Chapter 6

Photolithography

Objectives

- List the four components of the photoresist
- Describe the difference between +PR and –PR
- Describe a photolithography process sequence
- List four alignment and exposure systems
- Describe the wafer movement in a track-stepper integrated system.
- Explain relationships of resolution and depth of focus to wavelength and numerical aperture.

Introduction

Photolithography is :

- Temporarily coat photoresist on wafer and Transfers designed pattern to photoresist
- Most important process in IC fabrication
- To consume 40 to 50% total wafer process time
- Determines the minimum feature size, e.g. 0.18um technology in 2000, 70nm technology in 2004

Applications of Photolithography

- Main application: IC patterning process
- Other applications: Printed electronic board, nameplate, printer plate, and *et al*.

IC Fabrication Flow

EDA $\xrightarrow{\text{e-Beam or Photo}}$ Mask or Reticle $\longrightarrow$ PR $\xrightarrow[\text{Etch}]{\text{Ion Implant}}$ Chip

Photolithography

EDA: Electronic Design Automation

PR: Photoresist

Photolithography Requirements

- High Resolution
- High PR Sensitivity
- Precision Alignment, say within 10% of minimum feature size
- Precise Process Parameters Control
- Low Defect Density

Photoresist

- Photo sensitive material, sensitive to ultraviolet (UV) but to visible light
- It’s why we use yellow light to illuminate and call “*yellow room*”
- Transfer design image on it through exposure and development
- Very similar to the photo sensitive coating on the film for camera
- Positive and negative types

Photoresist

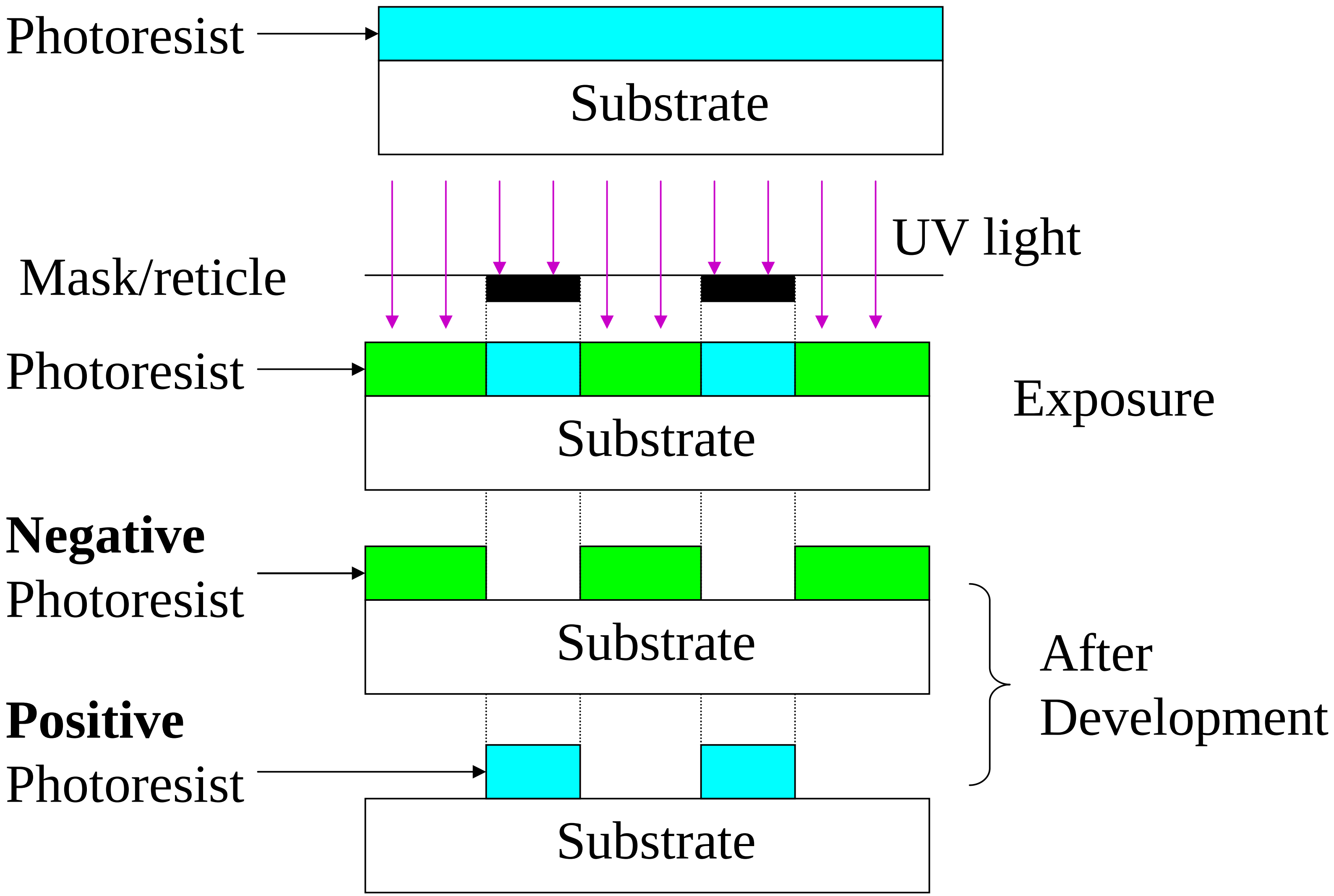
Negative Photoresist

- Becomes insoluble after exposure
- When developed, the unexposed parts dissolved.
- Cheaper with poor resolution

Positive Photoresist

- Becomes soluble after exposure, *(photosolubilization)*
- When developed, the exposed parts dissolved
- Expensive with better resolution

Negative and Positive Photoresists



Photoresist Composition

- Polymer
- Solvents
- Sensitizers
- Additives

Polymer

- Solid organic material
- Transfers designed pattern to wafer surface
- Changes solubility due to photochemical reaction when exposed to UV light.
- Positive PR: from insoluble to soluble
- Negative PR: from soluble to insoluble

Solvent

- Dissolves polymers into liquid
- Allow application of thin PR layers by spinning
- 75% of PR before spin coating
- Acetate-type solvent for positive PR; xylene (C_8H_{10}) for negative PR

Sensitizers

- Controls and/or modifies photochemical reaction of resist during exposure.
- Determines exposure time and intensity

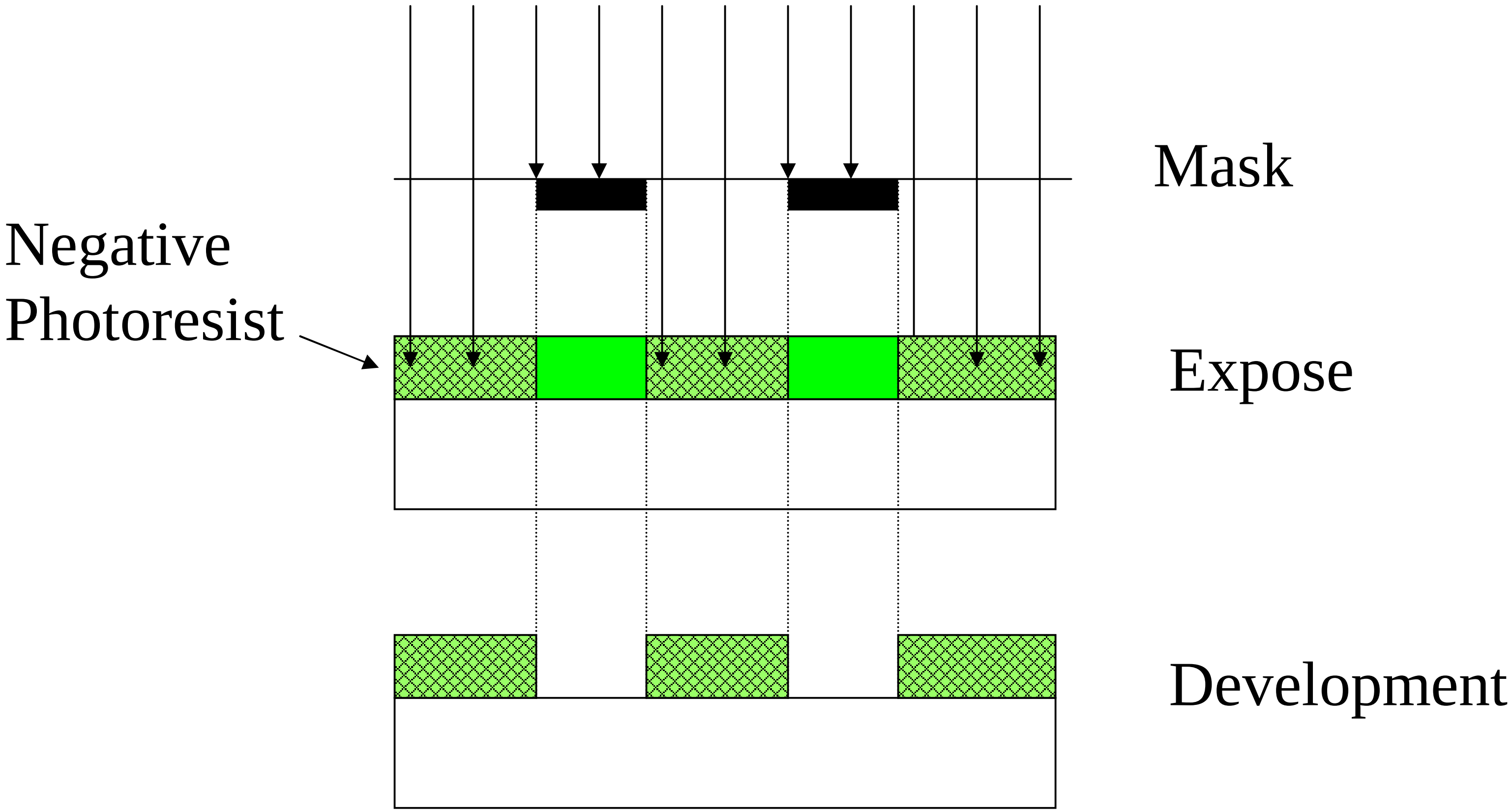
Additives

- Various added chemical to achieve desired process results, such as dyes to reduce reflection.

Negative Resist

- Most negative PR are polyisoprene type
- Exposed PR becomes cross-linked polymer
- Cross-linked polymer has higher chemical etch resistance.
- Unexposed part will be dissolved in development solution.

Negative Photoresist

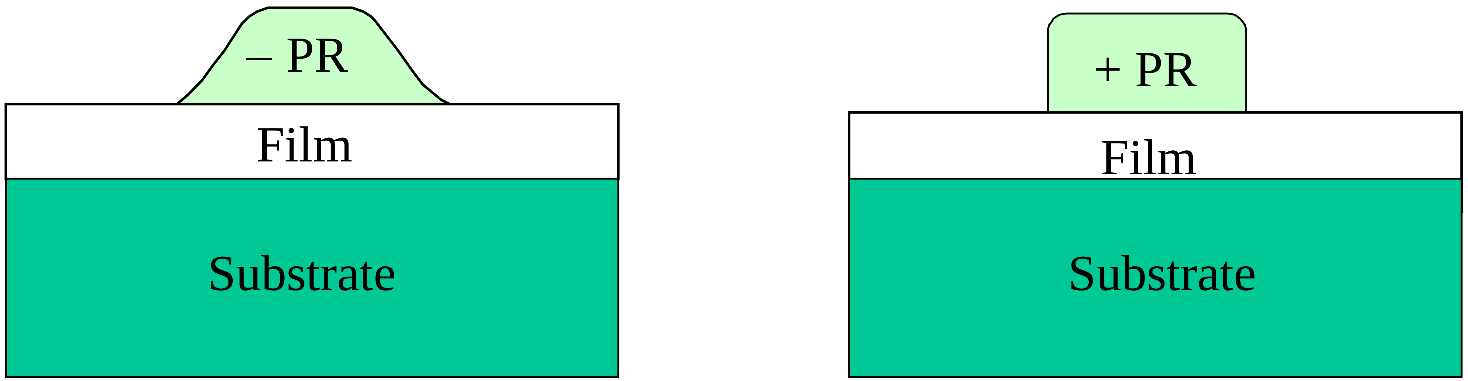


Negative Photoresist

Disadvantages

- Polymer absorbs the development solvent
- Poor resolution due to PR swelling
- Environmental and safety issues due to the main solvents xylene.

Comparison of Photoresists



Positive Photoresist

- Exposed part dissolve in developer solution
- Image the same that on the mask
- Higher resolution
- Commonly used in advanced IC fabs

Question

- Positive photoresist can achieve much higher resolution than negative photoresist, why didn't people use it before the 1980s?

- Positive photoresist is much more expensive therefore negative photoresist was used until it had to be replaced when the minimum feature size was shrunk to smaller than 3 μm.

Chemically Amplified Photoresists

- To pattern a small feature, a shorter wavelength light source is required
- For deep ultraviolet (DUV), $\lambda \leq 248$ nm or 193 nm
- Light source: excimer lasers
- Light intensity is lower than I-line (365 nm) or G-line (436 nm) from high-pressure mercury lamp
- Need different kind of photoresist

Chemically Amplified Photoresists

- Catalysis effect is used to increase the effective sensitivity of the photoresist
- A photo-acid is created in PR when it exposes to DUV light
- During PEB, head-induced acid diffusion causes amplification in a catalytic reaction
- Acid removes protection groups
- Exposed part will be removed by developer

Requirement of Photoresist

- **High resolution**
  - Thinner PR film has higher the resolution
  - Thinner PR film, the lower the etching and ion implantation resistance
- **High etch resistance**
- **Good adhesion**
- **Wider process latitude**
  - Higher tolerance to process conditions like spin rate, baking temperature and exposure flux

Photoresist Physical Properties

- Photoresist must be able to withstand process conditions
  - Coating, spinning, baking, developing.
  - Etch resistance
  - Ion implantation blocking

Photoresist Performance Factors :

- Resolution
- Adhesion
- Expose rate, Sensitivity and Exposure Source
- Process latitude
- Pinholes
- Particle and Contamination Levels
- Step Coverage
- Thermal Flow

Resolution Capability

- The smallest opening or space that can produced in a photoresist layer.
- Related to particular processes including expose source and developing process.
- Thinner layer has better resolution.
- Etch and implantation barrier and pinhole-free require thicker layer
- Positive resist has better resolution due to the smaller size of polymer.

Photoresist Characteristics Summary

Parameter	Negative	Positive
Polymer	Polyisoprene	Novolac Resin
Photo-reaction	Polymerization	Photo-solubilization
Sensitizer	Provide free radicals for polymer cross-link	Changes film to base soluble
Additives	Dyes	Dyes

Photolithography Process

Basic Steps of Photolithography

1. Photoresist coating
2. Alignment and exposure
3. Development

Basic Steps, Old Technology

- Wafer clean
- Dehydration bake
- Spin coating primer and PR
- Soft bake
- Alignment and exposure
- Development
- Pattern inspection
- Hard bake

PR coating

Development

Basic Steps, Advanced Technology

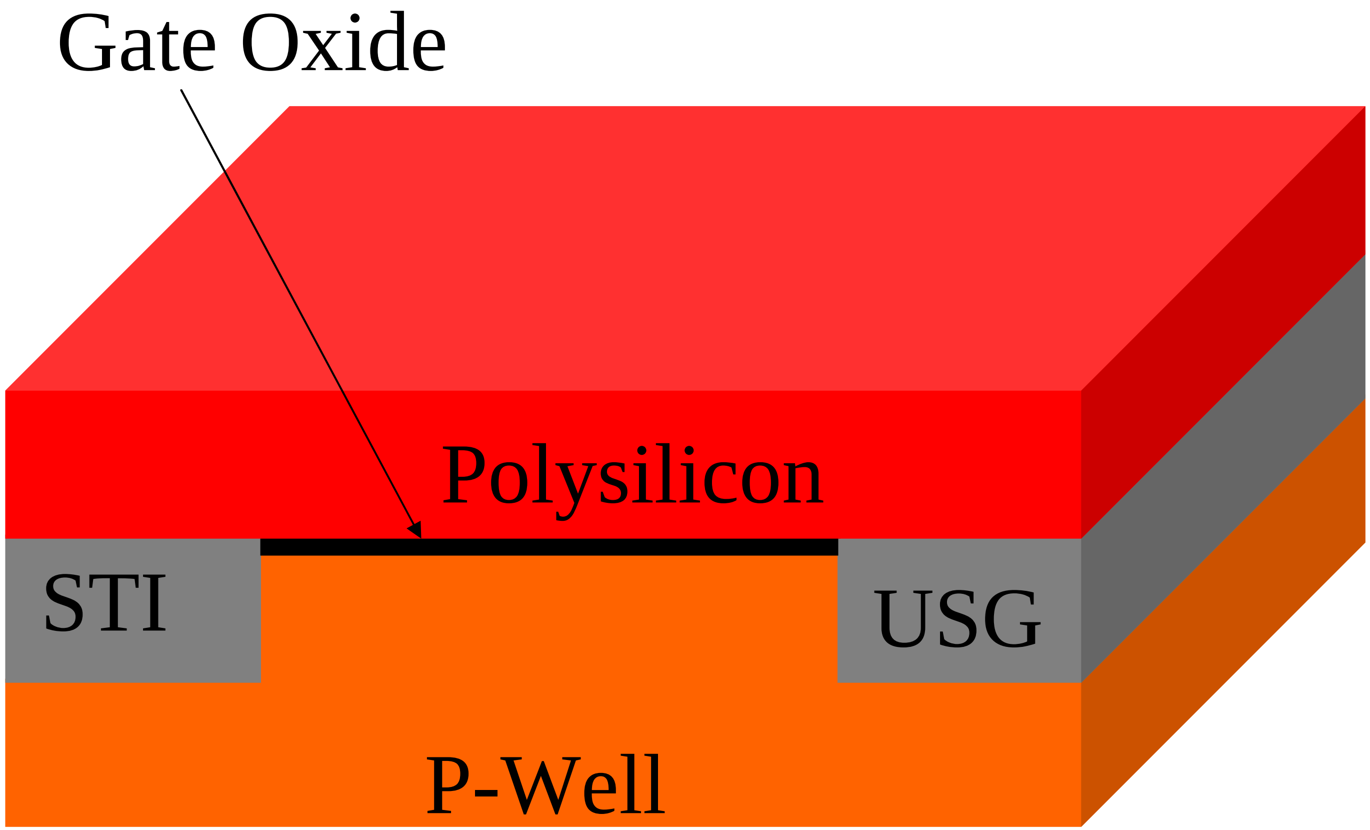
- Wafer clean
- Pre-bake and primer coating
- Photoresist spin coating
- Soft bake
- Alignment and exposure
- Post exposure bake
- Development
- Hard bake
- Pattern inspection

