Introduction to Nanofabrication

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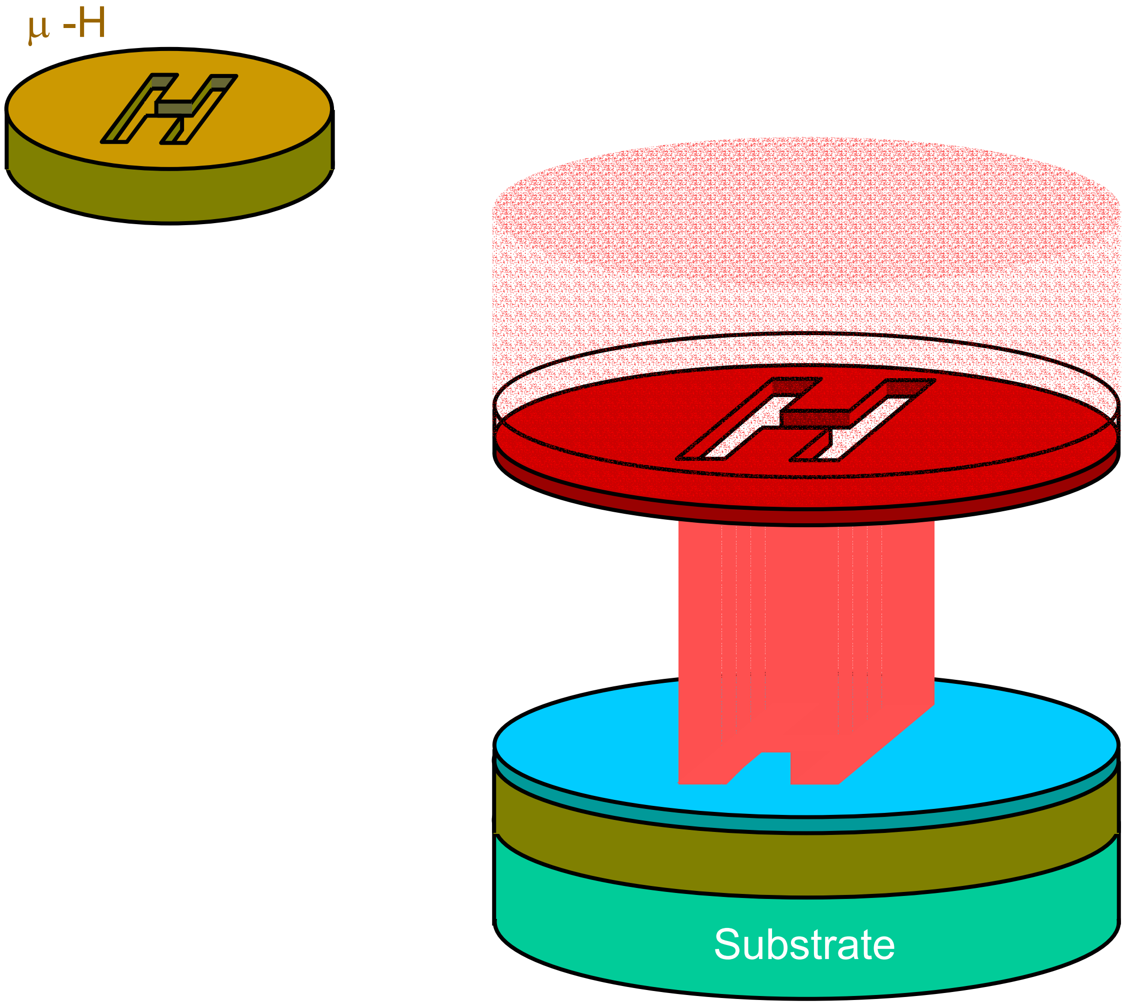
Typical Nanofabrication Steps

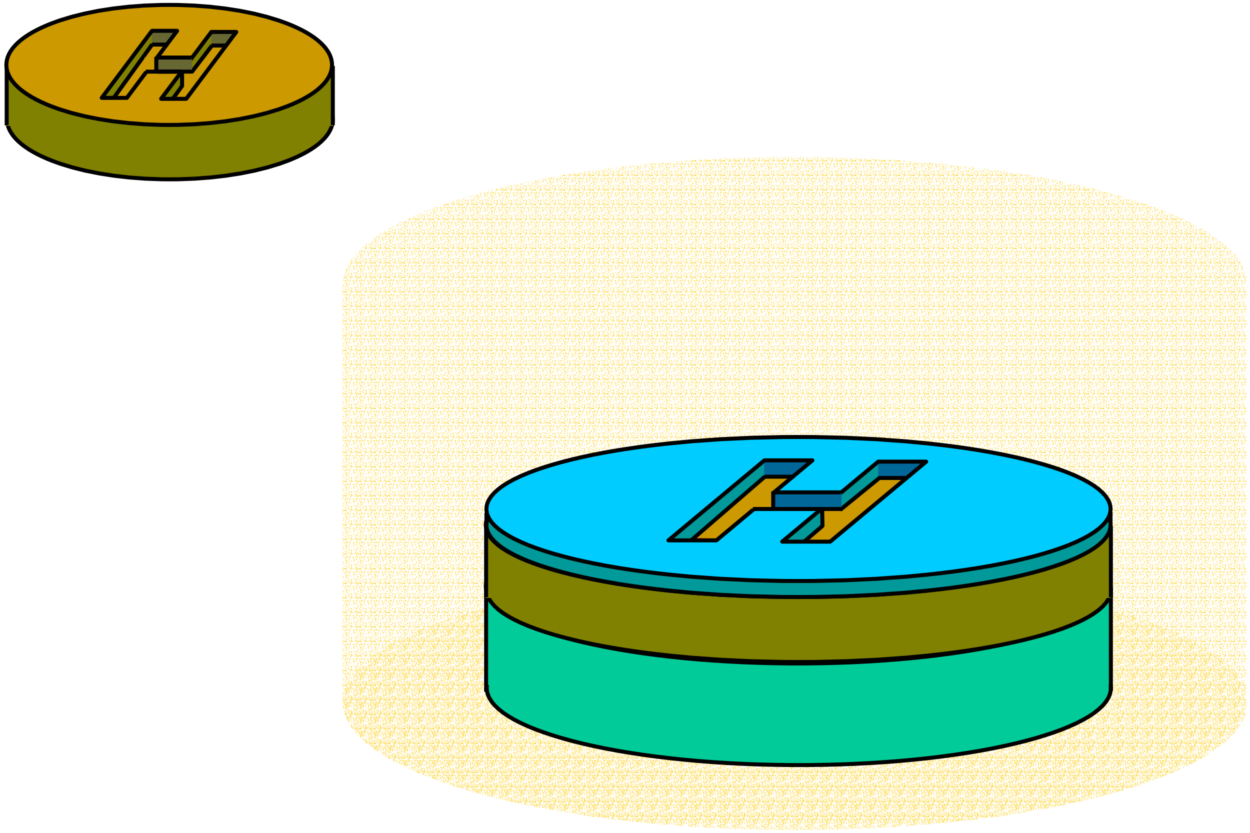


Radiation (Exposure)

Mask (Alignment)

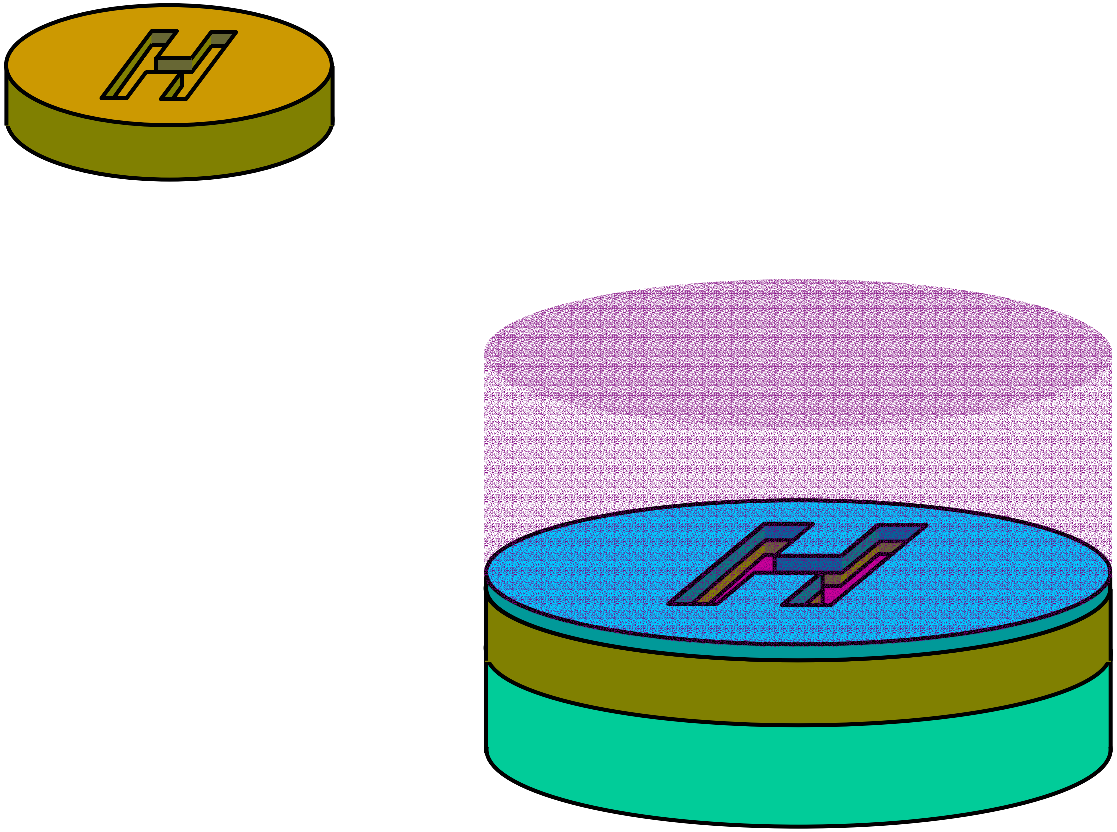
Photoresist (spin-Coating)

Thin Film (Deposition)



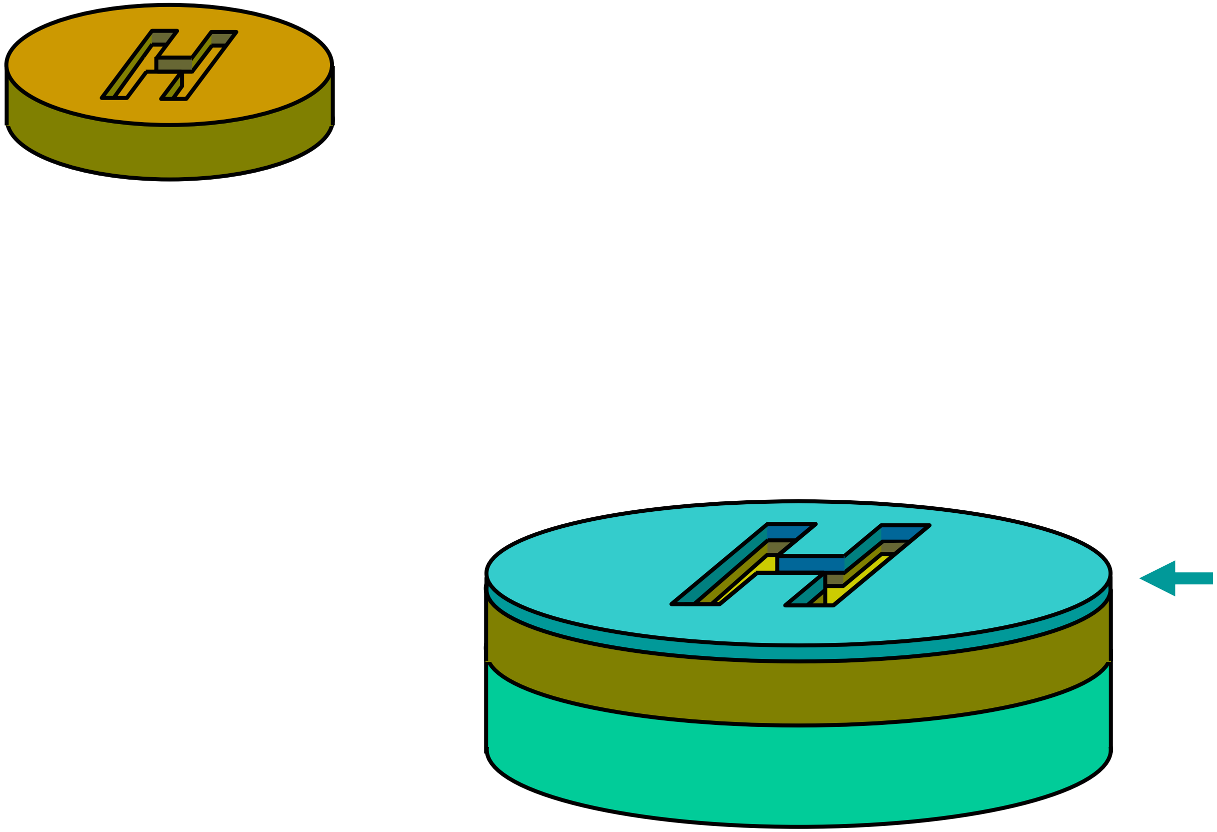
Developer

(Development)



