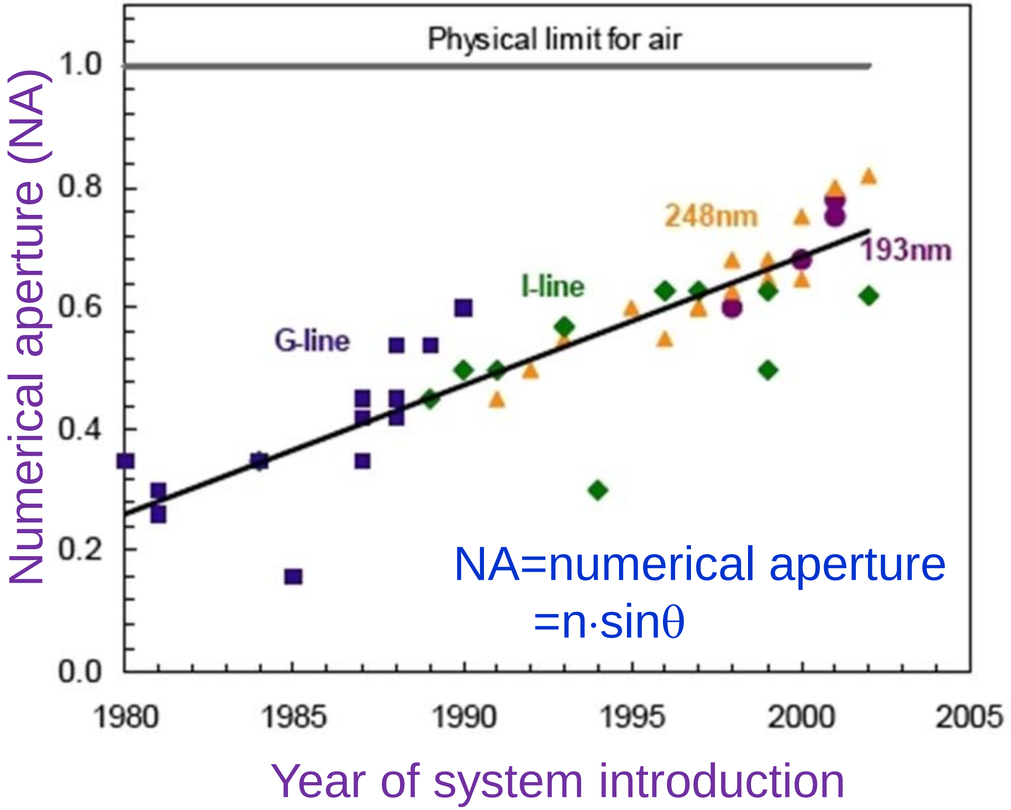


g-line: 436 nm; i-line 365 nm; Deep UV (KrF): 248 nm; ArF: 193 nm

Increase resolution by increasing numerical aperture NA to approach 1

- The physical limit to NA for exposure systems using air as a medium between the lens and the wafer is 1.
- The practical limit is somewhere ~0.93 (collecting angle α=68°, huge lens ~1000kg).
- Therefore, the resolution limit for 193nm exposure systems.

