Photo-Lithography

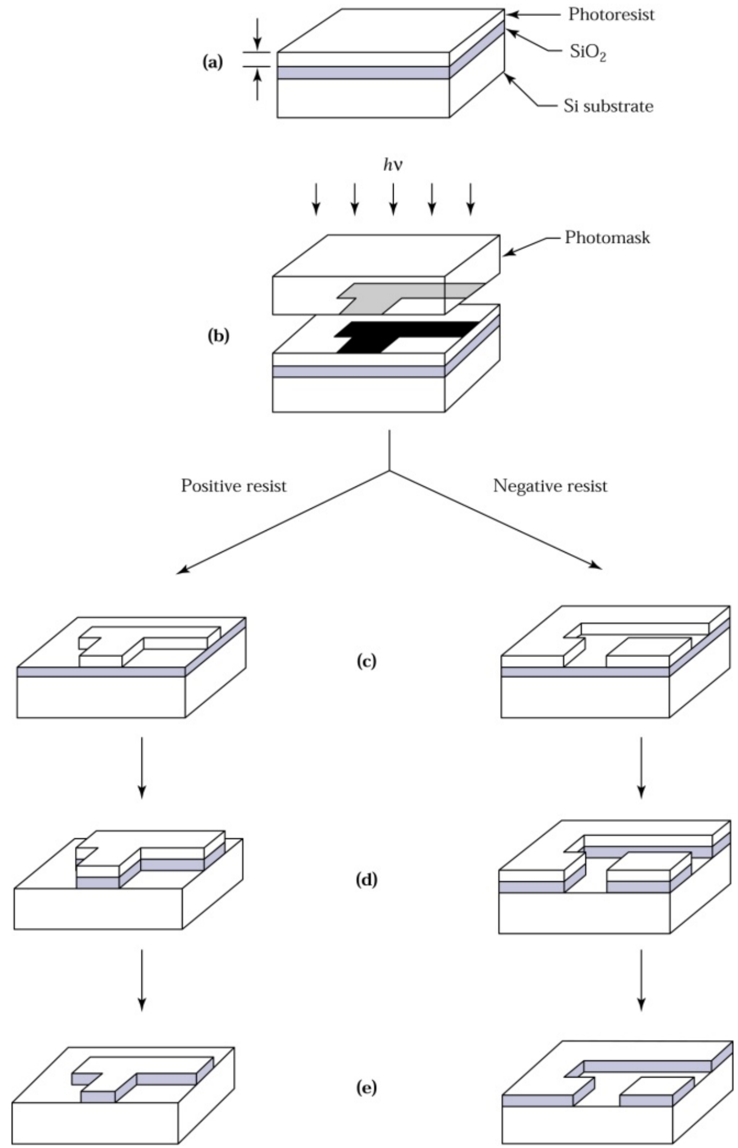
Content

- Introduction to photo-lithography process
- Basic optics
- Mask technology
- Photoresist process
- Resolution-enhanced technology (RET)
- Next-generation lithography technology
- Process Inspection

Introduction

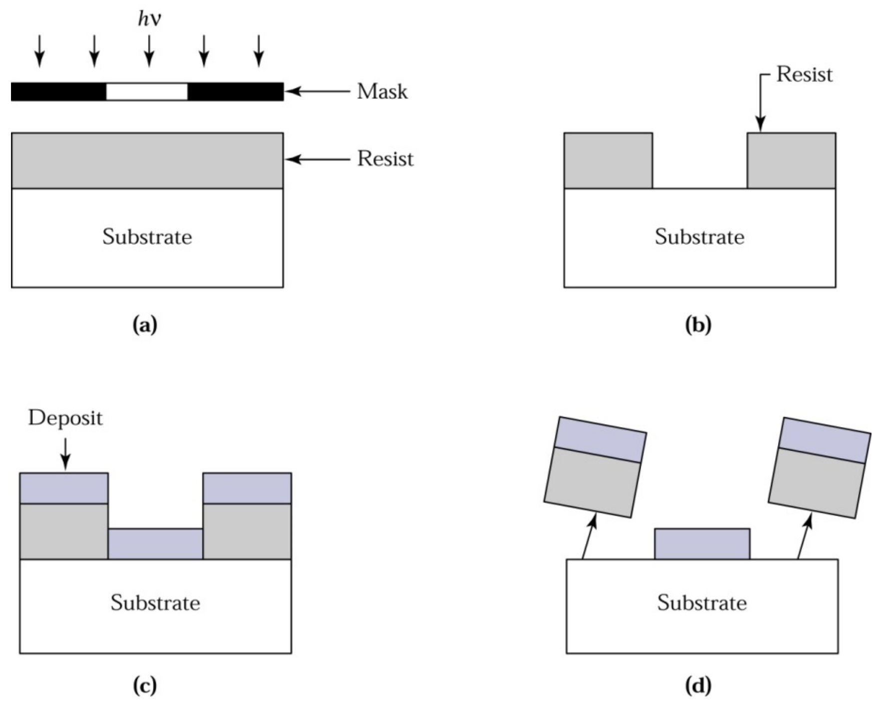
Pattern Transfer - I

- Photo Resist (PR) coating
- Soft bake
- Mask alignment
- Exposure
- Post exposure bake (PEB)
- PR Develop
- Hard bake
- Etching
- PR striping



Pattern Transfer - II

- Liftoff technique
  - PR patterning
  - Film deposition
  - PR dissolve
  - Film liftoff
- Application
  - >1μm IC technology
  - IC Packaging process
  - Compound semiconductor process
  - MEMS process
  - R&D



Terms Definition

➢ Resolution

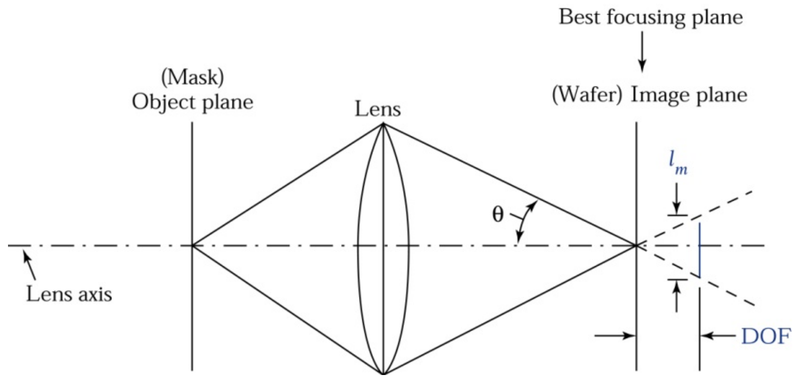
- The minimum feature dimension that can be transferred with high fidelity to a resist film.

$$R = k_1 \frac{\lambda}{NA}, \text{ where } NA = n \sin\theta$$

➢ Depth of Focus (DOF)

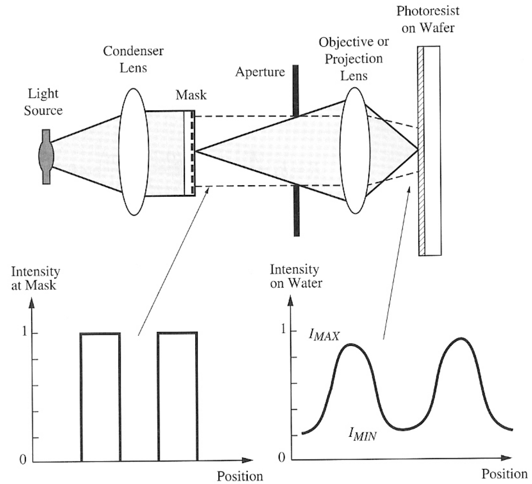
- There is a certain amount of defocus wherein the image will still remain within specifications.

$$DOF = \frac{\pm \frac{R}{2}}{\tan\theta} \approx \frac{\pm \frac{R}{2}}{\sin\theta} = k_2 \frac{\lambda}{NA^2}$$



➢ Modulation Transfer Function (MTF)

$$MTF \equiv \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

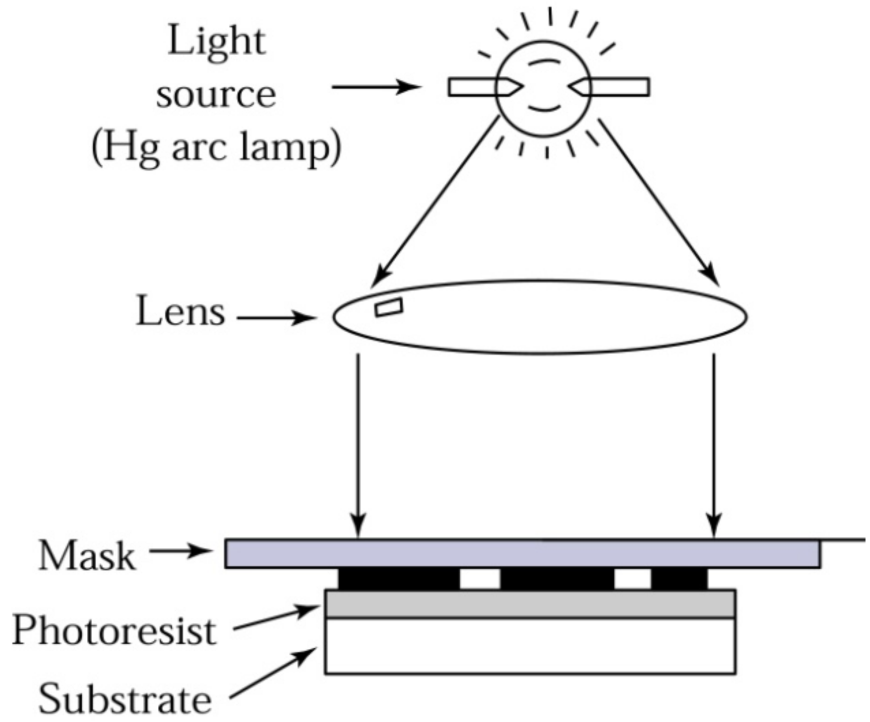


Terms Definition

- Registration (Overlay or Alignment)
  - The measure of how accurately patterns on successive masks can be aligned (overlaid) with respect to previously defined patterns.
- Source of overlay error
  - Relative placement error between mask and wafer
  - Distortion of magnification error of the lens
  - Vibration
  - Temperature drift
  - Atmosphere pressure drift.
  - Others

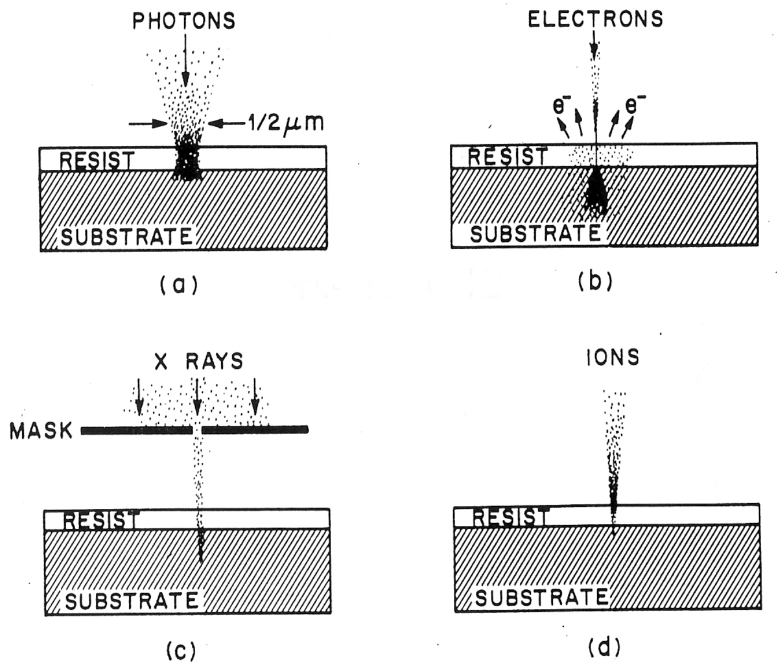
Key Components

- **Light source**
  - Short wavelength
  - High intensity
- **Optical system**
  - Large NA
  - Low power loss
- **Photo mask**
  - High contrast
  - Defect free
- **Photo resist**
  - High sensitivity
  - Good adhesion
  - High resist to subsequent etching process



Lithography Technology

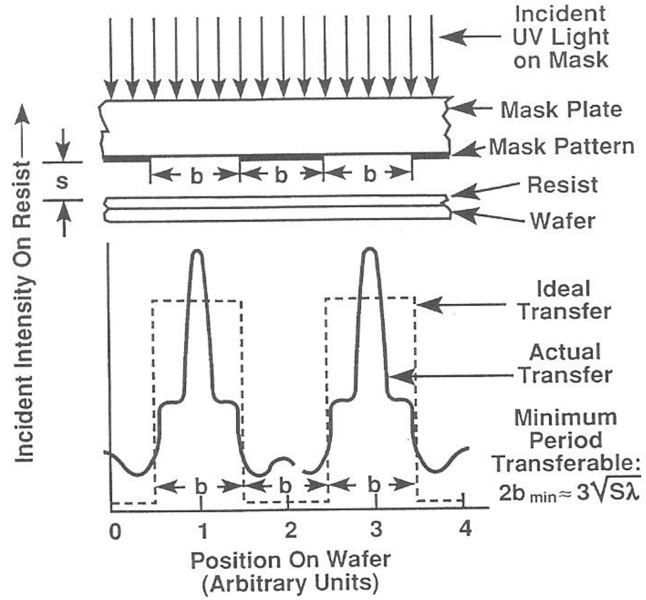
- Strategy
  - Photolithography - source, lens, mask, resist
  - Electron-beam lithography - throughput, mask, cost
  - X-ray lithography - source, mask, resist, cost
  - Ion-beam lithography - throughput, mask, cost
- Printing method
  - Contact printing - defect, lifetime, resolution
  - Proximity printing - defect, lifetime, resolution
  - Projection printing
  - Step and repeat - 10x, 5x, 4x, ...
  - Scanning - wafer-scan, raster scan, stripe-scan, step-scan

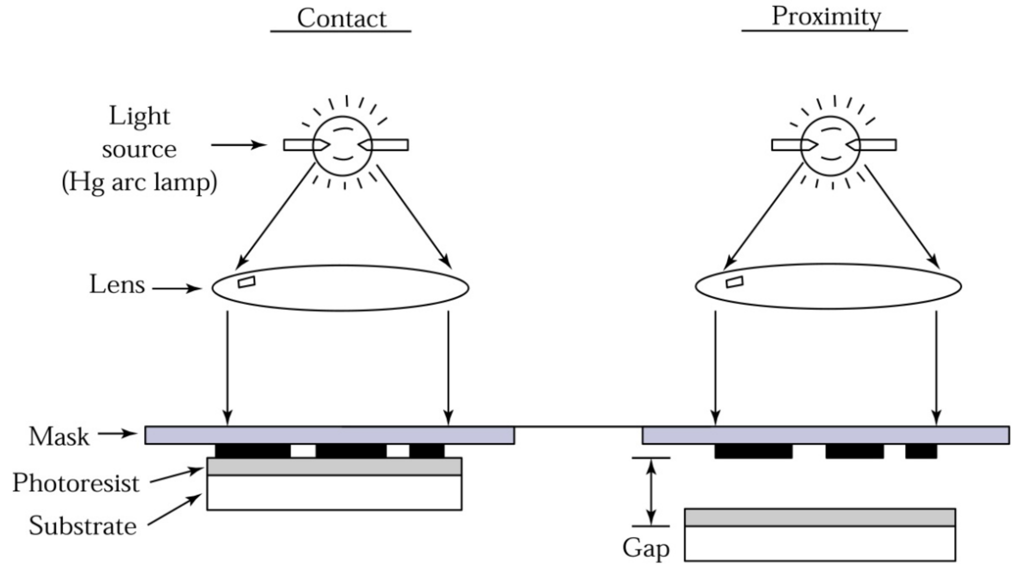


Exposure Methods - Shadowing Printing

- Fresnel Diffraction
- Contact printing
  - Resolution ~ 1μm
  - Dust on mask will damage PR pattern.
  - Mask pattern may be contaminated.
- Proximity printing
  - A small gap of 10-50 μm.
  - Longer mask lifetime.
  - Poorer resolution.

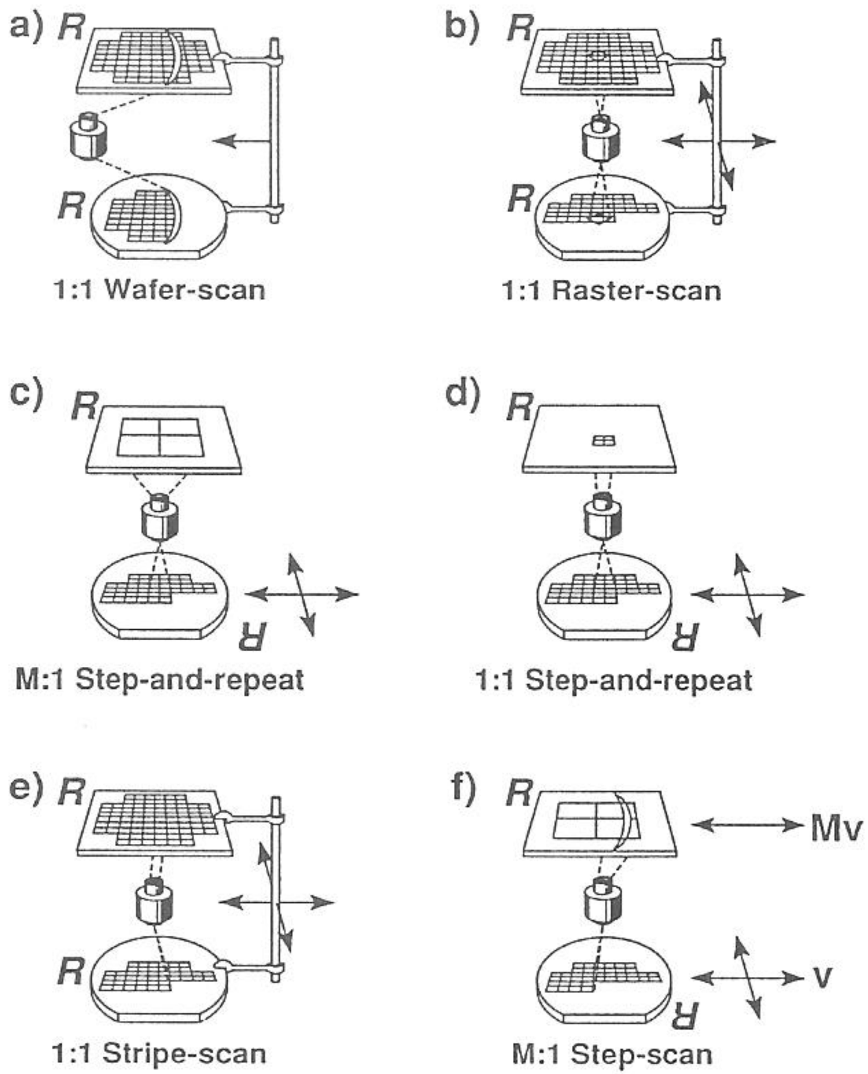
  $2b_{\min} = 3\sqrt{\lambda(s + z/2)}$, where s is the gap and z is the PR thickness.





Exposure Methods - Projection Printing

- ➢ Fraunhofer Diffraction
- ➢ Project an image of the mask pattern onto a resist-coated wafer several centimeters away from the mask.
  - 1:1 projection optical system is easier to design.
  - M:1 projection mask is easier to fabricate.
- ➢ Projection method
  - Scan
  - Step-and-repeat
  - Step-and-scan

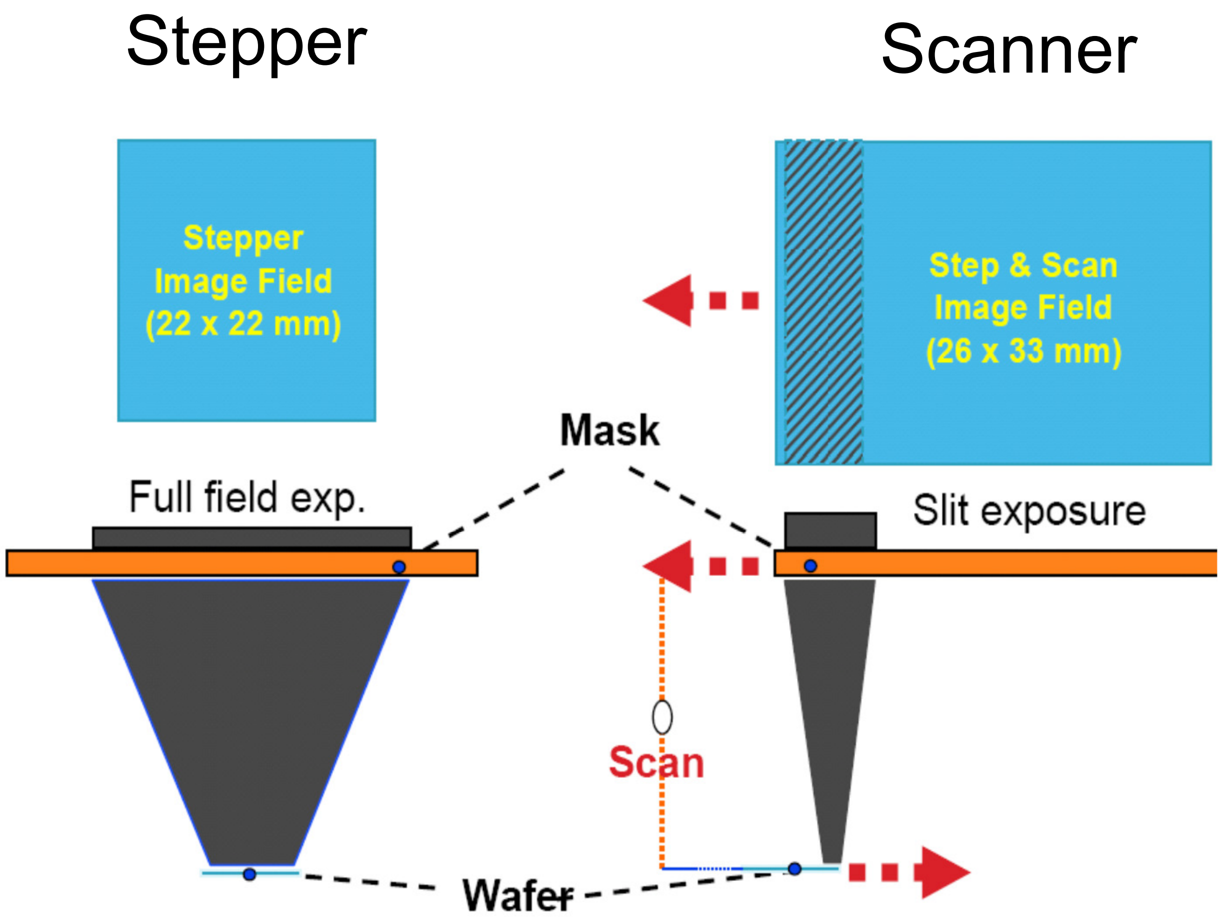


Stepper and Scanner

- Step-and-repeat (stepper) and step-and-scan (scanner) exposure are the most popular photolithography tools in advanced IC fabs.
- Reduction of image
  - 10:1 → 5:1 → 4:1 (trade-off between cost and precision of optics)
  - Refined resolution
  - Mask making greatly simplified
- Wave length evolution
  - G-line (436 nm) → I-line (365 nm) → KrF (248 nm) →ArF dry (193 nm) → ArF wet (193 nm) → EUV(13.5 nm) → BEUV (6.5 nm) ?
- More and more expensive

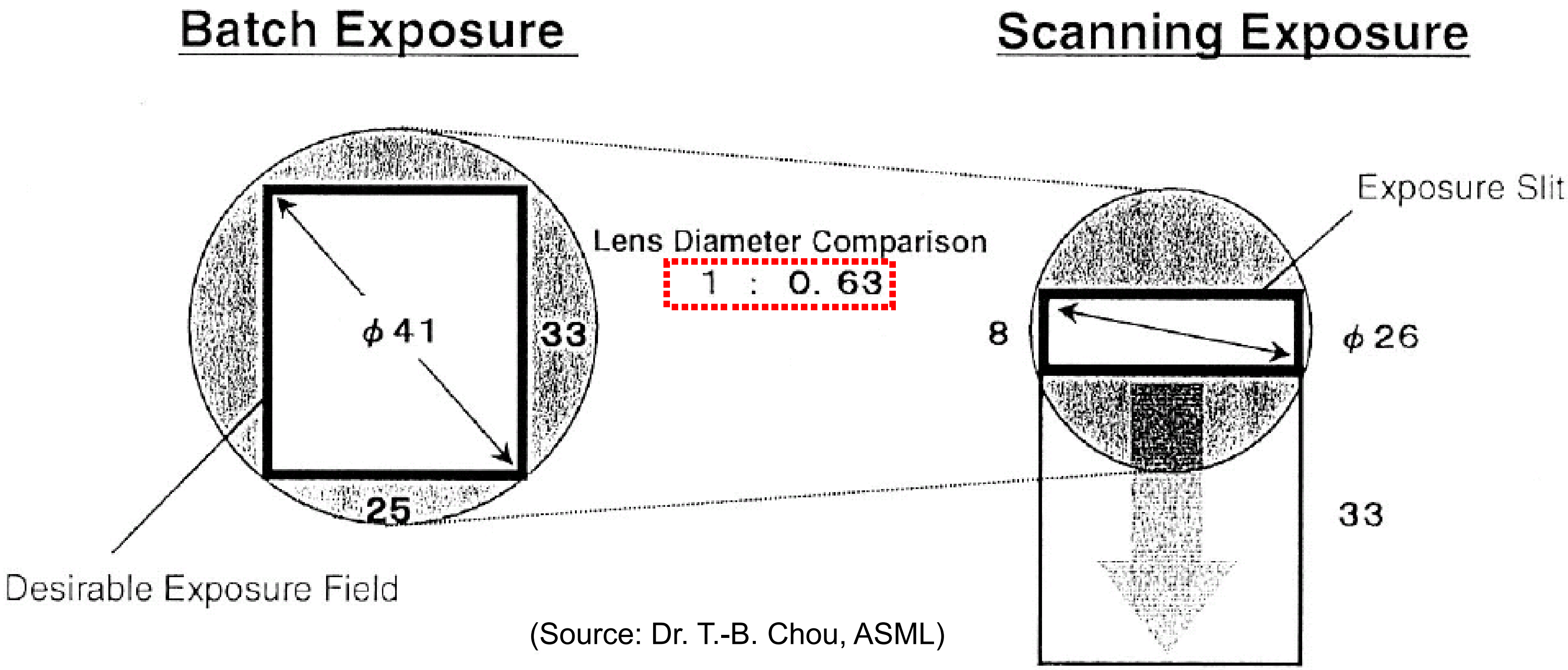
Benefits of Scanner

- Smaller lens
  - Better lens performance
  - Better CD control
  - Better matched overlay
- Larger (die) field size
- On-the-fly leveling (for adjusting the focus)
- Higher throughput



(Source: Dr. T.-B. Chou, ASML)

Lens Size Comparison

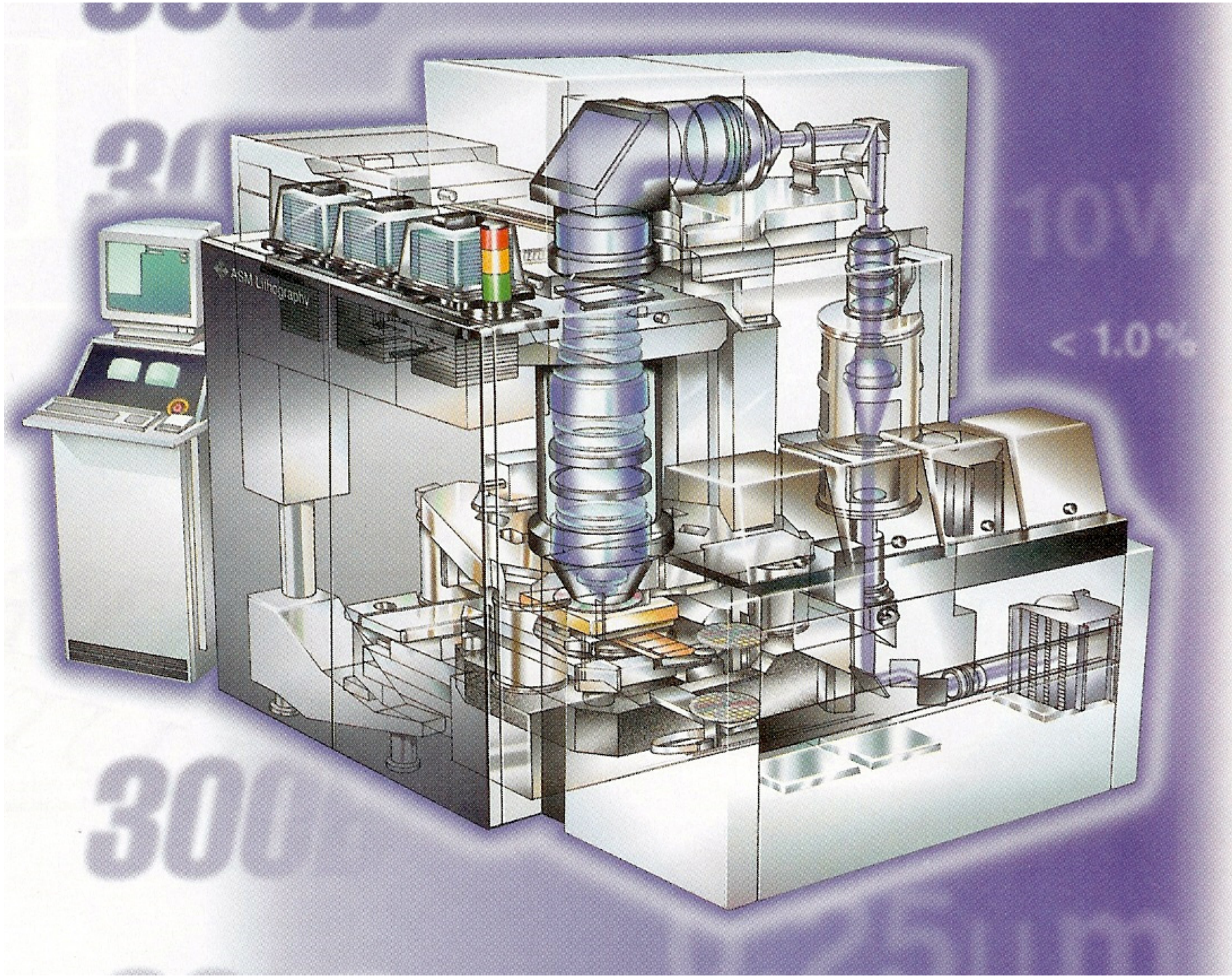


(Source: Dr. T.-B. Chou, ASML)

