Photolithography

Key Topics:

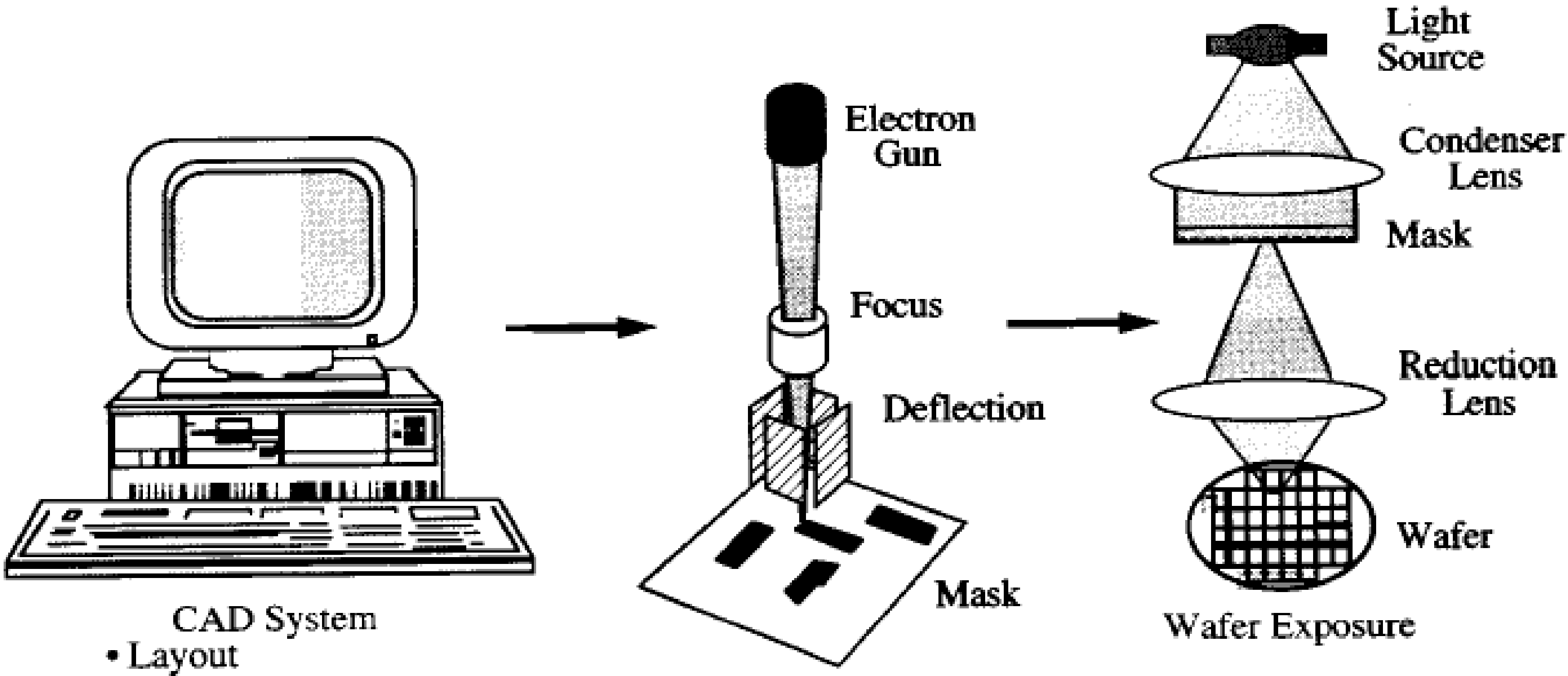
Photo = ϕως = (through) light

Litho = λιθος = stone

Graphy = γραϕη = writing

- Resolution
- Depth of Focus
- Overlay Errors
- Photoresist Response
- E-beam and X-ray lithography

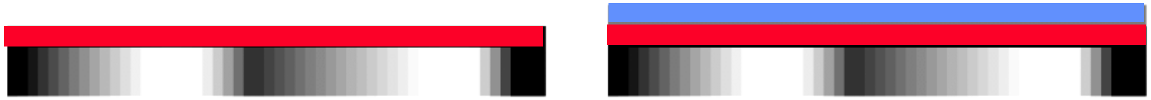
Design => Mask => Wafer



CAD System
- Layout
- Simulation
- Design Rule Checking

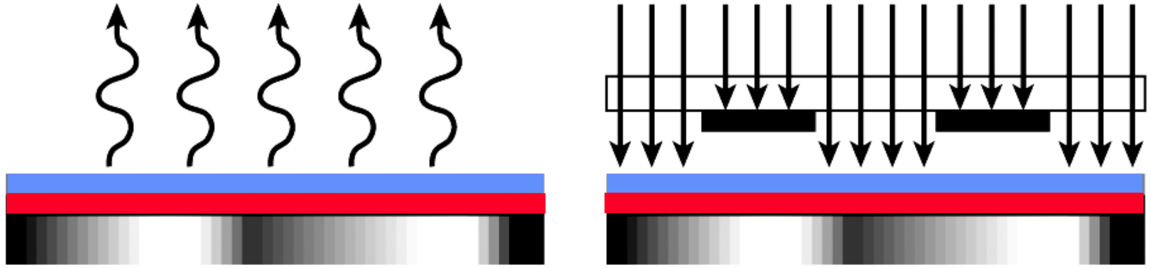
Mask Making

Wafer Exposure



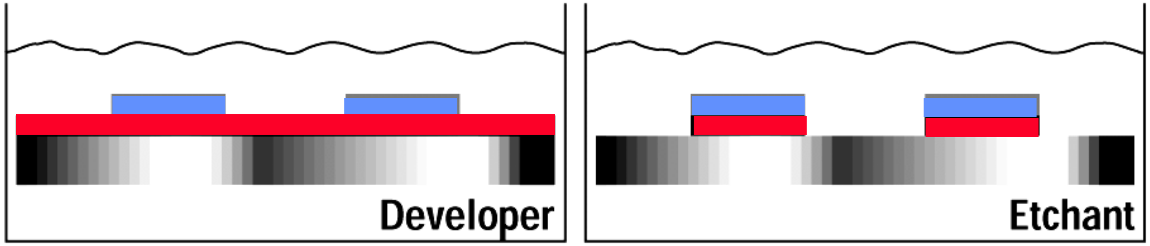
(1) Starting wafer with layer to be patterned

(2) Coat with photoresist



(3) Bake the resist to set its dissolution properties

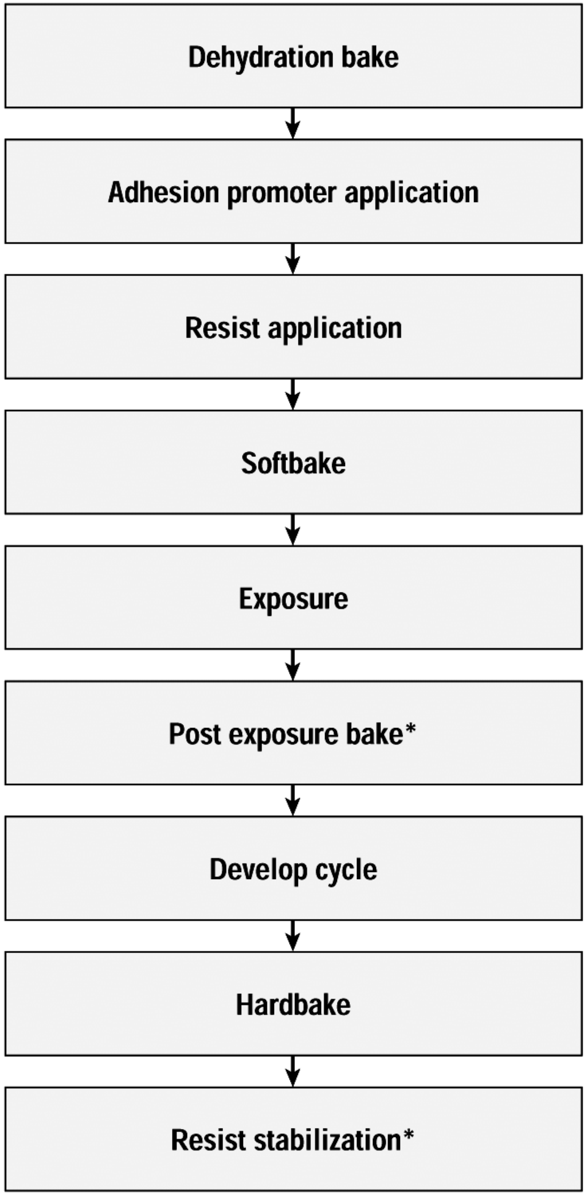
(4) Expose resist by shining light through a photomask



(5) Immerse exposed wafer in developer

(6) Etch the film

Figure 1.5 Steps required for a pattern transfer using optical lithography.

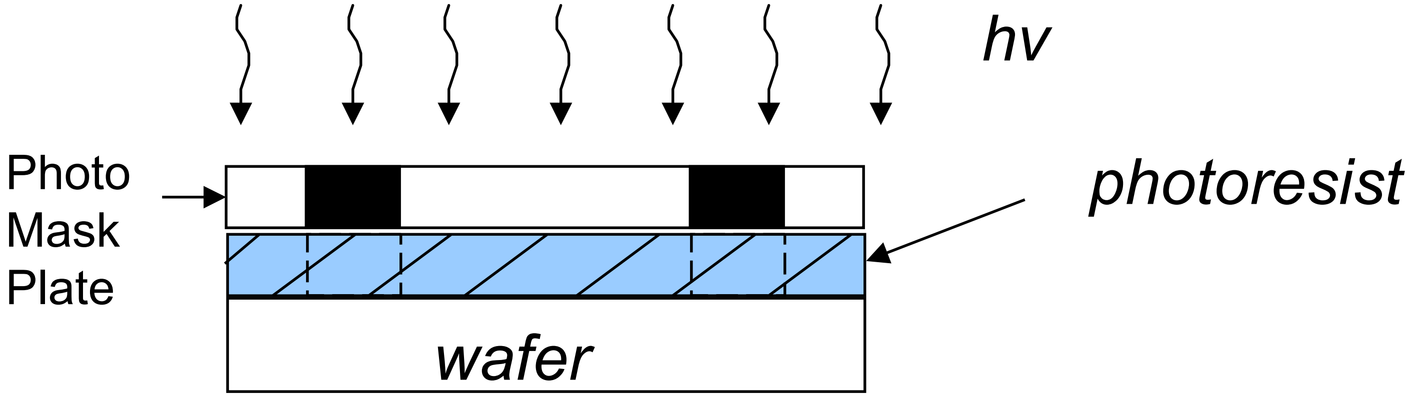


- Dehydration bake
- Adhesion promoter application
- Resist application
- Softbake
- Exposure
- Post exposure bake*
- Develop cycle
- Hardbake
- Resist stabilization*

*Optional steps

Figure 8.9 Typical process flow in a photolithography step.

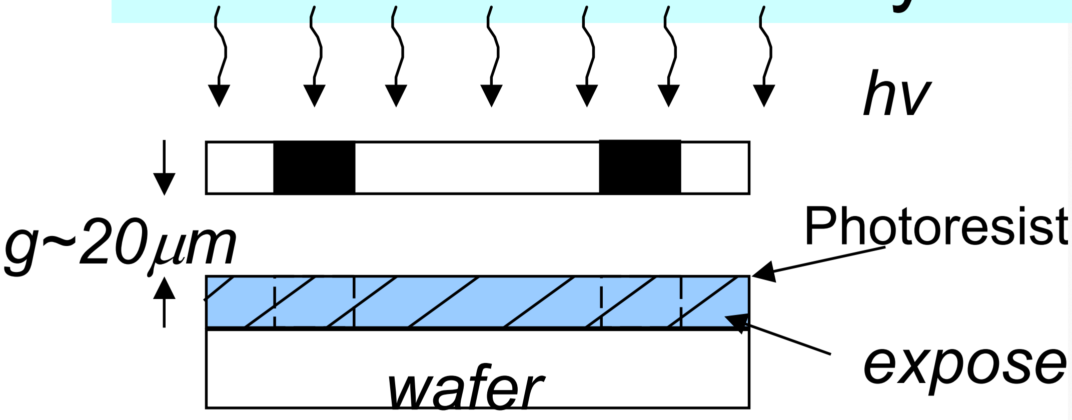
Contact Printing



→ Resolution R < 0.5μm

→ mask plate is easily damaged or accumulates defects

Proximity Printing



$$R = k(\lambda g)^{1/2}$$

~ 1μm for visible photons,
much smaller for X-ray lithography

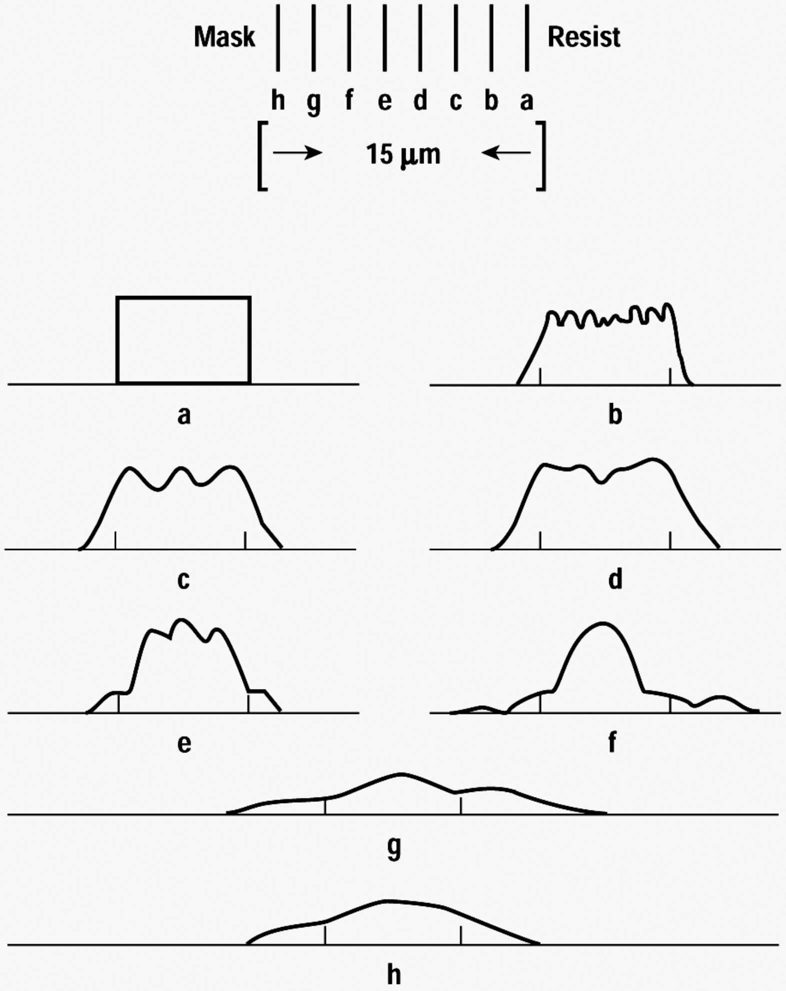
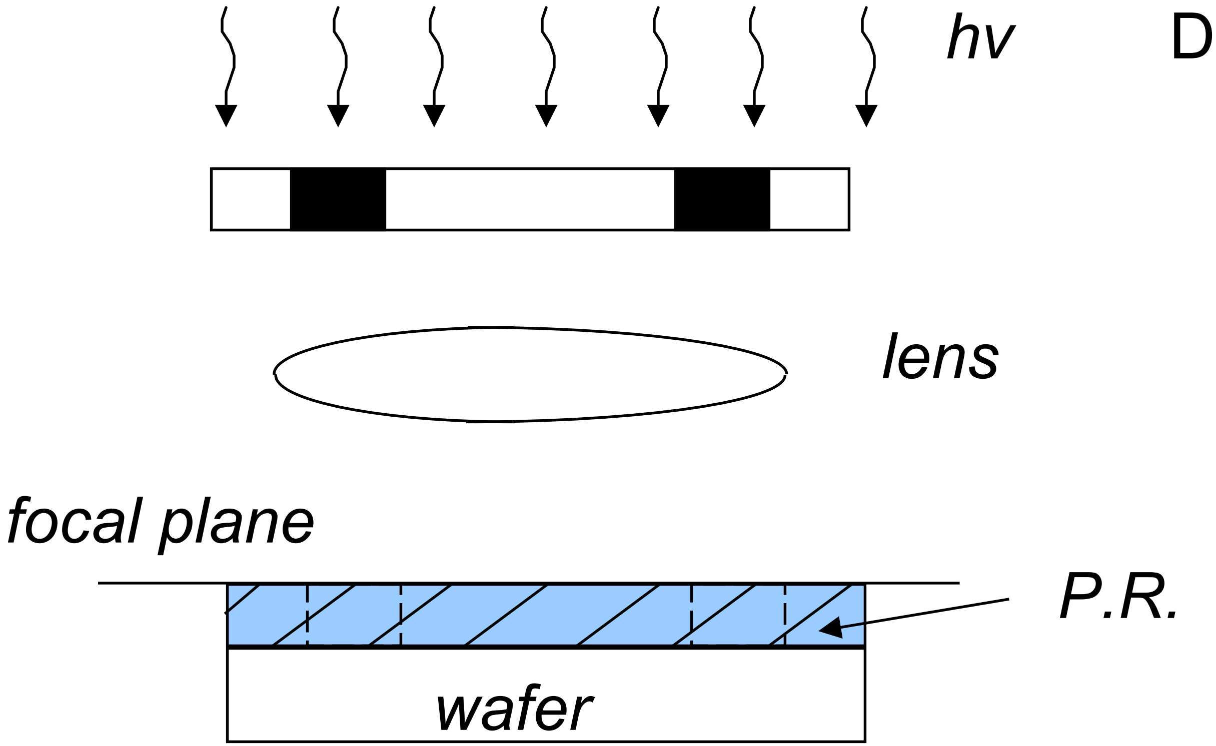


Figure 7.16 Intensity as a function of position on the wafer for a proximity printing system where the gap increases linearly from g 5 0 to g 5 15 mm *(after Geikas and Ables)*.