$$R = \frac{k_1 \lambda}{NA} \le \frac{0.25 \times 193}{0.93} = 52 \text{ nm}$$



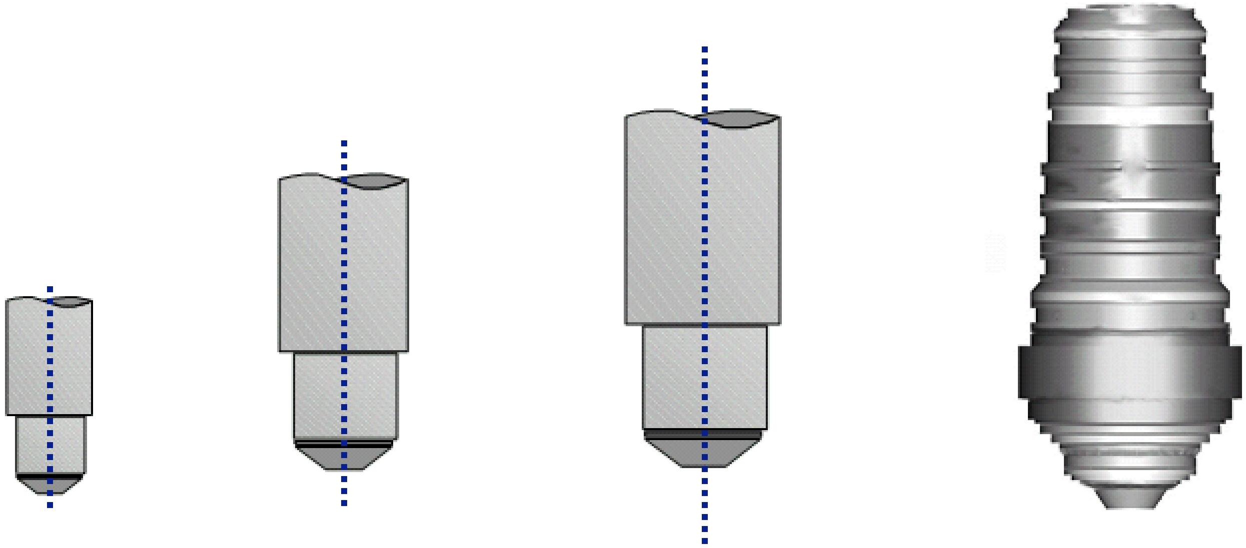
NA=numerical aperture
=n·sinθ

$$P_{min} = \frac{\lambda}{2\,NA}$$

k_1 for $R = \frac{P_{min}}{2}$ is 0.25

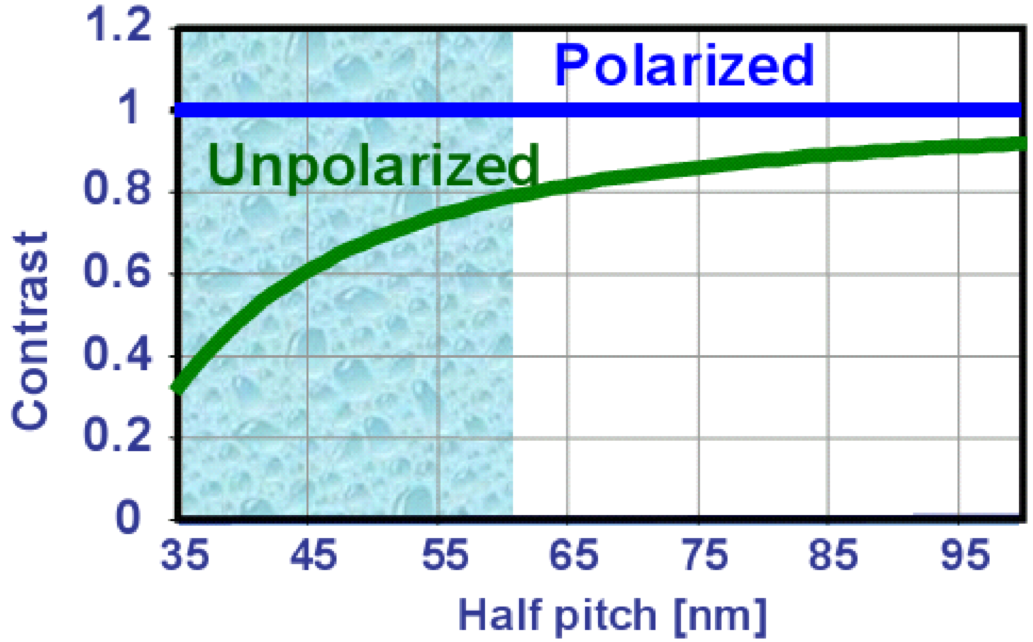
Bigger and Heavier Lens

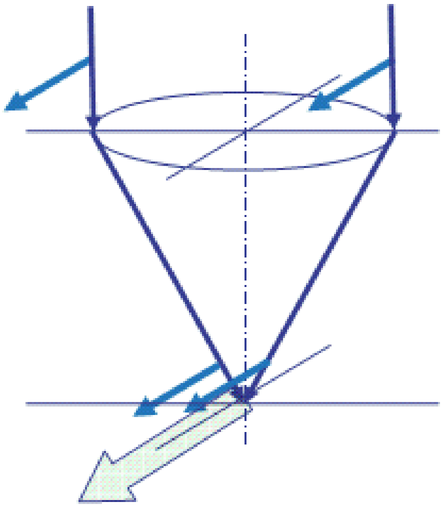
Milestones of Progress in Lens Technology