Track-stepper integrated system

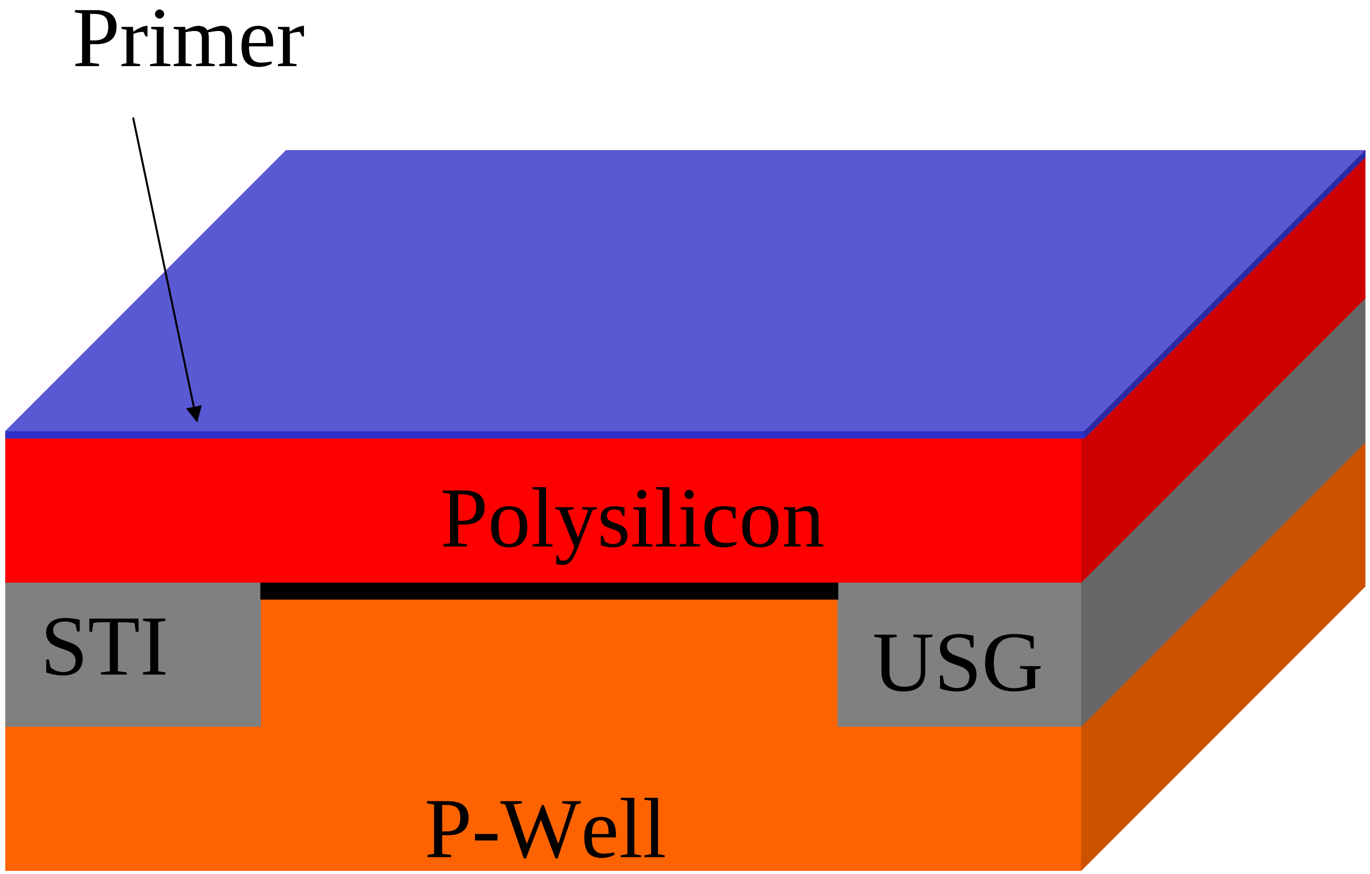
PR coating

Development

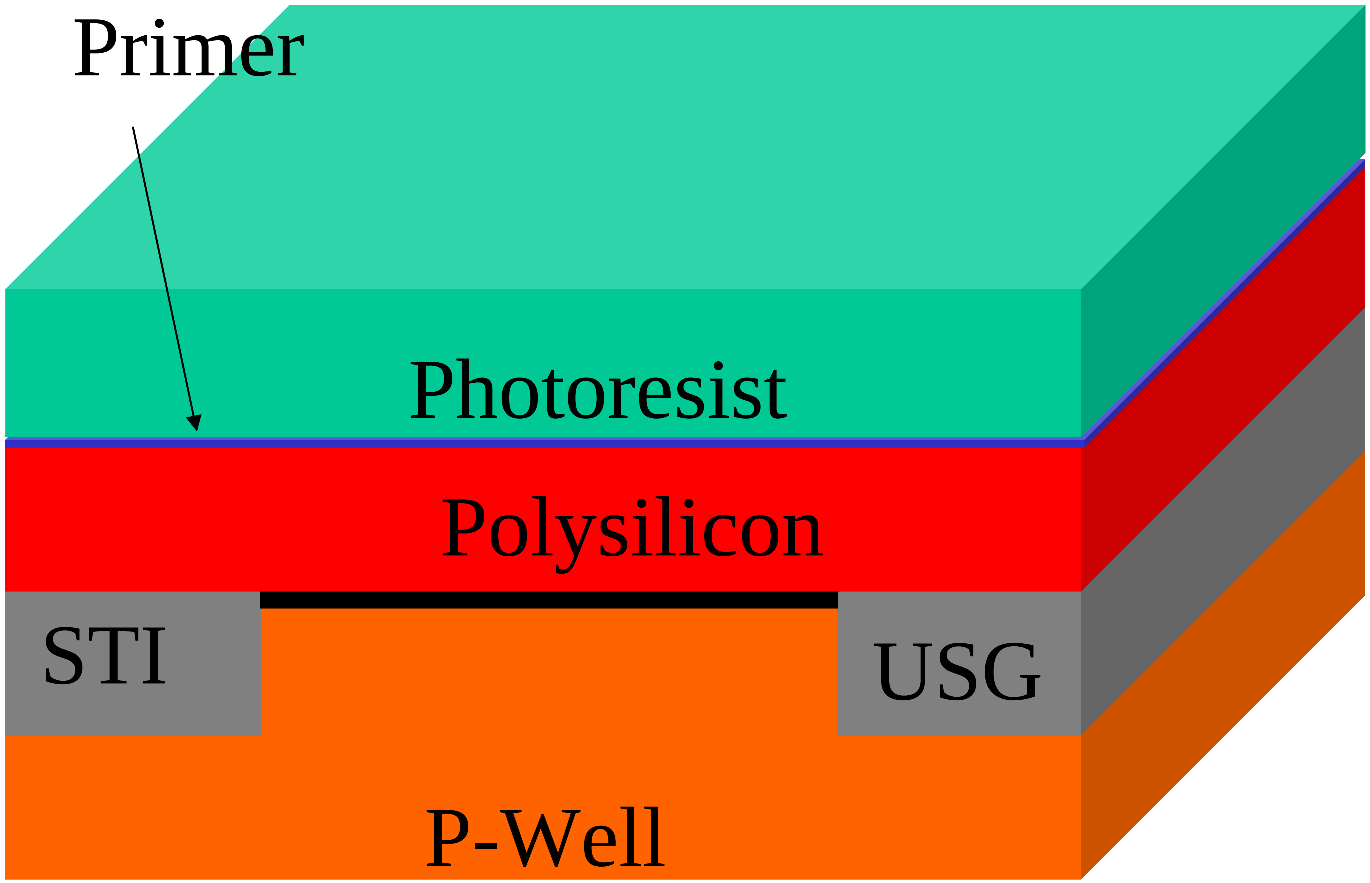
Wafer Clean



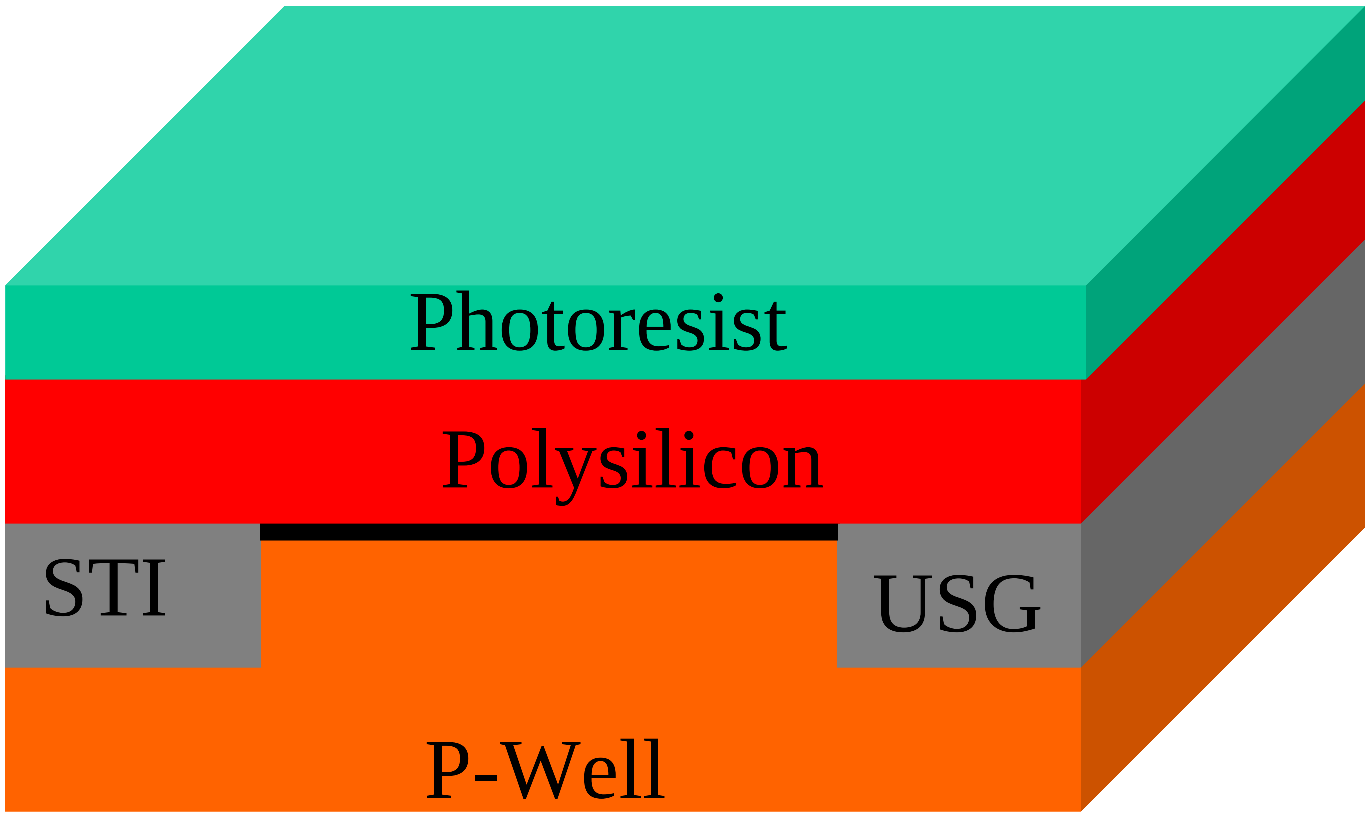
Pre-bake and Primer Vapor



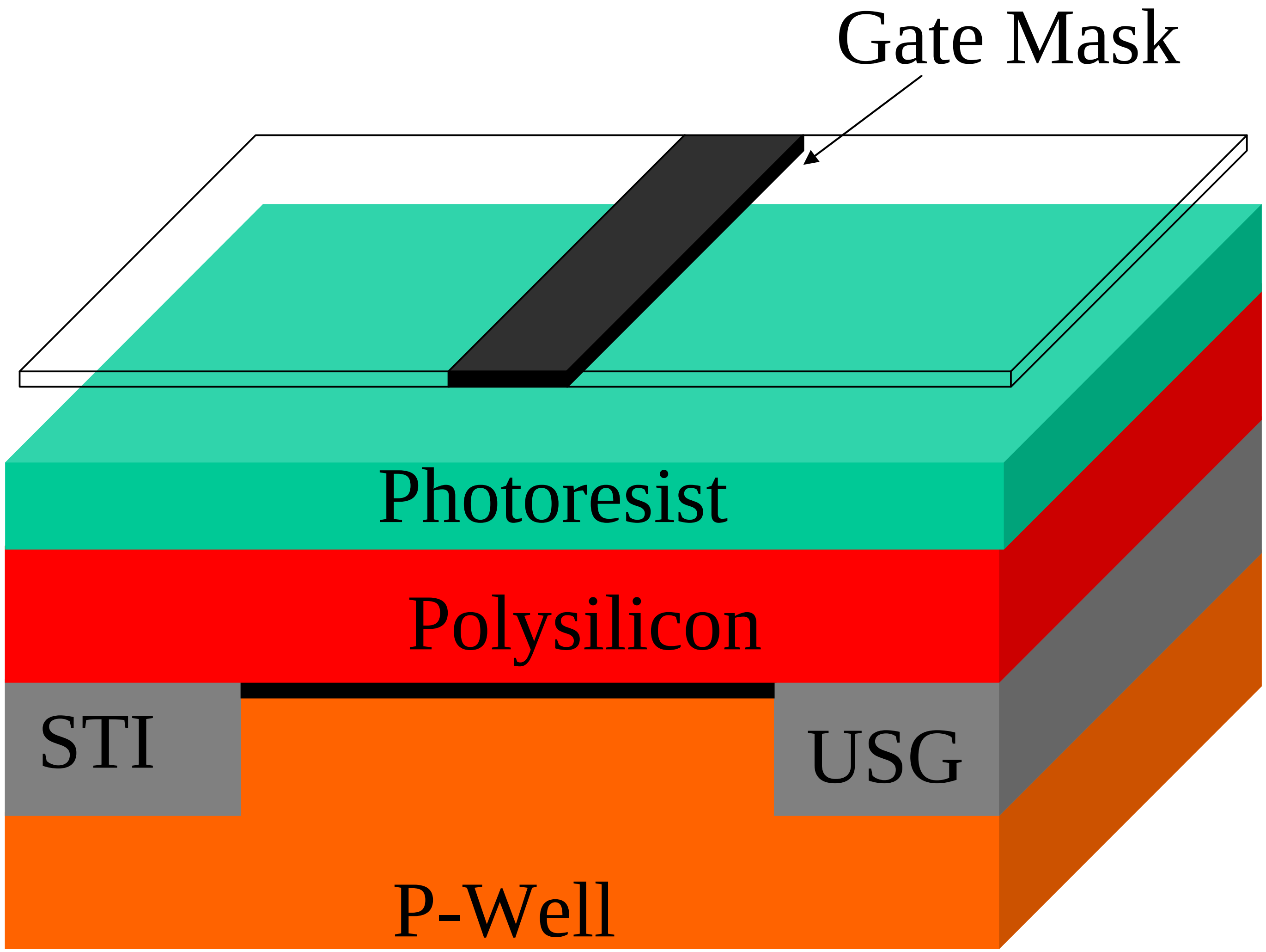
Photoresist Coating



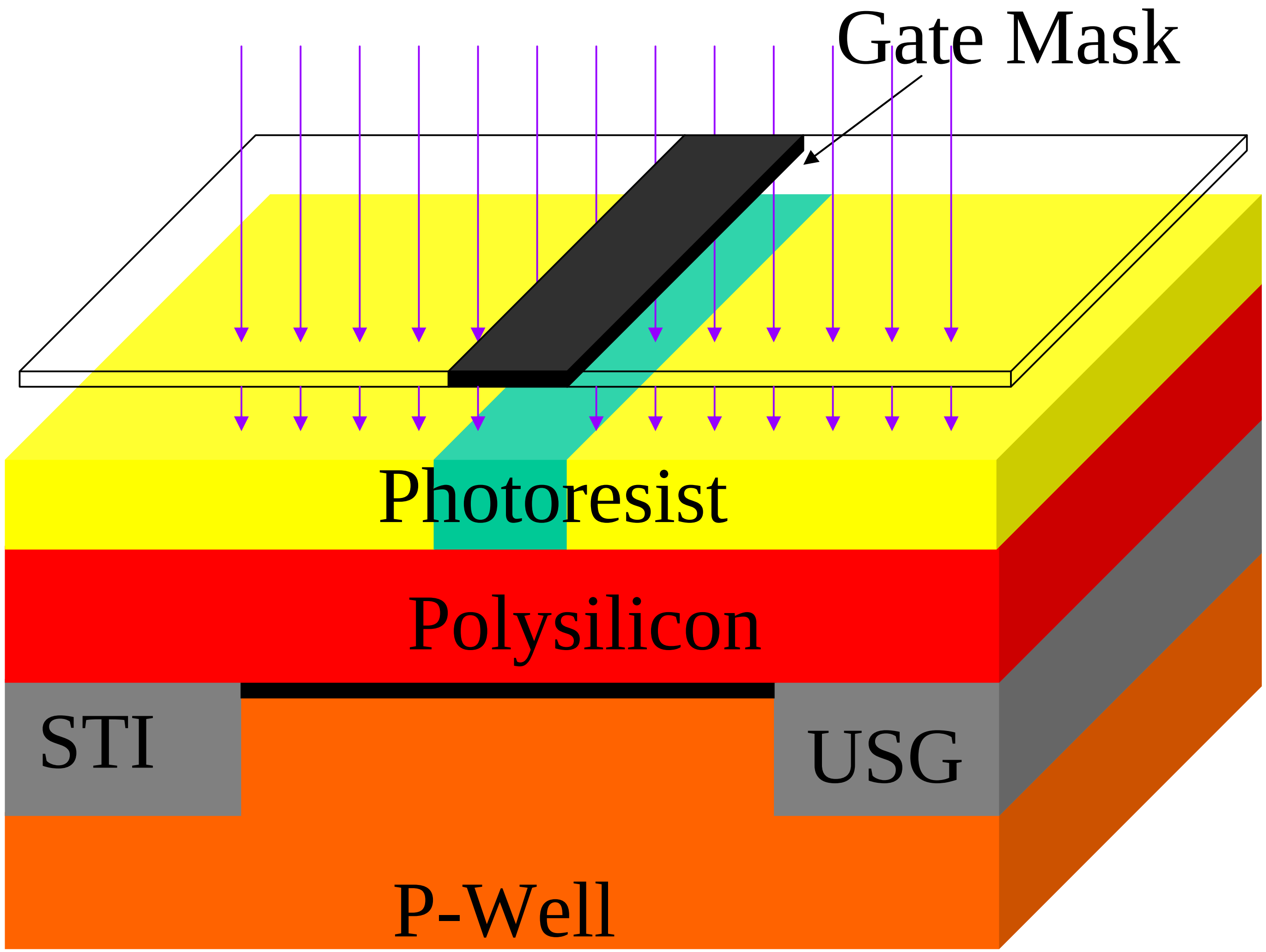
Soft Bake



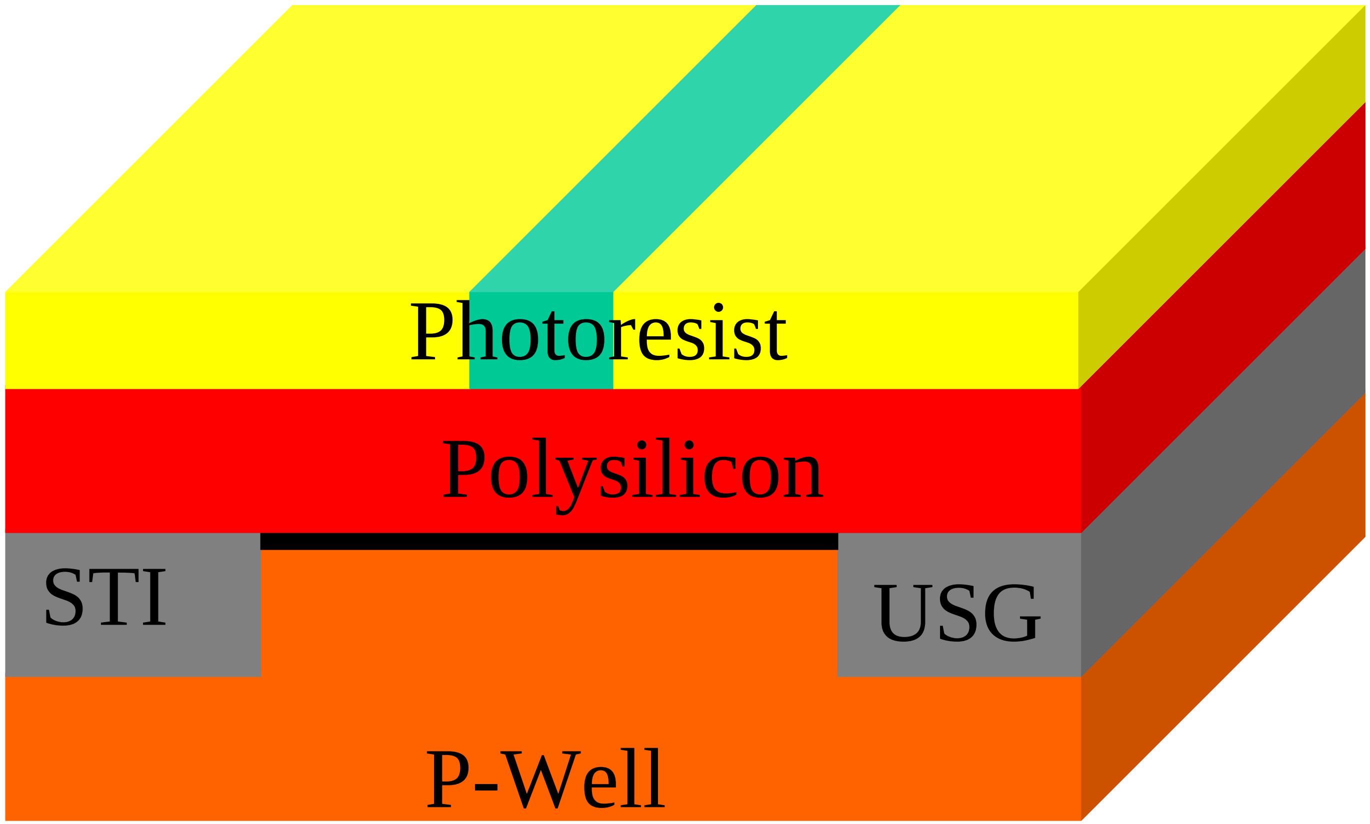
Alignment and Exposure



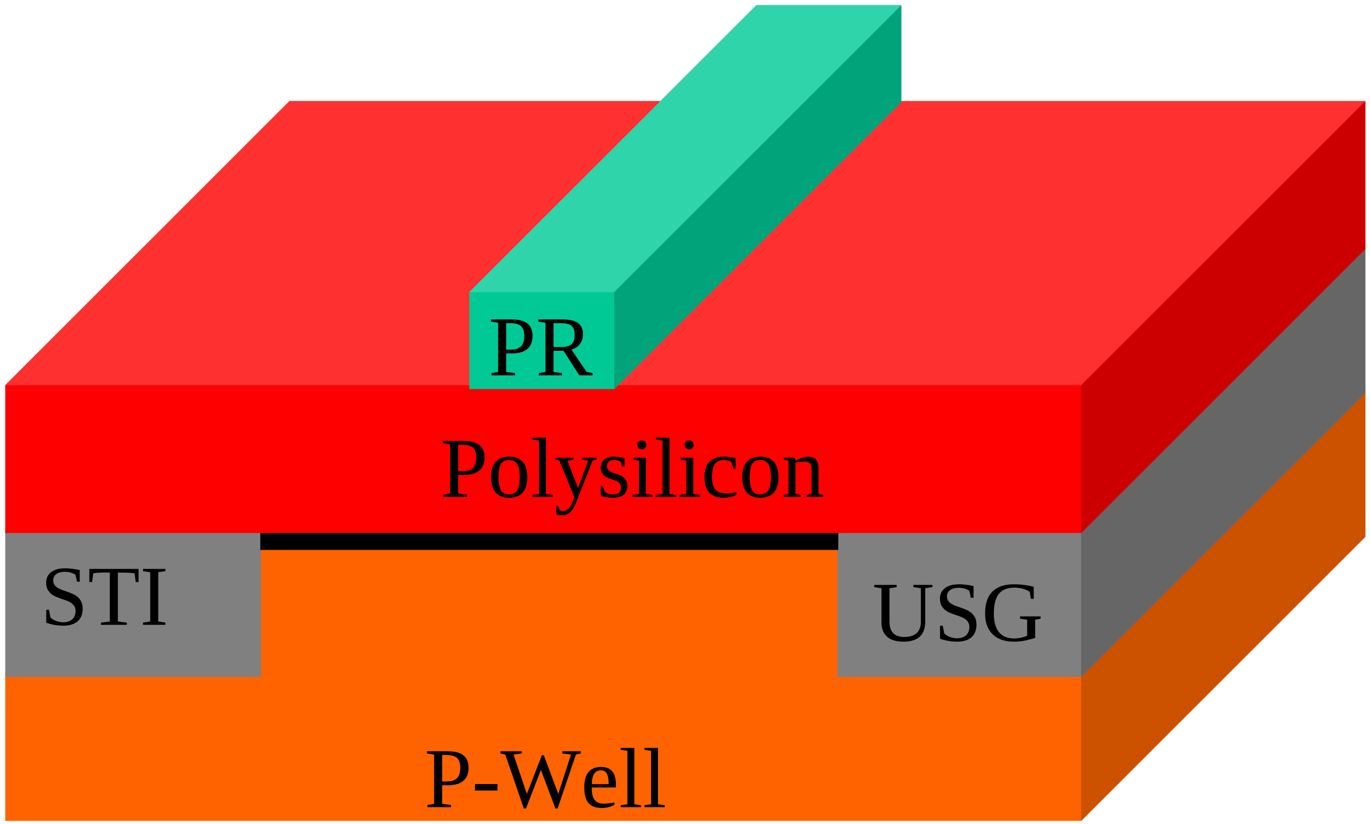
Alignment and Exposure



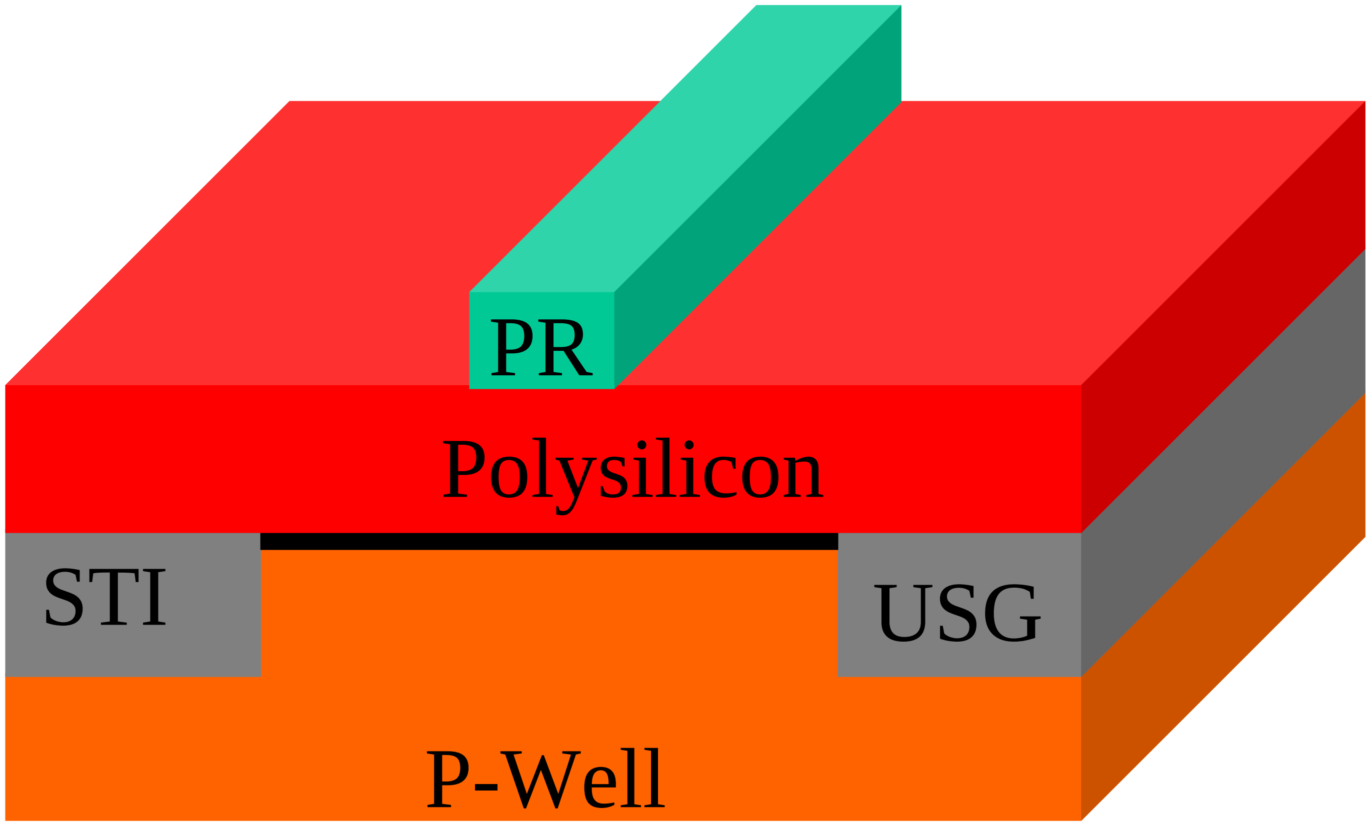
Post Exposure Bake



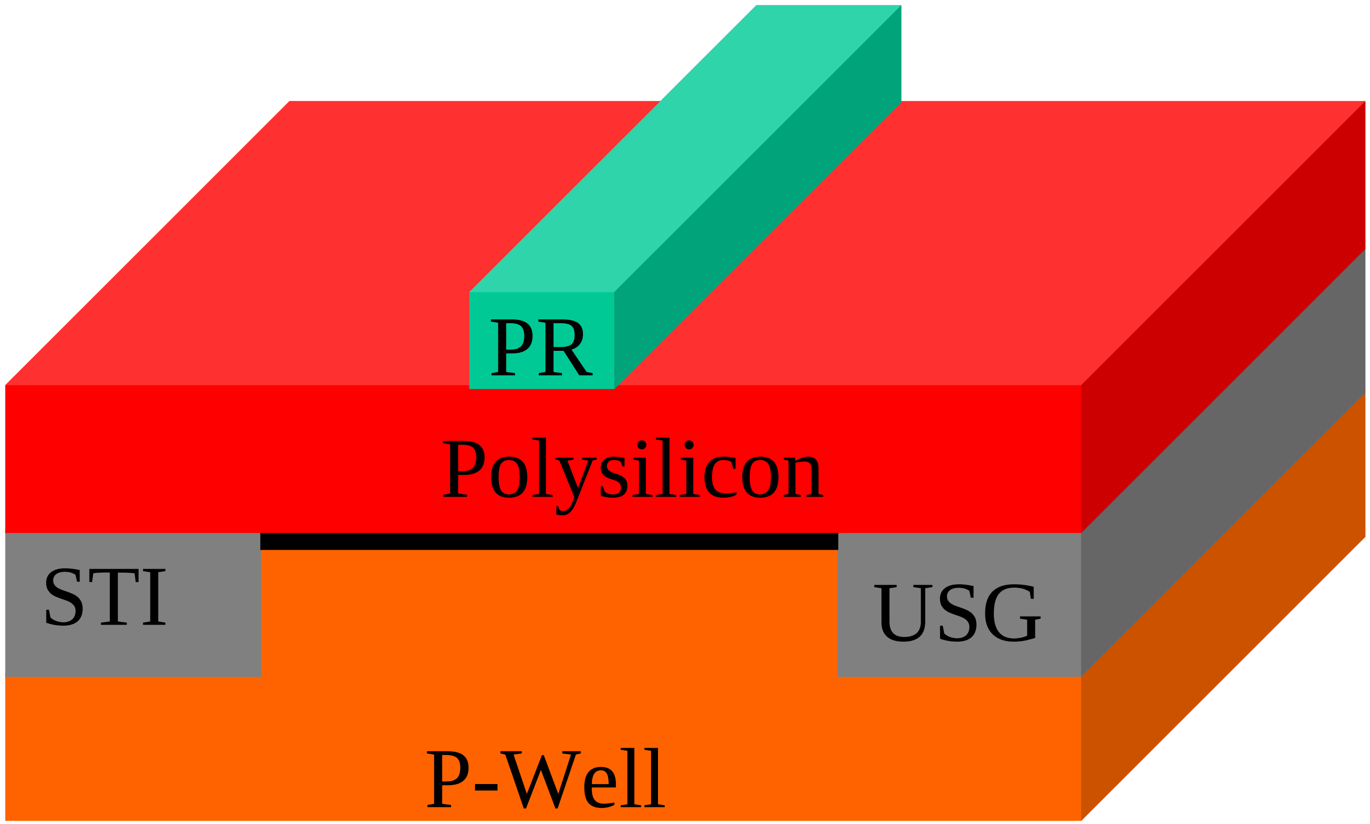
Development



Hard Bake



Pattern Inspection



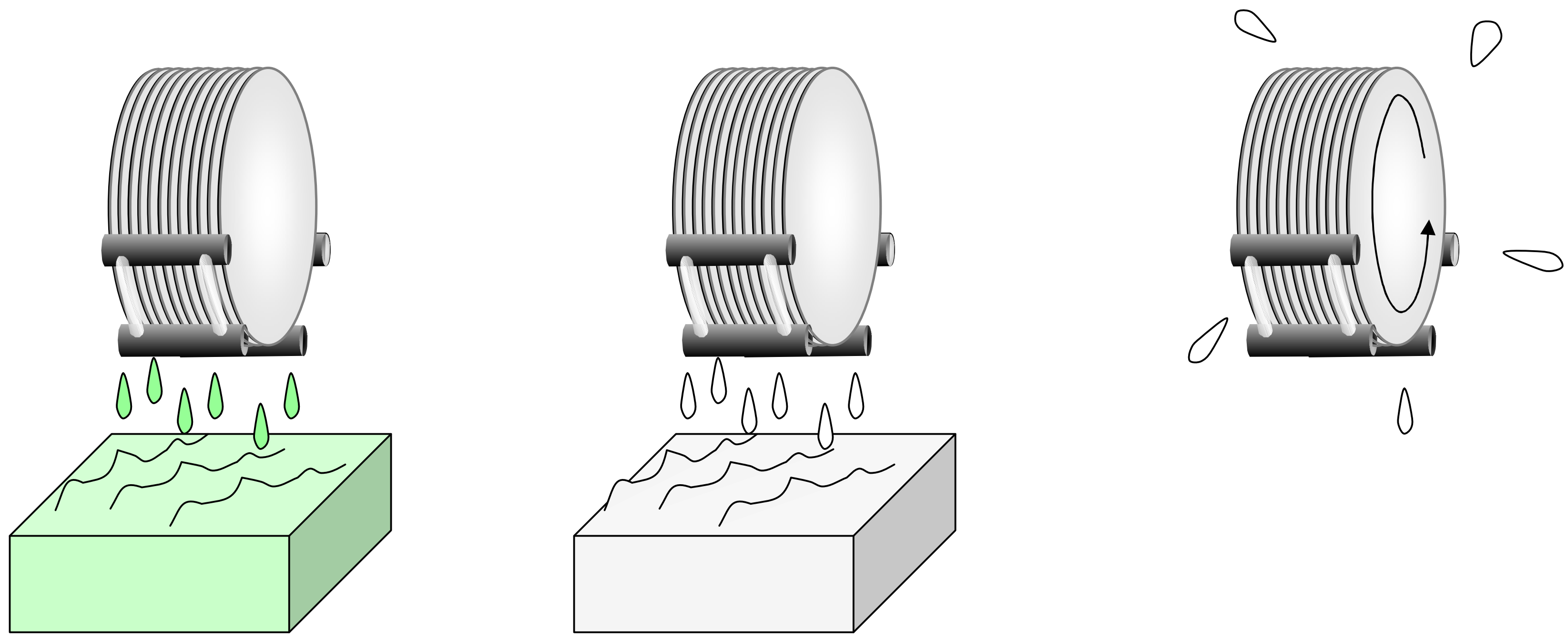
Wafer Clean

- Remove contaminants
- Remove particulate
- Reduce pinholes and other defects
- Improve photoresist adhesion
- Basic steps
  - Chemical clean
  - Rinse
  - Dry

Photolithography Process, Clean

- Older ways
  - High-pressure nitrogen blow-off
  - Rotating brush scrubber
  - High-pressure water stream

Wafer Clean Process



Chemical Clean　　Rinse　　Dry

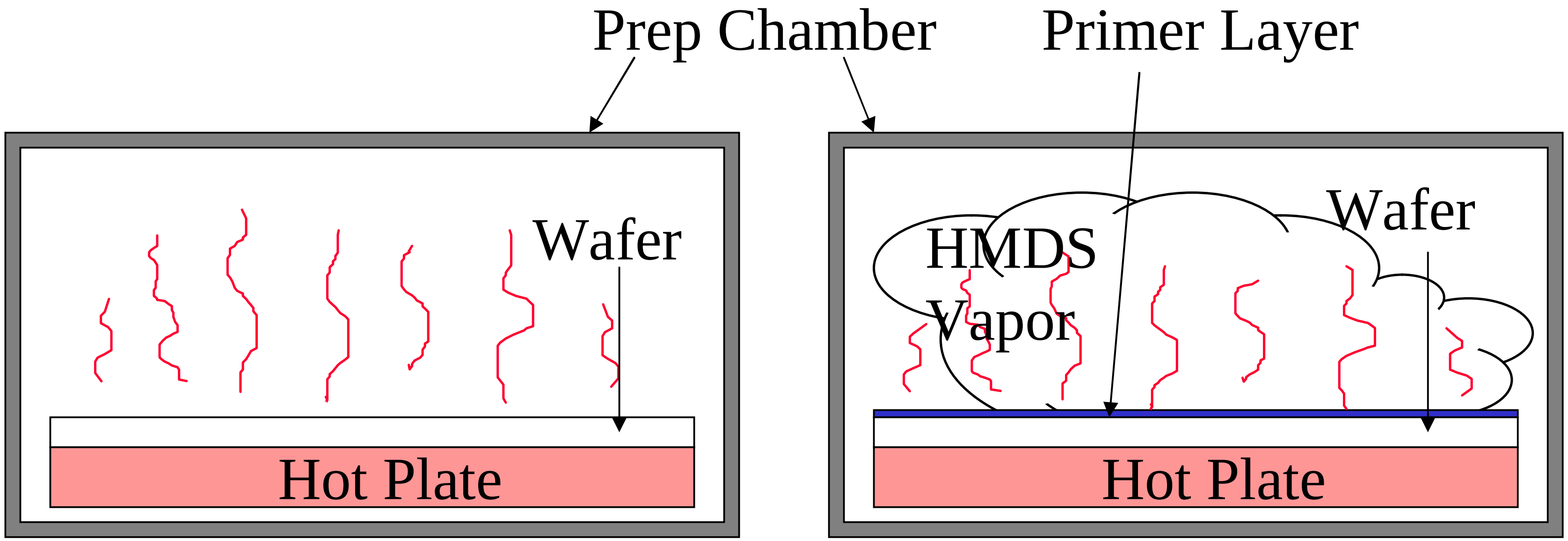
Photolithography Process, Prebake

- Dehydration bake
- Remove moisture from wafer surface
- Promote adhesion between PR and surface
- Usually around 100 °C