- Area of exposure field: 25 × 33mm
- Available die size: 25 × 33mm
- Necessary lens diameter: ϕ 41 mm

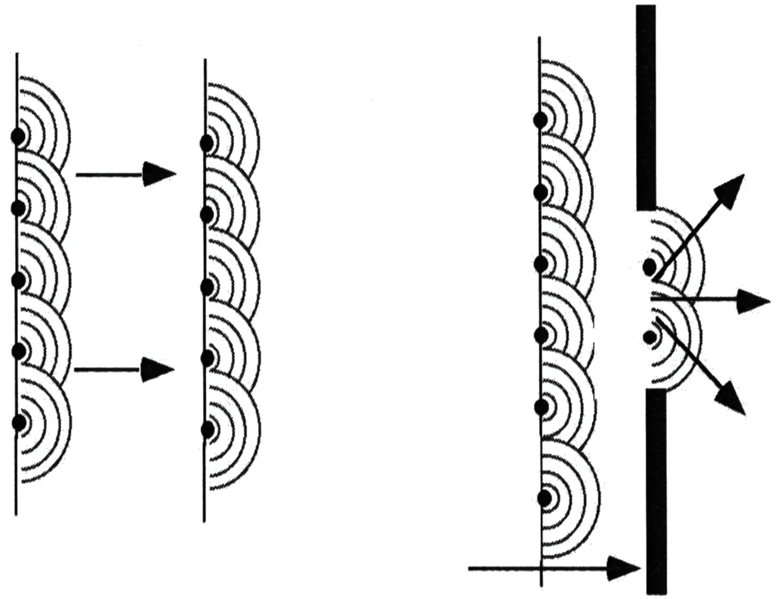
- Area of exposure field: 26 × 8mm
- Available die size: 26 × 33mm
- Necessary lens diameter: ϕ 25 mm

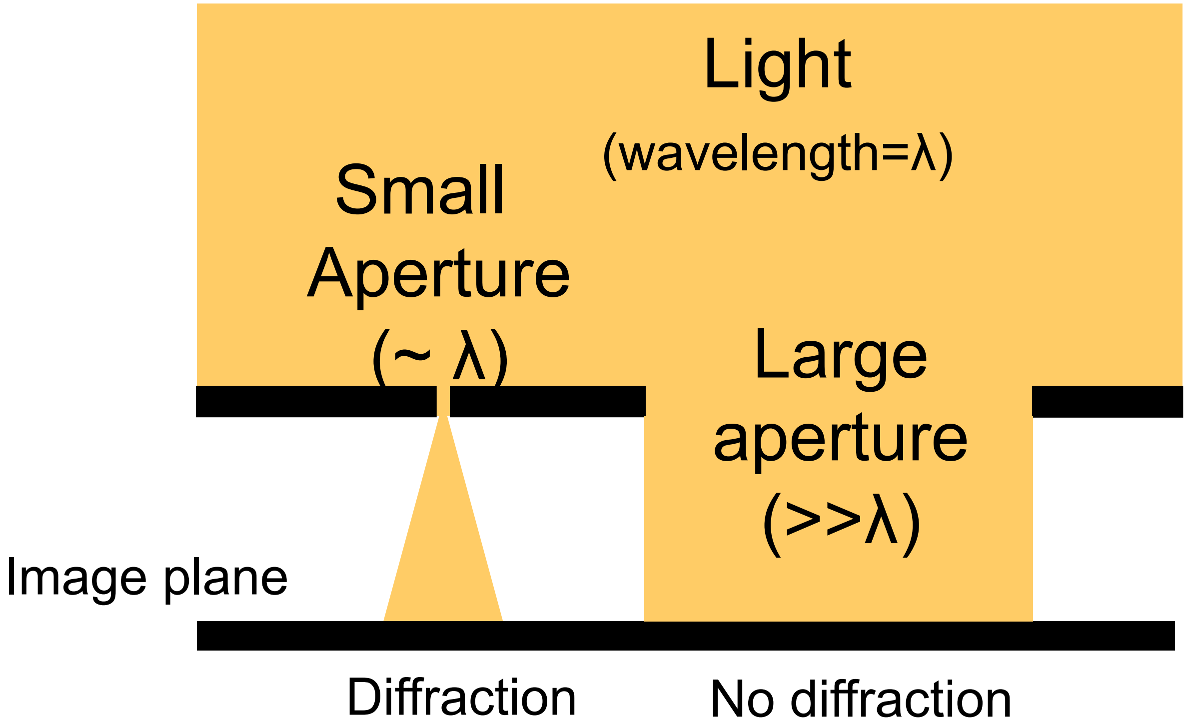
DUV Stepper

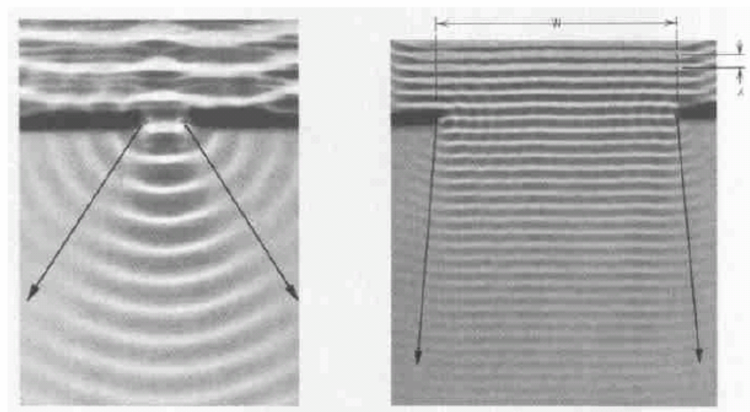


Basic Optics

Light Propagation



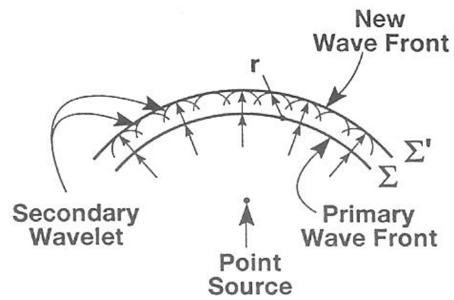


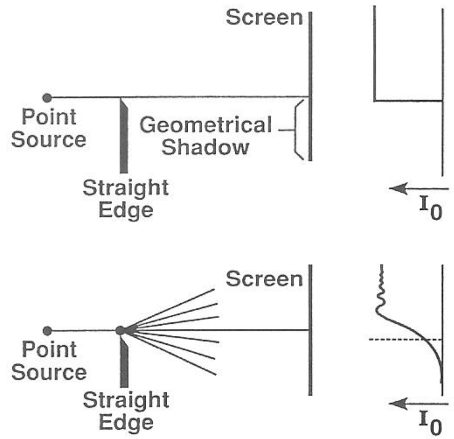


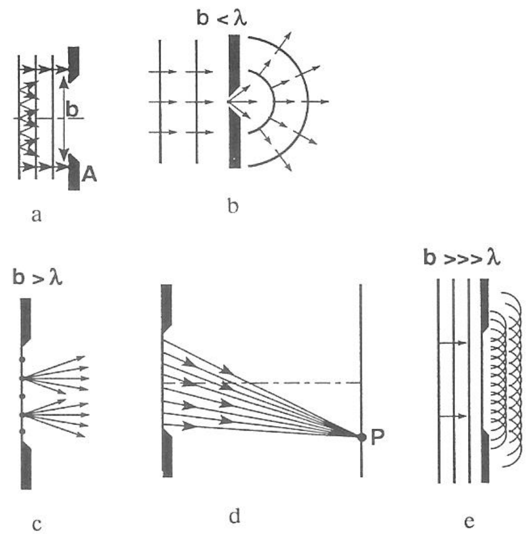
(left) in free space and (right) through a small aperture (right).

Diffraction - 1

- Huygens-Fresnel principle
  - Every point on a primary wave front serves as a source of spherical secondary waves (called wavelets) such that the primary wave front at some later time is the envelope of these wavelets. The wavelets advanced with a speed and frequency equal to those of the primary wave at each point in space.
- Diffraction
  - An edge of an opaque object placed between a point light source and a screen. The shadow cast by the edge is diffuse, consisting of alternate bright and dark bands that extend into the geometrical shadow. This bending of light around the edge is referred as diffraction.
  - Diffraction becomes significant as the aperture dimensions are comparable to the wavelength (λ) of light source.

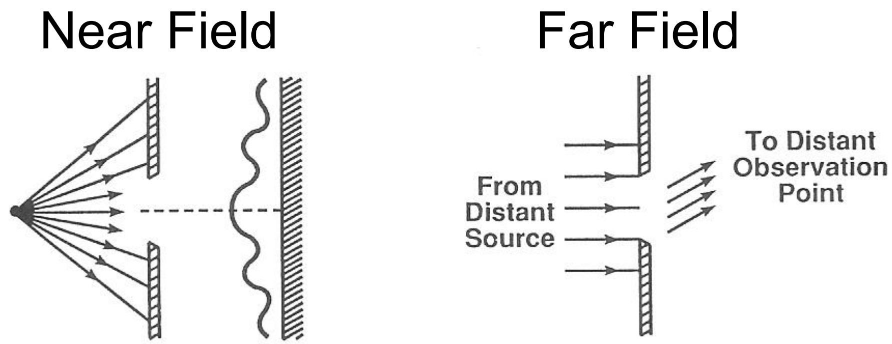


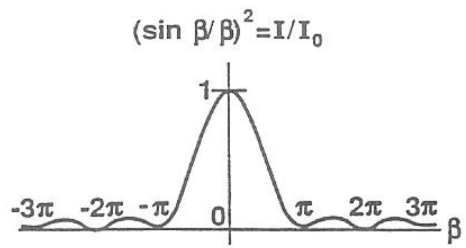




Diffraction - 2

- **Fresnel (near field) diffraction**
  - As the screen is moved further away, the image of the slit becomes increasingly more structured as the fringes become more prominent. This pattern, which is determined by the phase relationships between the secondary wavelets arriving at P, is referred as the Fresnel diffraction.
- **Fraunhofer (far field) diffraction**
  - By moving both the source and observation point away from the slit to a very large distance, the diffracted wave fronts are now planar. The diffraction pattern observed under these conditions is known as the Fraunhofer diffraction.



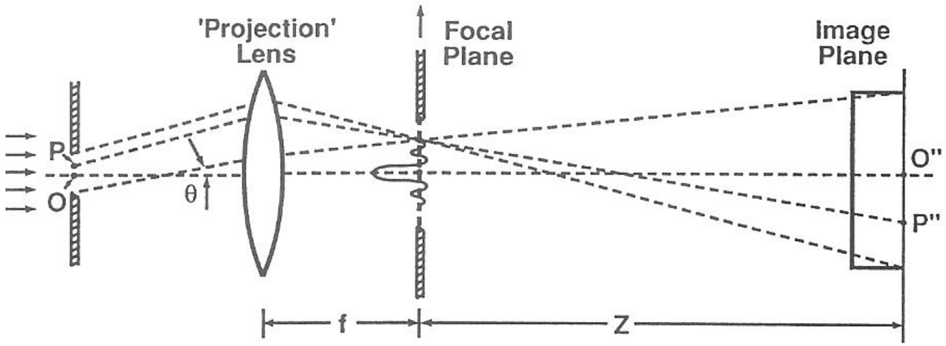


$$A(\theta) = A_o \frac{\sin\beta}{\beta} \text{ and } I(\theta) = A(\theta)^2 = I_o \frac{\sin^2\beta}{\beta^2}$$

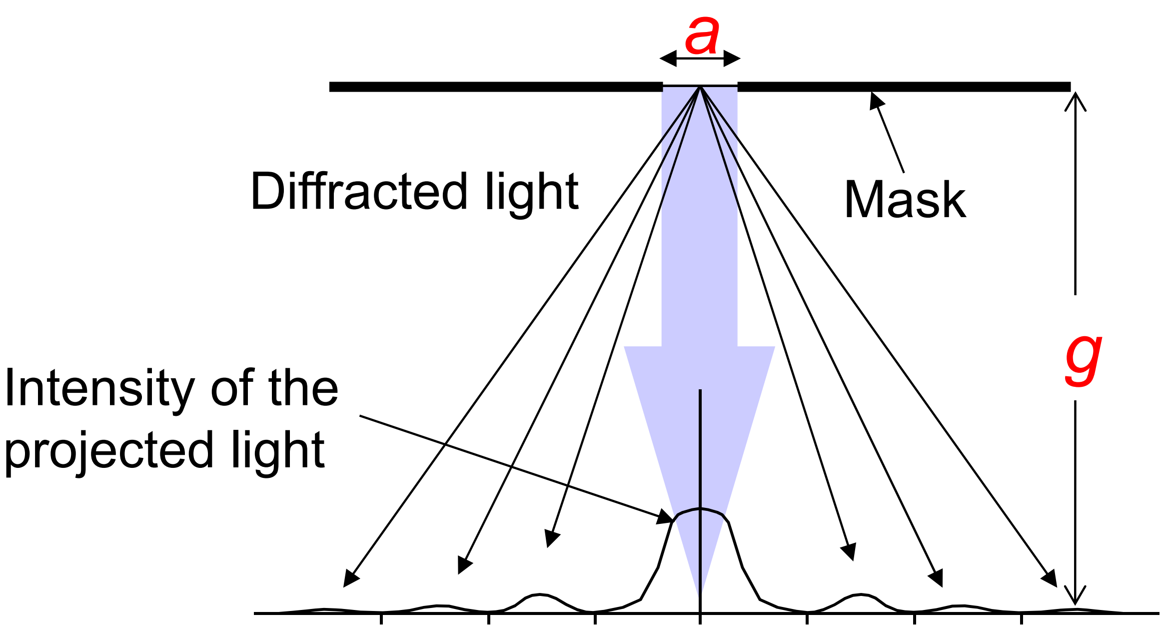
where $\beta = \pi b \sin\theta / \lambda$

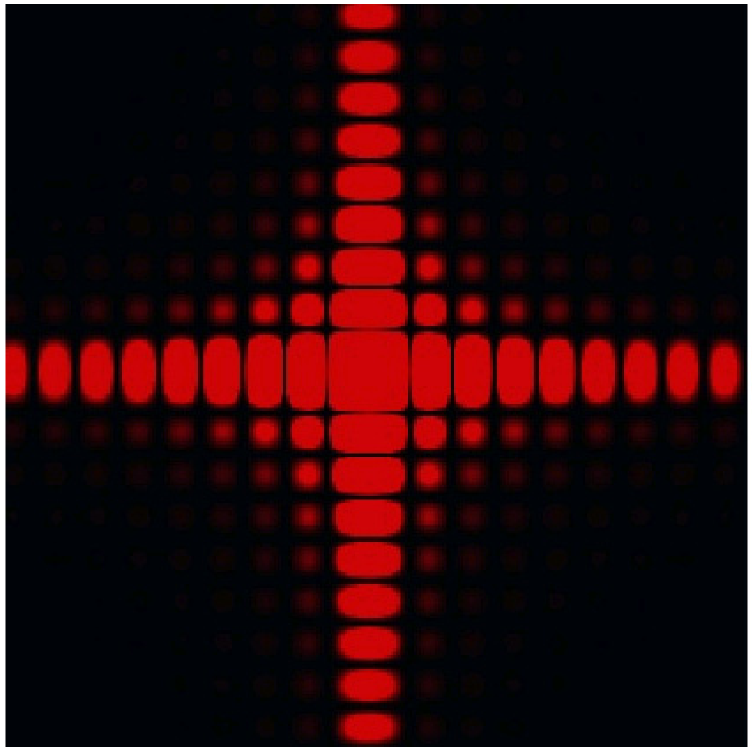
Diffraction - 3

- Diffraction affects resolution (R)
  - Contact and proximity systems: Fresnel diffraction.
  - Projection system: Fraunhofer diffraction.
  - Short-λ waves have less diffraction.
- Diffraction and image formation
  - The process of forming an image of the slit occurs in two steps, the first being diffraction at the aperture, and the second being collection of the diffracted light by the projection lens and subsequent focusing to form the image of the slit on the viewing screen.
  - All of the information pertaining to the image is contained in the diffraction pattern. Optical lens can collect more diffracted light can enhance the image fidelity.



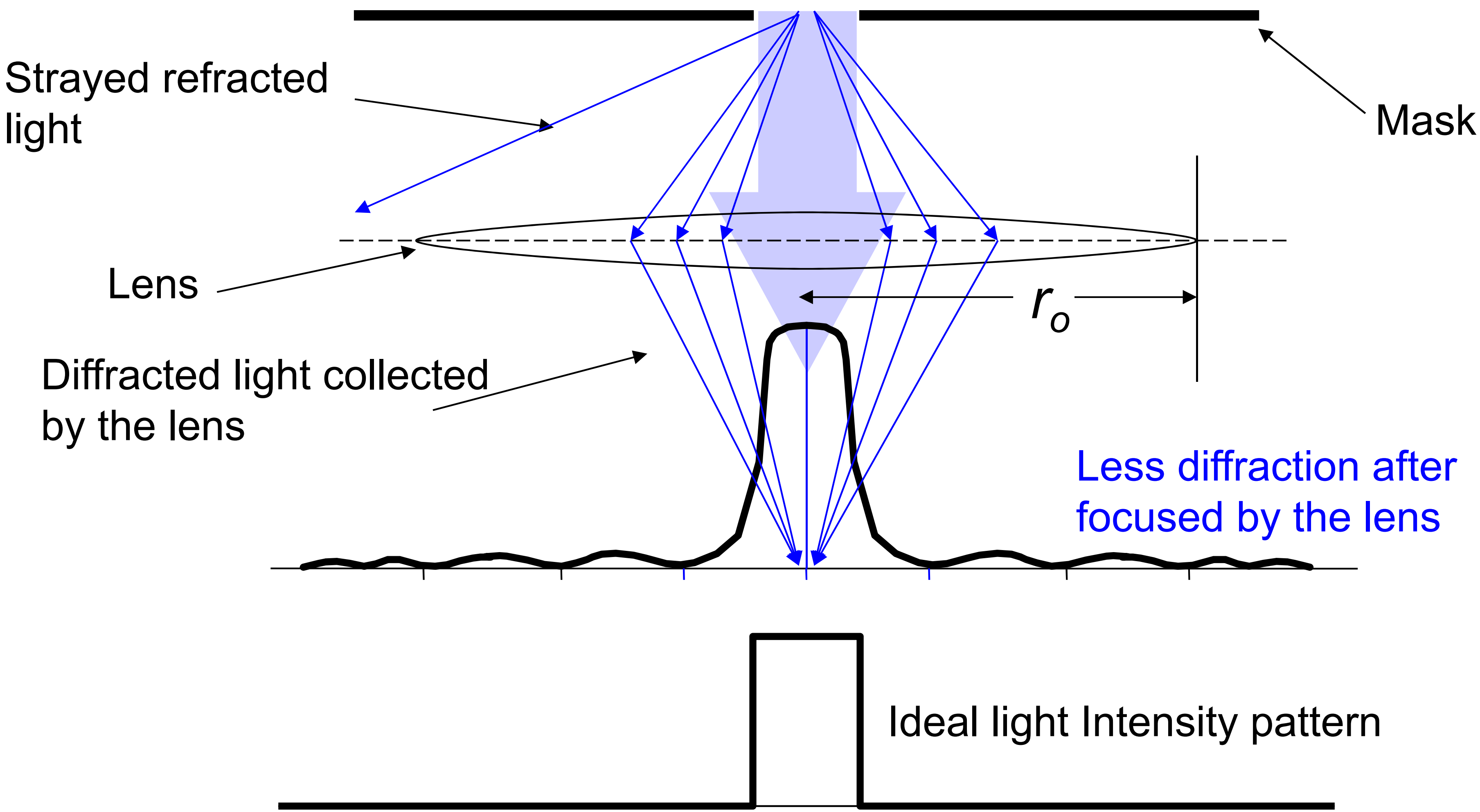
Light Diffraction without Lens



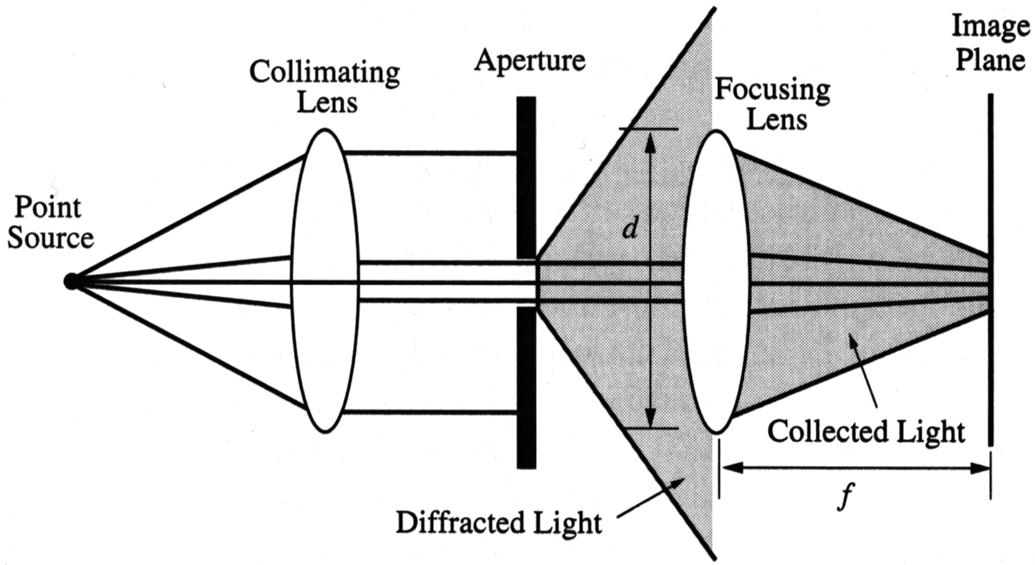


Diffraction patterns from a square aperture

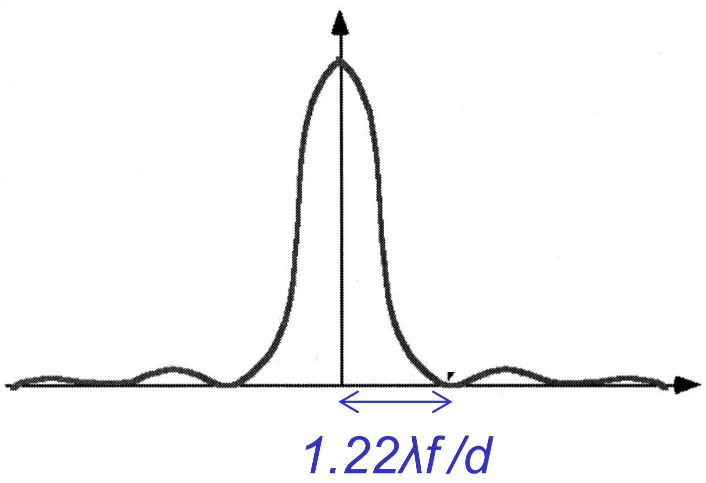
Light Diffraction with Lens

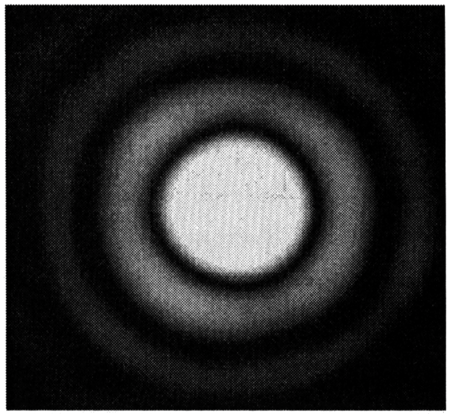


Fraunhofer Diffraction of a Circular Aperture



d: focus lens diameter
f: focal length





- "Airy disk" 2D pattern on the image plane with intensity (I) mathematically described by Bessel functions.
- Radius of the central maximum is $1.22\lambda f/d$

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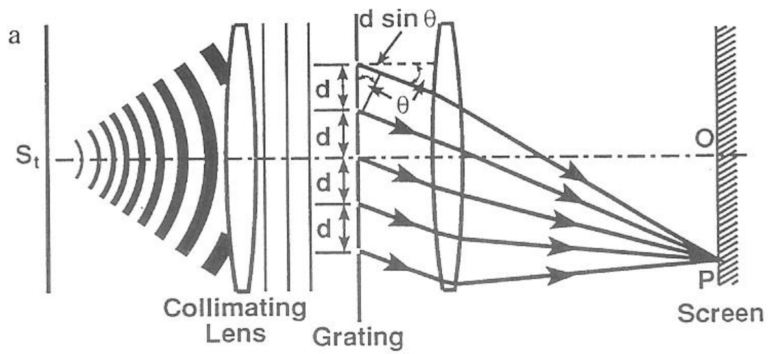
Grating - 1

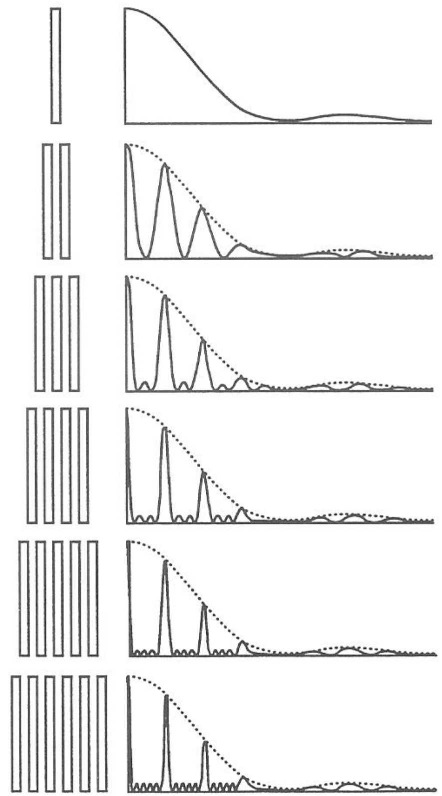
- Diffraction grating is an object consisting of a series of narrow slits.
  - Under Fraunhofer conditions, the wave fronts emerging from the lens are planar and are oriented at right angles to the axis of the system.
  - Each slit in the grating gives rise to a diffraction pattern in which the intensity distribution is a function of the slit width.
  - The flux density distribution function for the multiple-slit aperture (N slits) is

$$I(\theta)=I_o\frac{\sin^2\beta}{\beta^2}\frac{\sin^2(N\alpha)}{\sin^2\alpha},\ \text{where}\ \alpha=\pi d\sin\theta/\lambda\ \text{and}\ \beta=\frac{\pi b\sin\theta}{\lambda}$$

  - The principal maxima occur when $\sin(N\alpha)/\sin(\alpha)=N$, that is, when $\alpha=0, \pm\pi, \pm2\pi, \ldots\ldots, \pm m\pi$, which corresponds to angles(θ_m) that obey the expression:

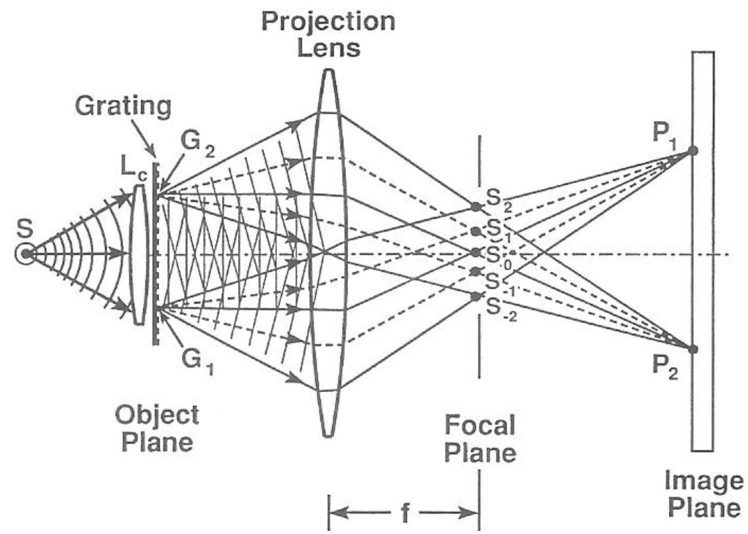
$$\sin\theta_m=\frac{m\lambda}{d}$$ where m, the *diffraction order*, is equal to 0, ±1, ±2, etc.





