



Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Lithography 2 – Lithography Processing

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Lesson Objectives - Photolithography

By the end of this photolithography lesson, you should be able to:

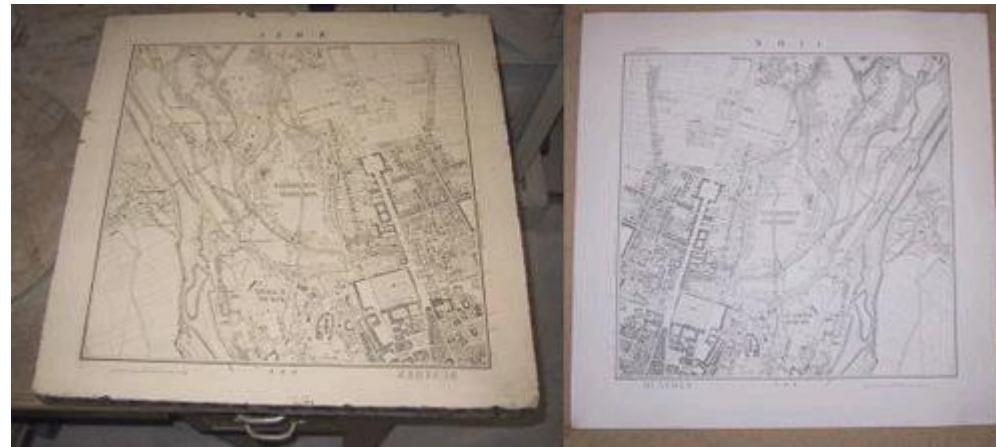
- Explain the basic concepts of photolithography, describe the eight main steps in photolithography, determine the resolution of printers, and the factors affecting resolution.
- Describe the types of printers and resists used in wafer manufacturing, and the chemistry behind the respective resists.
- Discuss the optical enhancement techniques in photolithography and describe the alternatives for advanced photolithography.

Lithography: Definition

- Creates a pattern on a silicon substrate
- Also known as **Photolithography**

In Greek origin,

Photo-litho-graphy: Light-stone-writing



Lithography stone
and mirror-image
print of a map of
Munich

Lithography is a printing process that uses chemical processes (in response to light) to create an image.

Lithography History

- Historically, lithography is a type of printing technology based on the chemical repellence of oil and water.
- Photo-litho-graphy (Latin) can be translated as “light-stone-writing”.
- In 1826, Joseph Nicephore Niepce in Chalon France took the first photograph using bitumen of Judea on a pewter plate, developed using oil of lavender and mineral spirits.
- In 1935, Louis Minsk of Eastman Kodak developed the first negative photoresist.
- In 1940, Otto Suess developed the first positive photoresist.
- In 1954, Louis Plambeck Jr. of Du Pont developed the Dycryl polymeric letterpress plate.



Lithography press for printing maps in Munich

Lithography - Overview



Watch the video lecture to view this animation.

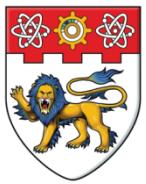
Fundamental Concept of Lithography

- **Lithography processing**
- **Lithography technology**
- **Resist technology**
- **Advanced lithography**

Lithography Processing – Lesson Overview

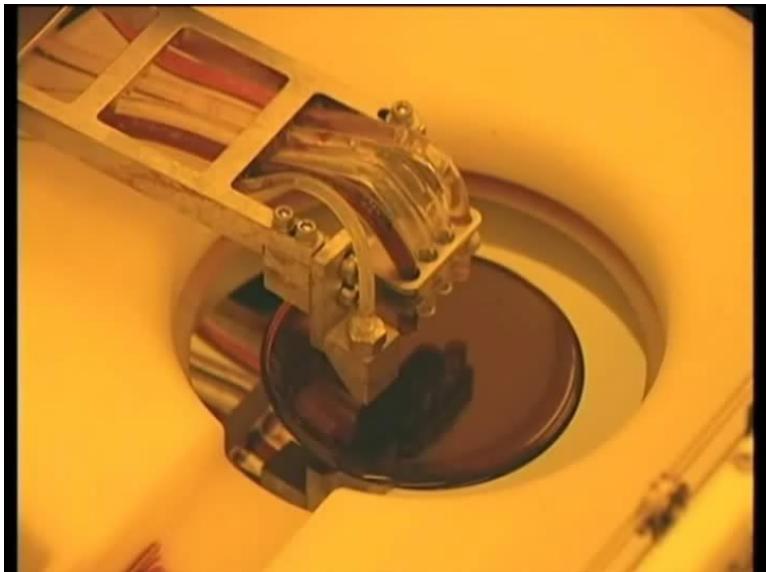
Lithography processing:

- Process overview
- UV light spectrum and resolution
- Negative and positive lithography (resist)
- Eight basic steps of the lithography process

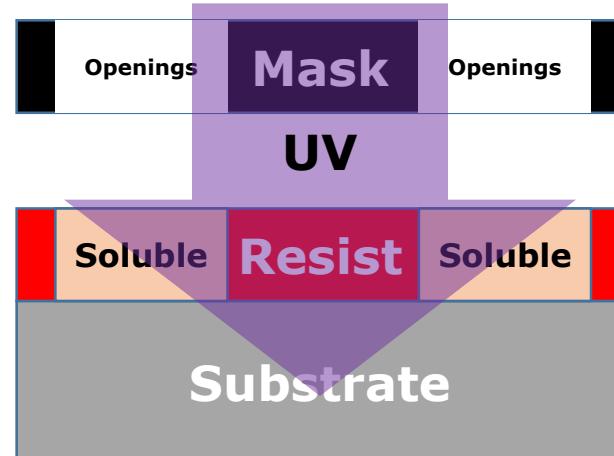


Process Overview

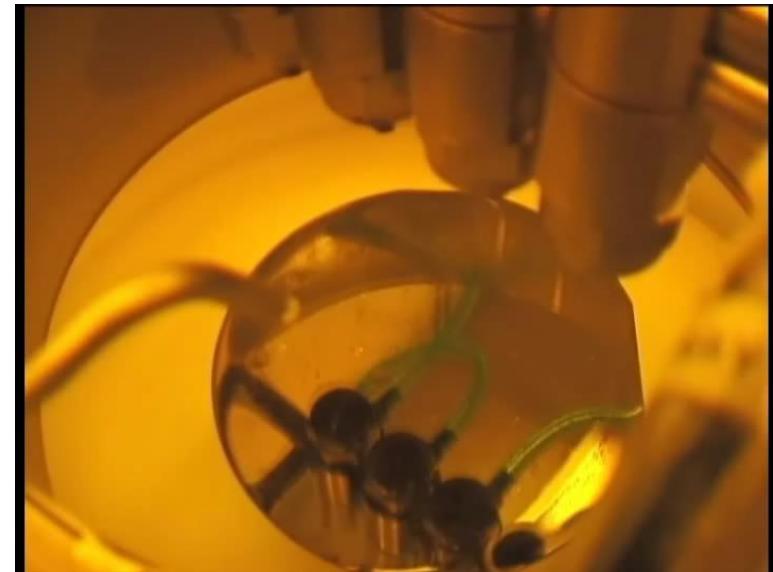
Process Overview – Coating, Exposure, and Developing



Coating



Expose



Soluble resist washed away by the developer (chemicals)

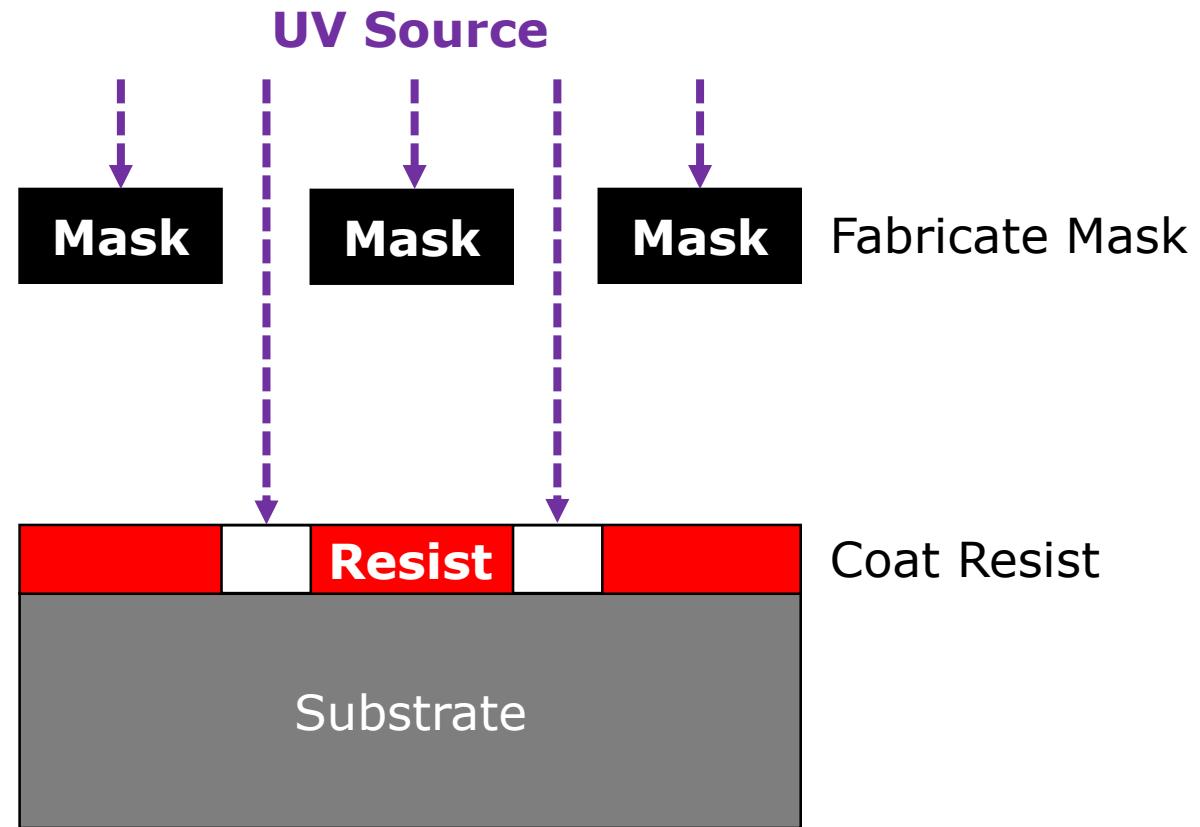


Developing

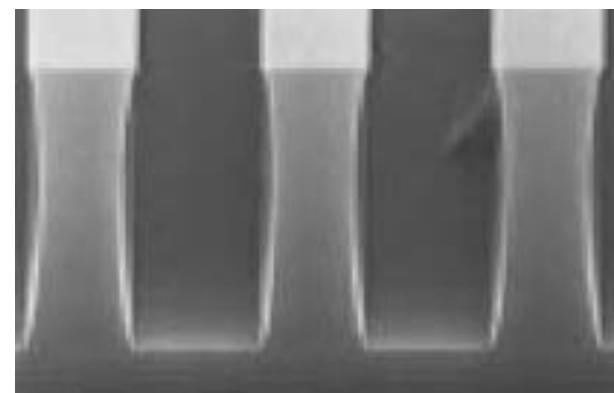
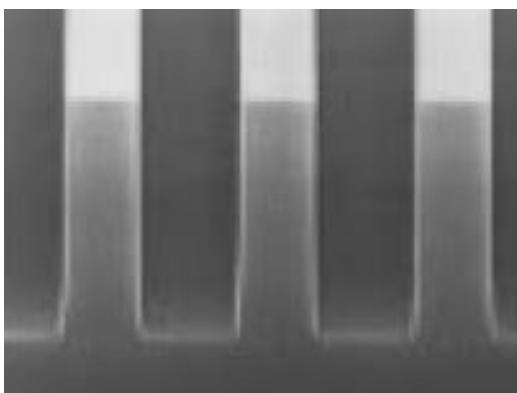
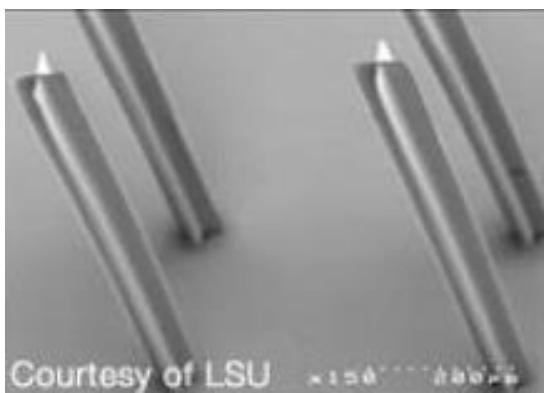
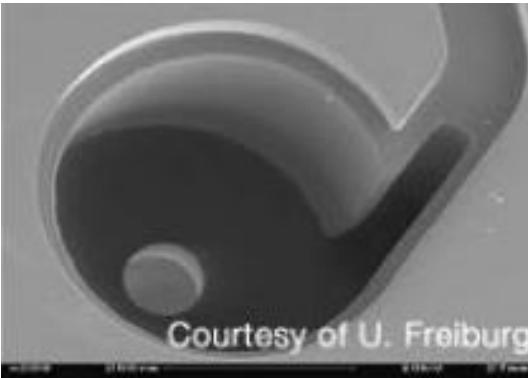
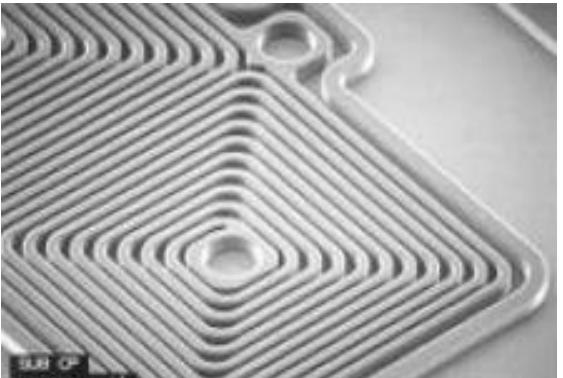
Lithography Concepts

Overview – Lithography process:

1. Coating
2. Expose
3. Developing



Lithographic Patterning



Shipley PR220 Resist Data Sheet (www.microhem.com)

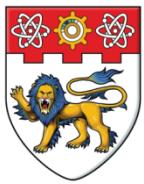
Types of Lithography

Three basic components of lithography:

UV Source

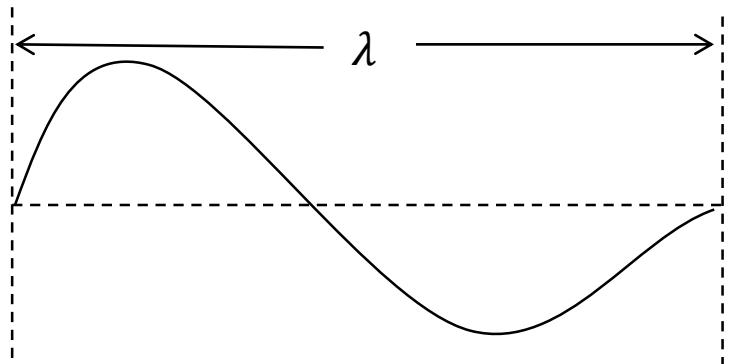
Resist

Mask



UV Light Spectrum and Resolution

Light Wavelength and Frequency



Light

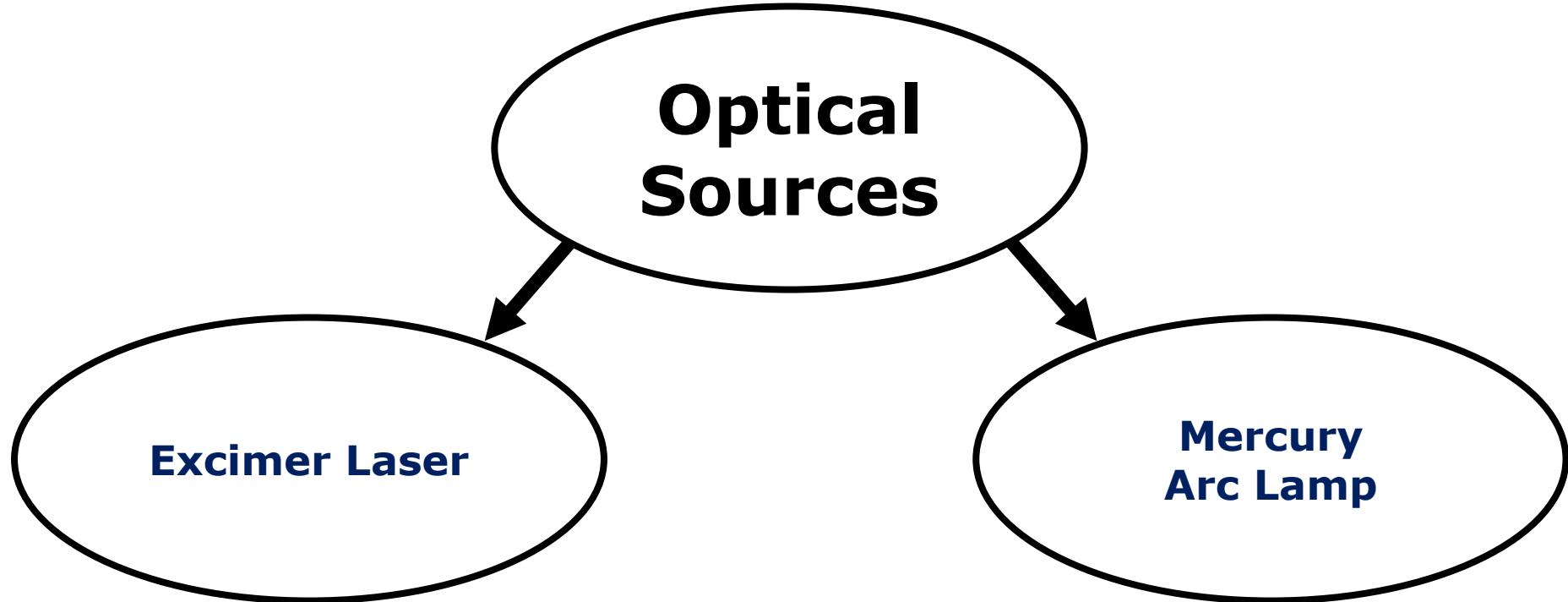
Light as a wave in electromagnetic spectrum:

$$\lambda = \frac{v}{f}$$

v = velocity of light, 3×10^8 m/sec

f = frequency in Hertz (cycles per second)

λ = wavelength, the physical length of one cycle of a frequency, expressed in metres

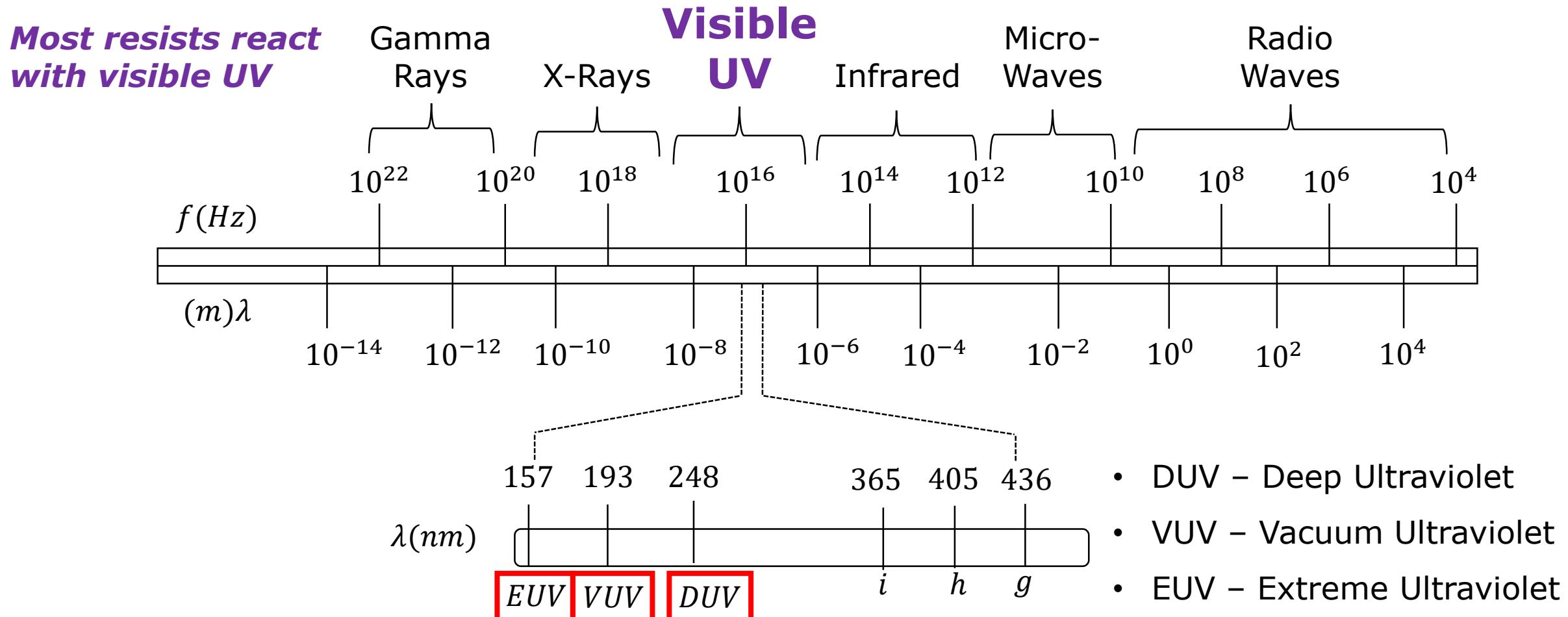


- Deep UV by excimer lasers
- $\text{Kr} + \text{NF}_3 + (\text{energy}) \rightarrow \text{KrF} + (\text{photon emission})$
- KrF: $\lambda = 248 \text{ nm}$ (used for $0.25 \mu\text{m}$)
- ArF: $\lambda = 193 \text{ nm}$ (used for $0.12 \mu\text{m}$)
- Hg vapour lamps: Hg plasma inside glass lamp
- Produces multiple wavelengths
- Limited in intensity
- "g" line: $\lambda = 436 \text{ nm}$ (used to mid 1980s)
- "i" line : $\lambda = 365 \text{ nm}$ (early 1990s, $> 0.3 \mu\text{m}$)



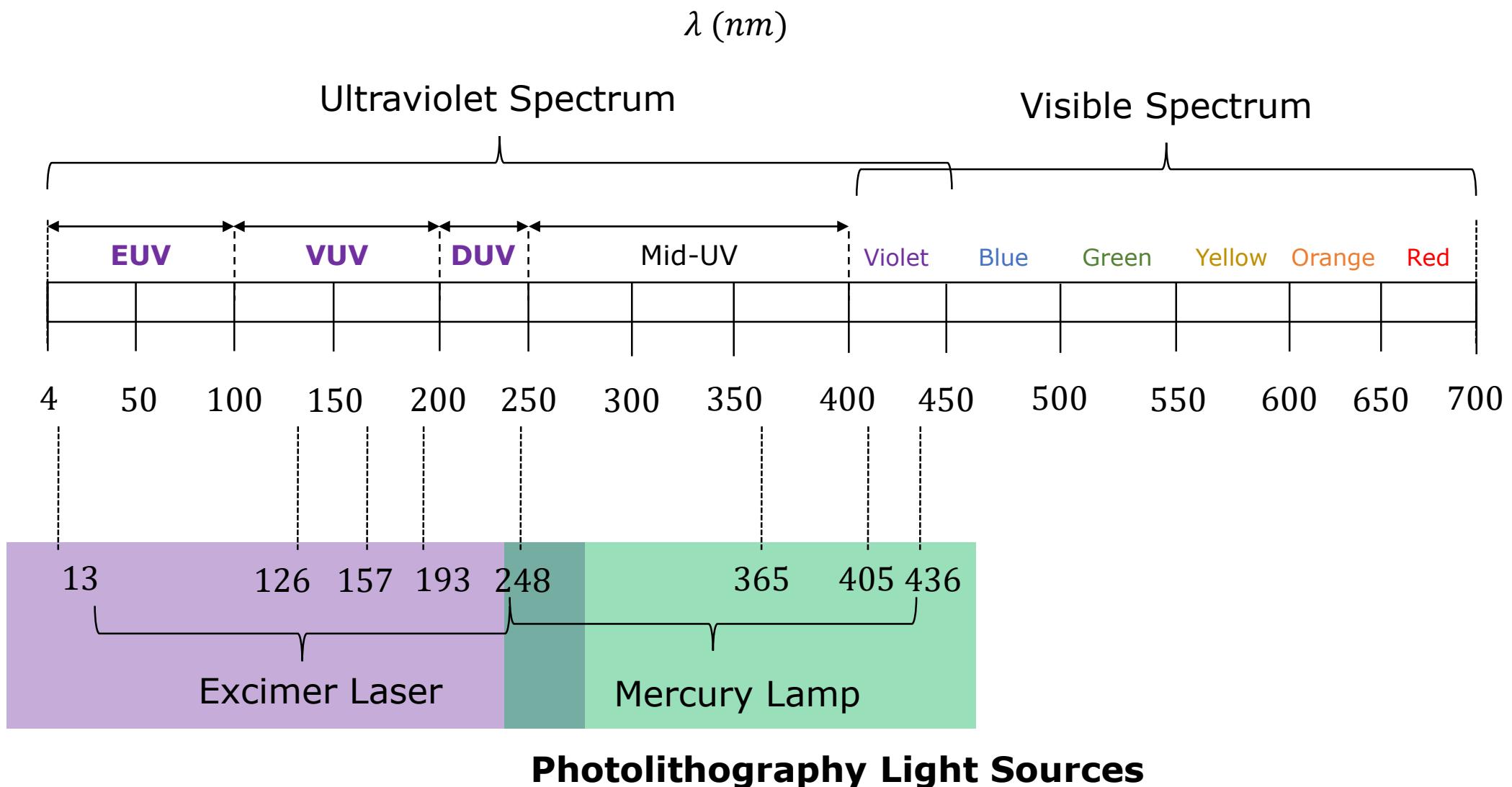
Pause and
read
carefully

Electromagnetic Spectrum of Light



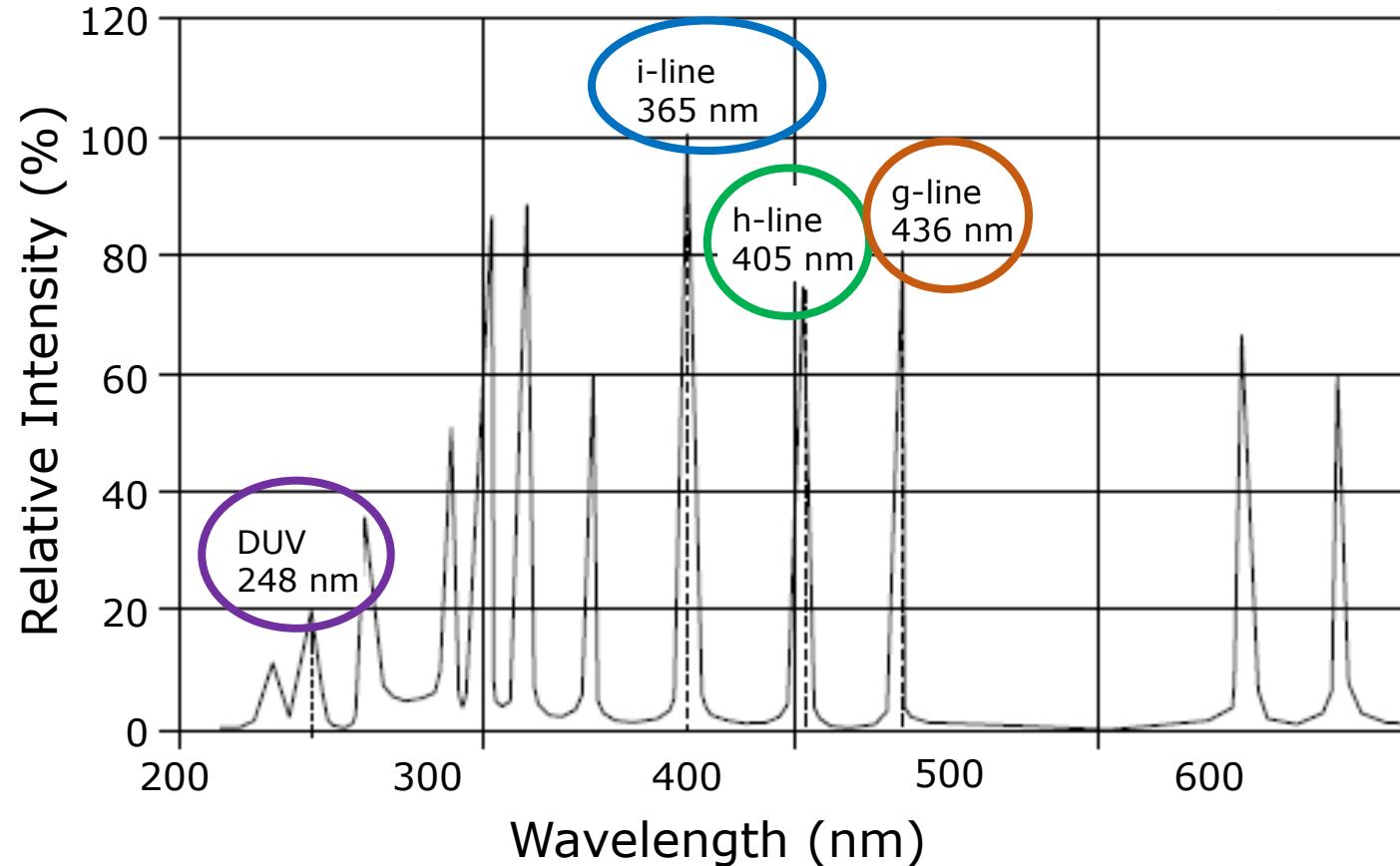
Common UV wavelengths used in optical lithography

Ultraviolet Spectrum



Emission Spectrum of Typical Mercury Arc Lamp

Emission Spectrum of High-Intensity Mercury Lamp



Typical Mercury Arc Lamp

Mercury lamp spectrum used with permission from USHIO Specialty Lighting Products.