- Integration with primer coating

Photolithography Process, Primer

- Promotes adhesion of PR to wafer surface
- Wildly 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

Pre-bake and Primer Vapor Coating



Dehydration Bake

Primer Vapor Coating

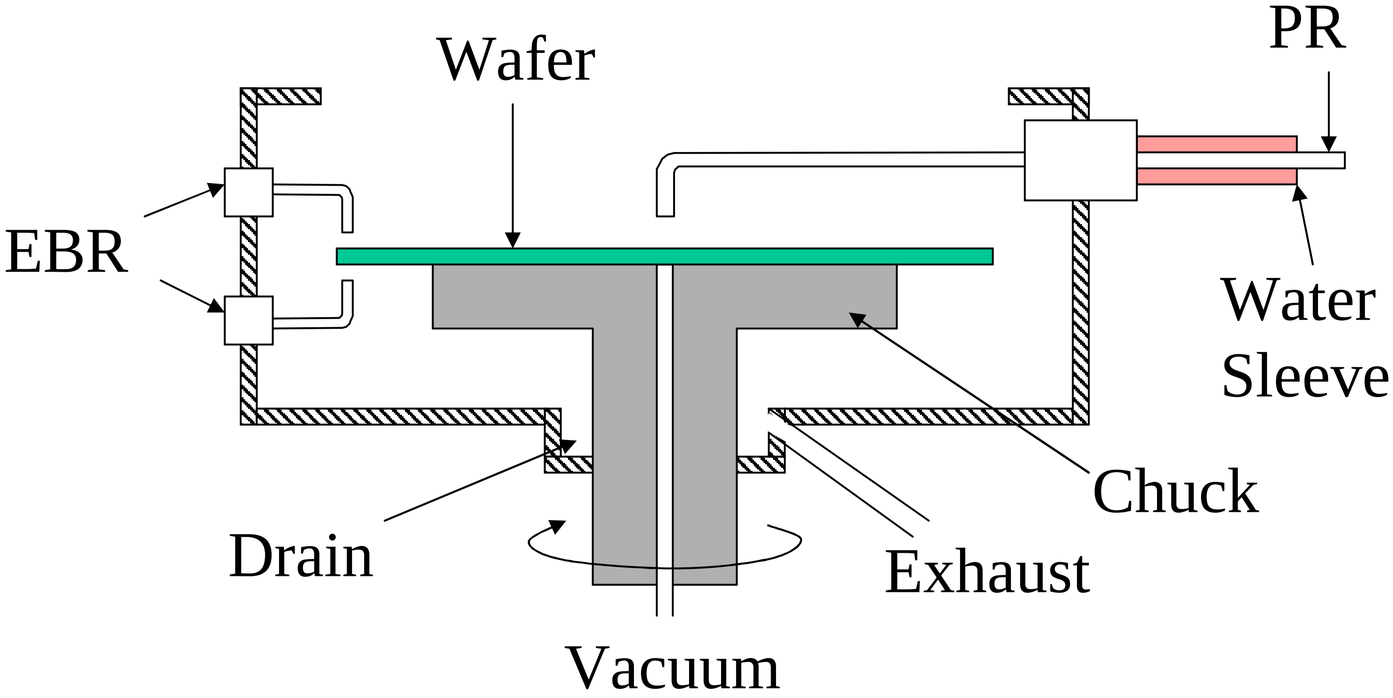
Wafer Cooling

- Wafer need to cool down
- Water-cooled chill plate
- Temperature can affect PR viscosity
  - Affect PR spin coating thickness

Spin Coating

- Wafer sit on a vacuum chuck
- Rotate at high speed
- Liquid photoresist applied at center of wafer
- Photoresist spread by centrifugal force
- Evenly coat on wafer surface

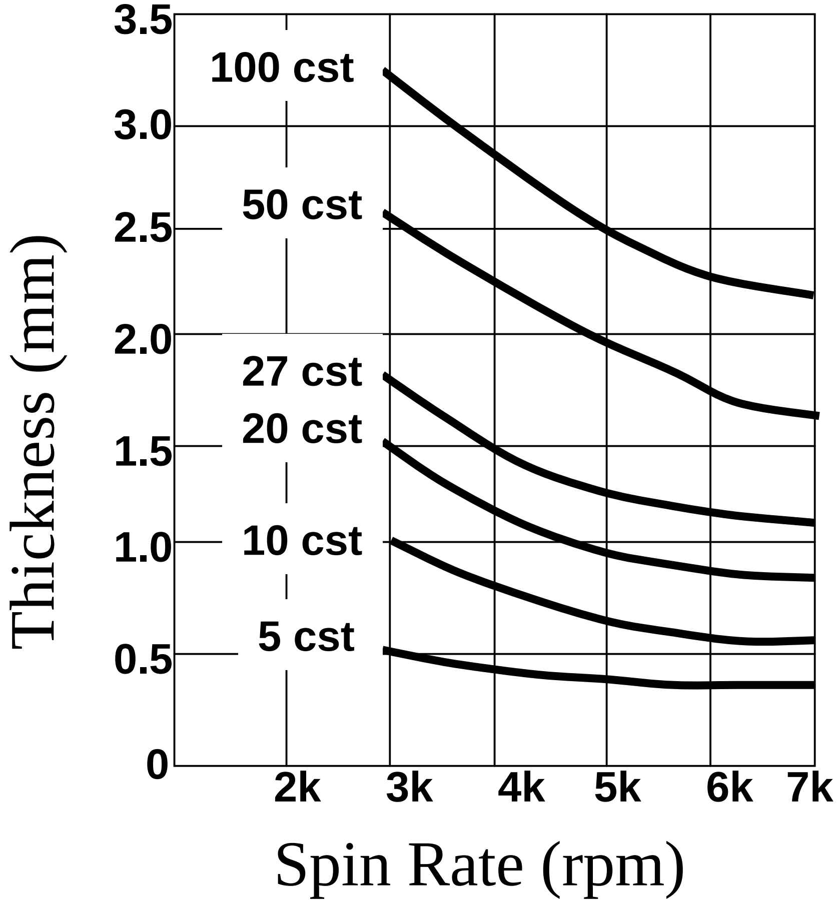
Photoresist Spin Coater



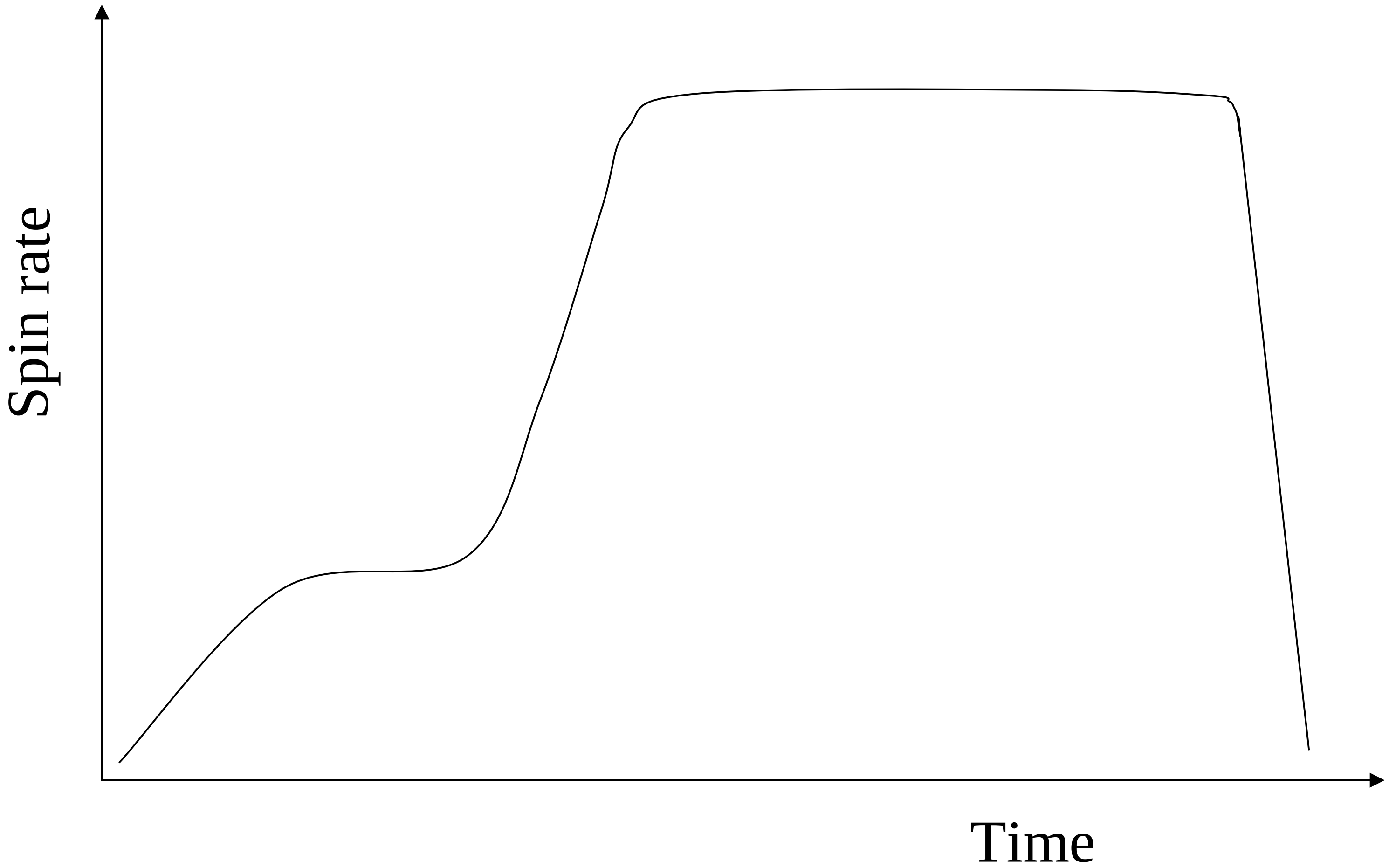
Viscosity

- Fluids stick on the solid surface
- Affect PR thickness in spin coating
- Related to PR type and temperature
- Need high spin rate for uniform coating

Relationship of Photoresist Thickness to Spin Rate and Viscosity



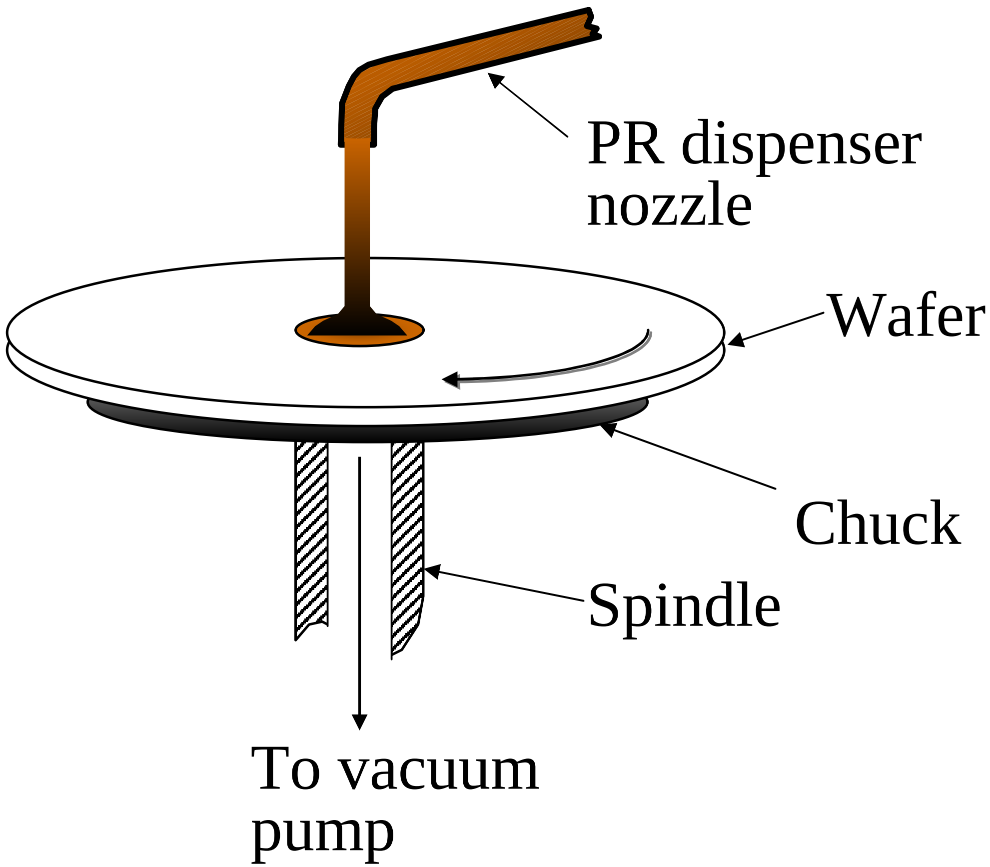
Dynamic Spin Rate



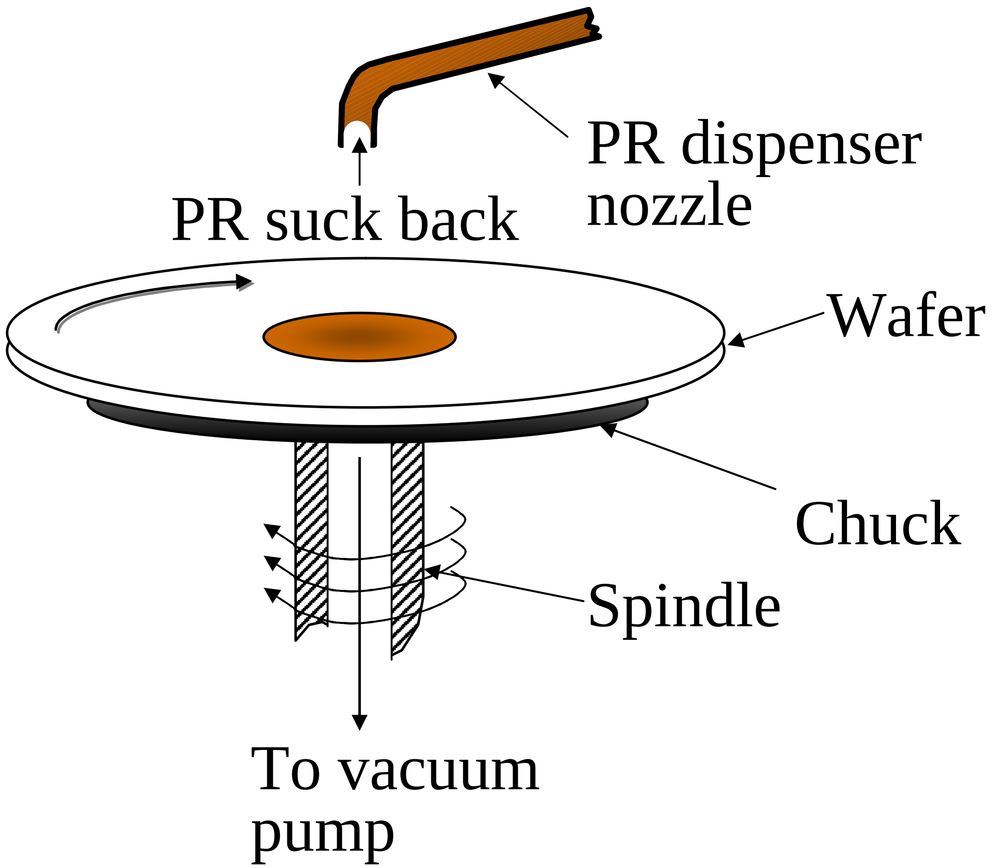
PR Spin Coater

- Photoresist spread on spinning wafer surface
- Wafer held on a vacuum chuck
- Slow spin ~ 500 rpm
- Ramp up to ~ 3000 - 7000 rpm