Etch (wet or Dry)

(Pattern Transfer)

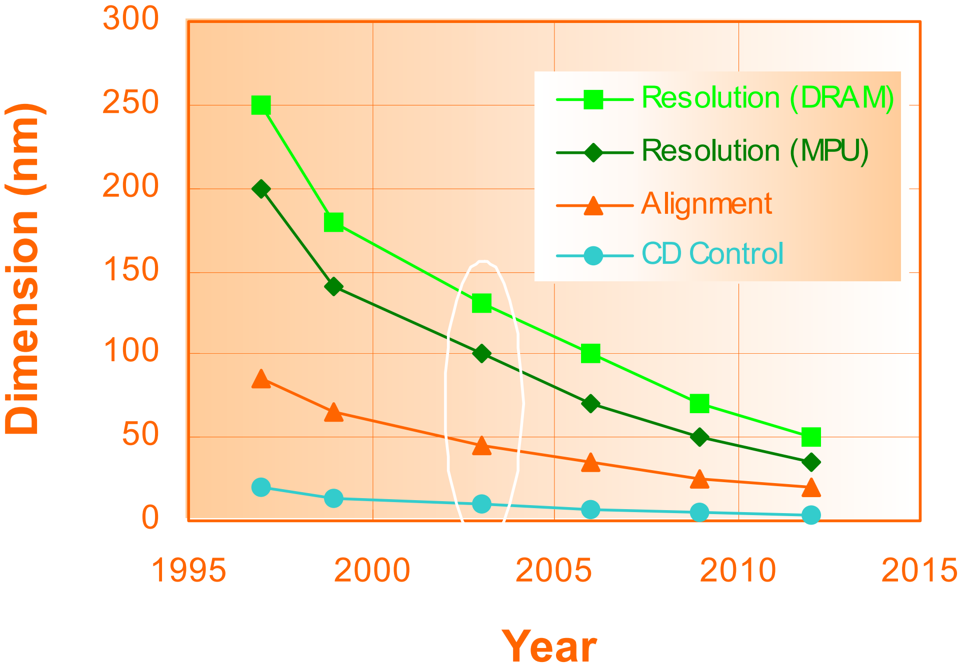


Stripper
(Remove Resist)

Nanofabrication and Its Trend

Typical Technologies Involved in Nanofabrication

- Thin Film Deposition
- Patterning
  - Lithography
- Film Modification
  - Etching



Why smaller? – faster, cheaper, more functionality, and new phenomenon

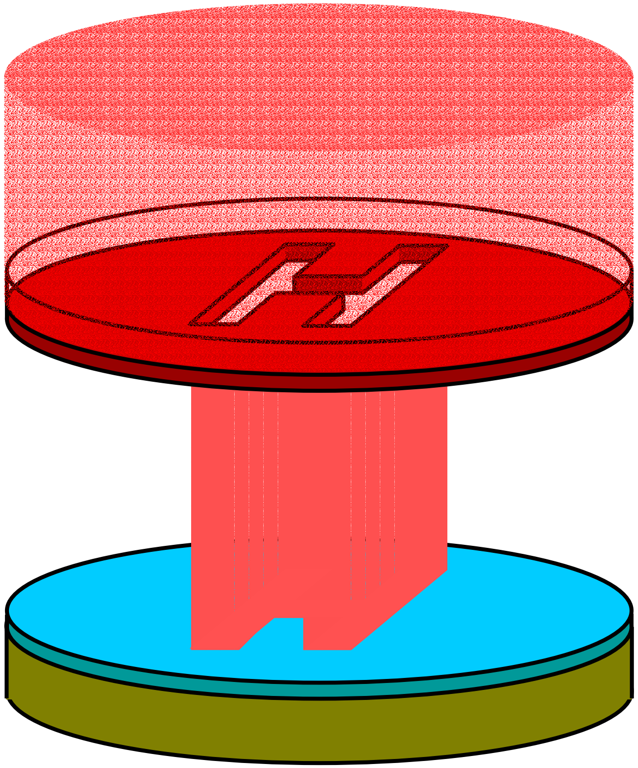
Outline

I. Lithography
  - Optical Lithography
  - E-beam Lithography

II. Thin Film Deposition
  - Physical Vapor Deposition (PVD)
  - Chemical Vapor Deposition (CVD)

III. Etching
  - Wet Etching
  - Dry Etching

Optical Lithography



I. Radiation System (Aligner)

II. Mask

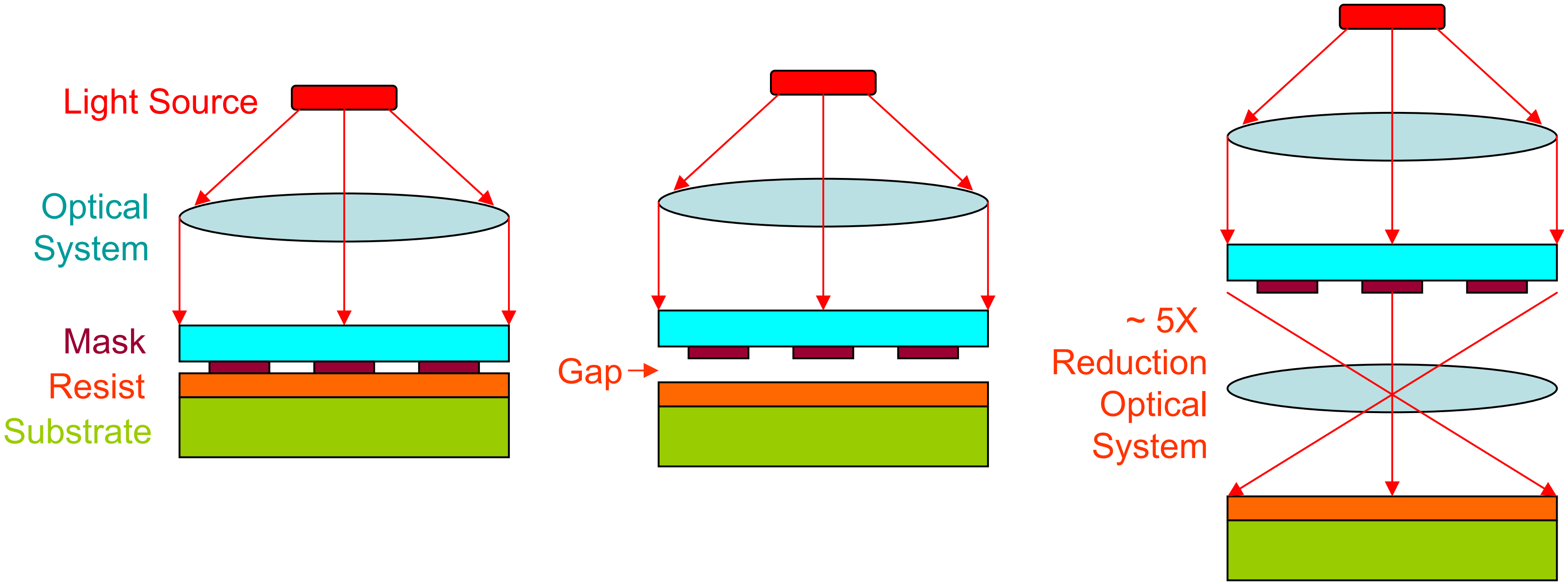
III. Photoresist

Three Types of Aligners

Contact Printing

Proximity Printing

Projection Printing



Characteristics of a Microlithography System

Resolution

The resolution of an optical system is its capability to distinguish closely spaced objects. For a microlithography system, resolution defines the minimum linewidth or space that the system can print.

Registration Capability

A measure of degree to which the pattern being printed can be fit (aligned) to previously printed patterns

- ➡ A microlithography exposure system is also called “aligner”

Dimensional Control

Ability to produce the same feature size with the same tolerance and position accuracy across an entire wafer and wafer-to-wafer

Throughput

The time to complete a print

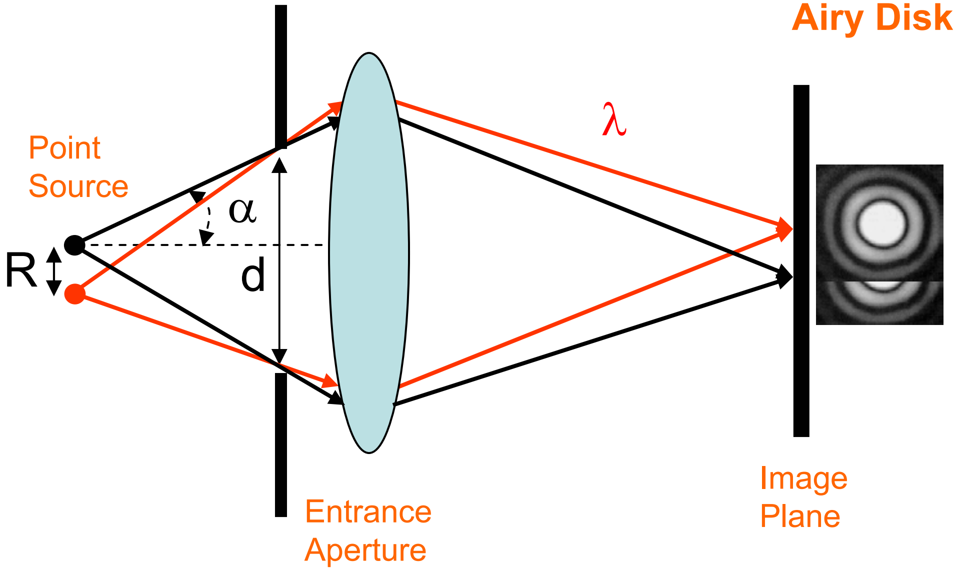
Resolution – Diffraction of Optical System

Fraunhofer Diffraction (far field - project system)

What is the smallest distance, R, an optical system can resolve?

Rayleigh suggested that a reasonable criterion was that the central maximum of each point sources lie at the first minimum of the Airy disk