Mercury Arc Lamp Intensity Peaks



**Pause and
read
carefully**

UV Light Wavelength (nm)	Descriptor	Critical Dimension Resolution (μm)
436	g-line	0.5
405	h-line	0.4
365	i-line	0.35
248	Deep UV (DUV)	0.25

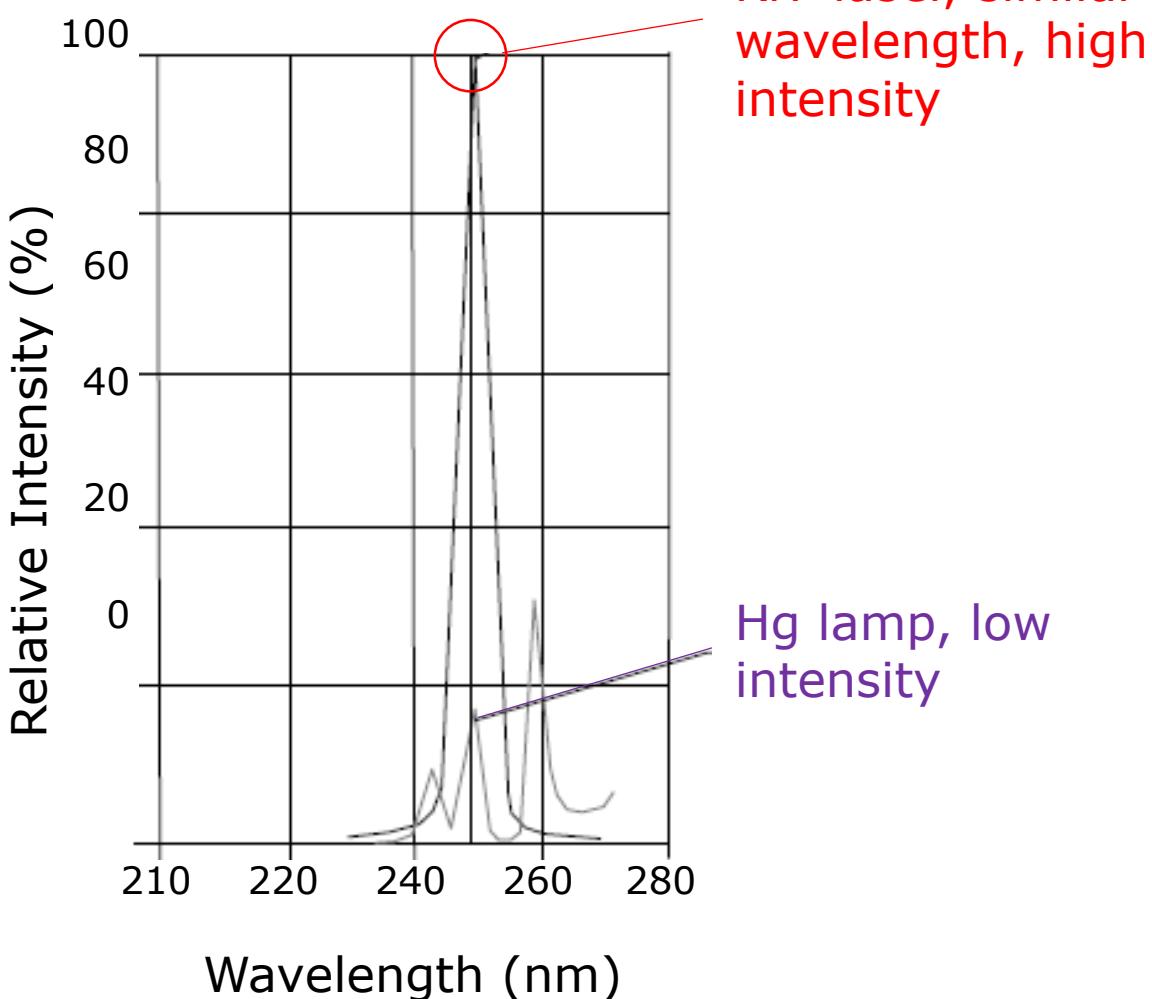


For resolution, the higher the better – able to pattern smaller scale

- 1. Resolution is the ability to differentiate between two closely spaced features on the wafer.**
- 2. The actual dimensions of the patterned images are the feature sizes.**
- 3. The minimum feature size is the Critical Dimension (CD).**
- 4. Resolution is important for critical dimension.**

Light Intensity

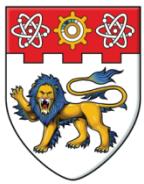
- Higher intensity = Shorter exposure time
- Lower intensity = Longer exposure time
- KrF laser is preferred over Hg lamp DUV (248 nm)



Excimer Laser Sources

Different materials to achieve different wavelengths

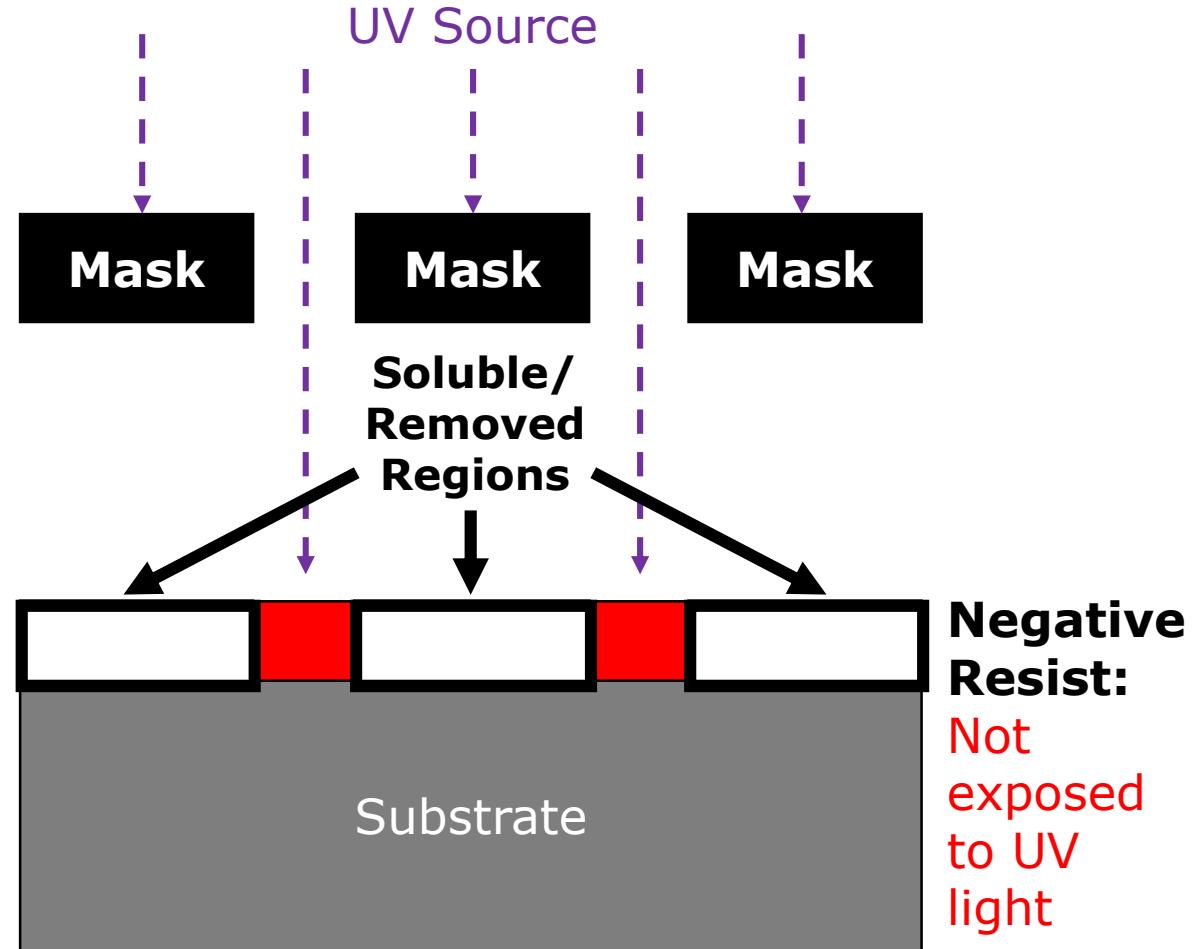
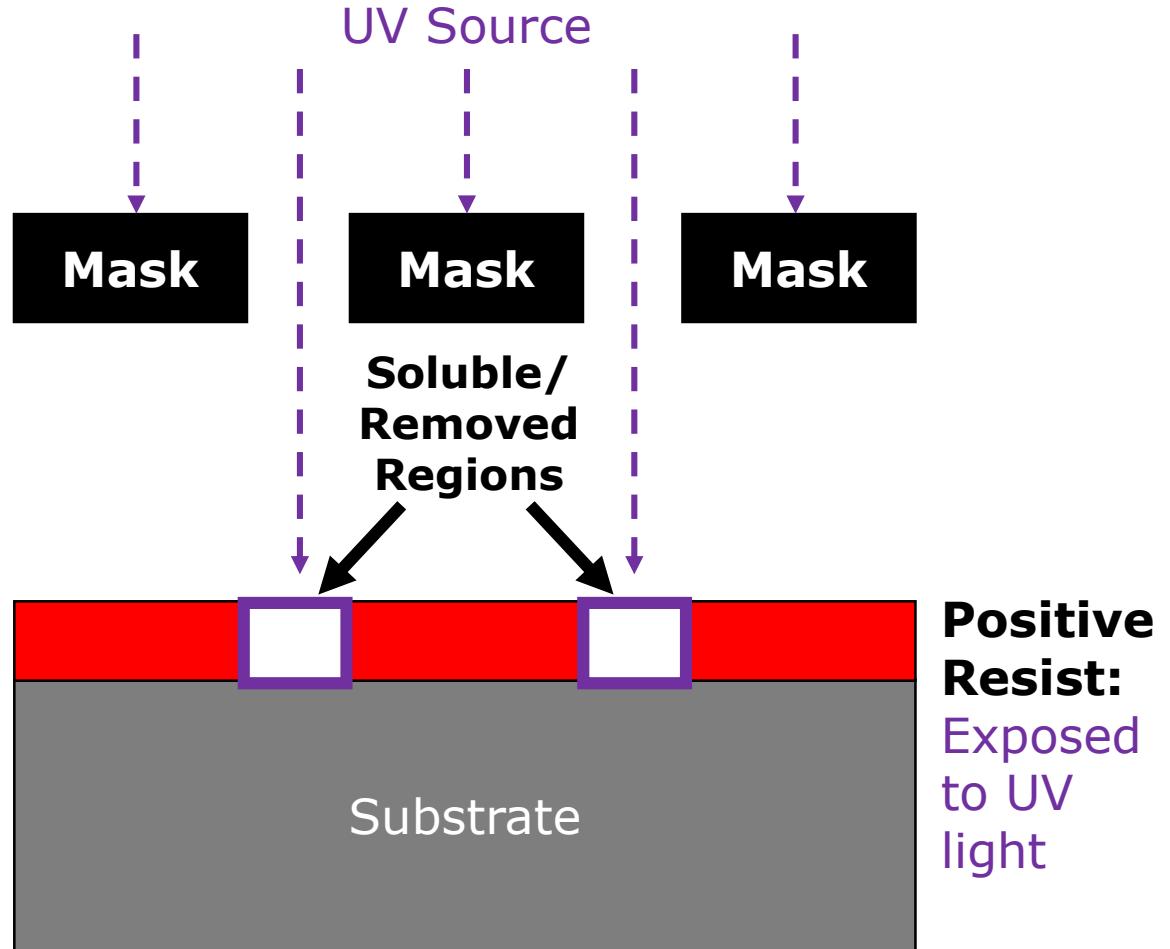
Material	Wavelength (nm)	CD Resolution (μm)
KrF	248	≤ 0.25
ArF	193	≤ 0.18
F_2	157	≤ 0.15



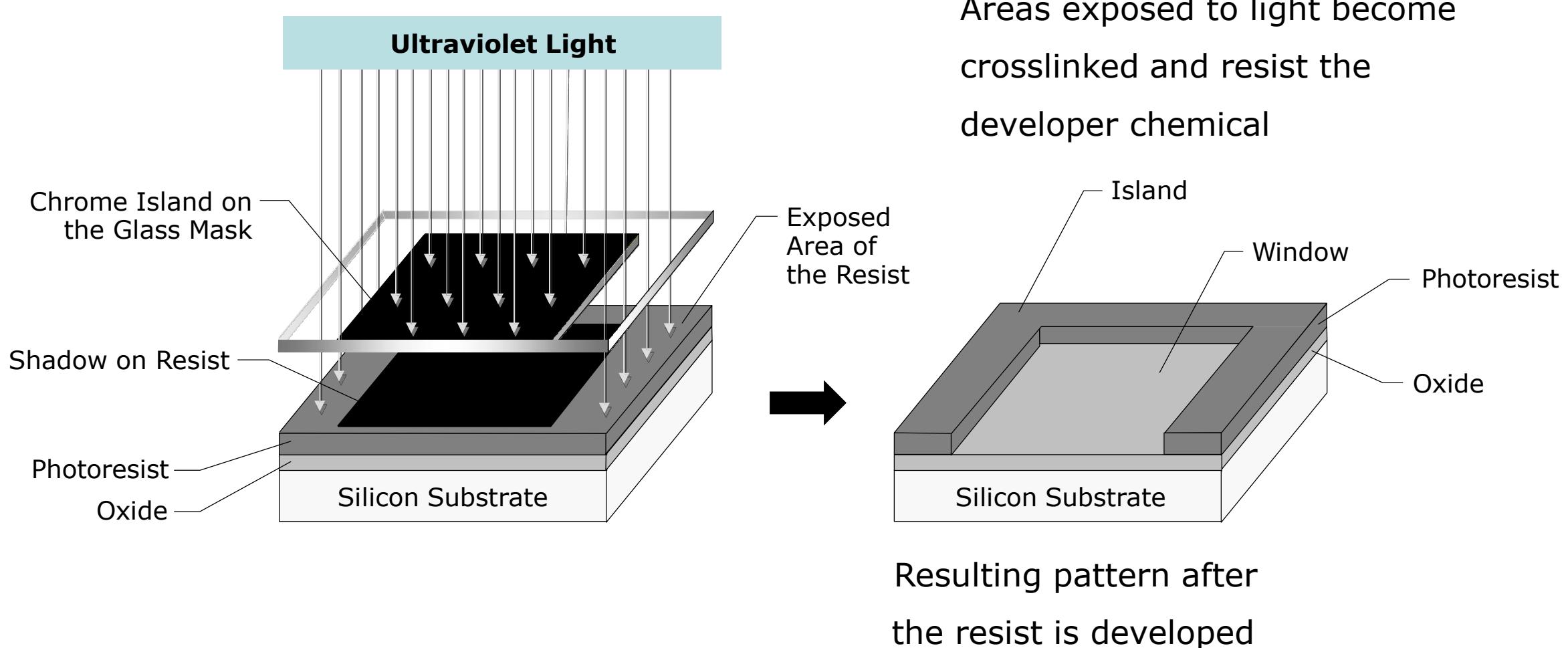
Negative and Positive Lithography (Resist)

Types of Resists

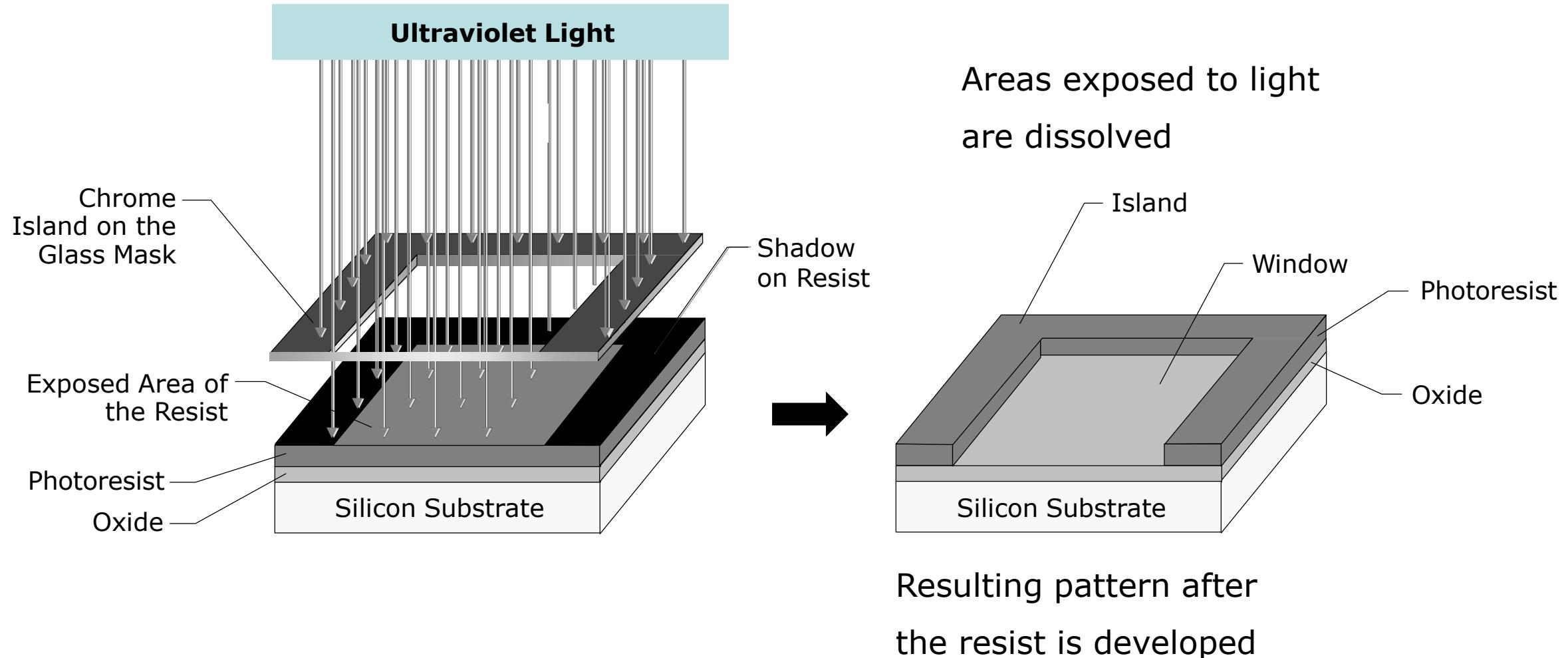
- Resist is a polymer chemical that is sensitive to light.



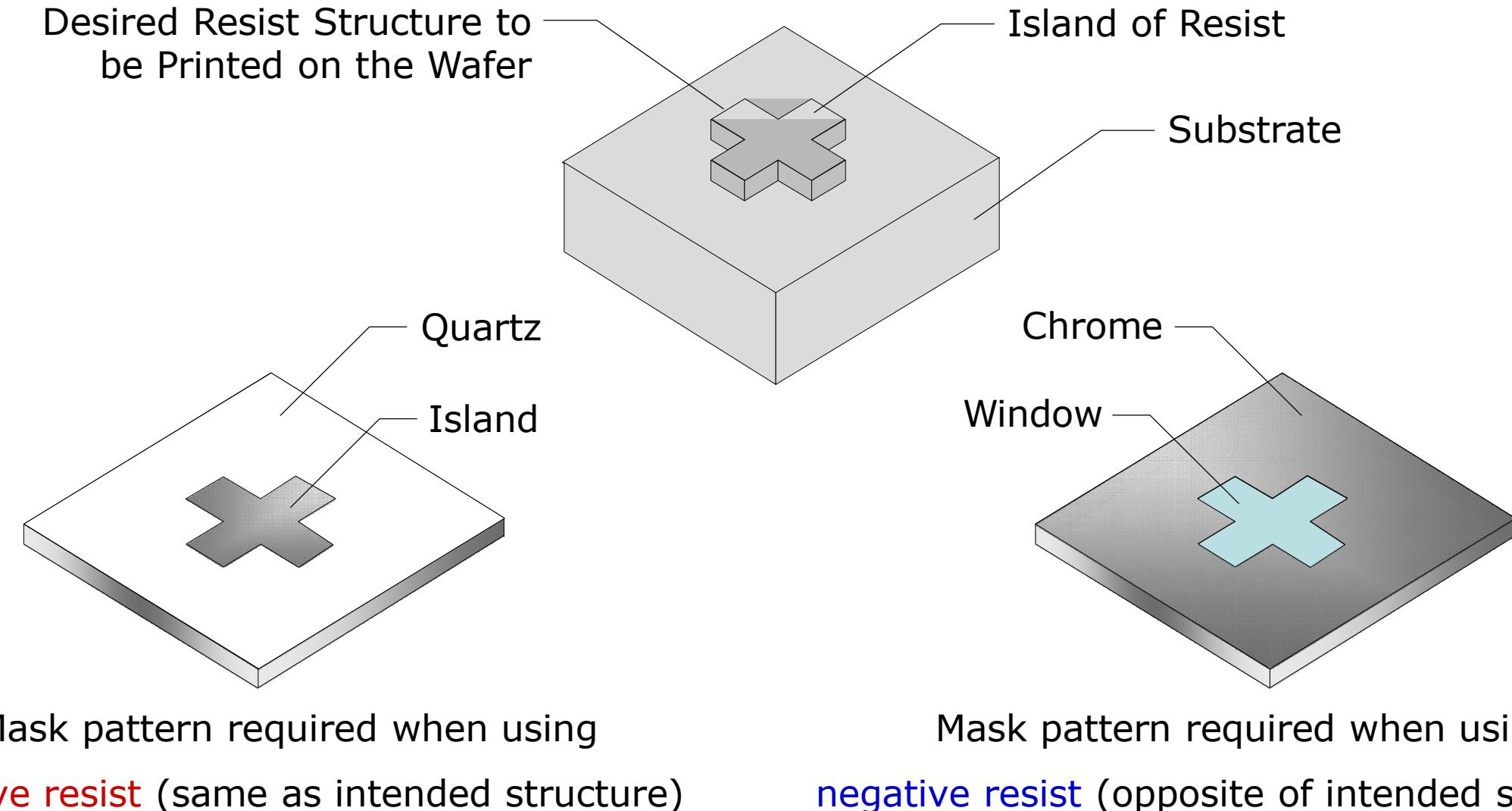
Negative Lithography



Positive Lithography



Relationship Between Mask and Resist

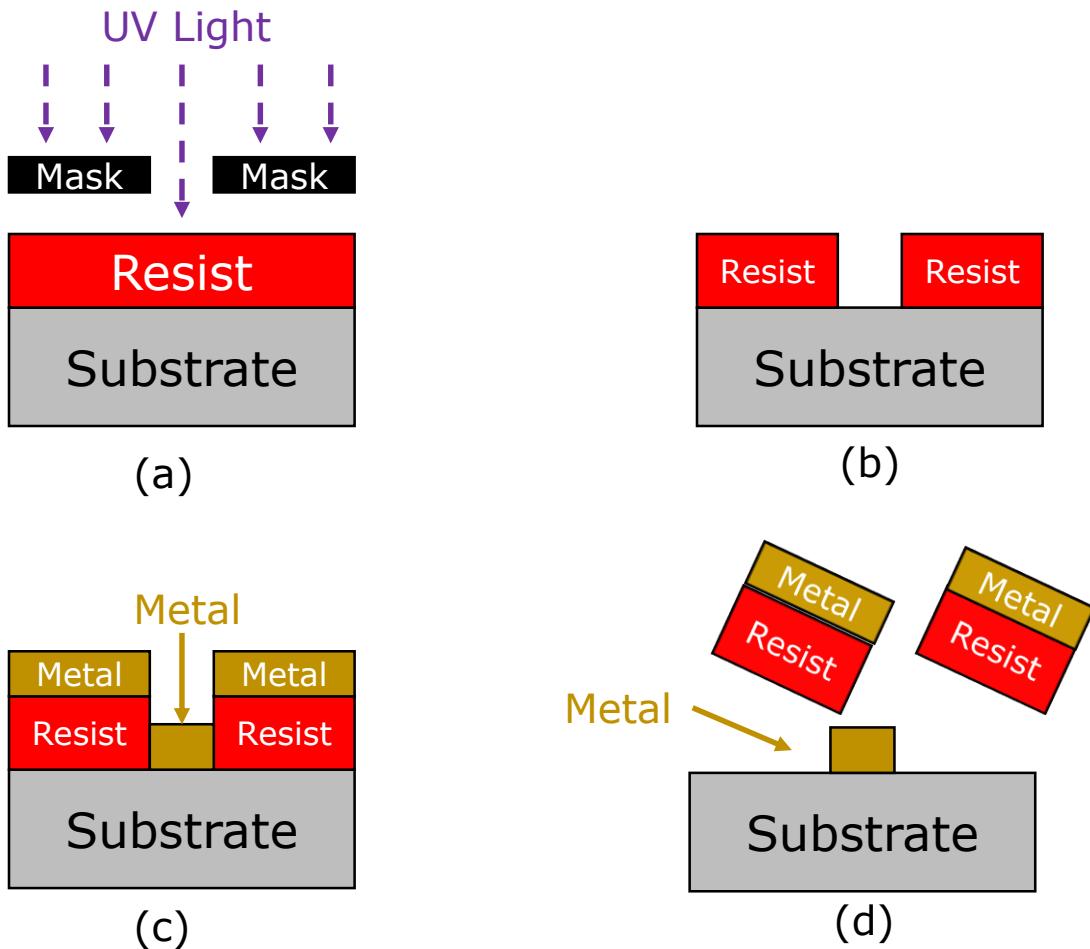


Pause and observe carefully

Main Functions of Resist

- Protect underlying films such as SiO_2 , Al, polysilicon, Si_3N_4 etc. from etching
- Define windows for metal-contact and thin film deposition
- Prevent ions from penetrating the underlying Si during selective ion implantation
- Lift-off process used to create metal patterns on the substrate

Lift-off Process



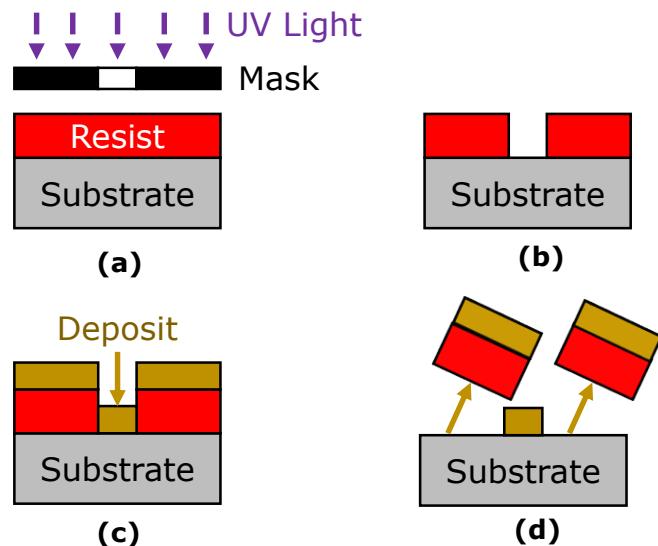
- The substrate is coated with resist. Then the resist is exposed through a mask with the desired pattern.
- The resist is developed to obtain the desired pattern on the substrate.
- The metal film is deposited onto the resist-patterned substrate.
- The metal-deposited resist is removed (acetone is usually used). The metal pattern will remain on the substrate.

Practice Question



**Pause and
try out this
question**

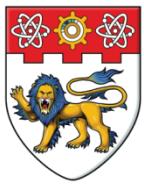
A lift-off process is used mostly to create metallic interconnections. Starting with a positive photoresist pattern, formed on a wafer, provide sketches to illustrate a typical lift-off process.



- a) Coat the wafer with photoresist and expose the photoresist.
- b) Remove exposed resist.
- c) Deposit metal film.
- d) Remove metal on resist: Metal pattern remains on silicon.

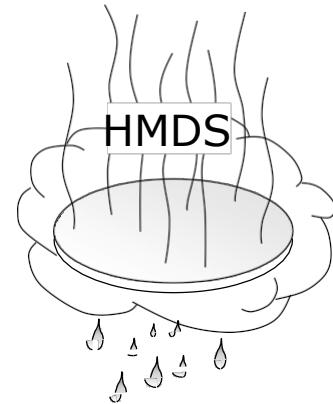
Lift-off process in microstructuring technology is a method of creating structures (patterning) of a target material on the surface of a substrate (eg. Wafer) using a sacrificial material.

It is an additive technique as opposed to more traditional subtracting technique like etching.