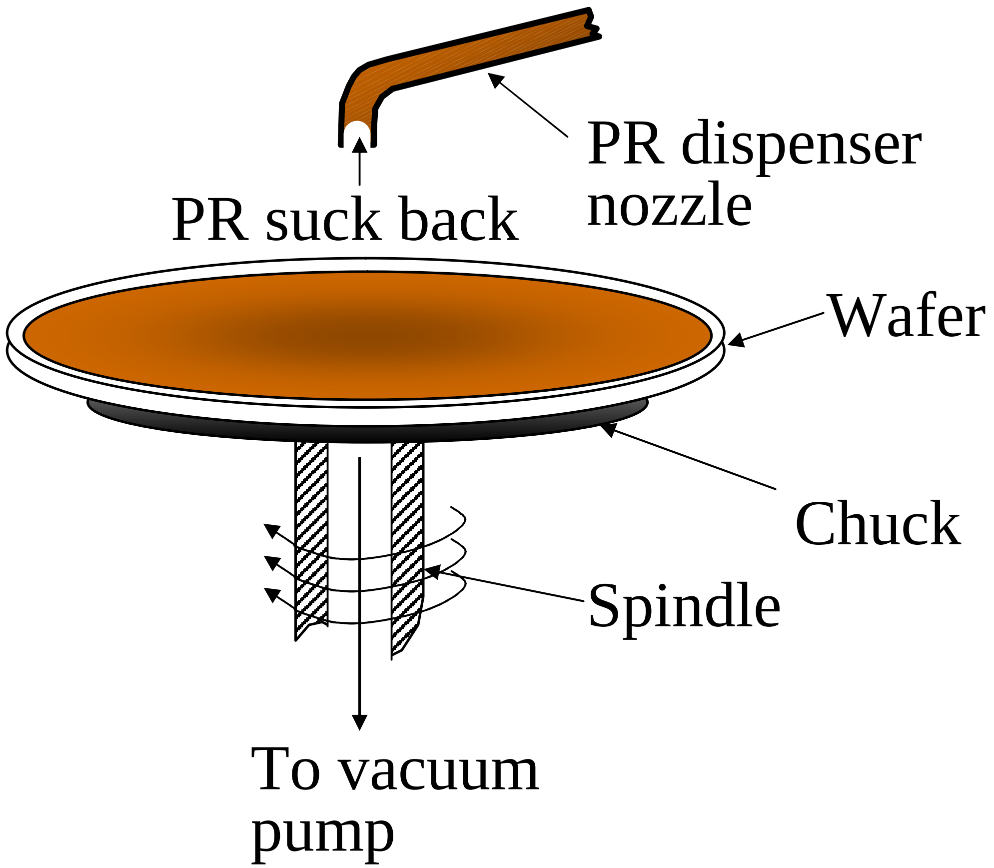
Photoresist Applying



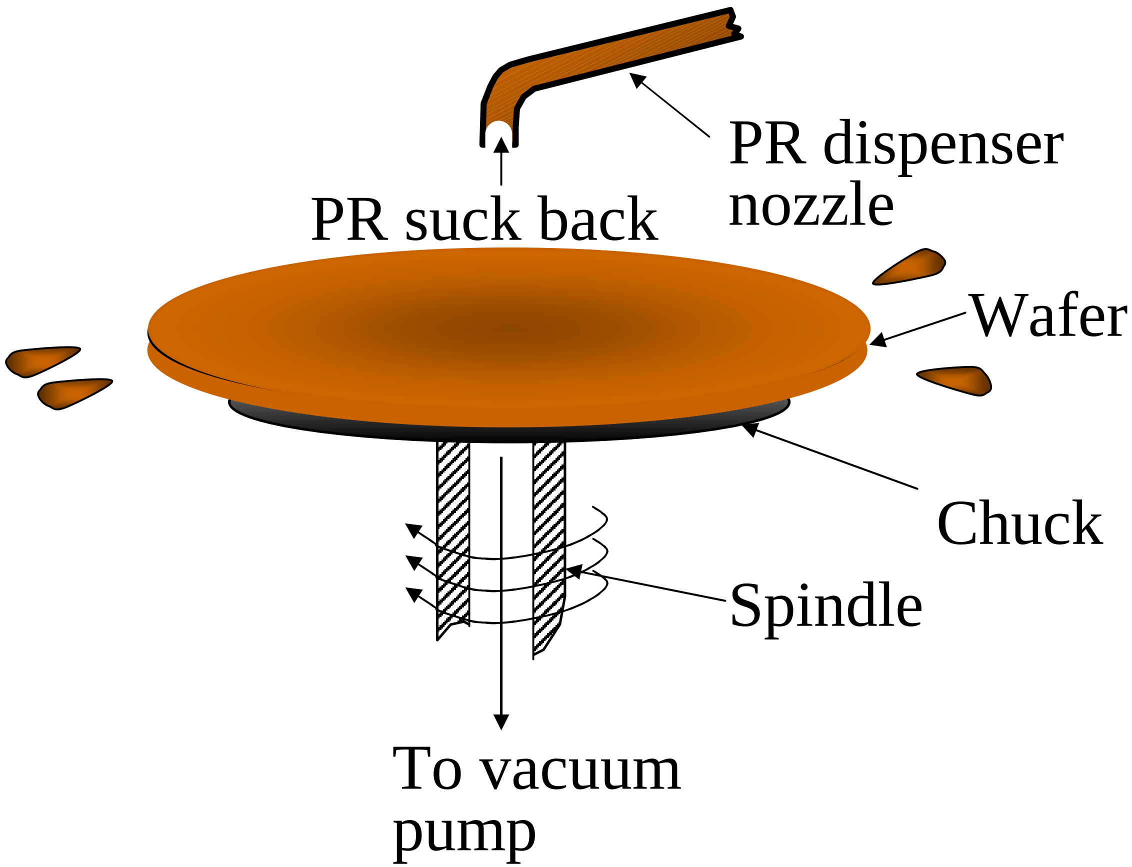
Photoresist Suck Back



Photoresist Spin Coating



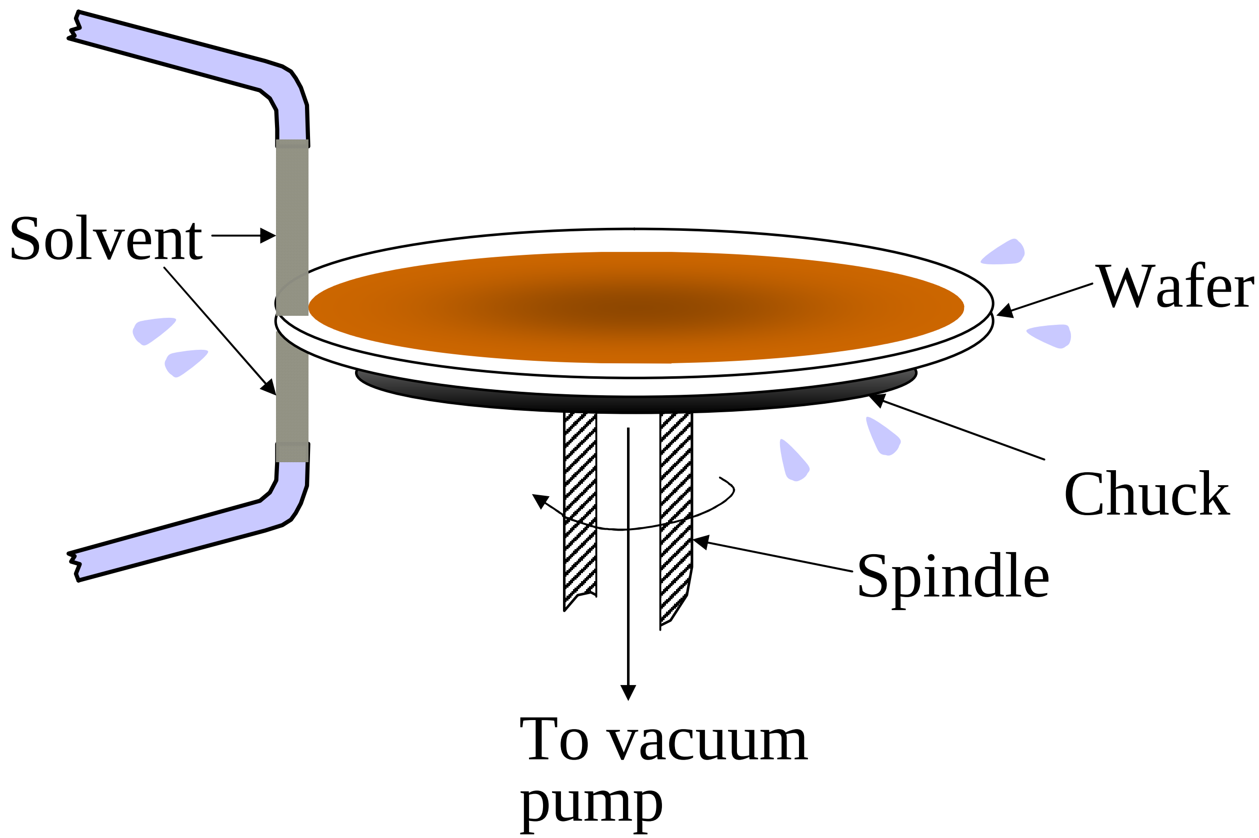
Photoresist Spin Coating



Edge Bead Removal (EBR)

- PR spread to the edges and backside
- PR could flakes off during mechanical handling and causes particles
- Front and back chemical EBR

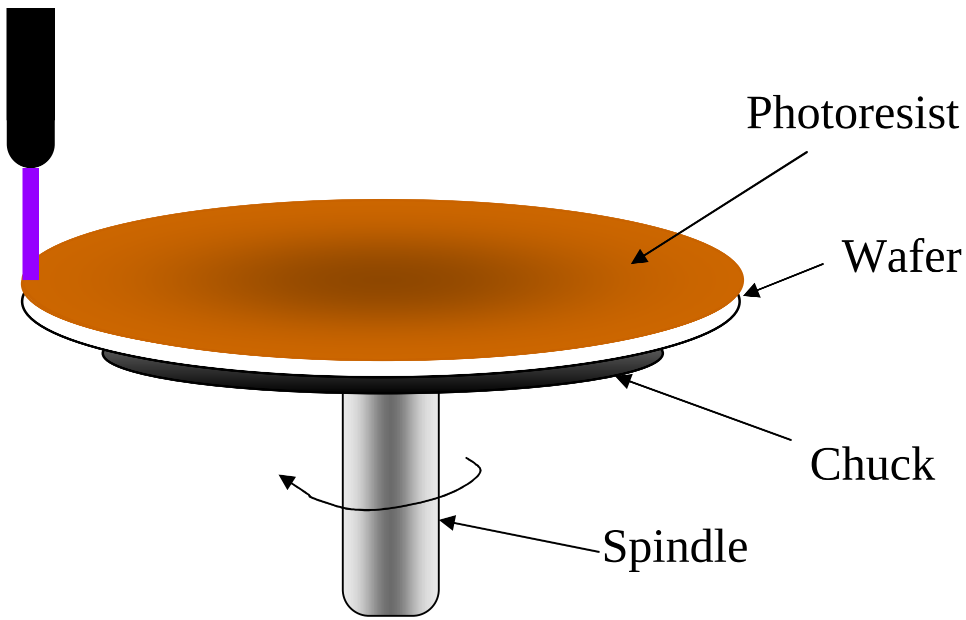
Edge Bead Removal



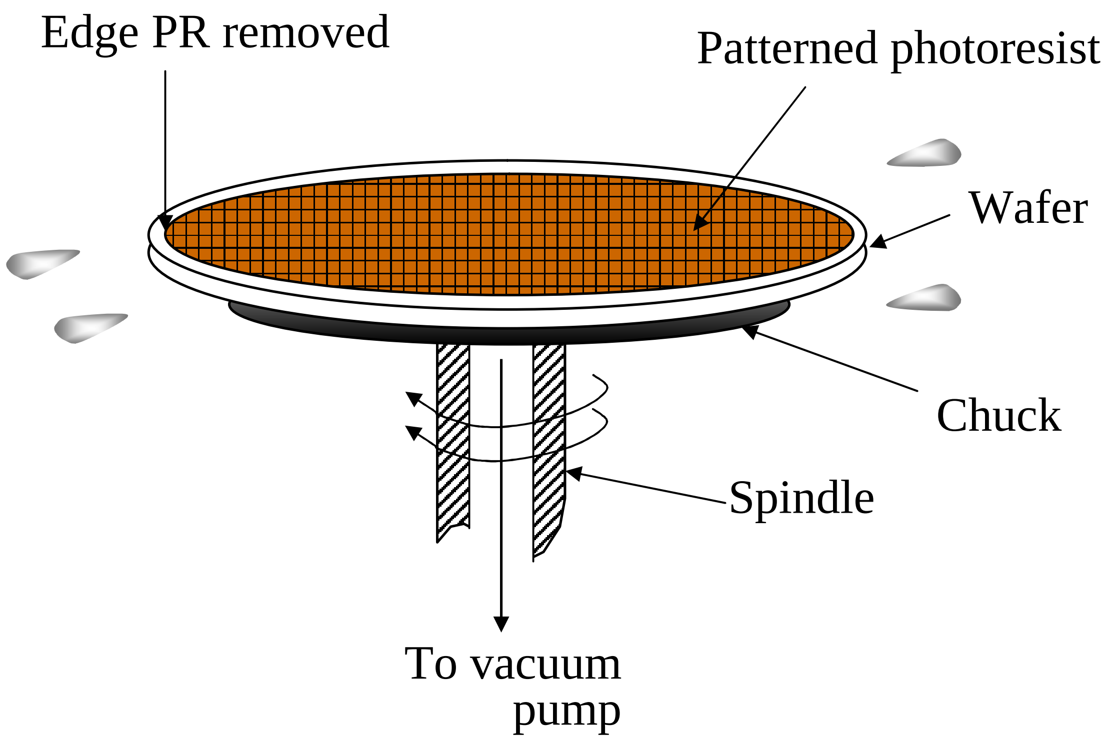
Optical Edge Bead Removal

- After alignment and exposure
- Front-side wafer edge expose (WEE)
- Exposed photoresist at edge dissolves during development

Optical Edge Bead Removal



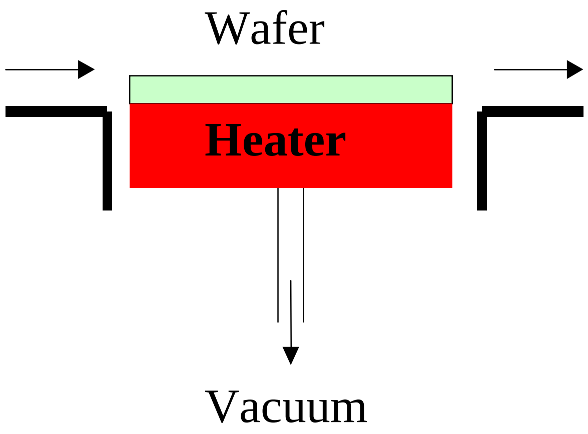
Developer Spin Off



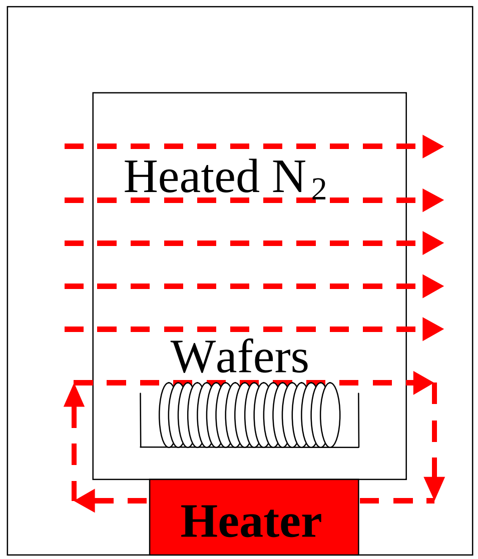
Soft Bake

- Evaporating most of solvent (> 80%) in PR
- Solvents help to make a thin PR but absorb radiation and affect adhesion
- Soft baking time and temperature are determined by PR types and specific process
- 90~110°C for 30 min. in oven; 10~15 min. for hotplate
- Over bake: polymerized, less photo-sensitivity
- Under bake: affect adhesion and exposure

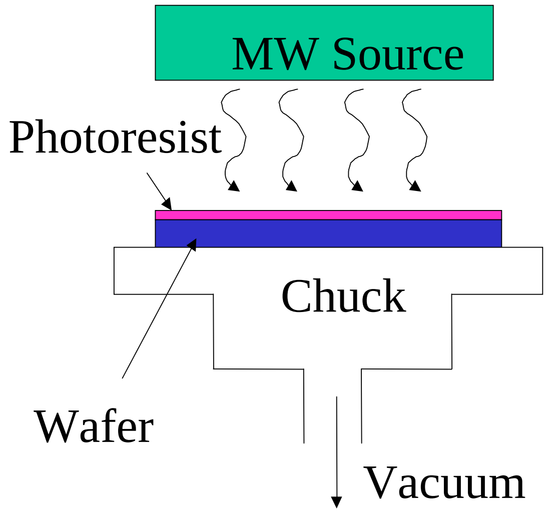
Baking Tools



Hot plate



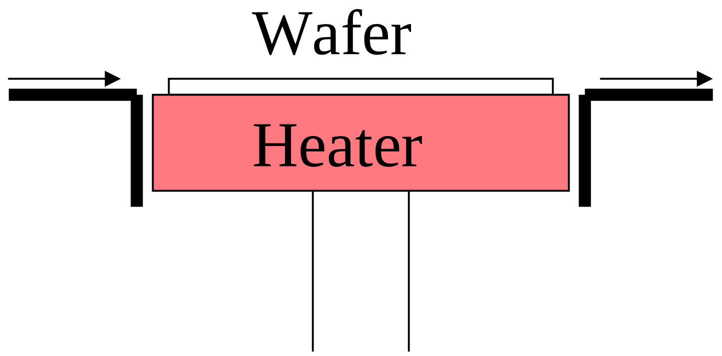
Convection oven



Microwave oven

Hot Plates

- Widely used in the industry
- Back side heating, no surface "crust"
- In-line track system



Wafer Cooling

- Need to cool down to ambient temperature after baking
- Water-cooled chill plate
- Silicon thermal expansion rate: 2.5×10^{-6}/°C
- For 8 inch (200 mm) wafer, <u>1°C thermal change causes 0.5 μm difference in diameter</u>

Alignment and Exposure

- Most critical process for IC fabrication
- Most expensive tool (stepper) in an IC fab.
- Most challenging technology
- Determines the minimum feature size
- Currently 0.18 μm and pushing to 0.13 μm

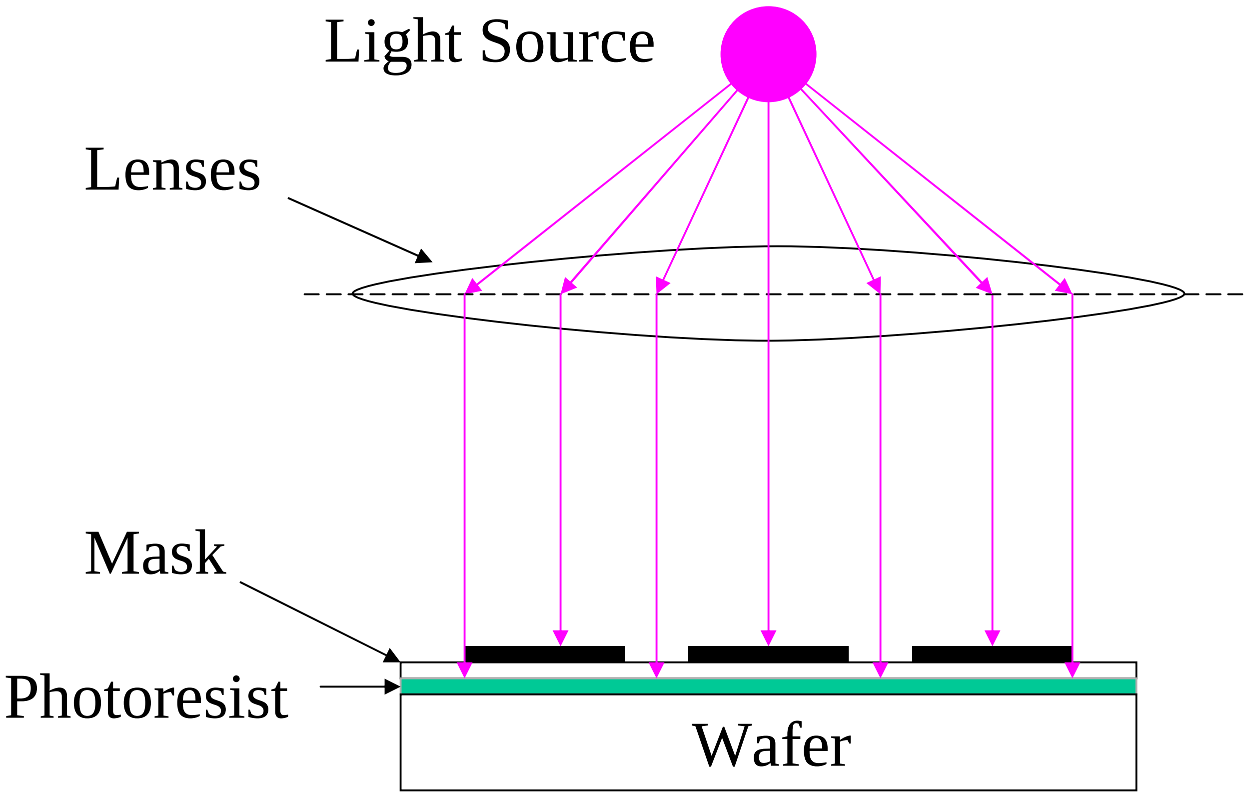
Alignment and Exposure Tools

- Contact printer
- Proximity printer
- Projection printer
- Stepper

Contact Printer

- Simple equipment. Widely used before mid-70s
- Resolution: capable for sub-micron
- Use of UV light source
- Image ratio 1:1
- Direct mask-wafer contact, limited mask lifetime
- Particle contamination issue

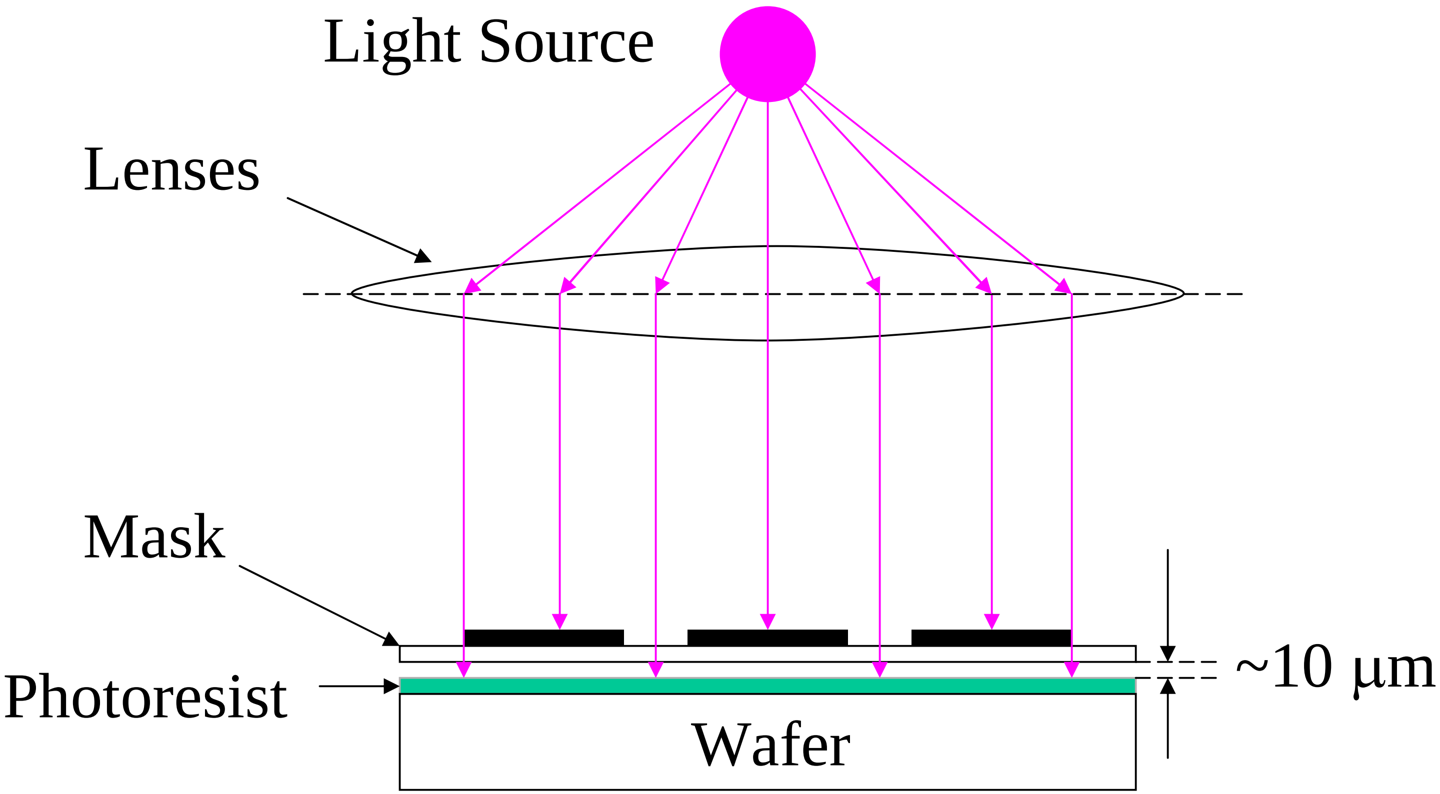
Contact Printer



Proximity Printer

- 10 ~ 20 μm distance from wafer surface. No direct contact
- Use of UV light
- Image ratio 1:1
- Less particles and longer mask lifetime
- Resolution: > 2 μm