➡ **Rayleigh Criterion**



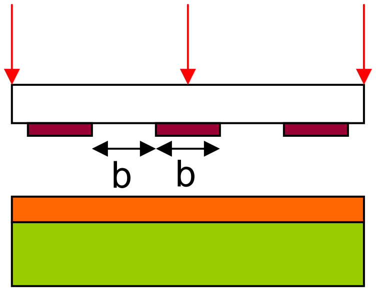
$$\boxed{R = 0.61\frac{\lambda}{NA}}$$

Where: $NA = n\sin(\alpha)$

Numerical Aperture

-- System's capability to collect diffracted light

Resolution Limit of Project Aligner



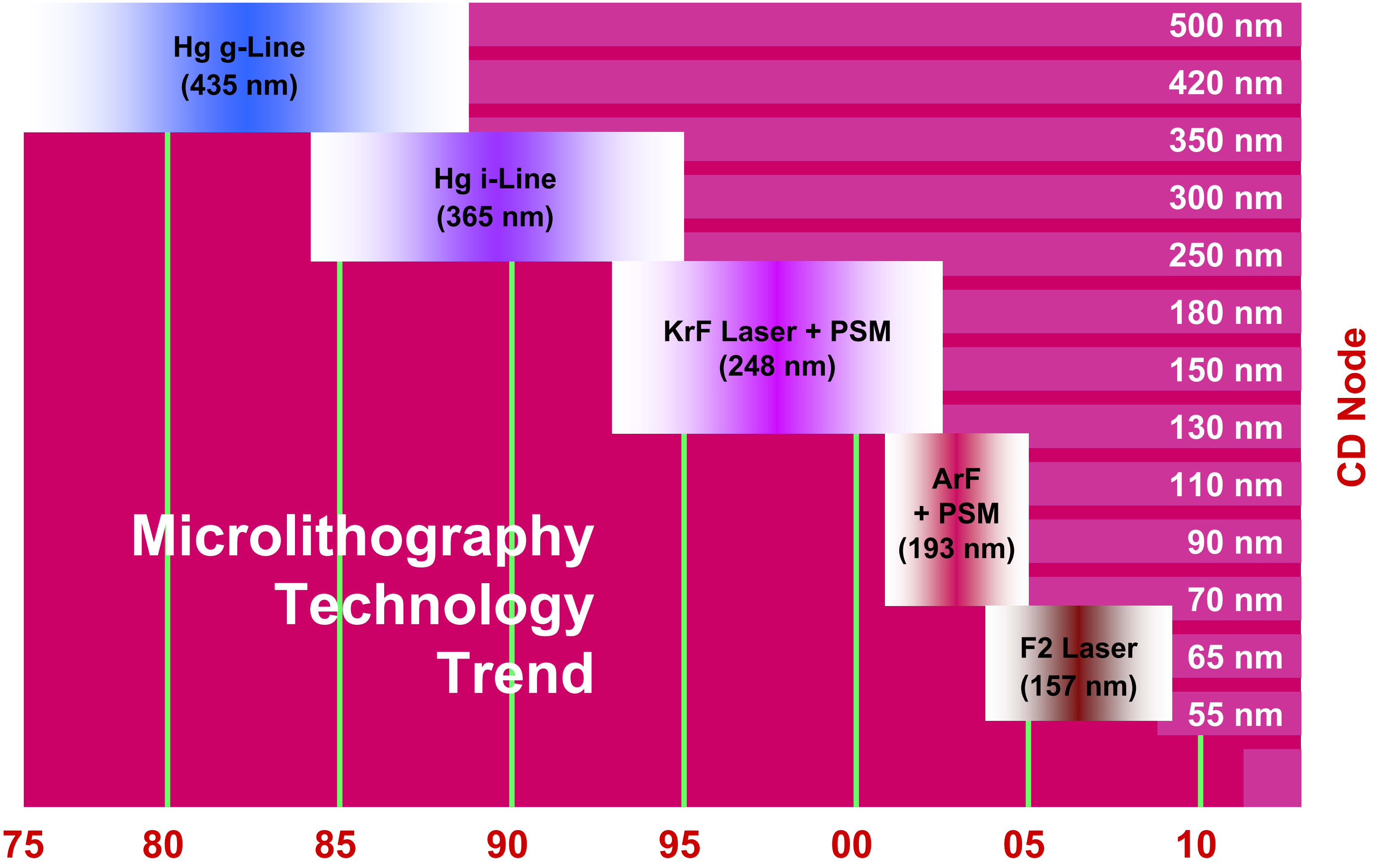
$$2b = K_1 \frac{\lambda}{NA}$$

$k_1 \approx 0.3 - 0.9$
depends on the lithography system

Resolution Improvement Method

- Decrease λ
- Increase NA
- Reduce K1

Reduce Wavelength



Depth of Focus (DOF) Requirement

DOF - The range over which there are clear optical images

$$DOF = K_2 \frac{\lambda}{NA^2} \qquad \propto \frac{1}{NA^2}$$

DOF decreases much faster than that of resolution when NA increase!

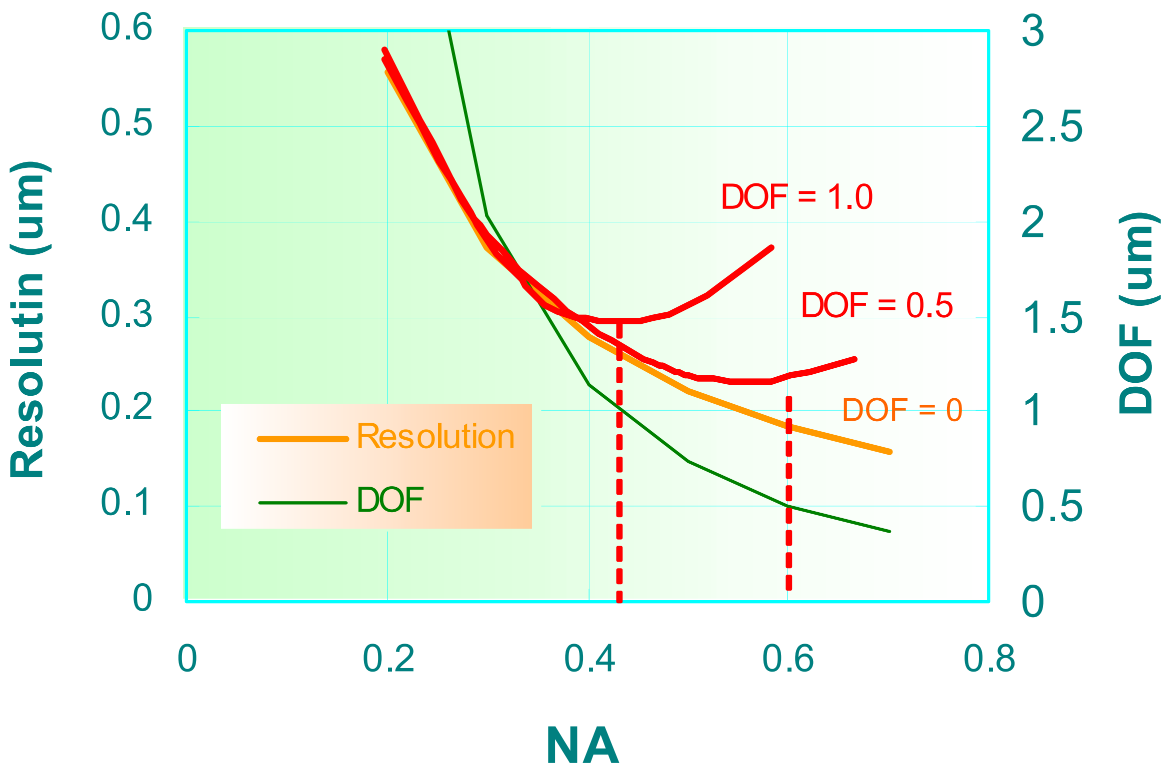
Why need to meet DOF Requirement?

- Substrate is not flat (~ 10 um across a wafer)
- There are previously fabricated patterns on the wafer (~ um)

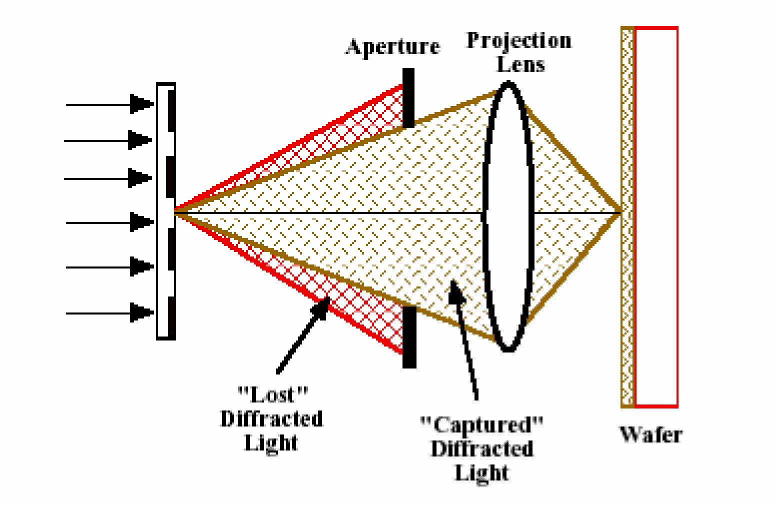
Example

$K_2 = 0.5$, $\lambda = 435$ nm (G-line), NA = 0.6, DOF ~ 0.6 um!

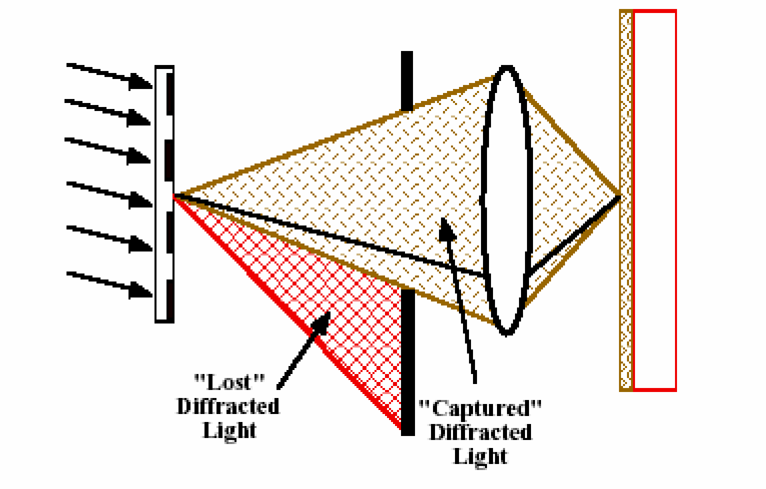
DOF and Practical Resolution



Off-Axis Illumination



High-order diffracted light is lost



Some high-order diffracted light is captured

Resolution of Contact and Proximity Printing

– Fresnel Diffraction (near filed)

Contact Printing:

$$2b = k\sqrt{0.5\lambda d}$$

Proximity Printing:

$$2b = k\sqrt{\lambda(s + 0.5d)} = k\sqrt{0.5\lambda d} \cdot \sqrt{1 + \frac{2s}{d}}$$

λ = exposure wavelength

d = resist thickness

2b = line-space pitch resolution

s = mask-resist spacing

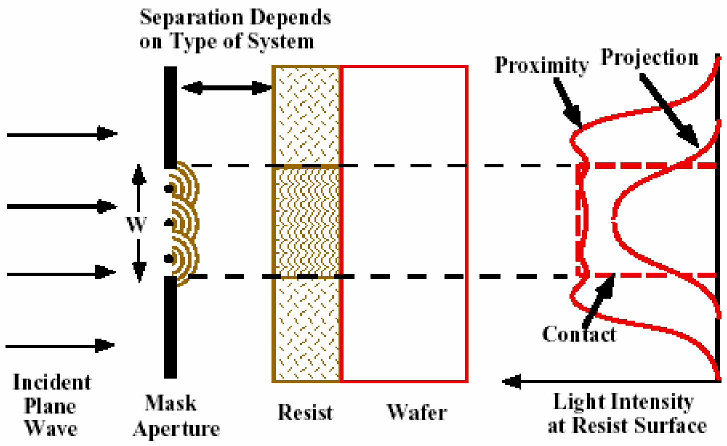
k ~ 3

Example

λ = 435 nm (g-line)
d = 0.5 μm
s = 10 μm

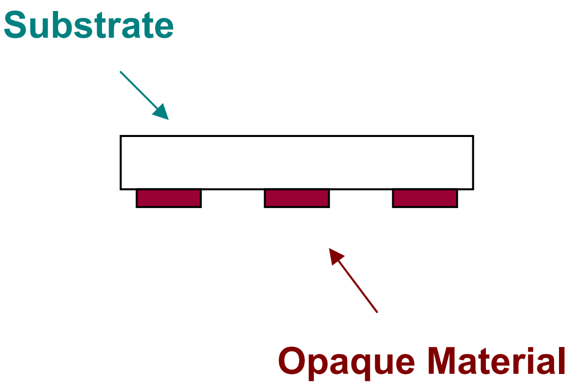
b (contact)	~ 0.5 μm
b (Proximity)	~ 2.6 μm

Comparison of Three Systems



System	Pros	Cons
Contact	• High resolution • Low cost • High throughput	• Mask contamination and damage • Defects impact
Proximity	• Low mask contamination	• Poor resolution
Projection	• High resolution • Low mask contamination • High throughput	• Expensive

Mask Components



Substrate Requirement

- High transmission at exposure wavelength
- Small thermal expansion coefficient
- High degree of flatness
- Low non-linear effect

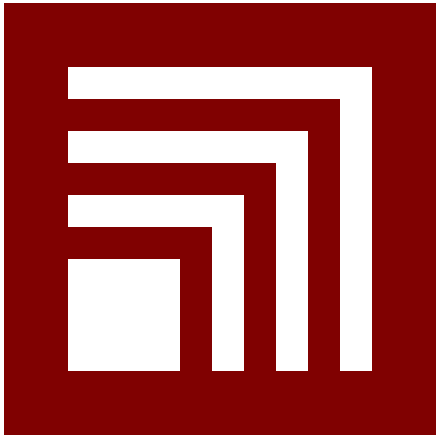
Common material: Quartz, fused-silica or borosilicate glasses