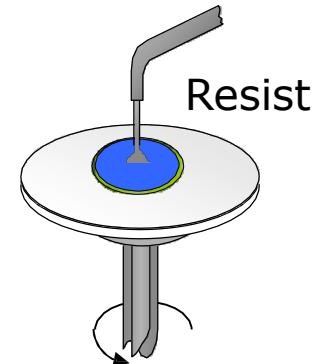


Eight Basic Steps of the Lithography Process

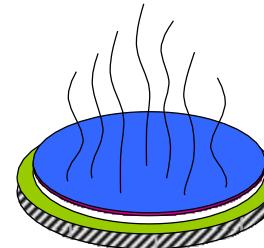
Eight Steps of Lithography



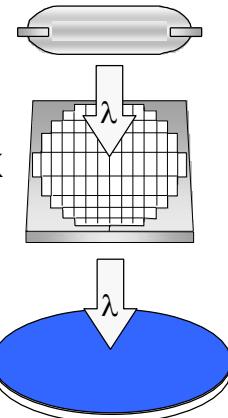
Step 1:
Vapour Prime



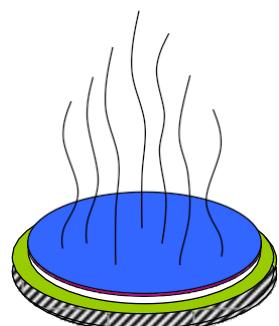
Step 2:
Spin Coat



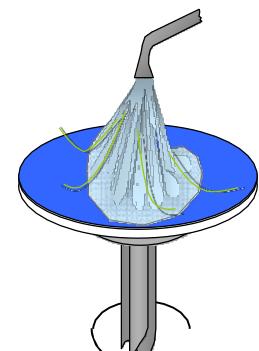
Step 3:
Soft Bake



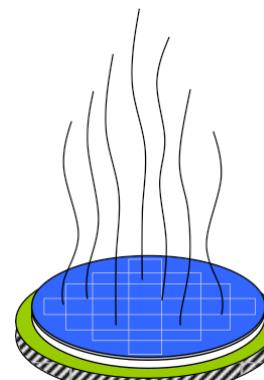
Step 4:
Alignment and Exposure



Step 5:
Post-Exposure Bake



Step 6:
Develop



Step 7:
Hard Bake



Step 8:
Develop Inspect

1. Vapour Prime Pre-Step – Dehydration Bake

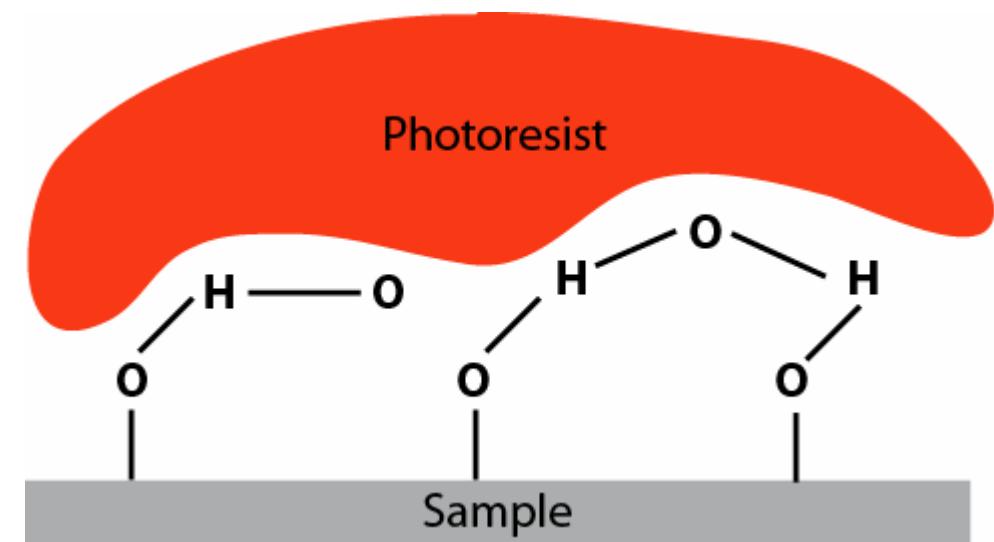
The pre-step of photolithography:

- Wafer dehydration bake – removal of water molecules on the wafer surface
- Ensures wafer surface is clean and dry

Cleaning the sample is very important to make sure that it is free from dust, dirt, or residual resist.

Dehydration baking will ensure that any H_2O on the sample evaporates out. This is especially important for samples that oxidise easily, for example like silicon.

The oxides will then bond to water vapour available in the air. When the resist is then coated onto the sample, the resist will adhere to the H_2O and not to the wafer surface.



Water presented on the wafer surface causes poor photoresist adhesion and resist lift-off due to surface contamination and presence of moisture layer.

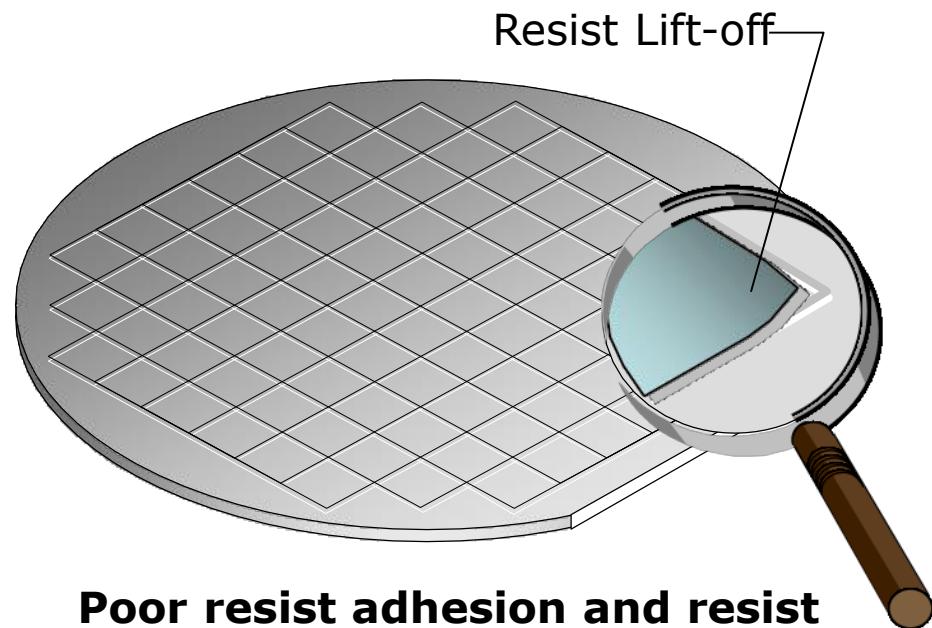
1. Vapour Prime – Cleaning and Dehydration Bake

The first step of photolithography:

- Usually integrated with the wafer dehydration bake on the same process
- Primes wafer with Hexamethyldisilazane (HMDS)
- Promotes good resist-to-wafer adhesion

Typical process sequence:

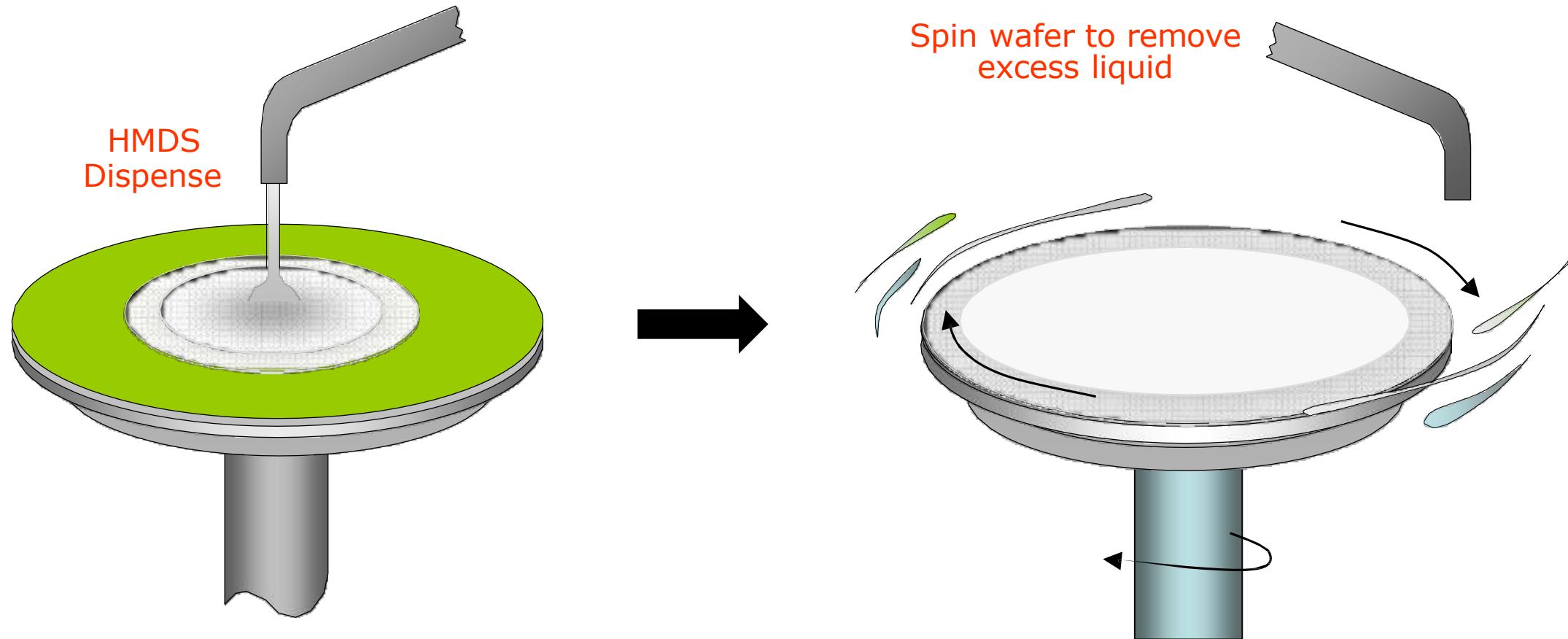
- Dehydration bake (200°C to 250°C)
- Vapour priming
- Priming techniques:
 - Puddle/ spray dispense and spin



Poor resist adhesion and resist lift off due to surface contamination and presence of moisture layer.

HMDS Priming Techniques

HMDS (liquid) dispense and spin:

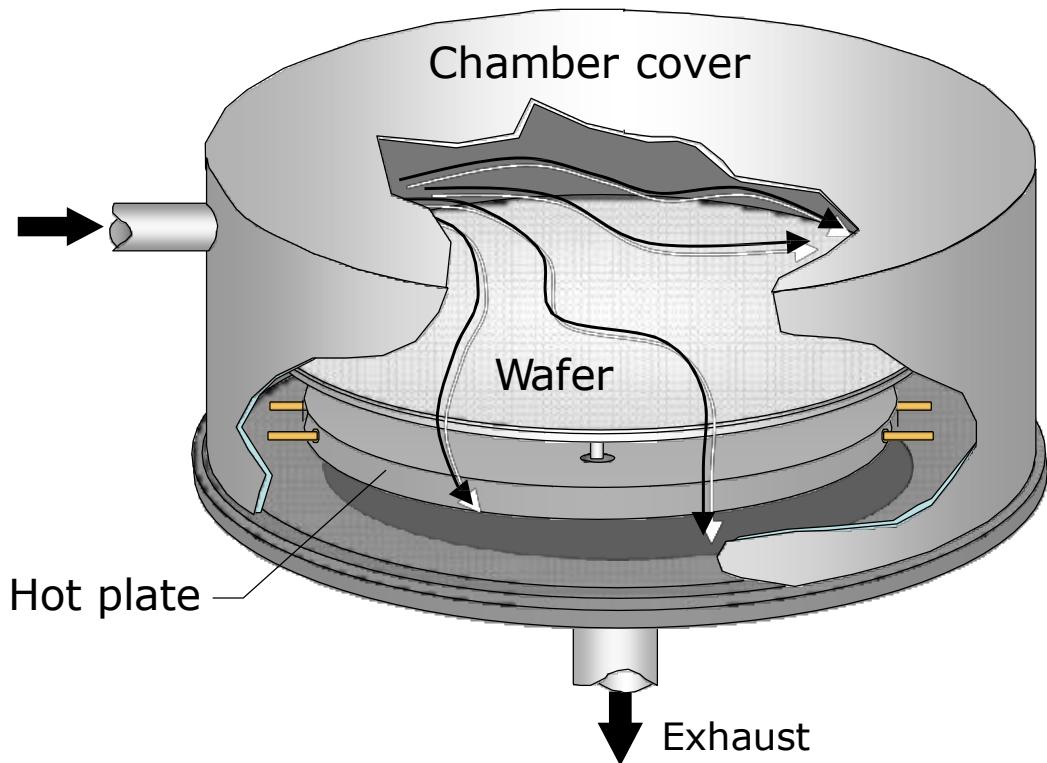


HMDS Priming Techniques

Dehydration bake and HMDS vapour prime:

Process Summary

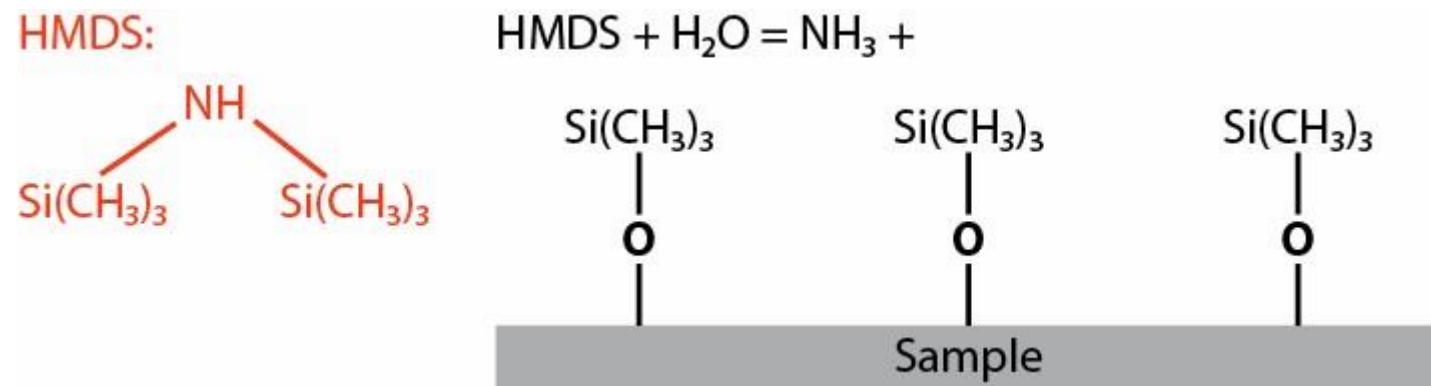
- Dehydration bake in an enclosed chamber with exhaust
- Hexamethyldisilazane (HMDS) prime
- Exhaust
- Clean and dry wafer surface (hydrophobic)
- Temperature $\sim 200^{\circ}\text{C}$ to 250°C
- Time ~ 60 seconds



Action of HMDS Priming on Silicon/ Oxide Surface

HMDS – Hexamethyldisilazane:

- HMDS turns wafer surface from hydrophilic to hydrophobic for better resist adhesion.
- Si-dioxide + H₂O + HMDS → Hexamethyldisiloxane + Ammonia

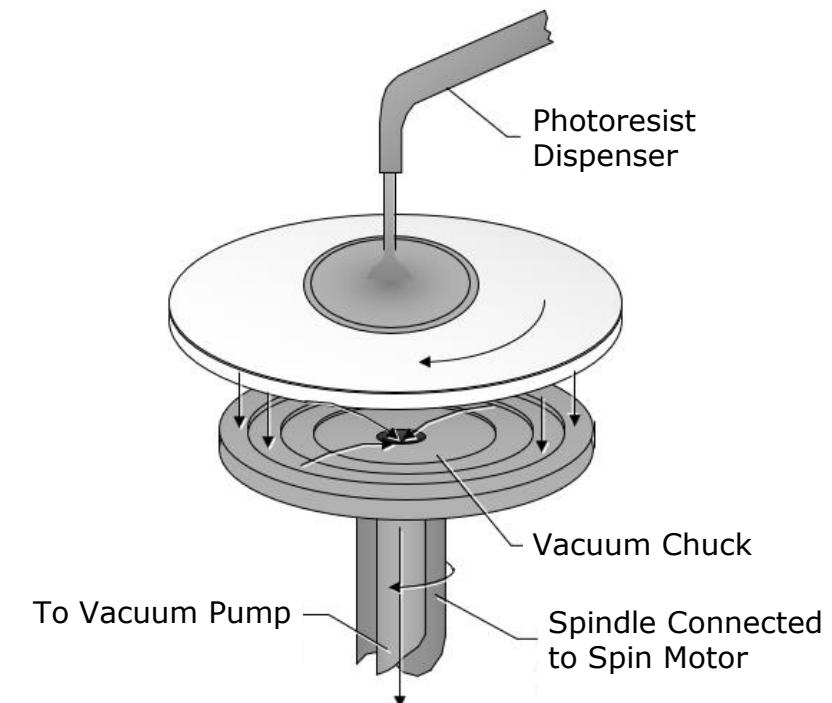
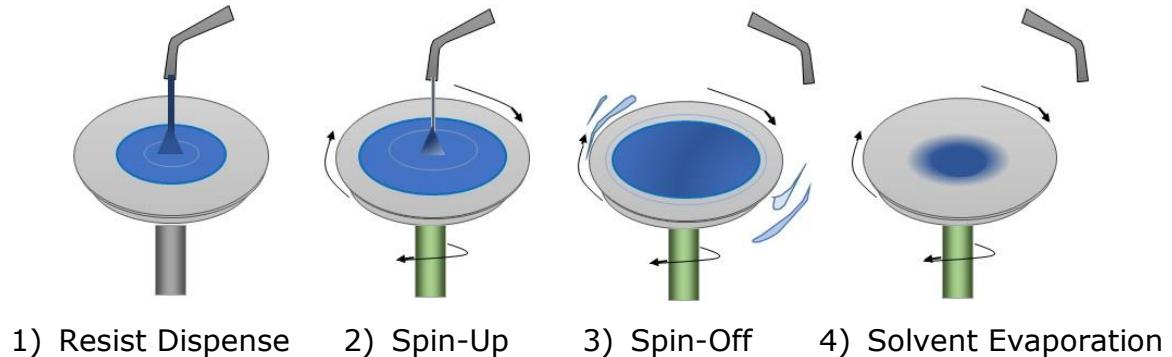


- After dehydration baking these oxidised samples, it is important to spin coat them first with HMDS primer. The HMDS primer will bond with the oxide groups to seal out the moisture.
- The Si(CH₃)₃ groups are compatible with the resist, creating adhesion between the sample and the resist.

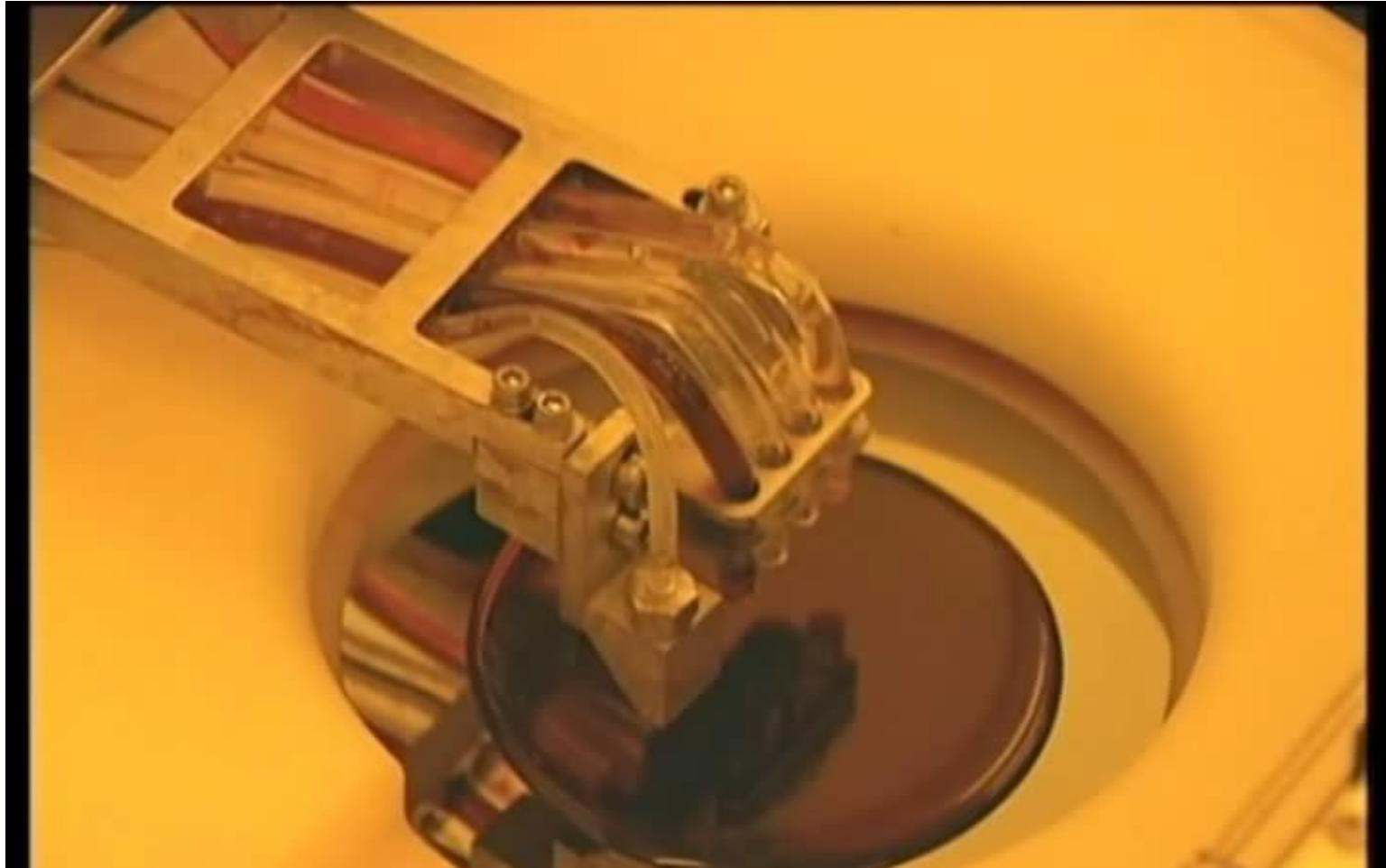
2. Spin Coat

Process Summary:

- The wafer is held onto the vacuum chuck
- Dispense ~ 5 ml of the resist at static or slow spread speed of $\omega_1 \sim 500$ rpm
- Ramp up to $\omega_2 \sim 3000$ to 5000 rpm
- Quality measures:
 - Time
 - Speed
 - Thickness
 - Uniformity
 - Particles and defects

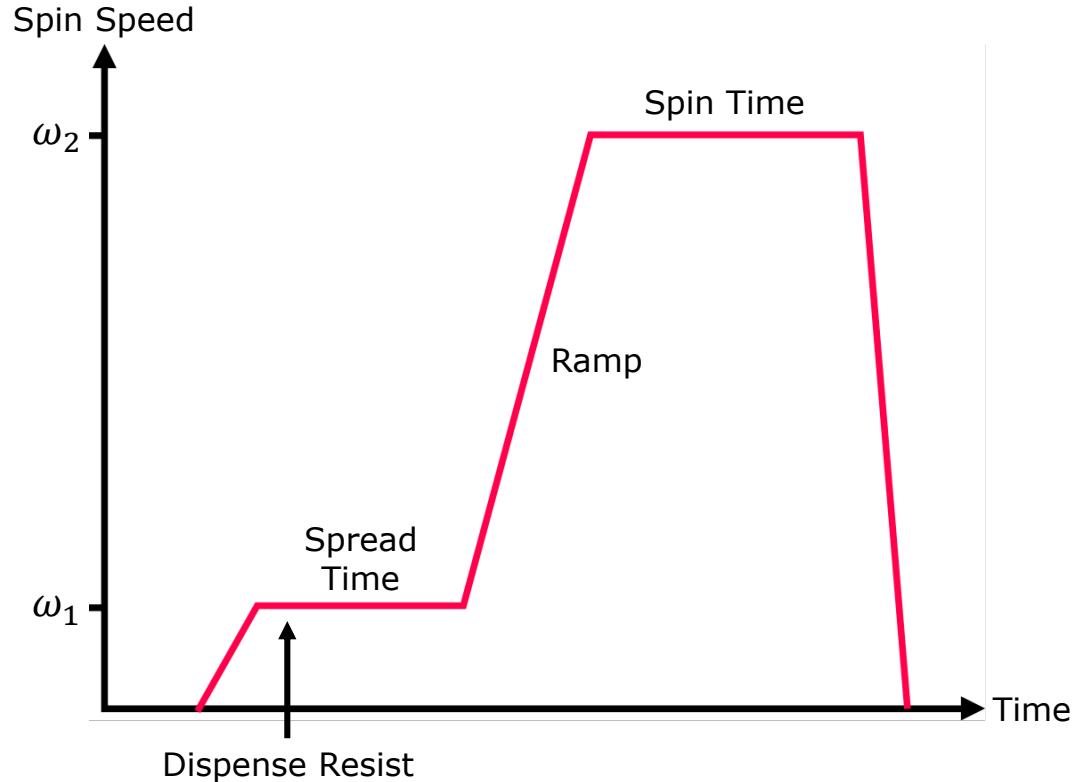


Resist Spin Coating



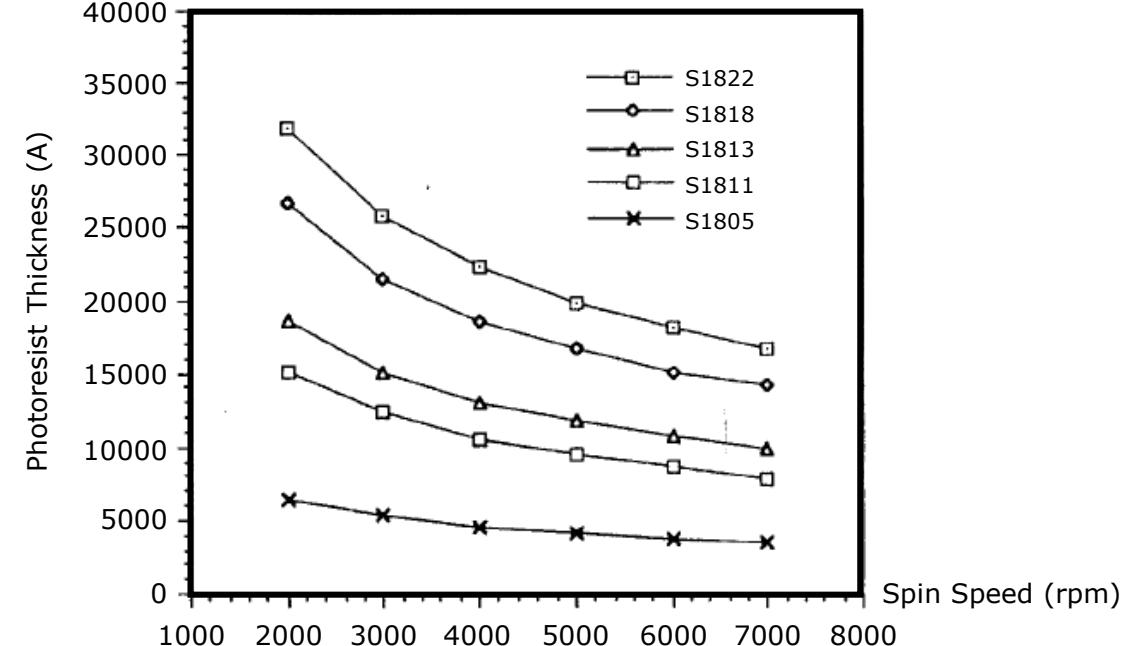
Watch the video lecture to view this video.