Proximity Printer

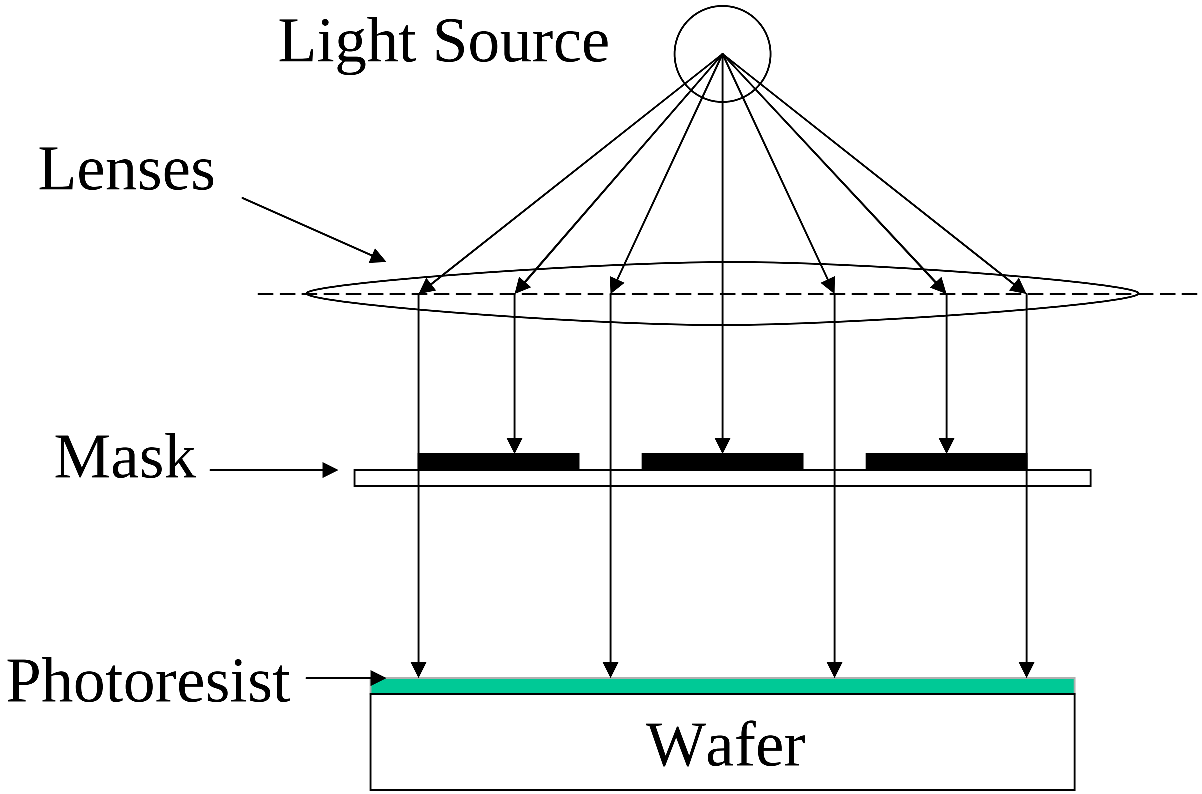


Projection Printer

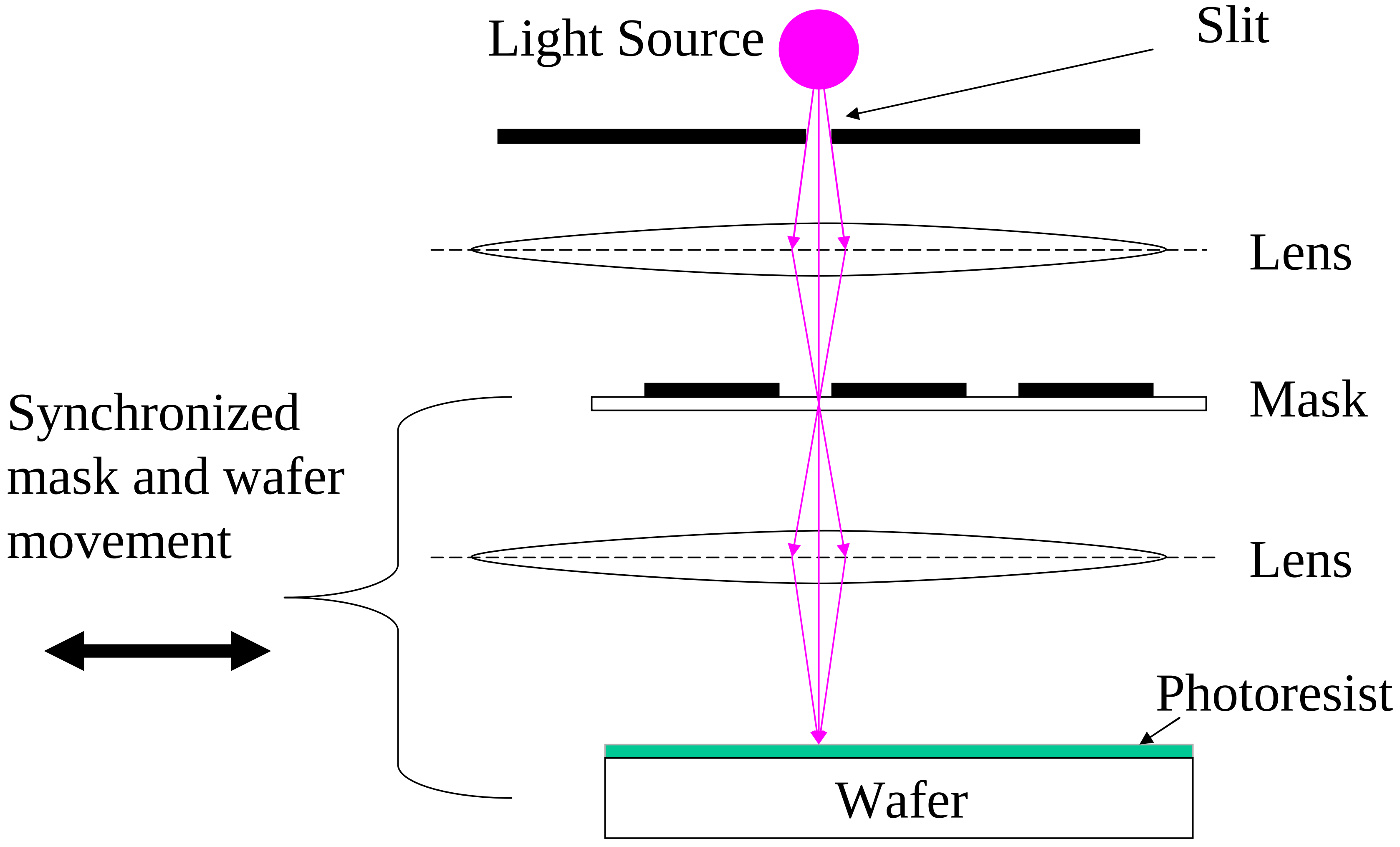
- Works like an overhead projector
- Mask to wafer ratio, 1:1
- Resolution to reach at 1 μm
- The scanning projection exposure system

  - the mask and wafer stage move synchronously, allowing UV light source scanning across the mask to refocus and expose PR across the wafer

Projection System



Scanning Projection System



Stepper

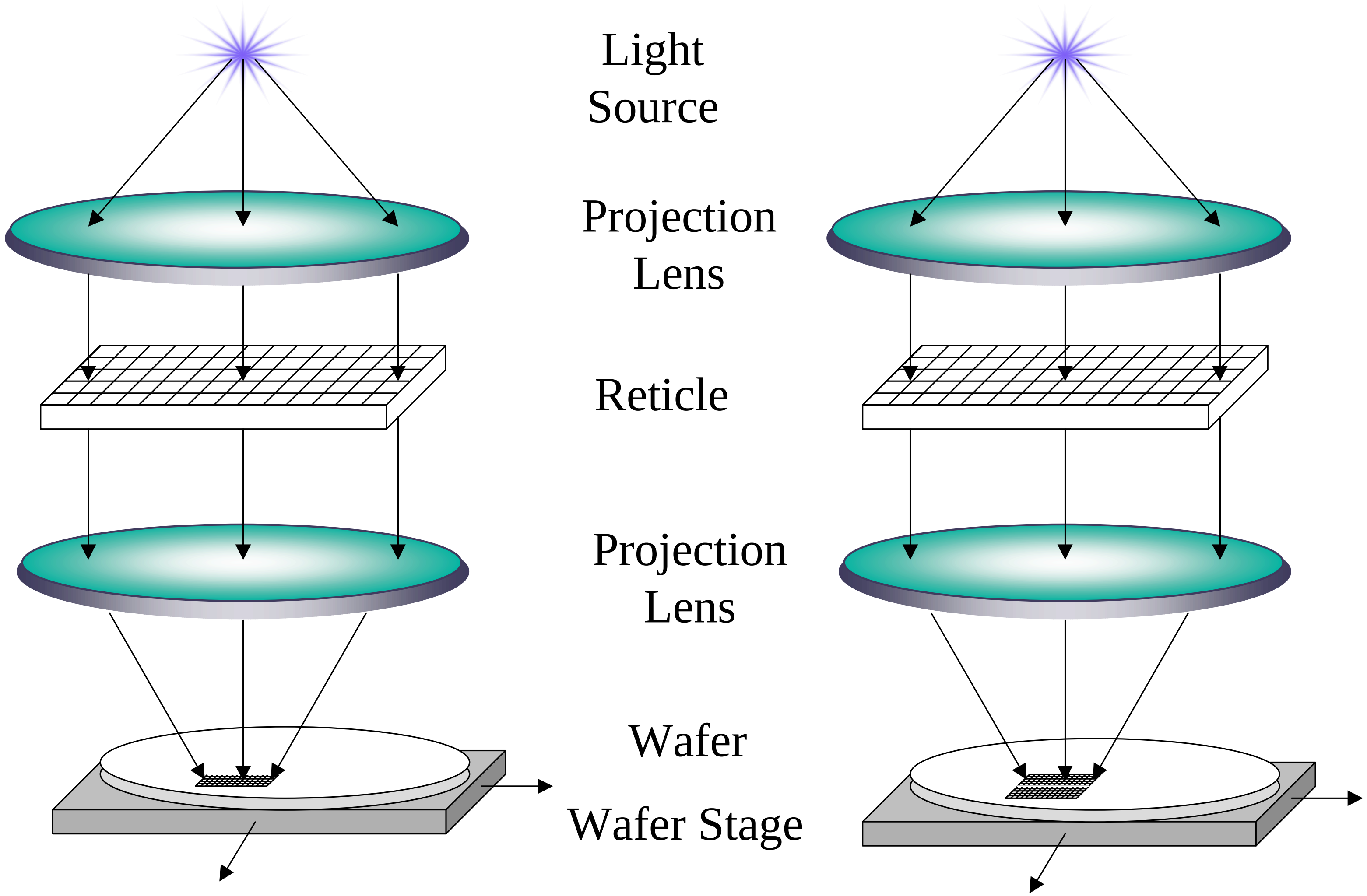
- Most popular used photolithography tool in the advanced IC fabs
- Reduction of wafer image gives high resolution
- Use of deep UV light
- Reticle-to-wafer ratio ~ 10:1
- A reticle with 1.25 μm min. feature size say can achieve 0.125 μm min. feature size on wafer
- Very expensive ! (extremely complicated and precise)

Q & A

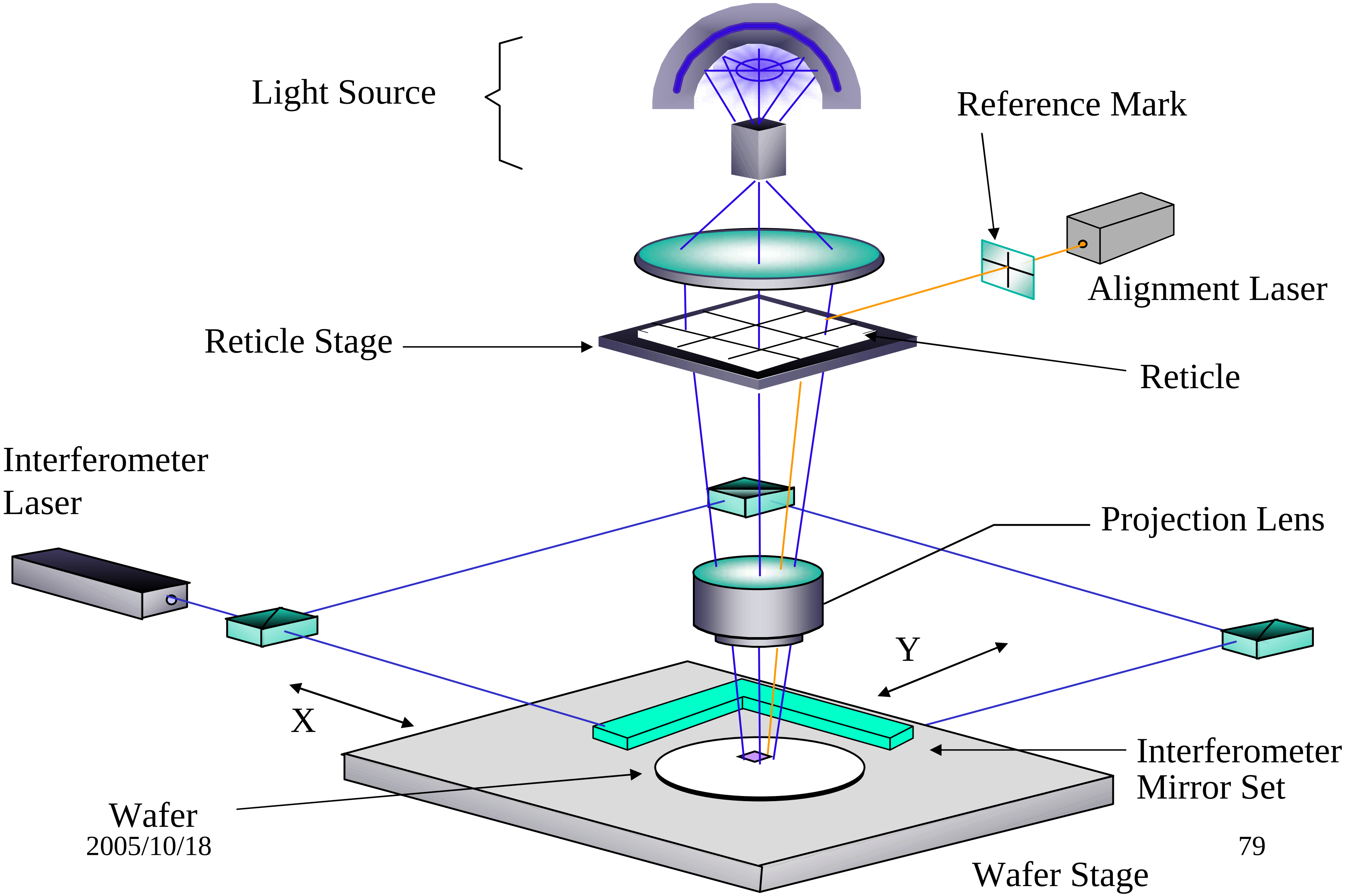
Q : Why does the 5:1 shrink ratio is more popular than the 10:1 shrink ratio?

A : 10:1 image shrink has better resolution than 5:1 image shrink. However, it only exposes a quarter of the area, which means total exposure time will be quadrupled. A trade-off between resolution and throughput.

Step-&-Repeat Alignment/Exposure



Step&Repeat Alignment System



Exposure Light Source

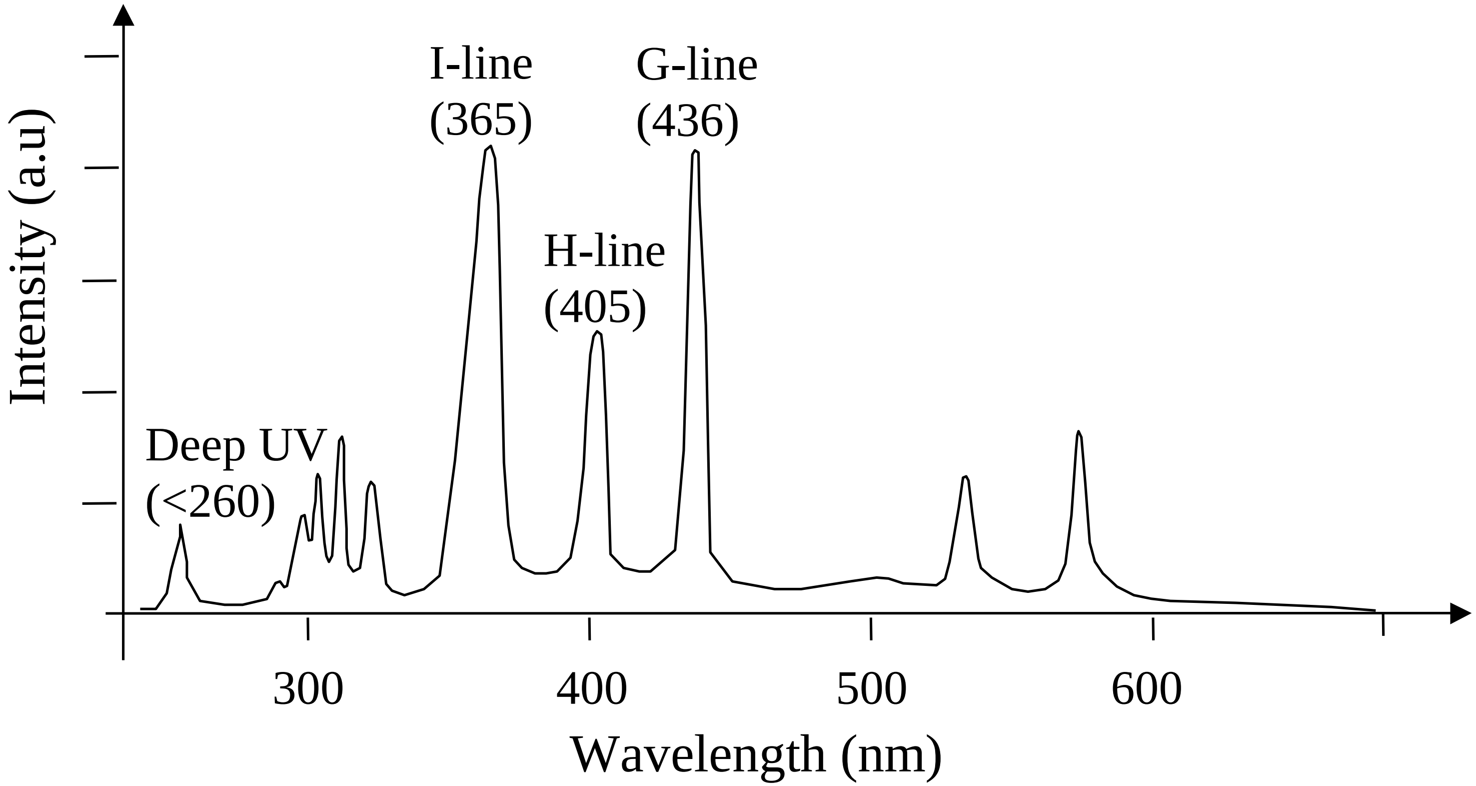
Should have :

- Short wavelength
- High intensity
- Stability

Includes :

- High-pressure mercury lamp
- Excimer laser

Spectrum of the Mercury Lamp



Photolithography Light Sources

	Name	**Wavelength (nm)**	**Application feature size (μm)**
Mercury Lamp	G-line	436	0.50
	H-line	405	
	I-line	365	0.35 to 0.25
Excimer Laser	XeF	351	
	XeCl	308	
	KrF (DUV)	248	0.25 to 0.15
	ArF	193	0.18 to 0.13
Fluorine Laser	F_2	157	0.13 to 0.1

Exposure Control

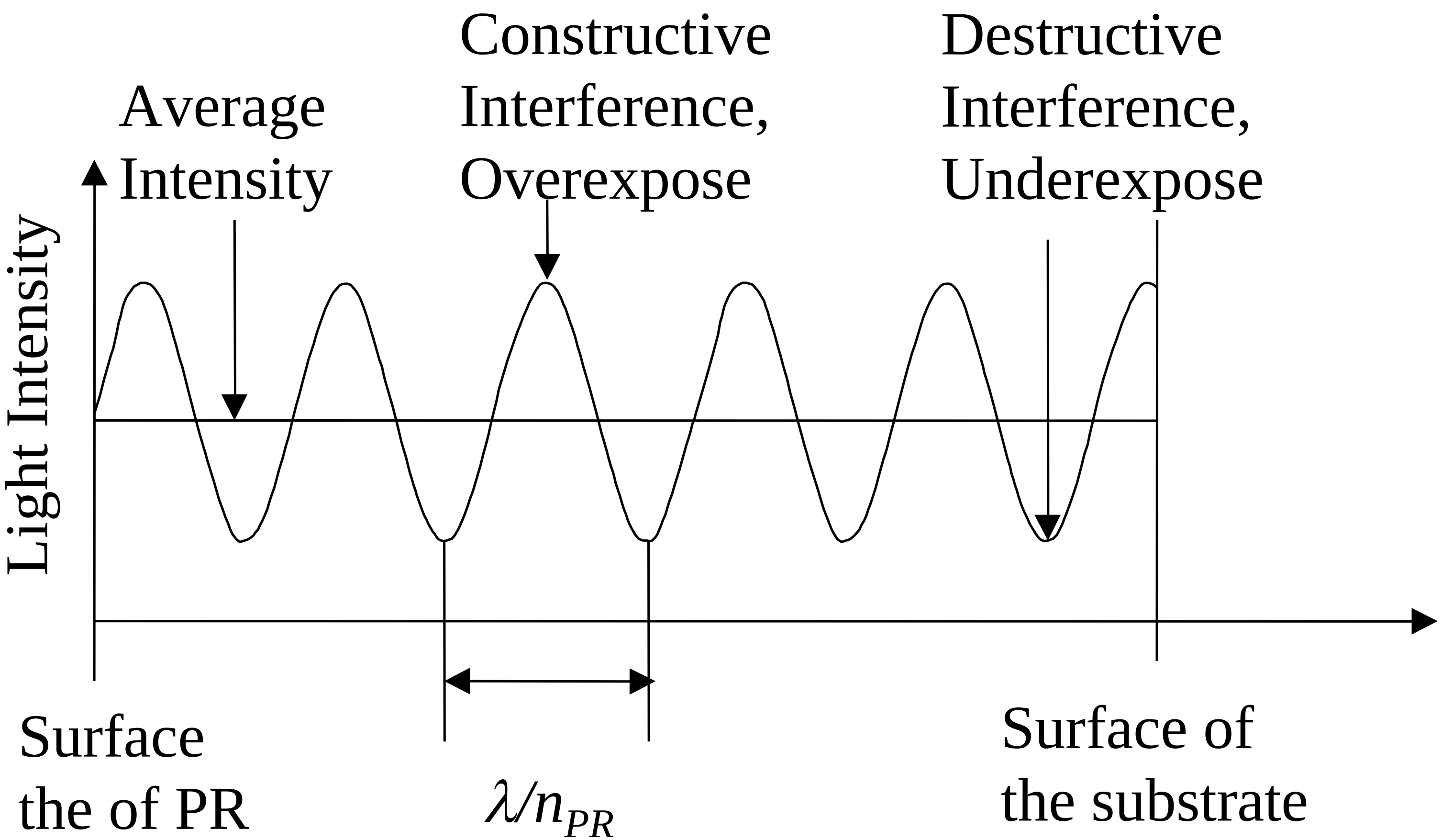
- Exposure light flux is controlled by production of light intensity and exposure time
- Very similar to the exposure of a camera
- Intensity controlled by electrical power
- Adjustable light intensity
- Routine light intensity calibration is required.

  Intensity, $\boldsymbol{I}$, measured in mW/cm^2

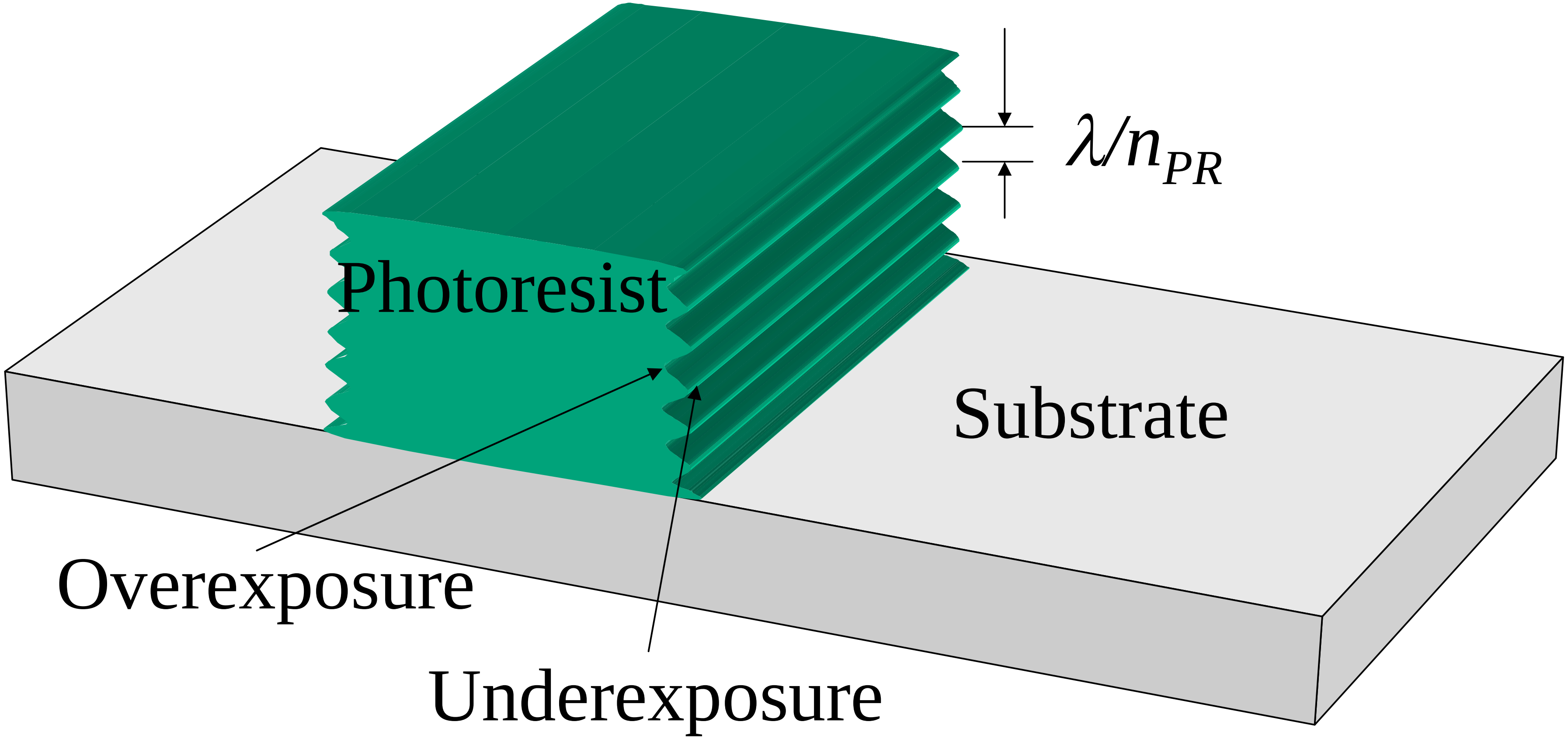
Standing Wave Effect

- Interference of the <u>incident and reflection lights</u>
- Due to constructive and destructive interference at different depth
- Periodically overexposure and underexposure
- Affects photolithography resolution.