Projection Printing

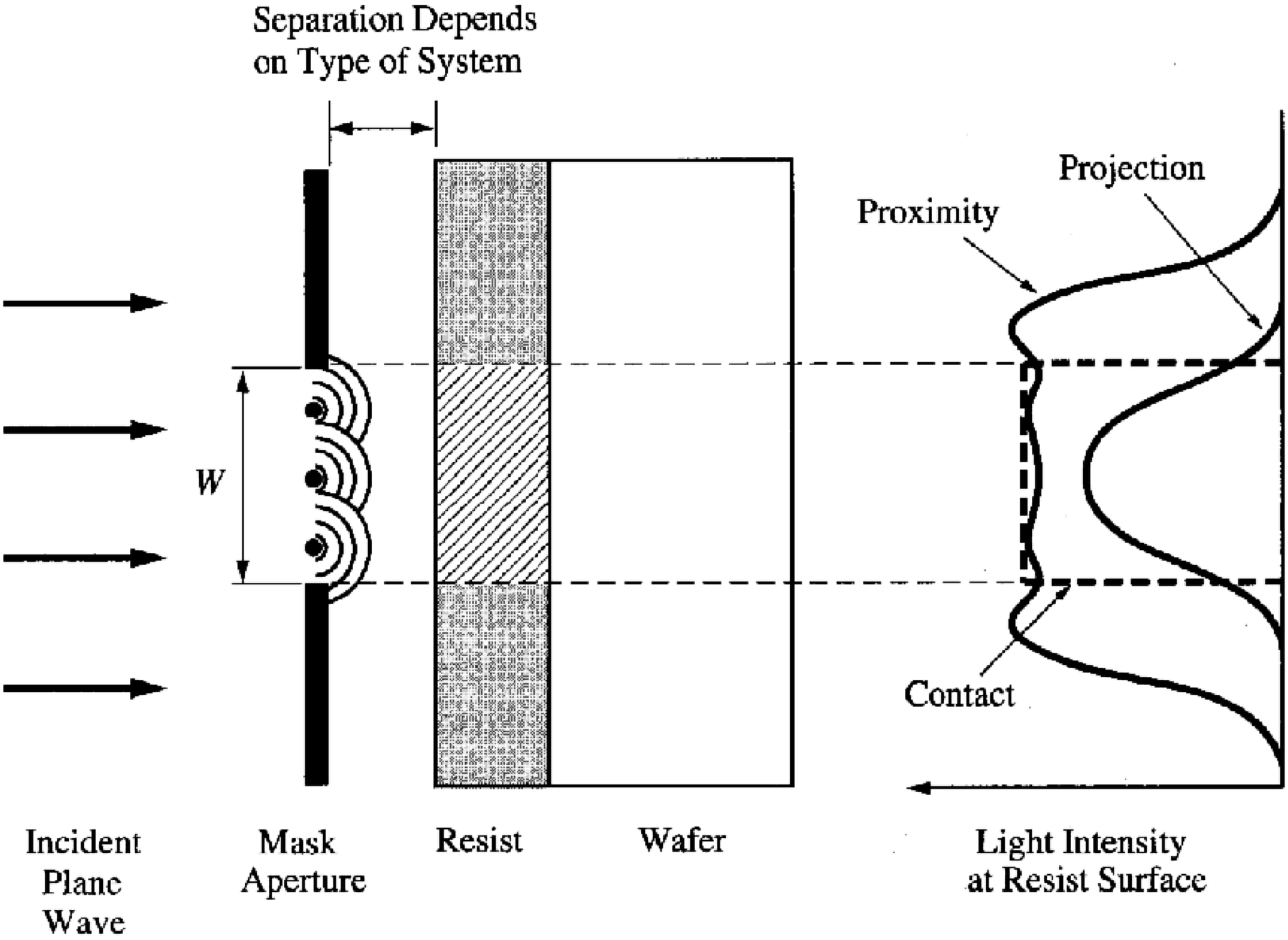


De-Magnification: nX

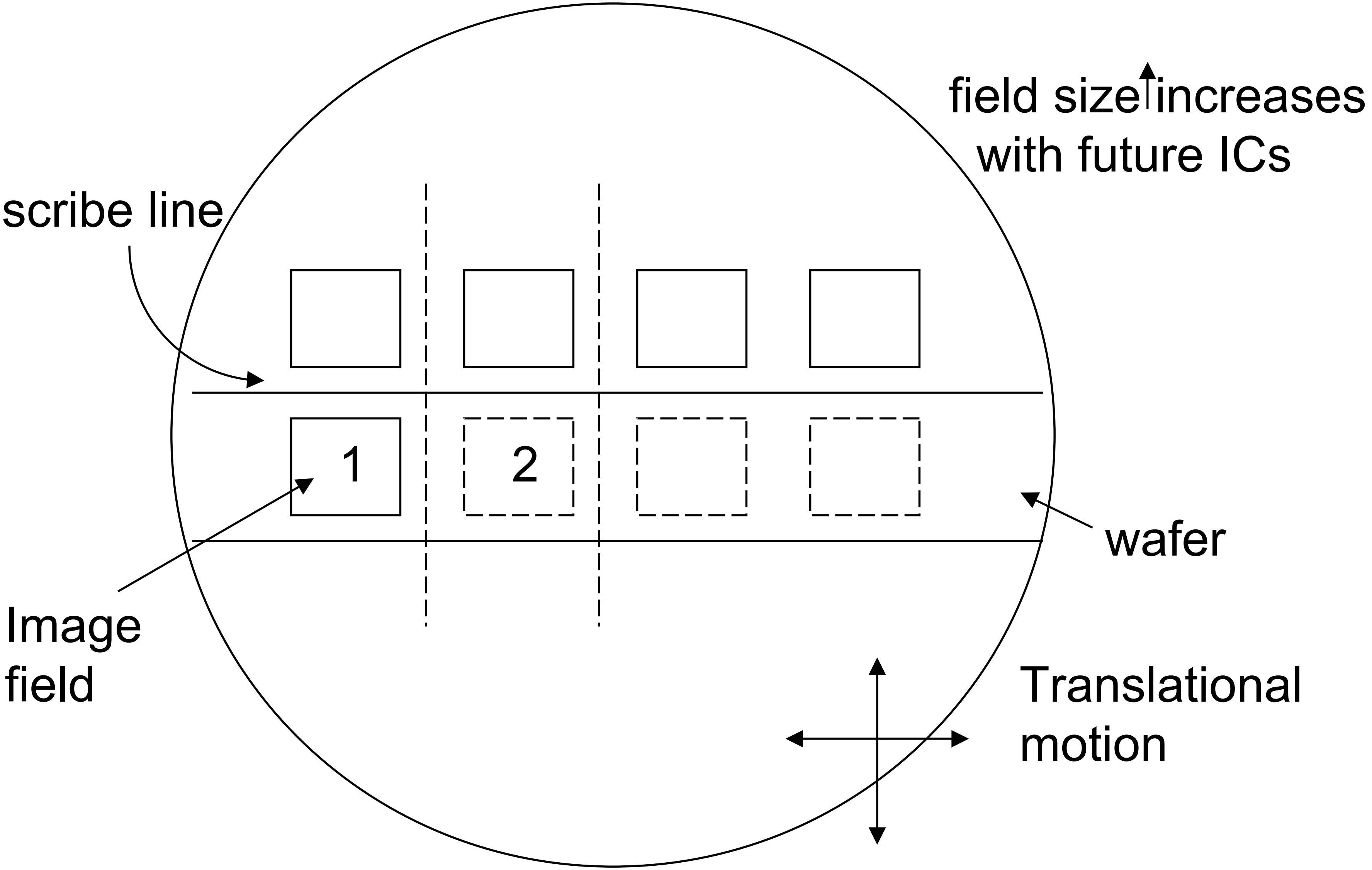
10X stepper
4X stepper
1X stepper

~0.2 μm resolution (deep UV photons)
tradeoff: optics complicated and expensive

Aerial Images formed by Contact Printing, Proximity Printing and Projection Printing



Optical Stepper



Excimer Laser Stepper

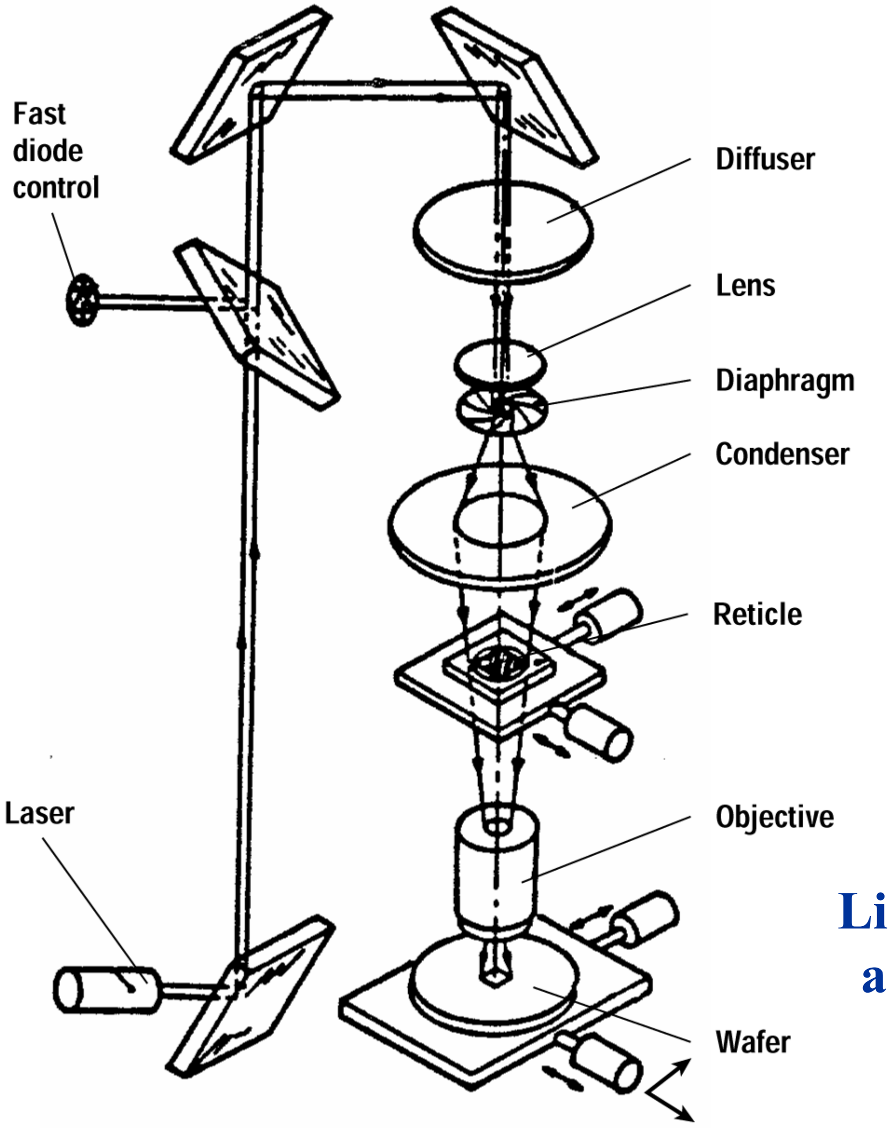
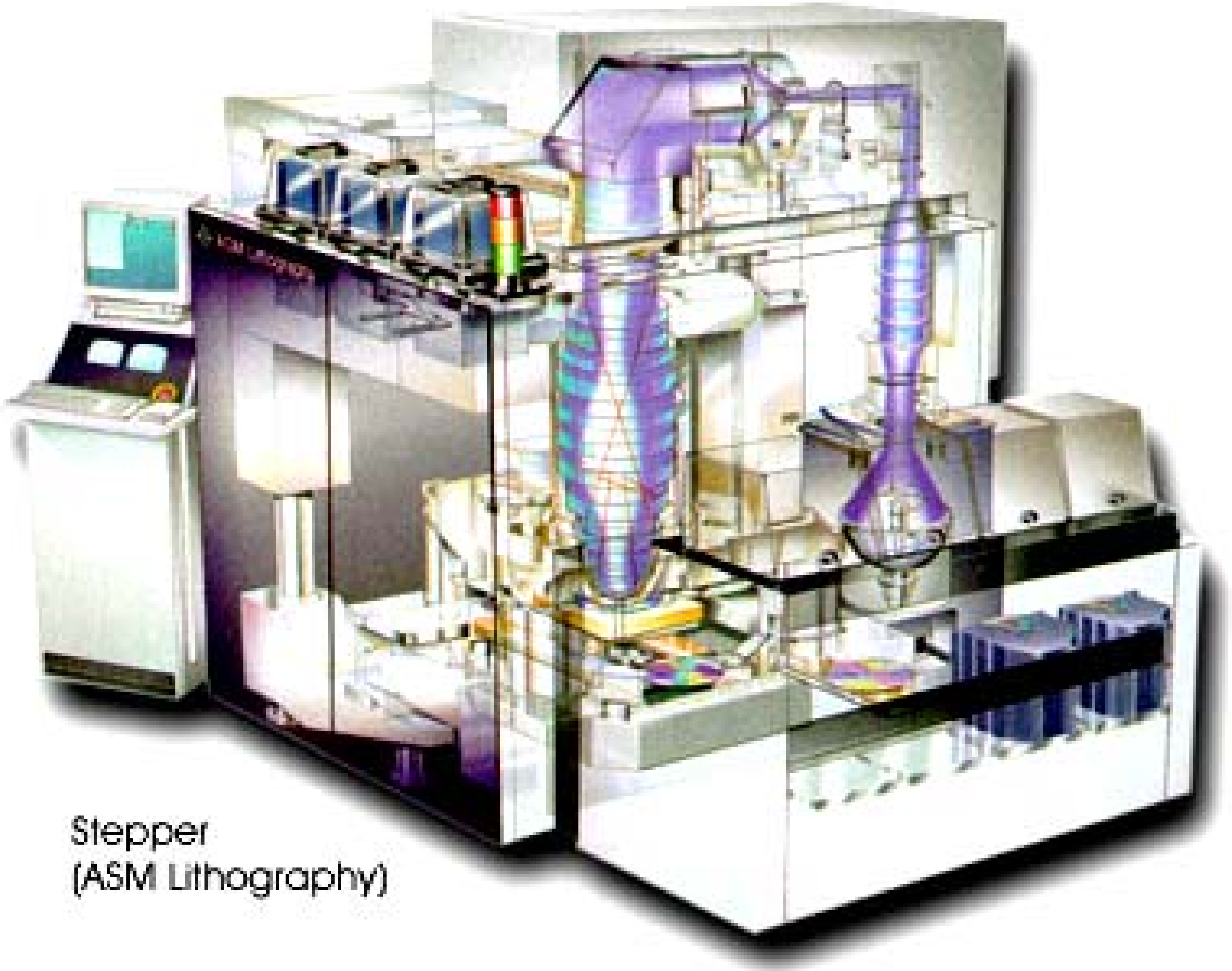


Figure 7.14 Optical train for an excimer laser stepper *(after Jain).*

Light is in pulses of 20 ns duration at a repetition rate of a few kHz. About 50 pulses are used.