Resist Spin Coating



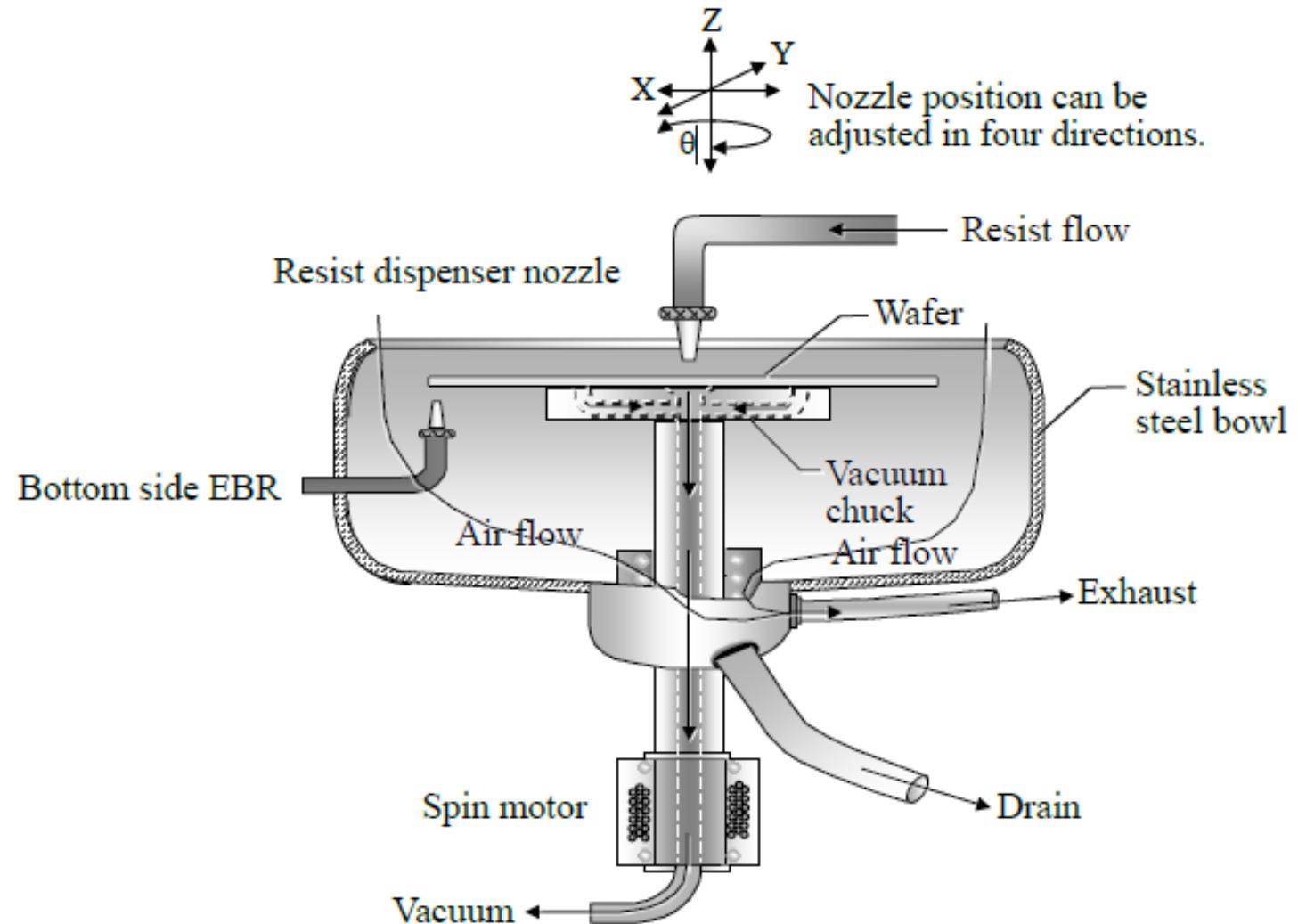
Pictorial representation of a simple resist spin coat cycle. If $\omega_1 > 0$, the dispense is said to be dynamic.

**Microposit S1800 Photo Resist Undyed Series:
Spin Speed Curves**



Resist layer thickness depends on the viscosity of resist and is inversely proportional to the square root of the spin speed, $t \propto 1/\omega_2$.

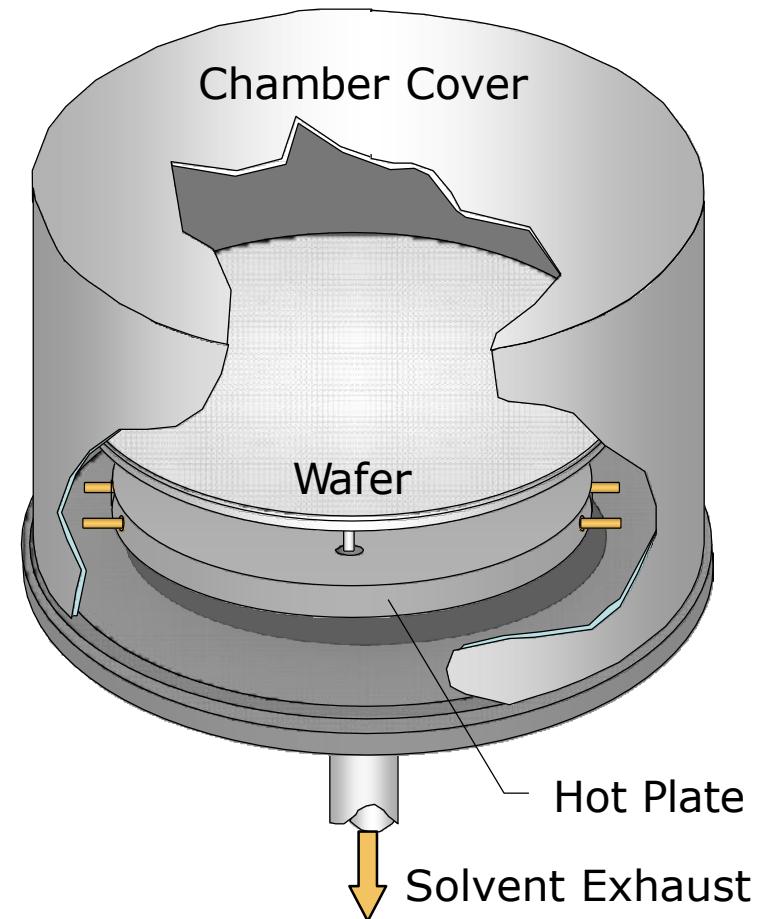
Resist Dispense Nozzle



3. Soft Bake

Characteristics of Soft Bake:

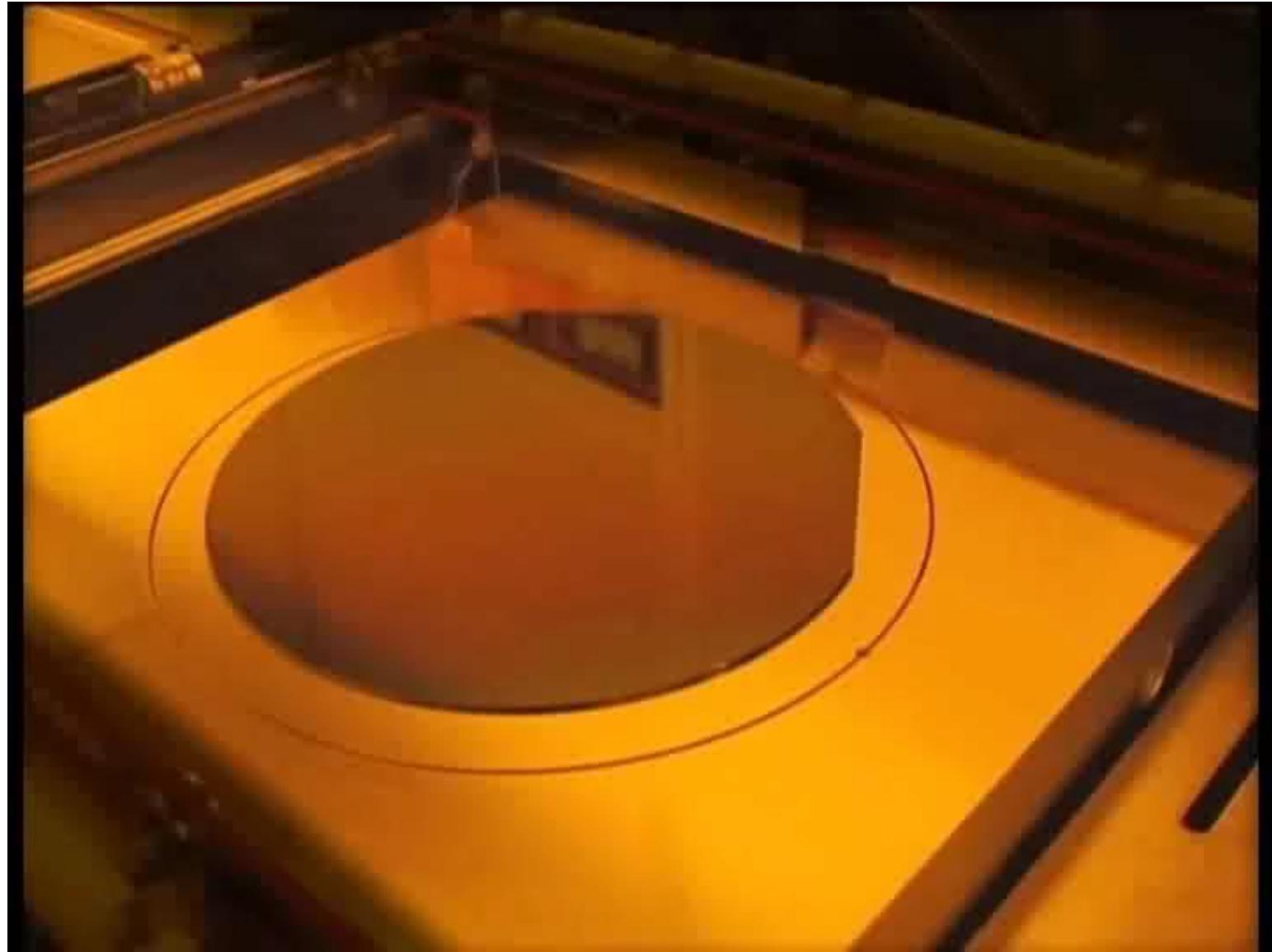
- Partial evaporation of resist solvents
- Improves resist-to-wafer adhesion
- Promotes resist uniformity on the wafer
- Optimises light absorbance characteristics of resist (optimises the photo-speed)
- Improves etch resistance and linewidth control during etching
- Drives off most of the solvent in the resist
- Typical bake temperatures are 90°C to 100°C:
 1. For about 30 seconds
 2. On a hot plate
 3. Followed by a cooling step on a cold plate



Soft Bake on Vacuum Hot Plate

3. Soft Bake

- Prebaking or Soft Bake makes the PR sensitive to UV light by removing the solvent component of the PR.
- A short prebake will prevent UV light from reaching the PAC (photoactive compound, will be further explained in Chapter Resist Technology) due to an excess of solvent remaining in the PR.
- Over-baking the sample will increase the sensitivity to UV light and, in severe cases, may destroy the PAC and reduce the solubility of the PR in the developer.

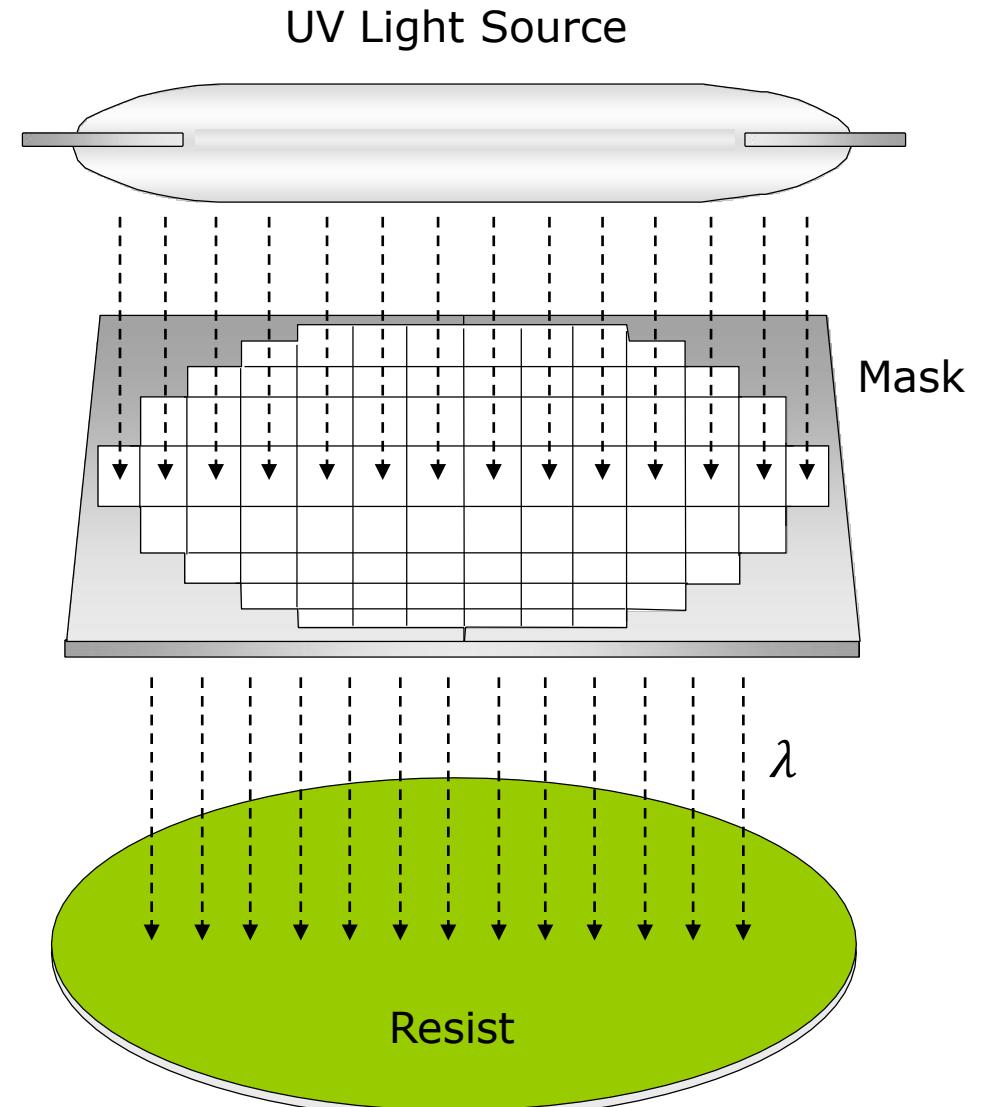


4. Alignment and Exposure

Process Summary:

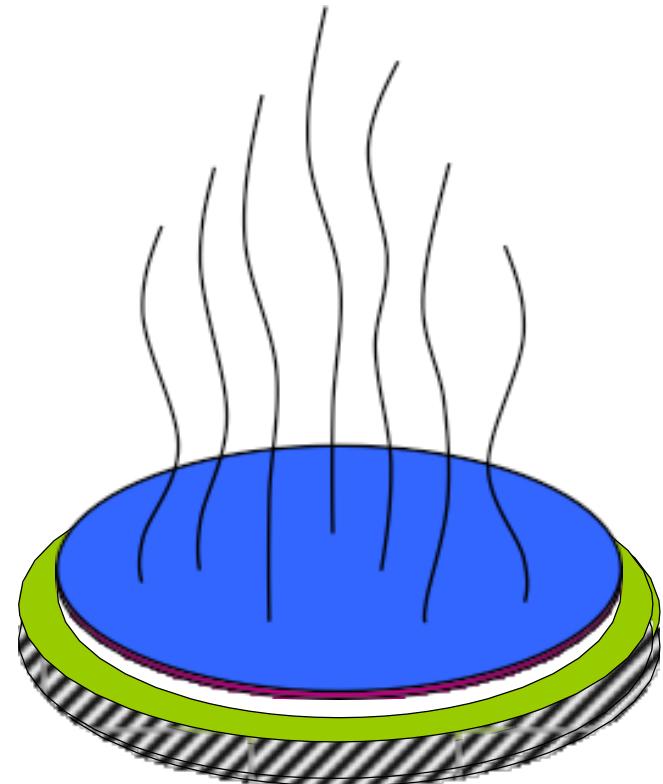
- Transfers the mask image to the resist-coated wafer
- Activates photo-sensitive components of the resist
- Quality measures:
 - Linewidth resolution
 - Overlay accuracy
 - Particles and defects

We will discuss further in “lithography technology” and “resist technology” sections.



5. Post-Exposure Bake

- Required for deep UV resists
- Typical temperatures 100°C to 110°C on a hot plate
- Immediately after exposure



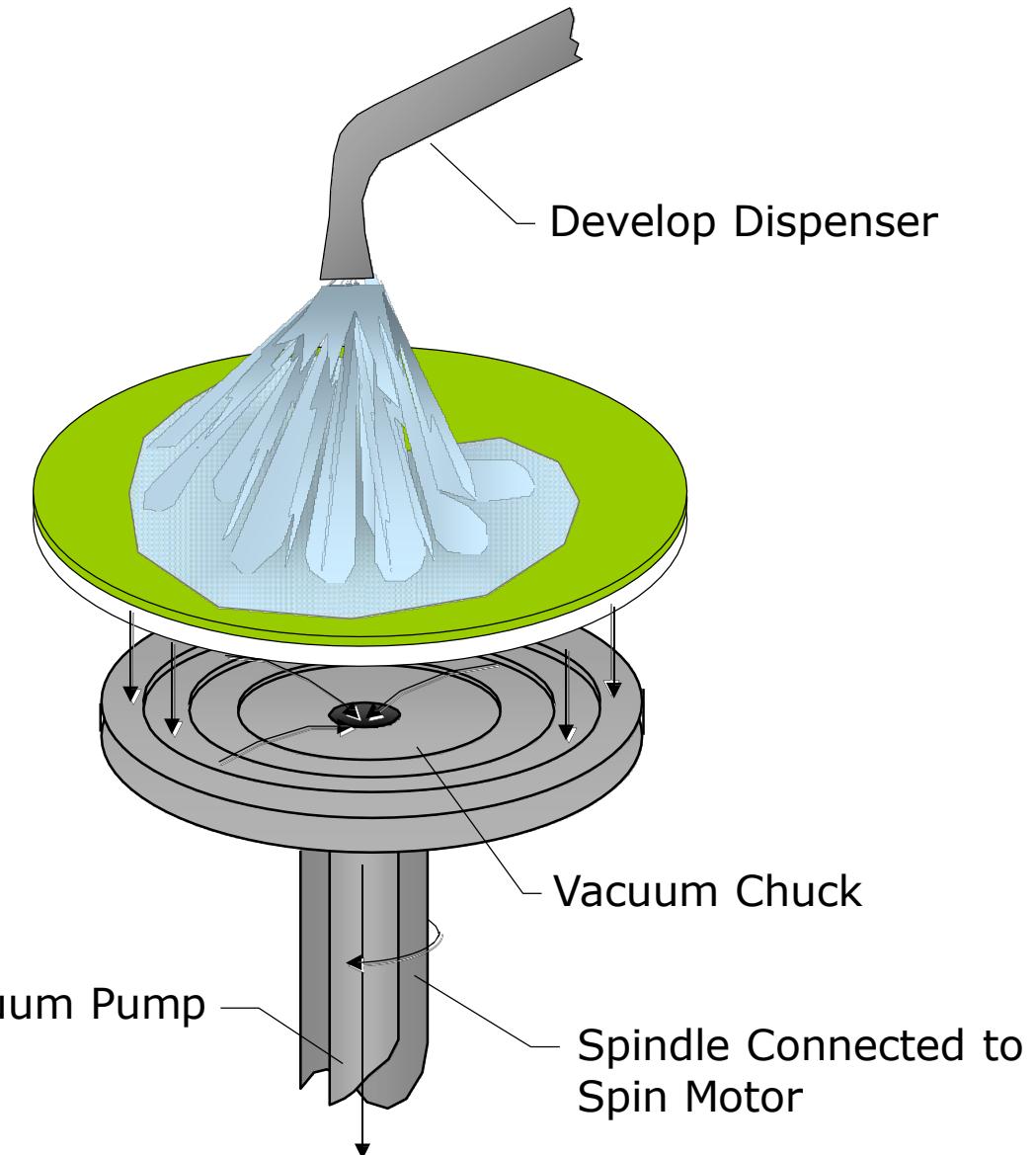
6. Developing

Purpose:

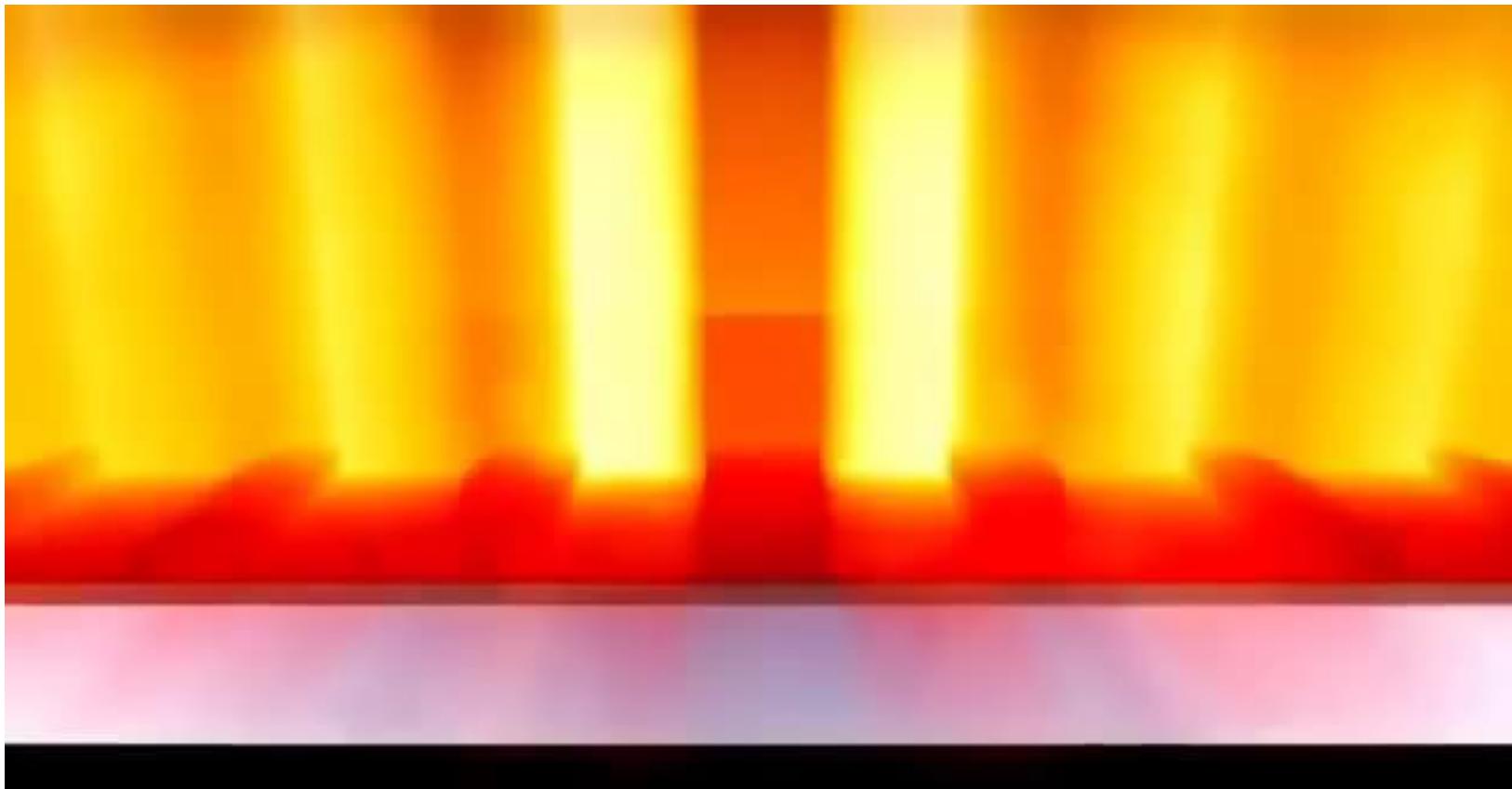
- Developing creates the pattern in the resist on the wafer surface.

Step Summary:

- The developer washes away the soluble region.
- The insoluble region remains on the wafer.



6. Develop – Animation



Watch the video lecture to view this animation.

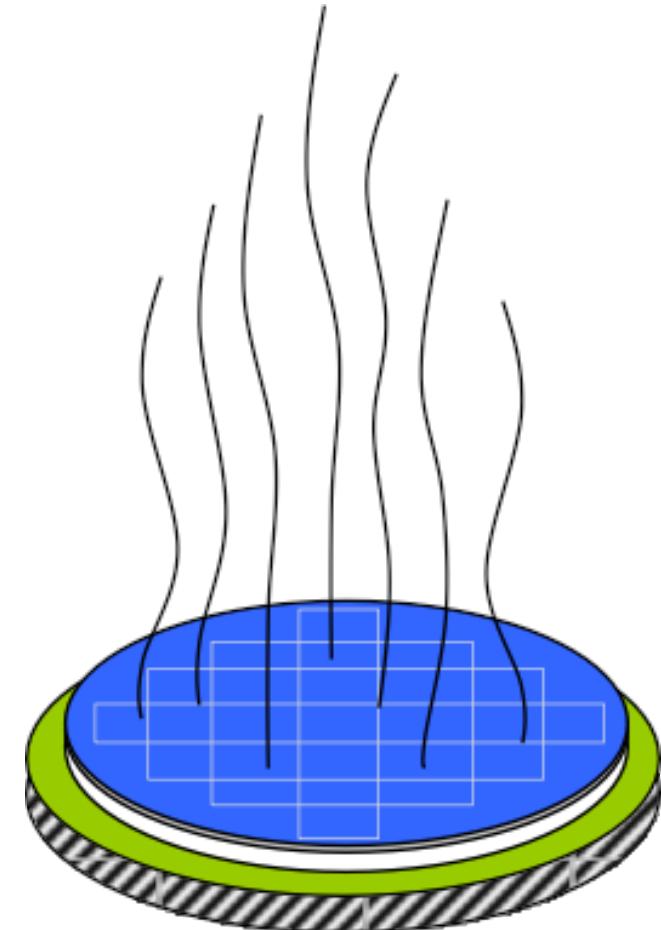
6. Develop – Video



Watch the video lecture to view this video.

7. Hard Bake

- A post-development thermal bake at about 110°C
- Evaporate remaining solvent
- Improve resist-to-wafer-adhesion



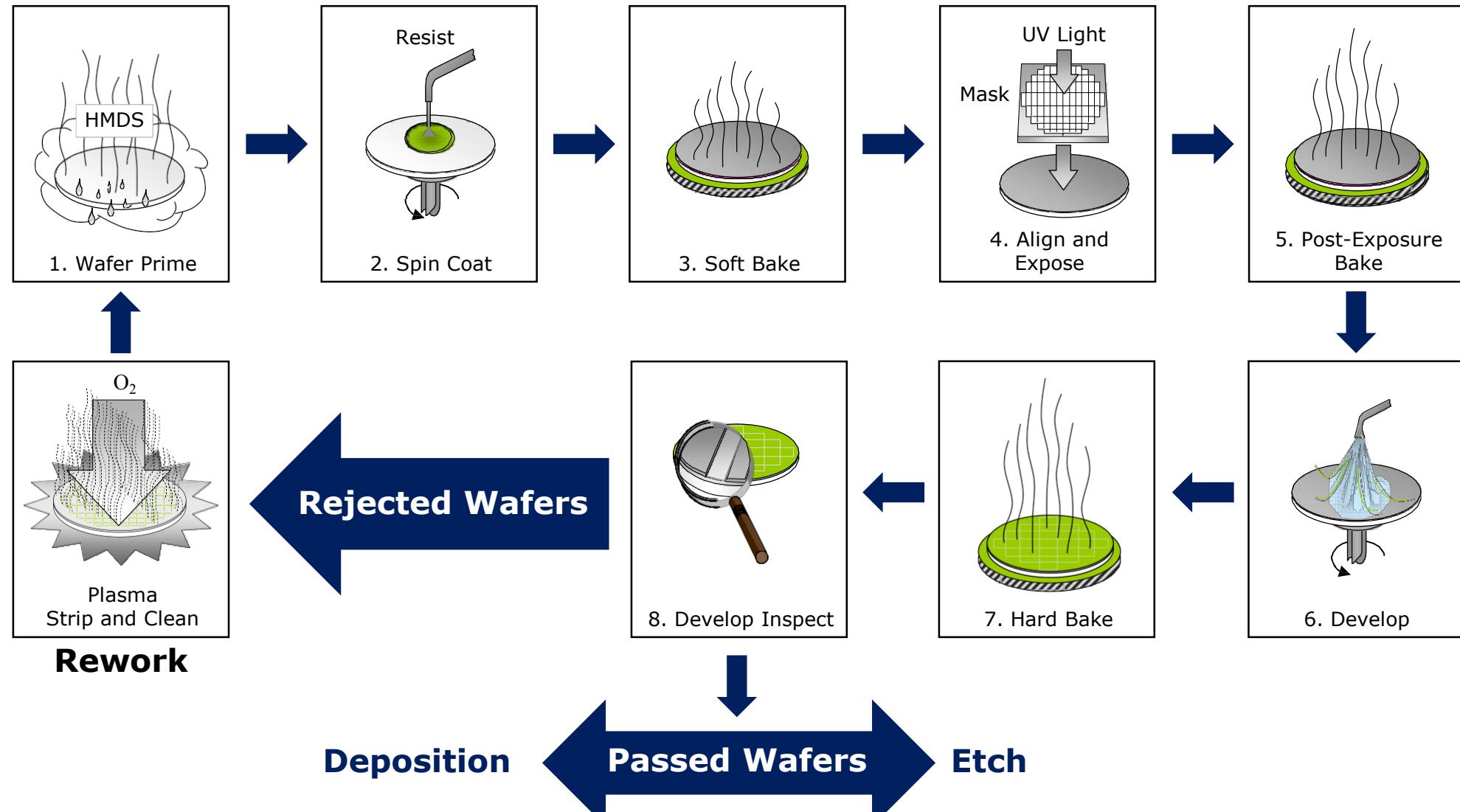
8. Develop Inspect

- Inspect to verify a quality pattern:
 1. Identify quality problems (defects)
 2. Characterise the performance of the photolithography process by providing feedback regarding the quality of the lithography process
 3. Prevents scrap
 4. Prevents passing defects to other areas such as etching or deposition
- Plasma Clean: Rework on defective resist-coated wafers
- Typically an automated operation
- Develop inspect rework flow