ASML Model #	-	PAS 2500/40	PAS 5500/300	*TWINSCAN AT:1100*
Wavelength	g-Line	I-Line	KrF	ArF
# Pixels (*E+6)	40	320	10.000 - 25.000	80.000
Pixel Factor	1	8	250 - 625	2000
Price Factor	1	10	80	100
Weight (kg)	2	20	250	500
Yr of First Proto	1975	1987	1995	2001

Hyper NA lens: Polarization to maximize contrast





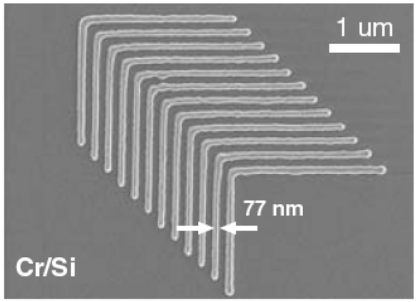
Constructive interference

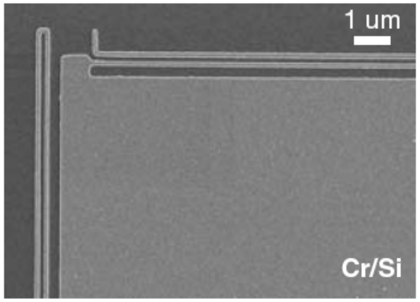
100% contrast

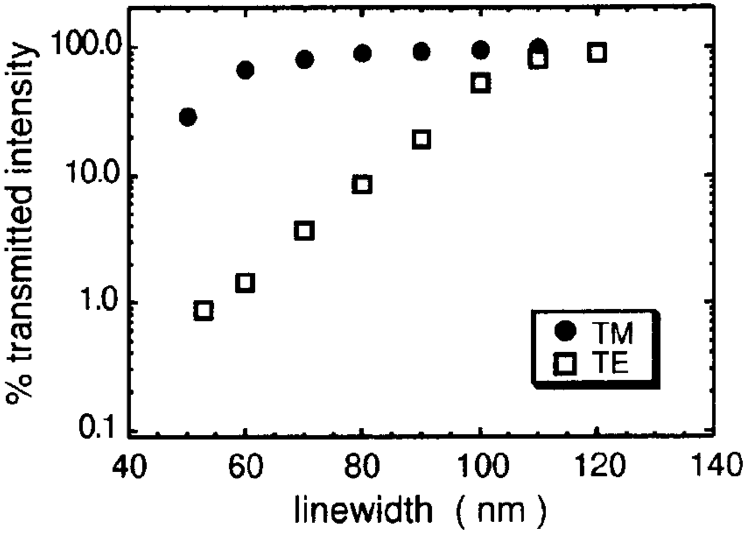
Polarization

- improves image contrast and exposure latitude
- enhances resolution with 5 nm

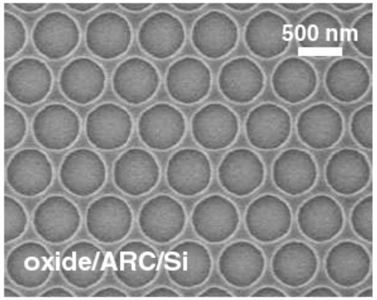
Resolution limit of *p*=λ/2NA can be overcome with contact printing