Grating - 2

- Grating with equal lines and spaces of width b.
  - Uniform illumination of the equal line and space pattern produces a diffraction pattern with an intensity profile depending on the grating period (1/2b) and the wavelength (λ). The diffracted orders from a given point in the object plane are subsequently recombined at the image plane to give an optical reconstruction (image) of the object.
  - The +1, 0, and -1 orders contain information about the fundamental periodicity of the grating, whereas the higher orders define the edge slope.
  - Perfect image formation requires all of the diffracted light to be collected and combined with all other orders at the image plane.



Numerical Aperture

- The numerical aperture of the projection lens (NA_p) is defined in terms of the maximum cone angle of rays ψ_{max} subtended by the maximum pupil diameter at the image plane.
  - $NA_p = n \sin \Psi_{\max}$
    where n is the refractive index in image space.
  - The angle of diffraction corresponding to a given order m increases with increasing n.
  - Lenses with a larger NA can capture higher order of diffracted light and generate sharper image (higher resolution).
  - NA_p can be increased by using a larger lens or a medium with higher n. (In conventional tools, the medium is air with n =1.)

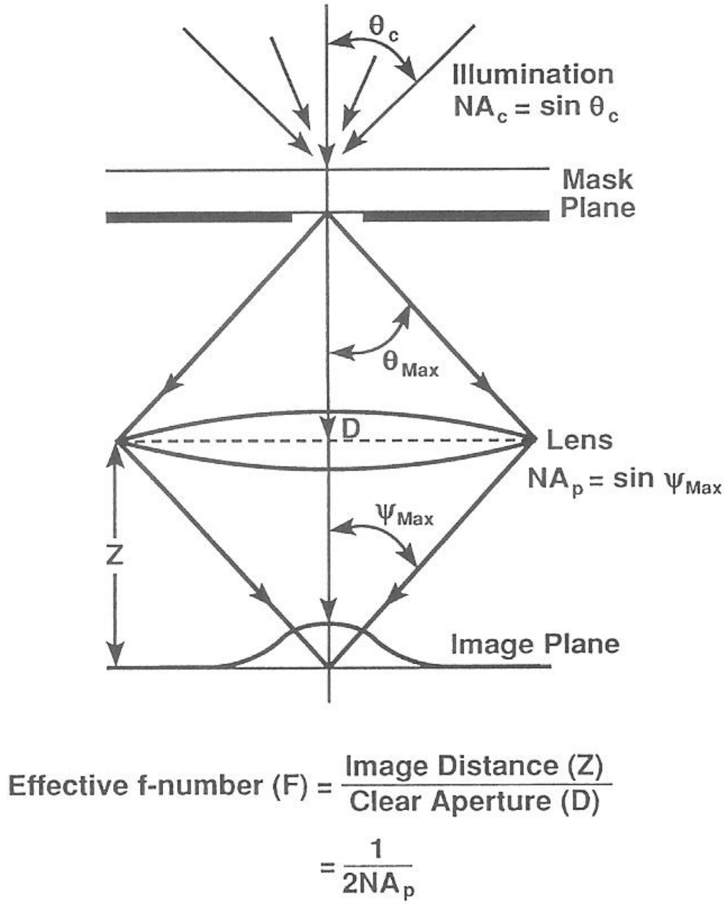


Image Contrast

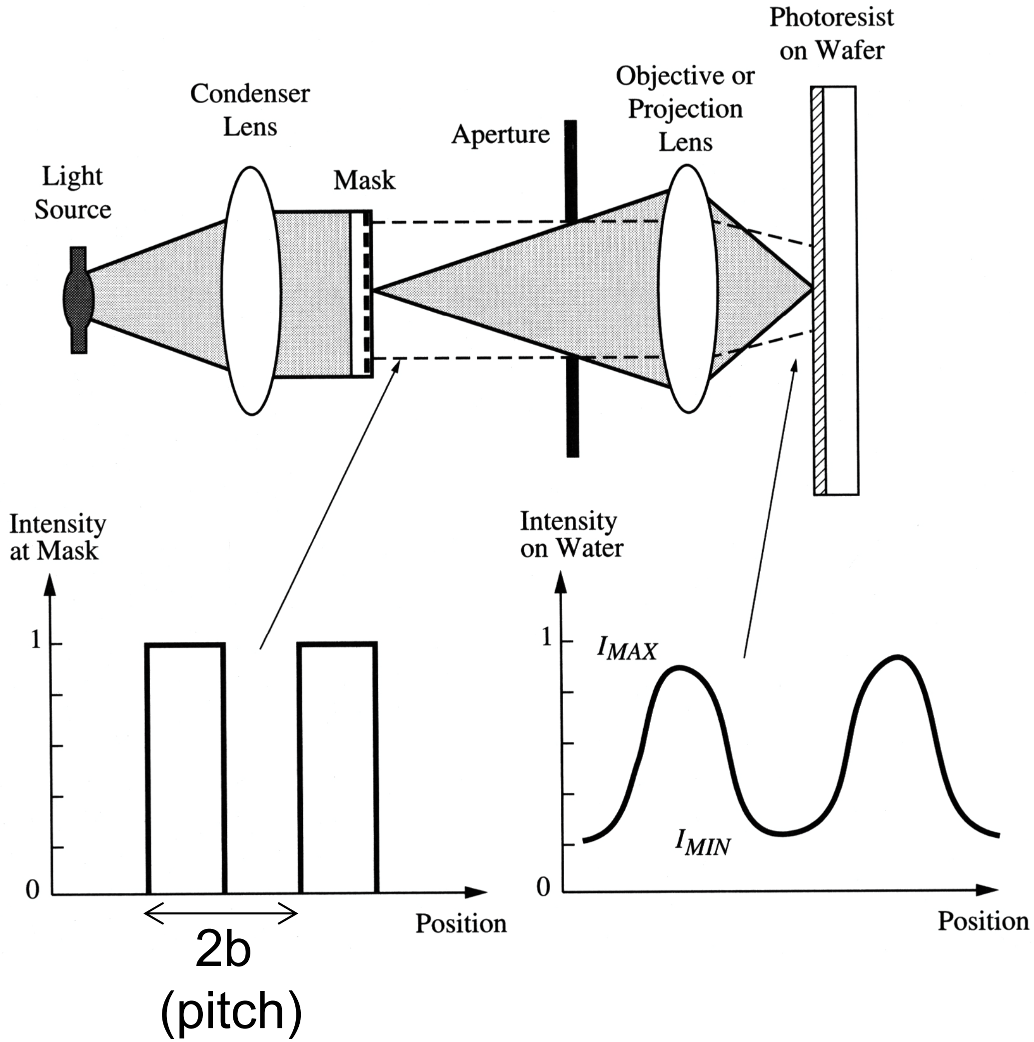
- Contrast of the image is expressed as the ratio of the modulation M of the image

$$M = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

- Modulation Transfer Function (MTF) of an exposure system
  - It is defined as the ratio of the modulation in the image plane (wafer surface) to that in the object plane (mask).

$$MTF(\nu) = \frac{M_{image}(\nu)}{M_{opject}(\nu)} \approx \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

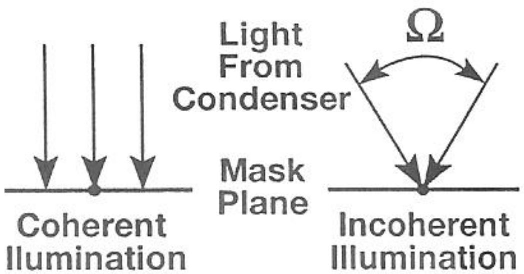
  - Generally MTF > 0.6 is needed for applications.

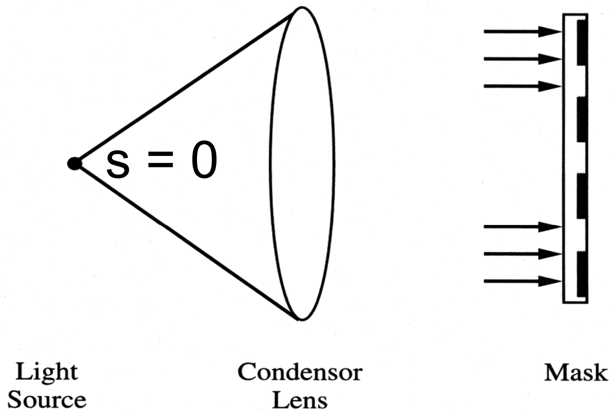


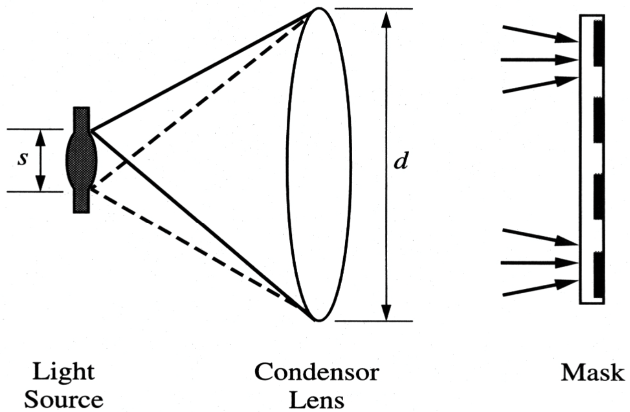
Coherence (σ)

- Coherence is defined as “the state of being together”.
  - Temporal coherence relates directly to the finite bandwidth of the source.
  - Spatial coherence relates to its finite extent in space.

$$\sigma = \frac{\text{size of the light source}}{\text{diameter of the condenser lens}} = \frac{s}{d}$$







Spatially coherent (σ = 0)

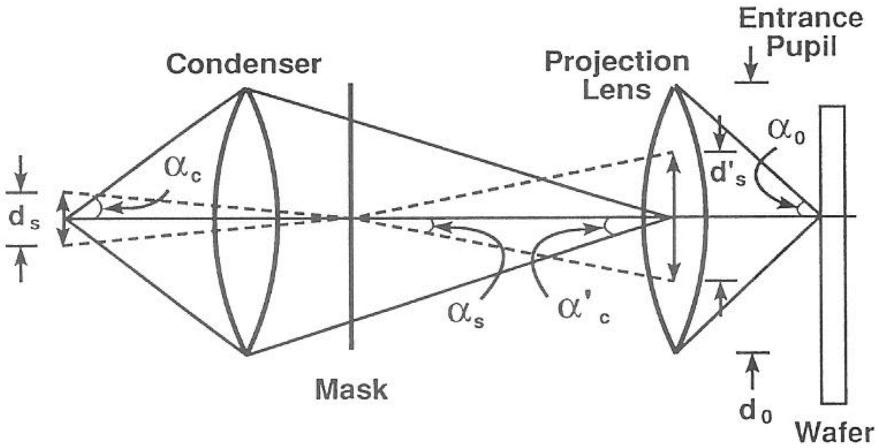
All of the plane waves strike the mask at exactly the same angle.

Partially coherent (σ > 0)

Light arrives at the mask from a variety of angles.

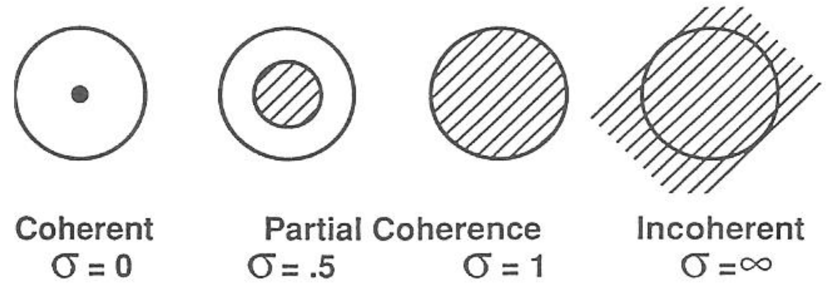
Degree of Coherence

- The degree of coherence is commonly expressed as $\sigma = {NA_c}/{NA_p}$
  - The coherence factor varies from 0 (for coherence radiation) to ∞ (for fully incoherence illumination). In between lies the domain of partial coherence corresponding to finite sources.
  - The image of the source is the effective size of the source, and the degree of coherence is given by $\sigma = {d_s'}/{d_o}$
  - Most projection systems used in lithography have coherence factors in the range 0.4~0.7.



$$M_c = \frac{\alpha_c}{\alpha'_c} = \frac{d'_s}{d_s} \qquad \sigma = \frac{d'_s}{d_o} = \frac{\alpha_s}{\alpha_o / M_o}$$

Change the effective source area by a stopper. The dashed area is the effective source area.

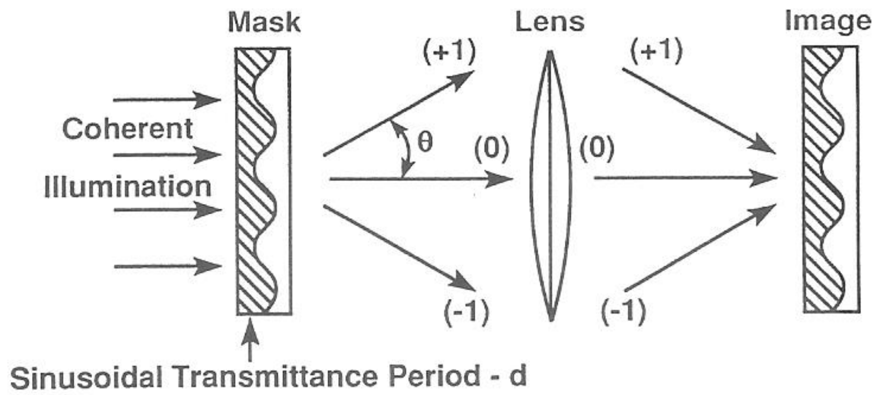


Effect of Coherence on MTF

- The angular dependence of the first order diffracted peak on grating frequency $\nu=1/d=1/2b$ is given by $\nu=\sin(\theta)/\lambda$.
- Coherence illumination

$\nu_{\max} = \dfrac{\sin\psi_{\max}}{\lambda} = \dfrac{NA}{\lambda}$, where the $\sin\psi_{\max}$ is the NA of the projection lens.

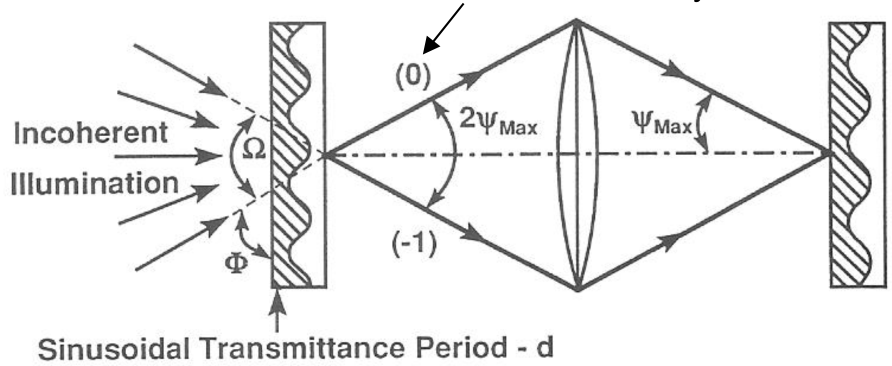
$$MTF = \begin{cases} 1, & as\ \ \nu \le \dfrac{NA}{\lambda} \\ 0, & as\ \ \nu > \dfrac{NA}{\lambda} \end{cases}$$



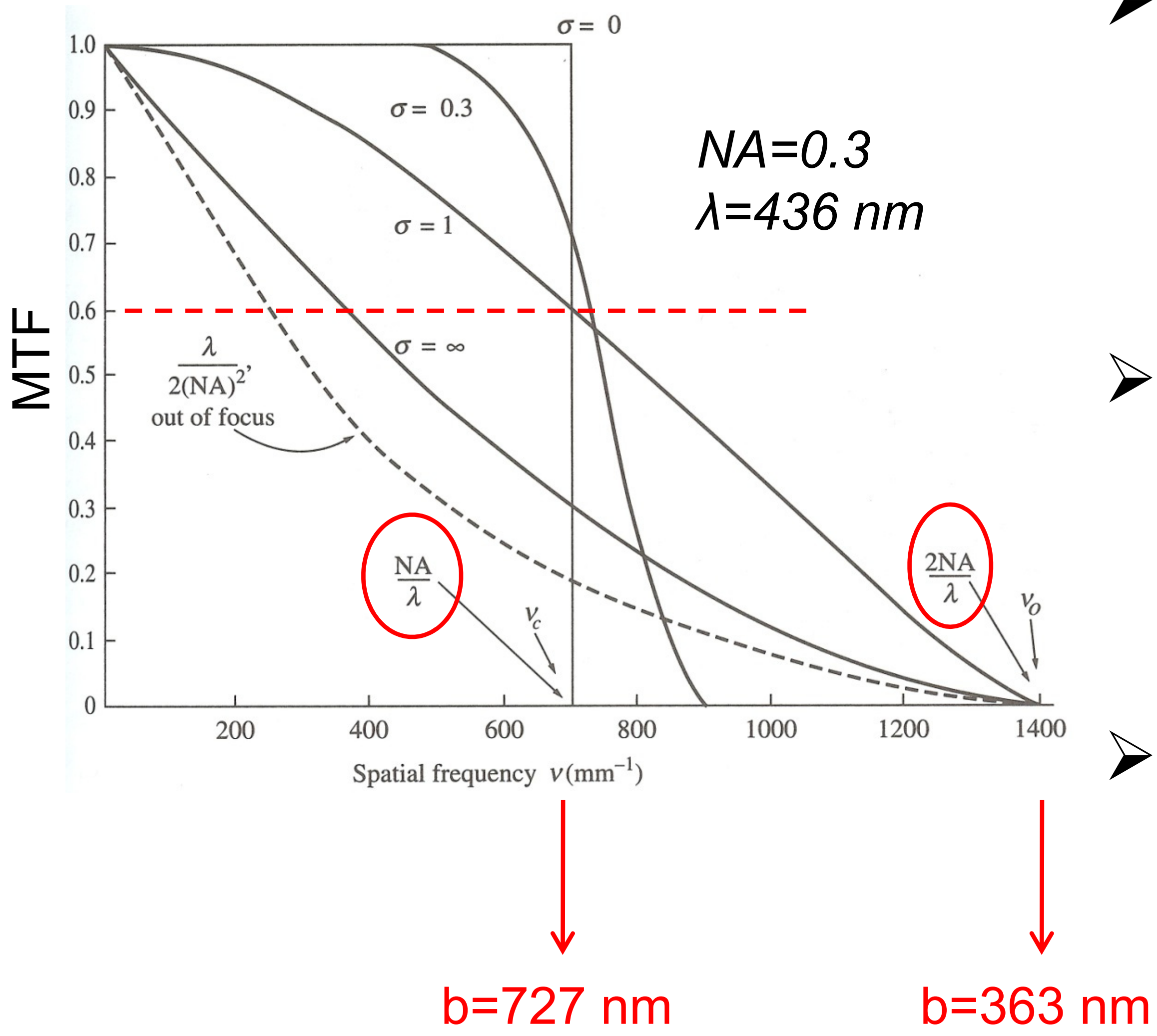
- Incoherence illumination

$$d(\sin\theta + \sin\phi) = n\lambda \Rightarrow \nu_{\max} = \frac{2NA}{\lambda}$$

$$MTF = \begin{cases} 0\sim 1, & as\ \ \nu \le \dfrac{2NA}{\lambda} \\ 0, & as\ \ \nu > \dfrac{2NA}{\lambda} \end{cases}$$



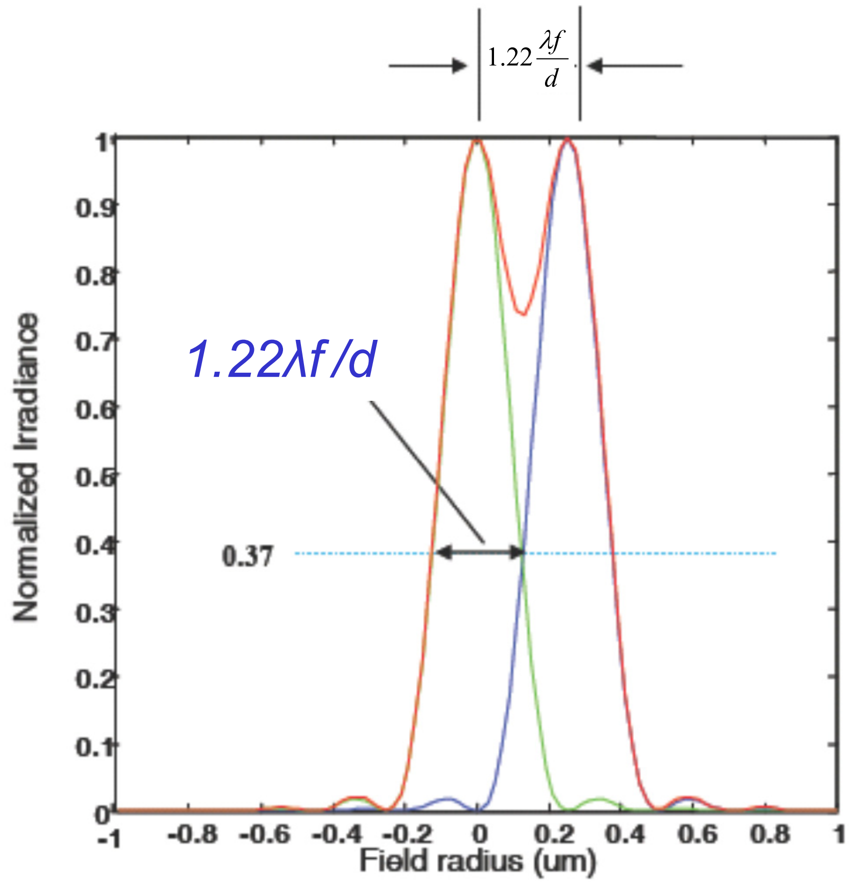
Resolution vs. MTF



- For a printer with σ = 0, the contrast is good as the image patterns are resolved, but the resolution is limited at NA/λ.
- Partial coherence can increase MTF in the ν range NA/λ ~ 2NA/λ, and thus has better resolution than coherence.
- Typical applications need MTF ≧ 0.6, which limits practical resolution.

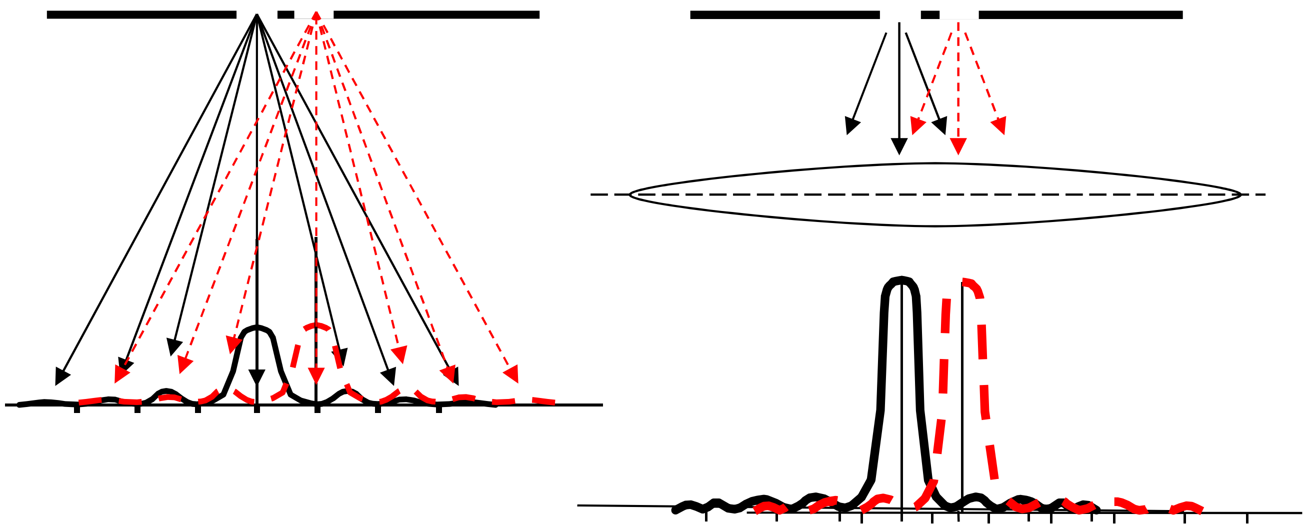
Rayleigh's Criterion for Resolution

- Resolution: the achievable and repeatable minimum feature size.
- For two point sources to be imaged, the closest distance between them can be resolved on the image plane is defined as the central maxima of each point image lie at the first minima of the adjacent point image.



Projection Systems

- Resolution and image quality can be significantly improved with ingenious optical system design.
- Fraunhofer diffraction dominates.



Resolution of Projection Systems

- According to Rayleigh's Criterion, resolution (R) for circular point sources is

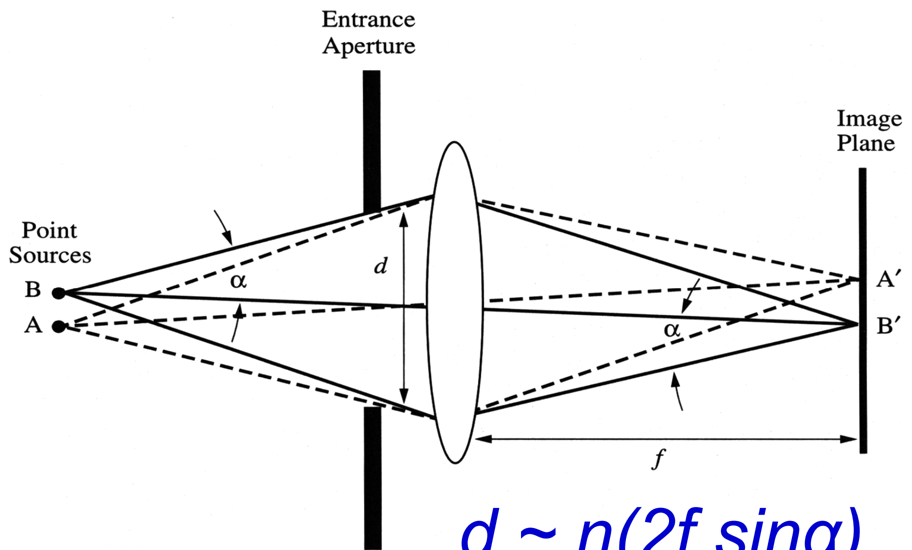
$$R = 1.22\lambda\frac{f}{d} \approx 1.22\frac{\lambda f}{n(2f\sin\alpha)} = 0.61\frac{\lambda}{n\sin\alpha} = 0.61\frac{\lambda}{NA}$$

α : the half - angle of the maximum cone of light that can enter or exit the lens.

n : refractive index. n = 1 in air or vacuum.

- Numerical Aperture, NA ≡ n sinα , capability of lens to collect diffraction light.
- General form:

$R = K_1\dfrac{\lambda}{NA}$, where K_1 is a system constant.



$d \sim n(2f\sin\alpha)$

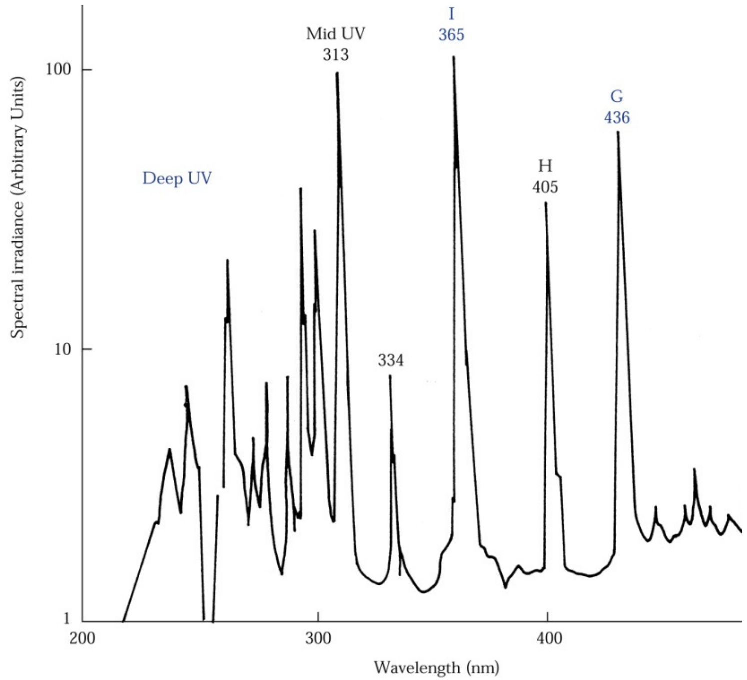
Resolution, Image Field, and Wavelength

- According to the Rayleigh's Criterion

$$R = K_1 \frac{\lambda}{NA}$$, where K_1 is a system constant.

- One obvious approach to extending optical lithography to smaller features is to reduce the wavelength to much shorter values.
- What limits the size of the image field for a given resolution is the ability of the lens design to correct for the various distortions and aberrations associated with image formation. Generally speaking, there is a trade-off between resolution and field size in the design of a lens.