Standing Wave Intensity



Standing Wave Effect on Photoresist



Post Exposure Bake (PEB)

- Photoresist's glass transition temperature, T_g
- Baking temperature is higher than T_g
- Induce thermal movement of photoresist molecules
- Rearrangement of the overexposed and underexposed PR molecules
- Average out standing wave effect,
- Smooth PR sidewall and improve resolution

PEB (cont.)

- For DUV chemical amplified photoresist, PEB provides the heat needed for acid diffusion and amplification.
- After the PEB process, the images of the exposed areas appear on the photoresist, due to the significant chemical change after the acid amplification

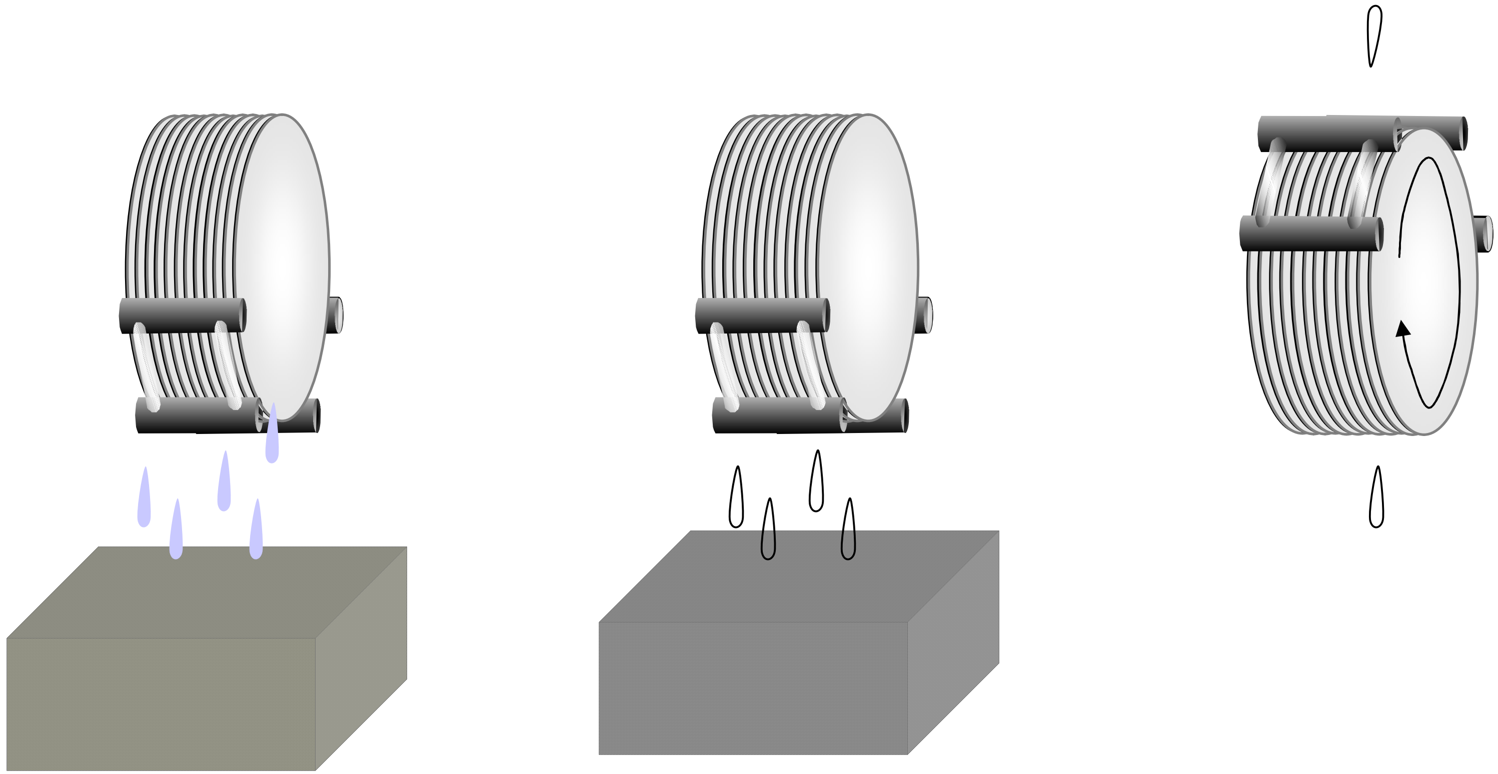
Post Exposure Bake Steps

- PEB normally uses hot plate at 110 to 130 °C for about 1 minute.
- 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,
- Overbaking will cause polymerization and affects photoresist development

Development

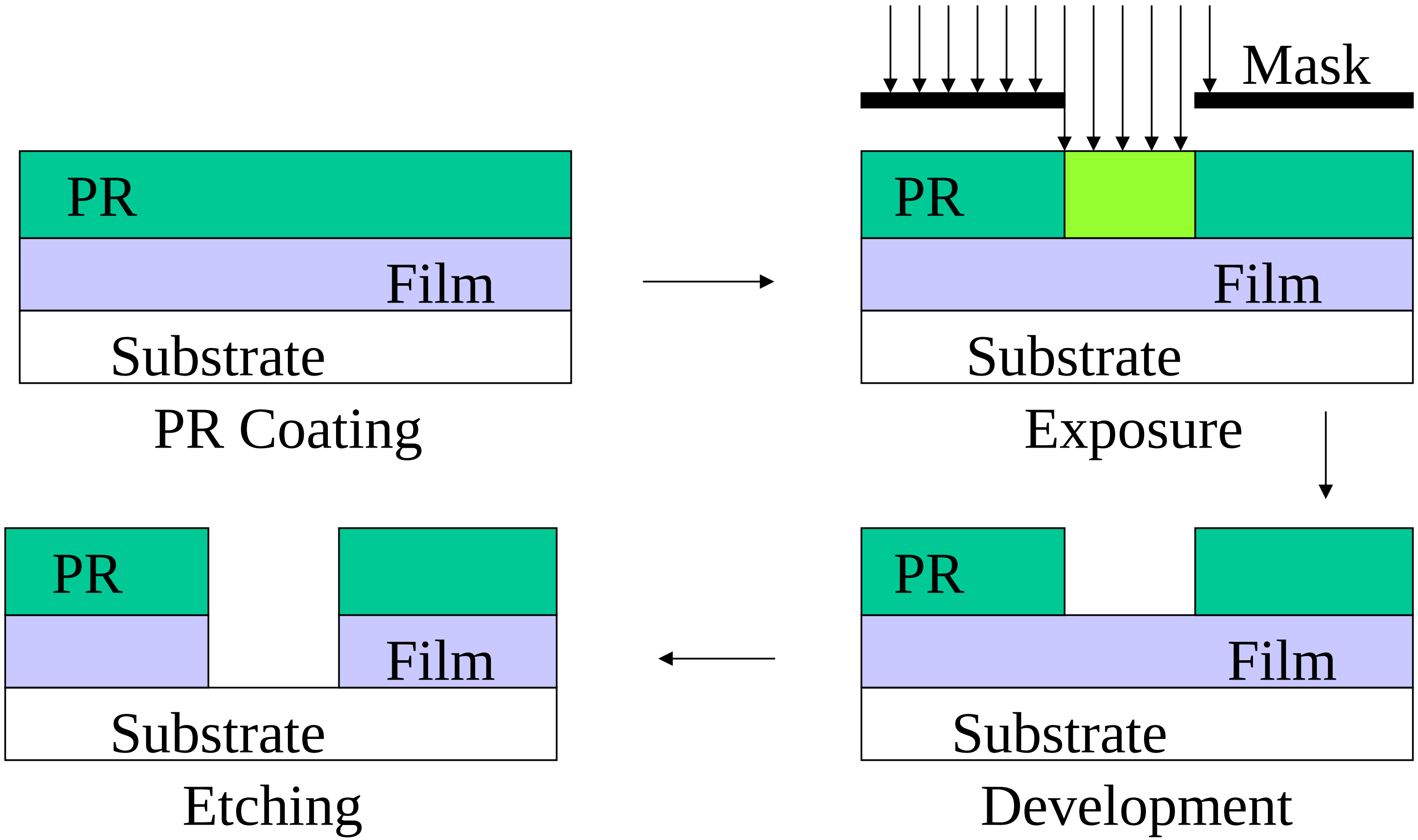
- Developer solvent dissolves the softened part of photoresist
- Transfer the pattern from mask or reticle to photoresist
- Three basic steps:
  - Development
  - Rinse
  - Dry

Development: Immersion

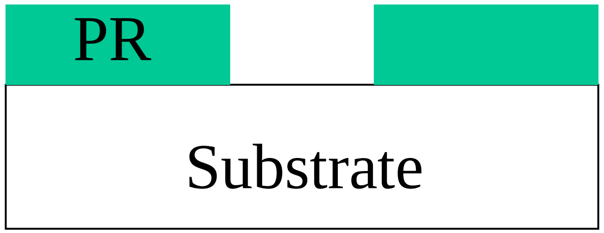


Develop　　Rinse　　Spin Dry

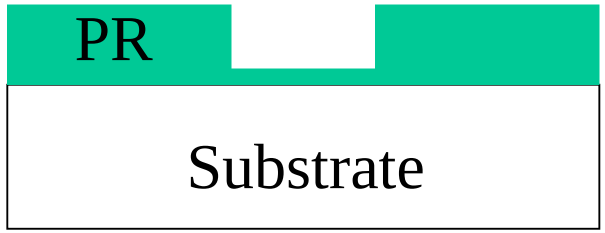
Development – to make etch or implantation perfect



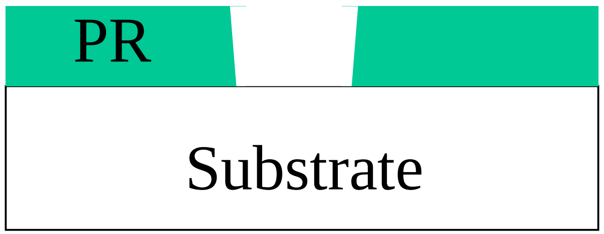
Development Profiles



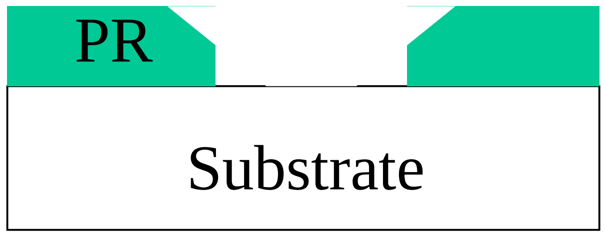
Normal Development



Incomplete Development



Under Development



Over Development

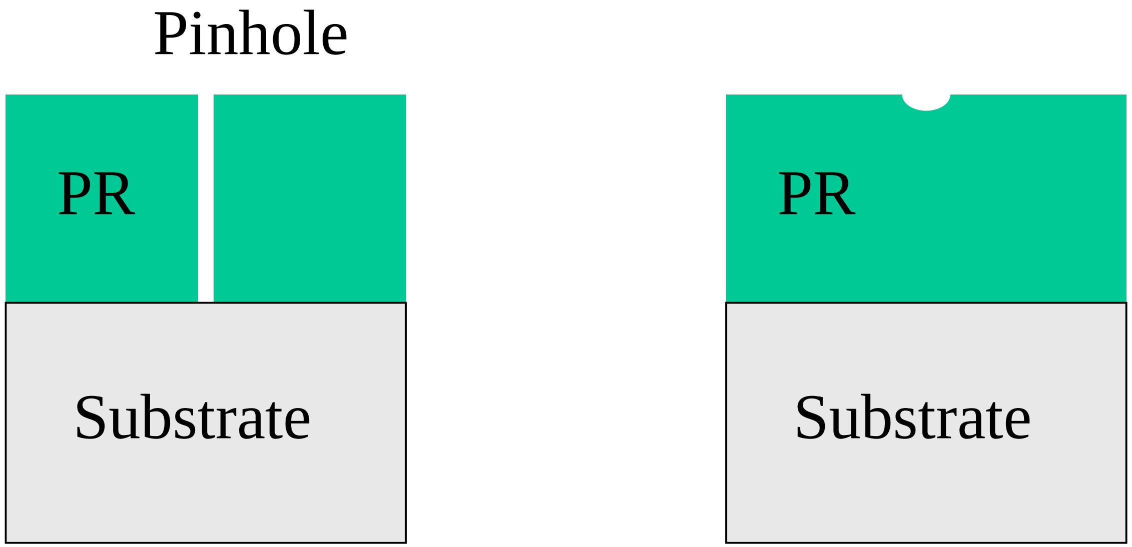
Developer Solutions

	Positive PR	Negative PR
Developer	TMAH	Xylene
Rinse	DI Water	n-Butylacetate

Hard Bake

- Evaporating all solvents in PR
- Improving etch and implantation resistance
- Improve PR adhesion with surface
- Polymerize and stabilize photoresist
- PR flow to fill pinhole

PR Pinhole Fill by Thermal Flow



Hard Bake (cont.)

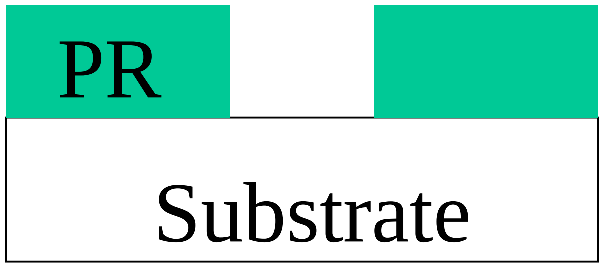
- Hot plate is commonly used
- Can be performed in a oven after inspection
- Hard bake temperature: 100 to 130 °C
- Baking time is about 1 to 2 minutes
- Hard bake temperature normally is higher than the soft bake temperature for the same kind of photoresist

Improper Hard Bake

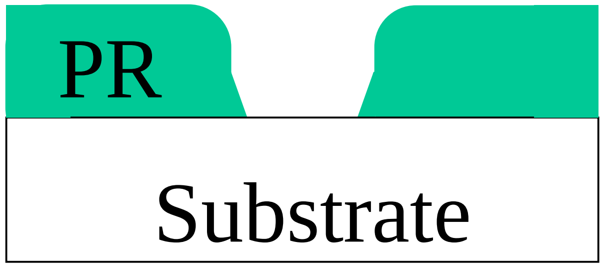
- Under-bake
  - Photoresist is not filly polymerized
  - High photoresist etch rate
  - Poor adhesion
- Over-baking
  - PR flow and bad resolution

Photoresist Flow

- Over-baking can causes too much PR flow, which affects photolithography resolution.



Normal Baking



Over Baking

Pattern Inspection

- Inspection, stripped PR and rework
  - Photoresist pattern is temporary
  - Etch or ion implantation pattern is permanent.
- Photolithography process can rework
- Can’t rework after etch or implantation.
- Scanning electron microscope (SEM) for small feature size (< 0.5 um)
- Optical microscope for large feature size

Q & A

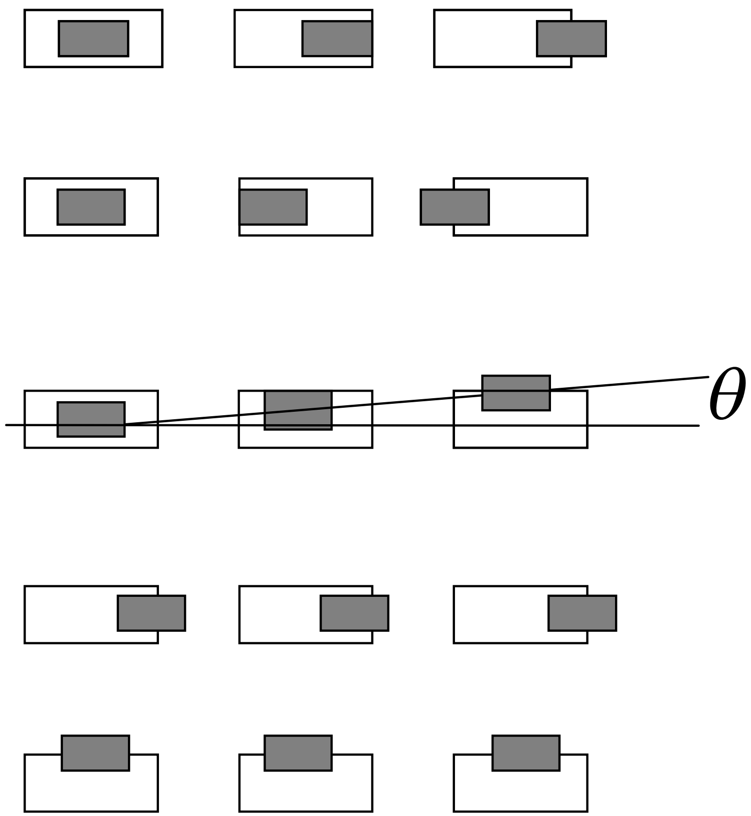
- Why can't optical microscope be used for the 0.25 μm feature inspection?

- Because the feature size (0.25 μm = 2500 Å) is smaller than the wavelength of the visible light, which is from 3900 Å (violet) to 7500 Å (red)..

Pattern Inspection

- Overlay or alignment
  - run-out, run-in, reticle rotation, wafer rotation, misplacement in X-direction, and misplacement in Y-direction
- Critical dimension (CD) loss
- Surface irregularities such as scratches, pin holes, stains, contamination, etc.