See Plummer et al , Ch 5

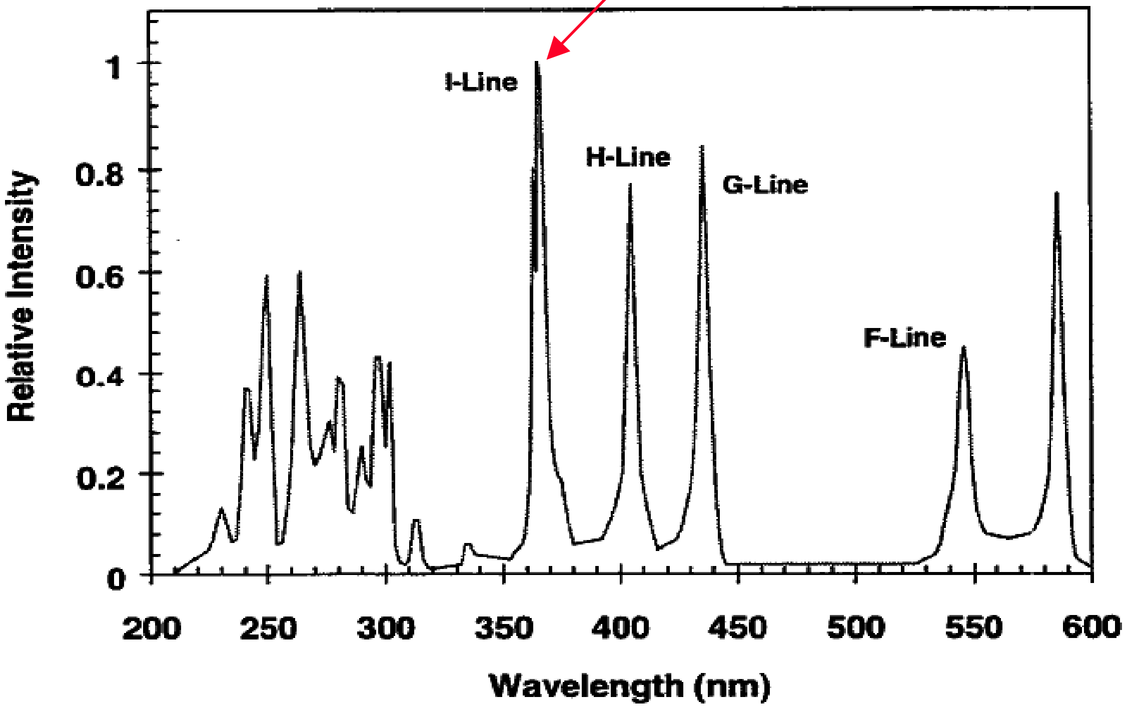
Excimer Laser Stepper



Stepper
(ASM Lithography)

Photon sources

- Hg Arc lamps 436(G-line), 405(H-line), 365(I-line) nm
- Excimer lasers: KrF (248nm) and ArF (193nm)
- Laser pulsed plasma (13nm, EUV)

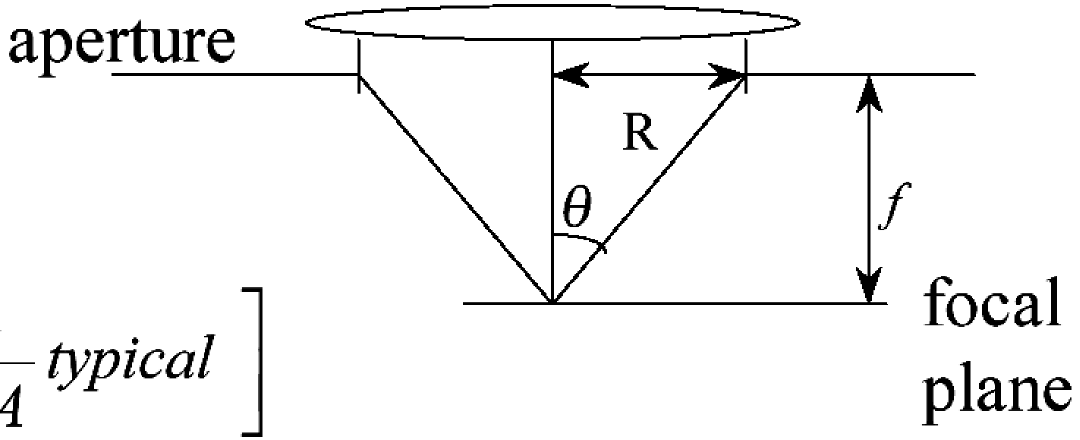


Source Monitoring

- Filters can be used to limit exposure wavelengths
- Intensity uniformity has to be better than several % over the collection area
- Needs spectral exposure meter for routine calibration due to aging

Projection Printing Considerations

(1) Resolution



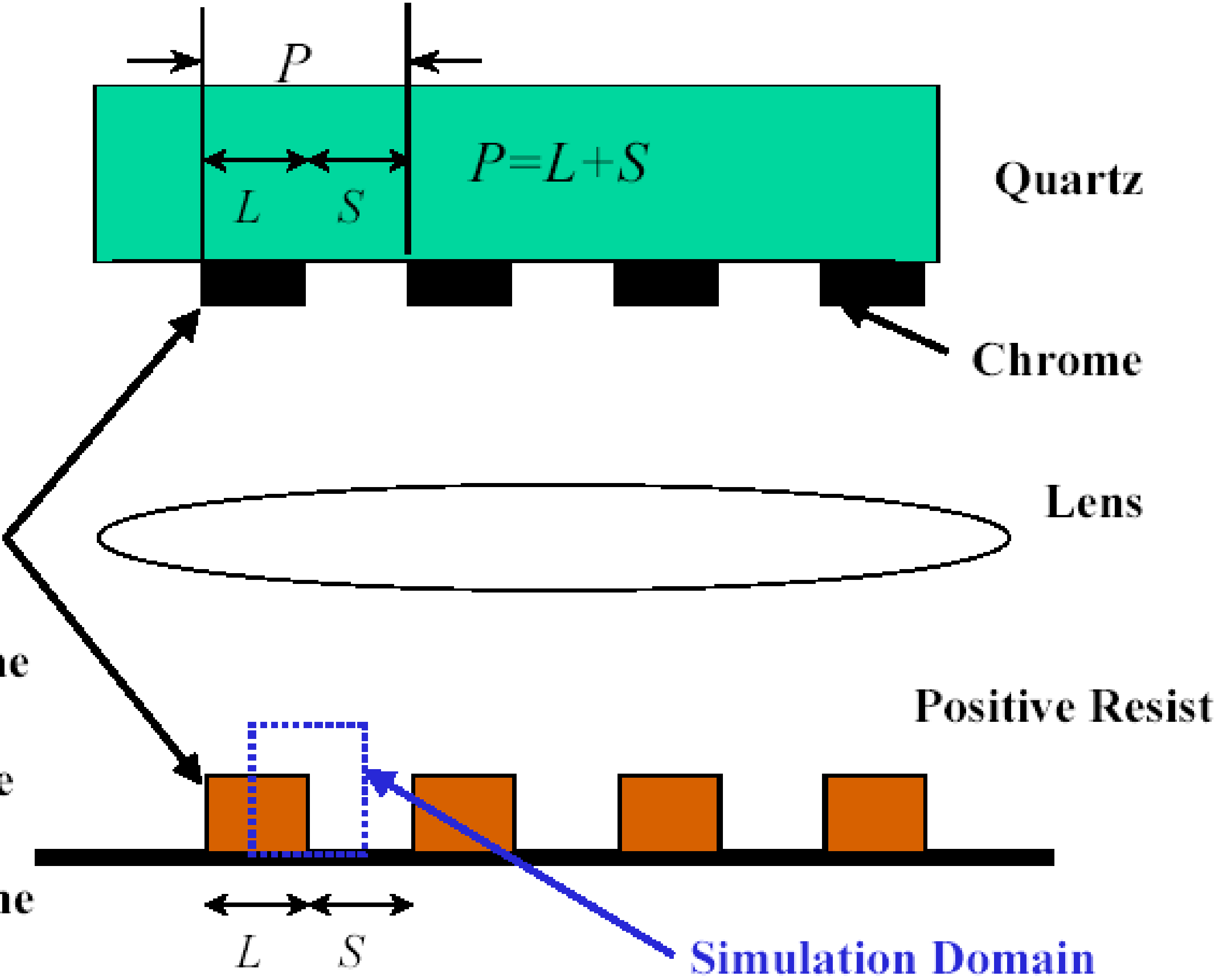
$$l_m = k_1 \frac{\lambda}{NA} \qquad \left[0.6 \frac{\lambda}{NA} \; typical \right]$$

$NA \equiv$ *numerical aperture of lens.*

$= \sin \theta$

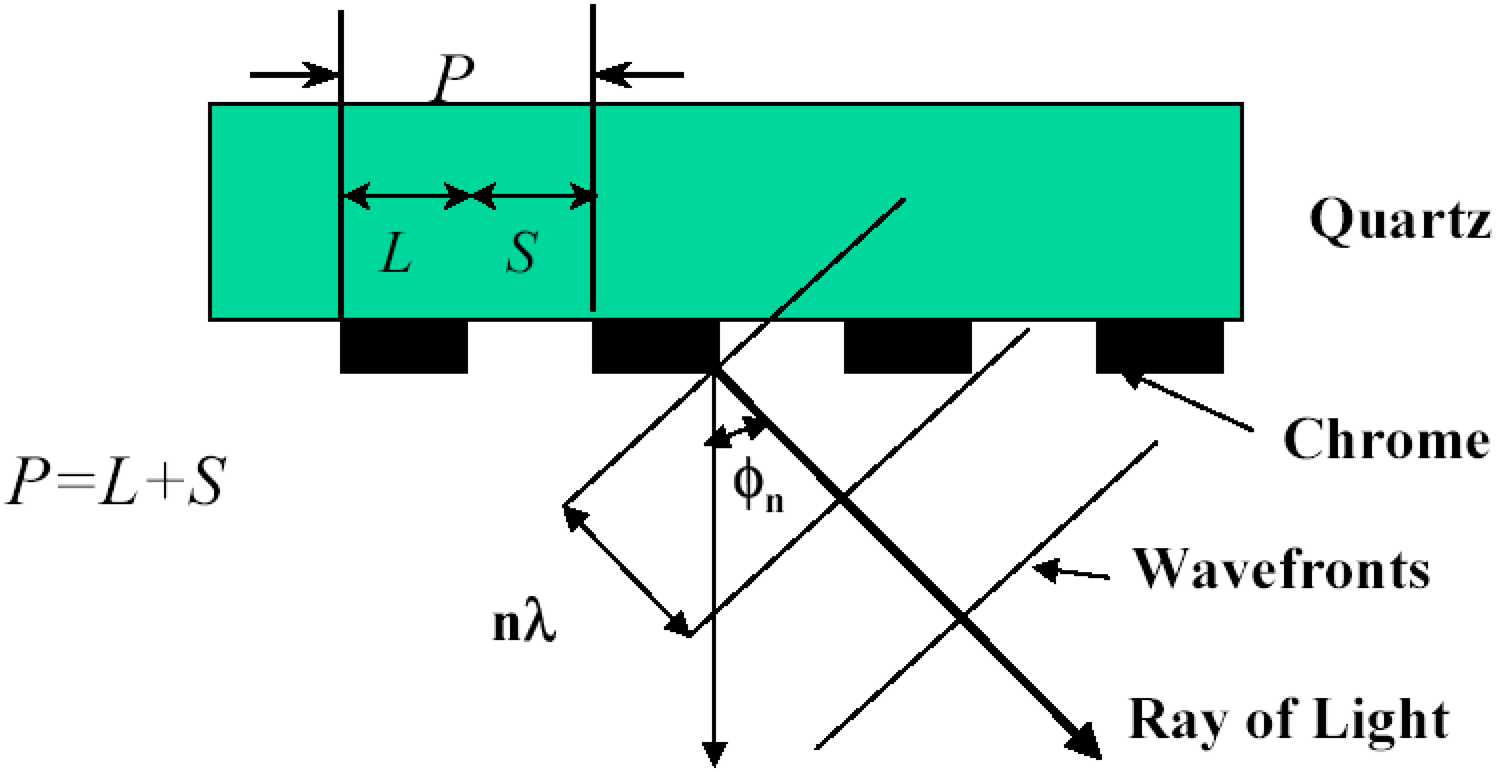
k_1 = a constant between 0.25 and 1, depending on optics, resist, and process latitude

Line and Space Definition for EE143



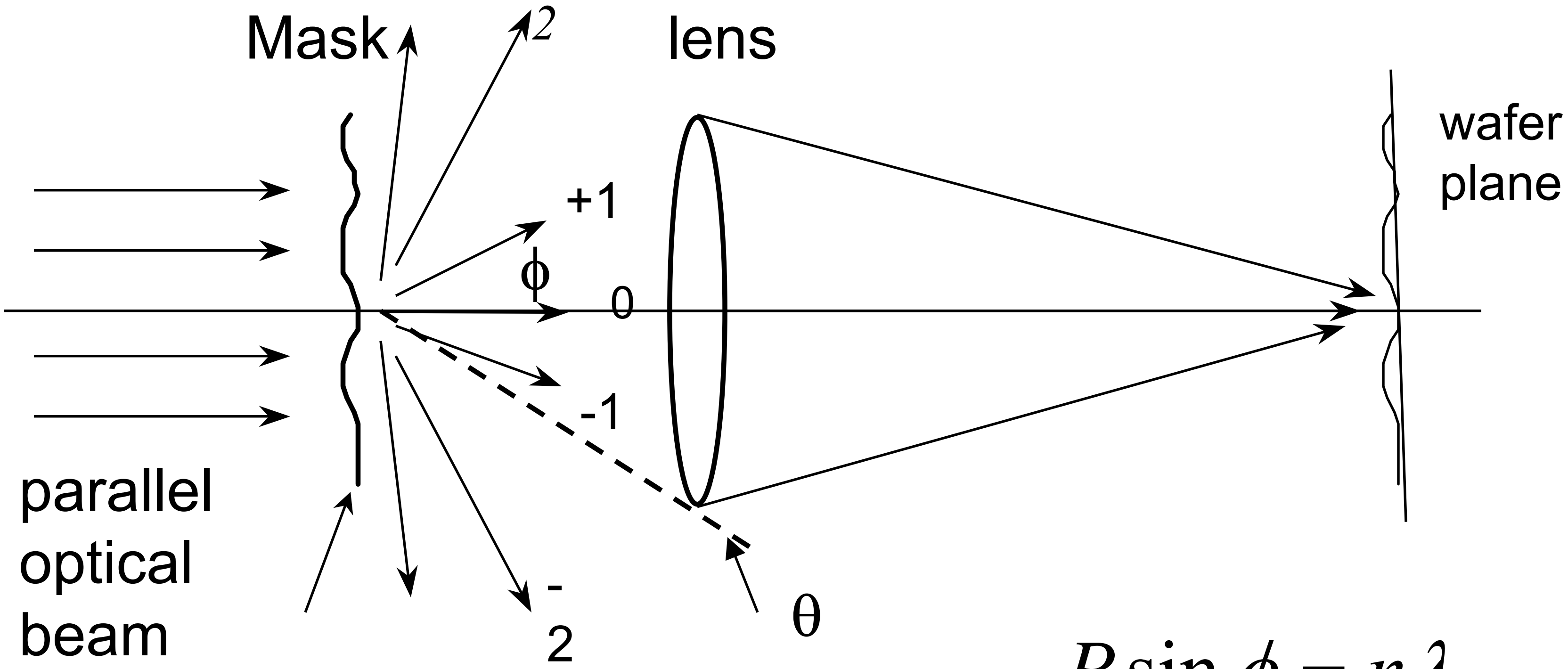
A line of chrome on the mask produces a line of resist remaining on the wafer