Laser	Wavelength (nm)	Bandwidth (nm)
XeF	351, 353	0.5
N_2	337	0.1
XeCl	308	0.5
KrF	248	1
ArF	193	0.1
F_2	157	0.1



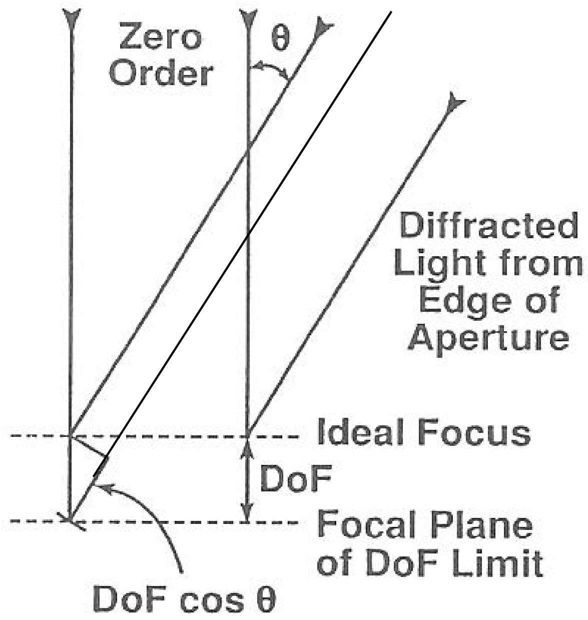
Depth of Focus (DOF)

- DOF is defined as the range that light is in focus and can achieve good resolution of projected image.
- The Rayleigh DOF:
  - At the Rayleigh limit of defocus, the optical path difference between the on-axis zero order and the order coming from the edge of the entrance pupil can be no greater than λ/4.

$$\frac{\lambda}{4} = DoF - DoF\cos\theta = DoF(1-\cos\theta)$$

$$\cos\theta = 1 - 2\sin^2(\theta/2) \text{ and } \sin\left(\frac{\theta}{2}\right) \approx \frac{NA}{2} \Rightarrow \frac{\lambda}{4} = DoF\frac{(NA)^2}{2}$$

  - The Rayleigh limit for DoF is given by $DoF = \pm\frac{\lambda}{2(NA)^2}$ and could be expressed as $DoF = \pm K_2\frac{\lambda}{(NA)^2}$ considering the other factors.



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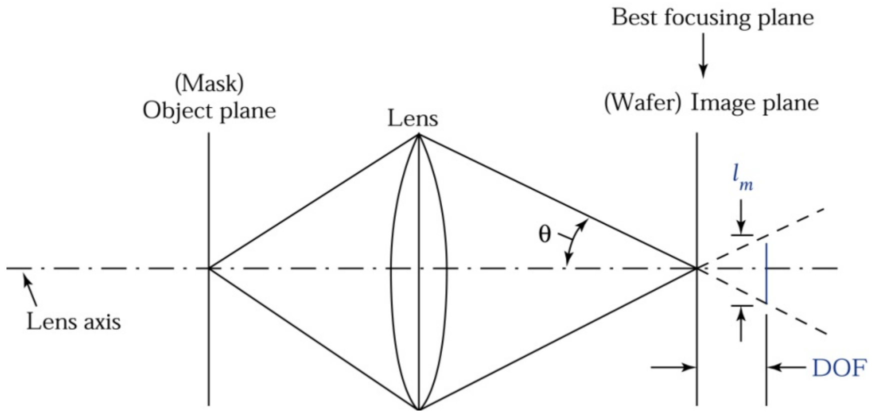
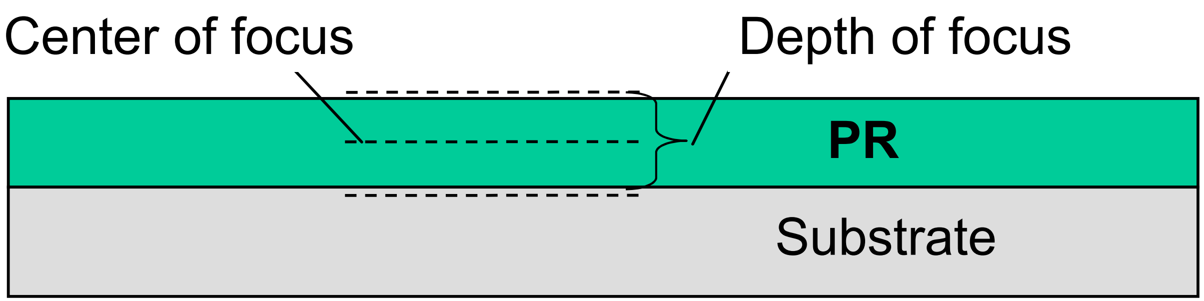
Resolution and DOF Trade-off

- $R = K_1 \dfrac{\lambda}{NA}$ and $DoF = \pm K_2 \dfrac{\lambda}{(NA)^2}$
  - R ↓ as λ↓ or NA↑
  - DOF ↓ as λ↓ or NA↑



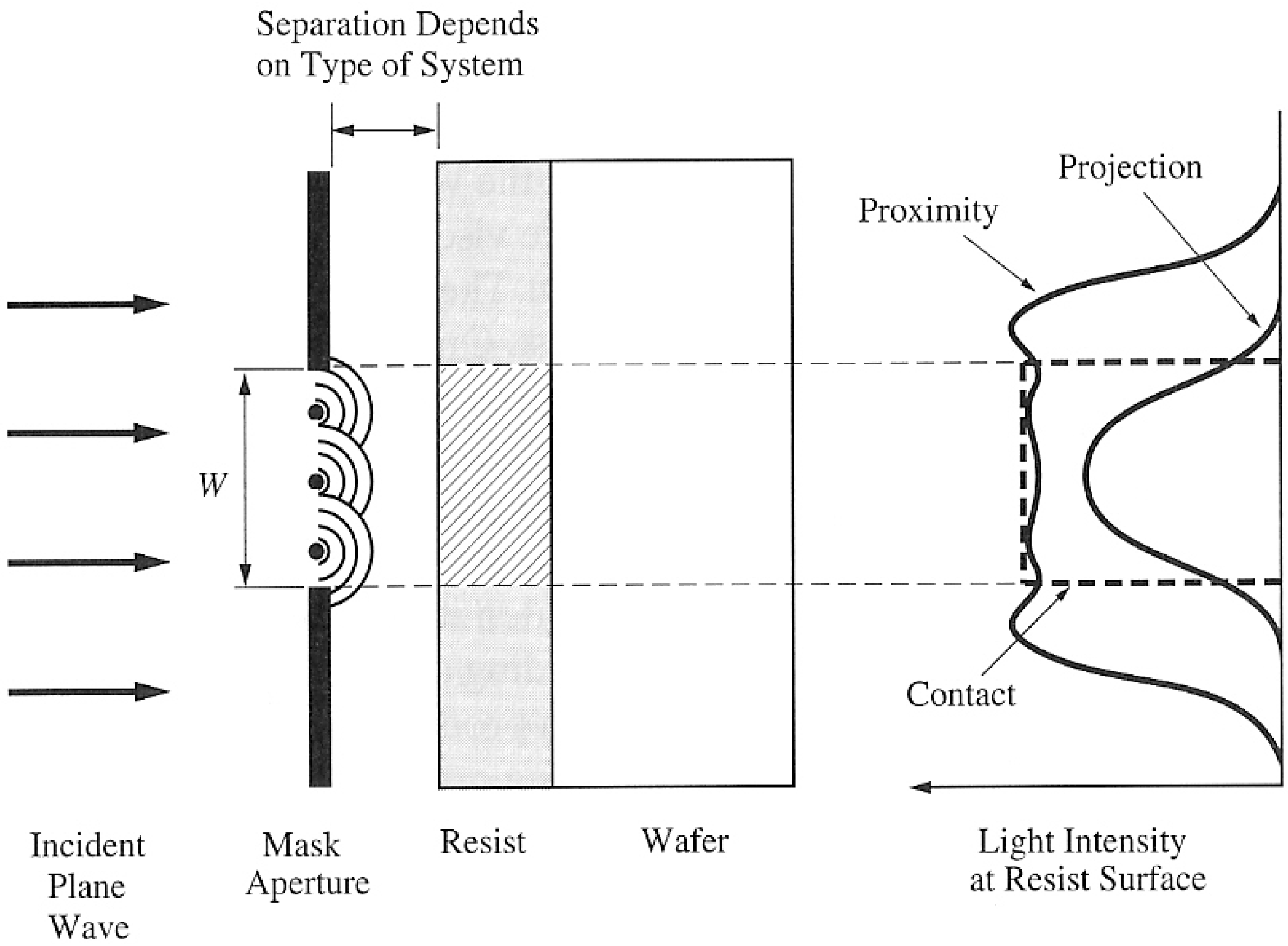
- Smaller NA, larger DOF
  - Ex: Disposable cameras with very small lenses
  - Almost everything is in focus, but resolution is bad.
  - Prefer to reduce λ than increase NA to improve resolution.
- High resolution, small DOF
  - Focus at the middle of PR layer.
  - Require surface planarization, a motive for CMP process development.



How to Improve Resolution

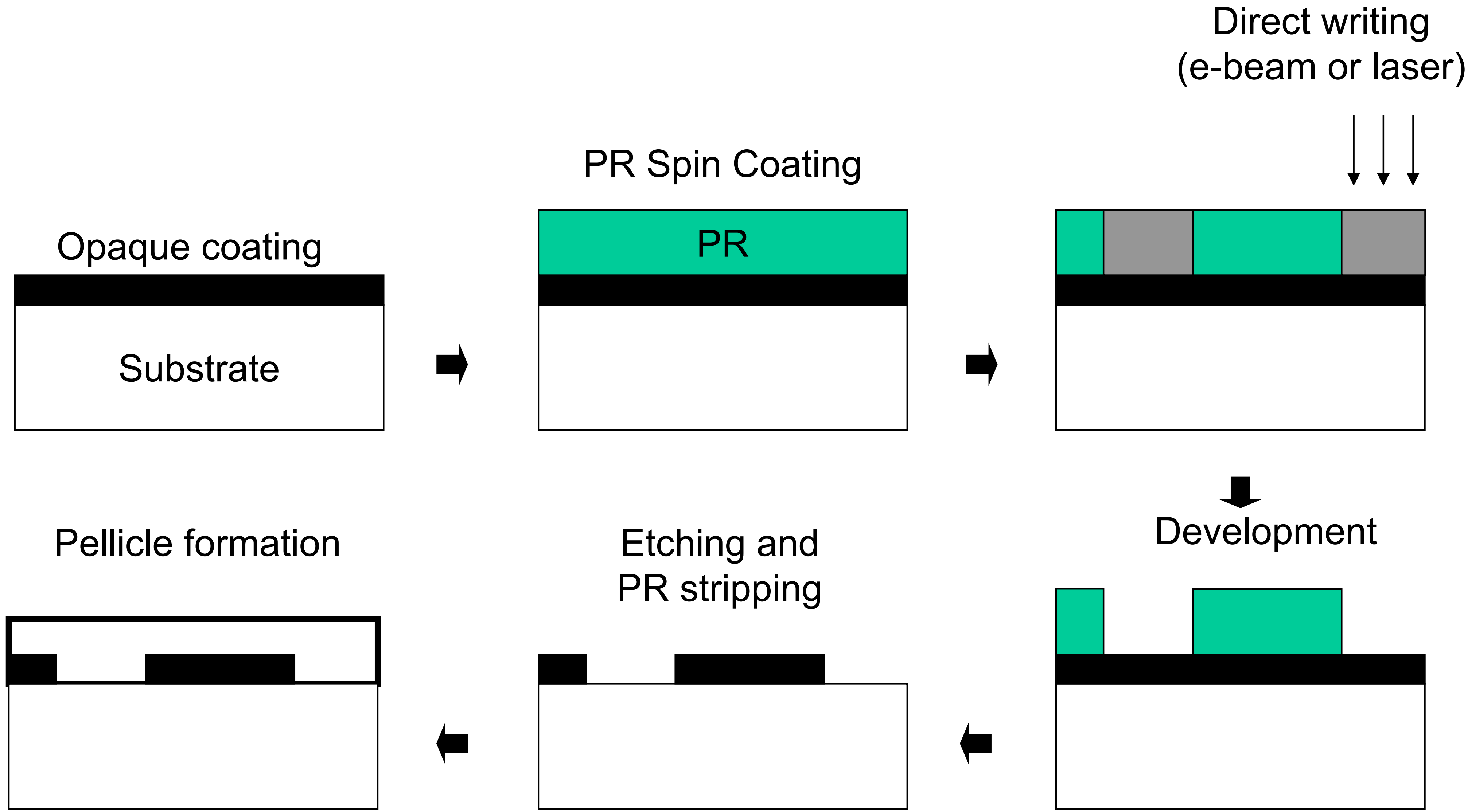
- Increase NA
  - Larger lens, could be too expensive and unpractical
  - Reduce DOF and cause fabrication difficulties
- Reduce wavelength
  - UV → DUV → EUV → BEUV → X-Ray
  - Need to develop new light source, PR, and optical systems
- Reduce K_1
  - K_1 relates to exposure tool, PR processing, mask, and other resolution enhancement techniques.
  - Ex. Phase shift mask

Resolution Comparison

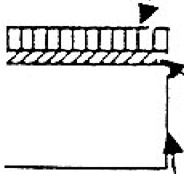


Mask

Binary Type Mask Making



Photoplate Structure



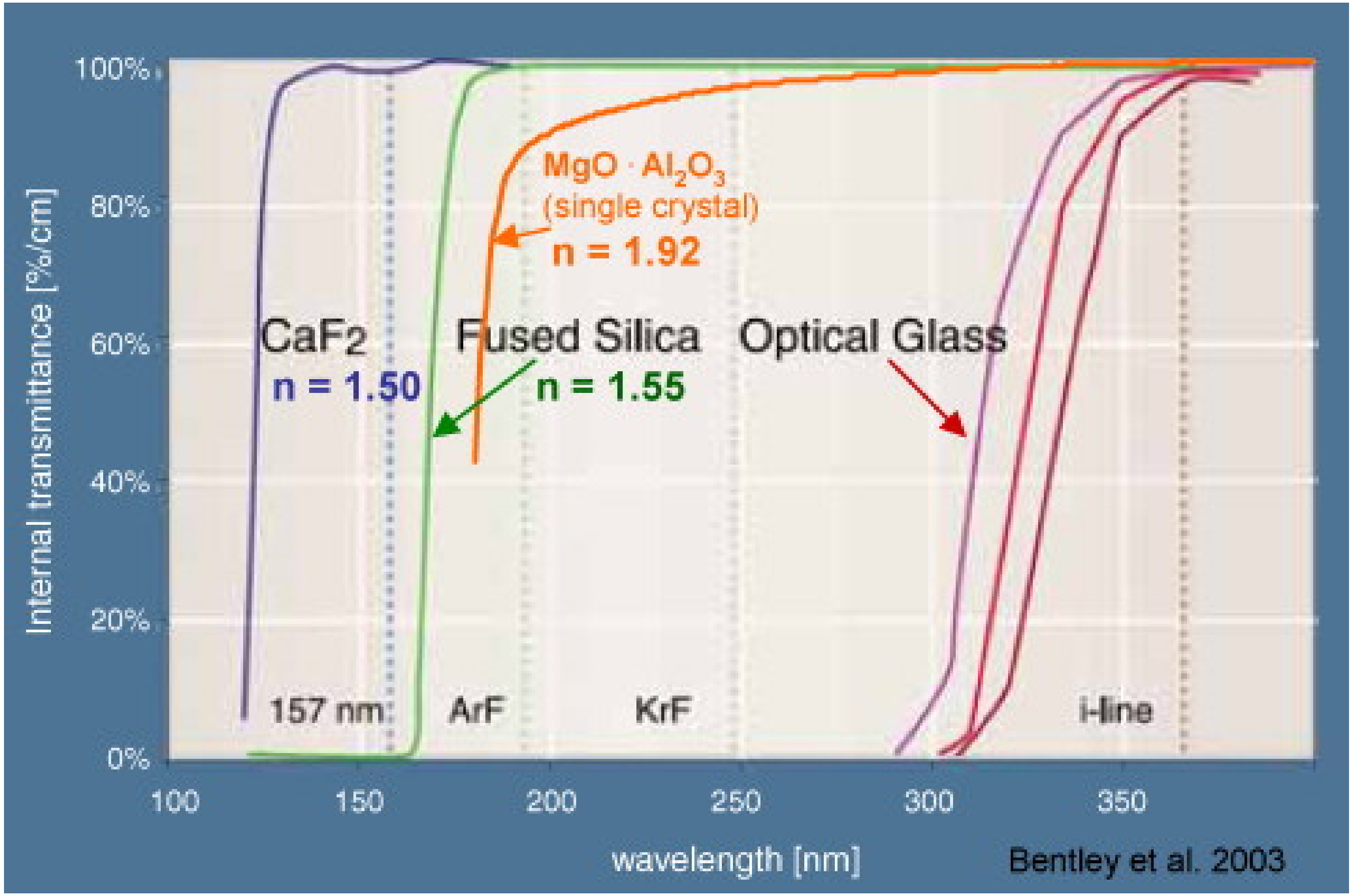
- Resist
  - Optical Resist
    - Positive
    - Negative
  - E-Beam Resist
    - Positive
    - Negative
- Chrome Layer
  - Shiny Type
  - Mid Reflective Type
  - Low Reflective Type
- Glass Substrate
  - Quartz
  - Almino Silicate (Low expansion)
  - White Crown
  - Soda Lime

Chrome Layer	Structure	O.D.	R	Film Thickness
Shiny Type	Cr	3.0	52 %	800 Å
Mid Reflective Type	CrOx / Cr	3.0	33 %	900 Å
Low Reflective Type	CrOx / Cr	3.0	13 %	1000 Å

Glass Substrate	Thermal Expansion Coef.	Transmittance (t = 0.09″) 200nm	300nm	400nm	Hardness Vickers (Kg/mm²)
Quartz	$5\times10^{-7}/°C$	90%	92%	92%	810
Almino Silicate (Low expansion)	37	0	40	92	660
White Crown	93	0	7	90	470
Soda Lime	94	0	0	90	540

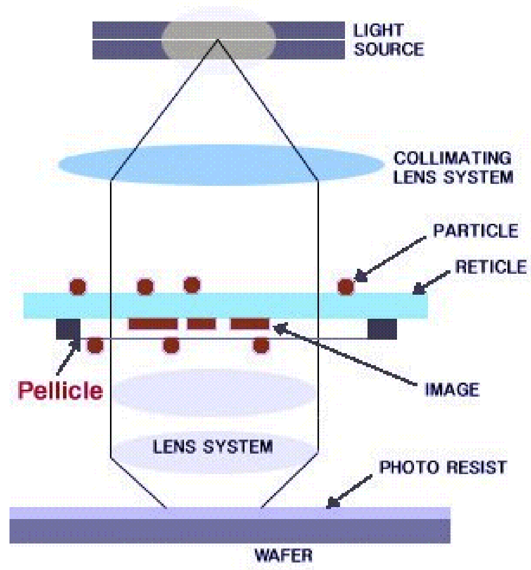
Transmission of Photo Plate

- For DUV lithography, quartz substrate needed.

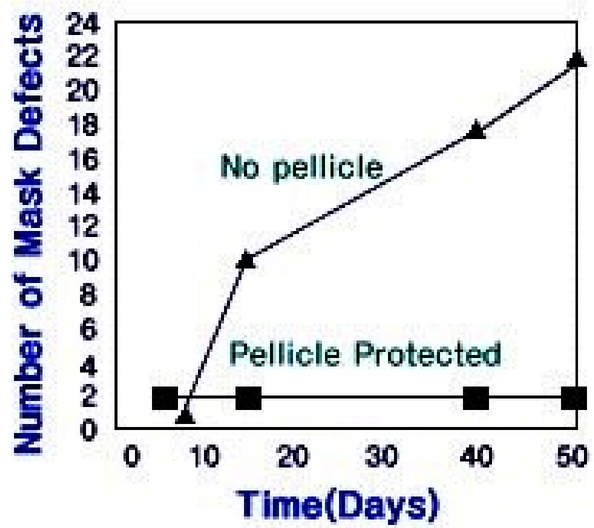


Pellicles

- Prevent the contamination of photo-masks.
- Increase the life time of photo-masks.
- Prevent the photo-mask defects from repeating handling.
- Transparent to the light source.

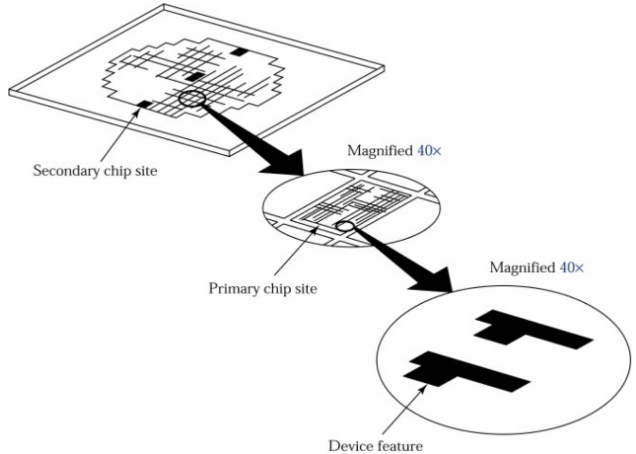


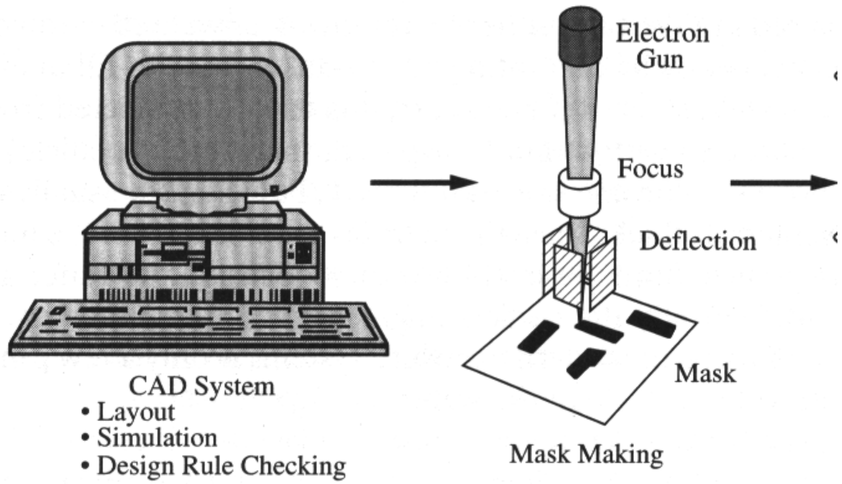
Item	G- & I-Line	DUV
Pellicle Membrane	HBP NC (Nitrocellulose)	Fluoro-Polymer
Membrane Adhesive	UV Curved Adhesive	Fluoro-Polymer Adhesive

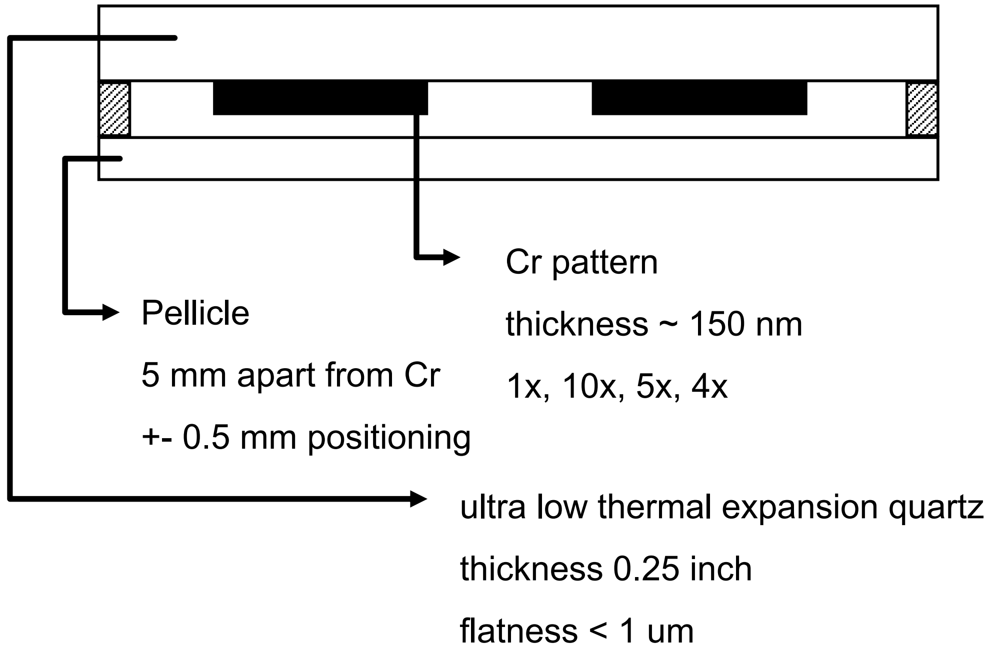


Mask Fabrication

- Pattern design
- Optical Proximity effect Correction (OPC)
- E-beam (or Laser-beam) write
- Develop and wet etching
- Pattern check
- Pellicle mount



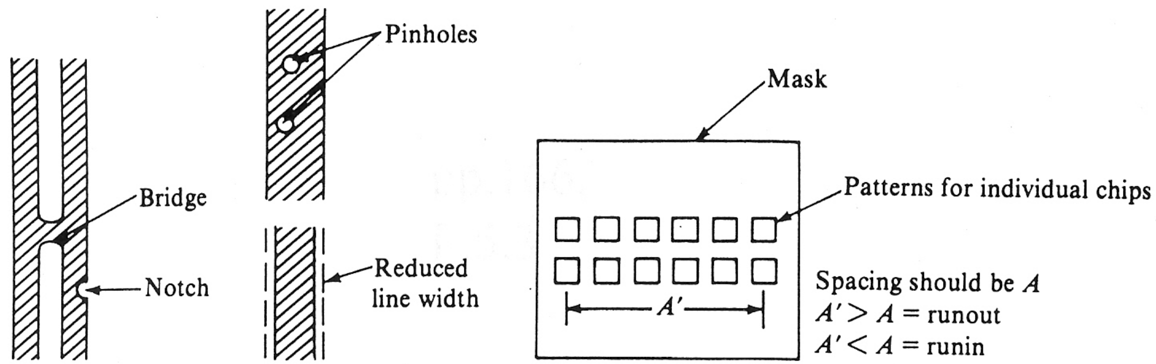


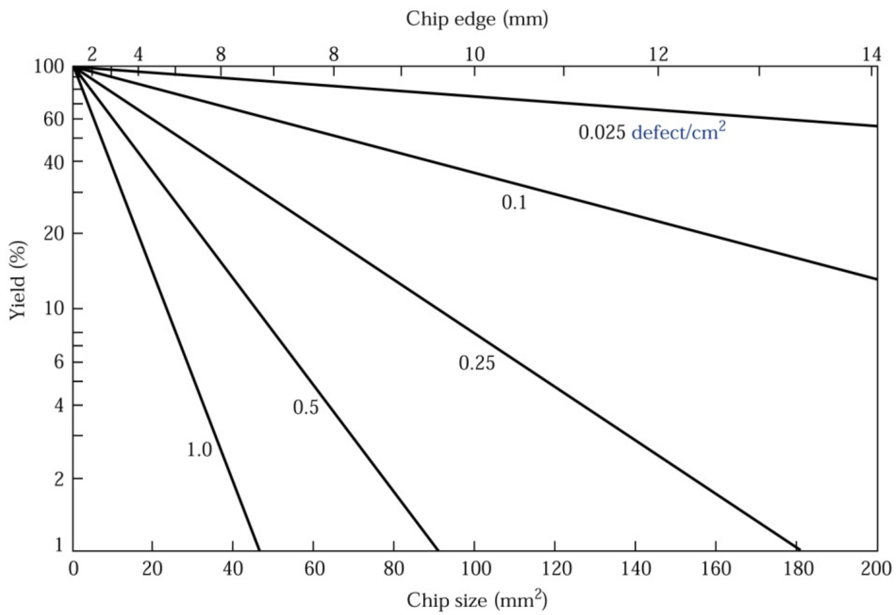


Mask Defects

$Yield \cong e^{-DA}$, where D is the defect density and A is the area of an IC chip

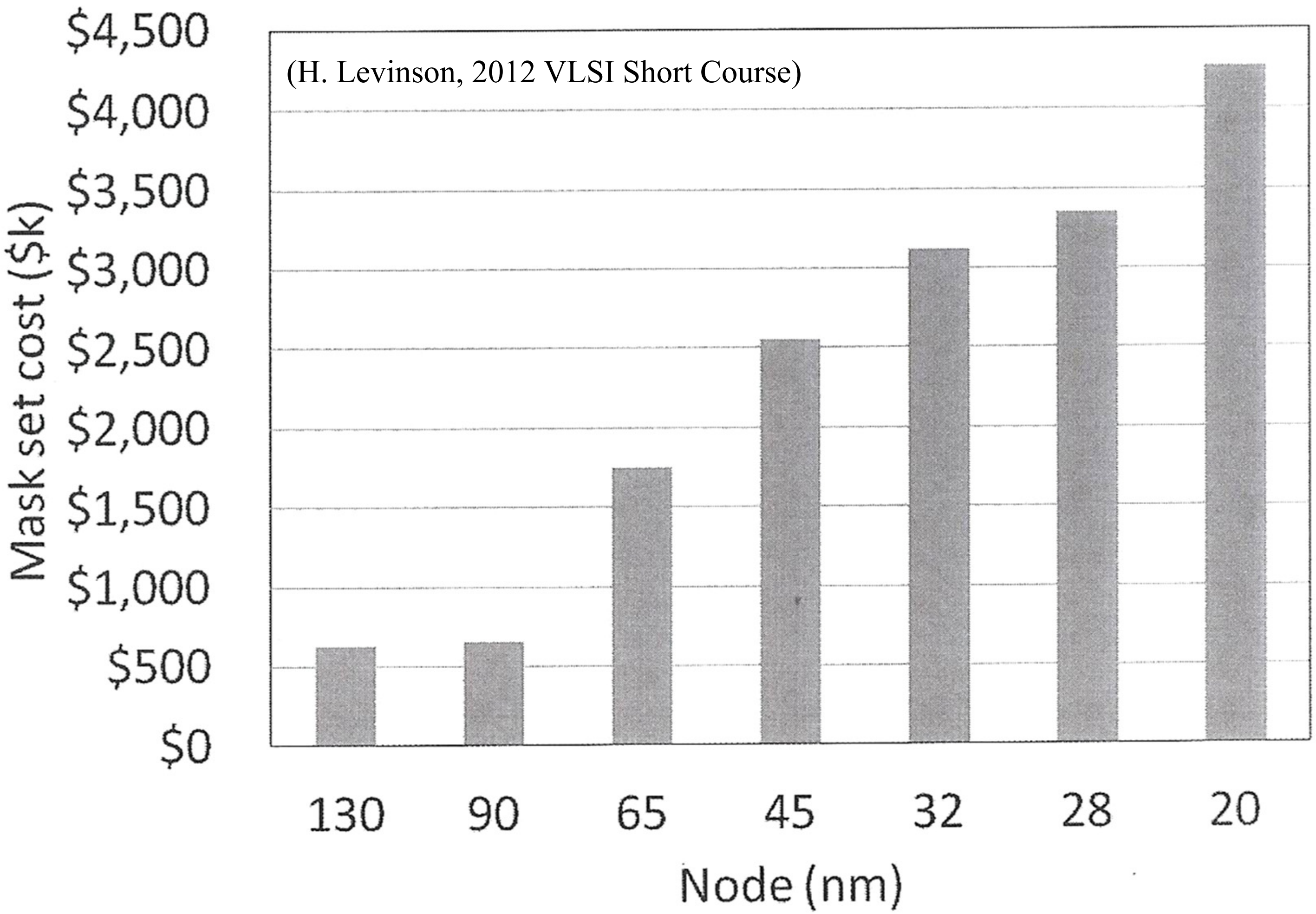
For N continuous mask step with the same defect density $Yield \cong e^{-NDA}$





Skyrocketing Mask Costs

- Mask costs at first year of technology introduction.