Misalignment Cases



Run-out

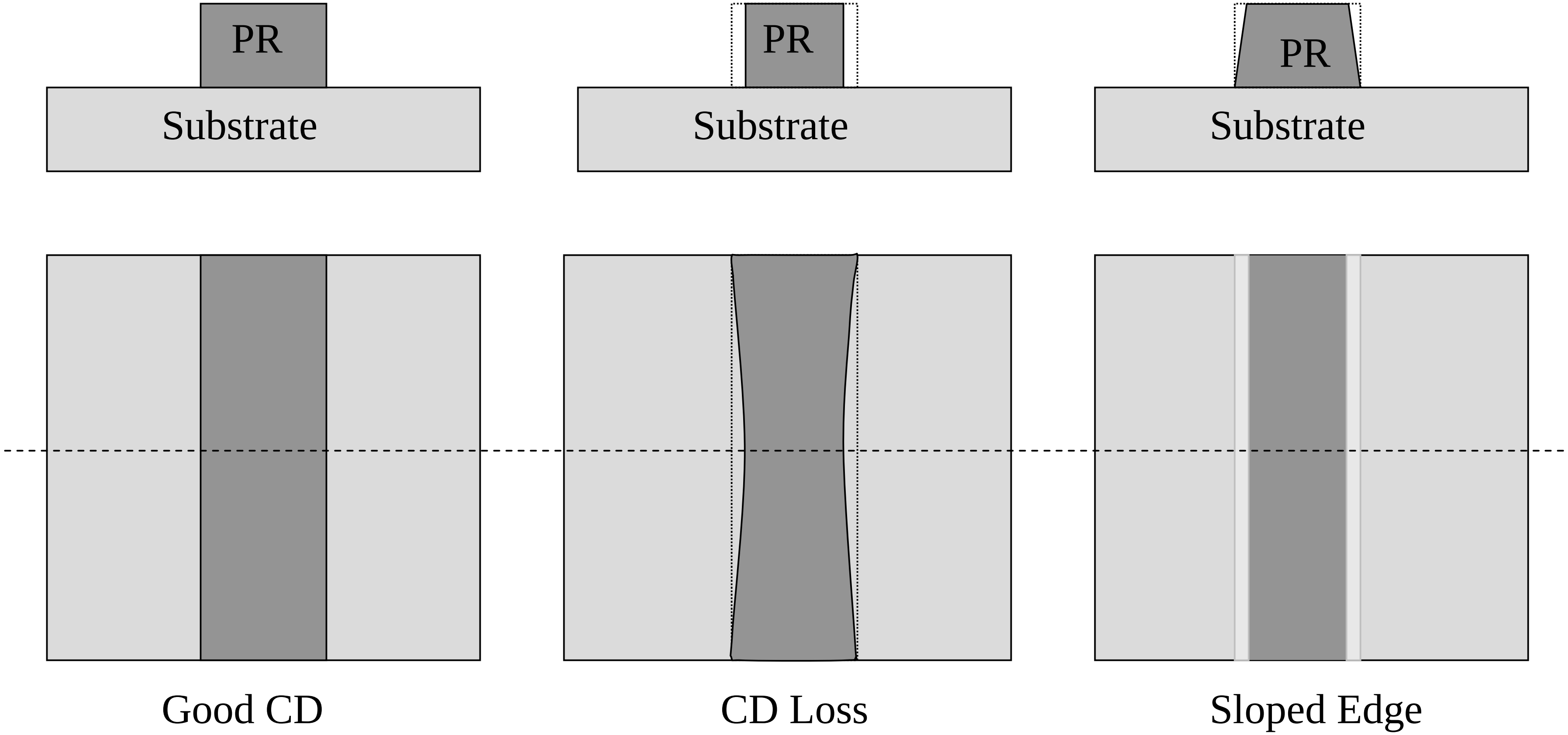
Run-in

Reticle rotation
Wafer rotation

Misplacement in x-direction

Misplacement in y-direction

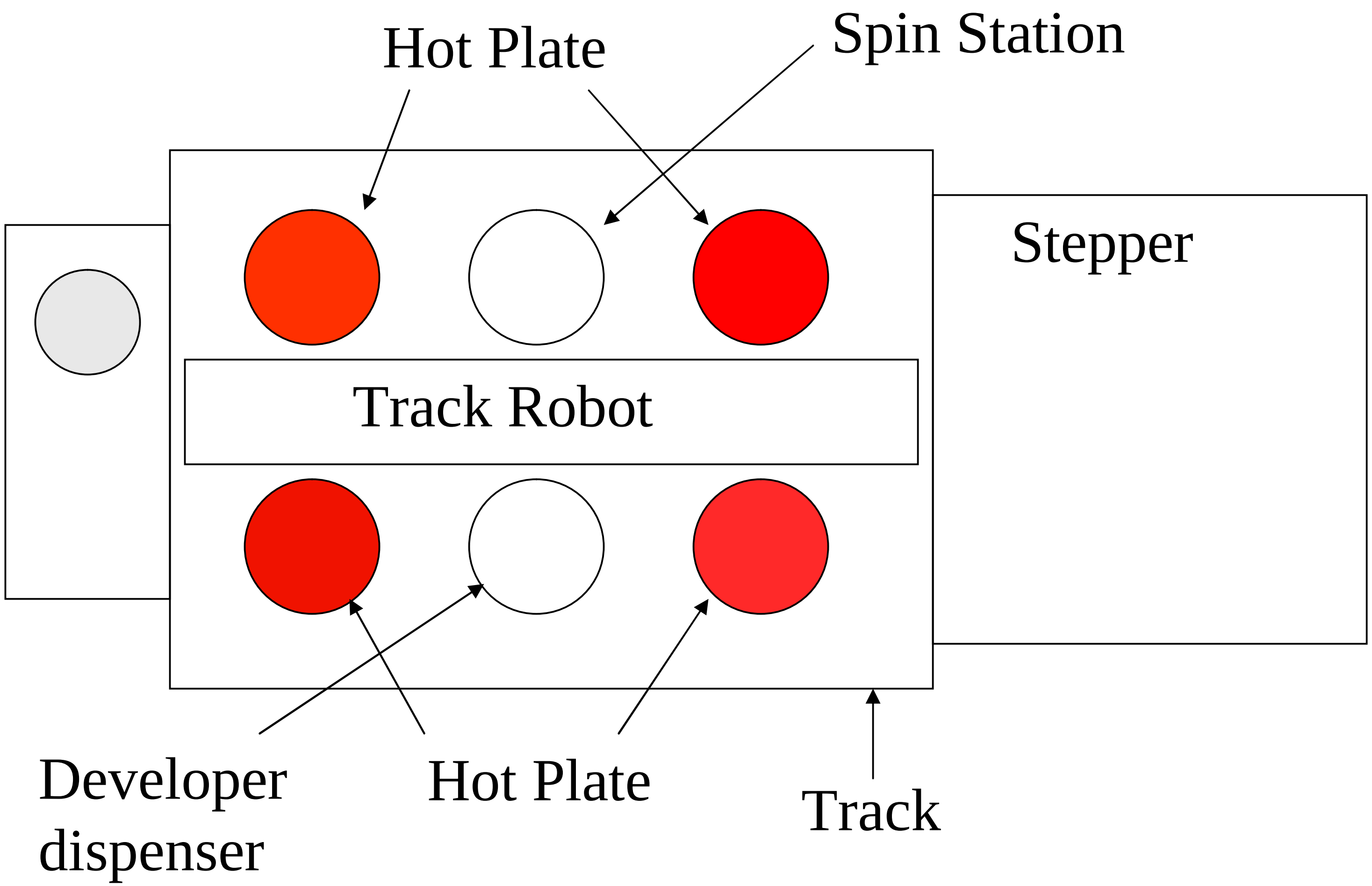
Critical Dimension



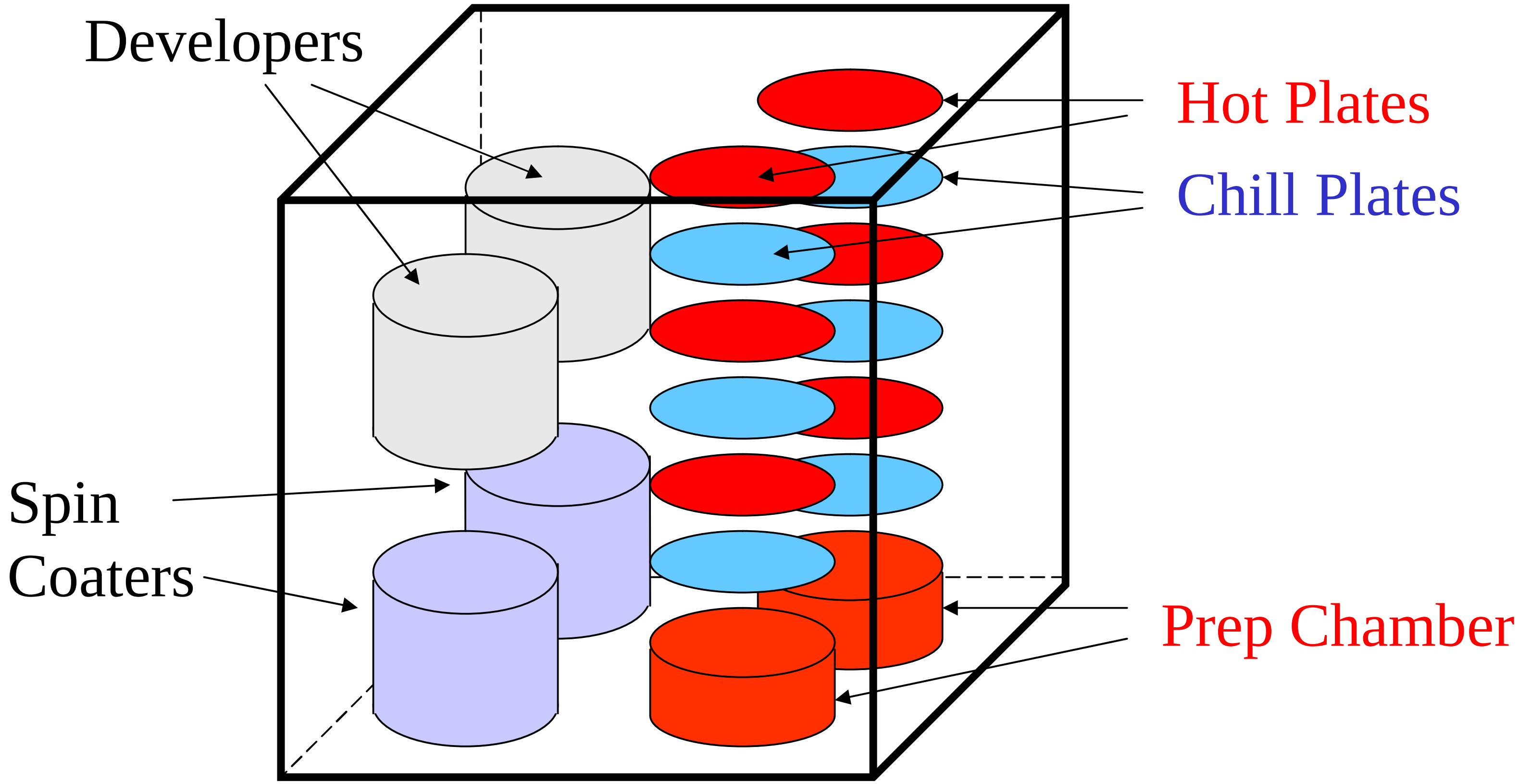
Track-Stepper System or Photo Cell

- Integrated process system of photoresist coating, exposure and development
- Center track robot
- Higher throughput
- Improves process yield

Wafer In


Hot Plate
Spin Station
Stepper
Track Robot
Developer dispenser
Hot Plate
Track

Stacked Track System



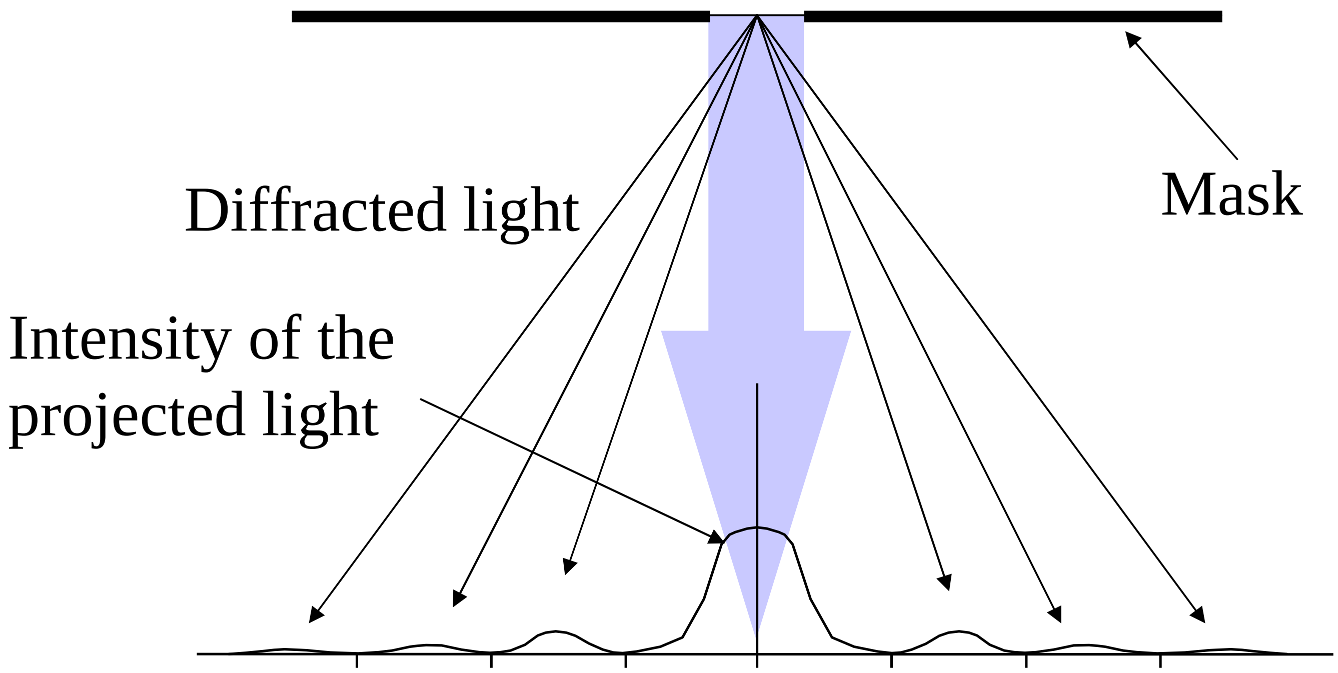
Future Trends

- Smaller feature size
- Higher resolution
- Reducing wavelength
- Phase-shift mask

Optical Lithography

- Optics
- Light diffraction
- Resolution
- Depth of focus (DOF)

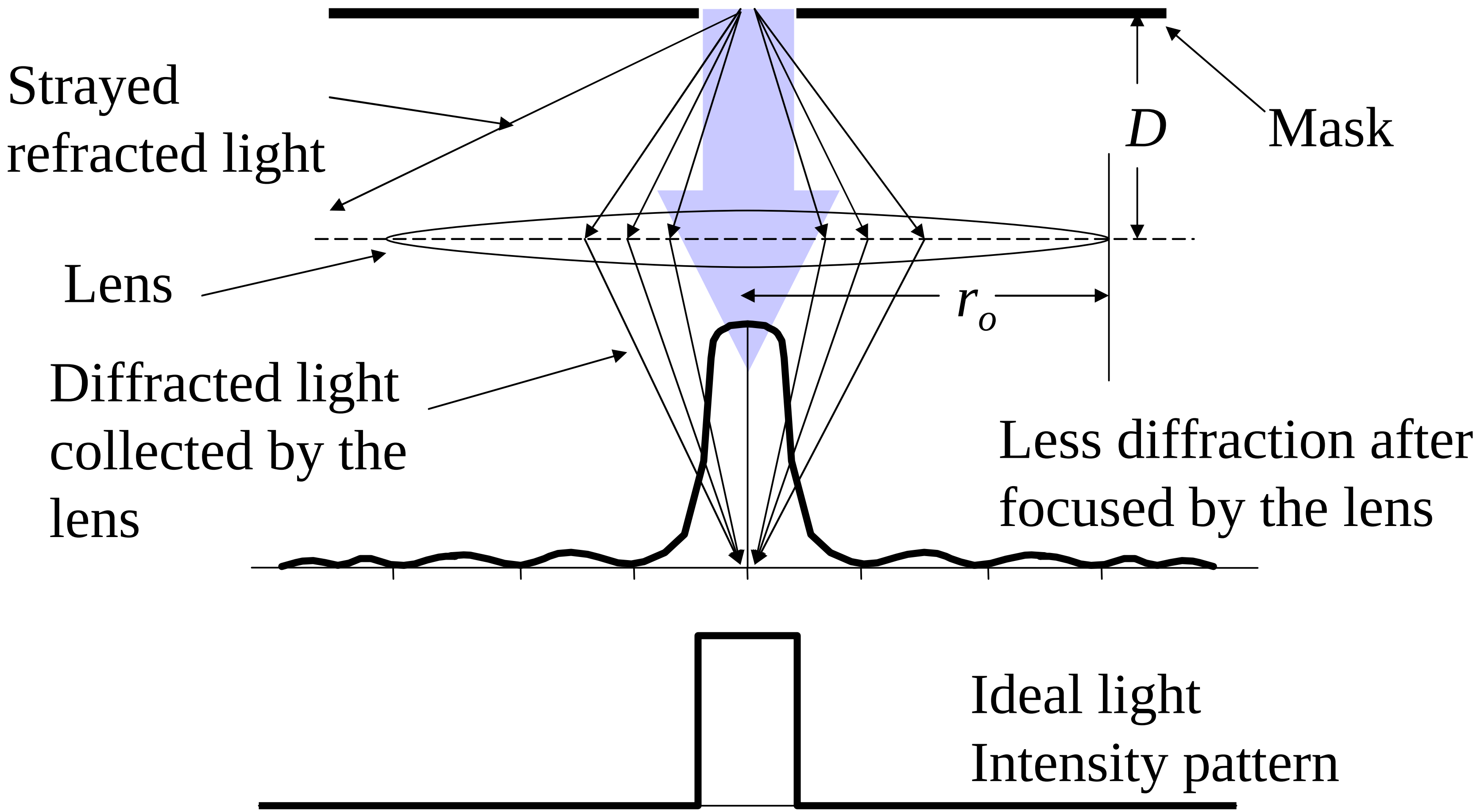
Light Diffraction Without Lens



Diffraction Reduction

- Short wavelength waves have less diffraction
- Optical lens can collect diffracted light and enhance the image

Light Diffraction With Lens



Numerical Aperture

- *NA* is the ability of a lens to collect diffracted light
- $NA = 2\, r_0 / D$
  - r_0 : radius of the lens
  - D : the distance of the object from the lens
- Lens with larger *NA* can capture higher order of diffracted light and generate sharper image.

(Optical) Resolution

- The achievable, repeatable minimum feature size
- Determined by the wavelength of the light and the numerical aperture of the system. The resolution can be expressed as

$$R = \frac{K_1 \lambda}{NA}$$

K_1 : the system constant, λ is the wavelength of the light,

$NA = 2\, r_o/D$, the numerical aperture

Exercise 1, $K_1 = 0.6$

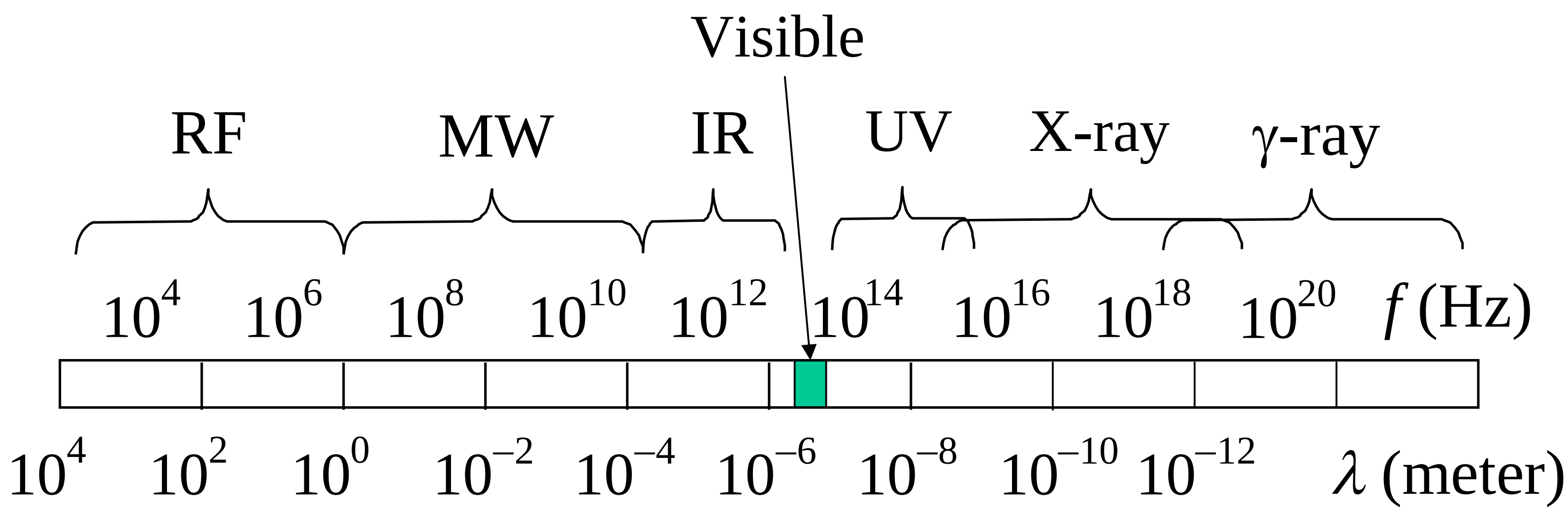
$$R = \frac{K_1 \lambda}{NA}$$

	λ	NA	R
G-line	**436 nm**	**0.60**	**___ μm**
I-line	**365 nm**	**0.60**	**___ μm**
DUV	**248 nm**	**0.60**	**___ μm**
	193 nm	**0.60**	**___ μm**

To Improve Resolution

- Increase NA
  - Larger lens, could be too expensive and unpractical
  - Reduce DOF and cause fabrication difficulties
- Reduce wavelength
  - Need to develop light source, PR and equipment
  - Limitation for reducing wavelength
  - From UV to DUV, to EUV, and to X-Ray
- Reduce K_1
  - Phase shift mask (PSM)

Wavelength and Frequency of Electromagnetic Wave



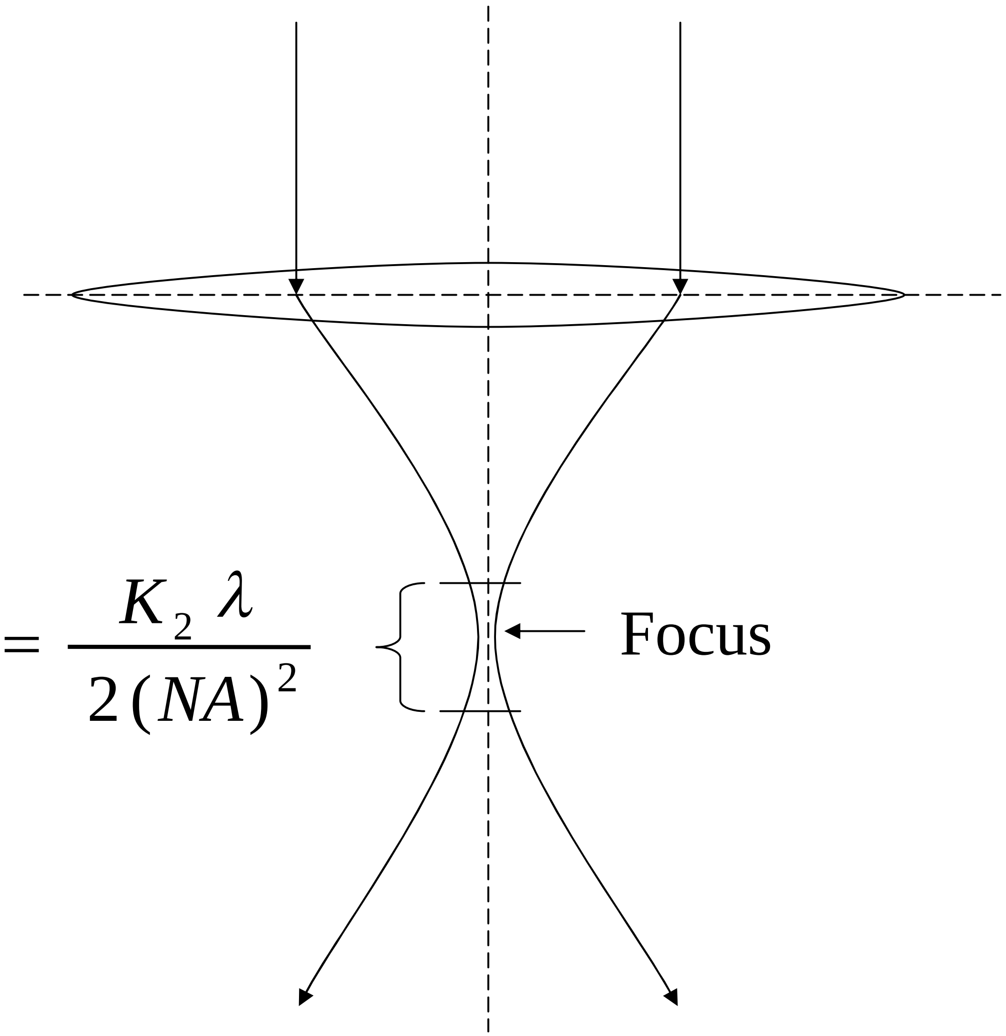
RF: Radio frequency; MW: Microwave; IR: infrared; and UV: ultraviolet

Depth of focus

- The range that light is in focus and can achieve good resolution of projected image
- Depth of focus can be expressed as:

$$DOF = \frac{K_2 \lambda}{2(NA)^2}$$

Depth of Focus

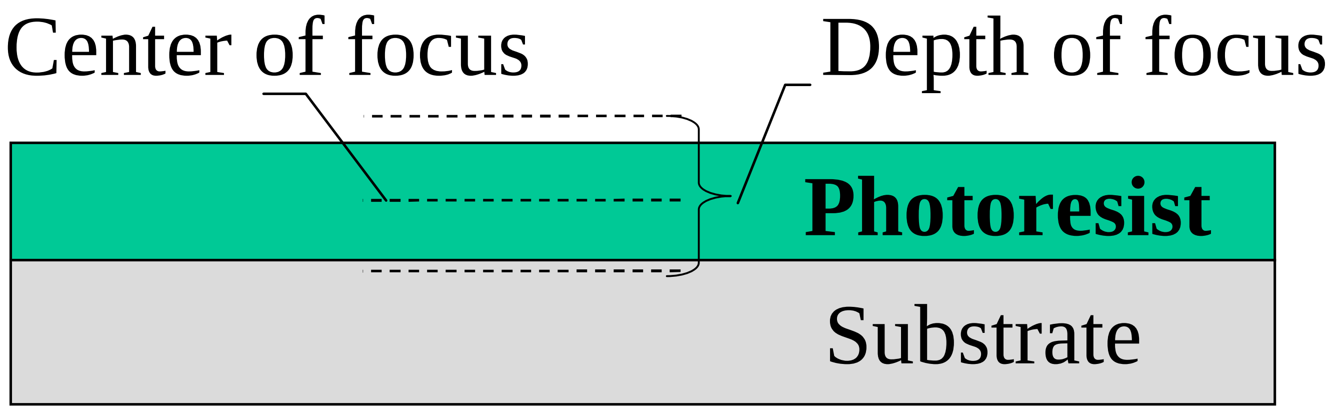


$$DOF = \frac{K_2 \lambda}{2(NA)^2}$$

Depth of Focus

- Smaller numerical aperture, larger DOF
  - Disposable cameras with very small lenses
  - Almost everything is in focus
  - But, with bad resolution
- Prefer to reduce wavelength than increase *NA* to improve resolution
- High resolution, small DOF
- Focus at the middle plane of PR layer

Focus on the Mid-Plain to Optimize the Resolution



Surface Planarization Requirement

- Higher resolution requires
  - Shorter λ
  - Larger *NA*.
- Both reduces *DOF*
- Wafer surface must be highly planarized.
- That's why CMP is significantly required for 0.25 μm feature patterning.