**Inspection Tool for Develop
Inspect**

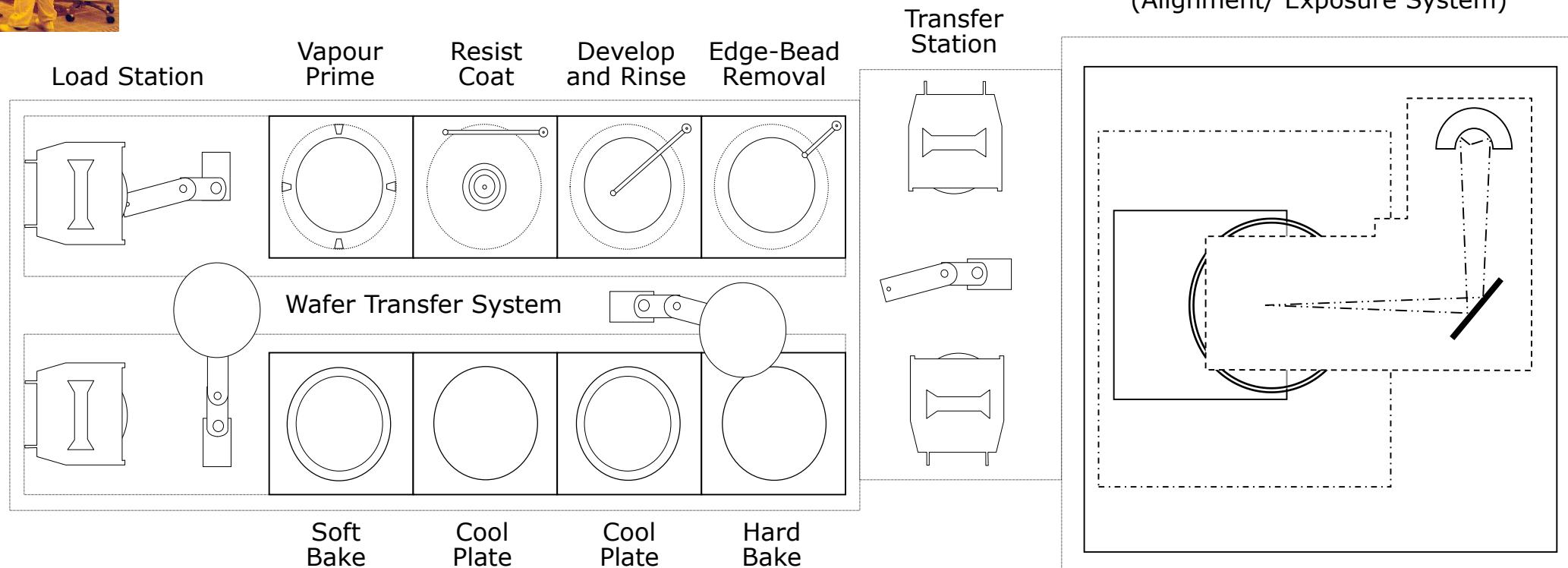
Develop Inspect and Rework Flow



Lithography Track System



Automated Wafer Rack



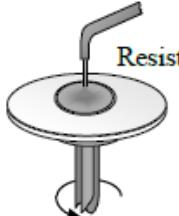
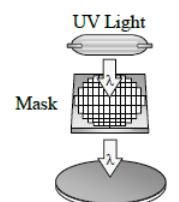
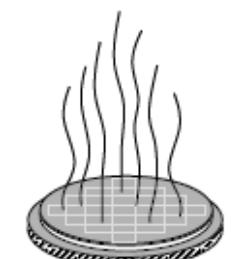
Summary



**Pause and
read**

Step	Purpose
1. Vapour Prime	De-bakes and primes wafer surface with HMDS to improve photoresist to wafer adhesion
2. Spin Coat	Spin coat photoresist to the target thickness
3. Soft Bake	<ul style="list-style-type: none"> • Partial evaporation of photoresist solvents • Improves photoresist-to-wafer adhesion promotes resist uniformity on the wafer • Optimises light absorbance characteristics of photoresist (exposure speed) • Improves etch resistance and linewidth control during etching
4. Alignment and Exposure	Transfers the mask image to the resist-coated wafer activates photo-sensitive components of photoresist
5. Post-Exposure Bake (PEB)	Required for DUV resist preventing non-uniform exposure along the thickness of the photoresist film
6. Develop	Dissolves the exposed photoresist
7. Hard Bake	<ul style="list-style-type: none"> • Evaporates the residual solvent in the photoresist • Hardens the resist for subsequent ion implant or etch processing • Improves resist-to-wafer adhesion
8. Develop Inspect	Checks the quality of process to ensure the desired pattern is transferred to photoresist layer

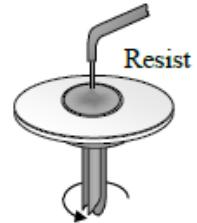
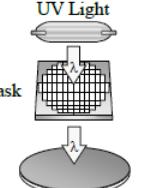
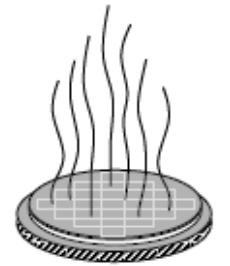
Fill in the Missing Information

		Promotes Wafer-Resist Adhesion	
Step 1: Vapour Prime 	Step 2: 	Step 3: 	Step 4: Alignment and Exposure 
Step 5: Post Exposure Bake 	Step 6: 	Step 7: 	Step 8: Develop Inspect 
Smooth-Out Possible Interference Effect		Evaporates Remaining Solvent	



Pause and try out this question

Fill in the Missing Information

Ensures Wafer is Clean and Dry	Coat Resist on Wafer	Promotes Wafer-Resist Adhesion	Induces Photochemical Reaction in Resist
Step 1: Vapour Prime 	Step 2: Spin Coat 	Step 3: Soft Bake 	Step 4: Alignment and Exposure 
Step 5: Post Exposure Bake 	Step 6: Develop 	Step 7: Hard Bake 	Step 8: Develop Inspect 
Smooth-Out Possible Interference Effect	Creates Pattern on Wafer	Evaporates Remaining Solvent	Identifies Quality Problems



Pause and observe carefully

Lithography Processing – Summary

Lithography processing:

- UV light is used as the exposure source in optical lithography. Smaller UV wavelength enables printing of smaller features.
- For a positive resist, regions exposed to UV light will be washed away by the developer, whereas for a negative resist, regions shaded from UV light will be washed away by the developer.
- The eight basic steps of lithography include vapour prime, spin coat, soft bake, alignment and exposure, post-exposure bake, develop, hard bake, and develop inspect, sequentially.



Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

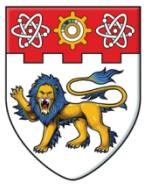
Lithography – Advanced Lithography

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Advanced lithography:

- Optical enhancement techniques
- Immersion lithography
- X-ray lithography
- E-beam and SCALPEL lithography



Optical Enhanced Techniques

Three Ways to Improve Resolution

Higher resolution:

- Can achieve a smaller feature size
- Smaller linewidth W_{min} is needed

Reduce λ :

- Shorter wavelength (436 nm, 365 nm, 248 nm, 193 nm, and 13.5 nm)

Reduce k_1 :

- Improved masks (CD control and phase shift masks)
- Resolution Enhancement Techniques (RET)

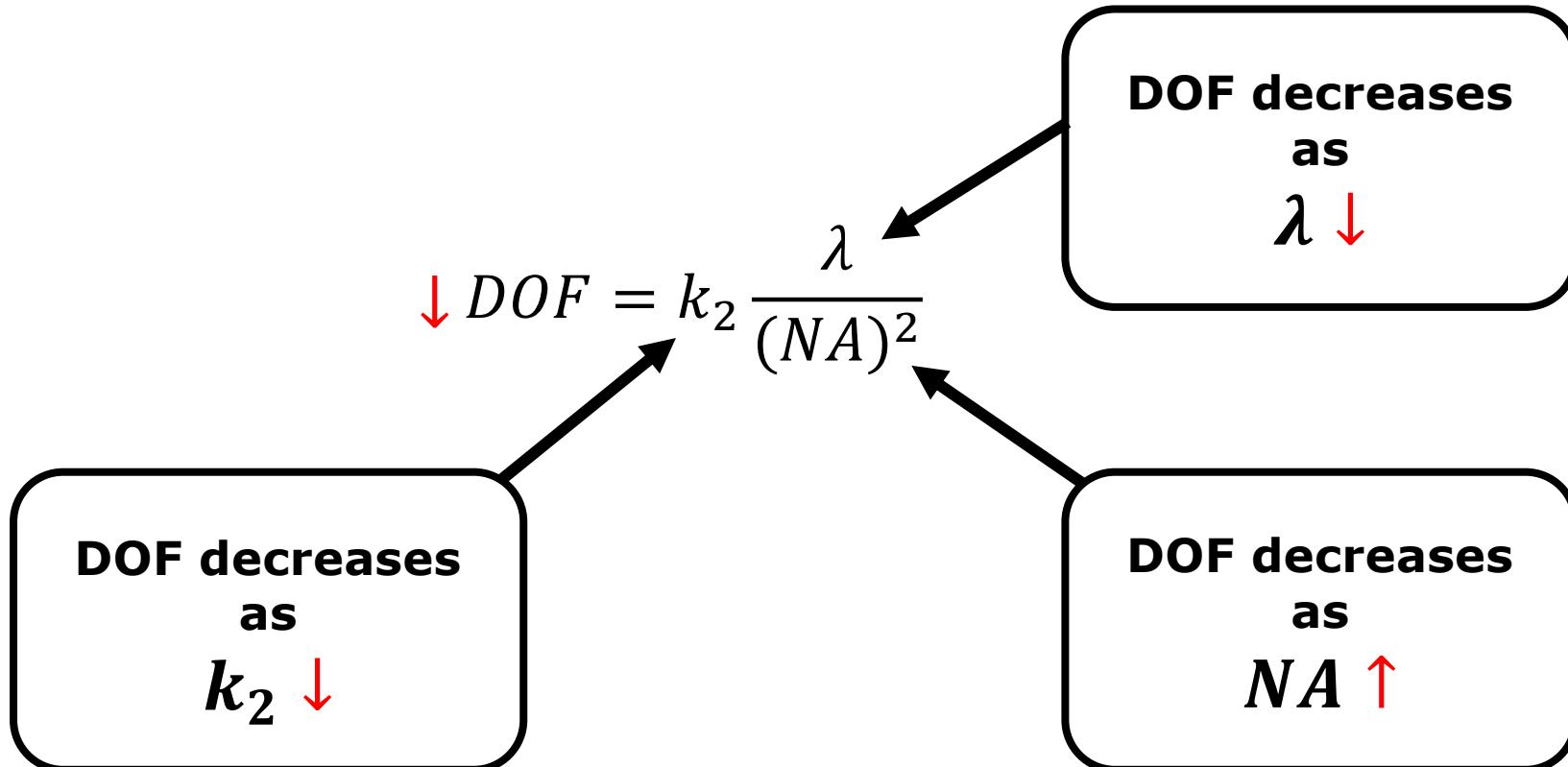
Increase NA:

- Historically 0.1 - 0.4, approaching 0.8
- Hyper-NA for immersion lithography $NA > 1$

$$W_{min} = k_1 \frac{\lambda}{(NA)}$$

→ $k_1 < 0.3$ achievable
 CD: Critical Dimension

Improvement in Resolution - Depth of Focus (DOF) Issue



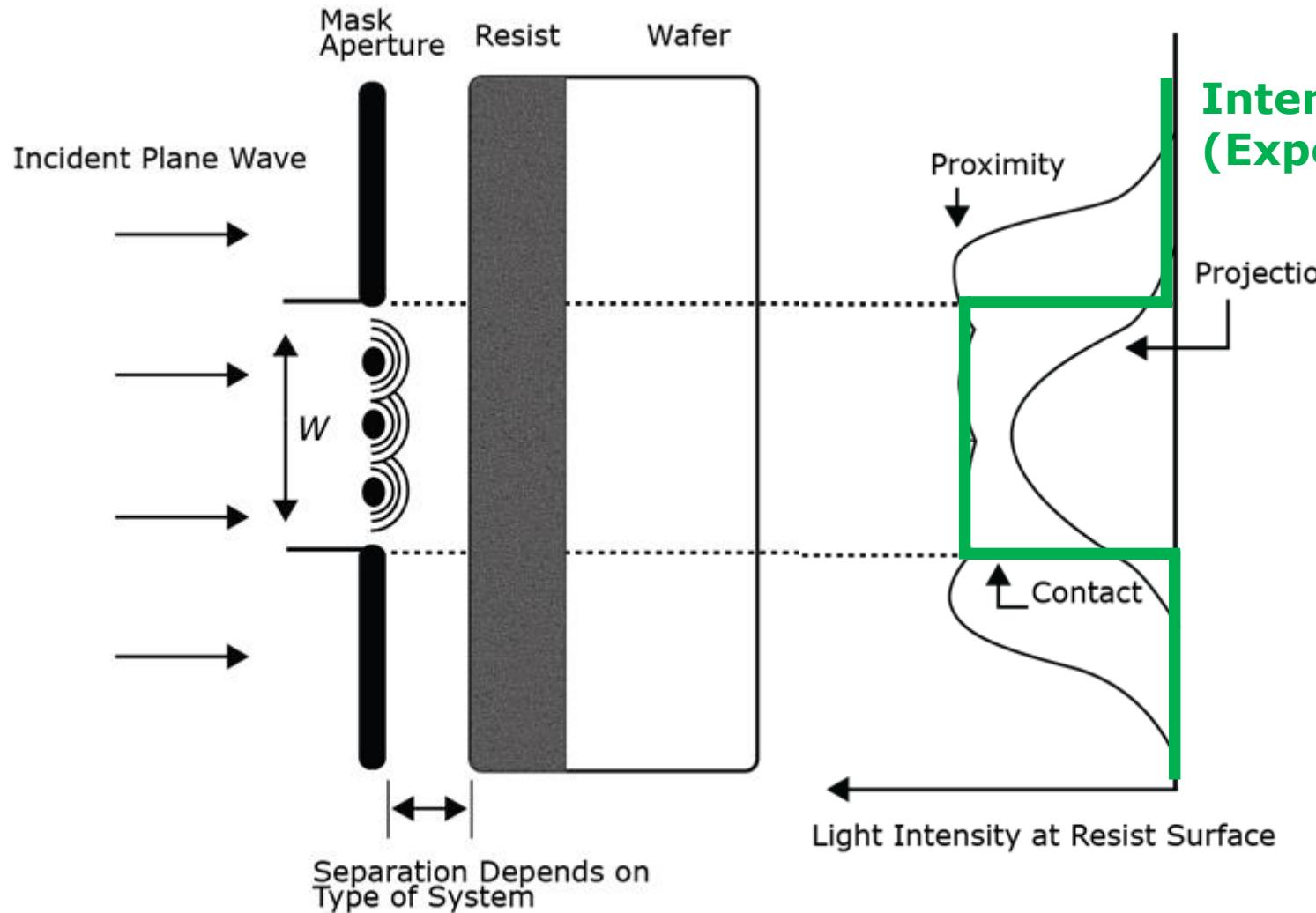
Nevertheless, wafers are made of PLANAR (very flat surface) with Chemical Mechanical Polishing (CMP) which allow the lithography systems to work with smaller DOF, resolving DOF issue.

Diffraction in Lithography

What is diffraction? Why is it a concern in lithography?

- Diffraction occurs when light passes through a narrow opening or a sharp edge.
- Interference patterns occur along the edge of the opening, causing a fuzzy image rather than the expected sharp edge that occurs between light and shadow.
- Light diffraction is a concern in photolithography because of the extremely small patterns of sharp edges and narrow spaces on reticles. Diffraction patterns rob exposure energy and scatter it, leading to exposure of unwanted areas of the resist.
- We can adopt optical enhancement techniques such as Optical Proximity Correction (OPC), Phase-Shift Masks (PSM) and Off-Axis Illumination (OAI).

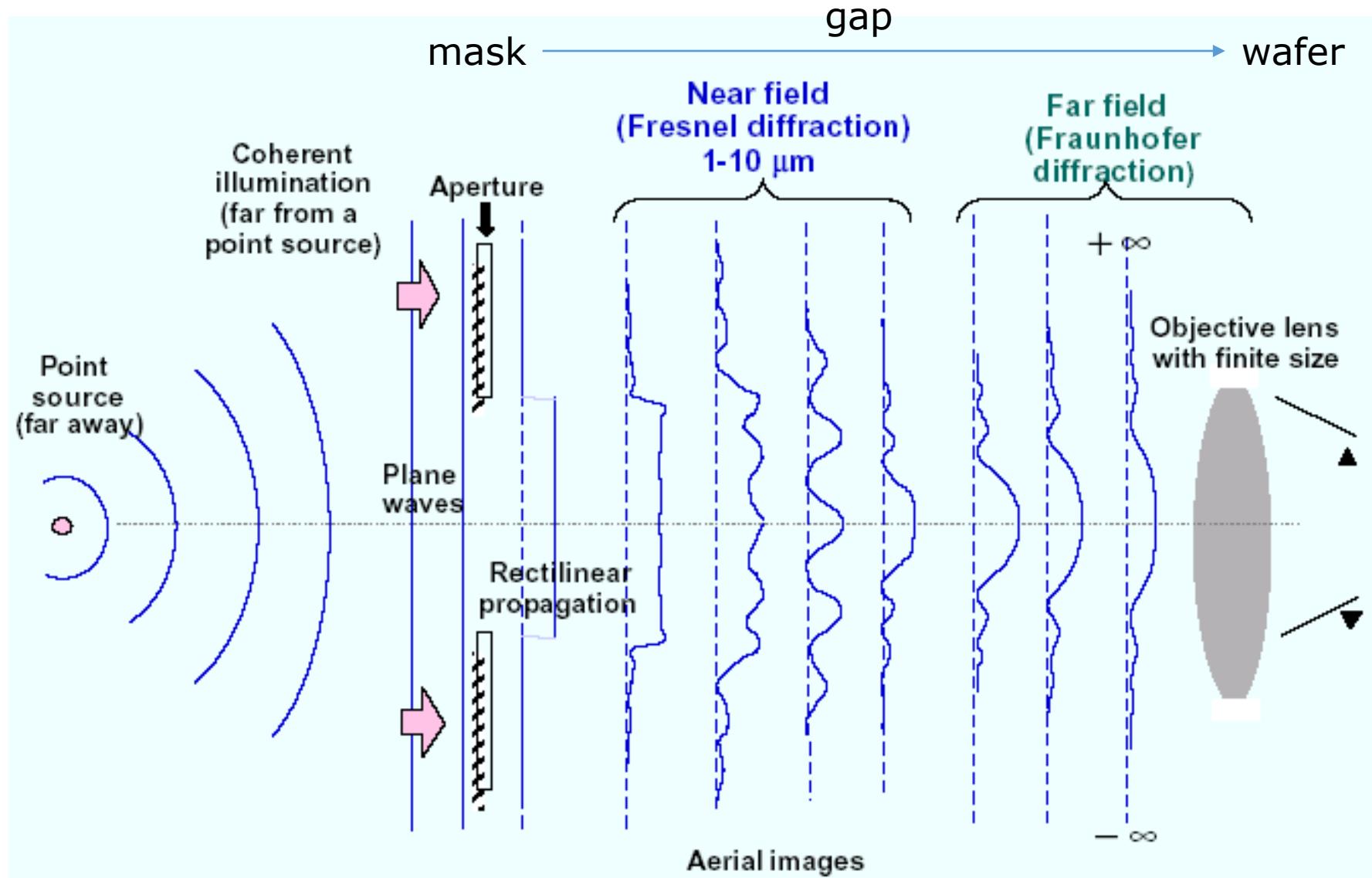
Diffraction in Lithography (Cont'd.)



Intensity on Contact Aligner (Expected Intensity)

- Aperture will create a diffraction pattern that will divert some of the light from its desired path, thereby decreasing the quality of the image.
- In lithography, there are two limiting cases (depending on the gap between the mask and the wafer): **Near field** image and **far field** image

Light Diffraction through an Aperture on Mask



- Aperture will create a diffraction pattern that will divert some of the light from its desired path, thereby decreasing the quality of the image
- In lithography, there are two limiting cases (depending on the gap between the mask and the wafer): **Near field** image and **far field** image

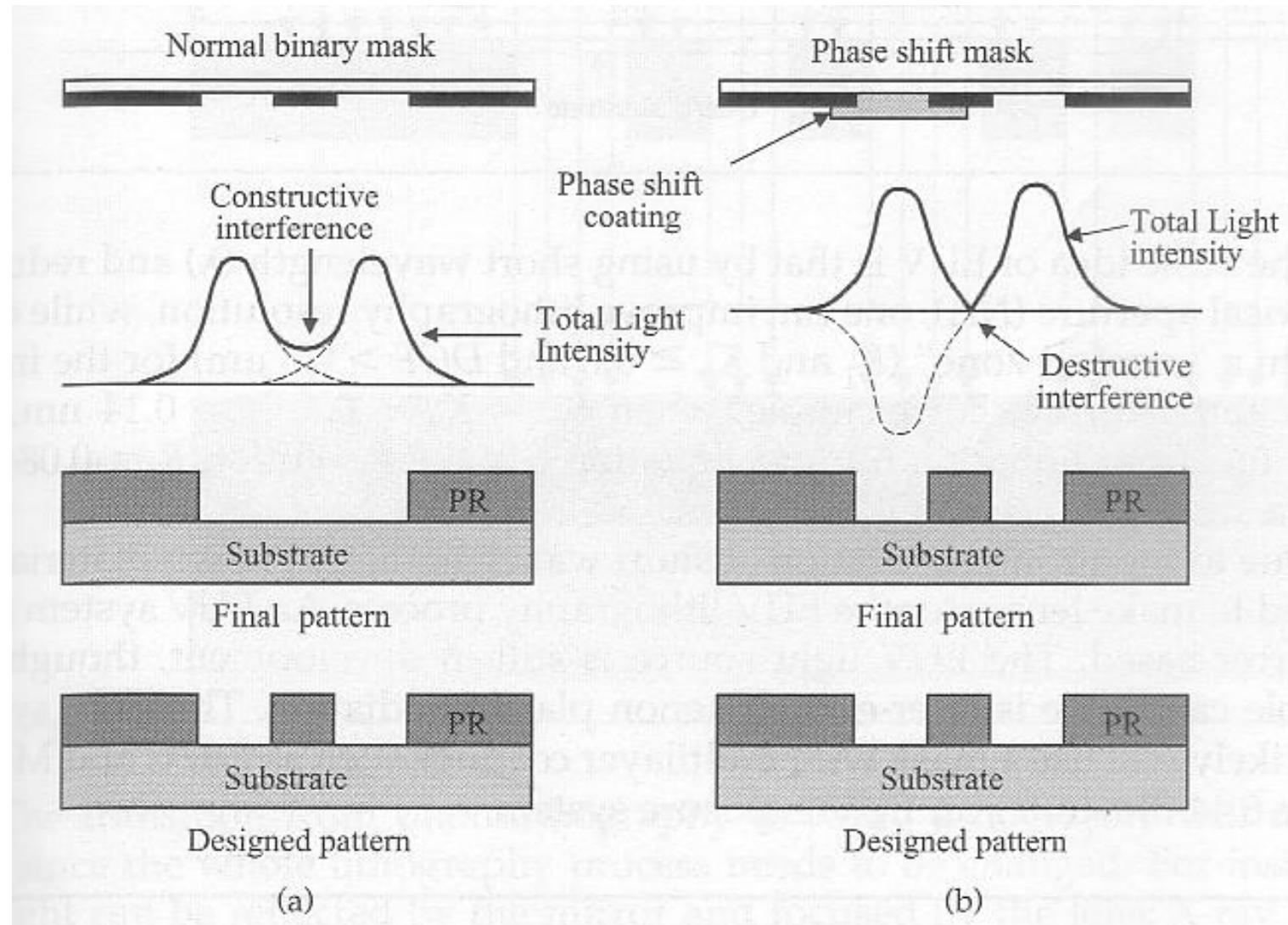
Optical Enhancement Technique

- **Phase-Shift Mask (PSM)**
- Optical Proximity Correction (OPC)
- Off-Axis Illumination (OAI)

Phase Shift Mask (PSM)

Phase-Shift Mask (PSM) is a method used to overcome problems associated with light diffraction through small openings patterned on the reticle.

With PSM, the reticle is modified with an additional transparent layer so that alternating clear regions cause the light to be phase-shifted 180° . This causes destructive interference, where light diffracted into the nominally dark area on the left will encounter destructive interference with light diffracted from the right clear area.



Optical Enhancement Technique

- Phase-Shift Mask (PSM)
- **Optical Proximity Correction (OPC)**
- Off-Axis Illumination (OAI)

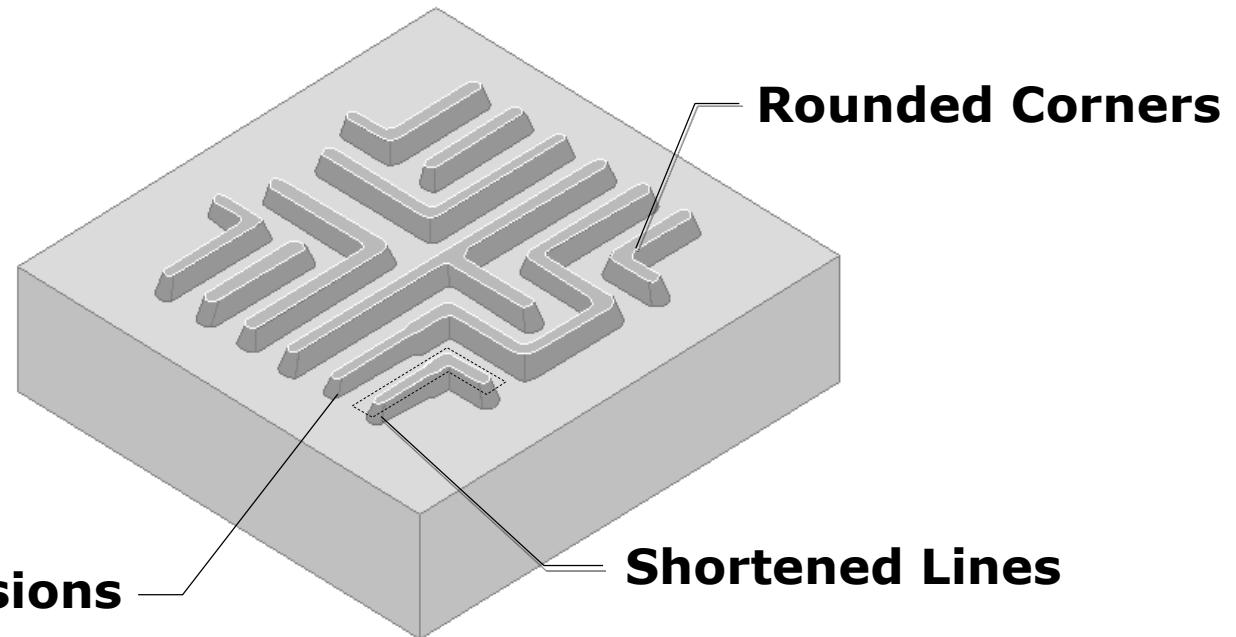
Optical Proximity Effect

High-frequency components of the diffracted light are lost for finite NA of lenses.

→ Ends and bows of narrow lines are not ideal

Use of optical proximity correction in the mask design. This is another approach to design a better mask (e.g. clever mask engineering based on software algorithms) can also improve resolution significantly.

The approach involves adding extra features to the mask, usually at corners where features are sharp, to compensate for the high-frequency information lost due to diffraction effects.