Opaque Material Requirement

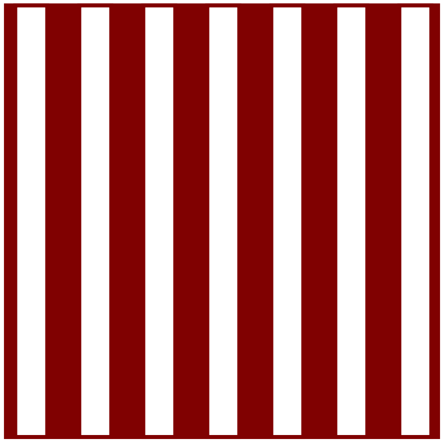
- No transmission at exposure wavelength
- Good adhesion to the substrate
- High degree of durability

Choice of material: Chrome, emulsion and ion oxide

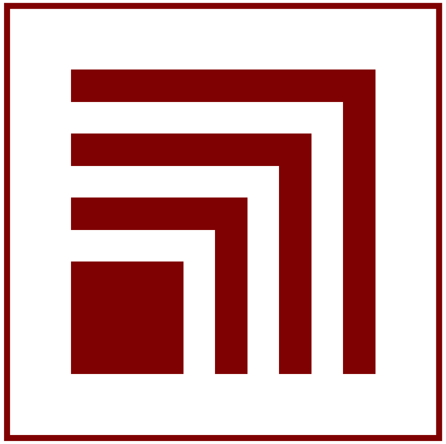
Mask Polarity



Dark-Field (negative)



Grating



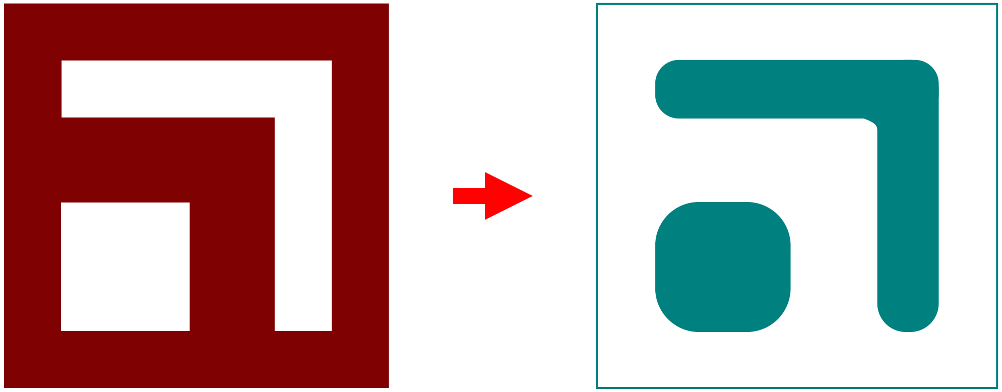
Clear-Field (Positive)

Dark-Field Mask:

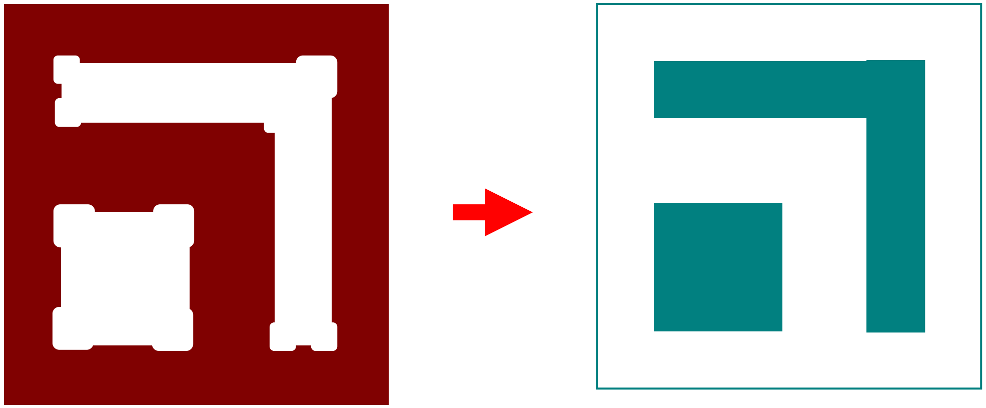
- Less adjacent/background exposure
- Less defect impact

Optical Proximity Correction (OPC)

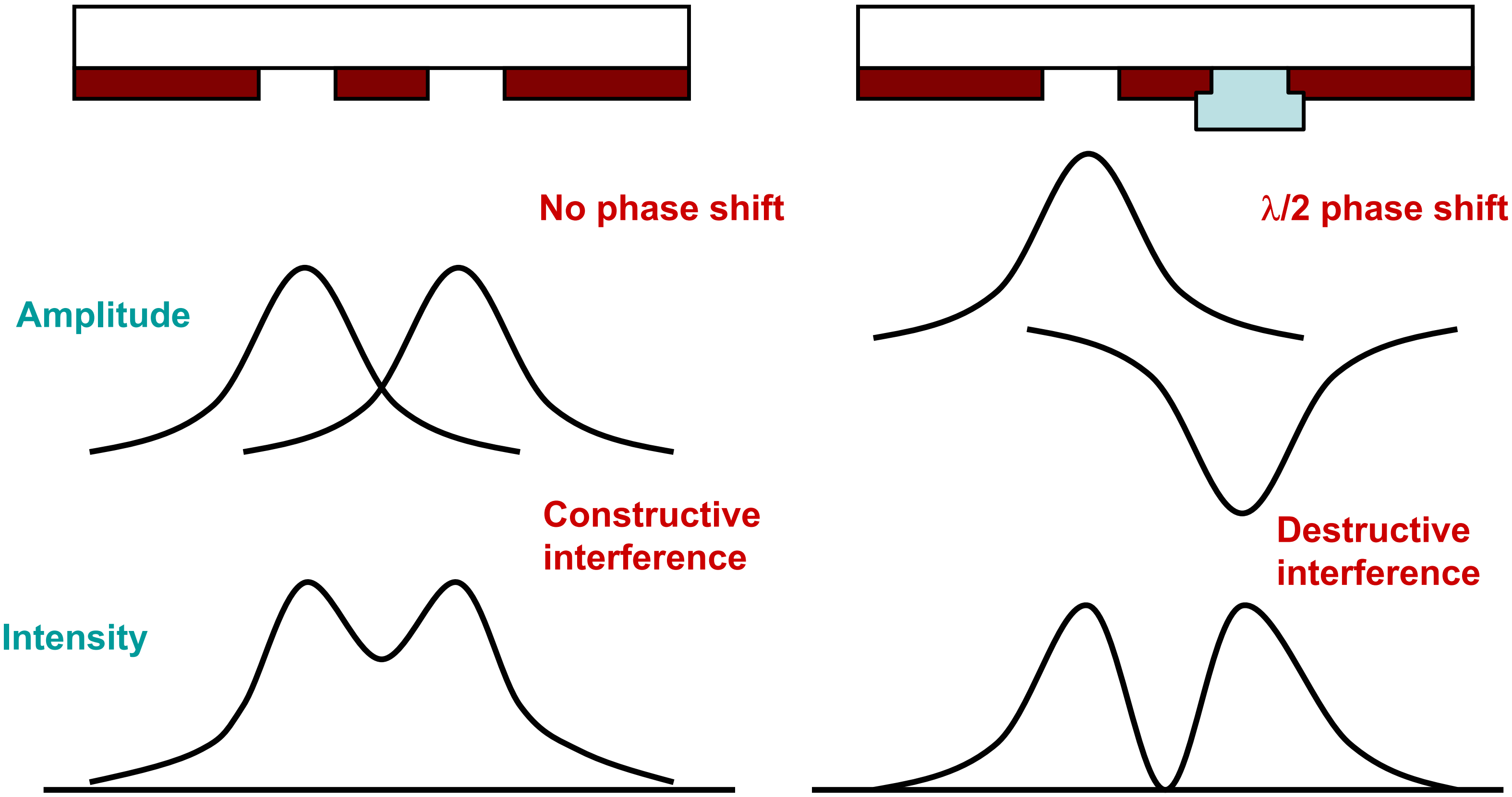
Without OPC



With OPC



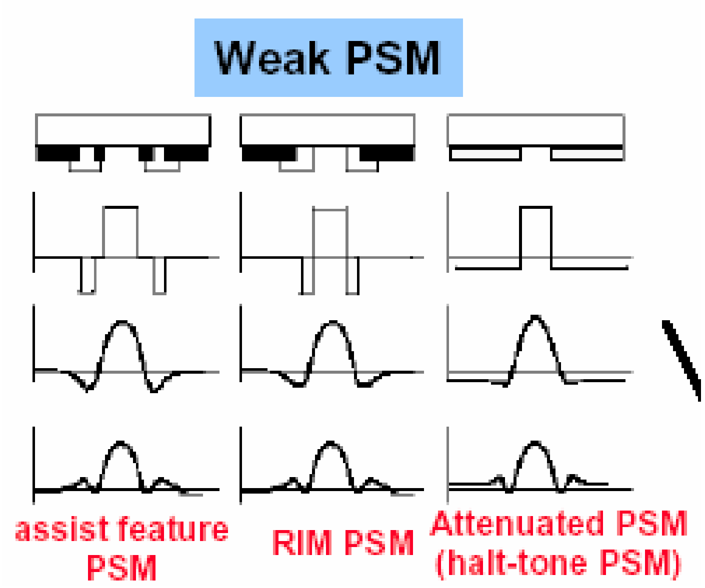
Phase-Shift Mask (PSM)



- Reduced MTF

- Reduce Linewidth
- Improved MTF

Example of PSM

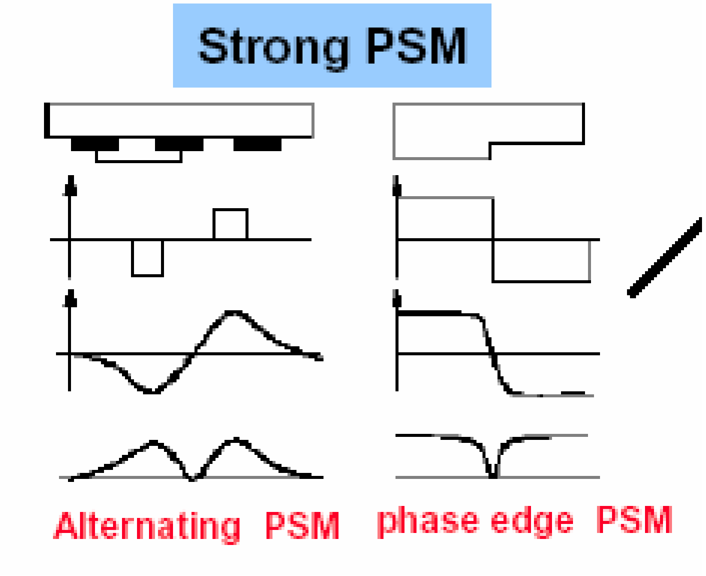


Weak PSM

assist feature PSM

RIM PSM

Attenuated PSM (half-tone PSM)



Strong PSM

Alternating PSM

phase edge PSM

Components of Photoresist

Conventional optical photoresist has three components:

1) Matrix material
2) Sensitizer
3) Solvent

Sensitizer

- Also called inhibitor
- Photoactive compound (PAC)
- Insoluble without radiation - preventing resist to be dissolved
- Take photochemical reaction upon exposing to light, transferring from dissolution inhibitor to dissolution enhancer

Matrix and Solvent

Matrix Material

- Also called resin
- Serves a binder
- Inert to radiation
- Dissolves fast in developer (~ 150 A/s)
- Provides resistant to etchers
- Provides adhesion to the substrate
- Contributes to the mechanical properties of the resist

Solvent

- Keep photoresist in liquid state
- Allows spin coating of the resist
- Solvent content determines resist’s viscosity and hence the its thickness