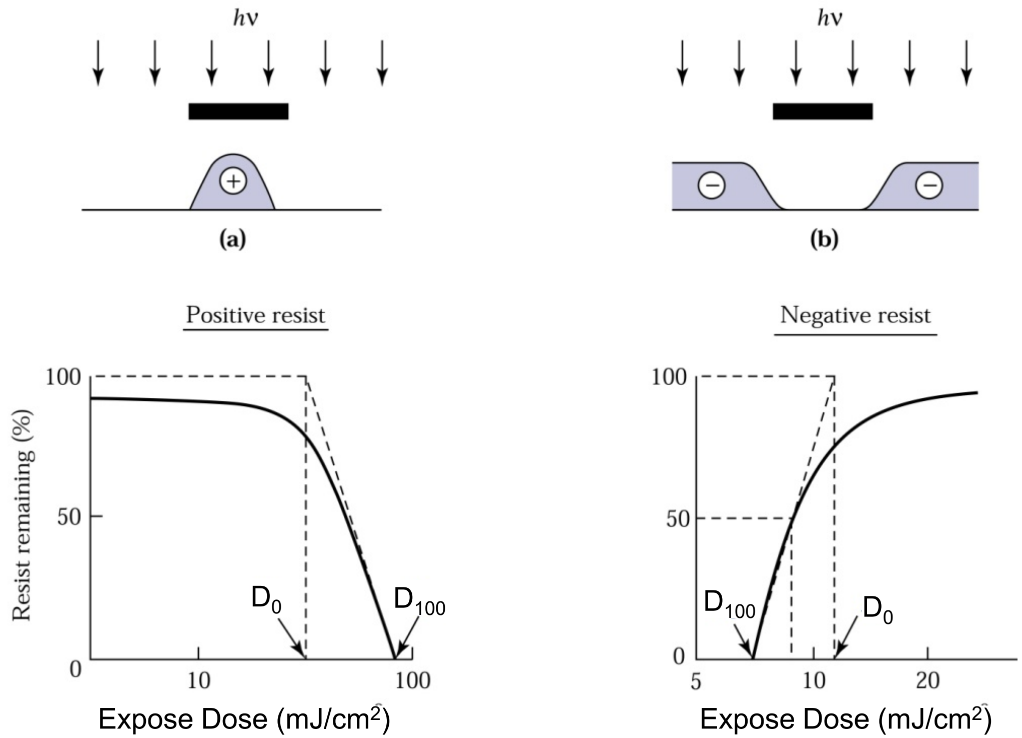
Photoresist

Photoresist (PR)

- Started with printed circuit.
- Adopted in 1950 in semiconductor industry.
- Photo sensitive material.
- Temporarily coated on wafer surface.
- Transference of designed image on it through exposure.
- Serves as a “soft” masking layer during etching.
- Very similar to the photo sensitive coating on the film for camera.
- Major composition: polymer, solvent, sensitizer, and additive.
- Positive and negative types.

Type of Photoresist

- Positive PR
  - Photo-sensitive compound, base resin, organic solvent.
  - Photo-sensitive compound absorbs radiation to change its chemical structure.
- Negative PR
  - Polymers and photo-sensitive compound
  - Photo-sensitive compound absorbs the optical energy and converts it into chemical energy to initiate a polymer linking reaction.



Contrast ratio : $\gamma \equiv ABS\left[\log\left(\frac{D_{100}}{D_0}\right)\right]^{-1}$

Requirements for PR

- High resolution
  - Thinner PR film has higher the resolution.
  - Thinner PR film, the lower the etching and ion implantation resistance.
- High sensitivity
  - Required for high throughput.
  - However, extremely high sensitivity would result in stability issue.
- High resistance to process-induced damage
  - Etch, ion implantation, thermal baking, etc.
- Good adhesion
- Wider process latitude
  - Higher tolerance to process condition change.

Components of PR

- Polymer (resin)
  - Solid organic material.
  - Transfers designed pattern to wafer surface.
  - Changes solubility due to photochemical reaction when exposed to UV light.
- Solvent
  - Dissolves polymers into liquid.
  - Allows application of thin PR layers by spinning
- Sensitizer
  - Controls and/or modifies photochemical reaction of resist during exposure.
  - Determines exposure time and intensity.
- Additive
  - Various added chemical to achieve desired process results, such as dyes to reduce reflection.

Negative PR

- Most negative PR are polyisoprene type.
- Exposed PR becomes cross-linked polymer.
- Cross-linked polymer has higher chemical etching resistance.
- Unexposed part will be dissolved in development solution.
- Disadvantages
  - Polymer absorbs the development solvent.
  - Poor resolution due to PR swelling.
  - Environmental and safety issues due to the main solvents xylene (C_8H_{10}).

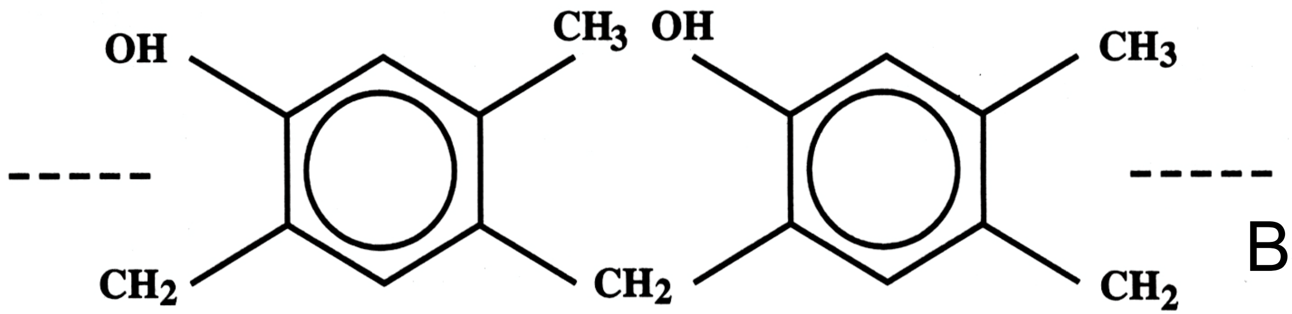
Positive PR

- Exposed part dissolves in developer solution.
- Image the same as that on the mask.
- Higher resolution.
- Commonly used in IC fabrication.
- DNQ-Novolac and Chemical Amplify Resist (CAR) types.

Conventional Positive PR

(for G- and I-line steppers)

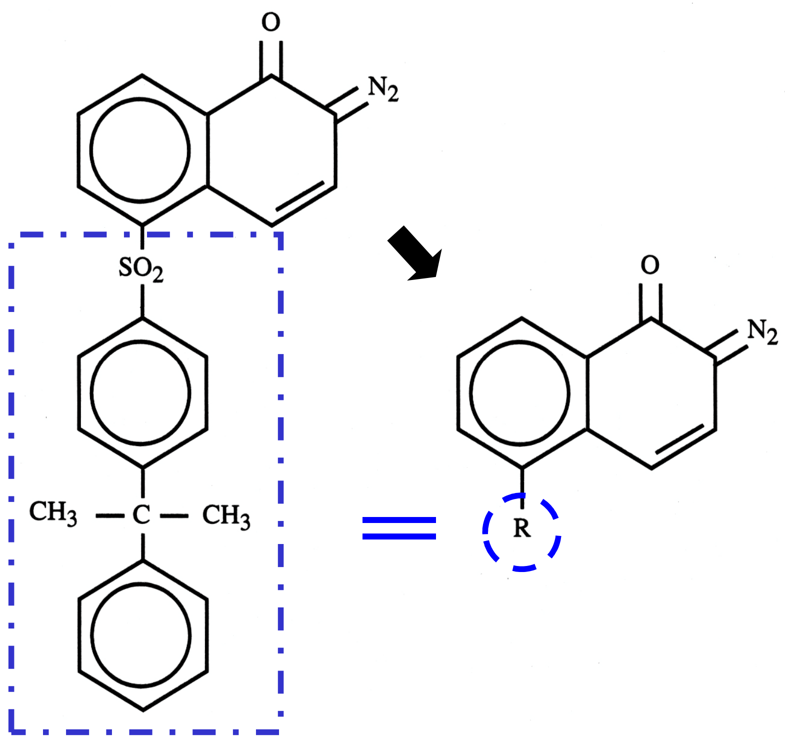
- Novolac resin polymer.
- Acetate type solvents.
- Sensitizer cross-linked within the resin.
- Energy from the light dissociates the sensitizer and breaks down the cross-links.
- Exposed resin becomes more soluble in base solution.



Basic structure of novolac

Diazonaphthoquinone/Novolac (DNQ)

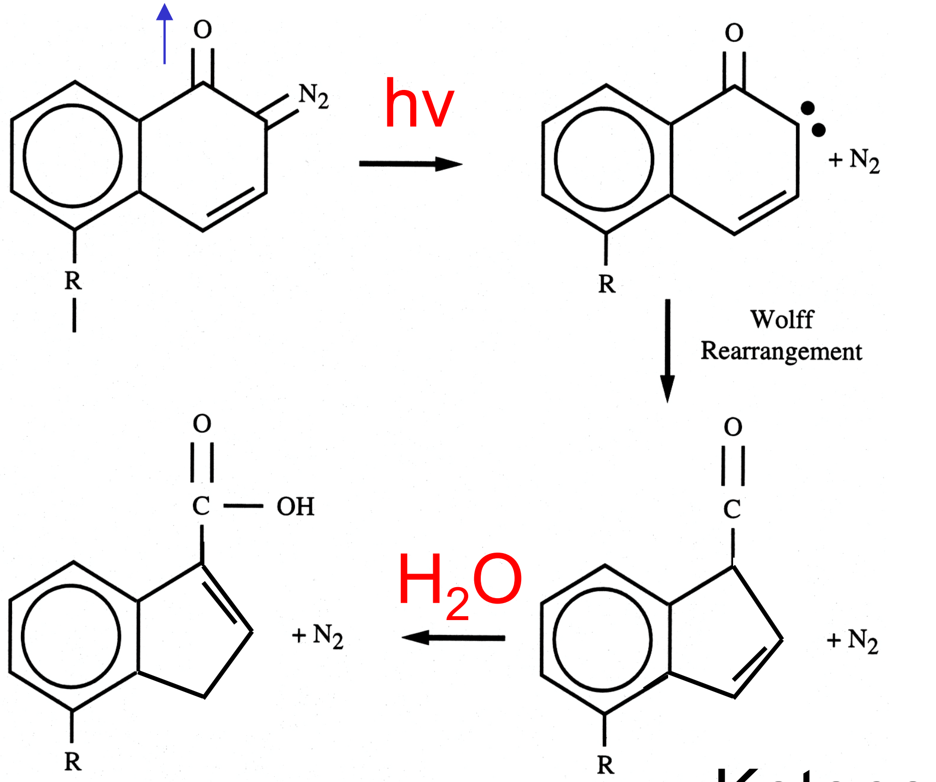
- Diazonaphthoquinone (DQ or DNQ):
  - It is a sensitizer.
  - Inhibitor, photoactive compound (PAC)
- Resin dissolution is inhibited before exposure.
- Resin dissolution is enhanced after exposure.
- Advantages:
  - Good thermal stability (200 °C or higher).
  - Non-sensitive to oxygen.
  - Reworkable, easily stripped.
  - Good plasma etch resistance.



Basic structure of **Diazonaphthoquinone (DNQ)**

DNQ Novolac Resist Function

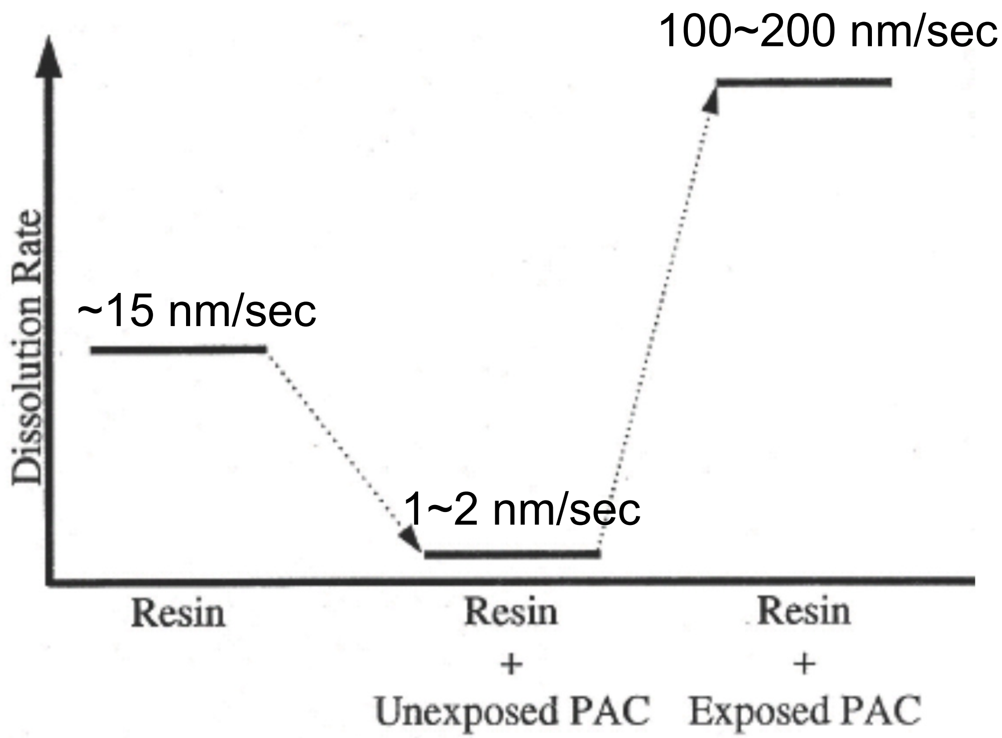
Low dissolution rate



Ketene

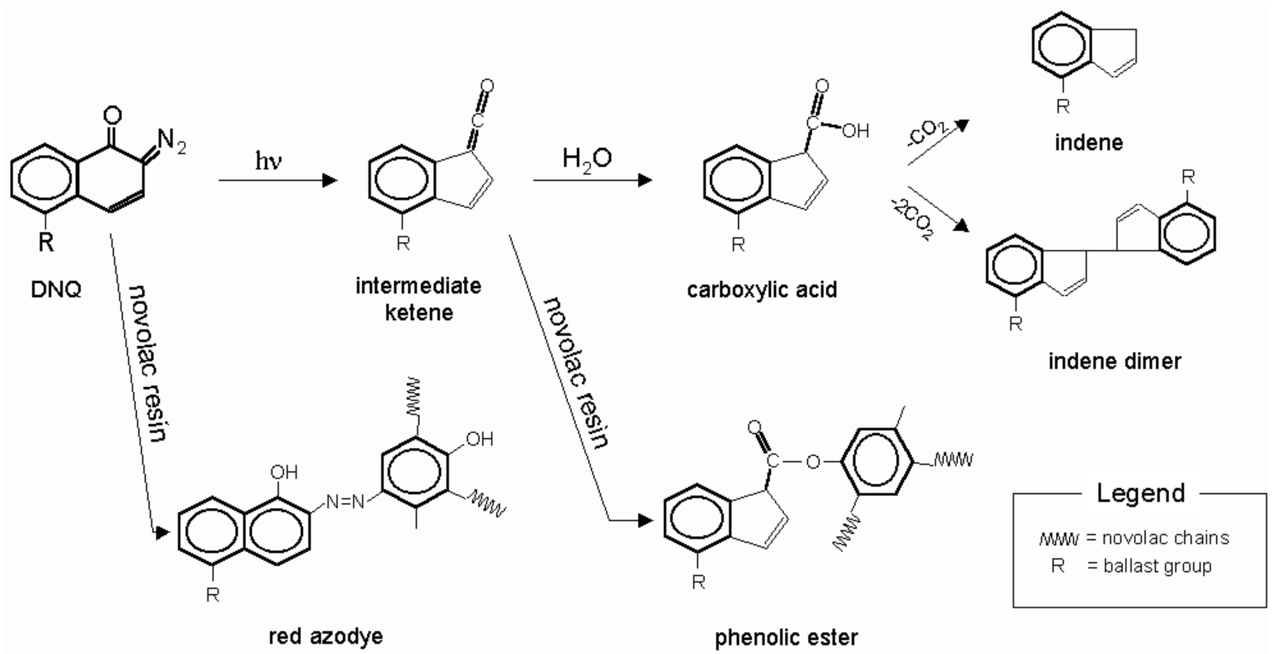
Indene carboxylic acid (ICA)

High dissolution rate



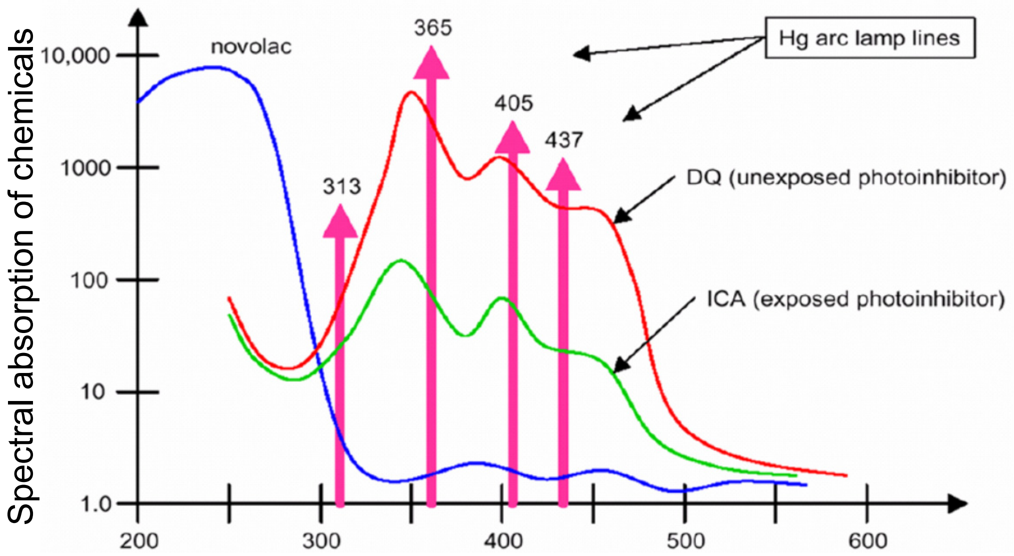
Side Reactions of DNQ Novolak Resist

- In general, DNQ-novolac resists are designed such that the dominant photolysis product is the indene carboxylic acid and other side reactions are suppressed.
    - DNQ-novolac resists are in fact slightly hydroscopic, and a low concentration of water is naturally present in resist films processed in moderately humid environments.
    - If DNQ-novolac resists are processed in very dry environments, the slower reaction of the ketene to form the phenol ester with the novolac resin can be promoted.



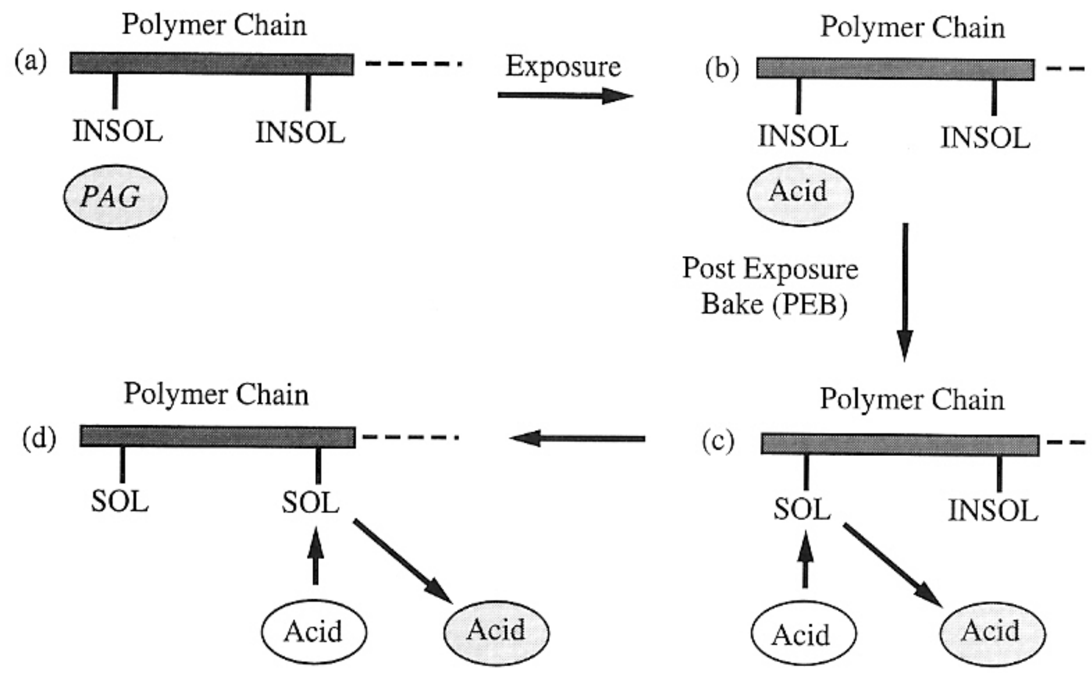
PR Issues for DUV Lithography

- Bleaching effect
  - With increasing exposure to radiation, the absorption bands of these molecules disappear as the compounds are converted to indene-carboxylic acid photoproducts.
  - This decrease in absorbance during exposure allows light to propagate to the bottom of thick and strongly absorbing resist films as the exposure proceeds, thus allowing for complete reaction of the DNQ throughout the thickness of a resist film.
- Novolac strongly absorbs DUV, making it not appropriate for DUV lithography application.
- Need different kind of PR with high sensitivity.



DUV Photo-Resist

- Chemically amplified (CA) resist.
  - PAG : photo-acid generator
  - INSOL : insoluble portion
  - SOL : soluble portion
- Reaction process
  - Light generates acid molecules from PAGs.
  - Acid molecules react with INSOLs during PEB.
  - Acid molecules are regenerated after each chemical reaction.



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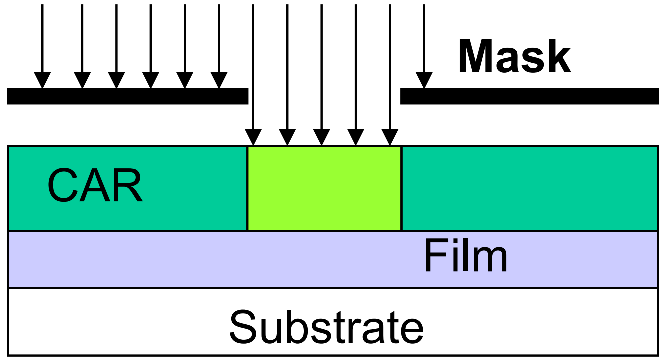
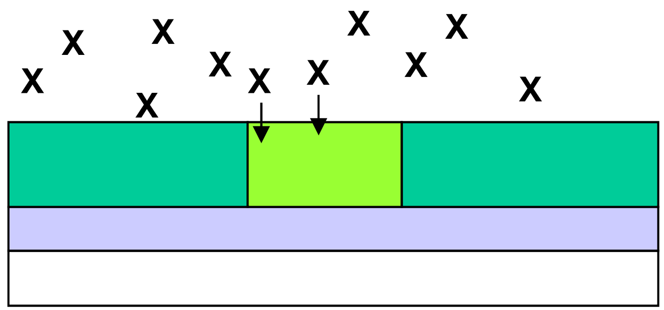
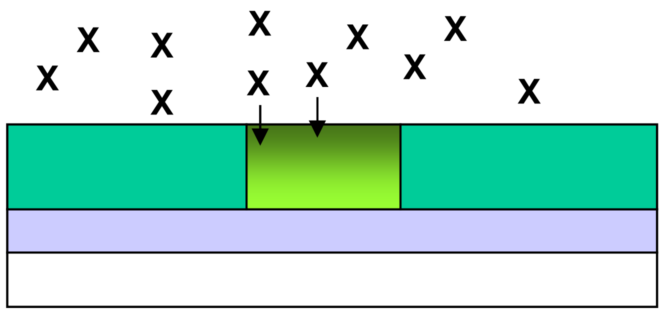
T-Topping in CAR

- Environment control
  - Due to contamination by amines, ammonia, amides (HMDS, cleaner ---) presenting in the atmosphere.
  - Tight atmosphere control needed in the working environment (i.e., track with mini-environment capability).