Bragg Condition

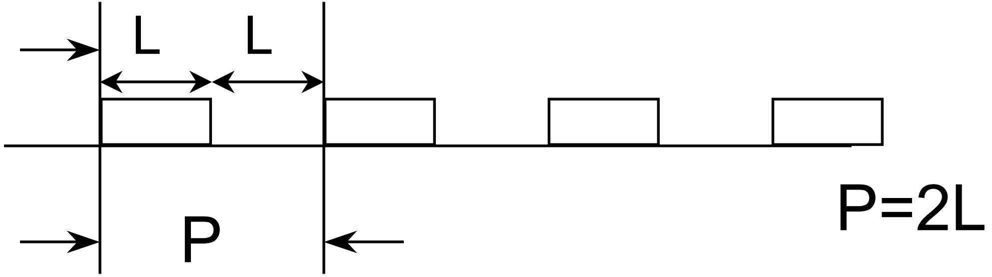


$$P \sin \varphi_n = n\lambda$$

Qualitative Explanation of image degradation by lens



grating with
spatial frequency 1/P



$$P \sin \phi = n\lambda$$

$$n = 0, \pm 1, \pm 2, \ldots$$

sin θ = NA of lens

Why $l_m \propto \dfrac{\lambda}{NA}$?

Mask Intensity

The lens has to collect *at least* the n=1 diffracted beams to show any spatially varying intensity on wafer.
Therefore P_m (= 2 l_m) $\propto \lambda$/ NA

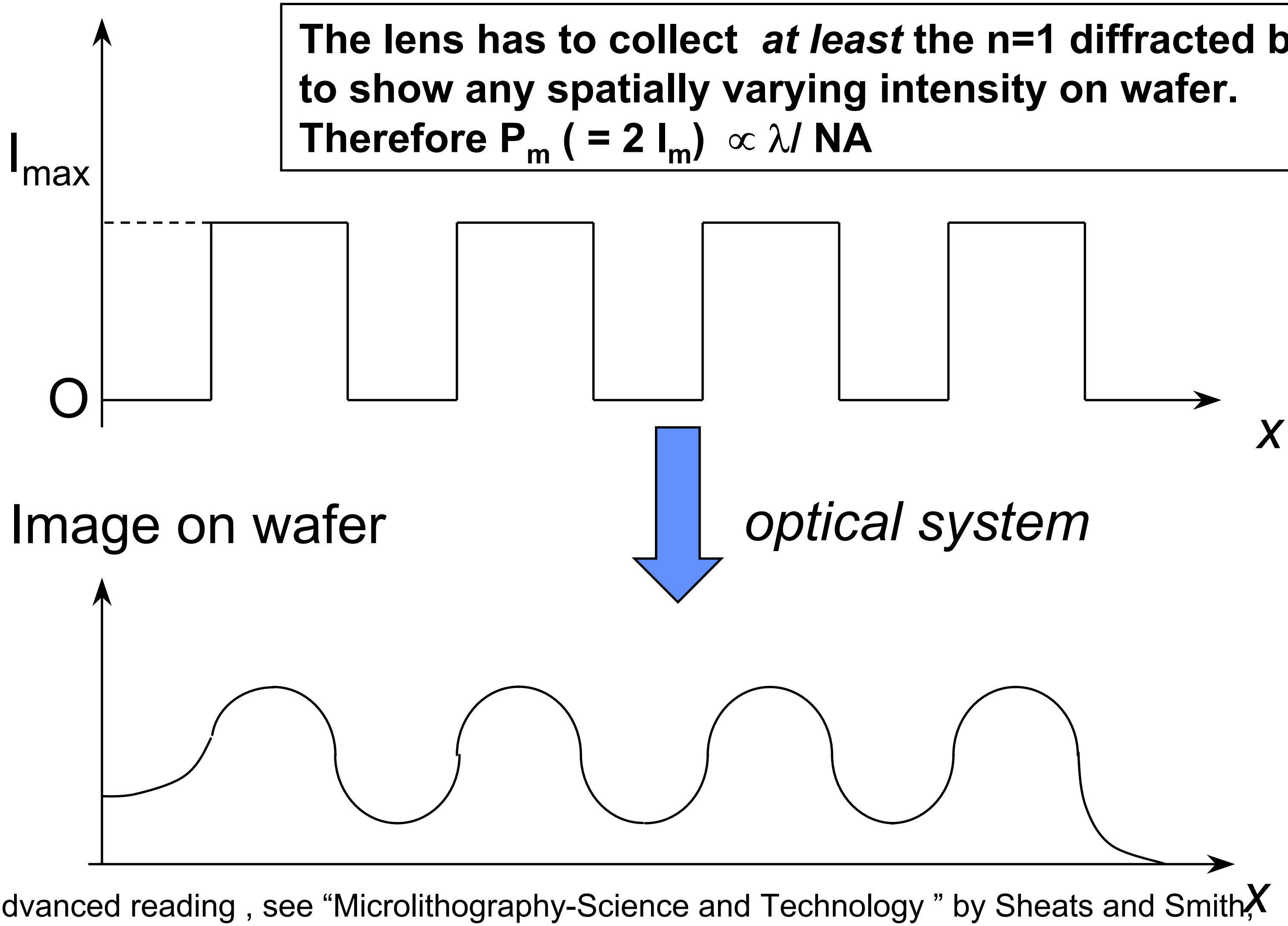
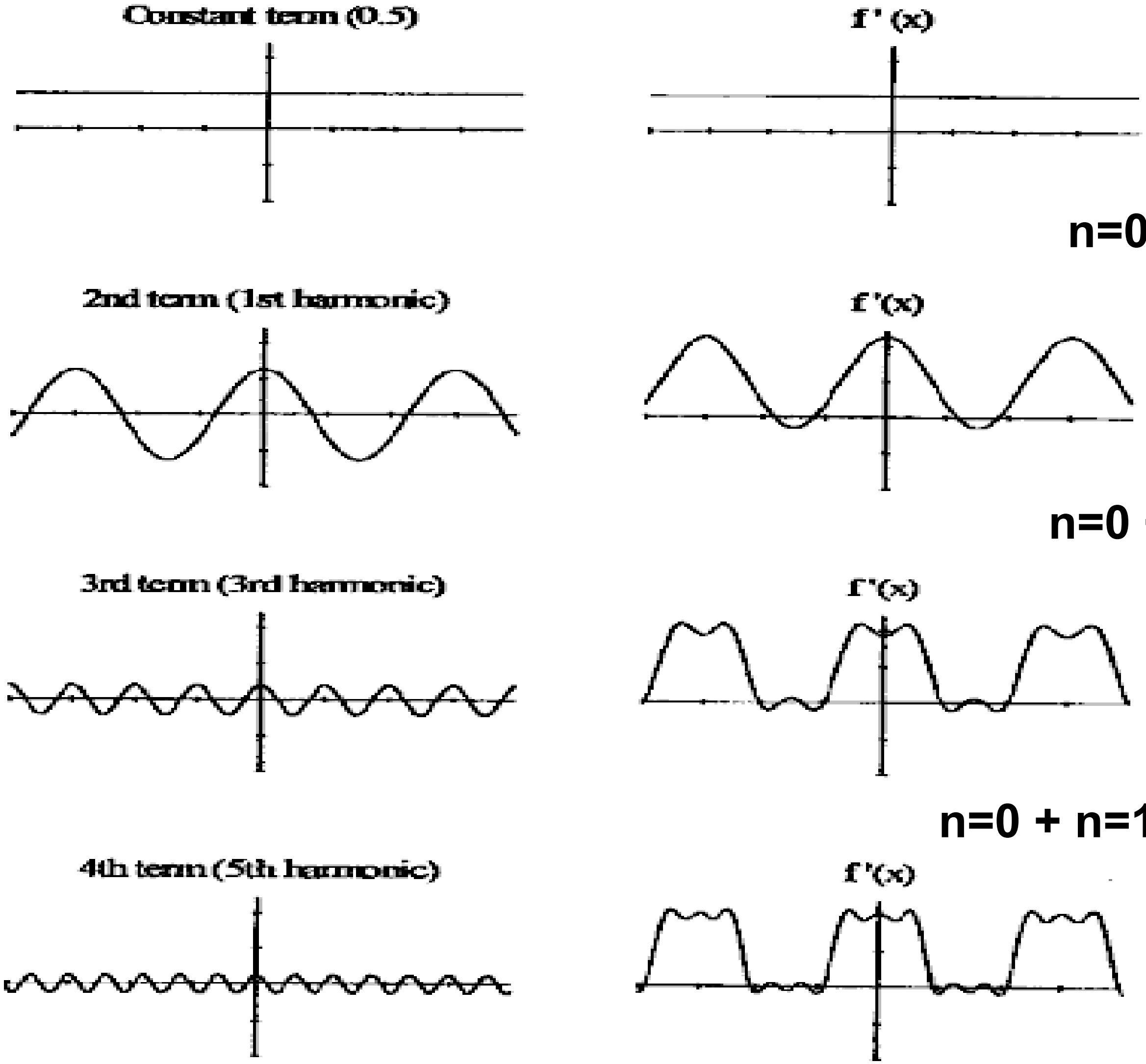


Image on wafer

For advanced reading , see “Microlithography-Science and Technology ” by Sheats and Smith,

Effect of Fourier Components on aerial image of a rectangular waveform

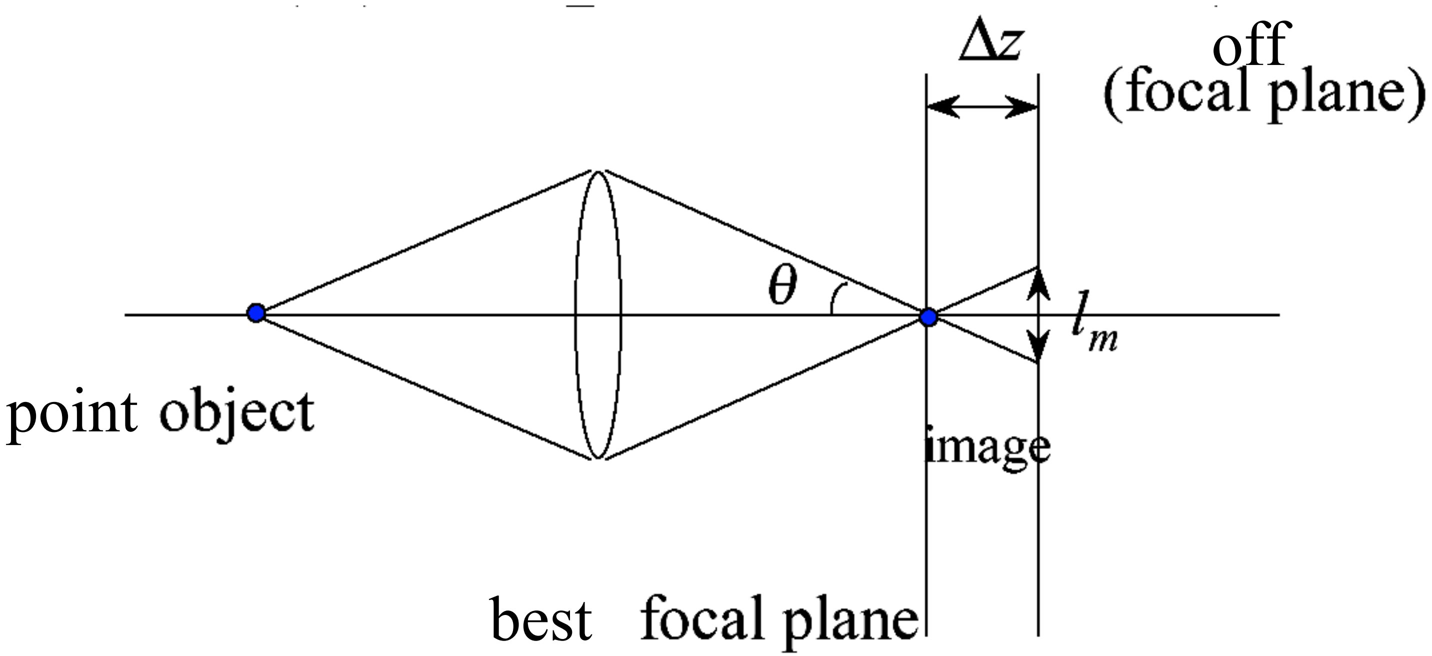


n=0 + n=1

n=0 + n=1 + n=3

n=0 + n=1 + n=3 + n=5

Depth of Focus (DOF)

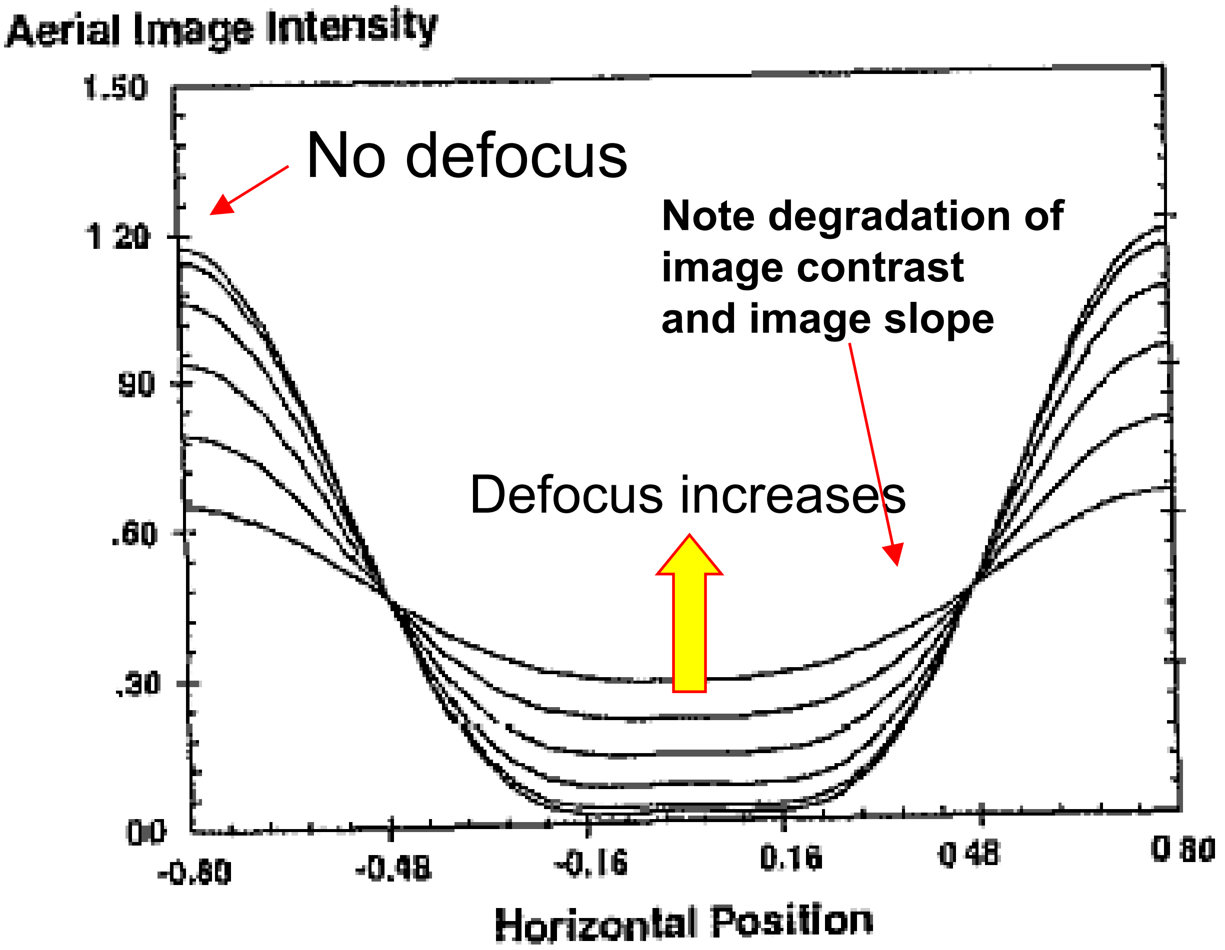


$$\Delta z = k_2 \frac{\lambda}{(NA)^2}$$

$$0.5 < k_2 < 1$$

$$\boxed{\approx \frac{\pm l_m/2}{\tan\theta} \approx \frac{\pm l_m/2}{\sin\theta} = \pm\frac{\lambda}{2(NA)^2} \quad \textit{for small } \theta}$$