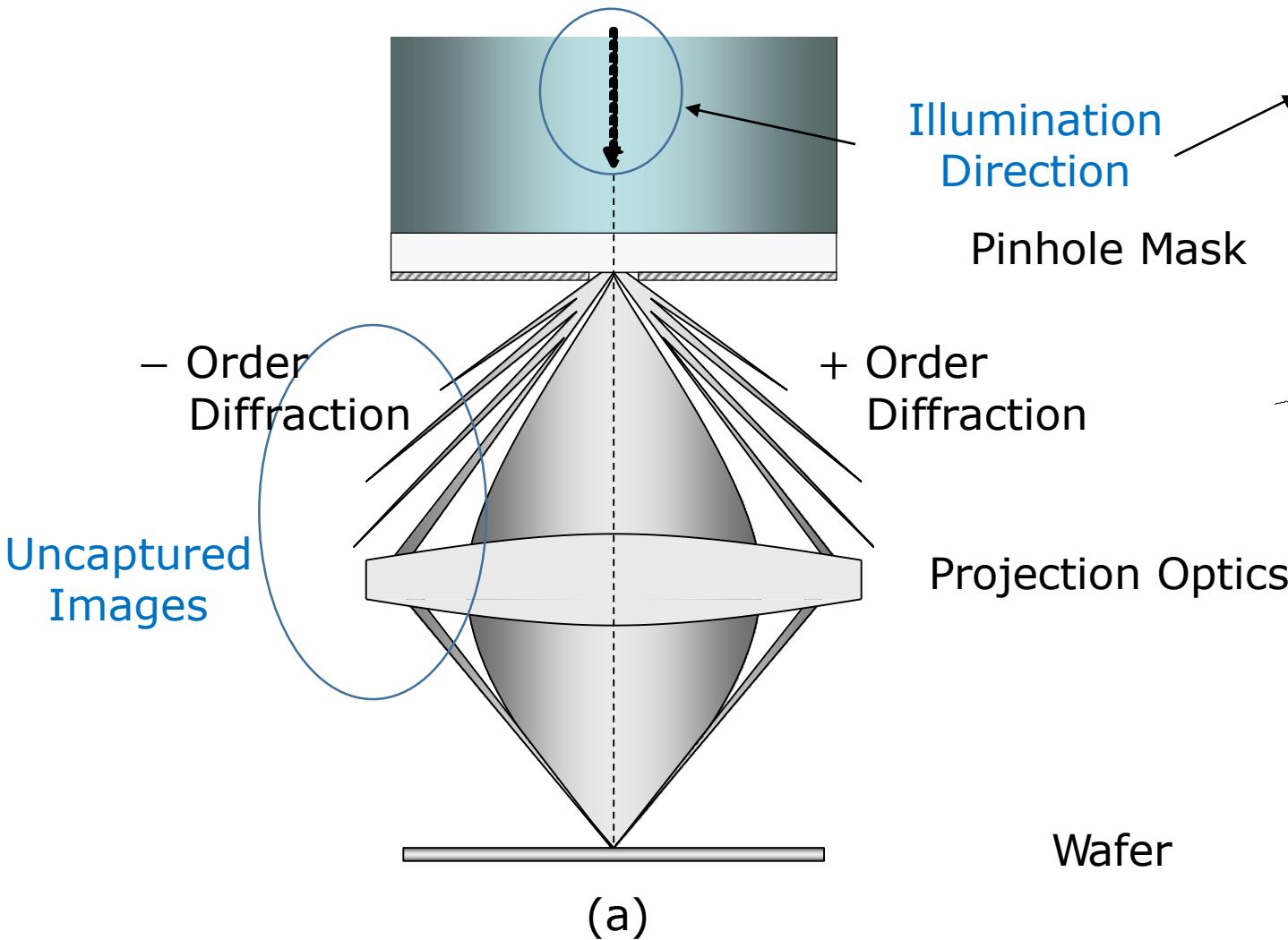


Optical Enhancement Technique

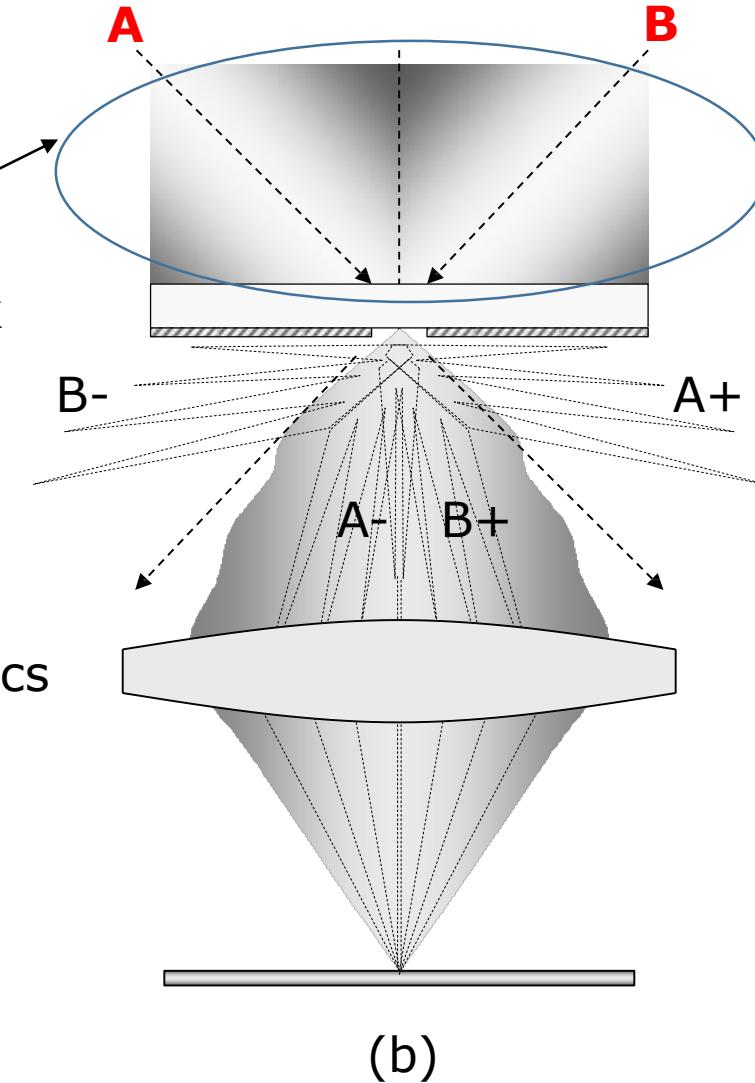
- Phase-Shift Mask (PSM)
- Optical Proximity Correction (OPC)
- **Off-Axis Illumination (OAI):**
 1. This allows the optical system to capture some of the higher order diffracted light, and hence can improve resolution.
 2. OAI has the incident exposure light that strikes the mask at an angle in order to align diffraction fringes with the lens.

Off-Axis Illumination

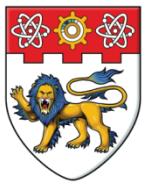
Conventional Illumination (On-Axis)



Off-Axis Illumination



If the incident light source is illuminated at an angle with respect to the lens system (off-axis), higher order diffracted rays can be collected using the lens of the same size.



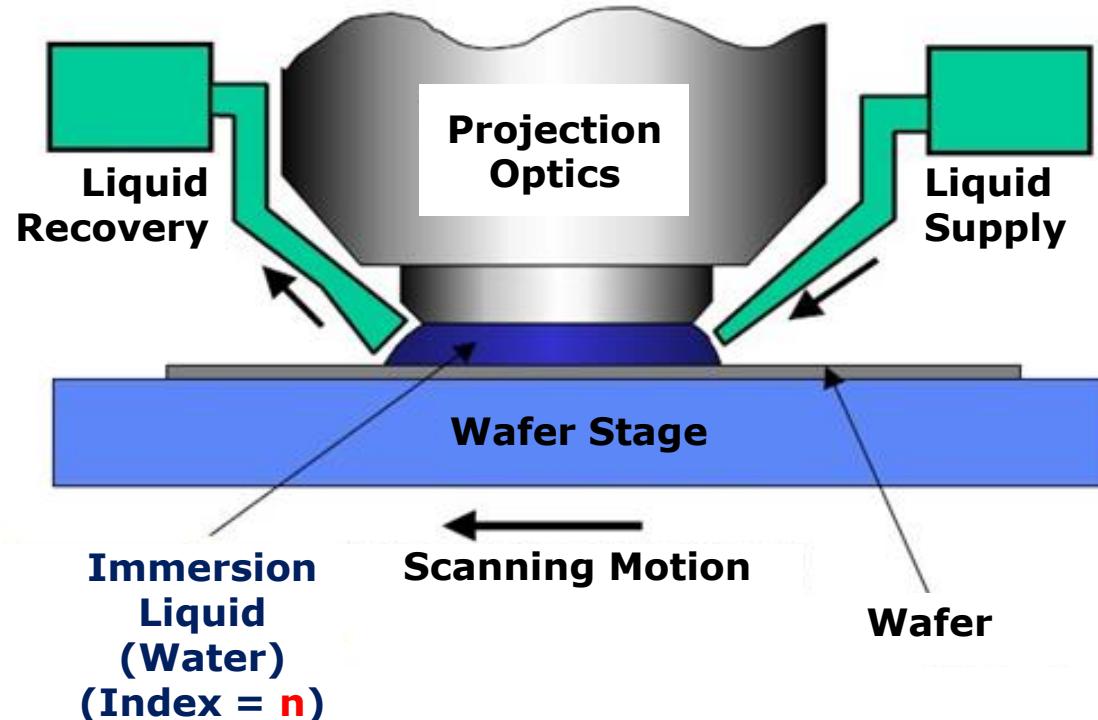
Immersion Lithography

Immersion Lithography– 2 Approaches

What is Immersion Lithography (IML)?

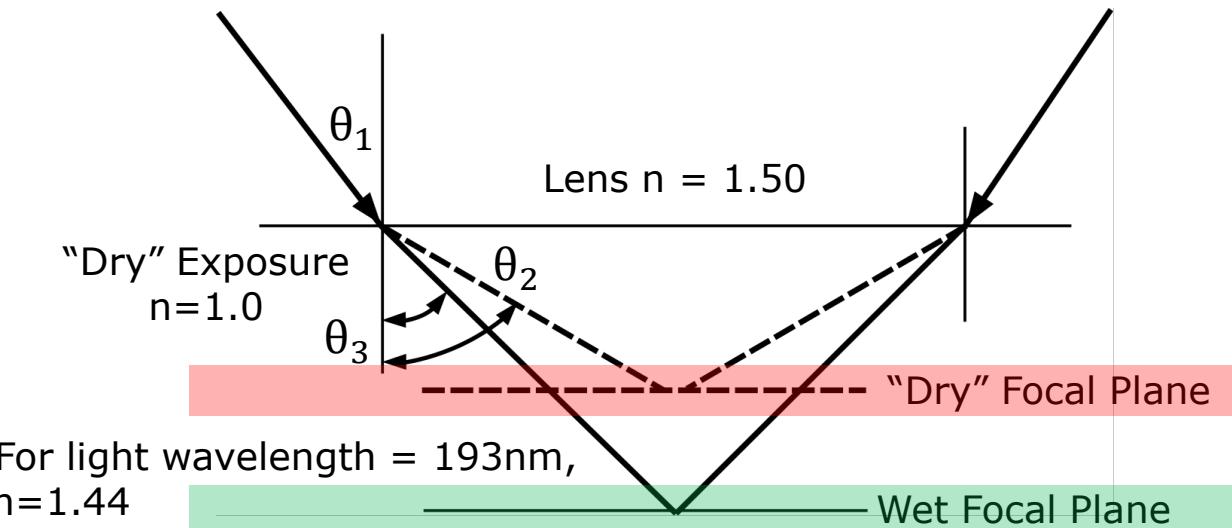
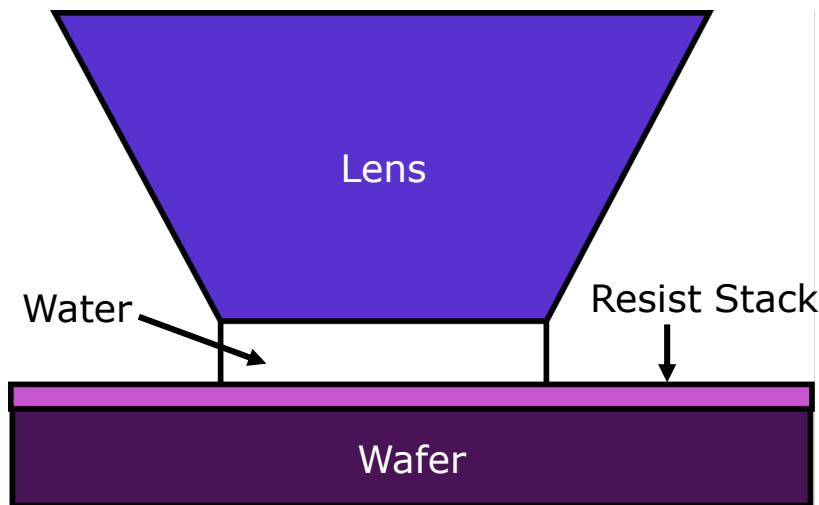
- **Approach 1:**
 - Same lens column design
 - Maintain resolution
 - Improve Depth of Focus (DOF)

- **Approach 2:**
 - Modified lens column: Hyper-NA (> 1.0)
 - Improve resolution
 - Lower DOF



Immersion Lithography – Depth of Focus

Approach 1: Lens of same NA as in air



$$W_{min} = k_1 \frac{\lambda}{(NA)} \text{ (Maintained)}$$

$$NA = n \sin \theta$$

Improvement in DOF

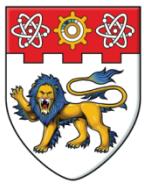
Immersion Lithography - Resolution

Approach 2: Modified NA

$\uparrow NA = \uparrow n \sin \theta$ (Exit angle θ of the lens for exposure does not change)

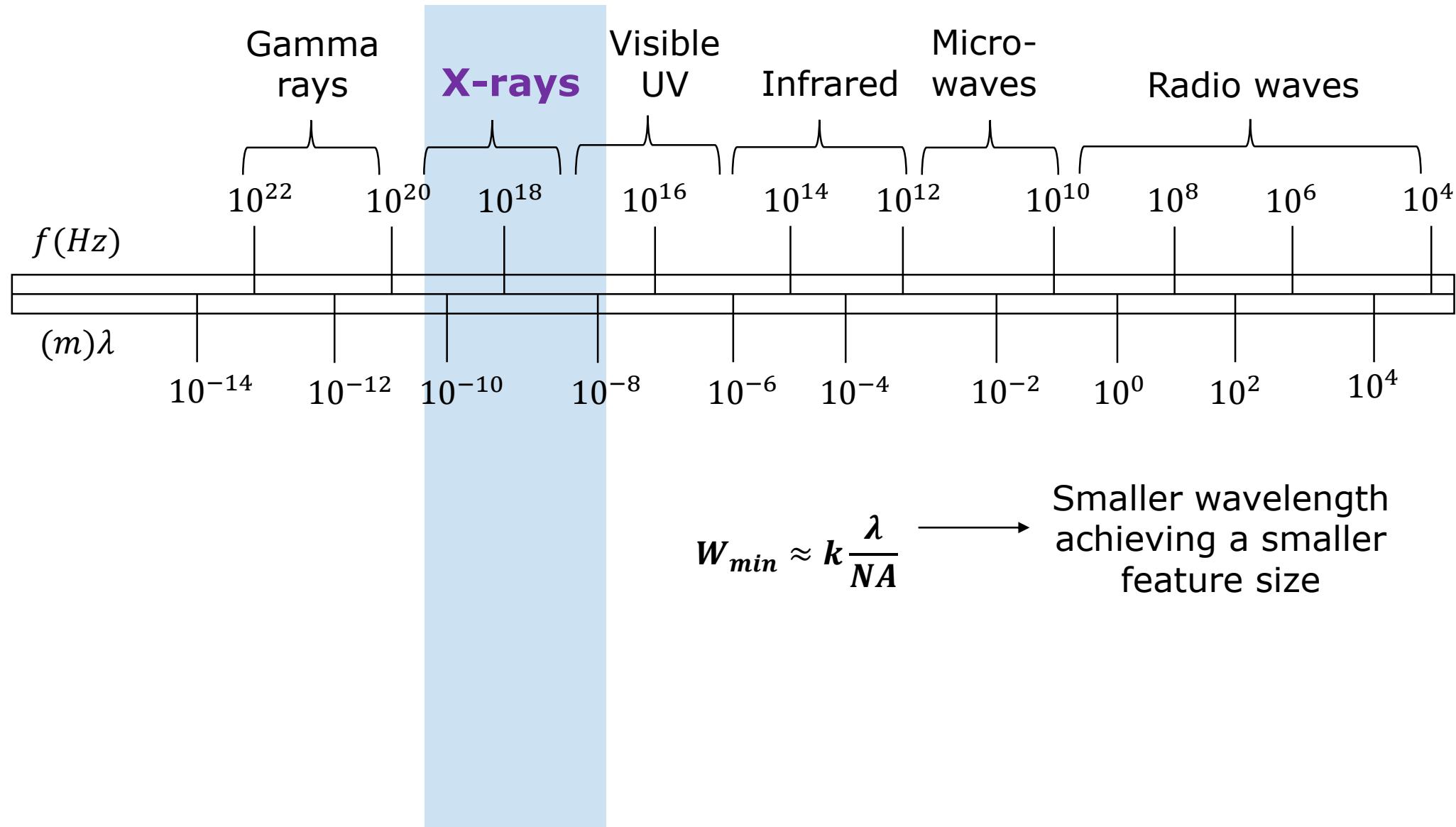
Higher resolution: $W_{min} = \frac{k_1 \lambda}{NA} = \frac{k_1 \lambda}{n \sin \theta}$

Lower DOF: $DOF = k_2 \frac{\lambda}{(NA)^2}$



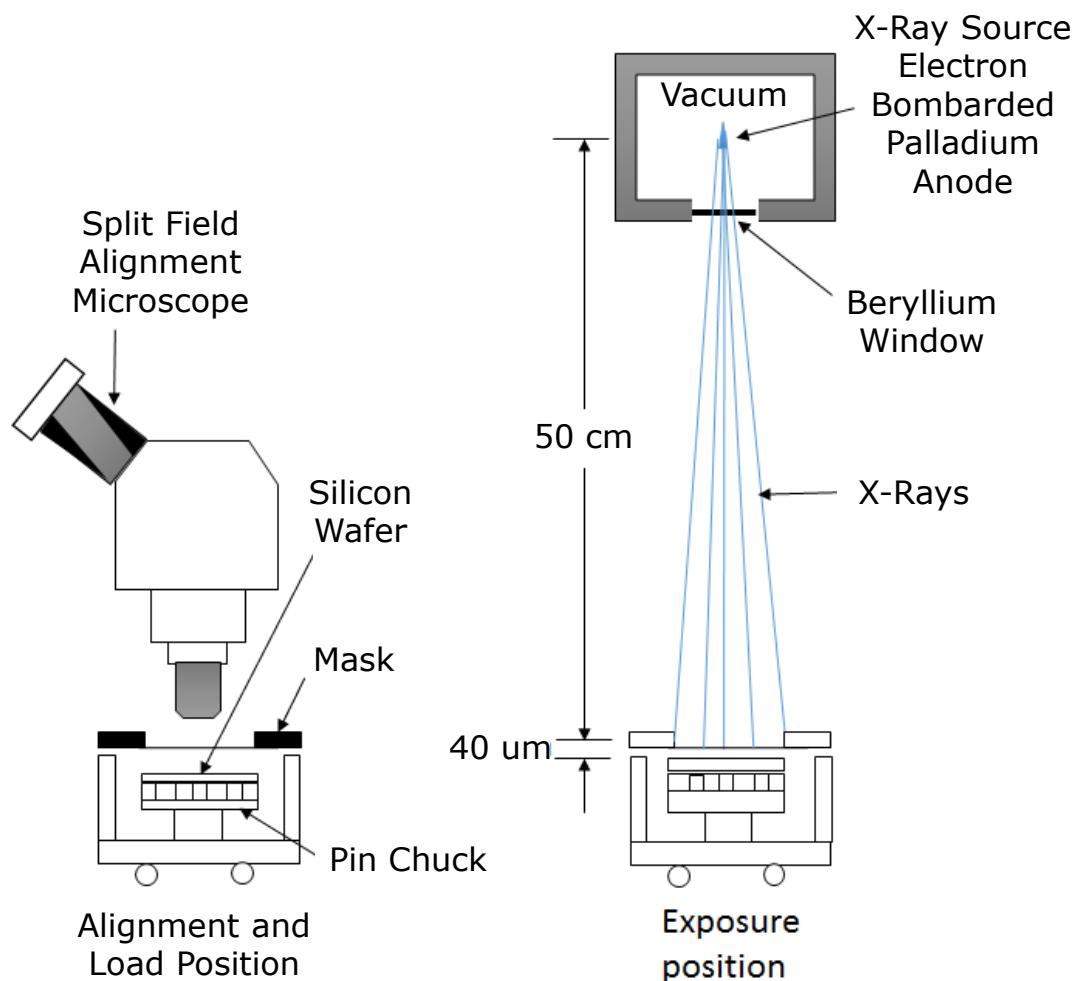
X-Ray Lithography

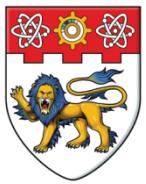
X-Ray Lithography



Schematic of an X-Ray Lithography System

- $\lambda \sim 1 \text{ nm}$ (extremely short wavelength for high resolution)
- X-rays are produced by synchrotron radiation in a high energy electron storage ring.
- Contamination becomes less of a concern because X-rays will penetrate most dust particles (low atomic number).
- No need for vacuum (little absorption of X-ray by air)
- No lens (transmission or reflection), because for X-ray, refractive index $n=1$; thus only proximity printing
- Proximity printing can still achieve high resolution ($< 30\text{nm}$) due to small λ .



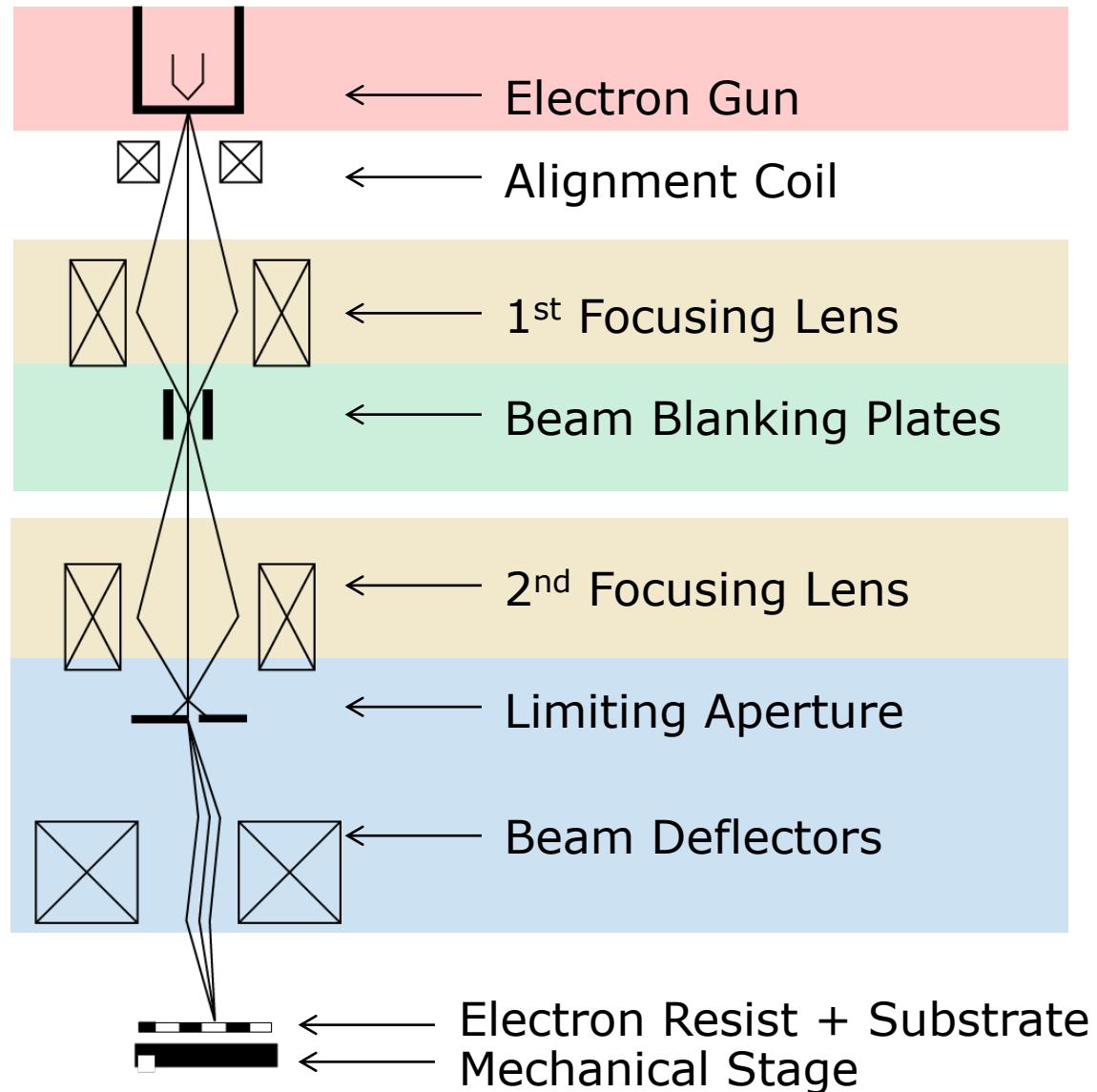


E-Beam and SCALPEL Lithography

Schematic of an Electron Beam Lithography System

System:

- Electron gun (or e-source)
- Focusing lens
- Beam blanking plates
- Beam deflectors (scan coils that direct beam horizontally and vertically)



Electron Beam Lithography

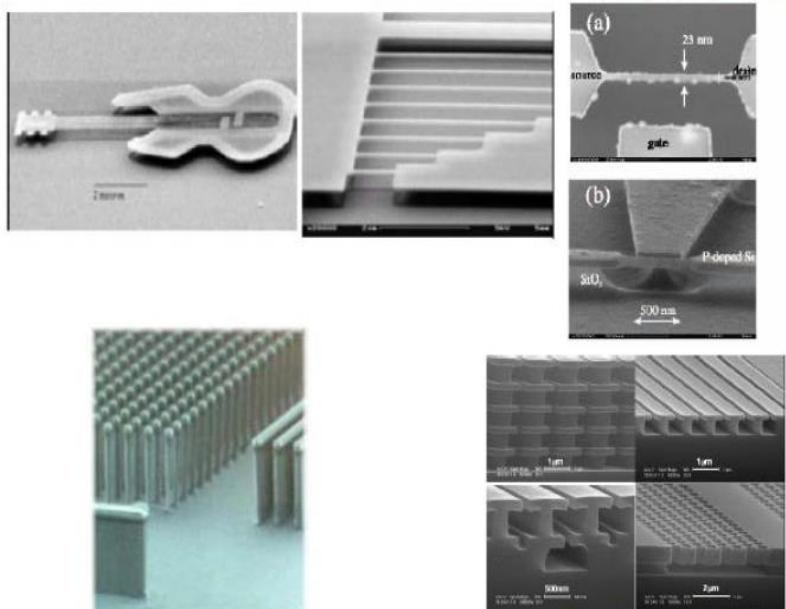
- The electron beam has a wavelength so small that diffraction is insignificant.
- The tool is just like an SEM with on-off capability controlled by a “beam blanker”.
- Accurate positioning (alignment): “see” the substrate first, then expose
- Beam spot diameter of 2 nm can be achieved, at a typical acceleration voltage of >20 keV.
- However, typical resolution ~15 nm (>> beam diameter), limited by proximity effect and lateral diffusion of secondary electrons.

De Broglie wavelength of electrons

$$\lambda = \frac{h}{\sqrt{2meV}}$$

Where m is the mass of electron, e is electronic charge, h is Plank's constant.

Nanofabrication by E-Beam Lithography



Advantages

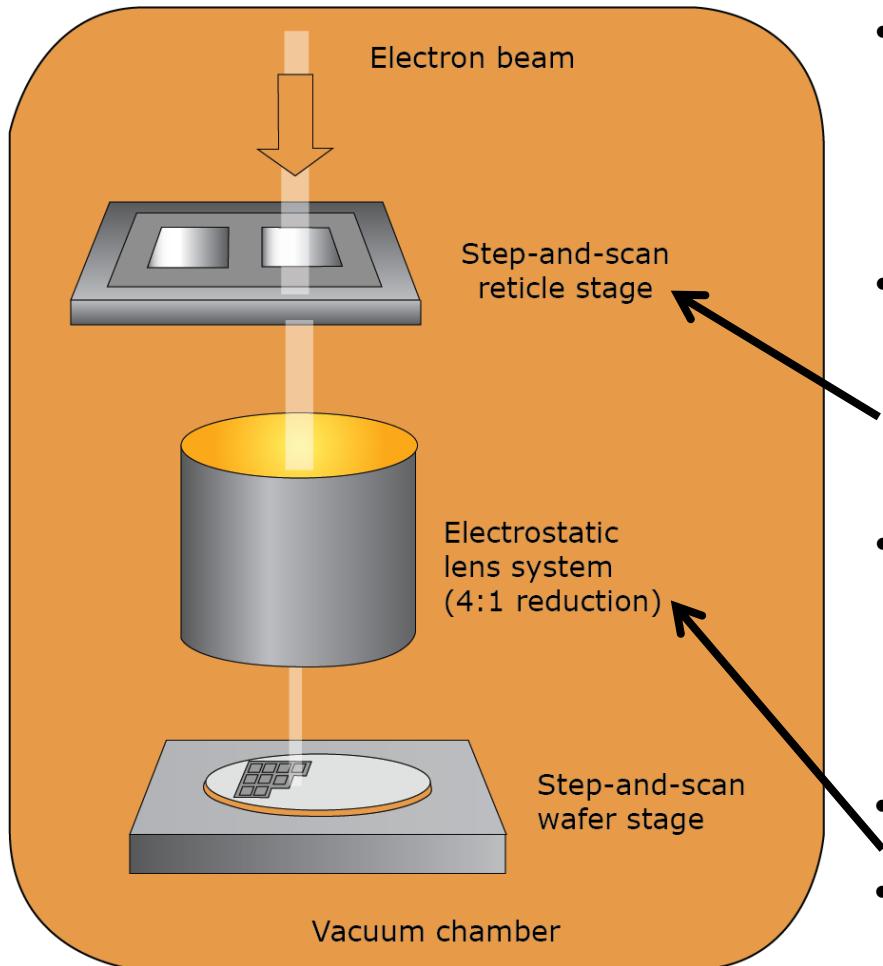
- Precise control of energy and dose
- Critical Dimension ~ 10 nm
- Beam focusing achieved using large electrostatic and magnetic field lenses
- Ability to register accurately over small areas
- Low defect densities

Disadvantages

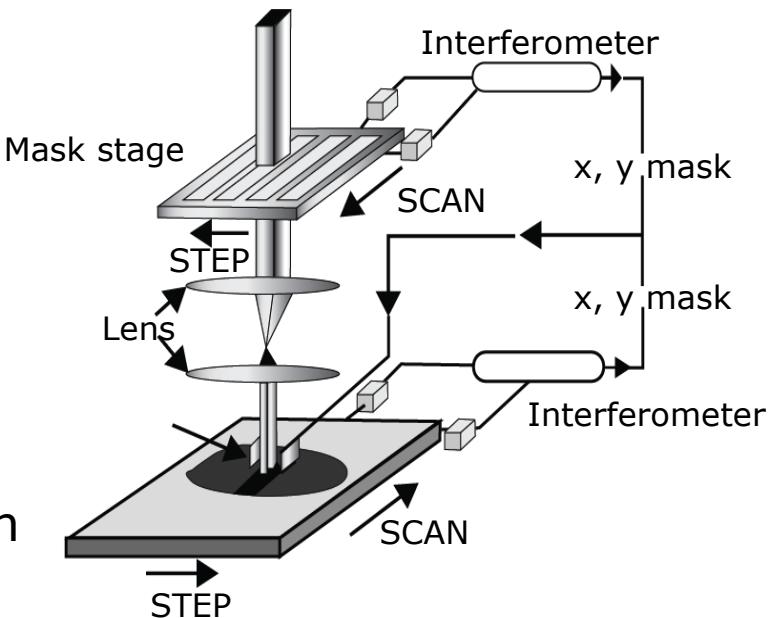
- Requires ultra-high vacuum system to drive electrons effectively
- Very sensitive to electronic and mechanical noise
- • Proximity effect - resolution degrades due to backscattering of electrons within the resist surface

SCALPEL: Basic Concept

- SCattering with Angular Limitation Projection Electron beam Lithography - Developed at Bell's lab



- Combine all the benefits of step-and-repeat imaging, size reduction, and the narrow beam resolution of e-beam lithography.
- Mask: Silicon nitride membrane (100 nm) patterned with 25 nm of W
- Thickness coupled with the atomic mass of W provides sufficient scattering contrast
- Step-and-scan with 4X reduction
- Decrease exposure time



Advanced Lithography – Summary

Advanced lithography:

- Optical enhancement techniques in UV lithography include phase shift mask, optical proximity correction, and off-axis illumination.
- Immersion lithography improves the resolution and depth of focus by performing UV light exposure in an immersion liquid.
- X-ray lithography uses X-ray as its exposure source, whereas e-beam lithography uses electron beam as its exposure source.
- SCALPEL combines all the benefits of step-and-repeat imaging, size reduction, and the narrow beam resolution of e-beam lithography to improve resolution and decrease exposure time.