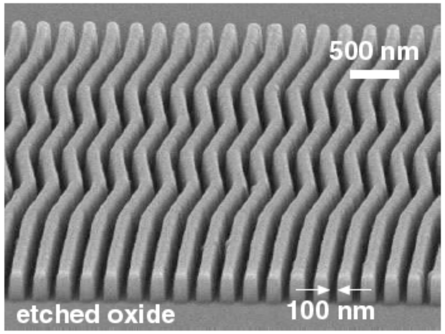






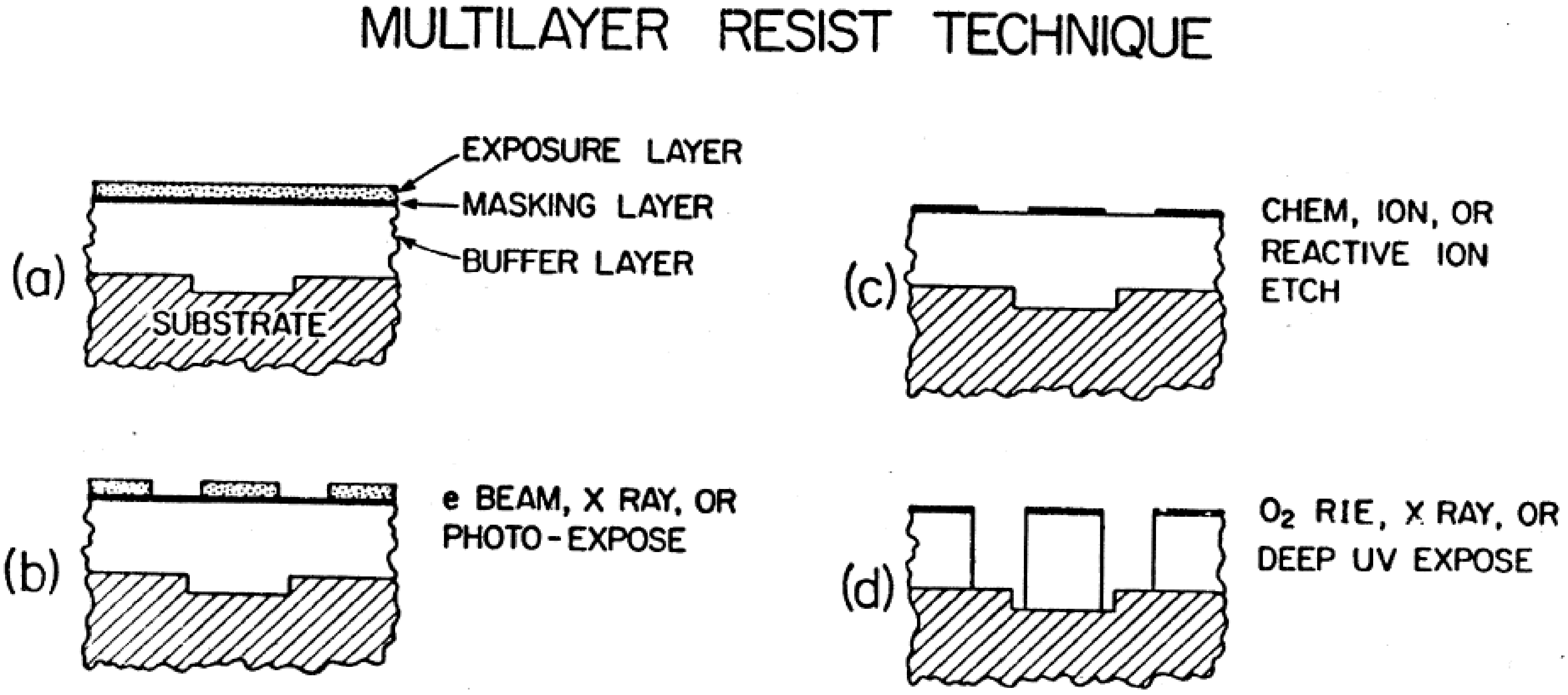
λ=220nm





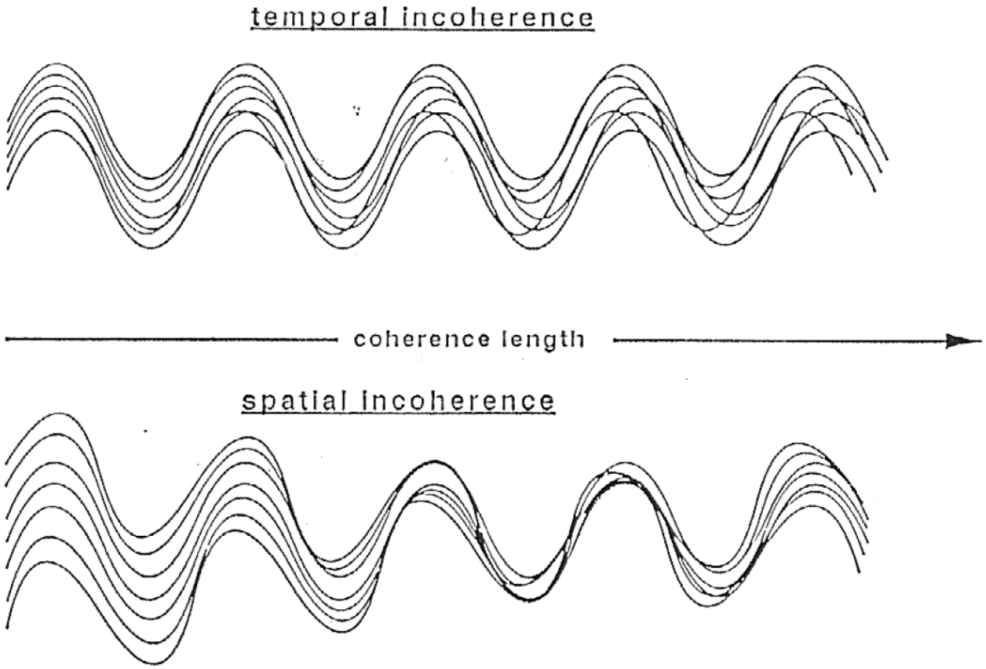
- Key is to make the mask flexible so that true contact can be maintained.
- Resolution is polarization dependent

Separate the functions of Image Recording and “Resistance”

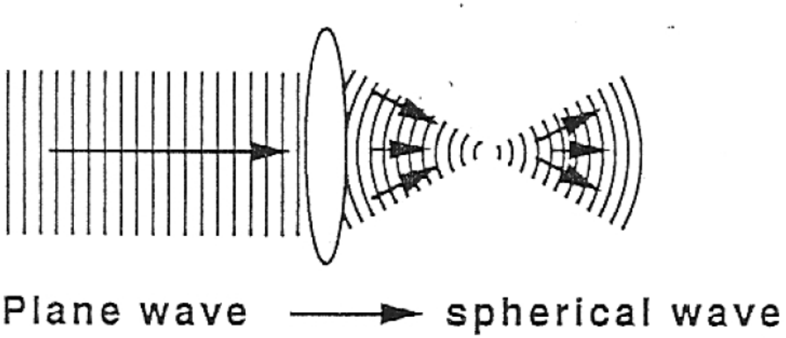


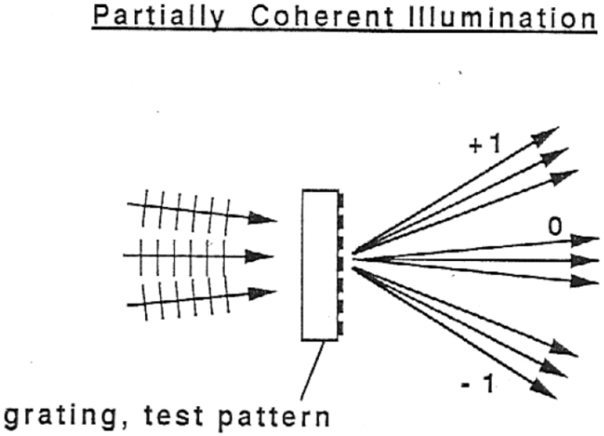
Can also perform the function of planarization, i.e. the substrate topology won’t affect the linewidth

Coherence of illumination



Perfectly coherent illumination





Overview of Projection Lithography

- Minimum linewidth (0.5*p*)

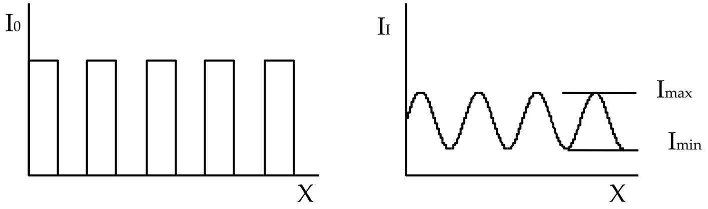
$$W_{min} = k_1 \lambda / \mathrm{NA}$$

- Depth of focus

$$DOF = k_2 \frac{\lambda}{(NA)^2} \quad \text{for NA} \le 0.5$$

$$DOF = k_3 \frac{\lambda}{2\left(1-\sqrt{1-NA^2}\right)} \quad \text{for NA>0.5}$$

skt12.12.



$$K = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}.$$

Optical Projection Lithography