Simulated aerial images with various degree of defocus



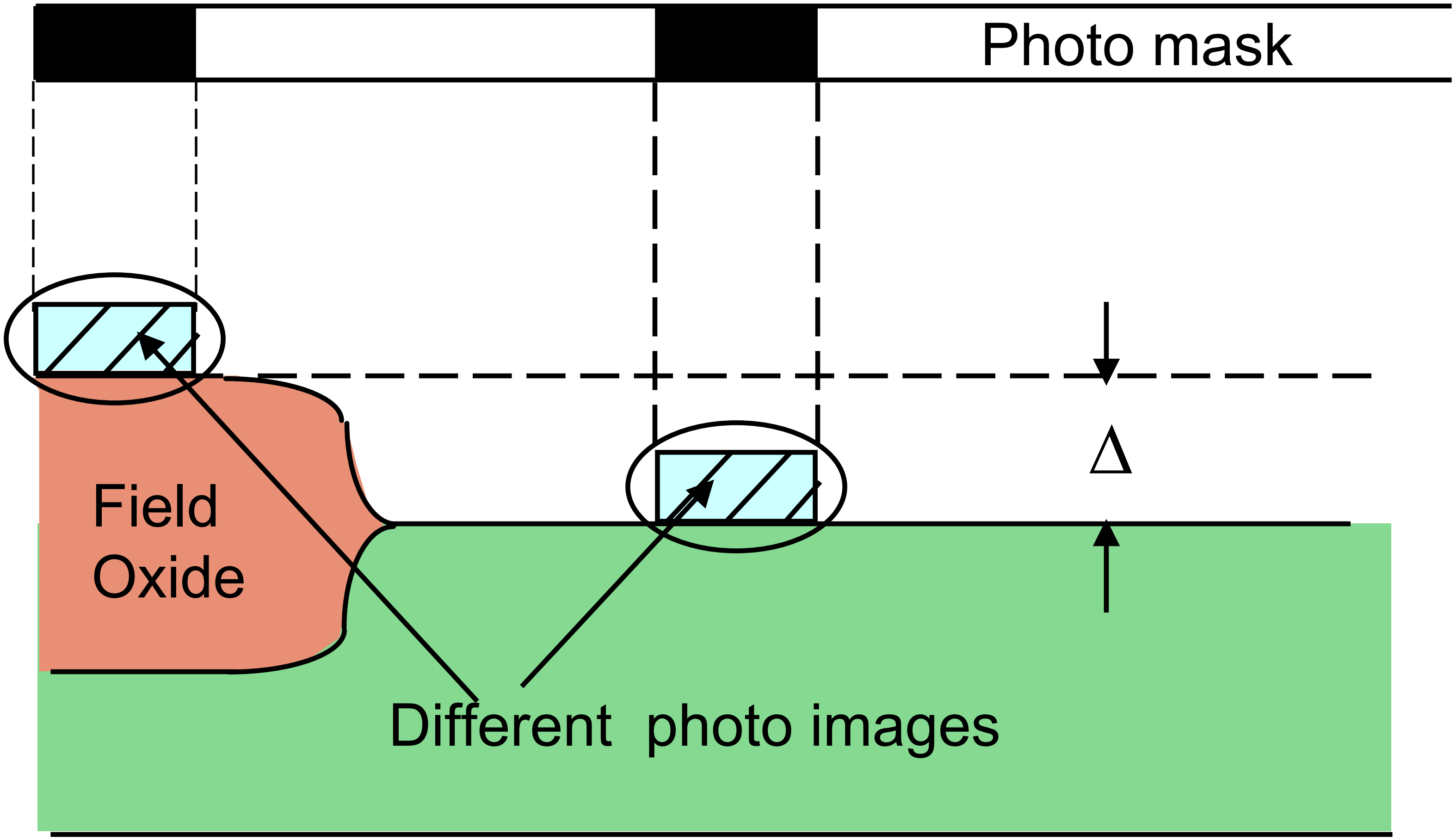
No defocus

Note degradation of image contrast and image slope

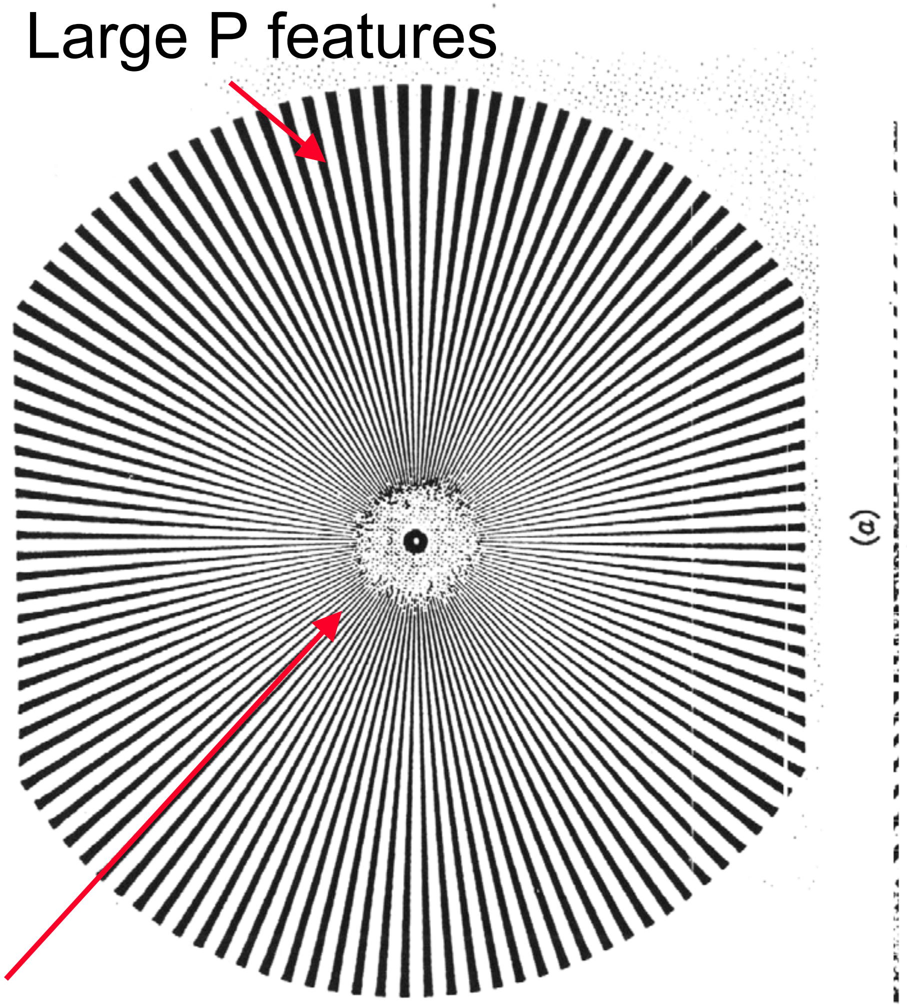
Defocus increases

FIG. 7.10 Aerial image intensity of a 0.8 λ /NA line and space pattern as focus is changed in steps of 0 4 Rayleigh units.

Example of DOF problem



Focus versus Extreme Defocus (an illustration)

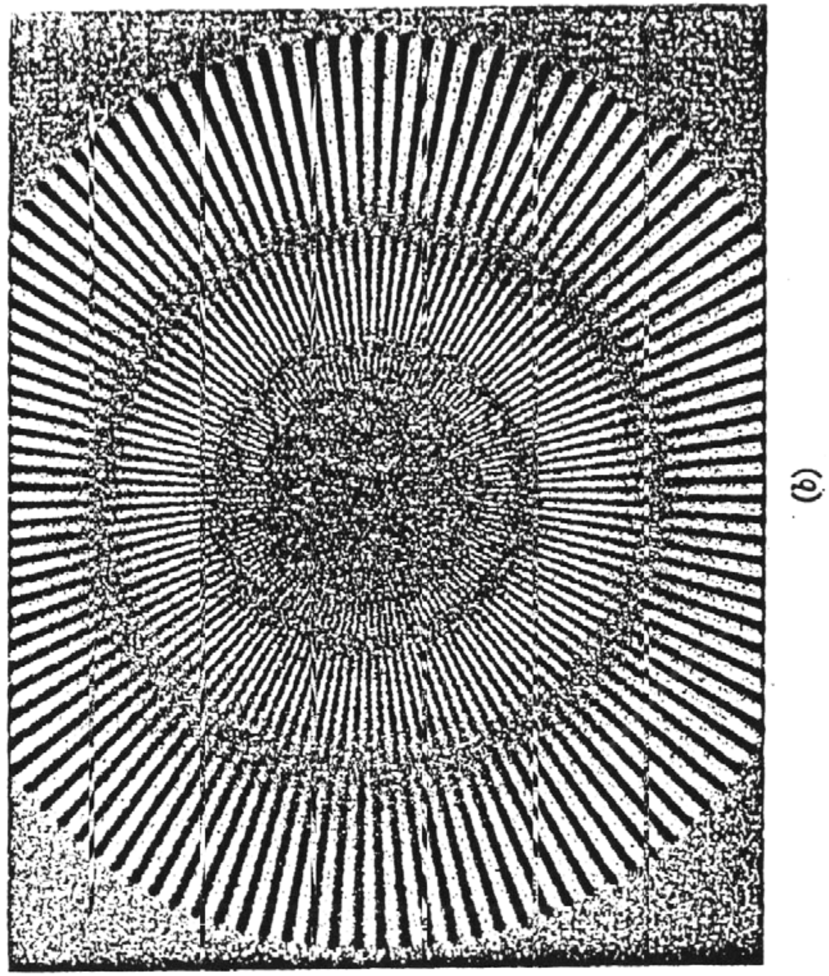


Large P features

Small P features

Best focus

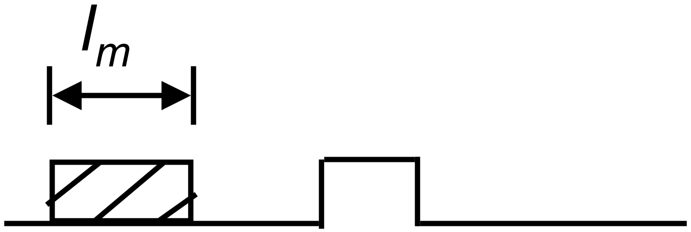
For Reference only



Extreme Defocus

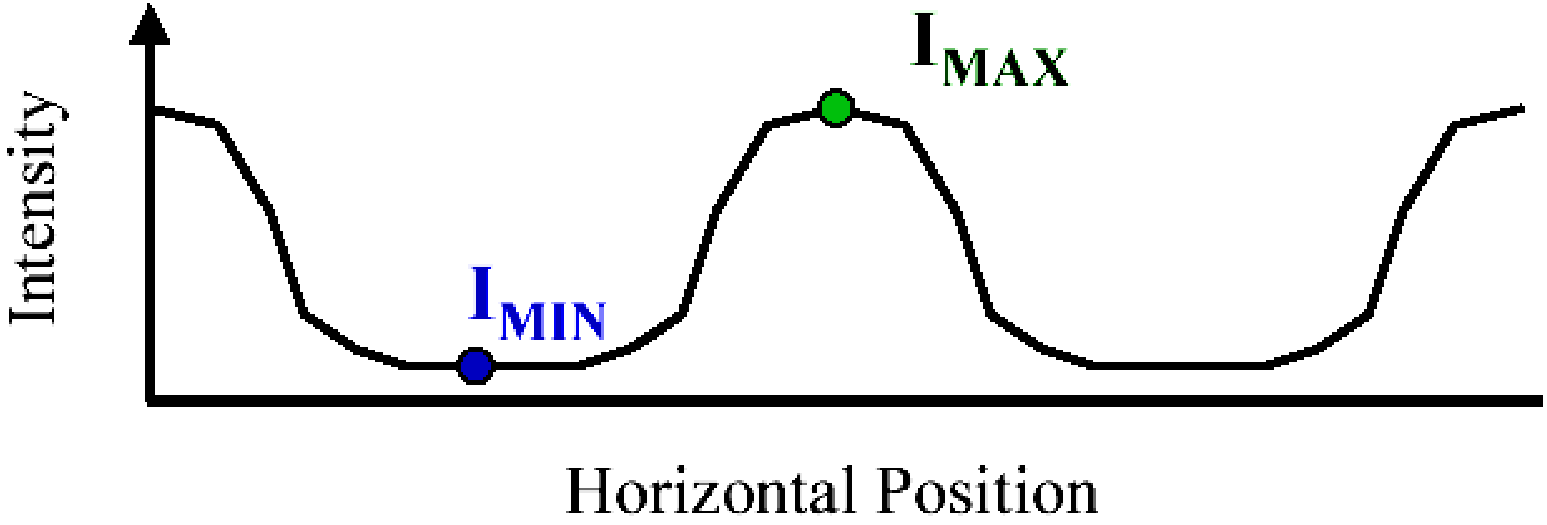
$$(1)\ l_m \cong 0.6\frac{\lambda}{NA} \quad want\ small\ l_m$$

$$(2)\ DOF = \pm\frac{\lambda}{2(NA)^2} \quad want\ large\ DOF$$



(1) and (2) require a compromise between λ and NA !