Practice Question 1

Which of the following is not considered a viable lithography method for the next generation lithography?



Pause and
try out this
question

- a) Optical lithography
- b) Extreme UV (EUV)
- c) SCALPEL
- d) X-ray lithography

Practice Question 2

A lithography exposure system deploys an Hg arc lamp with three available wavelengths – 436nm (g-line), 405nm (h-line) and 365nm (i-line) respectively. Assume the process dependent factor, $k = 1$.

- Determine the smallest feature size that is possible with this system for an allowable proximity gap of 0.6um.
- If the g- line of the lamp us being deployed, determine the maximum allowable proximity gap for the system to print a feature size of 1.5um.



**Pause and
try out this
question**

Answers:

- For smallest feature size, use 365nm (i-line), $W_{min} = \sqrt{k\lambda g} = \sqrt{365 \times 10^{-9} \times 0.6 \times 10^{-6}} = 4.68 \times 10^{-7} m$
- If 436nm (g-line) is used, $g = \frac{(W_{min})^2}{k\lambda} = \frac{(1.5 \times 10^{-6})^2}{436 \times 10^{-9}} = 5.16 \times 10^{-6} m$

Practice Question 3

Discuss the implication to the maximum allowable proximity gap of the exposure system mentioned in previous question (Q1) if

- a) The optical source is changed to X-ray as opposed to Hg arc lamp used in the earlier case.
- b) Phase shift masks are used in the exposure.



Pause and
try out this
question

Answers:

- a) If the optical source is changed to X-ray as opposed to Hg arc lamp used in the earlier case, λ is smaller, larger g (max allowable proximity)
- b) If the phase shift masks are used in the exposure, k is smaller, larger g (max allowable proximity)

Practice Question 4

What are the advantages and disadvantages for X-ray?



Pause and
try out this
question

Advantages of X-ray lithography

- High resolution
- Reduced diffraction effect

Disadvantages of X-ray lithography

- Expensive X-ray source
- Absorption problem (mask)
- Shadowing errors
- Non-monochromatic X-ray source
- Low throughput



Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Lithography 3 – Lithography Technology

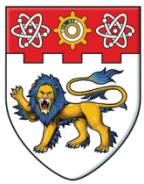
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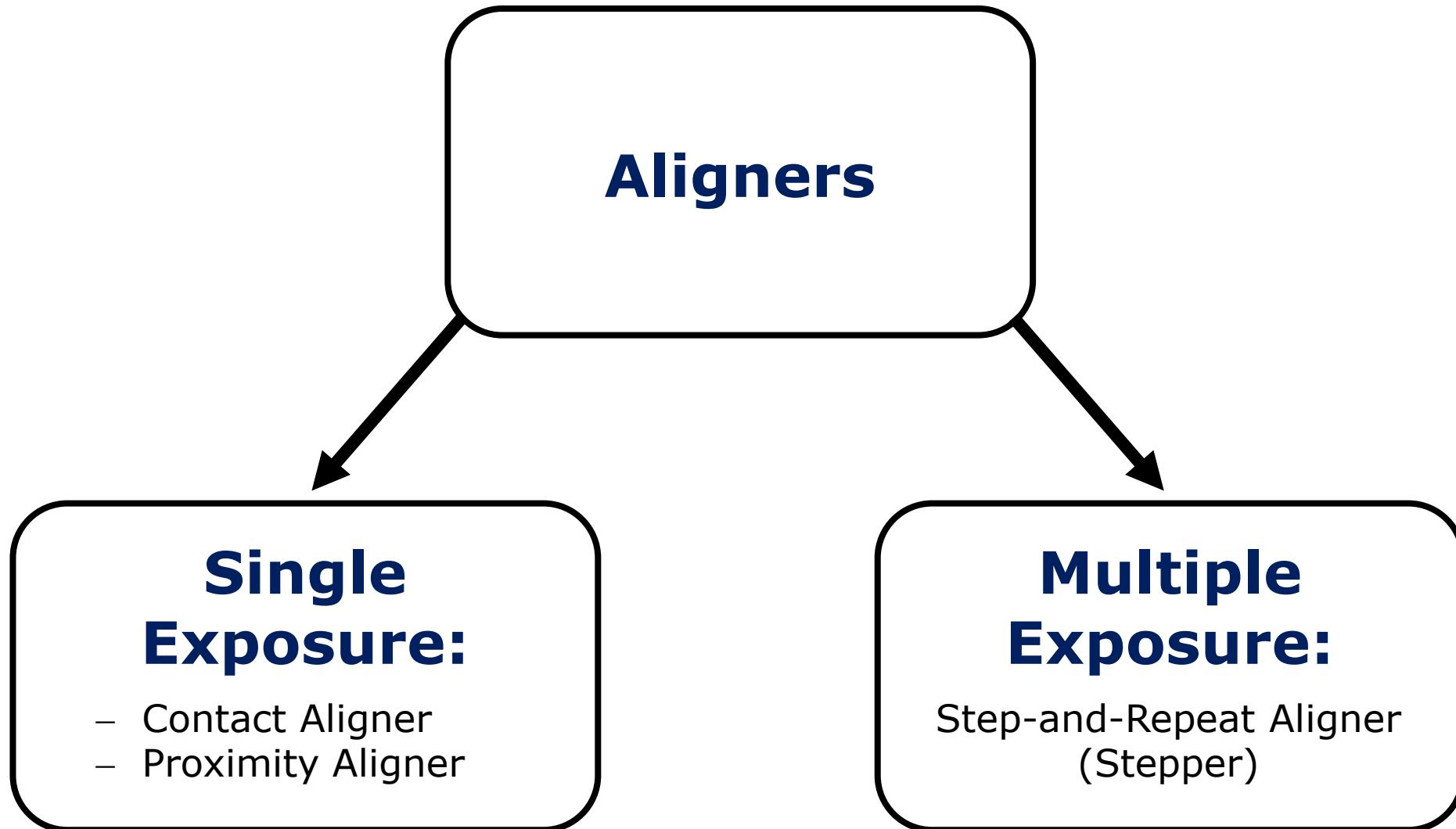
Lithography Technology – Lesson Overview

Lithography technology:

- Lithography equipment
- Resolution and its critical parameters
- Mask and reticle



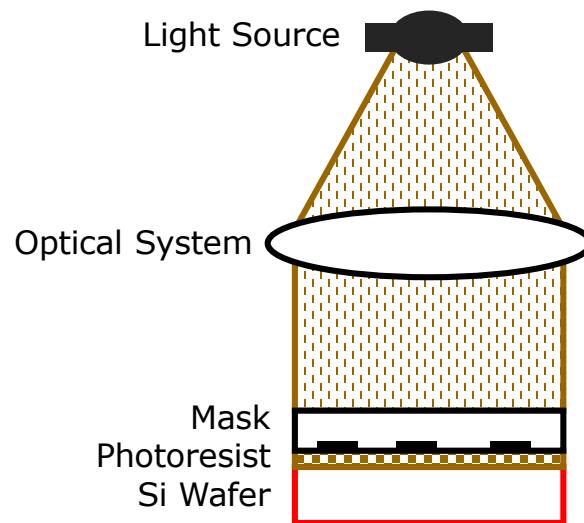
Lithography Equipment



UV exposure is sometimes known as “printing” because it “prints” the desired pattern onto the substrate using UV source.

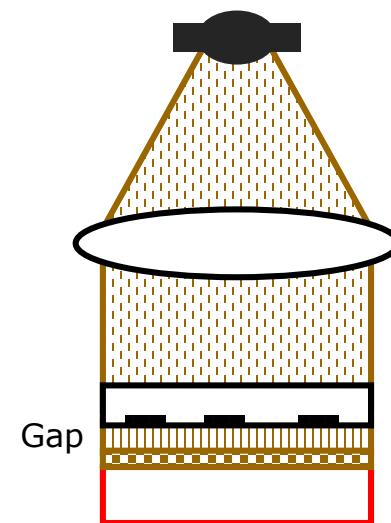
Three Basic UV Exposure Methods

Single Exposure



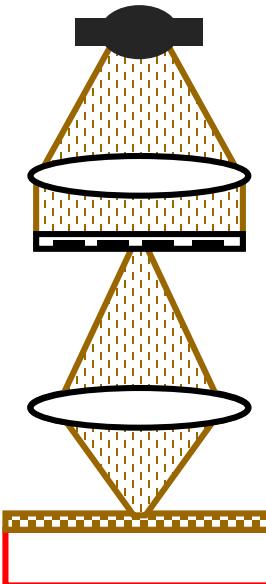
Contact Printing

Single Exposure

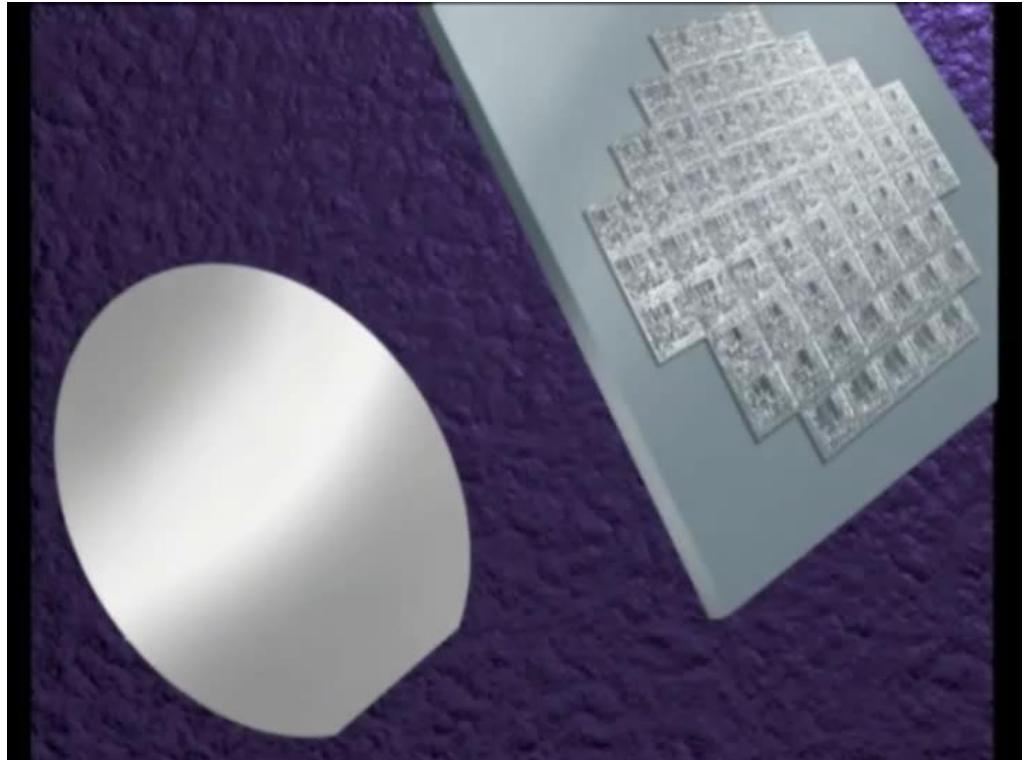


Proximity Printing

Multiple Exposures

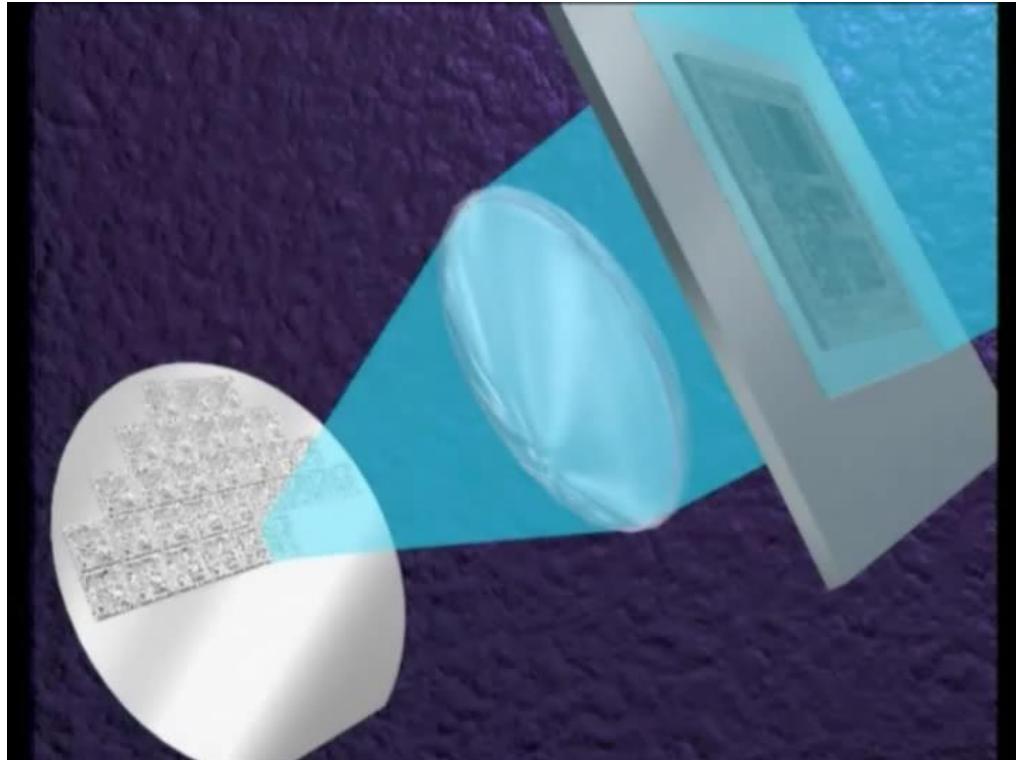


Projection Printing



Single Exposure

- Contact Aligner/ Printer
- Proximity Aligner/ Printer

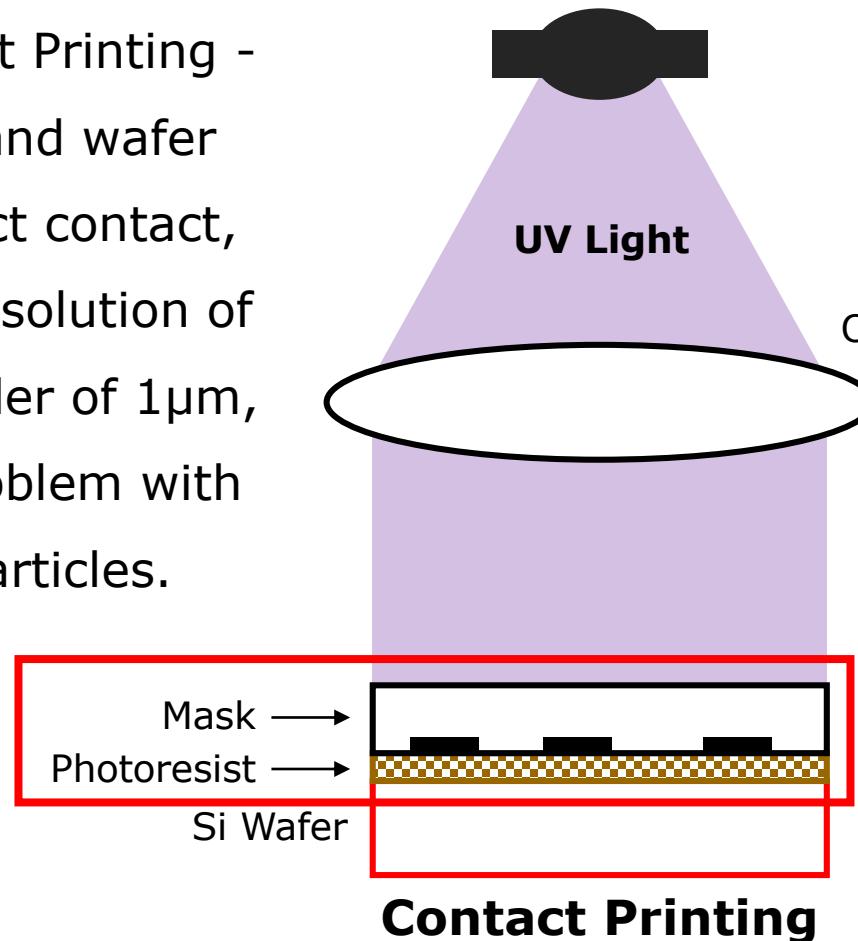


Multiple Exposure

- Step-and-Repeat Aligner (Stepper)

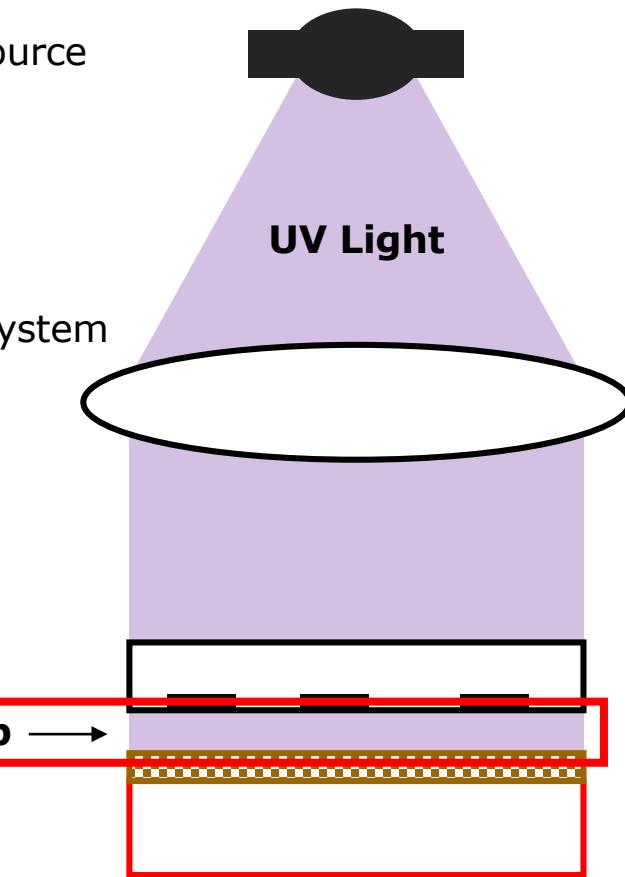
Contact and Proximity Aligners

Contact Printing - mask and wafer in direct contact, high resolution of the order of $1\mu\text{m}$, the problem with dust particles.



Light Source

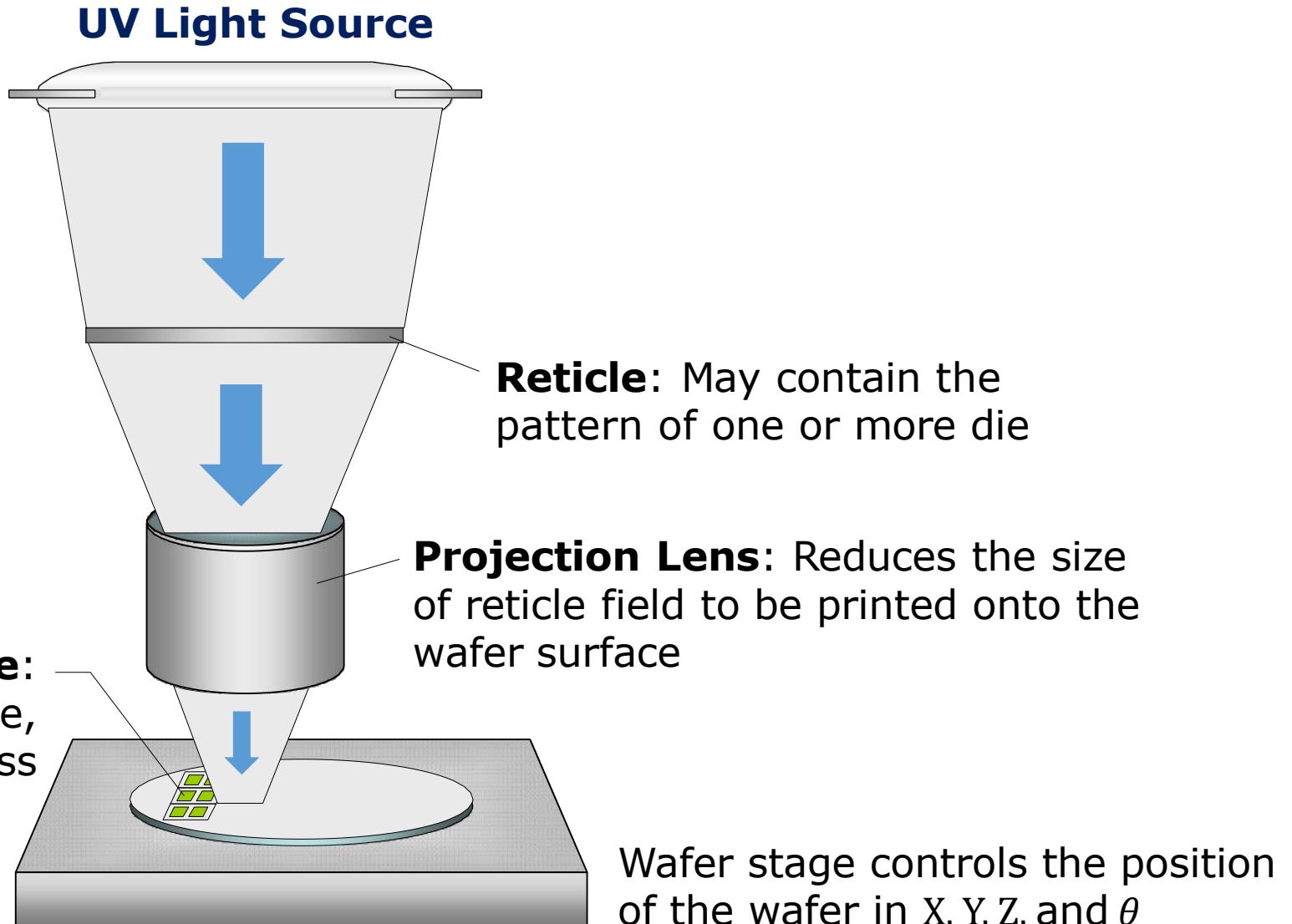
Optical System



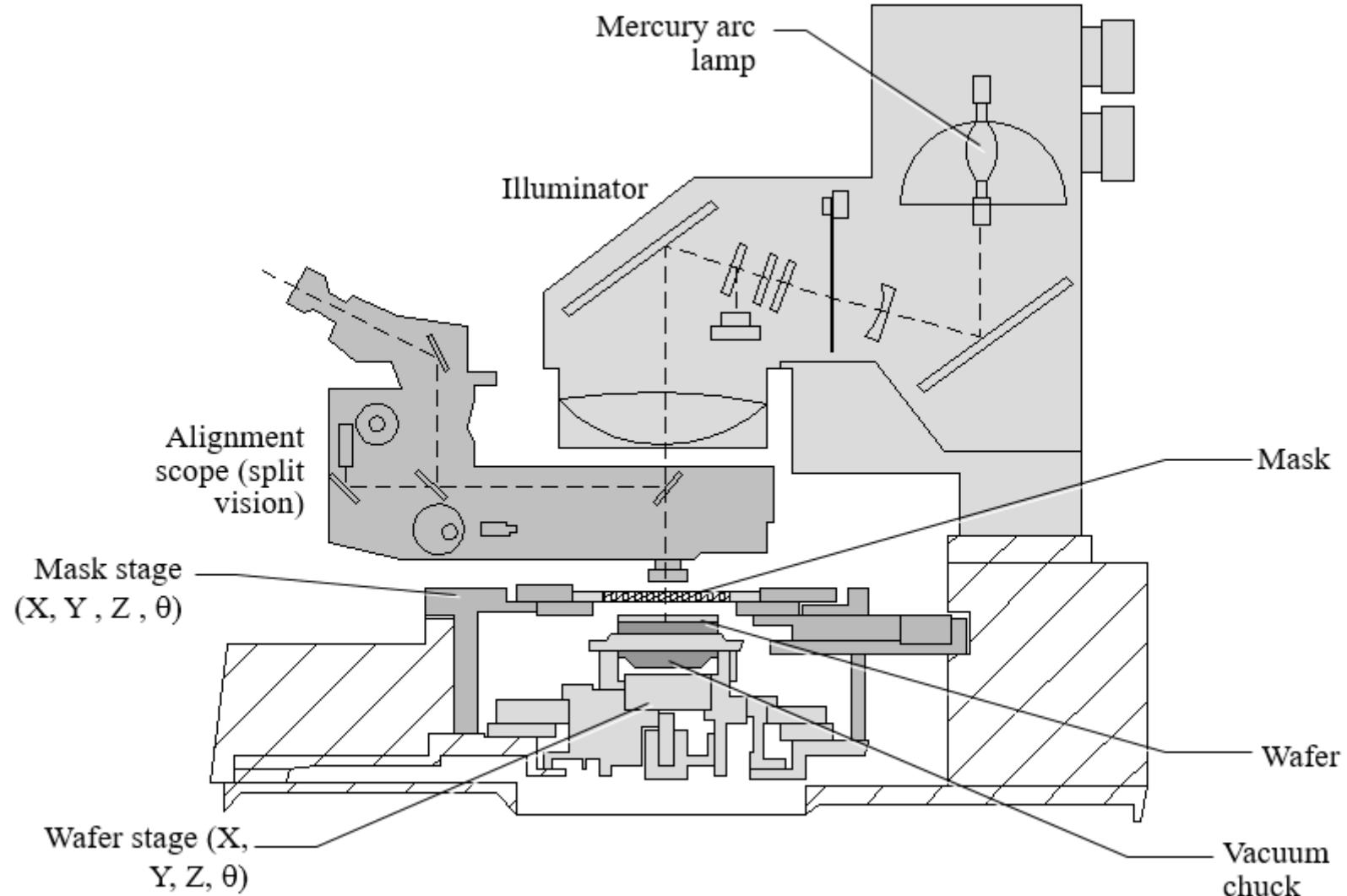
Proximity Printing
Prevents Dust Particles

Proximity Printing - mask and wafer in close proximity (a small gap of $10\text{-}50\mu\text{m}$ between mask and wafer), less damage by dust particles, the low resolution of the order of $2\text{-}5\mu\text{m}$ due to the fringe.