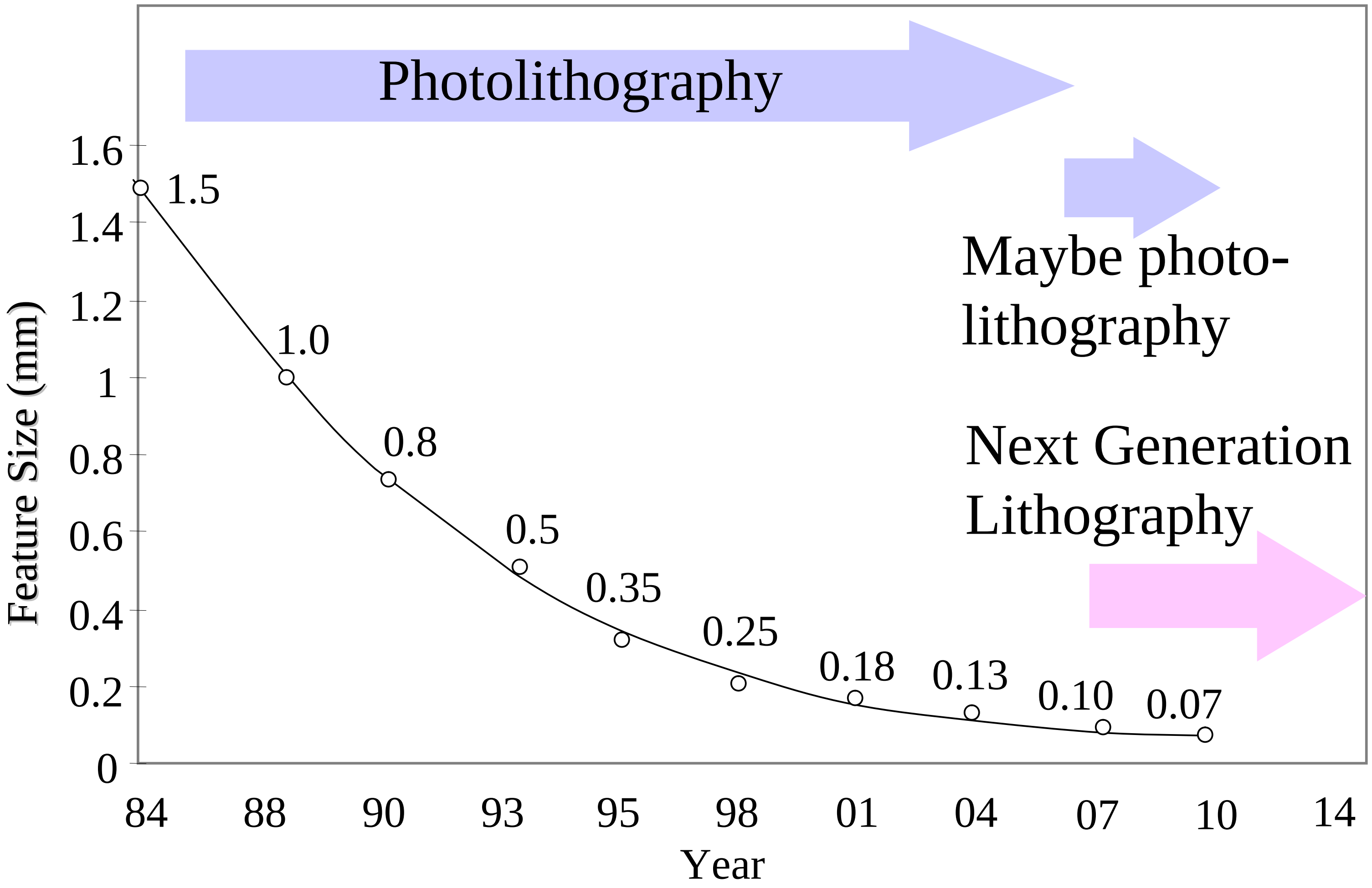
I-line and DUV

- Mercury i-line, 365 nm
  - Commonly used in 0.35 μm lithography
- DUV KrF excimer laser, 248 nm
  - 0.25 μm, 0.18 μm and 0.13 μm lithography
- ArF excimer laser,193 nm
  - Application: < 0.13 μm
- F_2 excimer laser 157 nm
  - Still in R&D, < 0.10 μm application

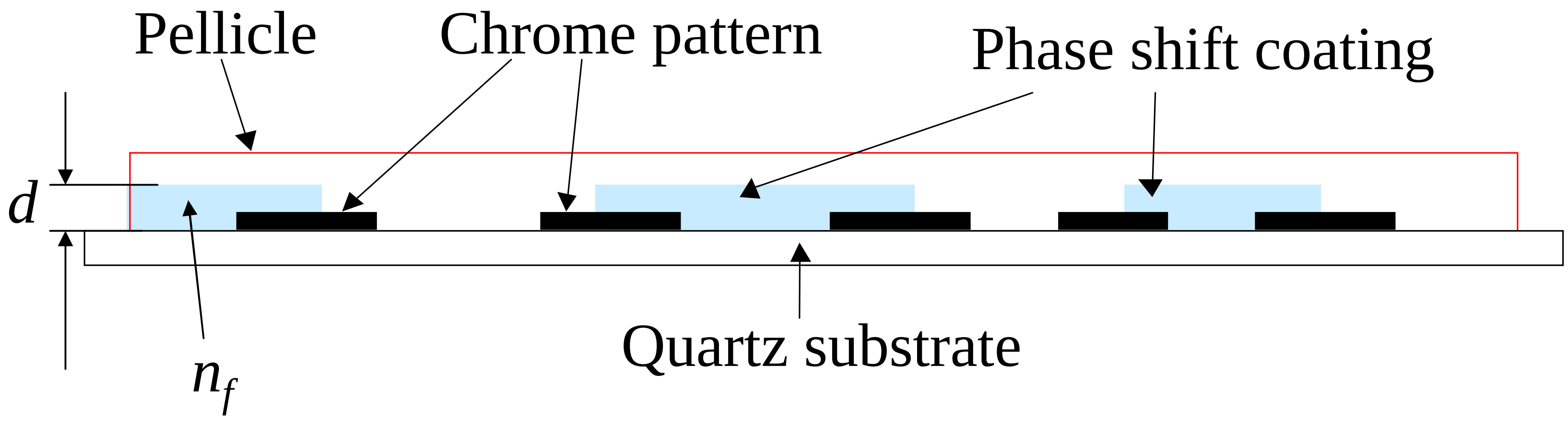
Silica and DUV

- SiO_2 strongly absorbs UV when $\lambda < 180$ nm
- Silica lenses and masks can't be used
- 157 nm F_2 laser photolithography
  - Fused silica with low OH concentration, fluorine doped silica, and calcium fluoride (CaF_2),
  - With phase-shift mask, even 0.035 μm is possible
- Further delay next generation lithography

Future Trends



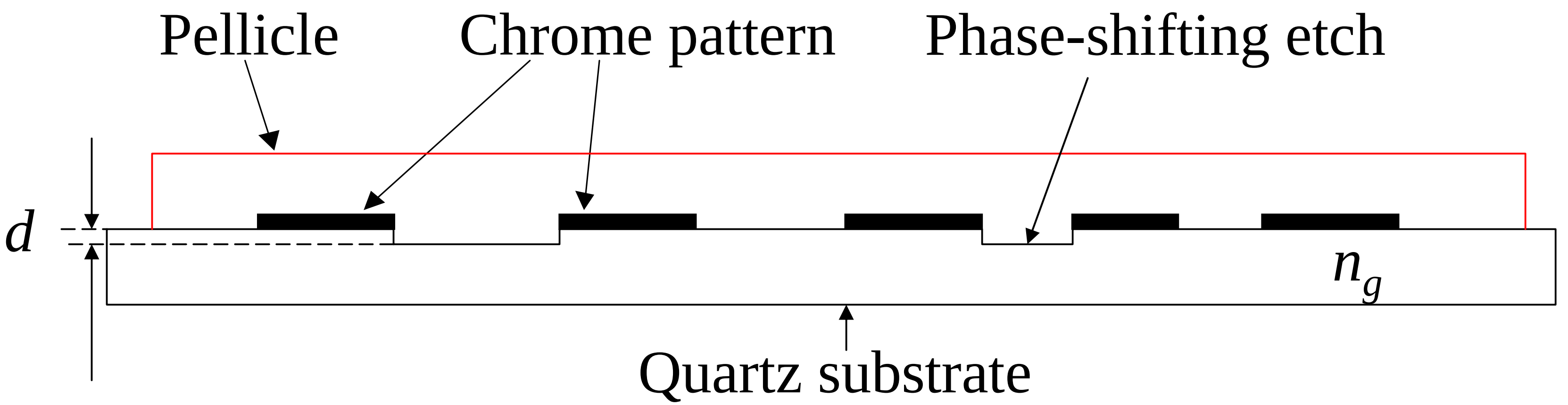
Phase Shift Mask



$$d(n_f - 1) = \lambda/2$$

n_f : Refractive index of phase shift coating

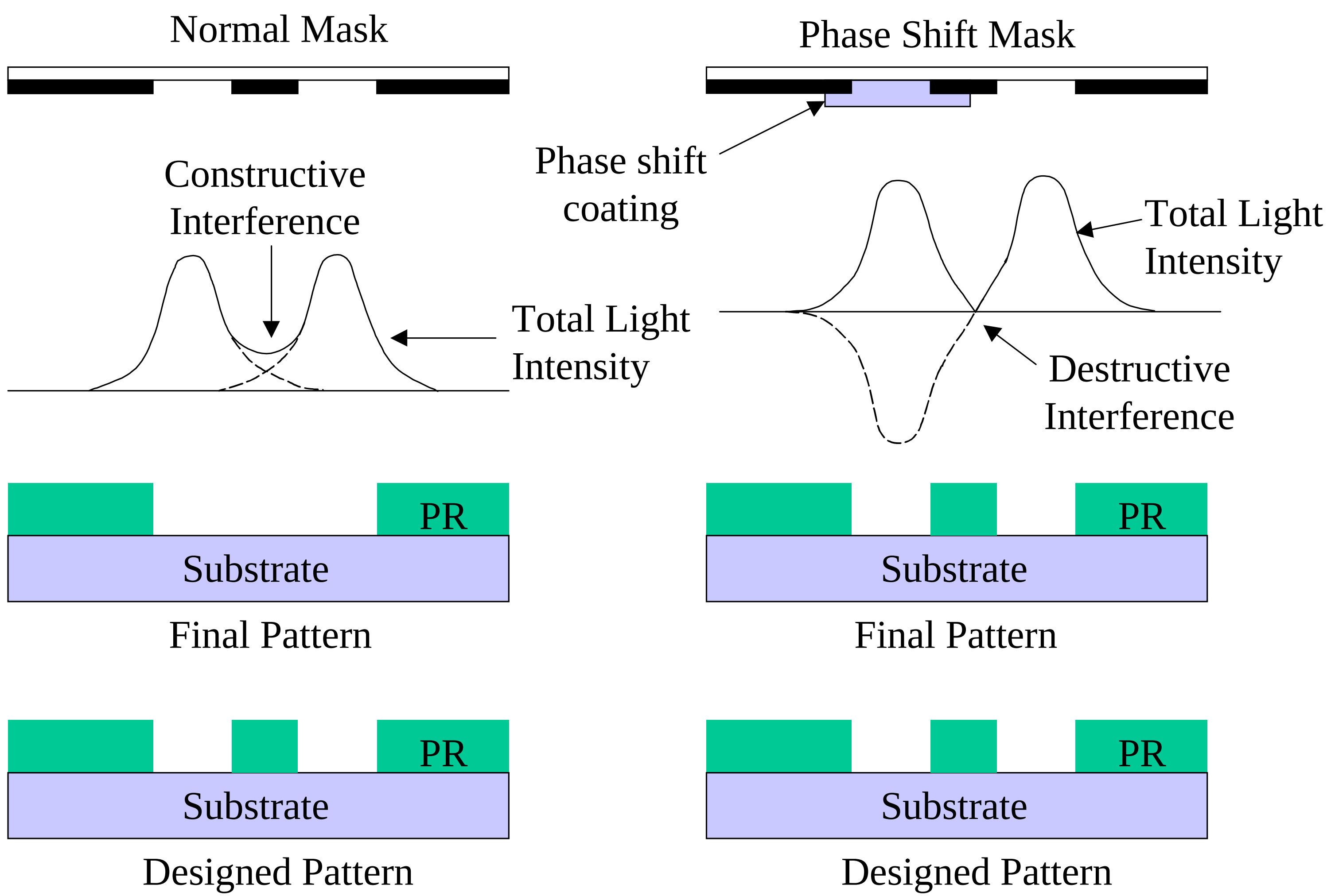
Phase Shift Mask



$$d(n_g - 1) = \lambda/2$$

n_g: refractive index of the quartz substrate

Phase Shift Mask Patterning



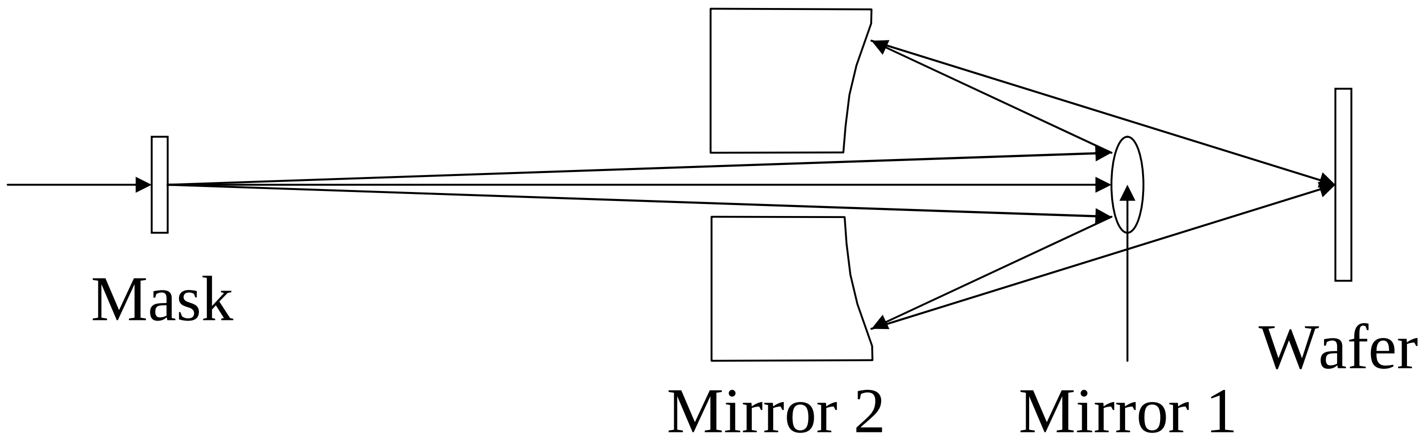
Next Generation Lithography (NGL)

- Extreme UV (EUV) lithography
- X-Ray lithography
- Maskless lithography - electron beam or ion beam
- Immersion lithography

EUV

- λ = 10 to 14 nm
- Short wavelength and reduced NA
- Mirror basis due to strong absorption at short wavelength
- Use a mask with Pd/C and Mo/Si multilayer coatings
- For 0.1 μm technology and beyond
- Still in development (support from Intel)

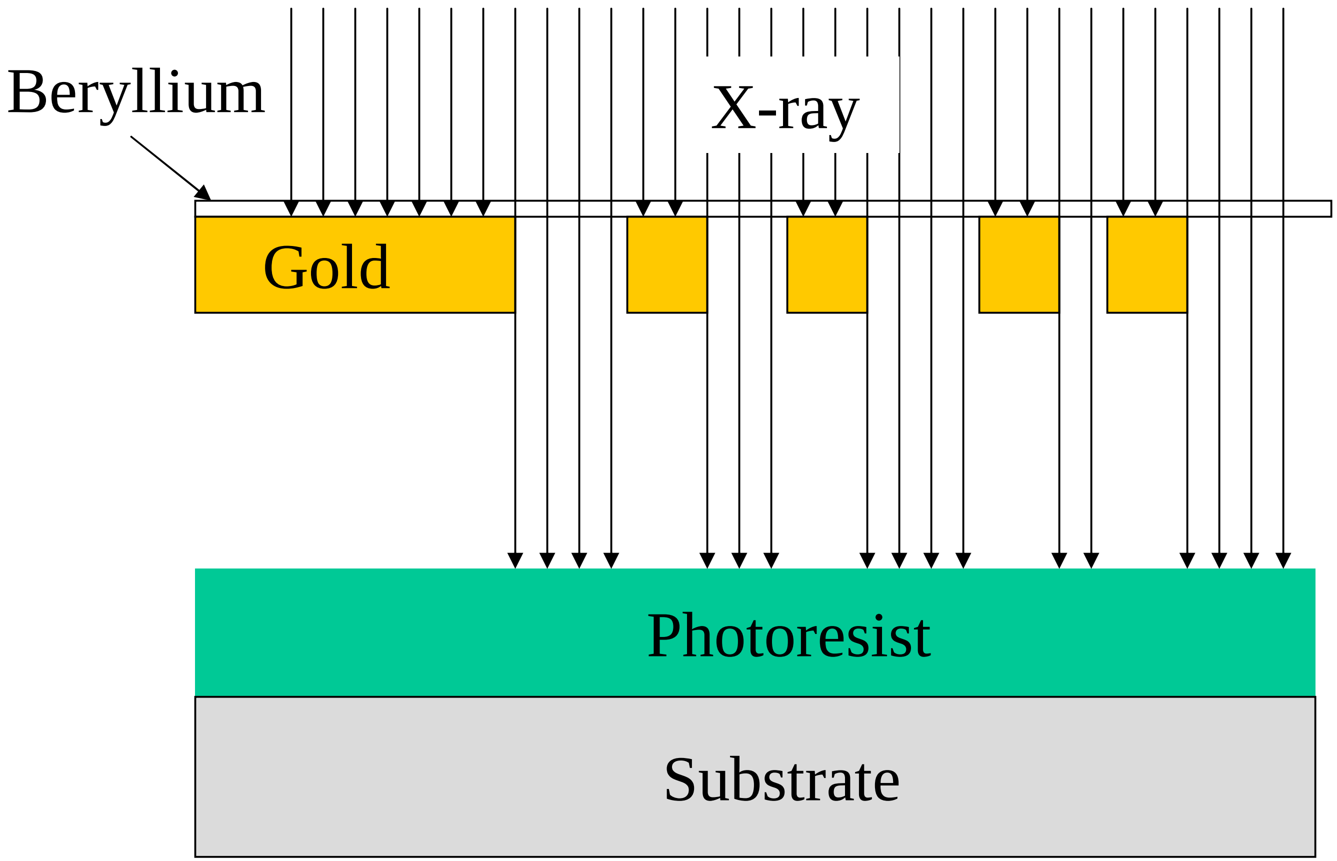
EUV Lithography



X-ray lithography

- Similar to proximity printer
- Difficult to find pure X-ray source (synchrotron radiation facility)
- Challenge on mask making (1:1)
- Very expensive! unlikely will be used in production

X-ray Printing



Optical Mask and X-ray Mask

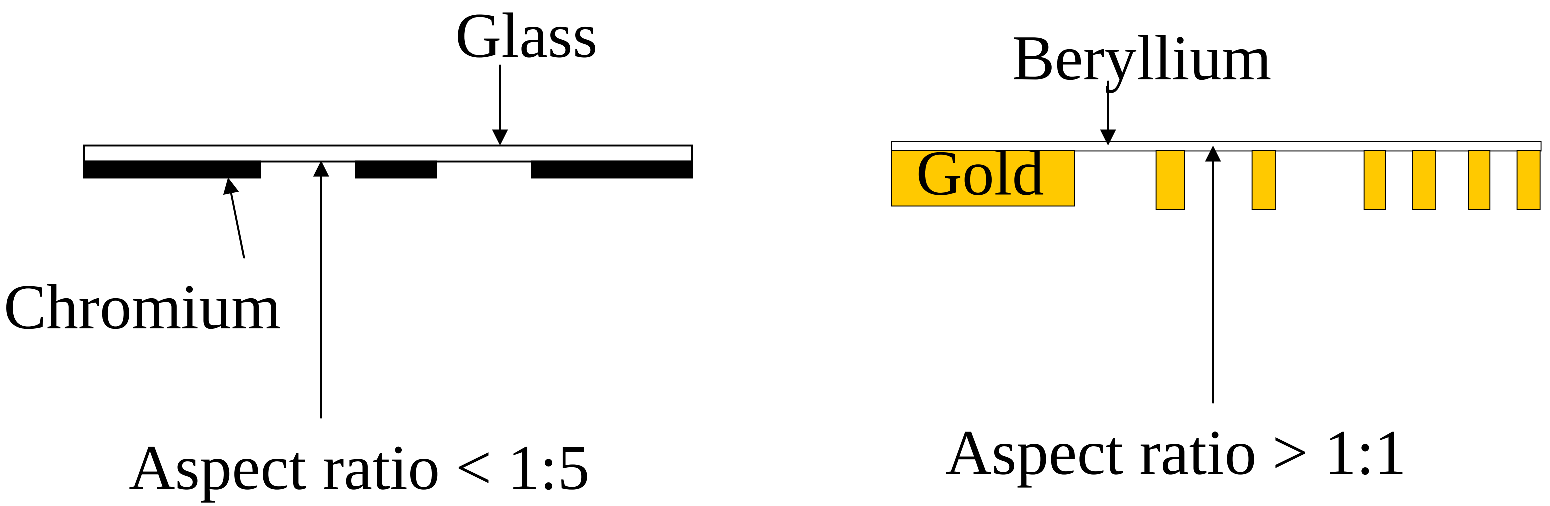


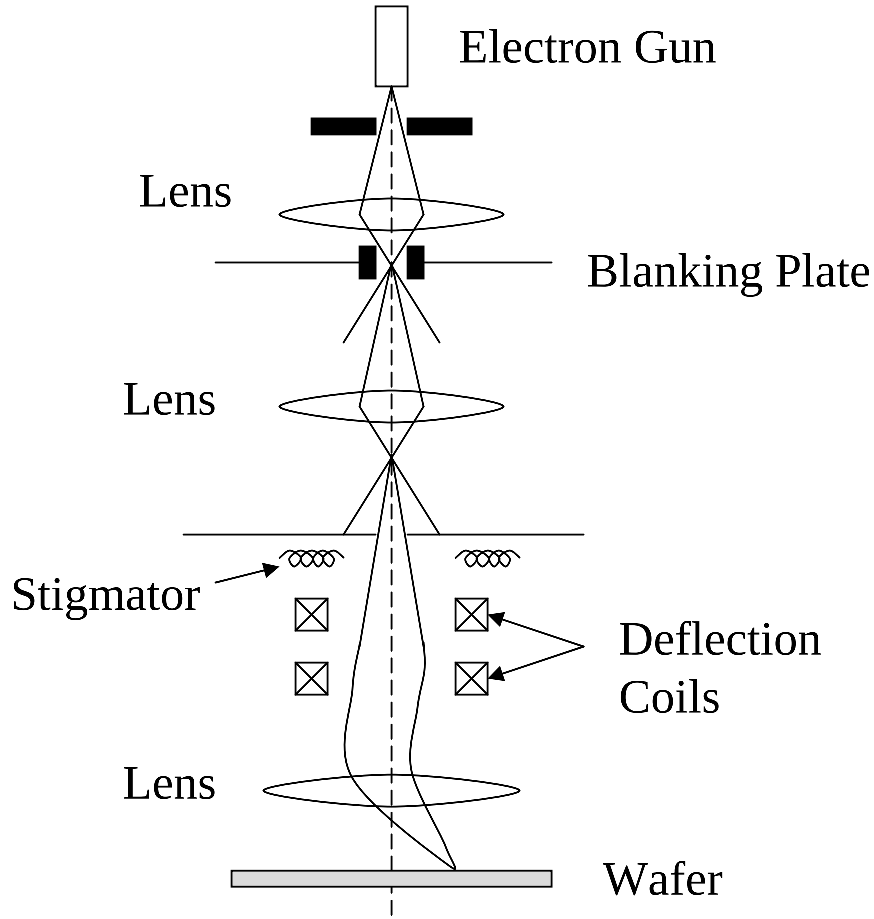
Photo Mask

X-ray Mask

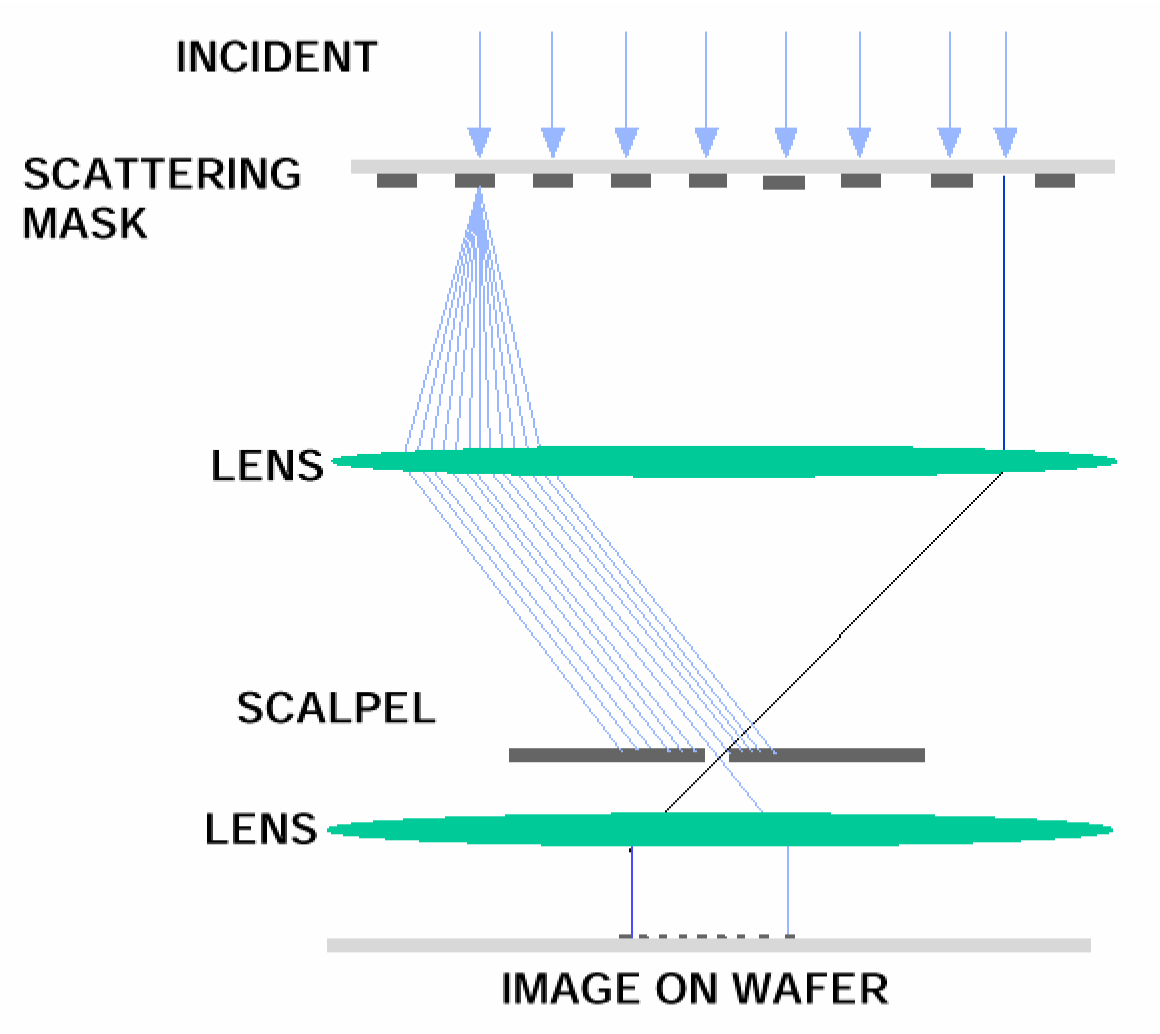
E-Beam

- Used for making mask and reticles
- Smallest geometry achieved : 0.014 μm
- Direct print possible, no mask is required
  - Low throughput
- Scattering exposure system (SCALPEL) looks promising
  - Tool development
  - Reticle making
  - Resist development
  - Very similar to stepper lithography

Electron Beam Lithography System



SCALPEL



Ion Beam Lithography

- Can achieve higher resolution
  - Direct writing and projection resist exposing
  - Direct ion implantation and ion beam sputtering patterned etch, save some process steps
- Serial writing, low throughput
- Unlikely will be used in the mass production
- Appropriate for mask and reticle repairing
- IC device defect detection and repairing

Immersion Lithography

- Fill DI water between light source and wafer
- Reach higher DOF

$$DOF = \frac{K_w \lambda}{2(NA)^2}$$

Kw : refractive index of water (1.43)

- Applied in 193 nm or 248 nm systems
- Likely to push further to 90 or beyond if refractive index increased
- TSMC proved result in 90 nm product with ASML