Image Quality Metric: Contrast

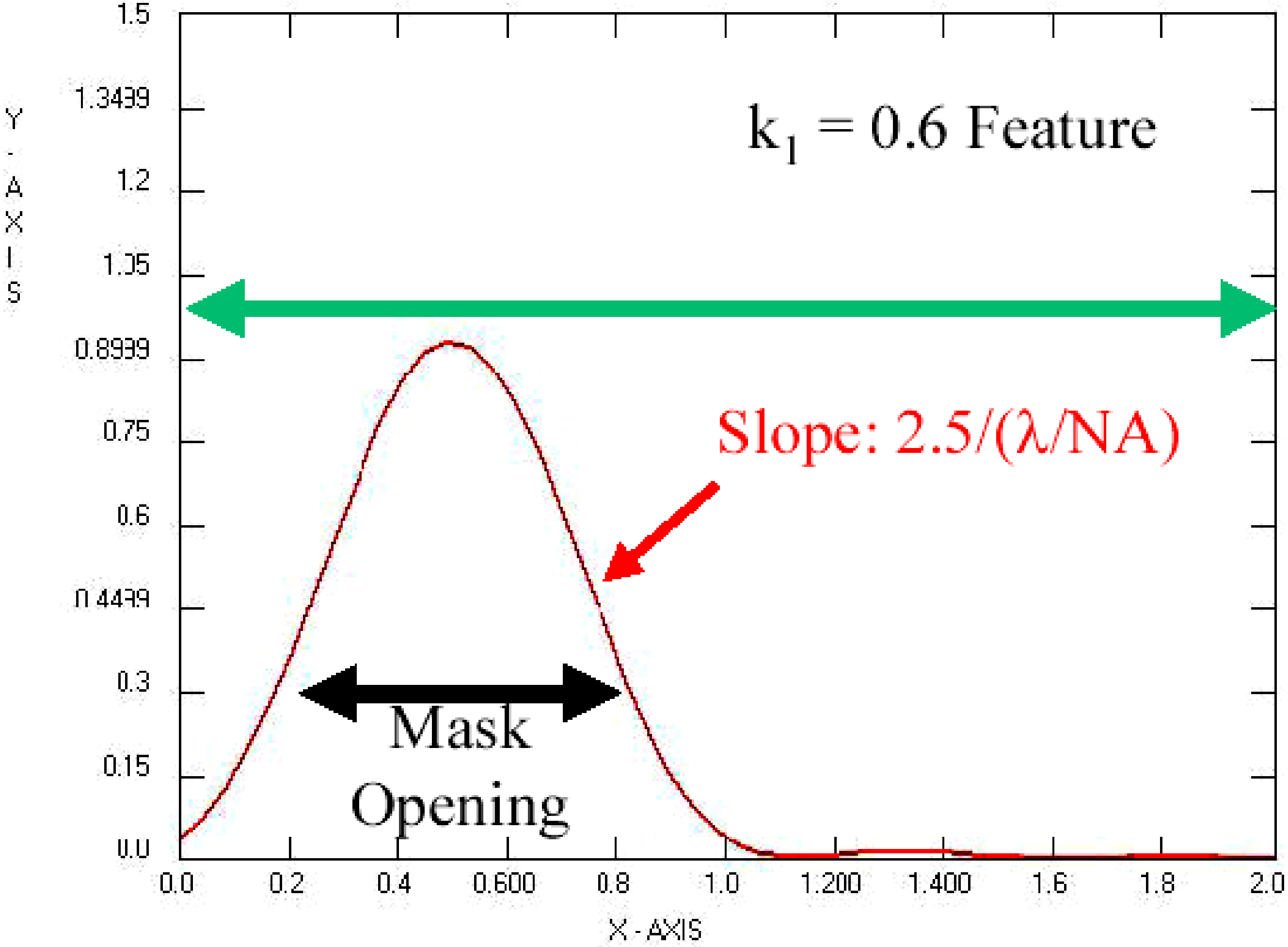


Contrast:

$$C = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}$$

The contrast is always between 0 (no variation) and 1 (perfect minimum).

Image Quality metric: Slope of image

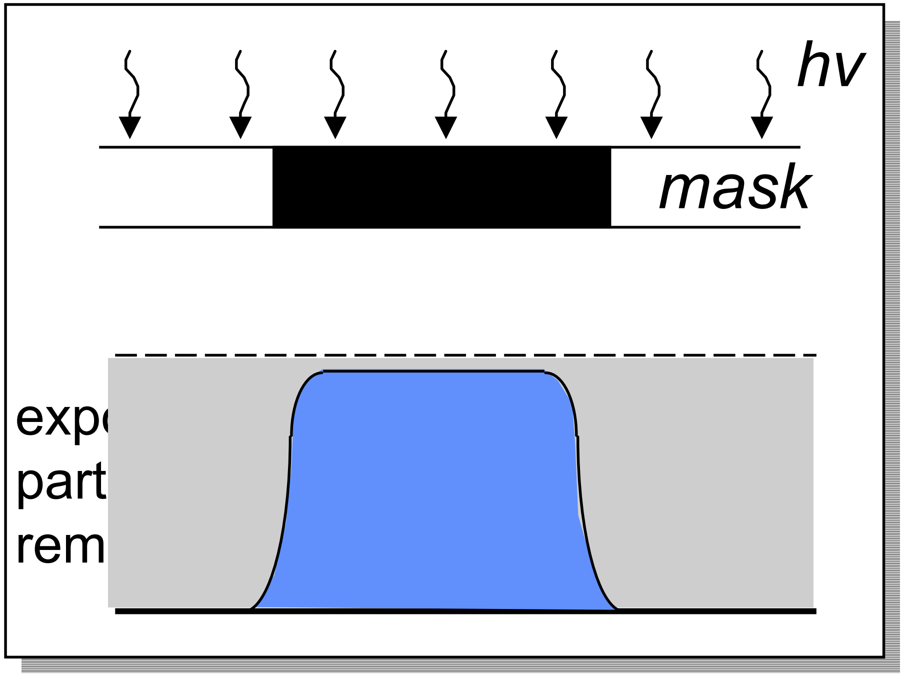


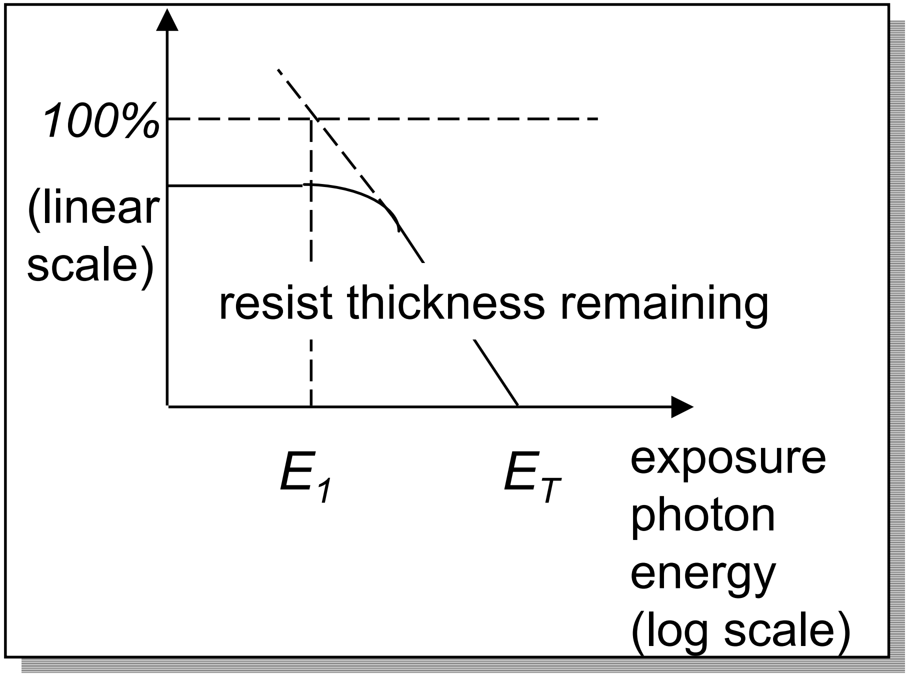
* simulated aerial image of an isolated line

Two Resist Types

- Negative Resist
  - Polymer (Molecular Weight (MW) ~65000)
  - Light Sensitive Additive Promotes Crosslinking
  - Volatile Solvents
  - Light breaks N-N => Crosslink Chains
  - Sensitive, hard, Swelling during Develop
- Positive Resist
  - Polymer (MW~5000)
  - Photoactive Inhibitor (20%)
  - Volatile Solvents
  - Inhibitor Looses N_2 => Alkali Soluble Acid
  - Develops by “etching” - No Swelling.

Positive Resist





E_T = *resist sensitivity*

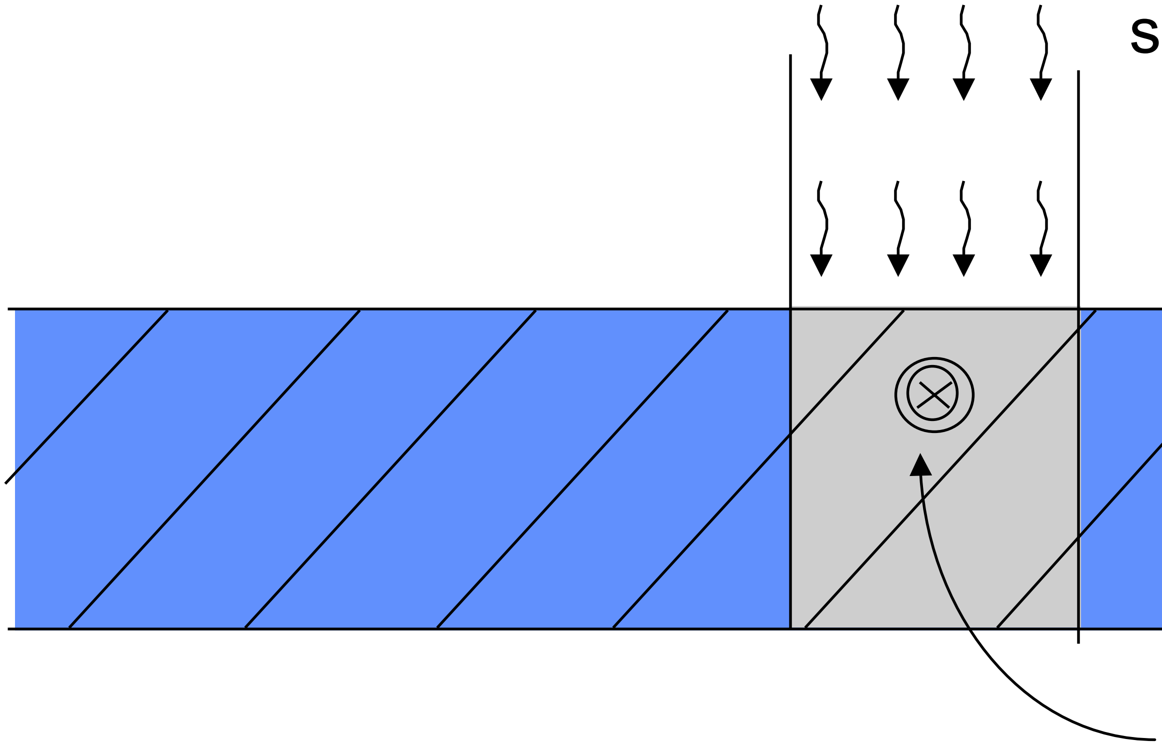
$$\textit{Resist contrast} \equiv \frac{1}{\log_{10}\left(\frac{E_T}{E_1}\right)}$$

LOG TO BASE 10

$\gamma \sim 5$ to 10

Note: In the 143 Reader,
γ is defined as natural log

Positive P.R. Mechanism



Photons deactivate sensitizer

⇒ less cross-linking

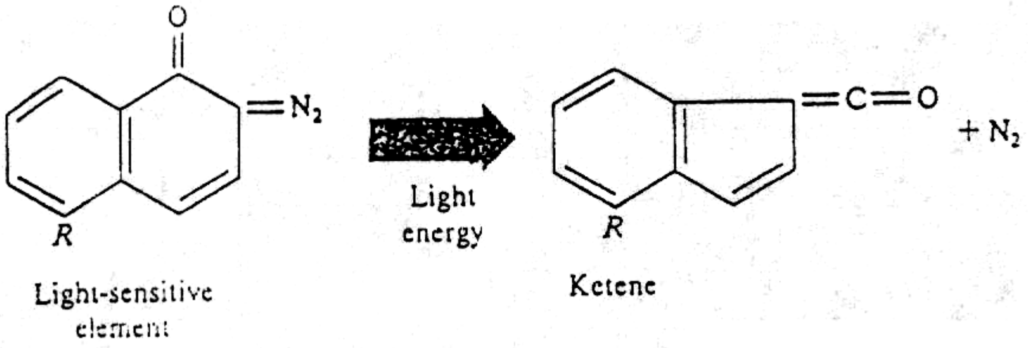
⇒ dissolve in developer solution

polymer + photosensitizer

Positive Resist Exposure Reaction

"diazide"

"ketene" - a = C = 0 group

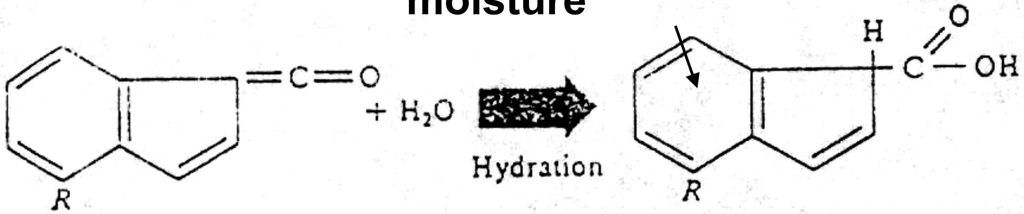


The ketene is short-lived intermediate

PAC

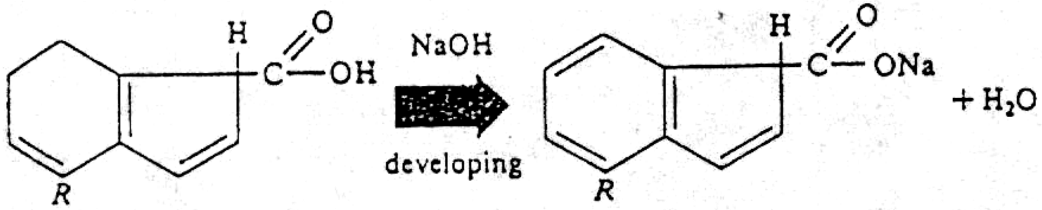
"carboxylic acid"

moisture

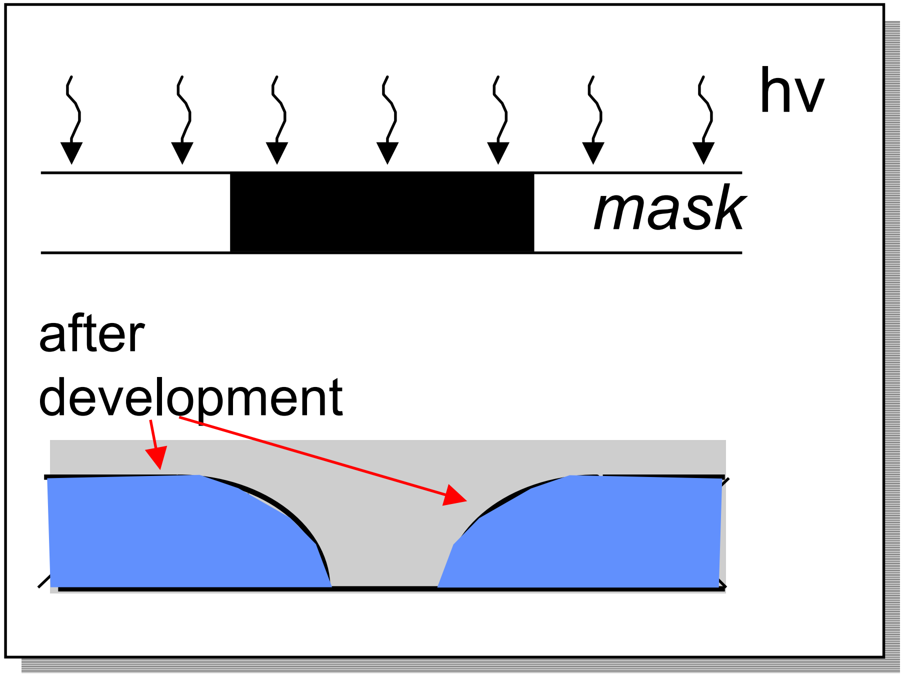


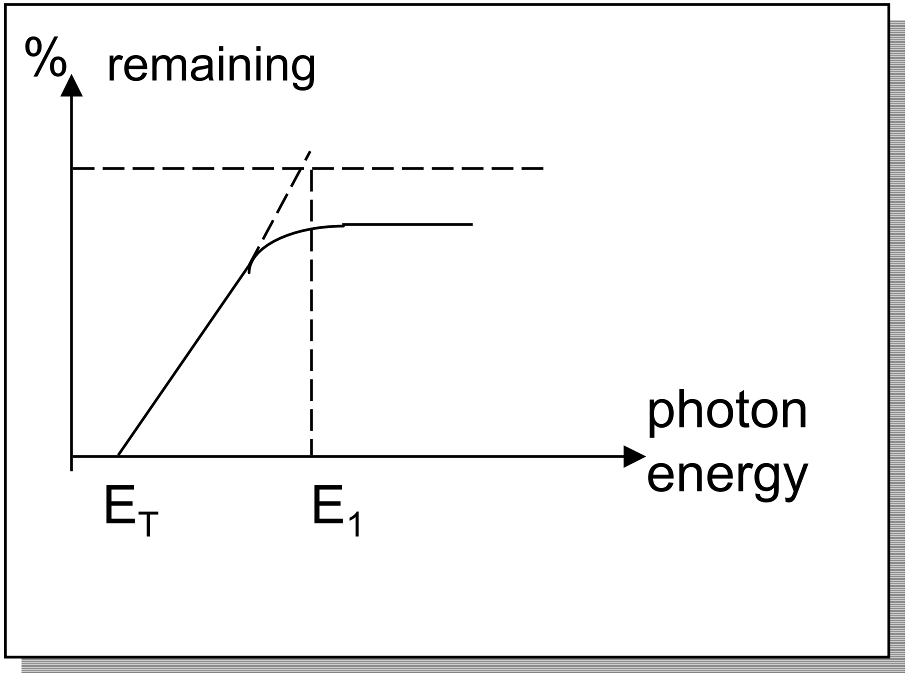
The carboxylic acid can react with the alkaline solution (the developer) to form a soluble ester.