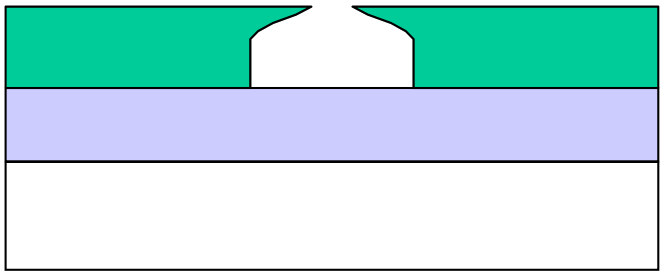




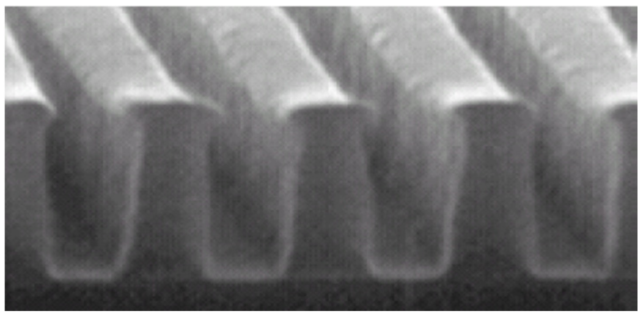
Base in atmosphere absorbs onto the PR surface and diffuse into the film



During PEB, base-acid neutralization occurs, less acid catalyst available for deprotection at air/PR interface



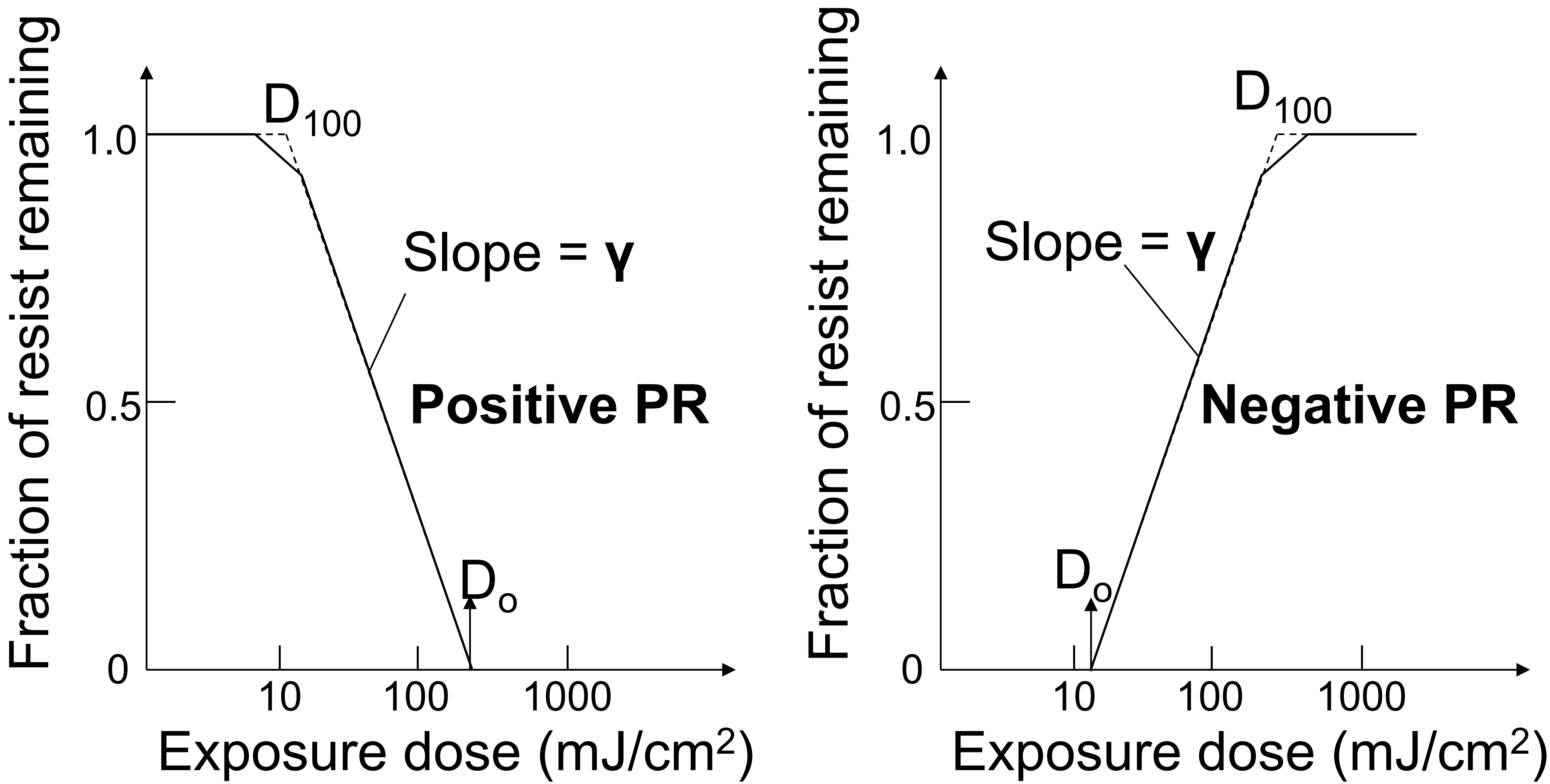
During development, surface devlop slower, resulting in “T-top”.



X: contaminants

Contrast Curves for Resist

- Contrast γ = slope of the transition line =ABS $(\log(D_{100}/D_0))^{-1}$
- Exposure dose = light intensity $\times$ exposure time



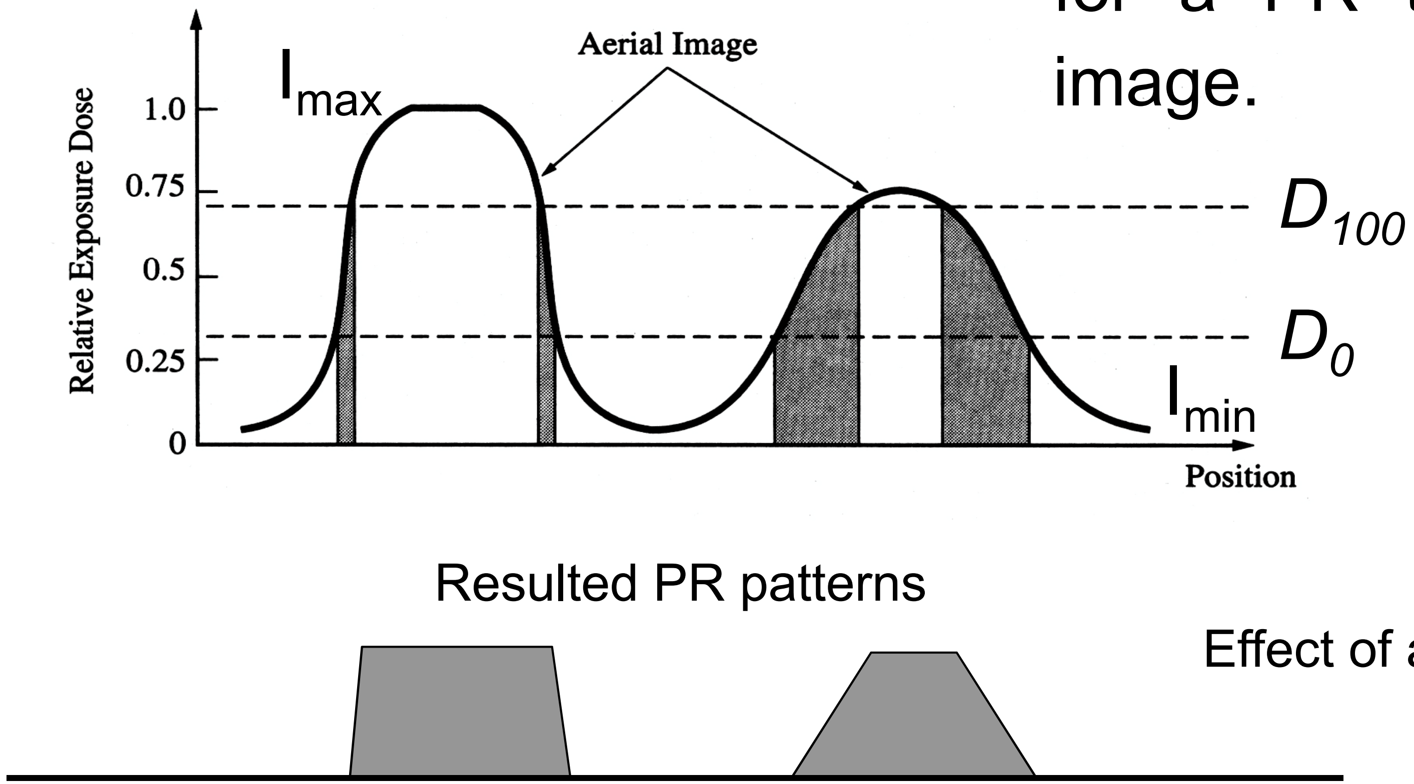
Contrast (γ) of PR

- The higher the contrast, the sharper the line edge.
- Contrast depends on many factors including soft bake, wavelength of exposing radiation, post exposure bake, development, and reflectivity of the wafer.
- For DNQ, typical D100 ~ 100 mJ/cm^2, $\gamma \sim 2 - 4$.
- For CAR, typical D100 ~ 20 - 40 mJ/cm^2, $\gamma \sim 5 - 10$.

Critical MTF (CMTF) for PR

$$CMTF = \frac{D_{100} - D_0}{D_{100} + D_0} = \frac{10^{1/\gamma} - 1}{10^{1/\gamma} + 1}.$$

- For DNQ, typical CMTF: ~0.4
- For CAR, typical CMTF: 0.1~ 0.2.
- CMTF must be smaller than MTF for a PR to resolve the aerial image.

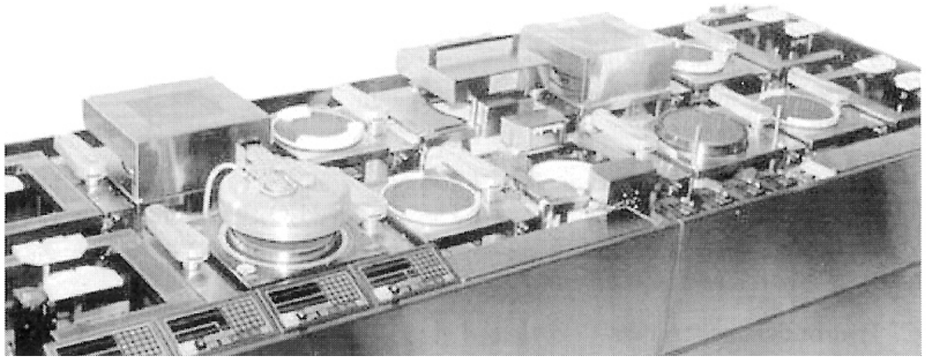


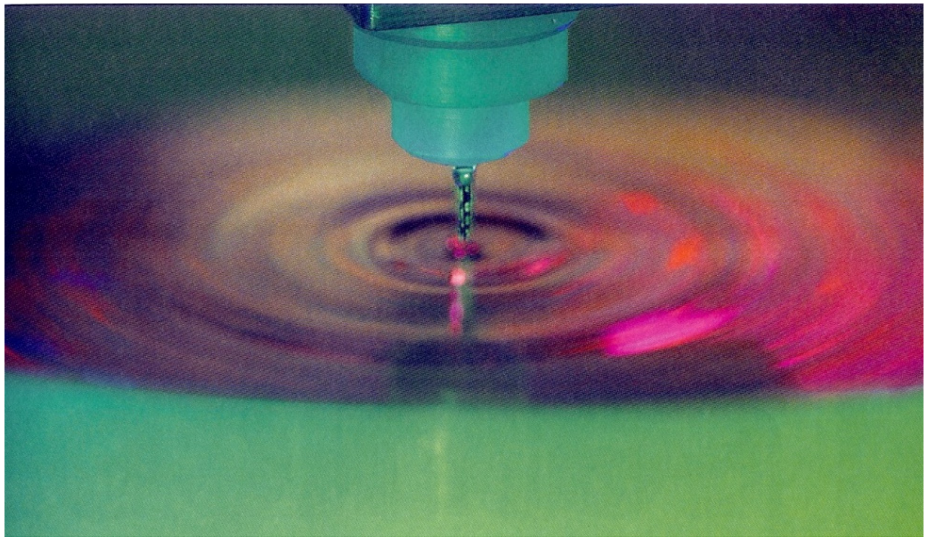
Effect of aerial image

PR Process

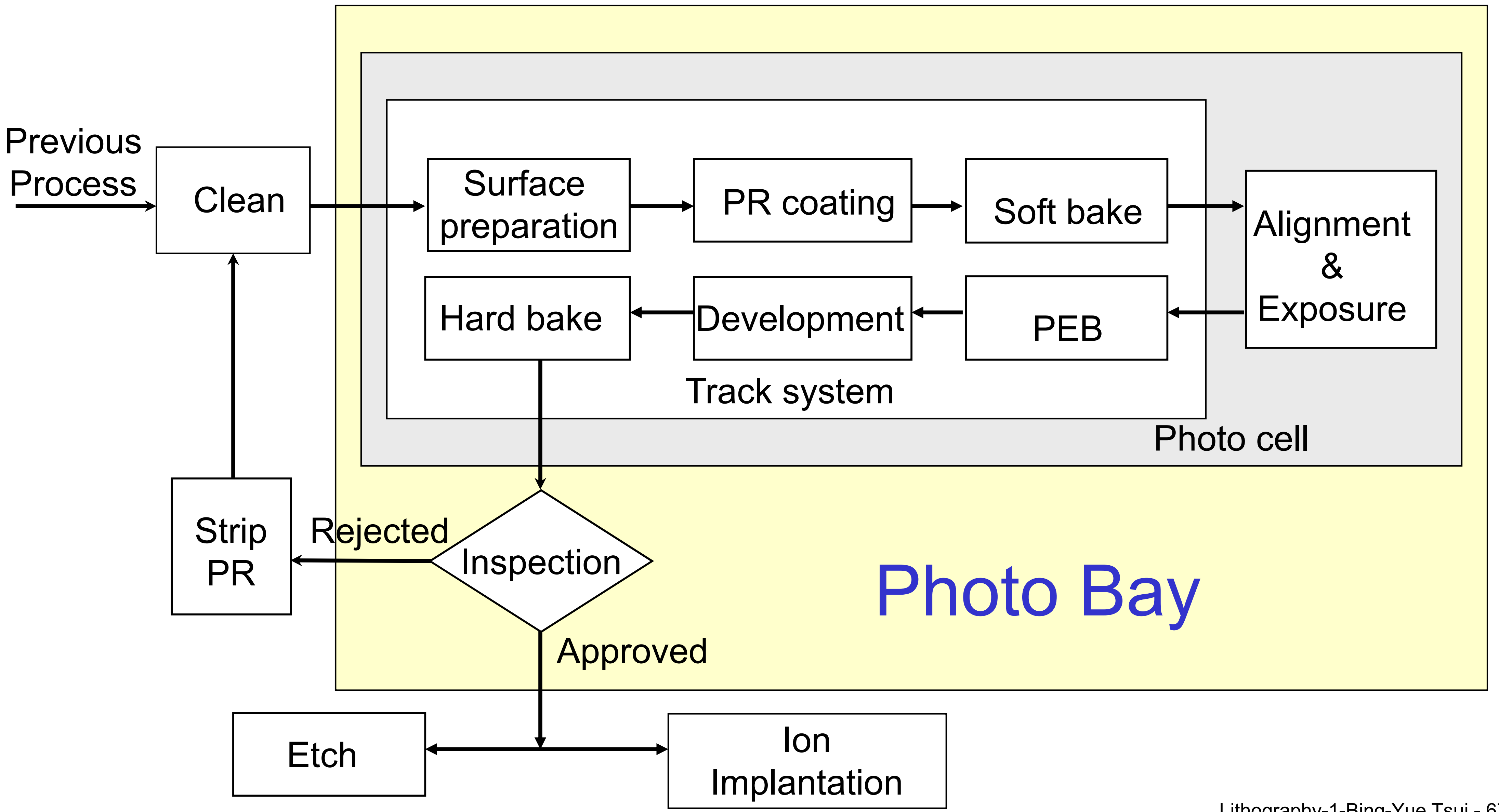
PR Process

- Pre-baking plate
- Adhesion promoter vapor deposition or spin coater (HMDS)
- PR spin coater (close cup)
  - 3000-6000 RPM for ~ 1 μm
  - Edge bead remove
- Soft baking plate
- Alignment and Exposure
- Post exposure baking (PEB) plate
- Develop spinner
- Hard bake plate





Schematic Lithography Process Flow

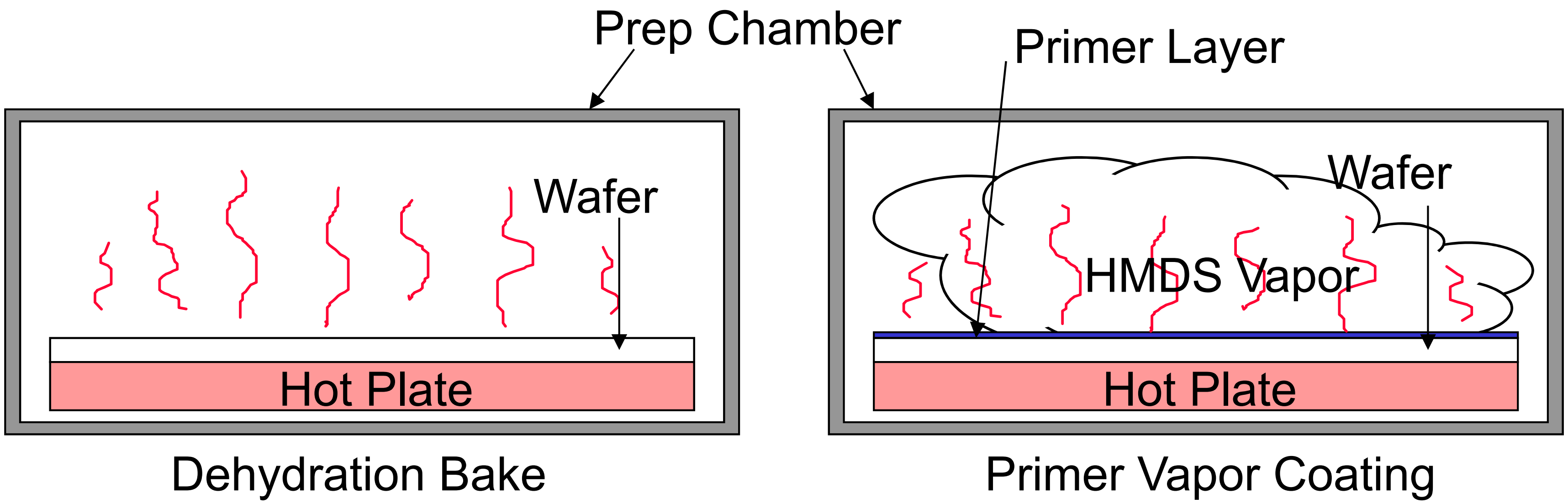


Wafer Clean and Prebake

- Wafer clean
  - Remove particulates
  - Reduce pinholes and other defects
  - Improve PR adhesion
- Prebake
  - Dehydration bake
  - Remove moisture from wafer surface
  - Promote adhesion between PR and surface
  - Usually around 100 °C
  - Integration with primer coating

Primer (HMDS) Coating

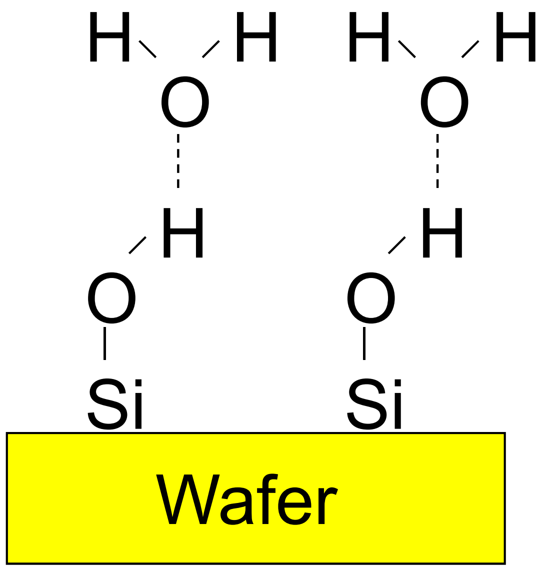
- Promotes adhesion of PR to wafer surface
- Widely used: Hexamethyldisilazane (HMDS)
- HMDS vapor coating prior to PR spin coating
- Usually performed *in situ* with pre-bake
- Chill plate to cool down wafer before PR coating



HMDS Treatment

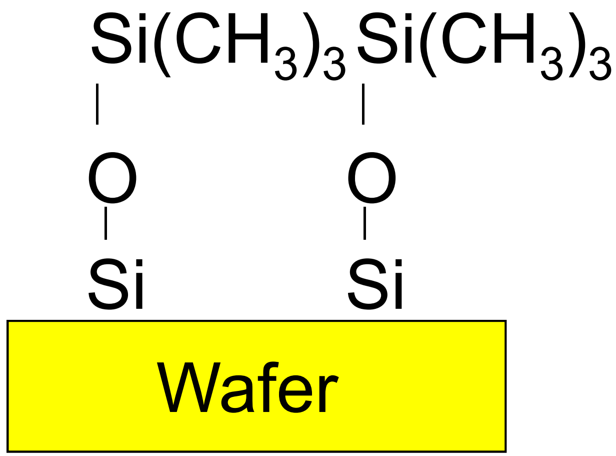
- Used to enhance PR surface adhesion
- HMDS: $(CH_3)_3SiNHSi(CH_3)_3$

After wafer cleaning



Hydrophilic surface

After HMDS treatment



Hydrophobic surface

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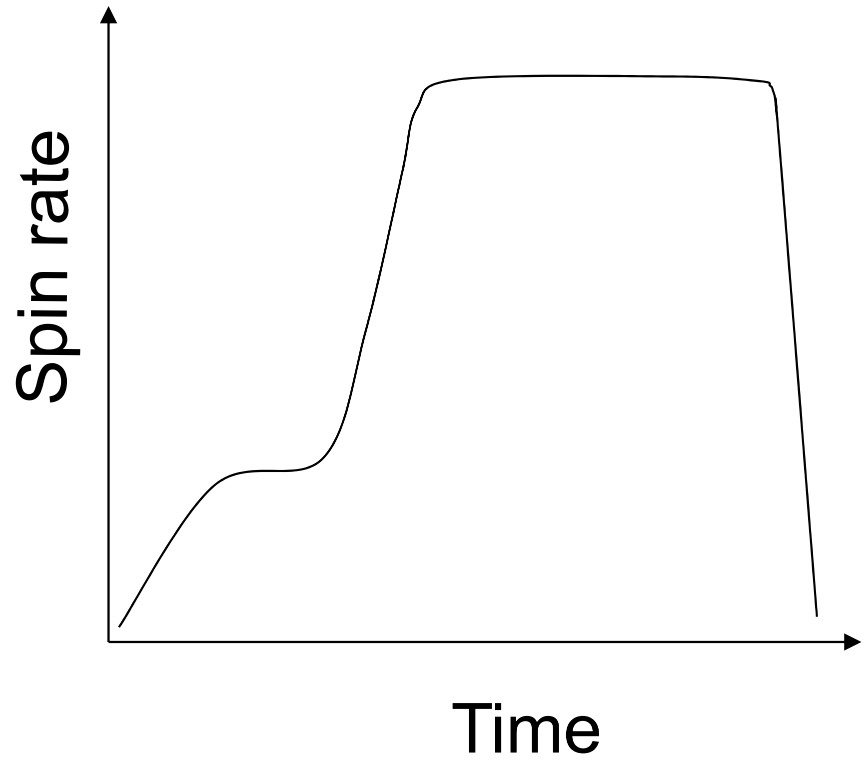
Spin Coating

➢ Main steps

- Wafer sits on a vacuum chuck
- Rotating at certain speed
- Liquid PR applied at the center of the wafer
- PR spreads by centrifugal force
- Evenly coat on wafer surface

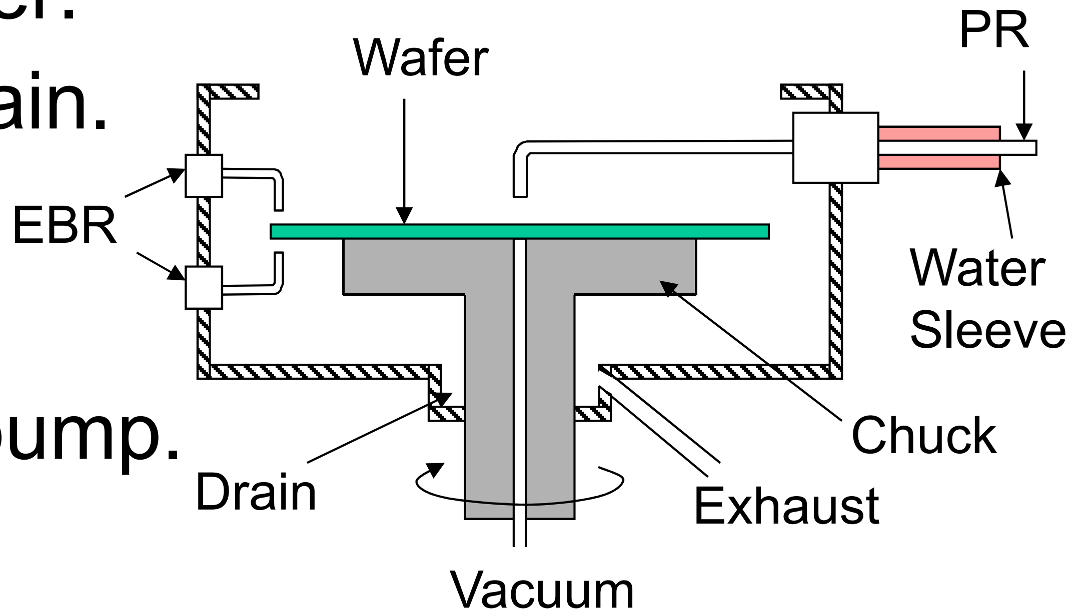
➢ Spin rate

- Drops PR on spinning wafer surface
- Wafer held on a vacuum chuck
- Slow spin ~ 500 rpm as PR is spreading
- After PR dropping, ramp up to 3000 ~ 7000 rpm to flatten the coated PR.

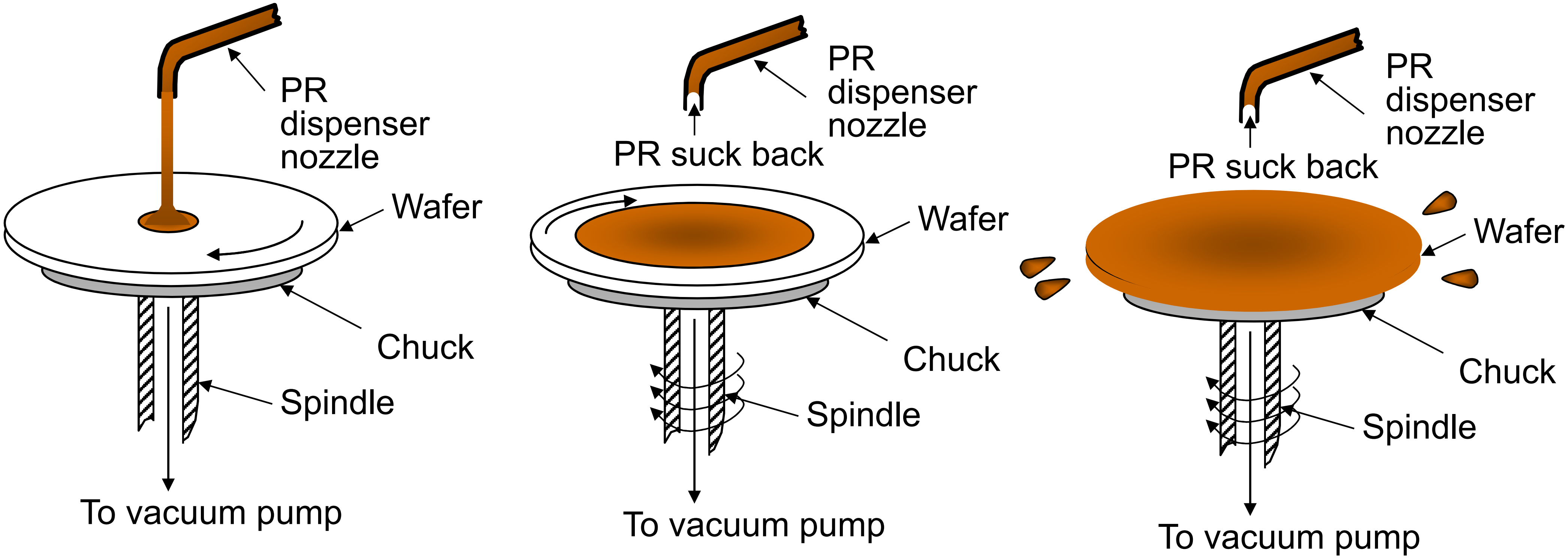


Spin Coater

- Automatic wafer loading system from the robot of a track system.
- Vacuum chuck to hold wafer.
- Resist containment and drain.
- Exhaust features.
- Controllable spin motor.
- Dispenser and dispenser pump.
- Edge bead removal (EBR)

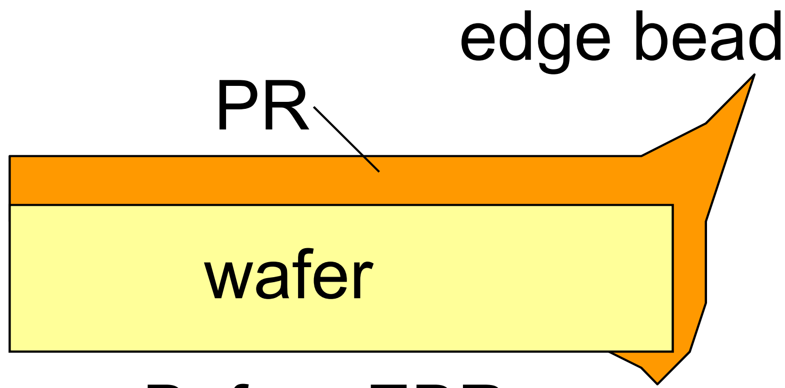


PR Applying

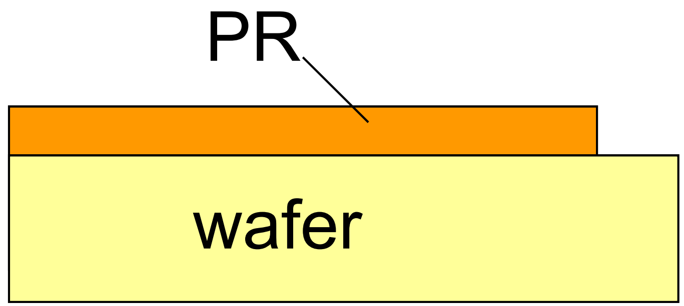

PR dispenser nozzle
Wafer
Chuck
Spindle
To vacuum pump
PR dispenser nozzle
PR suck back
Wafer
Chuck
Spindle
To vacuum pump
PR dispenser nozzle
PR suck back
Wafer
Chuck
Spindle
To vacuum pump

Edge Bead Removal (EBR)

- PR spreads to the edge and backside.
- Edge and backside PR would contaminate the robot arms that transfer the wafer or damage the wafer holder during processing.
- PR could also flake off during mechanical handling and cause particles.
- Methods:
  - Front and back chemical EBR;
  - Front optical EBR.