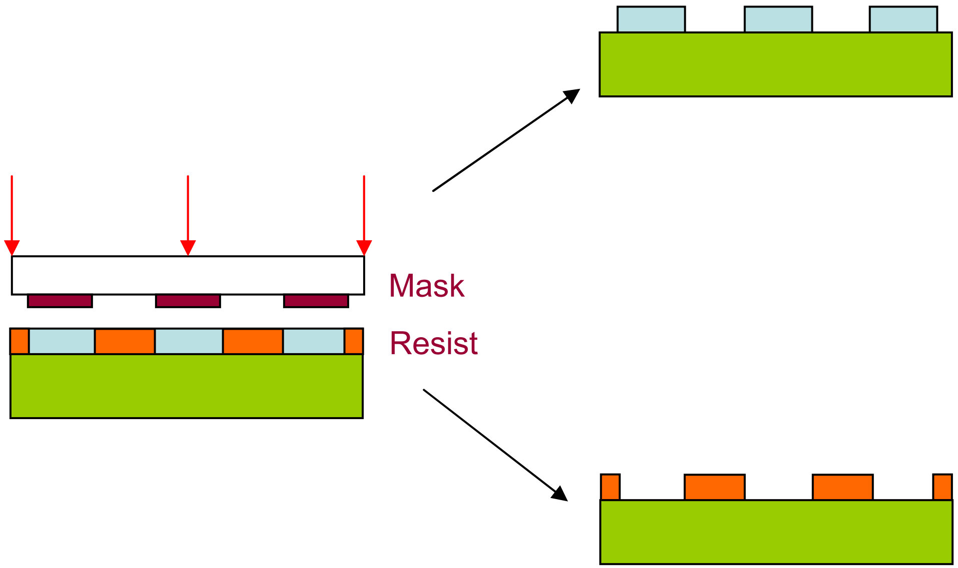
Function of PAC

Material	Dissolve Rate in Developer	Function of PAC
Matrix	150 A/s	NA
Matrix + Sensitizer without Radiation	10 – 20 A/s	Dissolution Inhibitor
Matrix + Sensitizer with Radiation	1000 – 2000 A/s	Dissolution Enhancer

Differential solubility before and after exposure:

100 : 1

Positive and Negative Photoresist



Positive Resist

- The solubility of exposed regions is much higher than the unexposed region in a solvent (called developer)
- Produces a positive image of the mask

Negative Resist

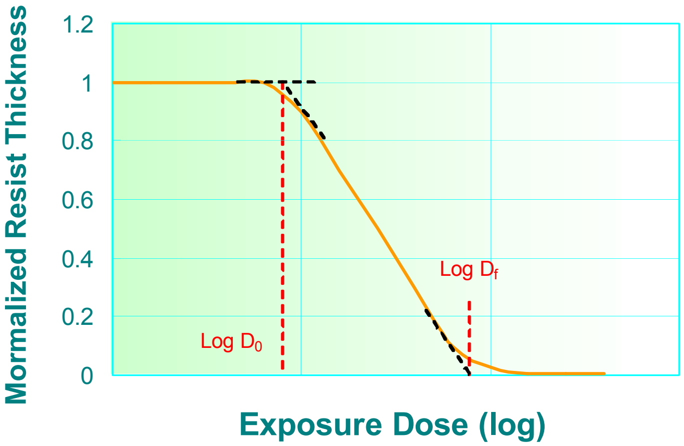
- The solubility of exposed regions is much lower than the unexposed region in developer
- Produces a negative image of the mask

Comparison of Positive and Negative Resists

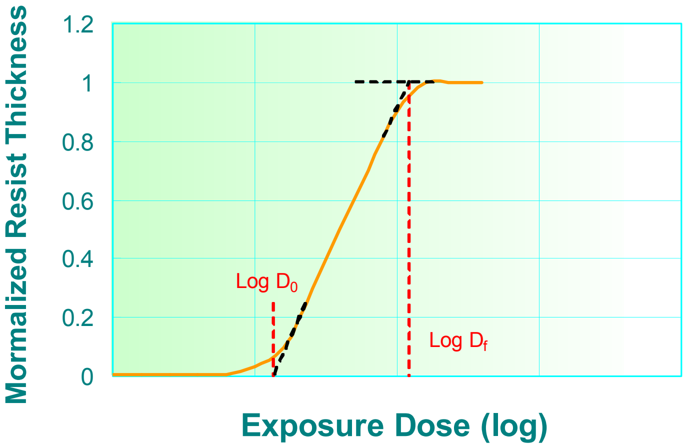
Property	Positive Photoresist	Negative Photoresist
Resolution	High	Low (~> 1um)
Developer	Temperature sensitive (-)	Temperature non-sensitive (+)
Mask Type	Dark-Field Mask: lower-defect	Clear-Field Mask: higher-defect
Rinse	In Water (+)	In solvent (n-Butylacetate) (-)
Cost	More Expensive	Cheaper
Exposure Speed		3-4 times faster (+)
Adhesion		Better
Backing	In air (+)	In Nitrogen (-)
Profile	Undercut (+)	Overcut (-)
Lift-off	In Acetone	In solvent (Methyl Ethyl Ketone) (-)

Resist Response Curve

Positive Resist



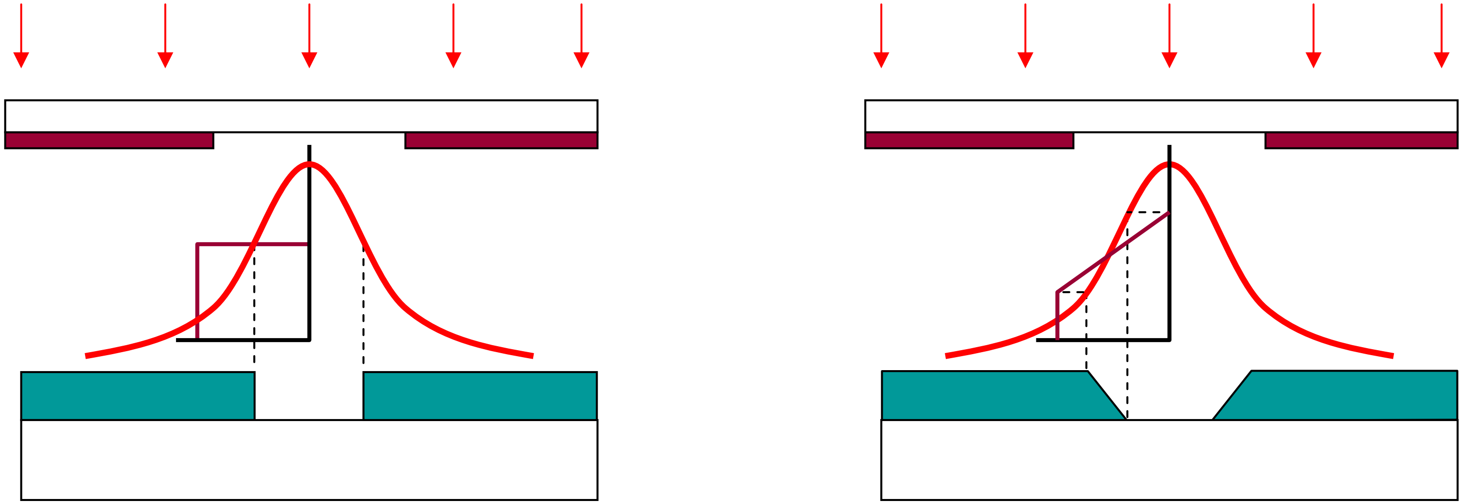
Negative Resist



D_0 – Initial dissolution dose **D_f – 100% dissolution dose**

Ideally, 1) $D_f \sim D_0$, 2) Small D_f

Response Curve vs. Resist Profile



The slop of the response curve determines:

- Resolution (minimum linewidth)
- Resist wall angle
- Linewidth control

Contrast

Contrast (γ)

= the slop of the response curve

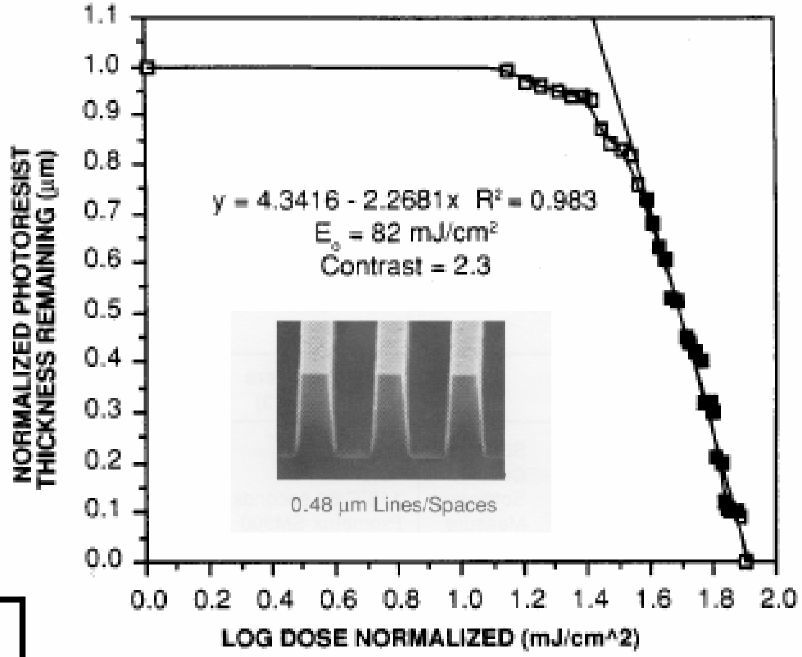
– ability of resist to distinguish between light and dark regions

$$\gamma = \frac{1}{\log\left(\frac{D_f}{D_0}\right)}$$

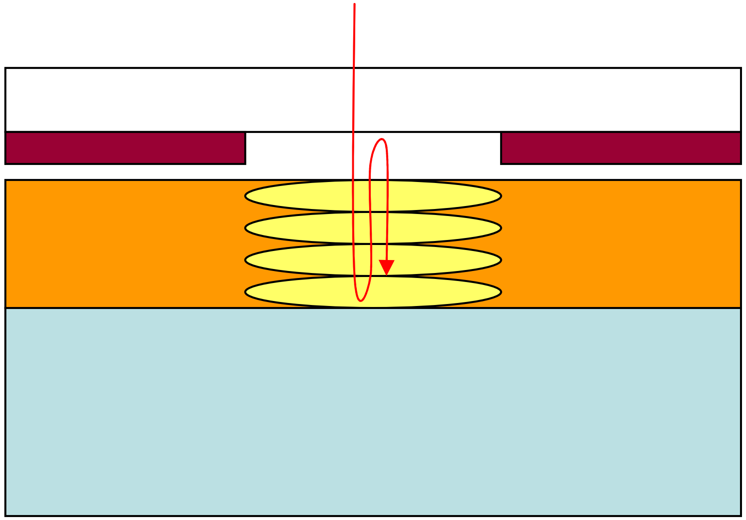
Resist	UV	DUV
γ_n	2 ~ 3	1 ~ 2
γ_p	5 ~ 10	3 ~ 6

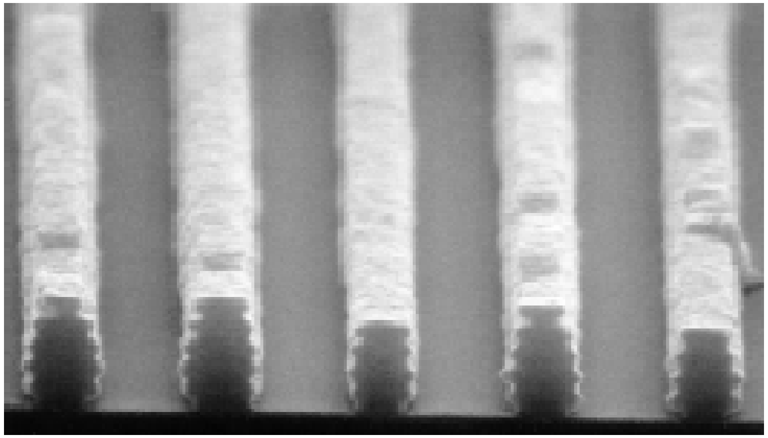
MICROPOSIT S1813 PHOTO RESIST

Figure 7. Contrast Curve

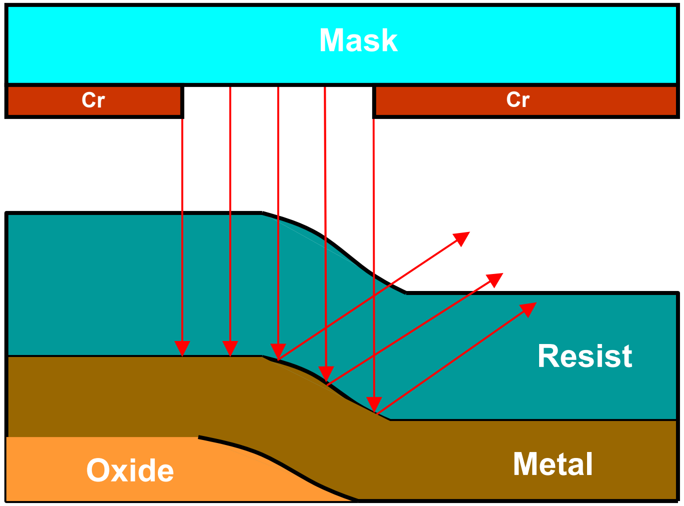


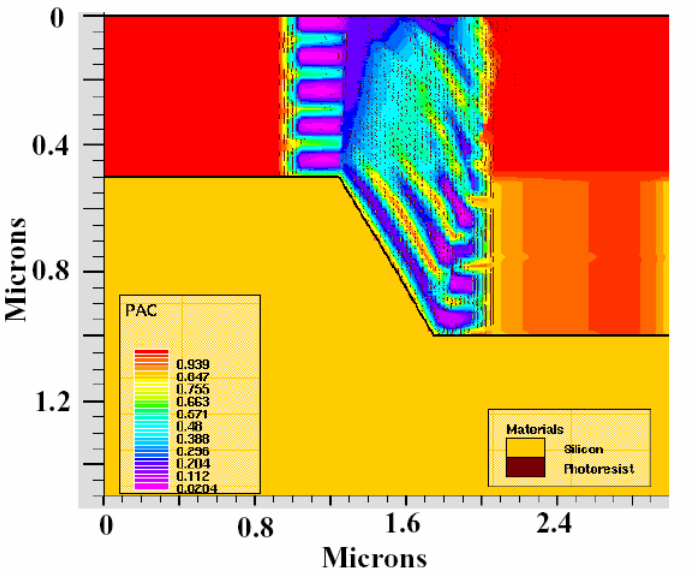
Surface Reflection – Standing Wave





Surface Topographic Effect





Imagine control is a problem for surface with significant topographic non-uniformity