"soluble ester"



Negative P.R. Mechanism





$$\gamma \equiv \frac{1}{\log\left(\dfrac{E_1}{E_T}\right)}$$

Log to base 10

hv => cross-linking => insoluble in developer solution.

Infinite Contrast Resist
$D_0=D_{100}=D_{critical}$

Finite Contrast Resist
$D_0 \neq D_{100}$

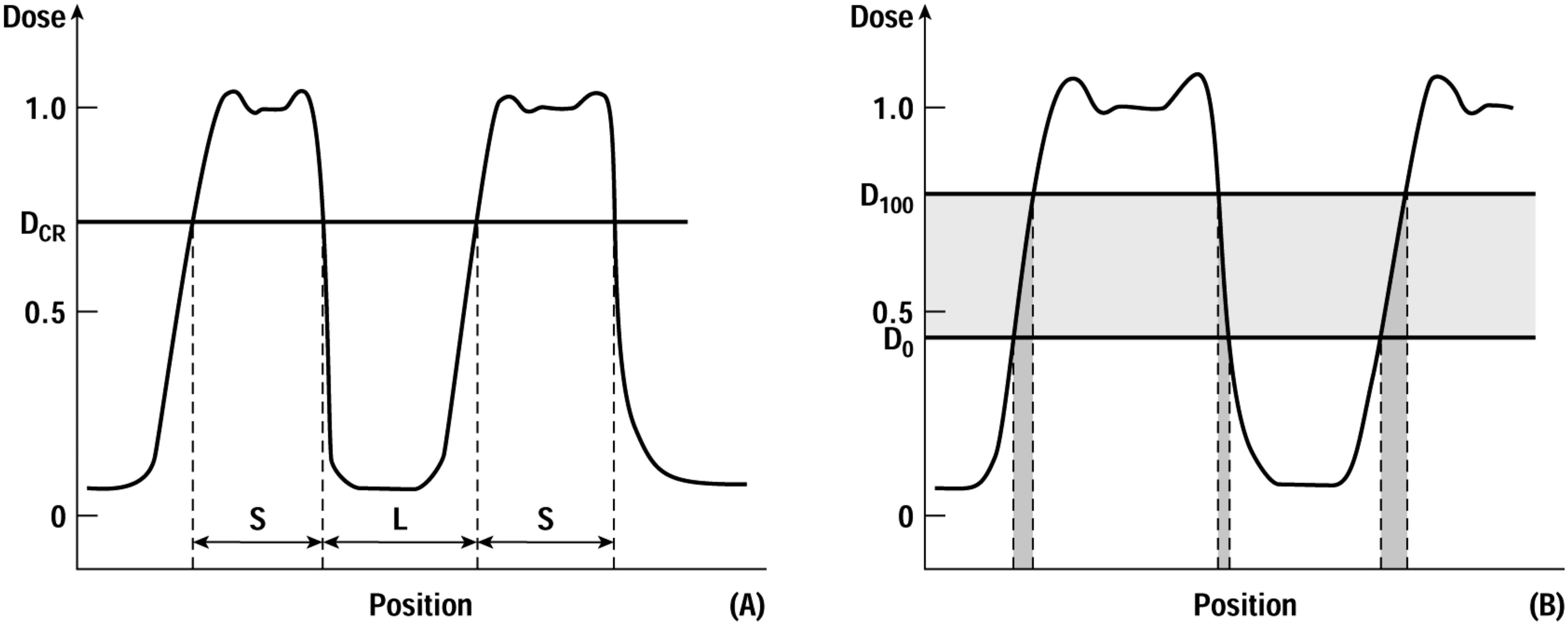
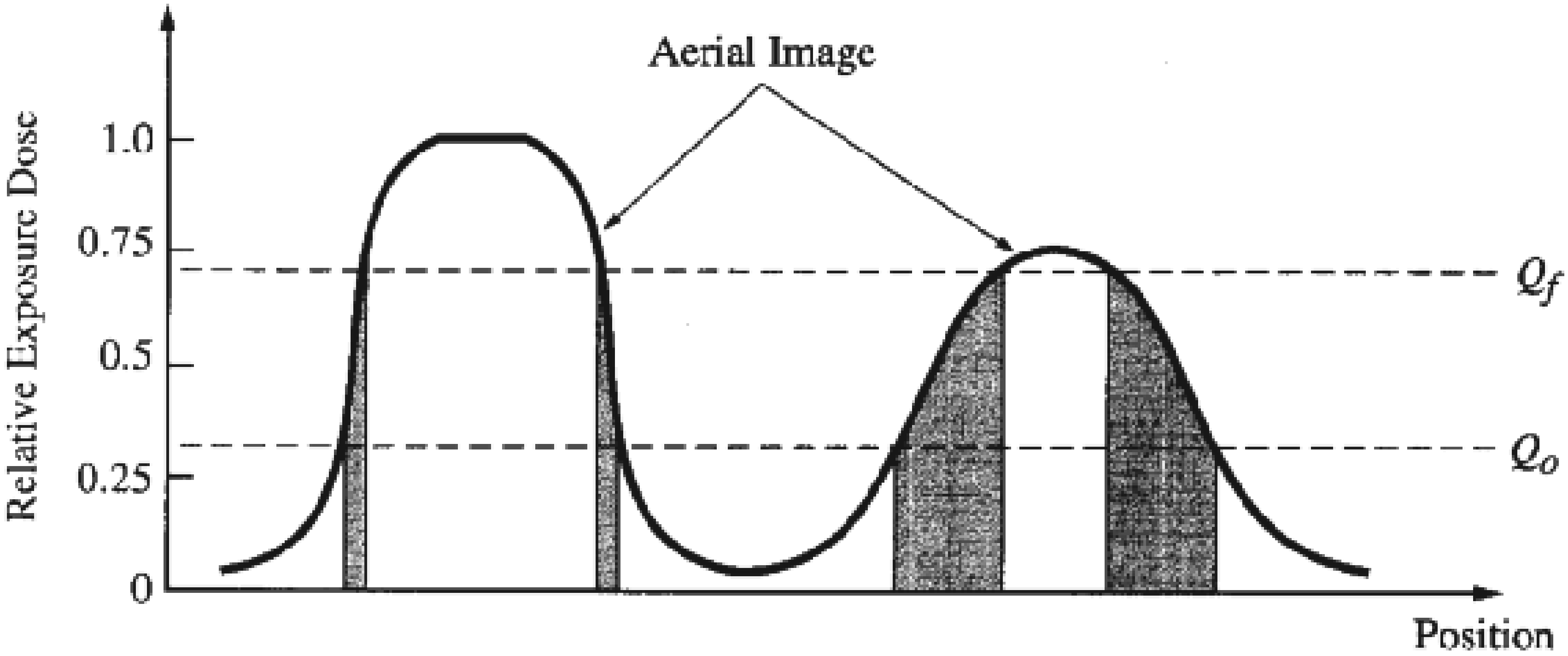


Figure 7.9 Plot of dose versus position on the wafer. Dose is given by the intensity of the light in the aerial image multiplied by the exposure time. Typical units are mJ/cm^2.

energy

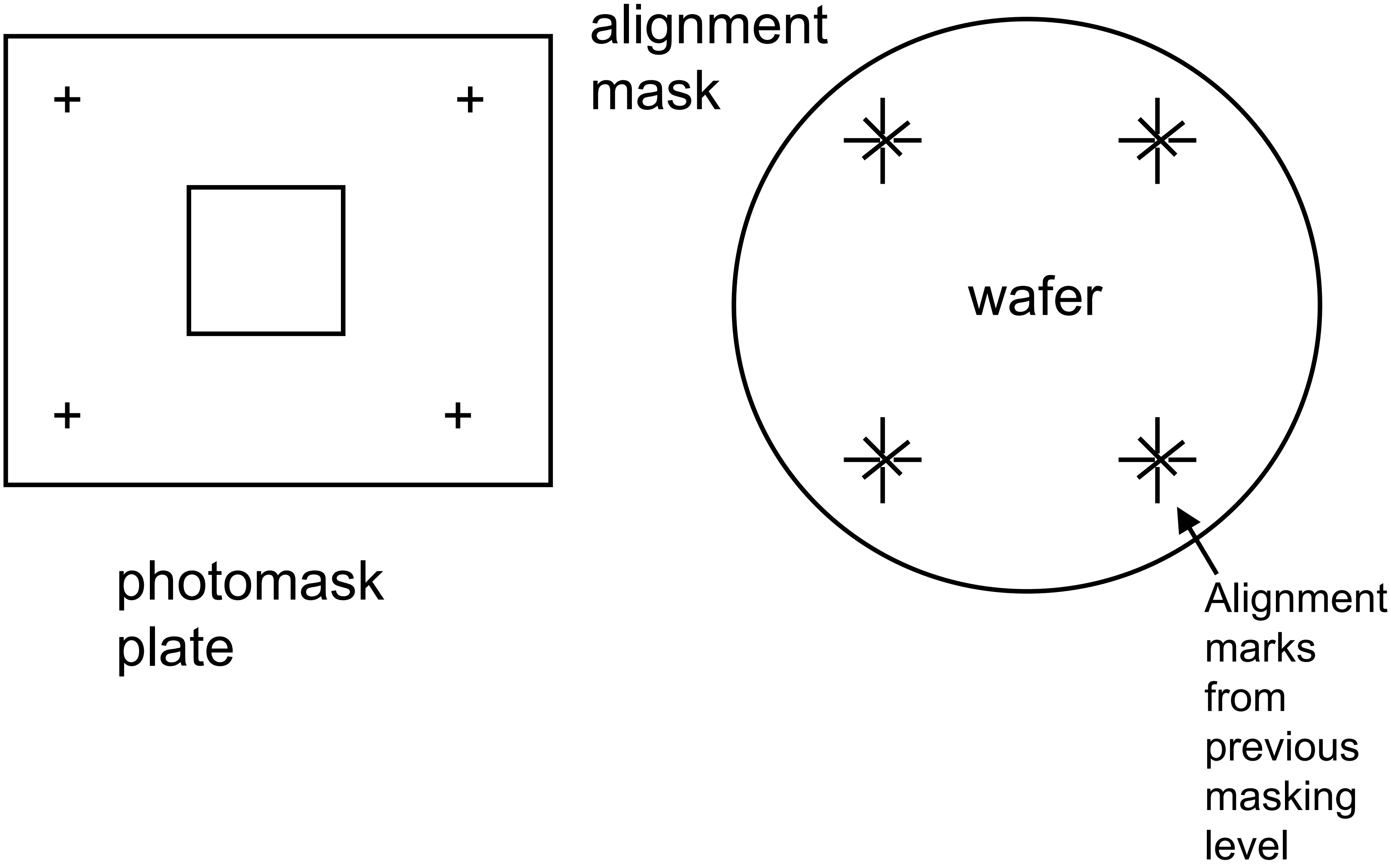
Figure 5–21 Example of how the quality of the aerial image and the resist contrast combine to produce the resist edge profile. The left side shows a sharp aerial image and steep resist edges (gray area). The example on the right shows a poorer aerial image and the resulting gradual edges on the resist profile.



Positive vs. Negative Photoresists

- **Positive P.R.:**
  - ✓ higher resolution
  - ✓ aqueous-based solvents
  - ✗ less sensitive
- **Negative P.R.:**
  - ✓ more sensitive => higher exposure throughput
  - ✓ relatively tolerant of developing conditions
  - ✓ better chemical resistance => better mask material
  - ✓ less expensive
  - ✗ lower resolution
  - ✗ organic-based solvents

Overlay Errors



alignment mask

photomask plate

wafer

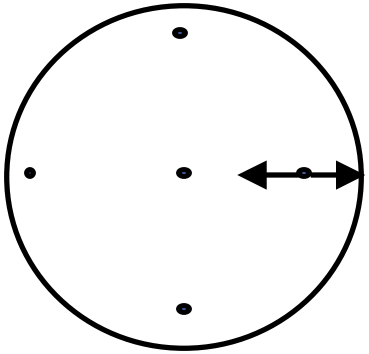
Alignment marks from previous masking level

(1) Thermal run-in/run-out errors

$$R = r \cdot \left(\Delta T_m \cdot \alpha_m - \Delta T_{si} \cdot \alpha_{si} \right)$$

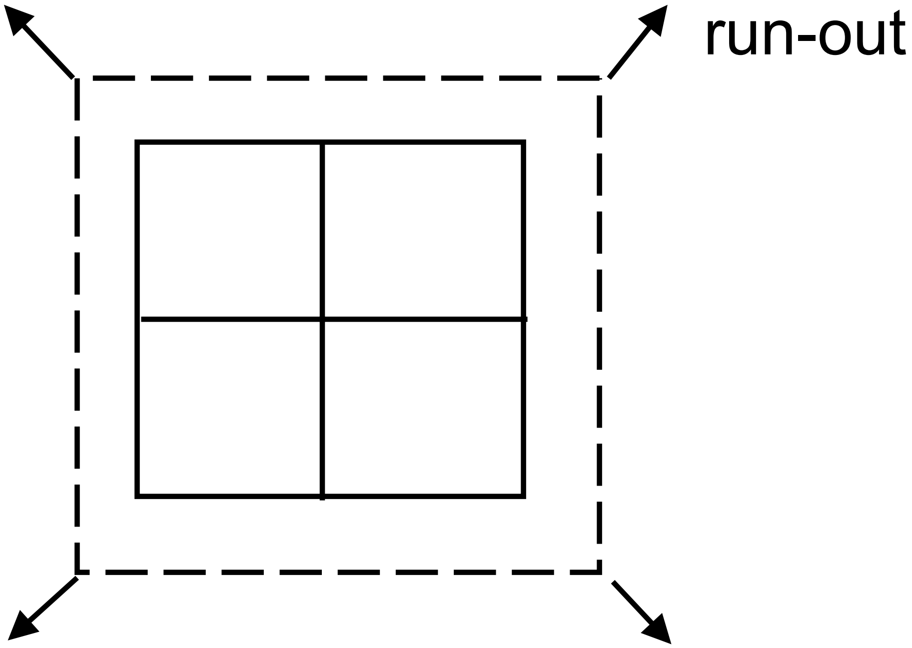
run-out error

wafer radius

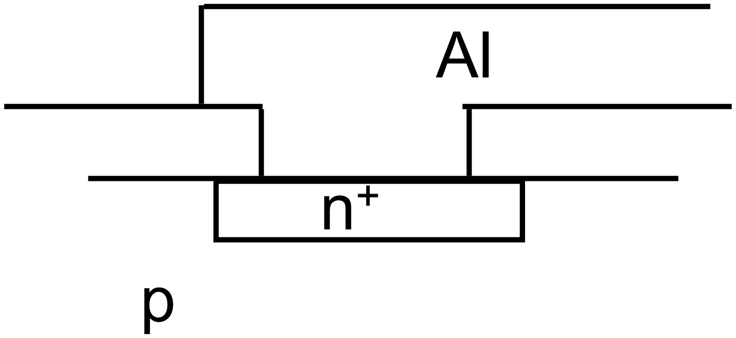


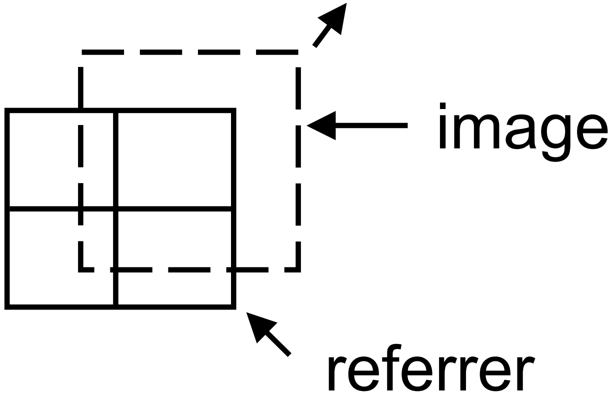
$$\Delta T_m, \Delta Tsi = change\ of\ mask\ and\ wafer\ temp.$$

$$\alpha_m, \alpha_{si} = coefficient\ of\ thermal\ expansion\ of\ mask\ \&\ Si$$