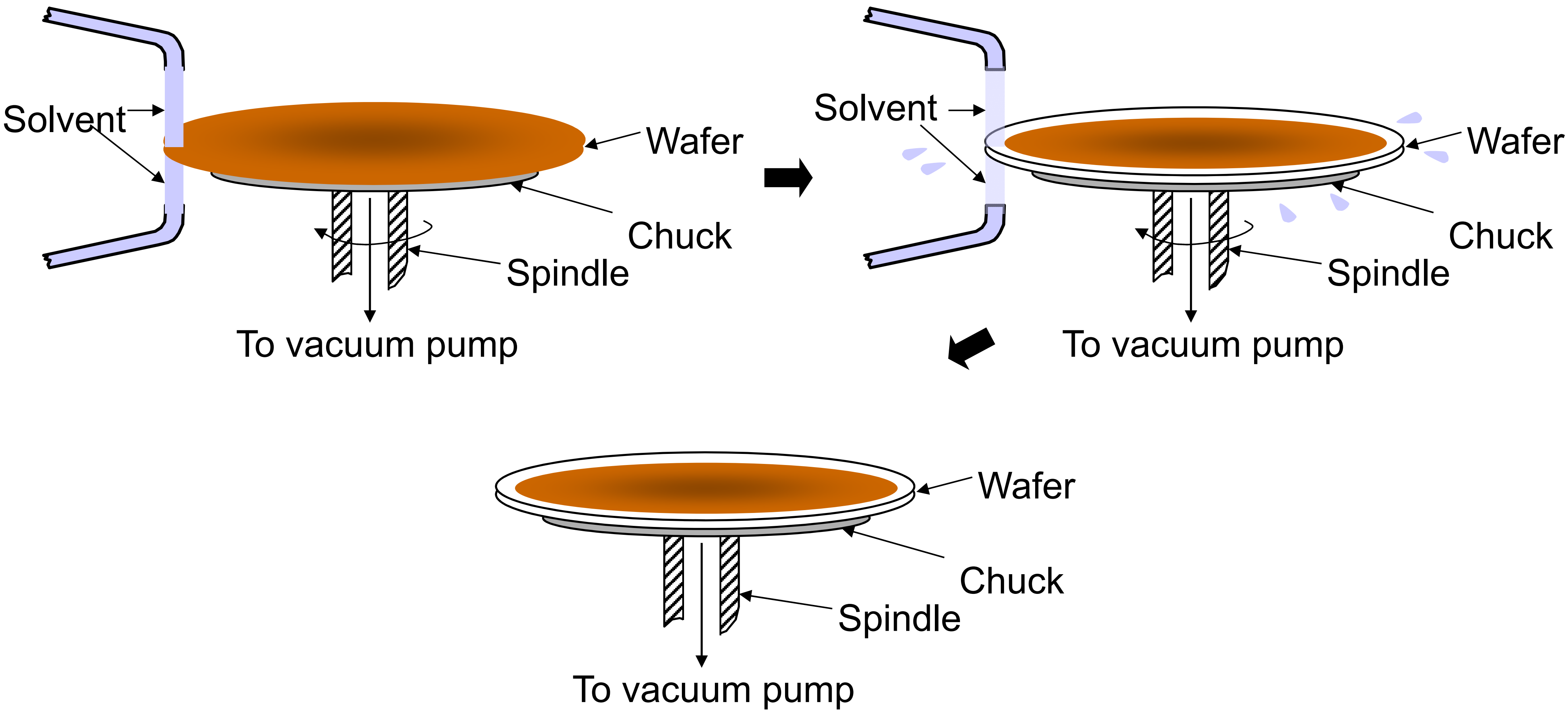


Before EBR



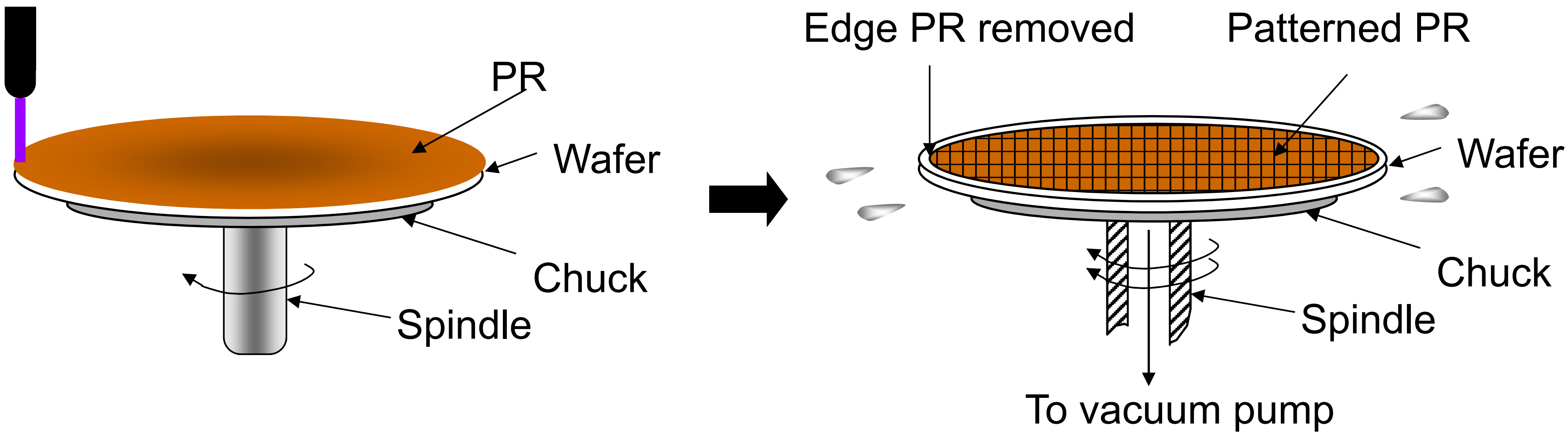
After EBR

Front and Back Chemical EBR



Optical Edge Bead Removal

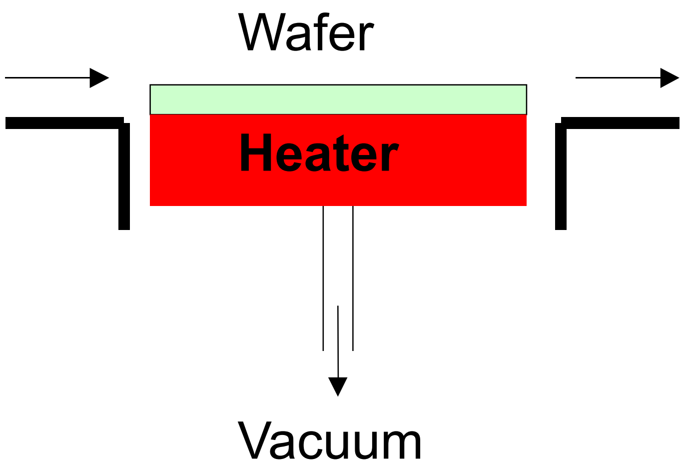
- Perform after alignment and exposure
- Wafer edge expose (WEE)
- Exposed PR at edge dissolves during development



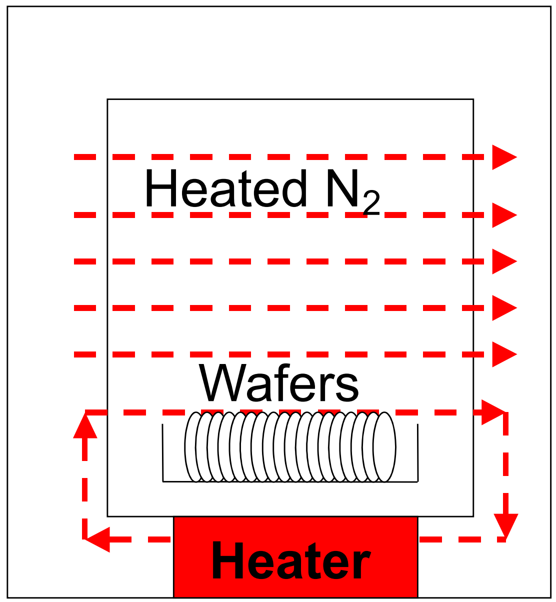
Soft Bake

- Evaporating most of solvents in PR.
- Solvents help make a thin and flattened PR, but they also absorb radiation and affect adhesion.
- Soft baking time and temperature are determined by the matrix evaluations.
- Over bake: polymerized, less photo-sensitivity.
- Under bake: affect adhesion and exposure.
- Types of baking system:
  - Hot plates (dominant)
  - Convection oven
  - Infrared oven
  - Microwave oven.

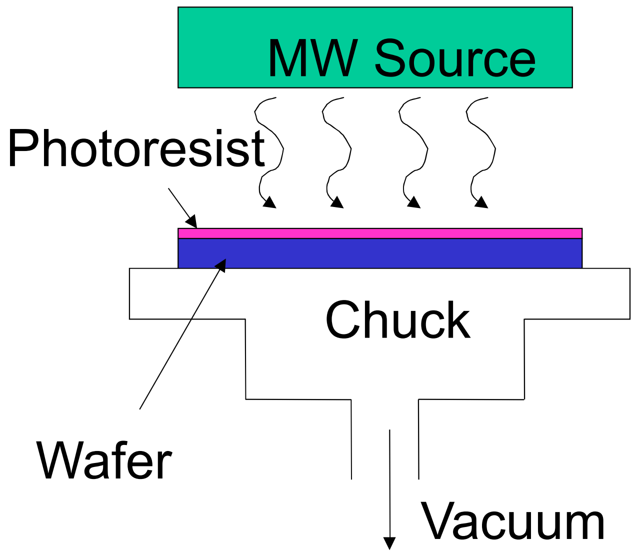
Baking Systems



Hot plate



Convection oven



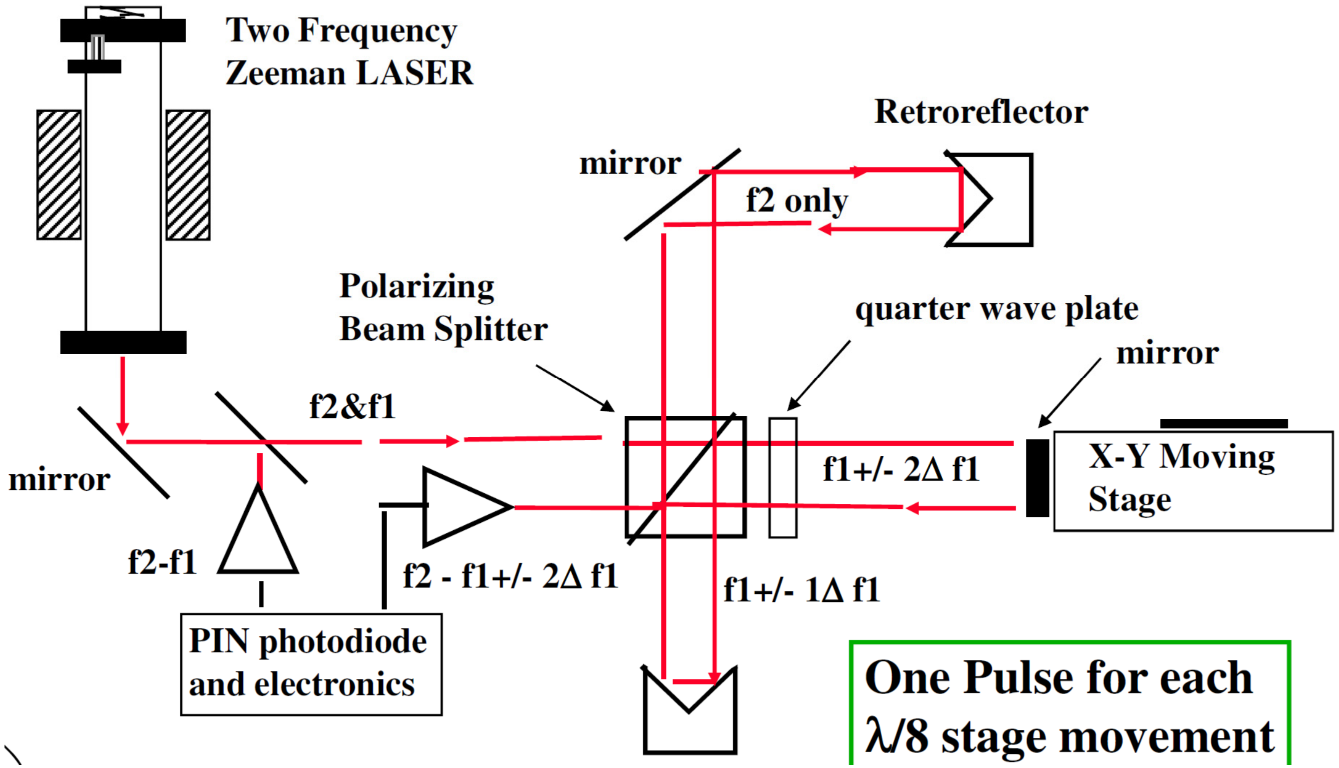
Microwave oven

Overlay (Alignment)

- Overlay (alignment) is as important as resolution in lithography. Modern CMOS integrated circuits have over 30 layers to be aligned.
- Strategy for alignment must be devised as part of the process design and chip layout. The strategy may include
  - Zero level wafer alignment marks
  - Zero and first level combined wafer alignment marks
  - Clear out exposures over wafer alignment marks for some levels
  - Use of street alignment marks
- Before alignment, wafers must be cooled down to ambient temperature for alignment precision.
  - Silicon thermal expansion coefficient: 2.5×10^{-6} /°C
  - For 8 inch (200 mm) wafer, 1 °C change causes 500 nm difference in diameter.

Stage Position

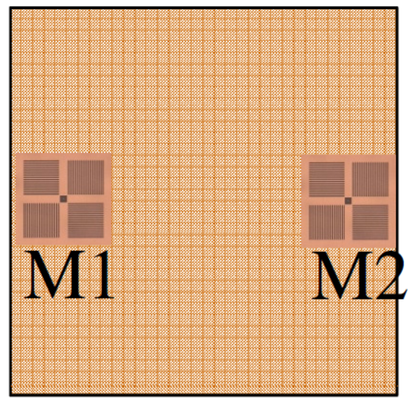
- The stage position is measured using a laser interferometer that has a fundamental accuracy of $\lambda/8$.
  - The interferometer measures the position of the mirrors on the x and y stages while the wafer is some distance from the mirrors on the stage.



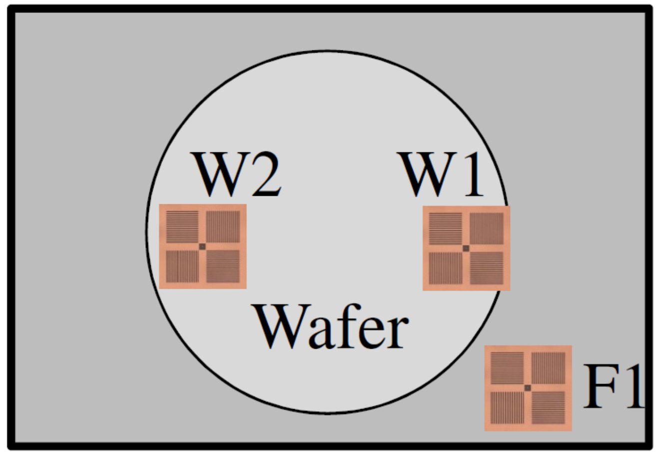
Type of Alignment

- Fiducial
  - Reticle alignment when there are no alignment marks on the wafer (zero or 1st level)
  - F1 aligned to M1 and F1 to M2
- Global
  - After both reticle and wafer exchange
  - F1 aligned to M1, W1 to M2, and W2 to M1
- Wafer
  - After wafer exchange W1 aligned to M1 and W2 to M1
- Mask
  - After mask exchange W1 aligned to M1 and W1 to M2

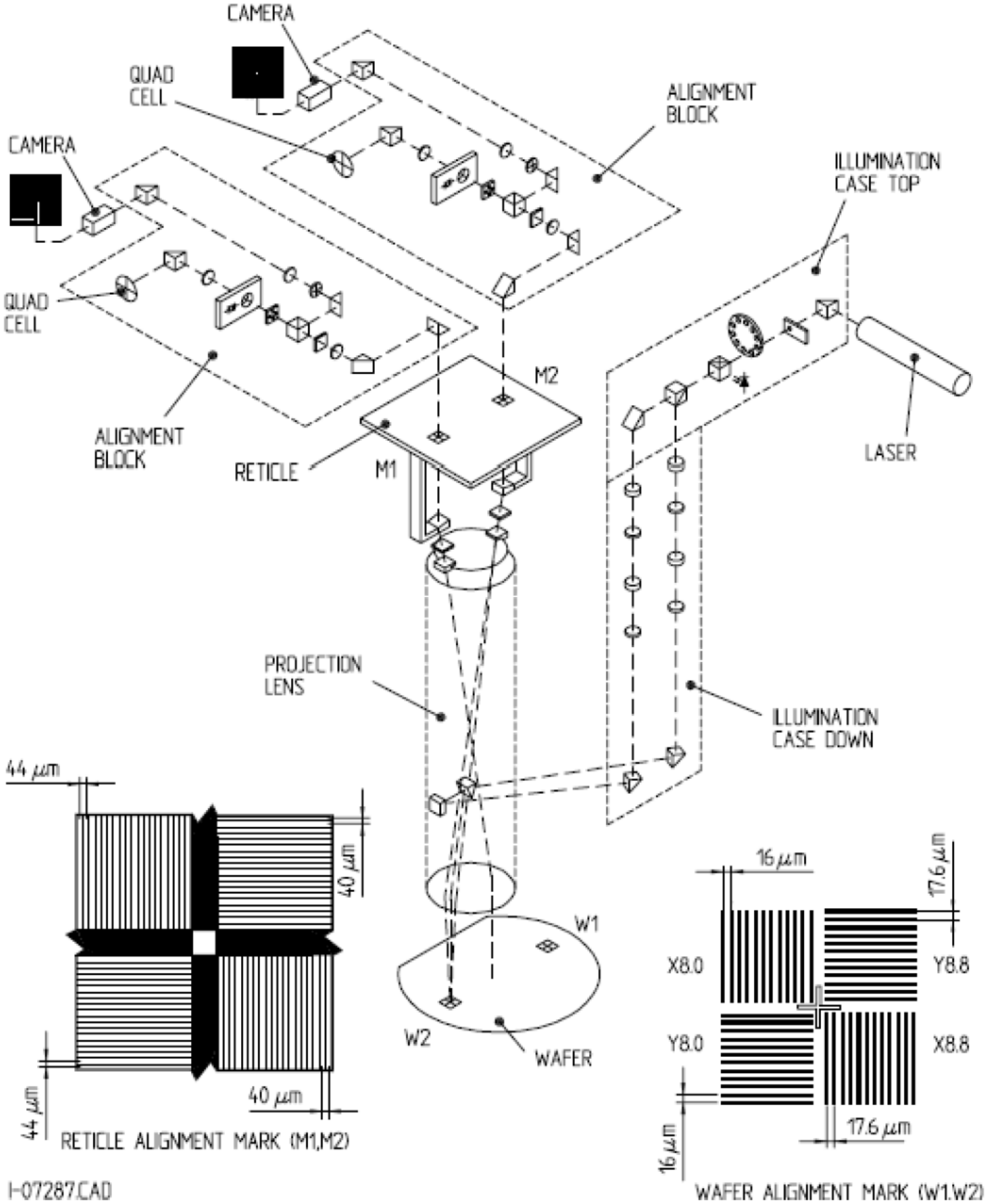
Mask



Stage



Alignment Optical Path

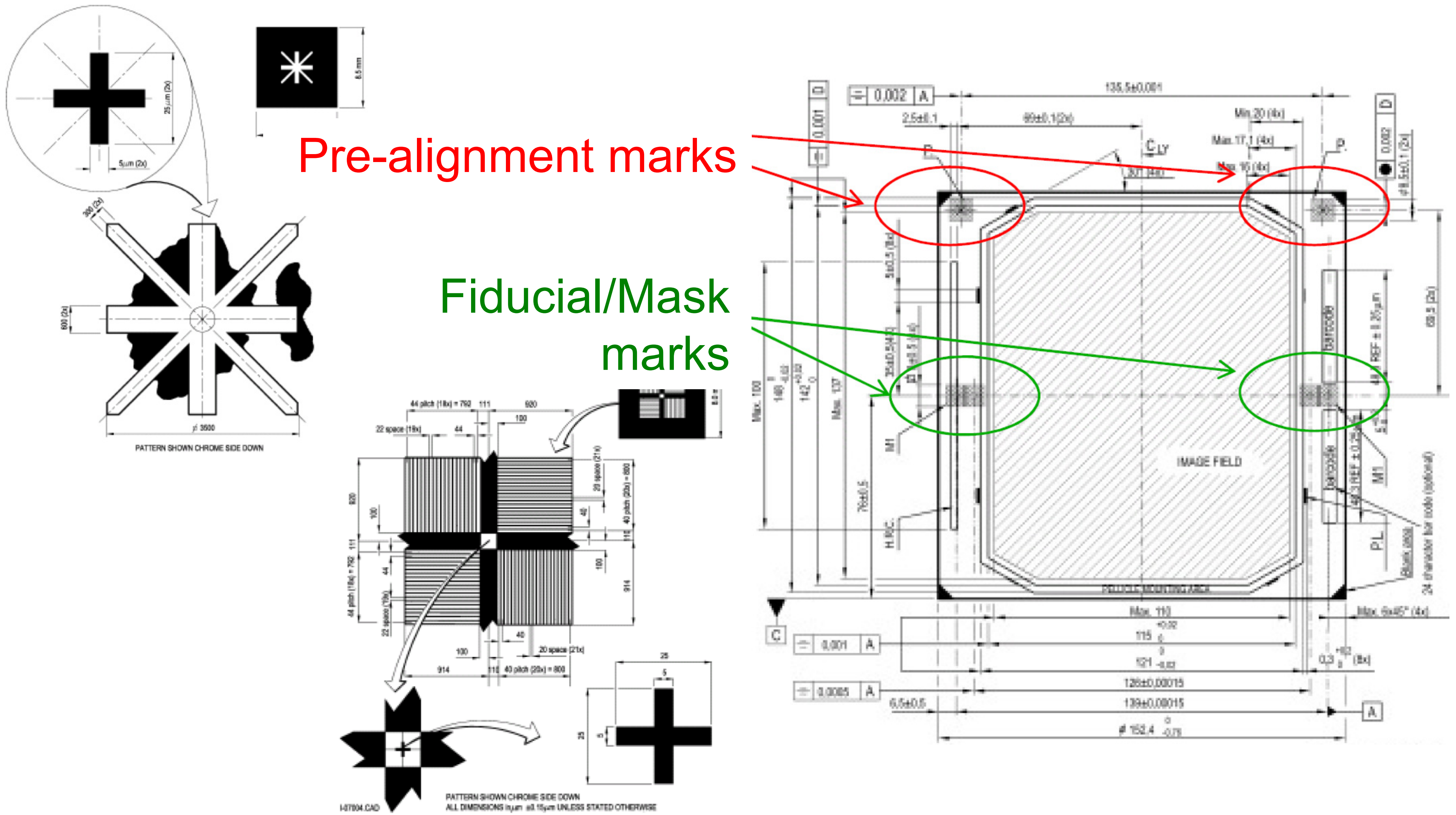


- The laser beam is split into two beams. One directed toward the left side of the wafer and the other directed toward the right side of the wafer, for alignment marks on the left or right side.
- Only one alignment mark is illuminated at a time.

Alignment Procedure

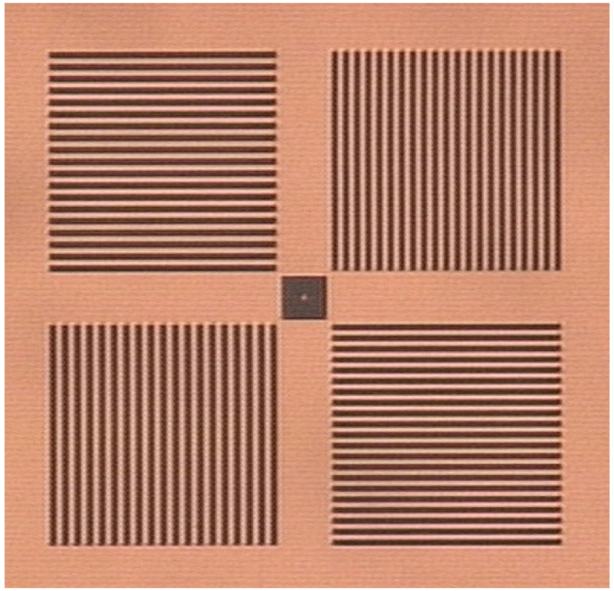
- Alignment involves placing the wafer/stage in a position such that the wafer/stage marks can be illuminated by the HeNe laser.
  - The reflected diffraction pattern goes back through the lens and the wafer image is reconstructed from the +/-1st order components of the diffraction pattern (the zero order is returned to the laser, higher orders are blocked).
  - The electric and magnetic fields are transferred through the lens as in a linear system resulting in a sinusoidal field image.
  - The intensity is the square of the field doubling the frequency of the diffraction grating on the wafer when viewed at the mask level.
  - This image is superimposed on the fiducial marks on the mask and a light detector measures the brightness as the stage is moved to find best alignment of the wafer to the mask.

Pre-alignment and Fiducial Marks

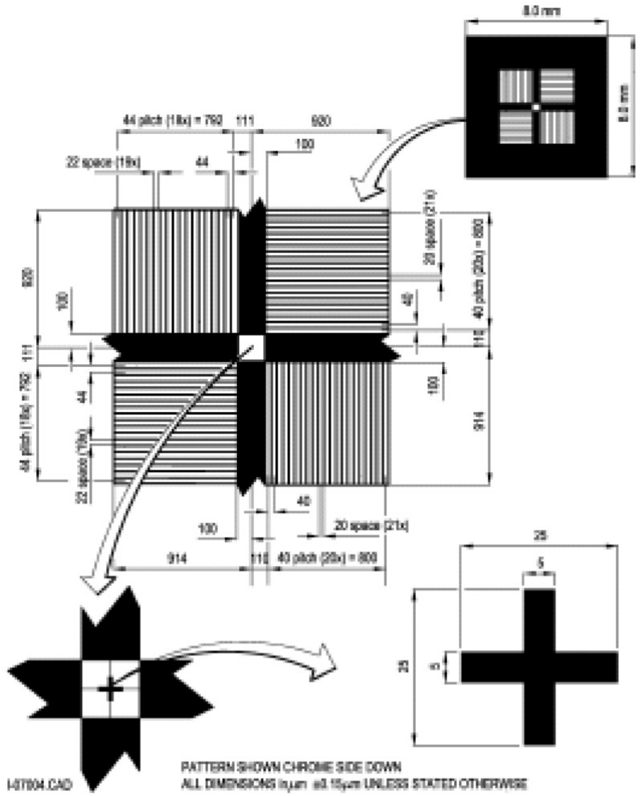


Mask Alignment Marks

- Two mask alignment marks are used for Through The Lens (TTL) alignment of the mask to the wafer in global and/or field by field alignment mode.

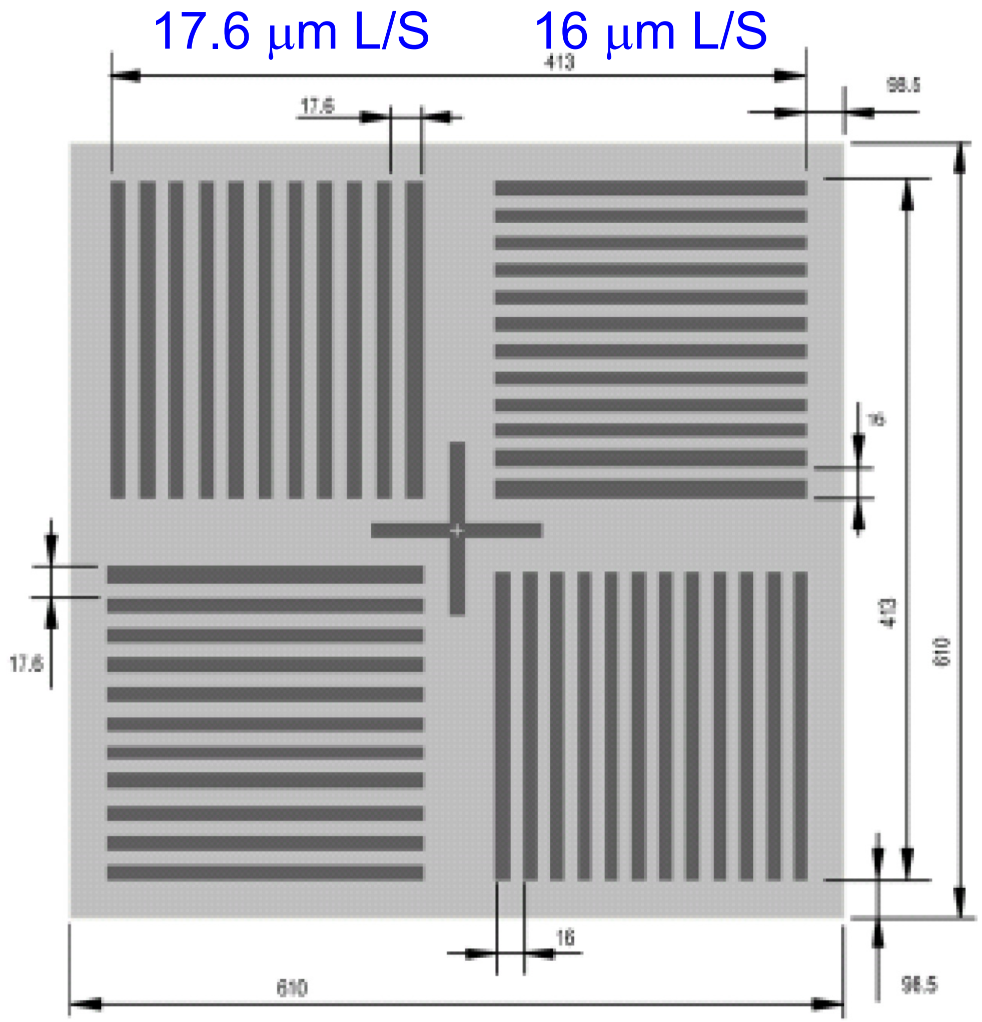


44 μm L/S 40 μm L/S



Wafer and Stage Primary Marks

- The 16 μm L/S wafer marks are transferred to the mask at 5X (5X stepper) for the lens magnification divided by two for the frequency doubling. This is 40 μm L/S equal to the period on the mask alignment marks (16x5÷2=40). The 17.6μm L/S becomes 44 μm L/S at the mask.
- The light from the wafer goes through the lens and through the mask alignment marks to the detector.
- The stage moves to determine the best alignment. Thus the wafer is aligned to the mask.