Surface Effect Elimination

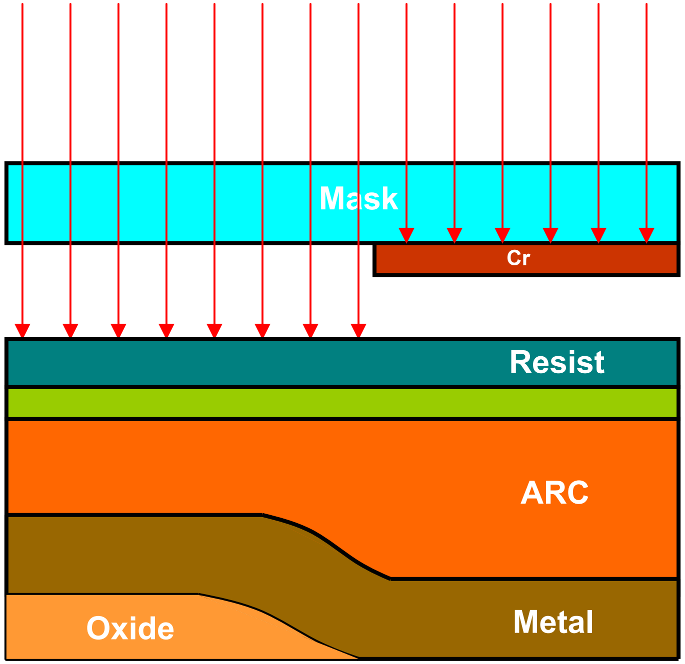
Standing Wave

- Substrate anti-reflection coating (ARC)
- Add unbleachable dyes to resist
- Post baking after exposure (before development)
- Multi-wavelength

Topographic Non-uniformity

- Substrate palanarization, e.g. CMP
- Planarized photolithography process

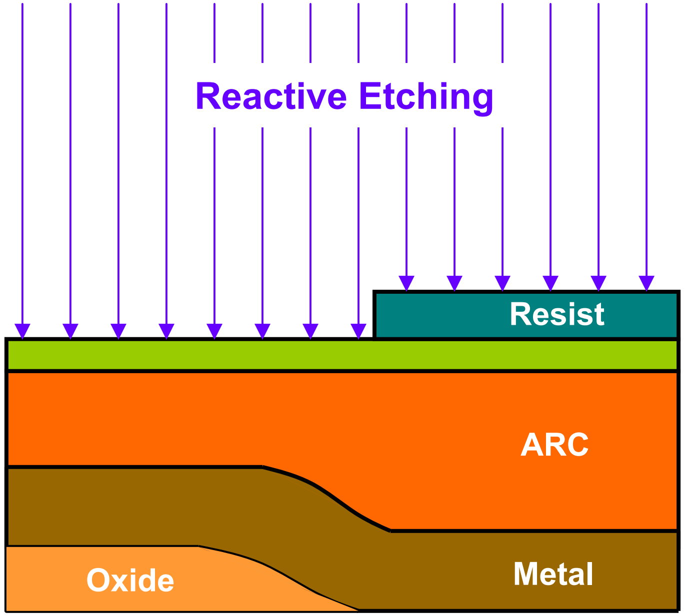
Tri-Layer Resist Process



Hard Mask (SiO2)

Planarization

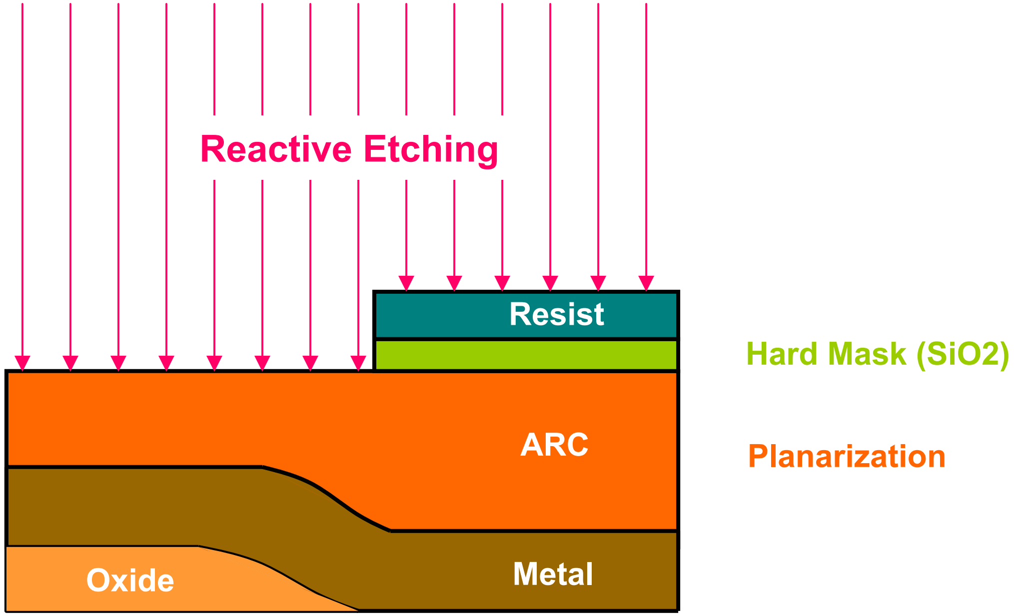
Tri-Layer Resist Process



Hard Mask (SiO2)

Planarization

Tri-Layer Resist Process



Adhesion Improvement and HMDS

Problems Associated with Poor Resist Adhesion

- Resist peel off from the substrate
- Severe undercut during wet etch
- Loss of resolution

Typical Solutions

- Substrate dehydration bake
- Use adhesion primer, e.g. HMDS

HMDS (Hexamethyldisilazane)

Application of HMDS

- Particular helpful for SiO2 surface
- Only monolayer is necessary

Two Typical Process

- Spin coating: 3000 – 6000 rpm for 20 -30 s
- Vapor priming: in vapor chamber for ~ 10 min

Typical Lithography Process Steps (S1800)

Dehydration bake: 150-200 °C, drive off water

Adhesion promoter: wafer primed with hexamethyldisilazane (HMDS)

Resist coating: static or dynamic dispense, spin coating on vacuum chuck @ 2-6 Krpm. Thickness (0.1 -10 µm) depends on speed and viscosity

Softbake: drive off solvents (115 °C, 30s)

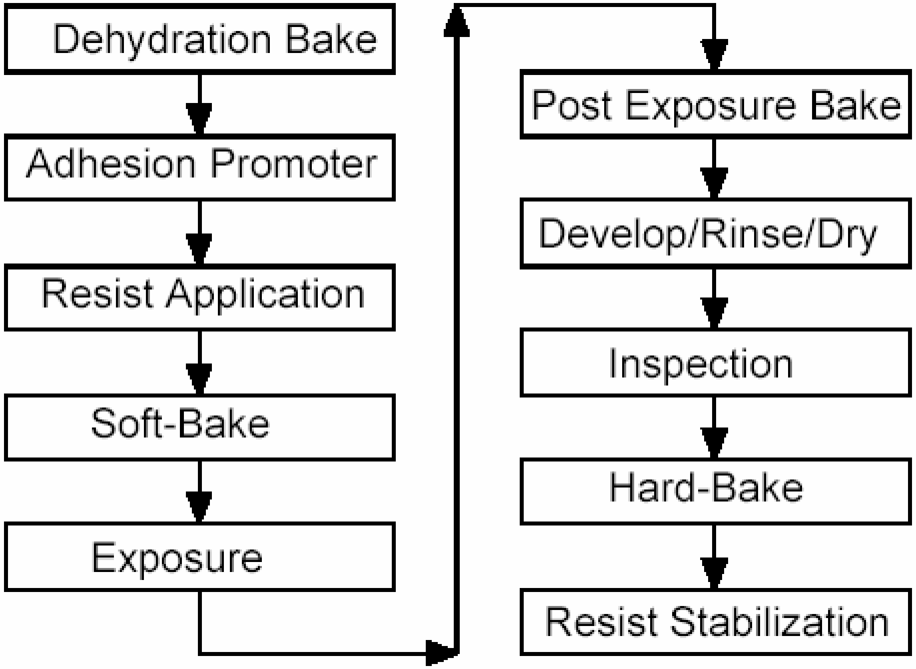
Exposure: 60 - 120 mJ cm^{-2}

Post-Exposure Bake: remove standing waves by diffusing PAC

Develop: Hydroxide, puddle or spray, with temperature control; rinse & dry bake (115°C) follows

Inspection: of critical dimension (CD) structures

Hard Bake: high temperature bake (115°C - 170°C) to harden resist against further energetic processes



Dehydration Bake

Adhesion Promoter

Resist Application

Soft-Bake

Exposure

Post Exposure Bake

Develop/Rinse/Dry

Inspection

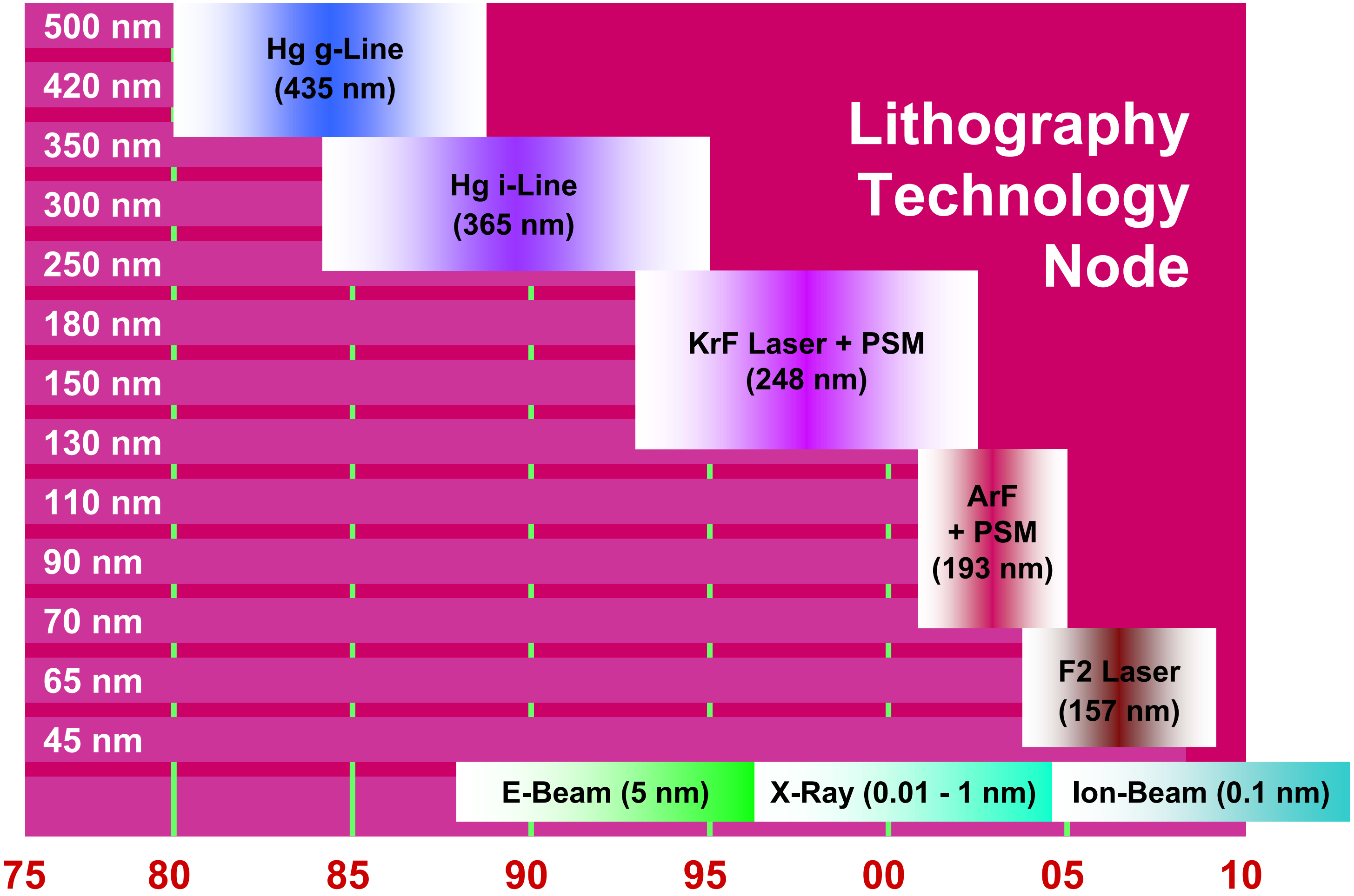
Hard-Bake

Resist Stabilization

Advanced Lithography Technology

- E-Beam Lithography
- X-Ray Lithography
- Focused Ion Beam Lithography
- Alternative Lithography
  - Soft-lithography
  - Imprinting lithography