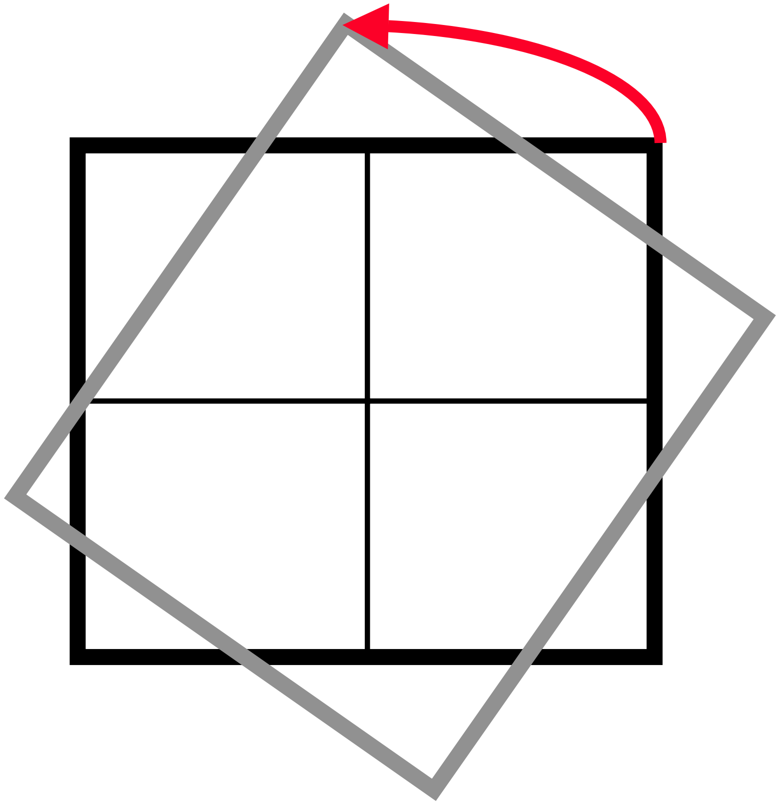


(2) Translational Error





(3) Rotational Error



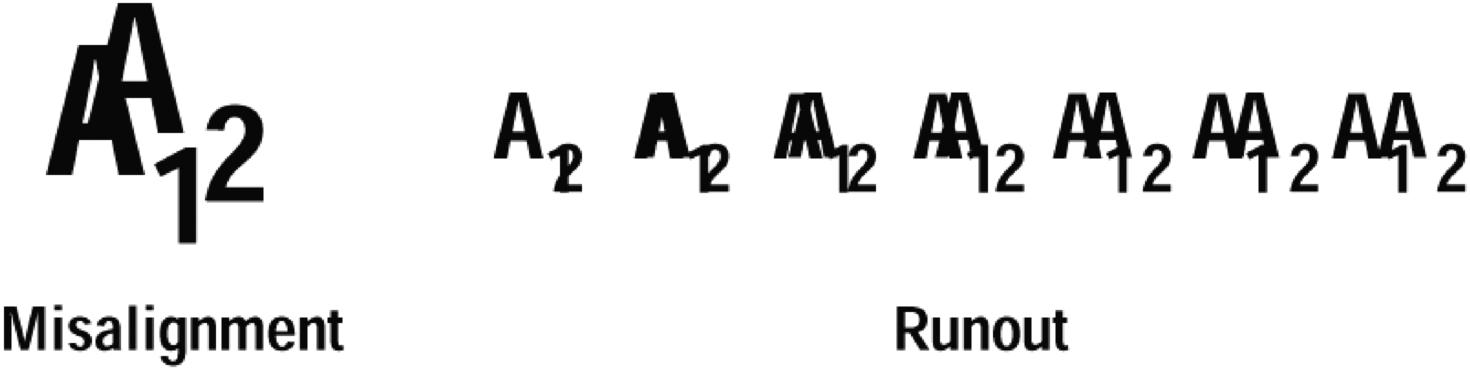
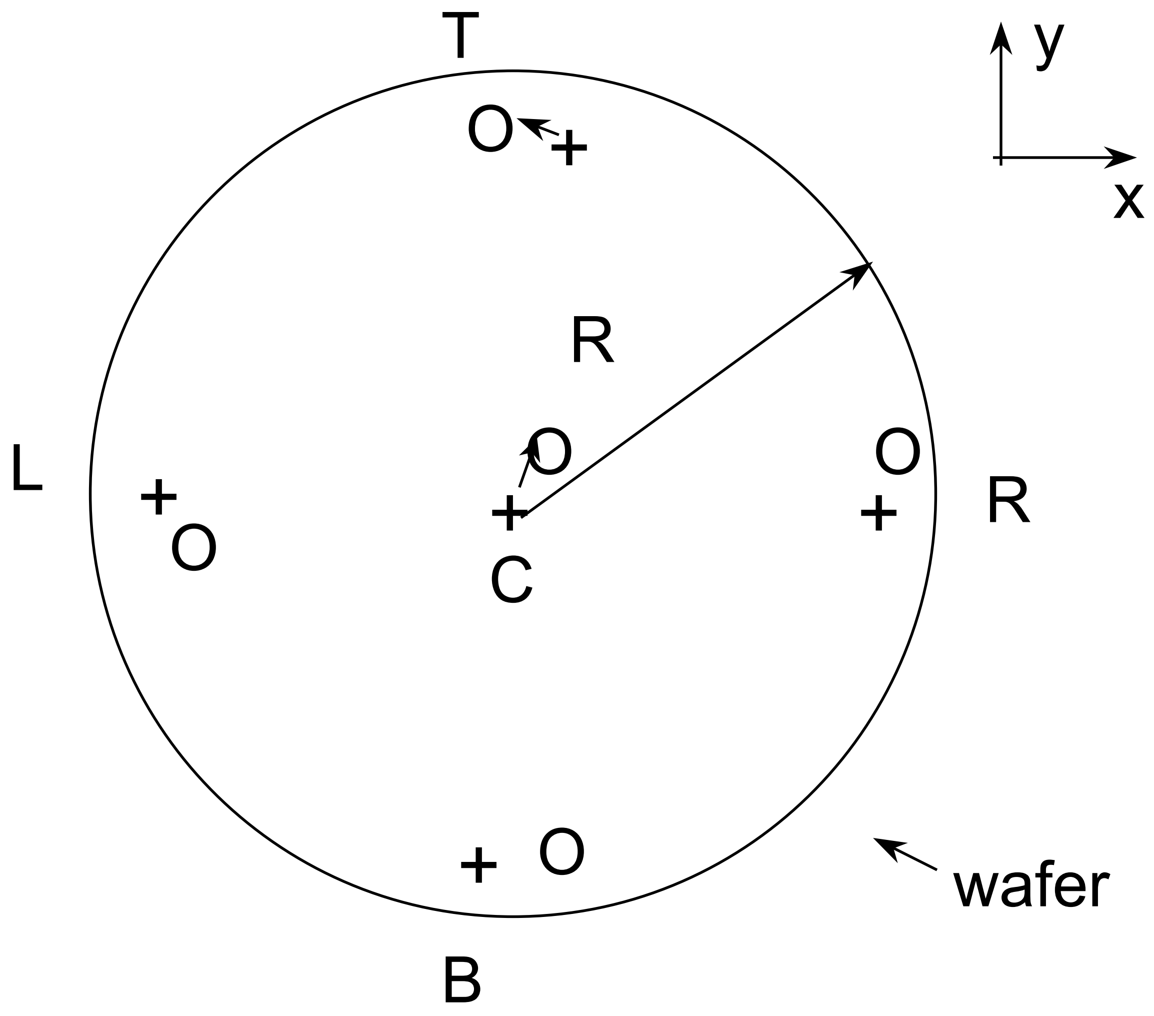


Figure 7.28 Two typical registration errors.

Characterization of Overlay Errors



O =optical image

+ =alignment marks on wafer

Example

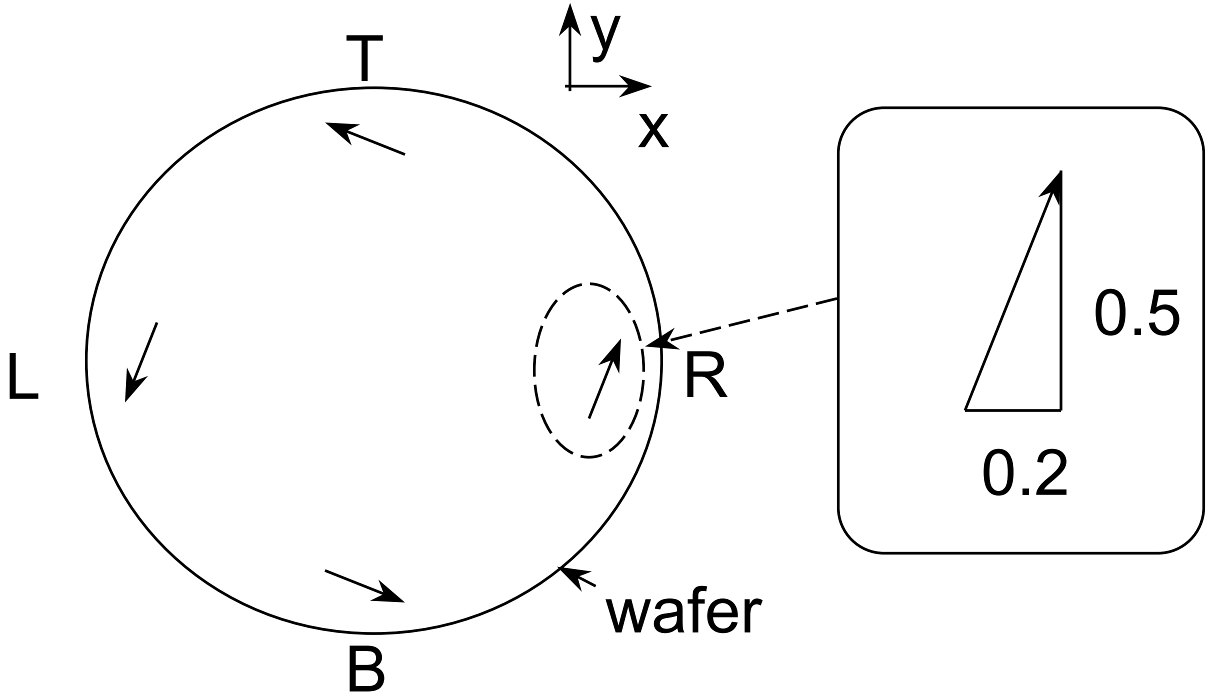
μm	T	R	C	L	B
x	0.0	0.7	0.5	0.3	1.0
y	0.7	1.0	0.5	0.0	0.3

* Center of wafer has only translation error

T_{error} = (0.5, 0.5)

After subtracting T_{error},

	T	R	C	L	B
x	-0.5	0.2	0	-0.2	0.5
y	0.2	0.5	0	-0.5	-0.2

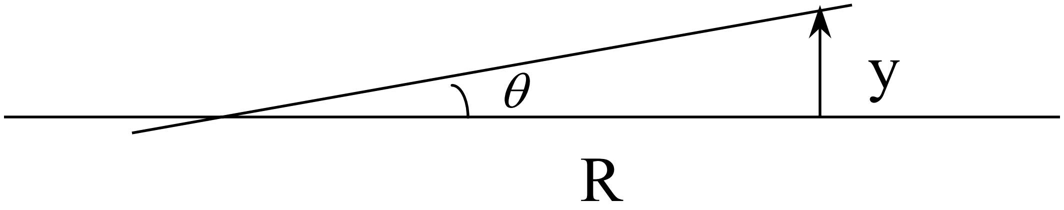


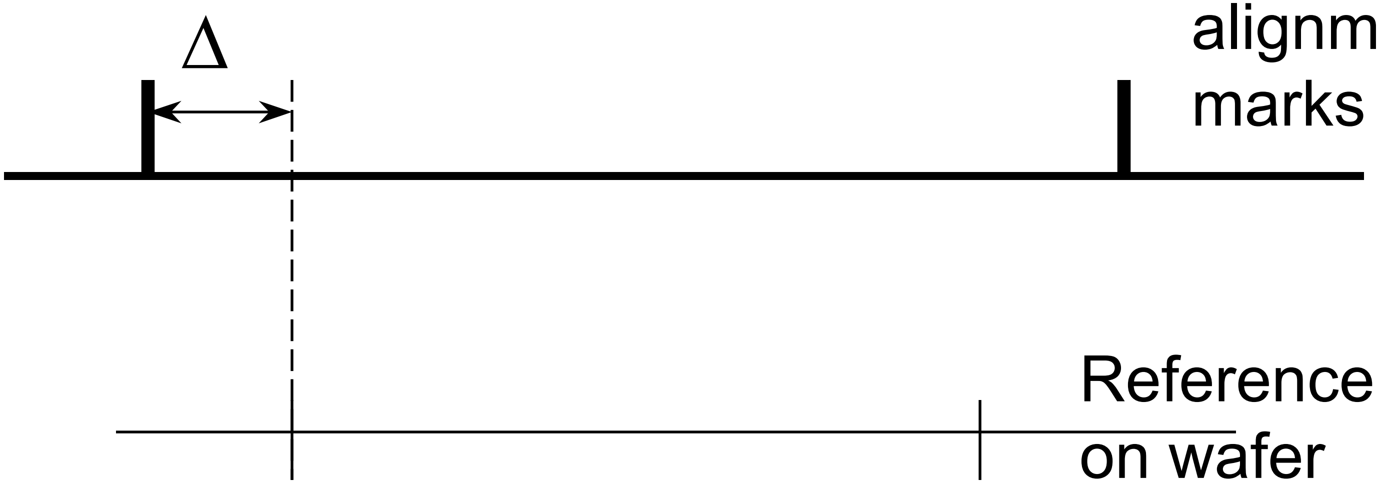
$$\therefore Run - out\ error = 0.2\,\mu m$$

$$\therefore Rotational\ \ error = 0.5\,\mu m\ [counter - clockwise]$$

$$If\ wafer\ diameter\ \ is\ 4'' \Rightarrow D = 10\,cm$$

$$\therefore\ Rotational\ \ error = \ \ 10^{-5}\ radians$$





Optical image of mask alignment marks

Reference marks on wafer

With thermal run-out, the alignment error is 1/2 of the image/reference difference [best scenario]