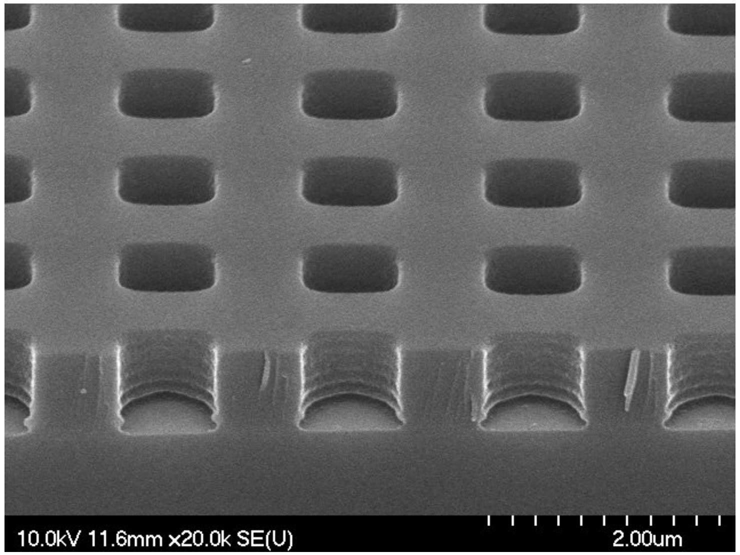


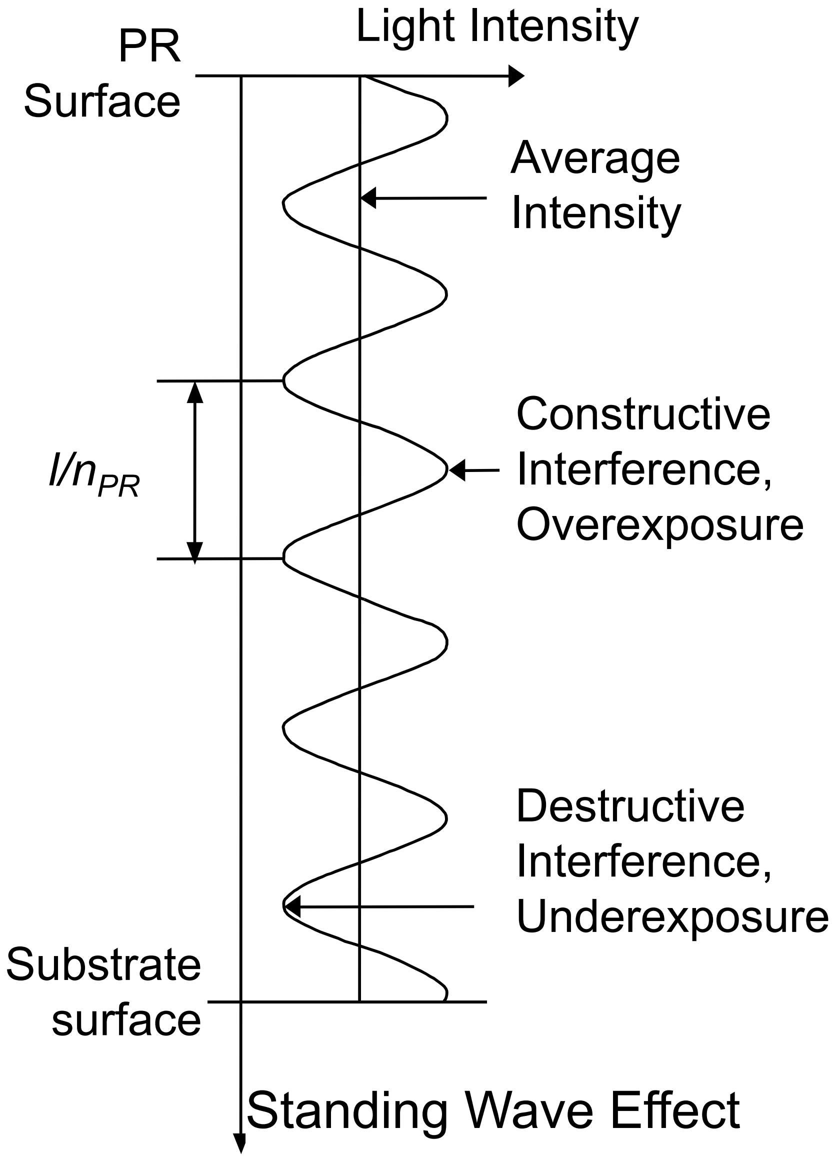
Mask Alignment

- In order to align a Mask to the stepper, the mask must have fiducial marks at given locations near the edge of the mask.
- Once the mask is placed on the platen, the mask pre-alignment marks are used to position the mask in the approximate correct location.
- The stage is moved to position special alignment marks attached to the stage at the correct position to do the mask fine alignment.
- Just like wafer alignment, the marks are illuminated with a HeNe laser and the mask is moved to give the best alignment position and then held in that position until removed from the stepper.

Post Exposure Bake (PEB) - 1

- Baking temperature higher than T_g (PR glass transition temperature)
  - Thermal movement of PR molecules
  - Rearrangement of the overexposed and underexposed PR molecules
  - Smooth PR sidewall and improve resolution
  - Average out standing wave effect





Post Exposure Bake (PEB) - 2

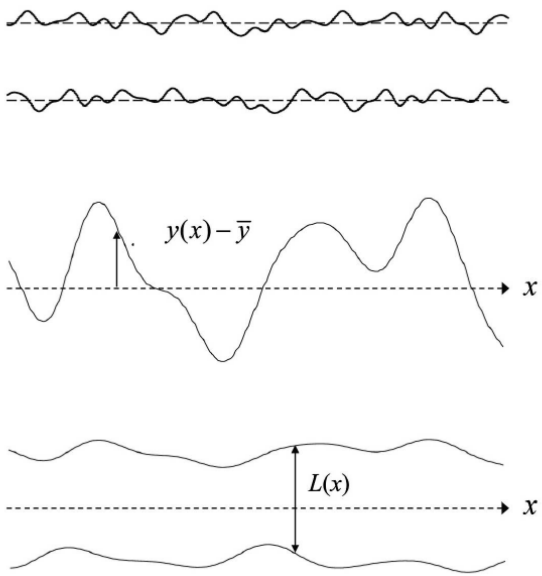
- For DUV chemical amplified PR, PEB provides the heat needed for acid diffusion and amplification.
- After the PEB process, the images of the exposed areas appear on the PR, due to the significant chemical change after the acid amplification
- PEB normally uses hot plate at 110 to 130 °C for ~ 1 min
- For the same kind of PR, PEB usually requires a higher temperature than soft bake.
- Insufficient PEB will not completely eliminate the standing wave pattern
- Over-baking will cause polymerization and affect PR development.

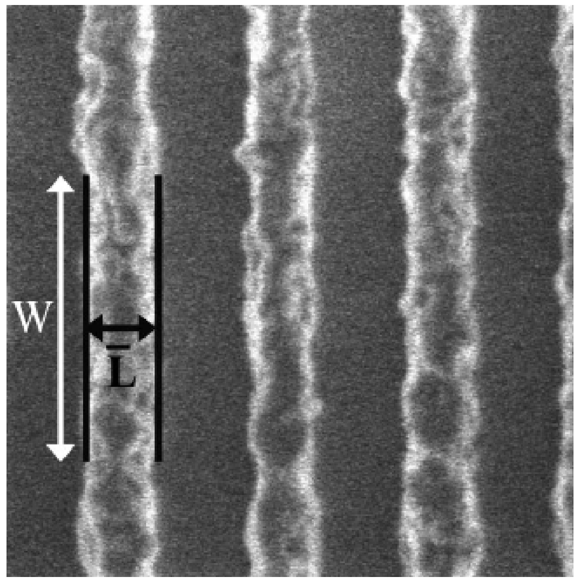
Line Edge Roughness (LER) - 1

- LER is a significant issue for resists for feature sizes smaller than 100 nm.
  - A measure of edge roughness is the standard deviation of the actual line edge relative to an average line edge.
  - s_{LER} is the standard deviation of LER. LWR is 3 times of the standard deviation of the line width roughness .
  - Edge roughness with $3\sigma \approx$ 3~5 nm has been measured typically for leading-edge ArF resists.

$$s_{LER} = \sqrt{\frac{1}{N-1}\sum_{m=1}^{N}\left[y(x_m) - \bar{y}\right]^2}$$

$$LWR = 3s_{LWR} = 3\sqrt{\frac{1}{N-1}\sum_{m=1}^{N}\left[L(x_m) - \bar{L}\right]^2}$$





Line Edge Roughness (LER) - 2

➢ Sources of LER

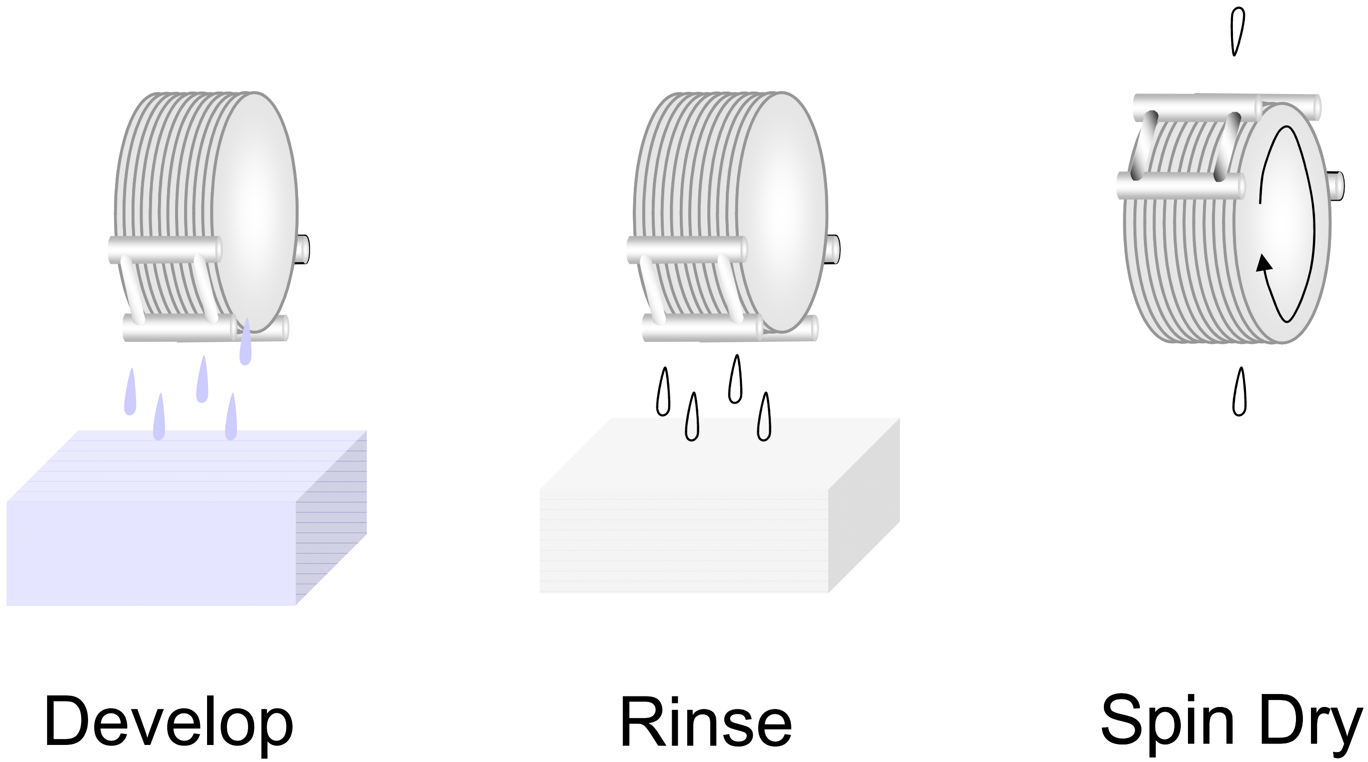
- Some LER certainly originates at the molecular level.
- An optical image that has a diffuse line.
- Transferred from LER on the mask.
- Statistical variations in the number of photons involved in exposing the resist.

➢ Techniques to improve LER

- As one might expect, diffusion (which occurs during post-exposure bake) serves to reduce LER. It is not a useful way to reduce LER for sub-50-nm lithography.
- Post-develop processing can reduce LER, including bakes, etches, vapor treatments, ozonation, and chemical rinses.
- Vapor smoothing and surface conditioning rinses appear to have the most benefit and can easily be implemented.
- Most of this improvement occurs at high spatial frequencies and not at the low-spatial-frequency LER that has the greatest impact on CD variability.

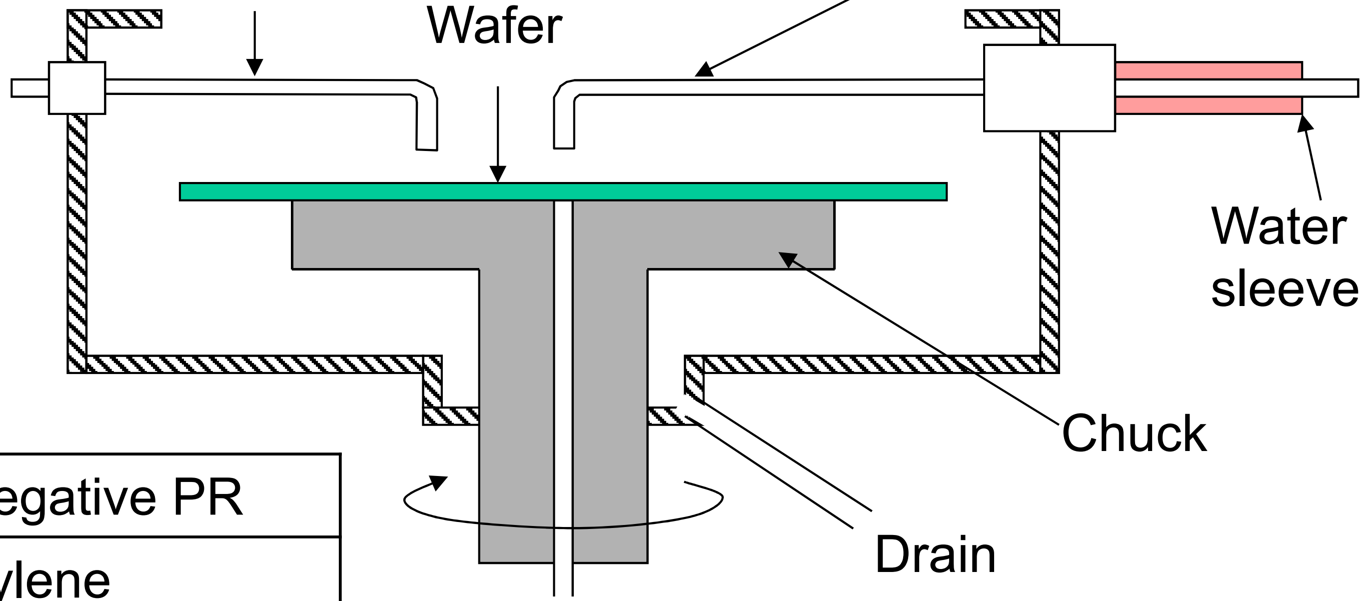
Development

- Developer solvent dissolves the softened part of PR
- Transfer the pattern from mask or reticle to PR
- Three basic steps:
  - Development
  - Rinse
  - Dry



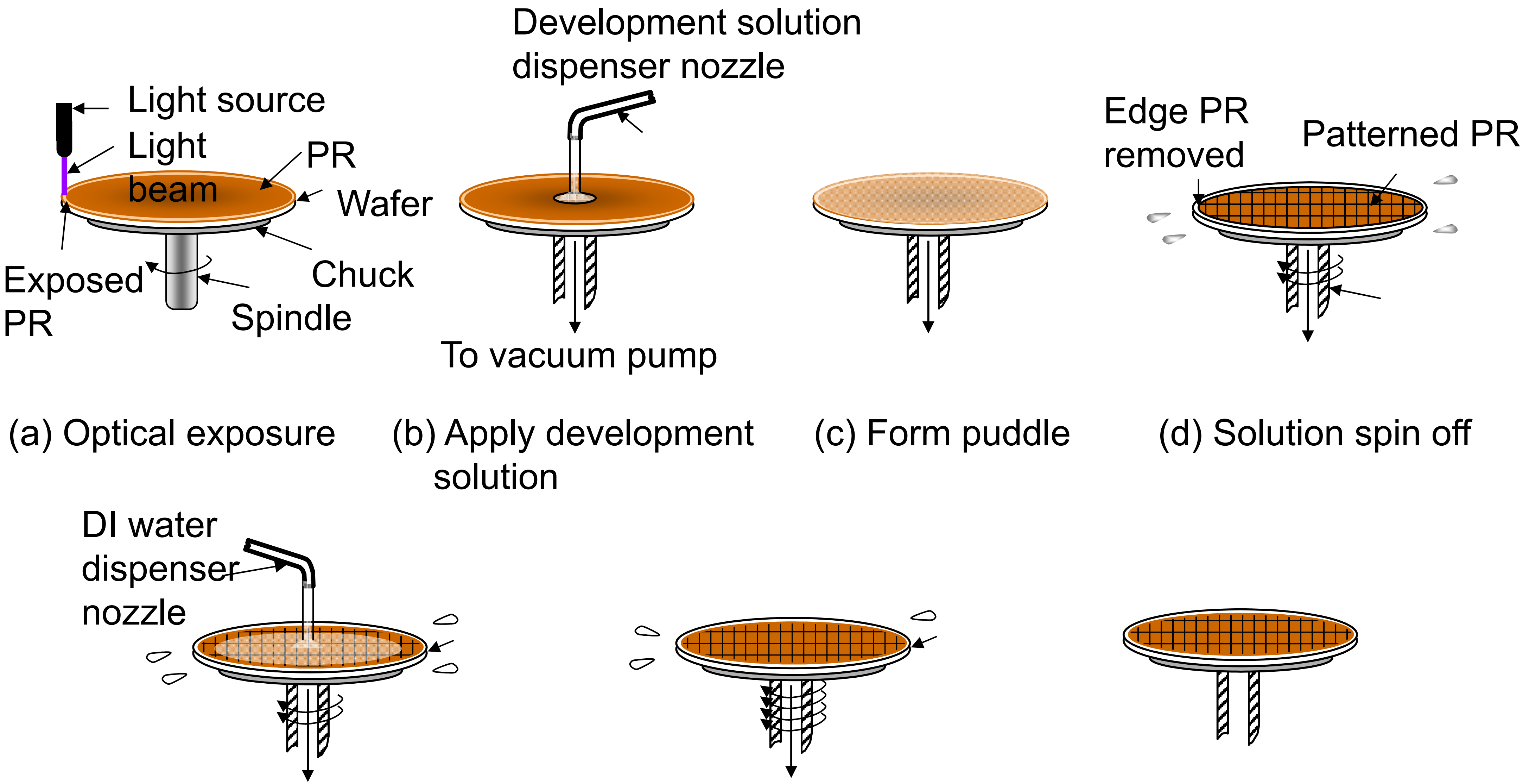
Developer and Rinse Solutions

- Positive PR normally uses weak base solution.
- The most commonly used one is the tetramethyl ammonium hydride (TMAH, $(CH_3)_4NOH$).



	Positive PR	Negative PR
Developer	TMAH	Xylene
Rinse	DI water	N-Butylacetate

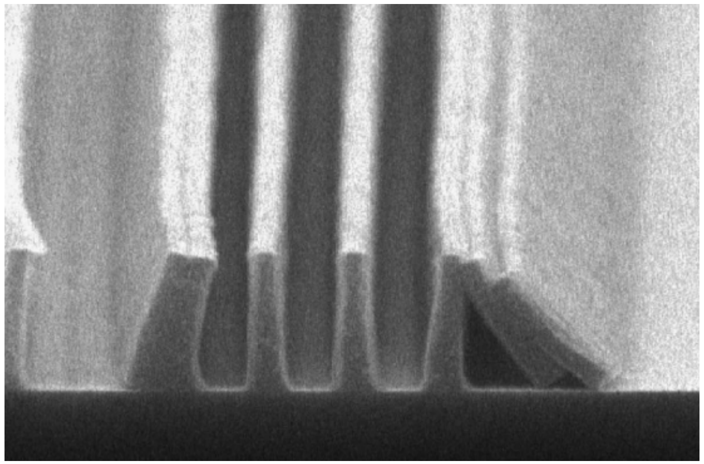
Optical EBR and Development Process



(a) Optical exposure
(b) Apply development solution
(c) Form puddle
(d) Solution spin off
(e) DI water rinse
(f) Spin dry
(g) Ready for the next step

Resist Collapse - 1

- Collapse phenomenon
  - As developer and rinse water are removed from developed wafers, surface-tension forces pull closely adjacent lines together.
  - This phenomenon fundamentally limits the aspect ratio of the resist features.
  - Resist collapse is common when aspect ratios exceed 4/1 (height/width) and can frequently occur for even smaller values.
  - Resist collapse can be reduced by adding a surfactant to the rinse liquid because they reduce the surface tension.
  - Heating the resist during development has also been proposed as a way to reduce pattern collapse by hardening the resist and therefore increasing its structural stability.

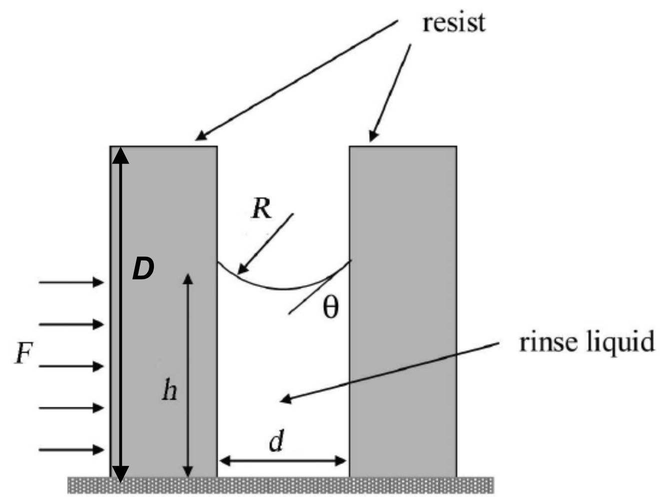


Resist Collapse - 2

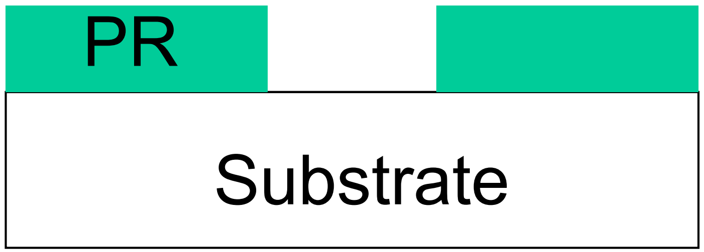
- Collapse kinetic
  - During the drying step, after the resist has been developed and rinsed, the space between adjacent resist lines is partially filled with fluid.
  - The fluid meniscus exhibits curvatures due to the differences in pressure across the fluid interface that result from surface tension in the confined geometry.
  - These differences in pressure exert forces on the resist features that act perpendicularly and inwardly from the resist sidewall.
  - These forces caused by pressure differences across the meniscus are given by:

$\Delta P = \frac{\gamma}{R}$, where γ is the surface tension and R is the radius of curvature.

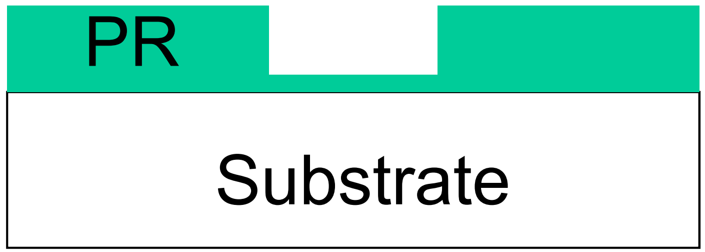
$$R = \frac{d}{2\cos\theta} \Rightarrow F = hD\frac{2\gamma\cos\theta}{d}$$



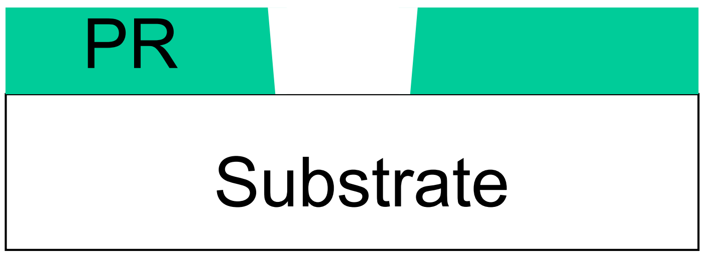
After Development Profiles



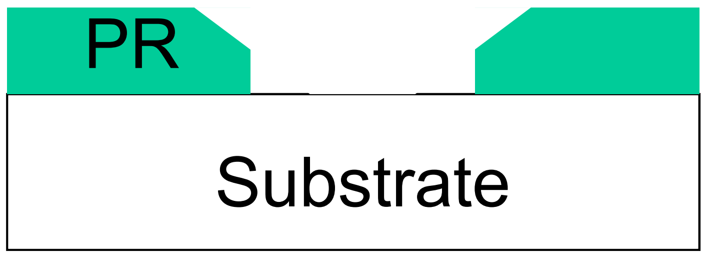
Normal Development



Incomplete Development



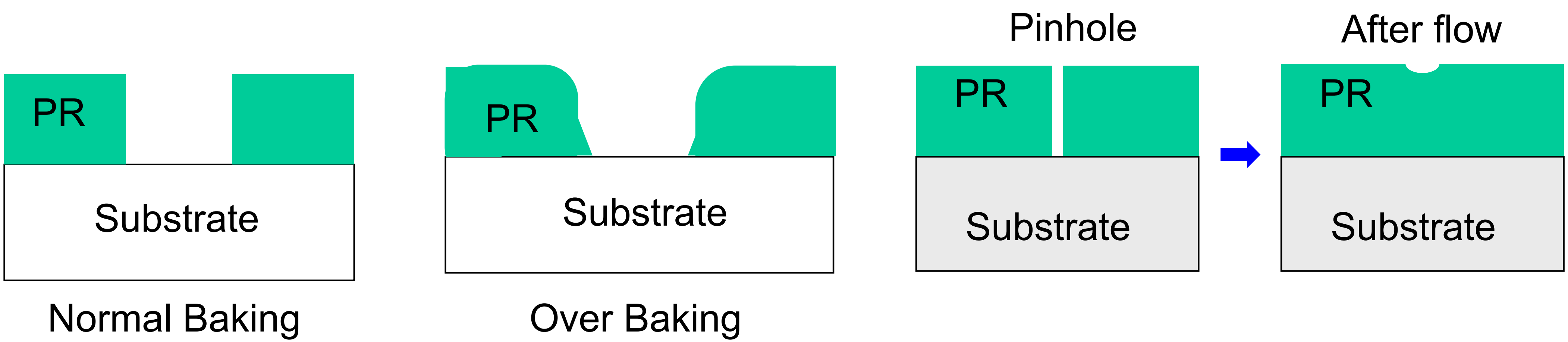
Under Development



Over Development

Hard Bake - 1

- Evaporate all solvent in PR.
- Improve etch and ion implantation resistance.
- Improve PR adhesion with surface.
- Polymerize and stabilize PR.
- PR flow to fill pinholes.



Hard Bake - 2

- Hot plate is commonly used.
- Can be performed in a oven.
- Hard bake temperature: 100 to 130 °C.
- Baking time is about 1 to 2 minutes.
- Hard bake temperature normally is higher than the soft bake temperature for the same kind of PR.
- Under-bake
  - PR is not fully polymerized
  - High PR etching rate
  - Poor adhesion
- Over-bake
  - PR flow and bad resolution