Lithography Technology Node

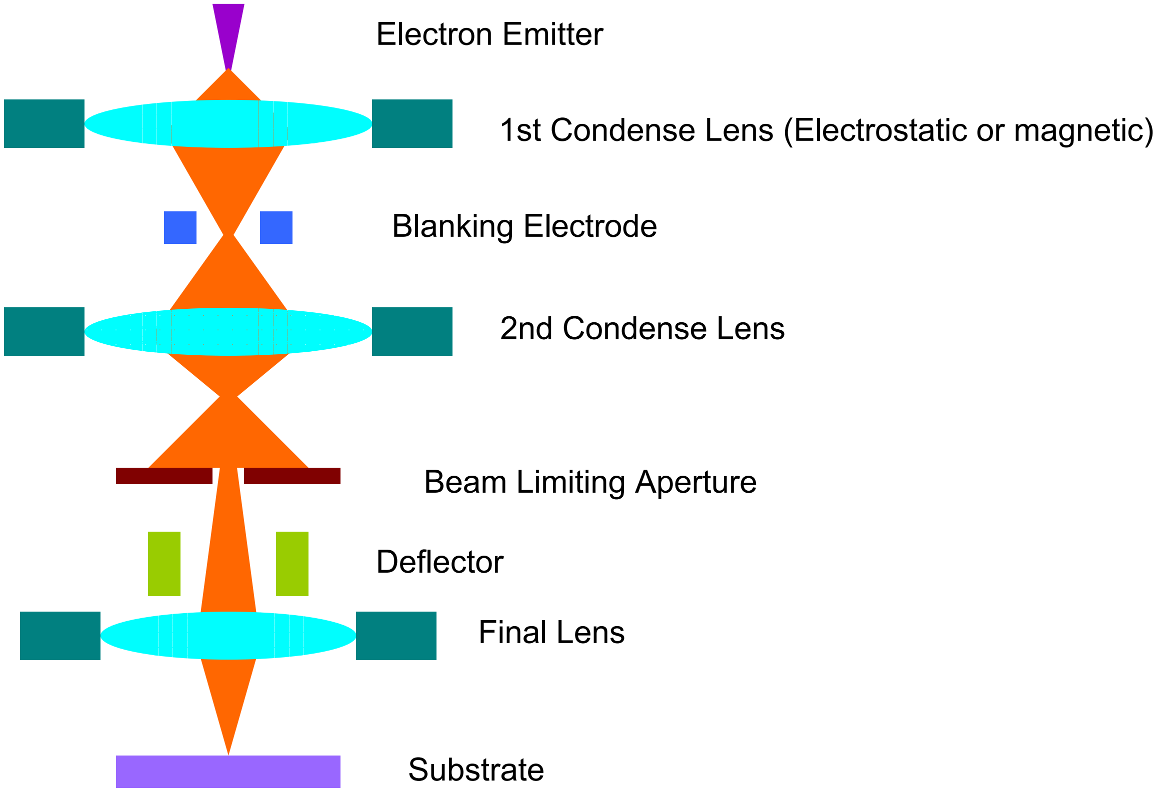


Electron-Beam Lithography (EBL)

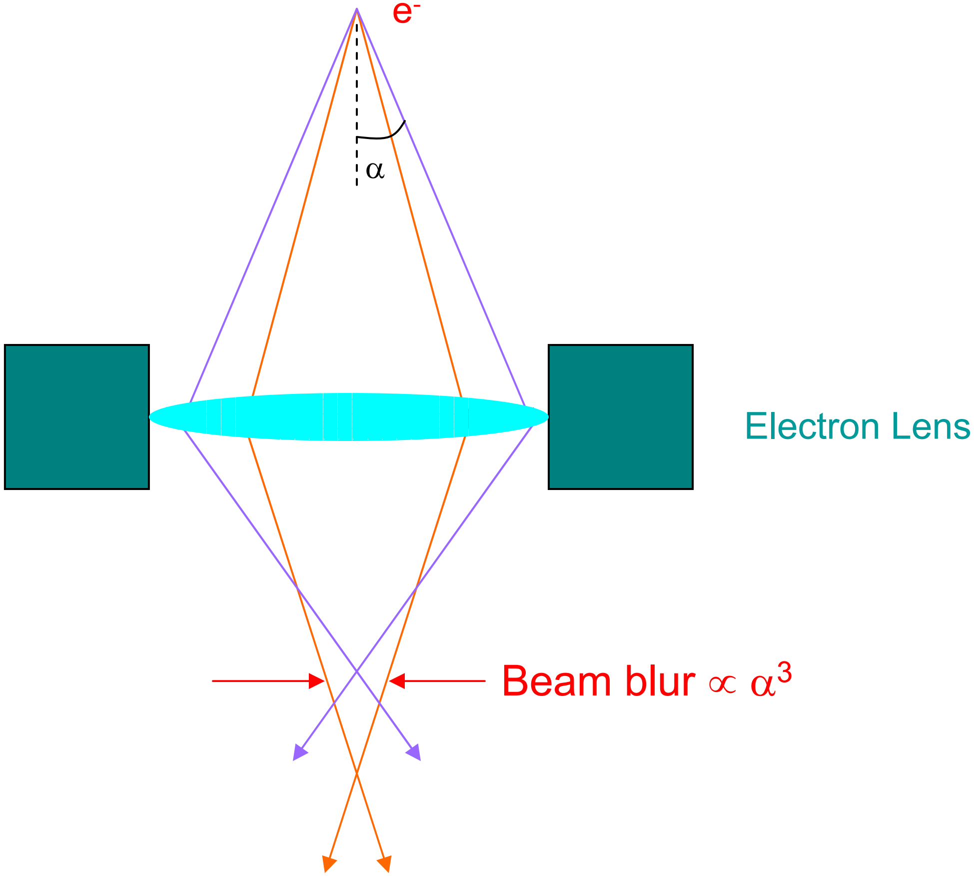
General Characteristics

- Diffraction is not a limitation on resolution
- Resolution depends on beam size, can reach ~ 5 nm
- Two applications:
  - Direct Writing
  - Projection (step and repeat)
- Issues:
  - Throughput of direct writing is very low – research tool or low pattern density manufacturing
  - Projection stepper is in development stage (primarily by Nikon). Mask making is the biggest challenge for projection method
  - Back-scattering and second electron result in proximity effect – reduce resolution with dense patterns
  - Operate in high vacuum (10-6 – 10-10 torr) – slow and expensive

Schematic of E-Beam System

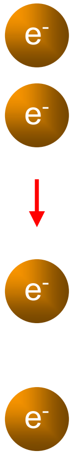


Spherical Aberration



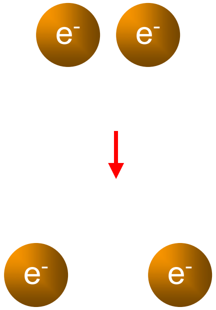
Coulomb Interaction

Boersch Effect



- Electrons repel each other in the beam direction
- Causes energy spread among electrons
- Result in chromatic aberration

Loeffler Effect



- Electrons repel/collide each other in the radial direction
- Causes trajectory change and energy spread among electrons
- Result in chromatic as well as spherical aberration

Beam Size (d)

$$\boxed{d = \sqrt{d_g^2 + d_s^2 + d_c^2 + d_d^2}}$$

$$d_g^2\,(Virtual\;\; Source) = \frac{d_v}{M}$$

(d$_v$ - Source size, M – demagnification)

$$d_s^2\,(Spherical\;\; Aberration) = \frac{1}{2} C_s \alpha^3$$

(C$_s$ – spherical aberration, α – beam convergence angle

C$_s$ $\propto$ f (focal length))

$$d_c^2\,(Chromatic\;\; Aberration) = C_c\,\alpha \frac{\Delta E}{V_b}$$

(C$_c$ – chromatic aberration, ΔE – electron energy spread,

V$_b$ – electron acceleration voltage)

$$d_d^2\,(Diffraction\;\; Limit) = 0.6 \frac{\lambda}{\alpha}$$

$$\lambda = \frac{1.2}{\sqrt{V_b}}(nm)$$

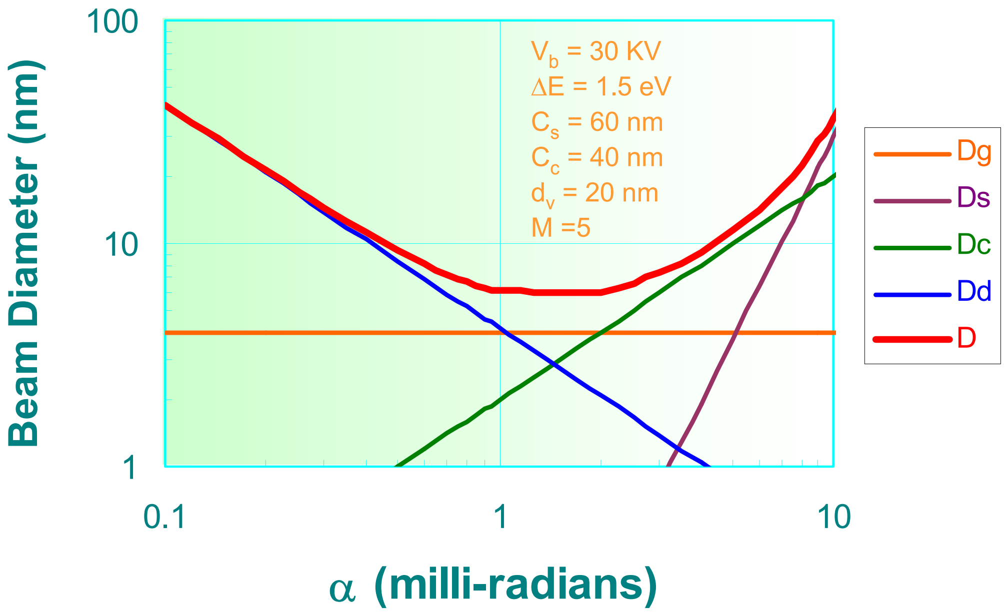
(electron wavelength)

For High Resolution:

↗ M, ↗ V$_b$, ↘ ΔE, ↘ f

What about α?

Resolution vs. Convergence Angle



DOF = d / α

Electron Source

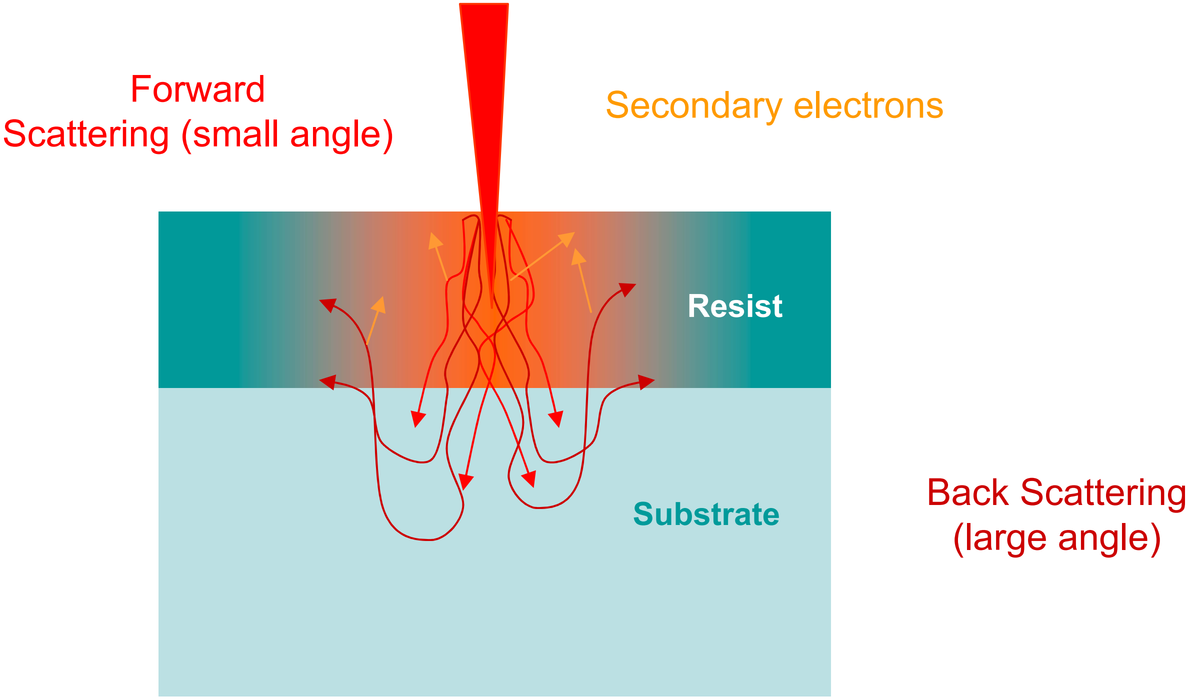
Thermionic Emission

Working Principle	Gun Material	Brightness (B) (A/cm^2/Sr)	Energy Width (eV)	Filament Temperature	Gun Vacuum (torr)
Electron Emission at High Temp.	**W**	**~ 10^5**	**2 - 3**	**~ 3000K**	**10^{-5} - 10^{-6}**
	LaB_6	**~ 10^6**	**2 - 3**	**2000 – 3000K**	**10^{-7} - 10^{-8}**

Field Emission

Working Principle	Gun Material	Brightness (B) (A/cm2Sr)	Energy Width (eV)	Filament Temperature	Gun Vacuum (torr)
Electron Tunneling in High field	**W**	**10^9 – 10^{10}**	**0.2 – 0.5**	**Room**	**< 10^{-9}**

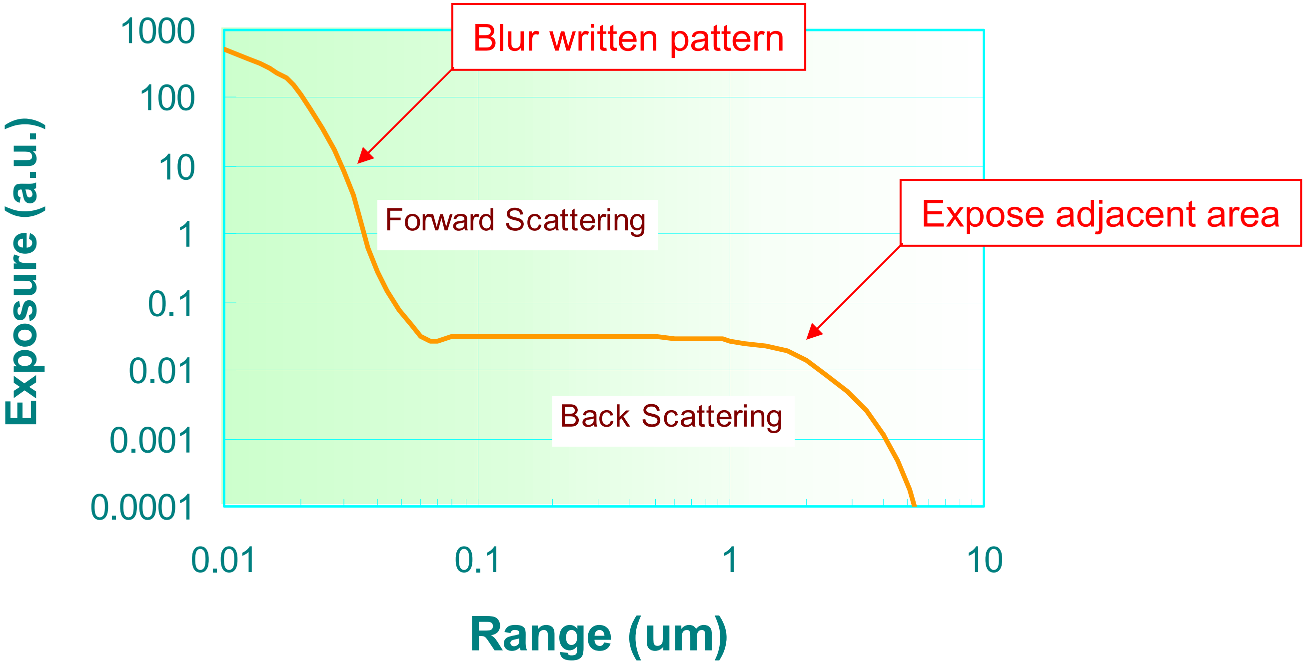
Electron Scattering in Resist and Substrate



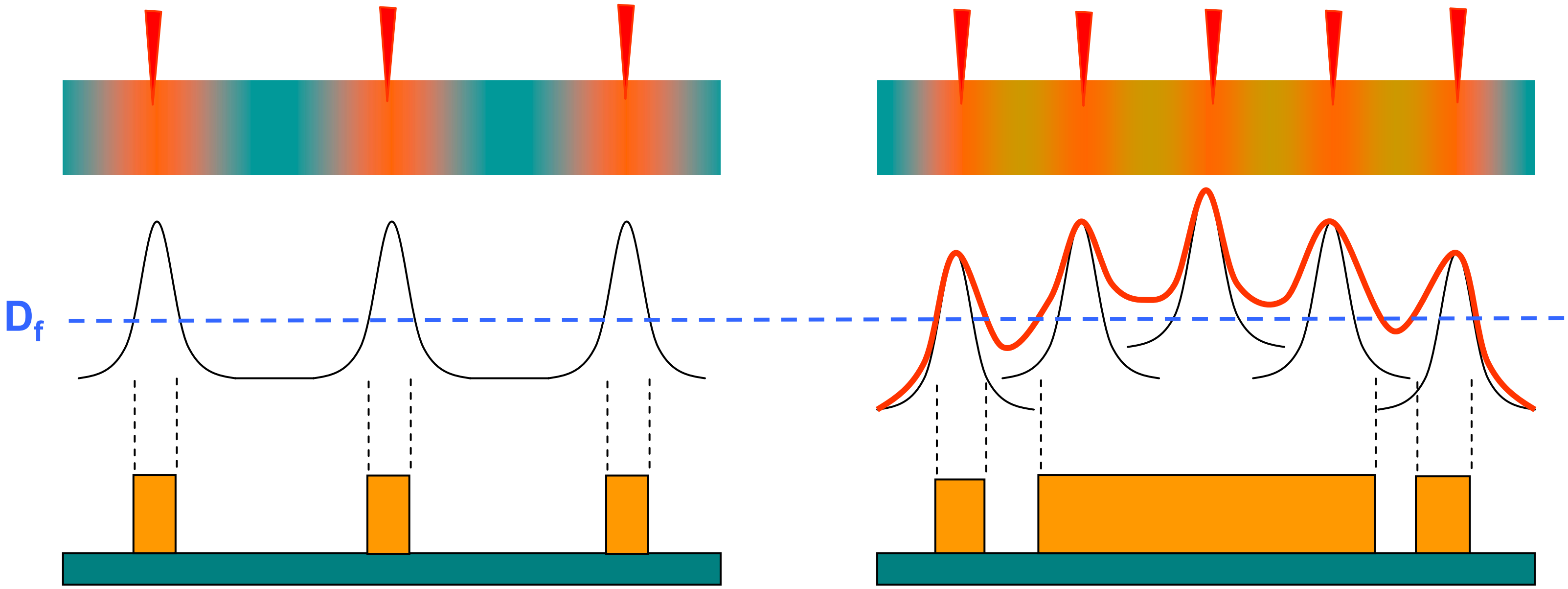
The scattered electrons also expose the resist!

Scattering Energy Distribution

Double Gaussian Distribution



Proximity Effect



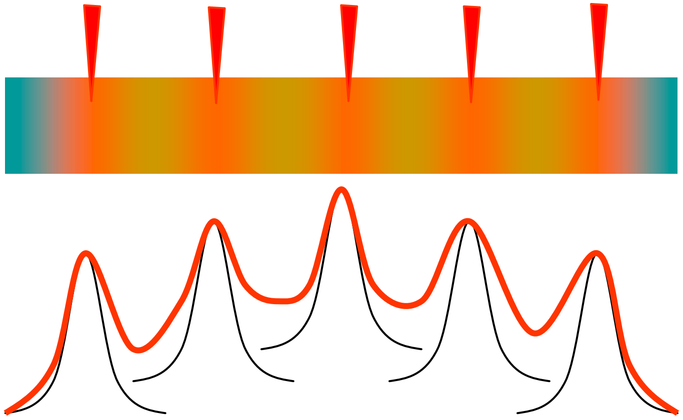
MTF is greatly reduced at high pattern density

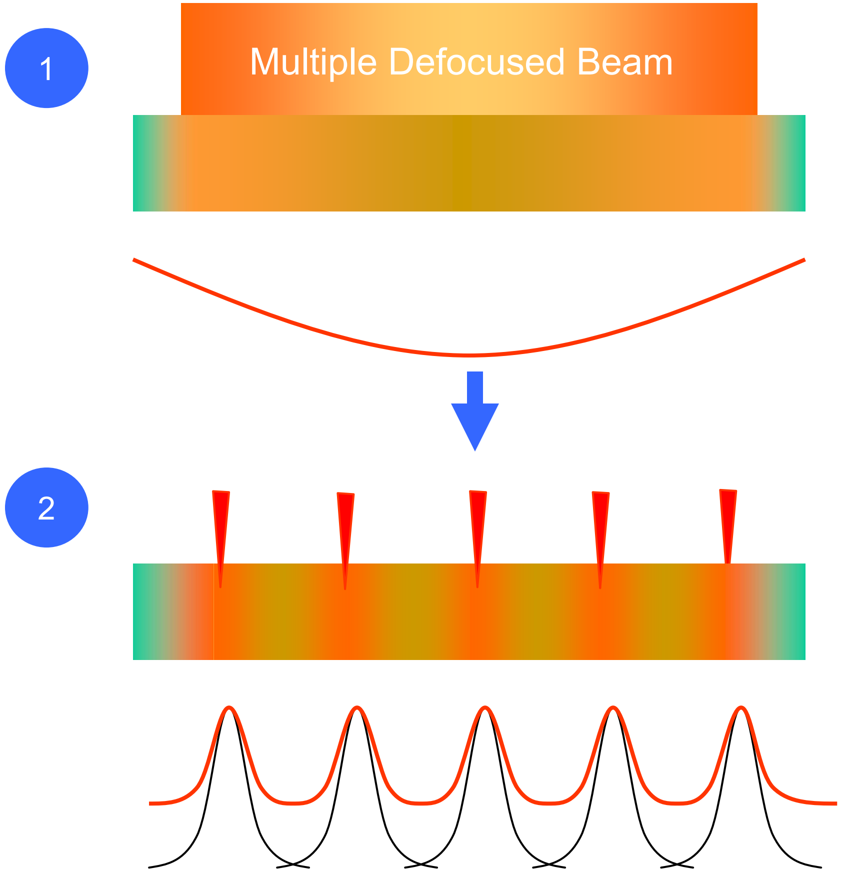
Proximity Effect Correction

- Use thin resist
- Use thin substrate
- Adjust acceleration voltage
- Split pattern into several writings using different doses
- Adjust pattern size and shapes (remember diffraction correction in mask engineering?)
- Adjust dose level to compensate scattering

Proximity Correction – “Ghost” Exposure

Without “Ghost”





Raith-150 EBL System at CIMS

Specification

- Direct Writing and SEM system
- Thermal assisted field emission (LaB_6)
- Acceleration voltage range: 200 – 30KV
- Probe Current Range: 5 pA -20 nA
- Field Size: 0.5 – 1000 μm
- Beam Size: 2 nm @ 30 KeV
- Lithography Resolution :   < 20 nm
- Field Stitching Capability: < 60nm
- Maximum wafer size: 6”
- Writing speed: 10MHz
- Load locked