Multiple Exposure: Step and Repeat Printing

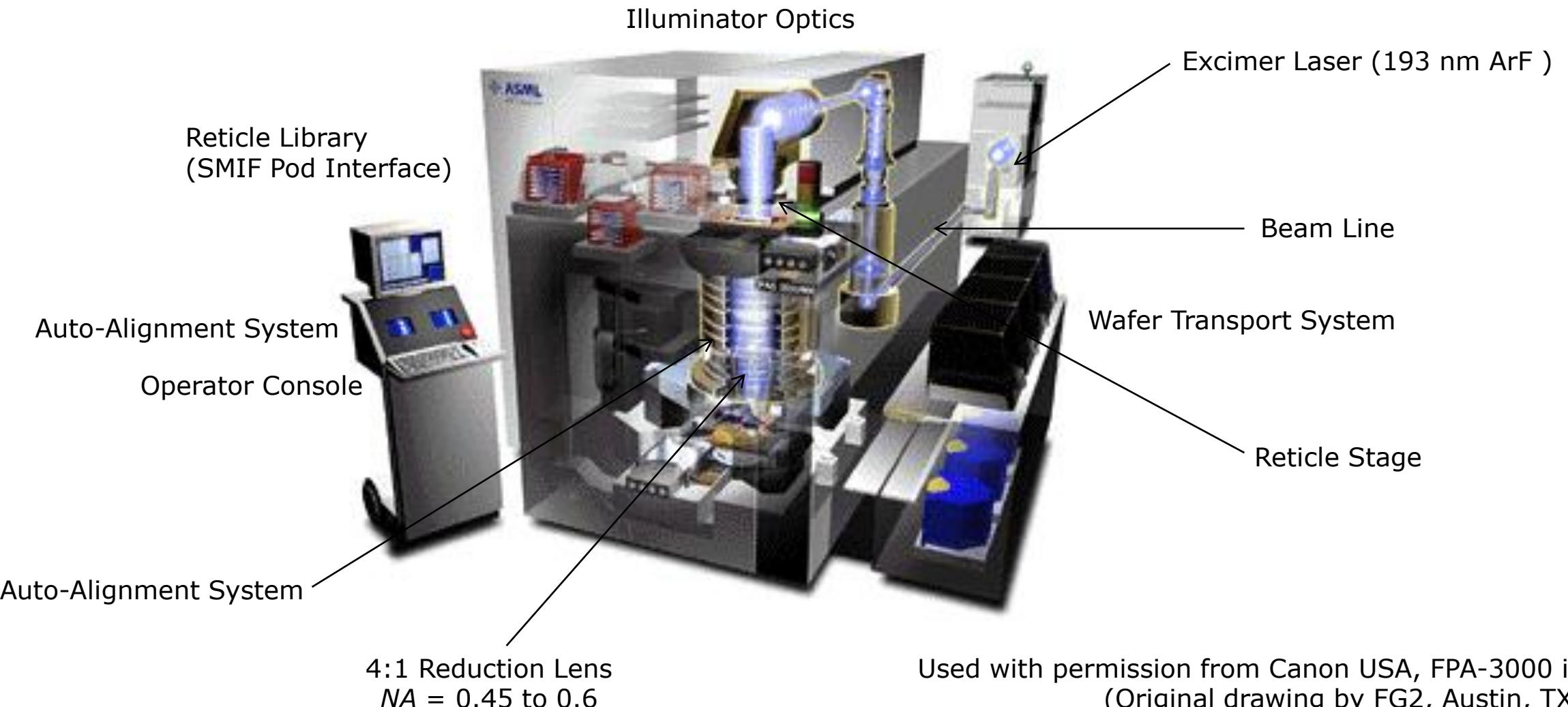


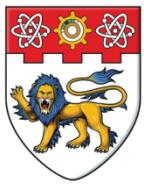
Contact/ Proximity Aligner



Used with permission from Canon USA,

Step-and-Repeat Projection Aligner





Resolution and its Critical Parameters

Resolution

The ability of an optical system to distinguish closely spaced objects.



**More challenging
to distinguish
small pattern.**

Minimum Linewidth/ Resolution for Proximity Aligner

- Resolution is the minimum linewidth achievable by the lithography equipment.
- Minimum linewidth (Resolution) for the proximity printer:

$$W_{min} \approx \sqrt{k_1 \lambda g}$$

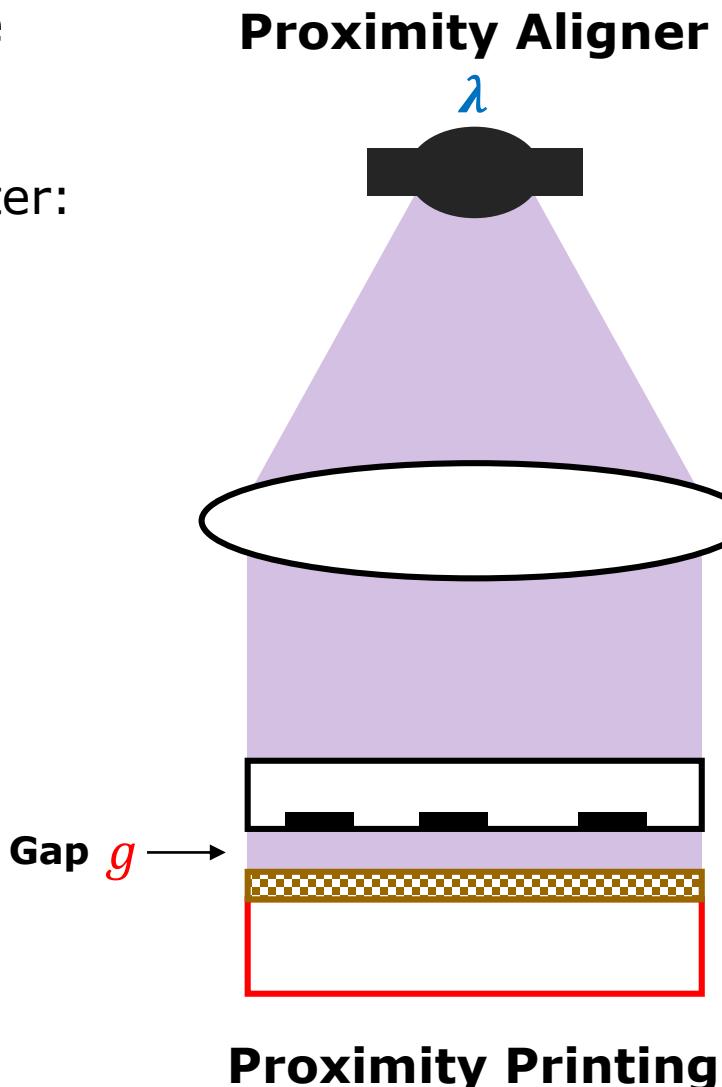
k_1 = Constant

λ = Wavelength of the exposure source

g = Gap between the mask and the wafer surface
(in the range of μm)

k_1 factor has no well-defined physical meaning.

It is an experimental parameter, depends on the lithography system and resist properties. Typical values are close to 1.



Pause and
read
carefully

Practice Question 1

Determine the maximum allowable proximity gap for near and deep UV sources as a function of the feature size. ($k_1 = 1$)

Near UV: $\lambda = 0.405 \mu m$ **Deep UV:** $\lambda = 0.248 \mu m$ (Linewidth) $W_{min} \approx \sqrt{k_1 \lambda g}$



Pause and
try out this
question

Linewidth (μm)	Maximum Gap for Near UV Source (μm)	Maximum Gap for Deep UV Source (μm)
2.5	15.43	25.2
2.0	9.88	16.13
1.0	2.47	4.03
0.5	0.62	1.01

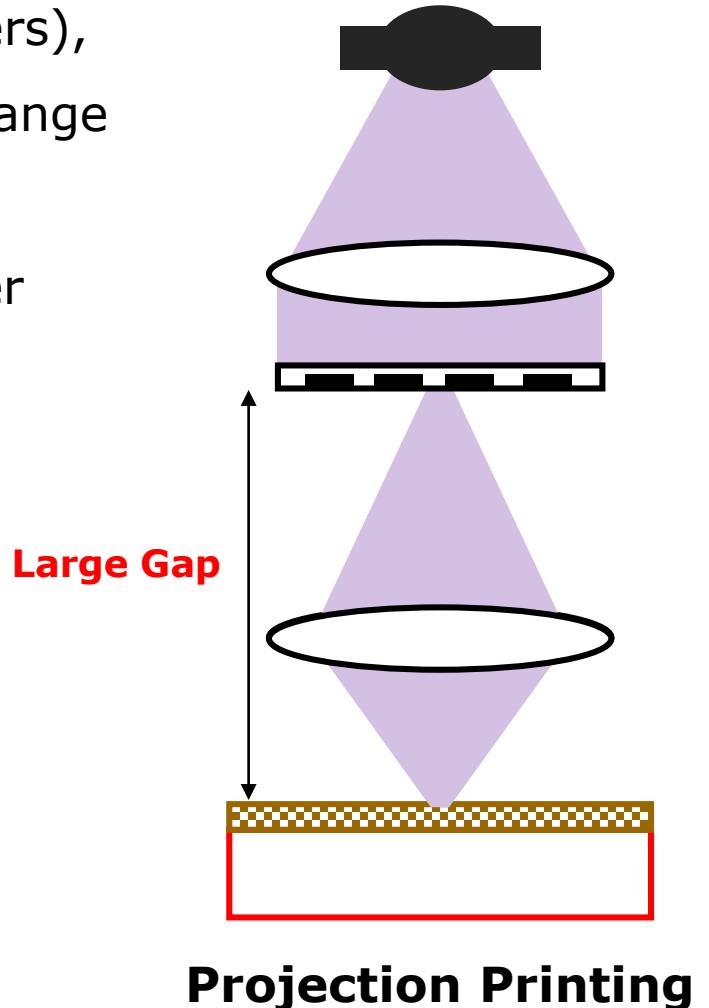
- As **feature size decreases, the maximum allowable gap decreases.**
- A **light source of lower wavelength** is better to overcome the above constraints in the maximum allowable gap.

Minimum Linewidth/ Resolution for Projection Aligner

- In projection aligner (also called step-and-repeat aligners), the gap between mask and wafer is very large (in the range of cm).
- Minimum linewidth (resolution) for the projection printer can be calculated using:

$$W_{min} \approx k_1 \frac{\lambda}{NA}$$

Where NA is called the numerical aperture.



**Pause and
read
carefully**

Numerical Aperture

- The numerical aperture (NA) of an optical system is a measure of the ability to collect light, which is a measure of the light gathering power.
- Numerical Aperture, (NA) can be defined as:

$$NA = n \sin \theta$$

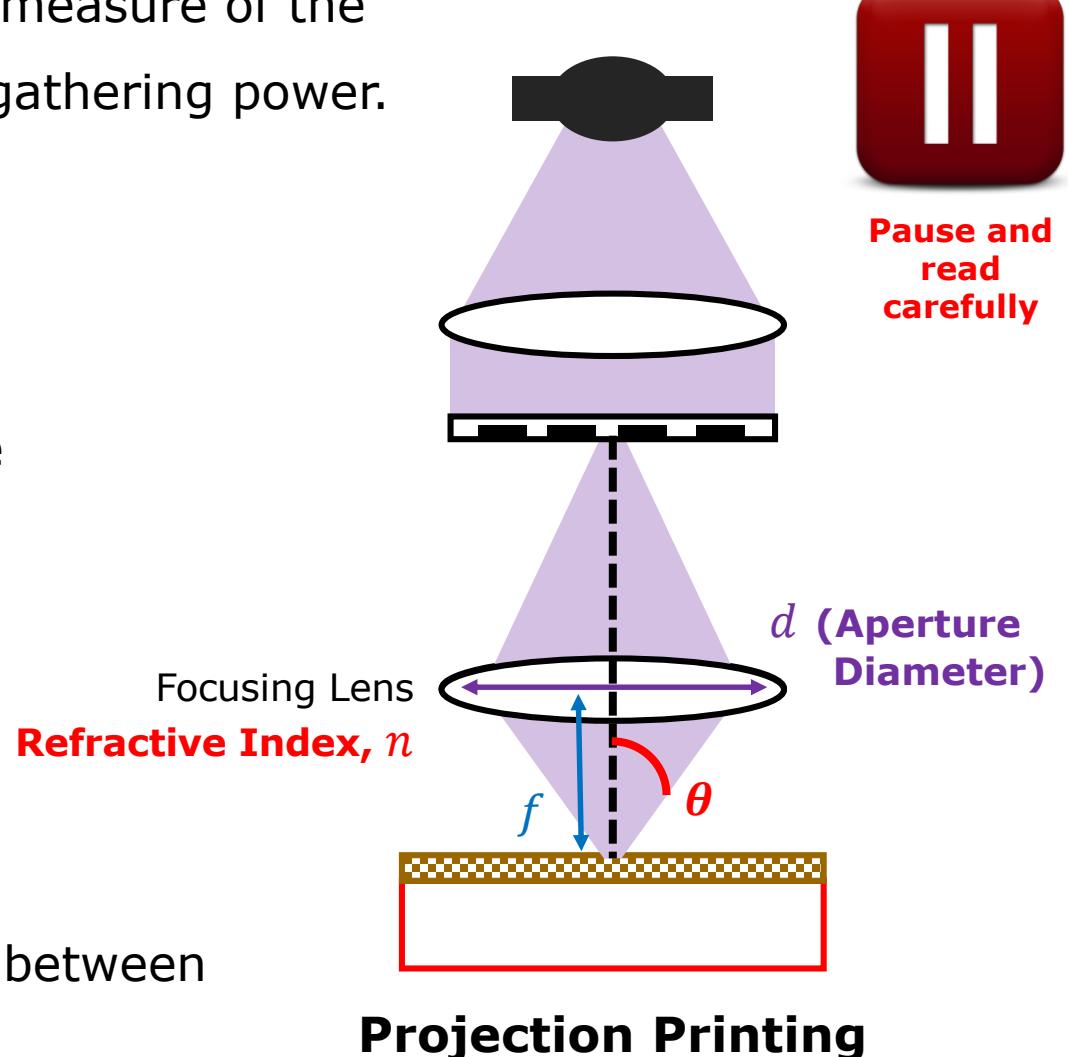
Where n = refraction index (the medium in which the system is immersed, in this $n = 1$ for air), and θ = one half the angle of acceptance of the objective lens.

When $n = 1$, the NA can be defined as

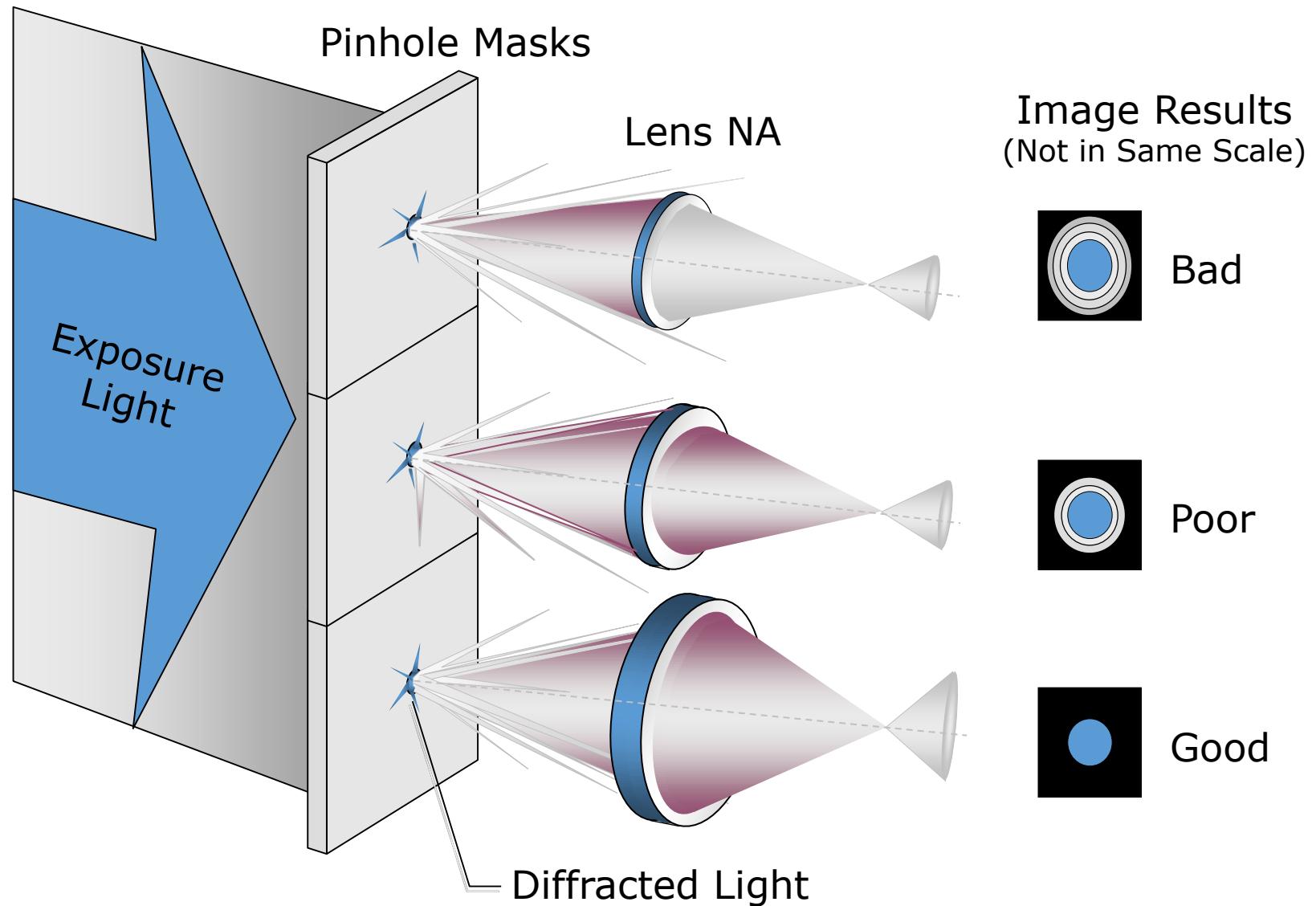
$$NA = \sin \theta \approx \tan \theta = \frac{d/2}{f} = \frac{d}{2f}$$

$\tan \theta \approx \sin \theta$ since θ is less than 12°

NA for projector objective is also the geometrical ratio between aperture and focal length.



Effect of Numerical Aperture on Imaging



Typical NA Values for Photolithography Tools

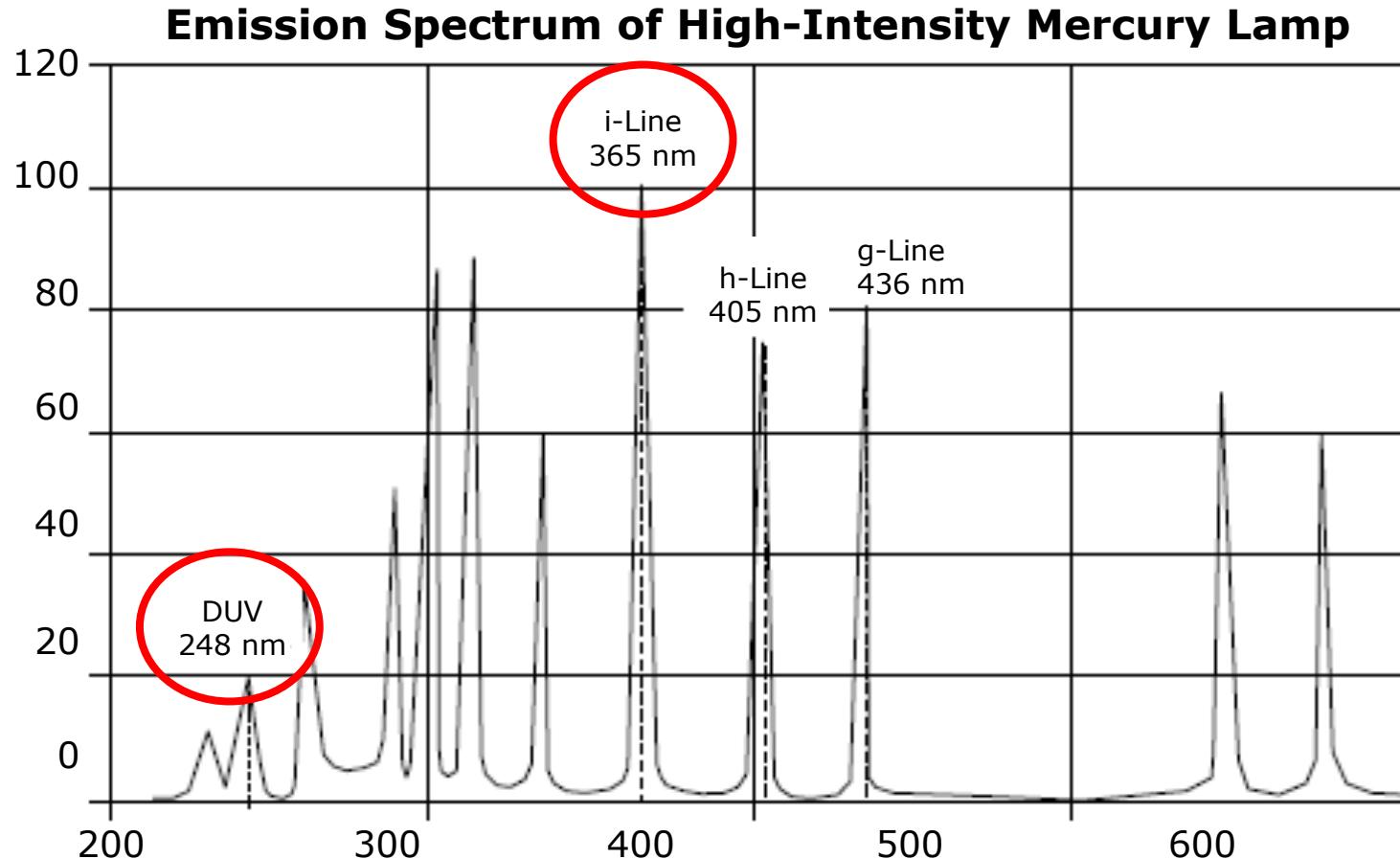
Type of Equipment	NA Value
Step-and-Repeat	0.60 - 0.68

Practice Question 2



A step-and-repeat aligner has an NA value of 0.6. By assuming $k_1=1$, which of the followings is/ are the most suitable UV source(s) to achieve resolution of **0.62 μm** ?

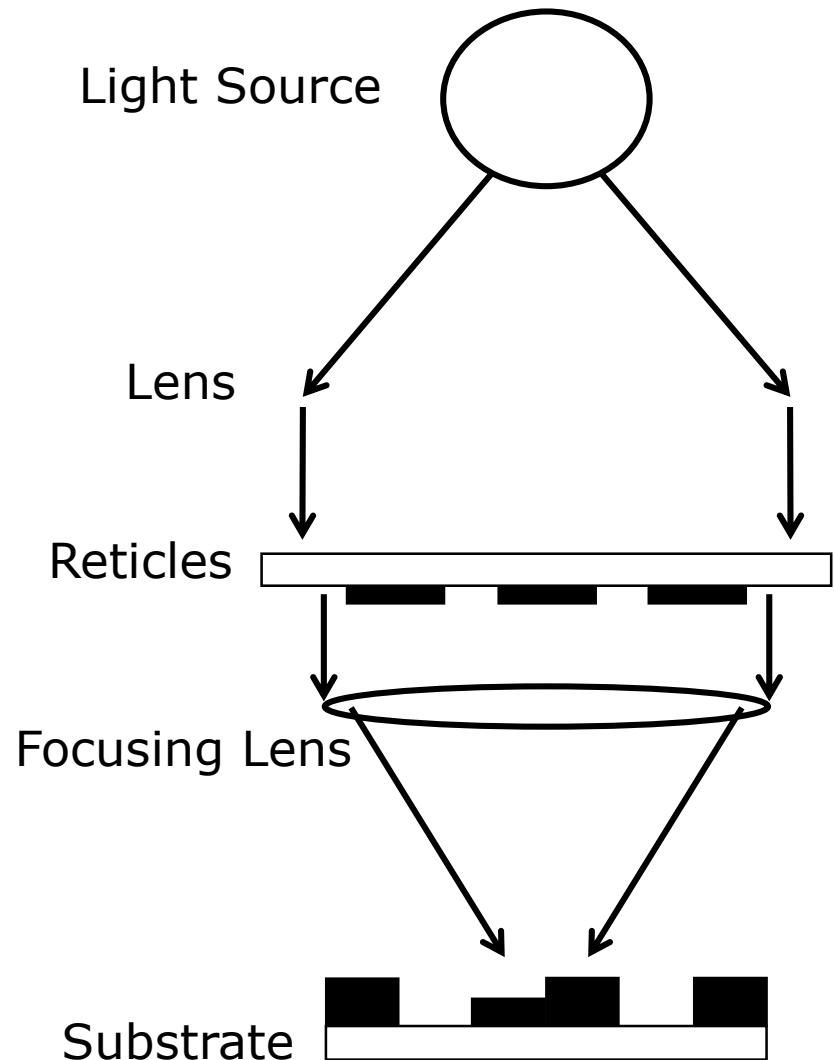
Pause and try out this question



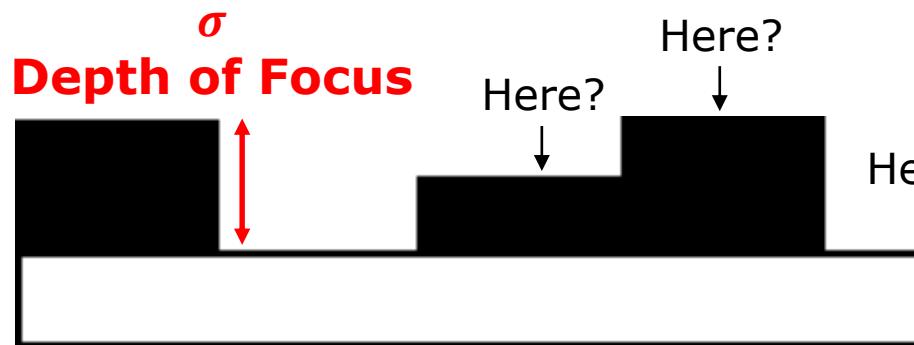
$$W_{min} \approx k_1 \frac{\lambda}{NA}$$

- The obtained λ value is 372 nm. UV sources with wavelengths smaller than 372 nm can be used. Both i-line and DUV can achieve such resolution.
- DUV has a lower intensity.
- Excimer laser which has a higher intensity can be used.

Lithography on Uneven Surface



Where should be focused?

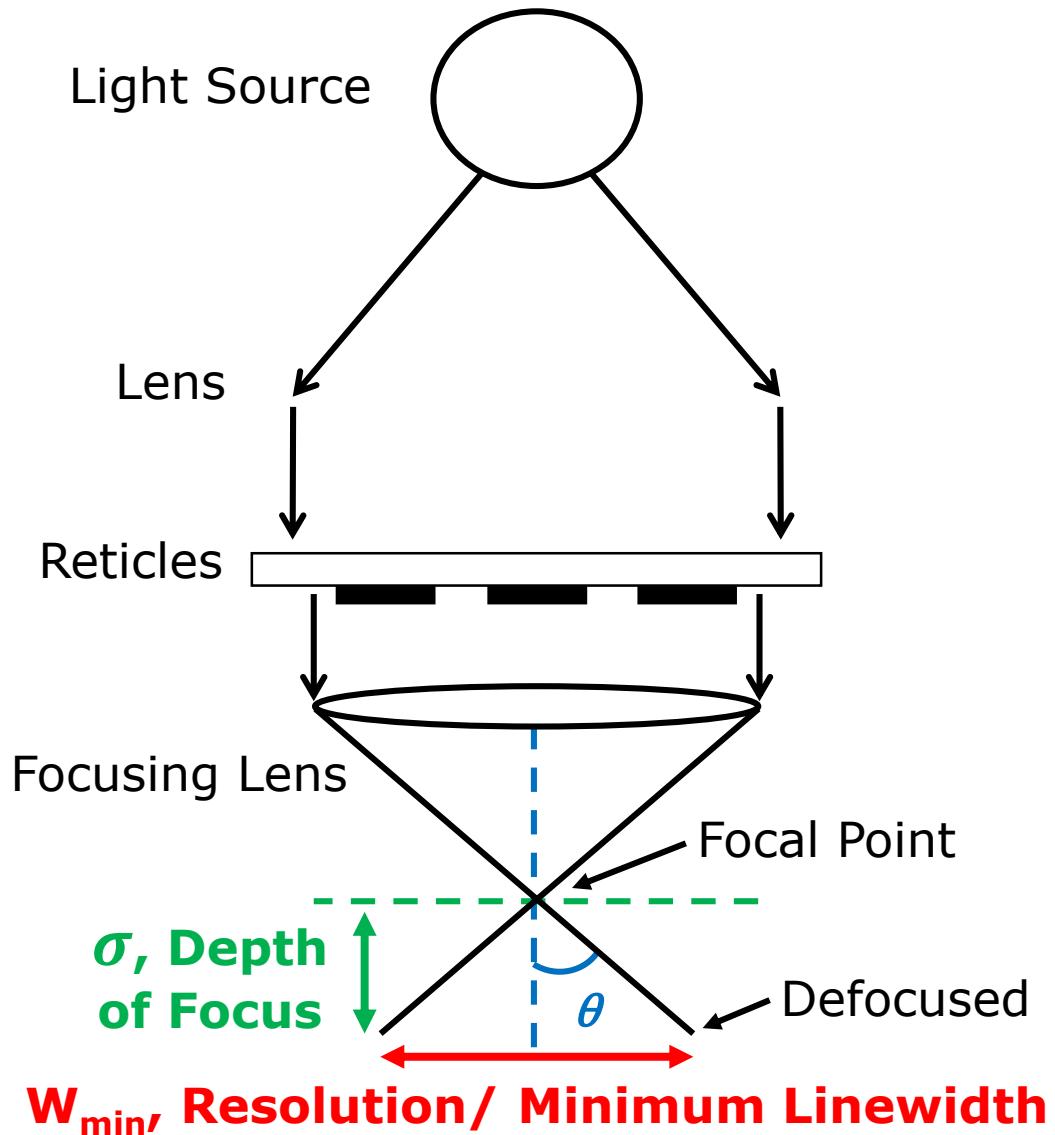


Depth of focus: Range of focus error that a process can tolerate.



Pause and
read
carefully

Depth of Focus – How to Deal With It?



Depth of focus:

$$\sigma = \pm \frac{W_{min}/2}{\tan \theta} \cong \pm \frac{k\lambda/2NA}{\sin \theta}$$

$$\sigma = \pm \frac{k\lambda/2NA}{NA/n} \cong \pm \frac{k_2\lambda}{(NA)^2}$$



Pause and
read
carefully

$\tan \theta \sim \sin \theta$ for $\theta < 12^\circ$

k and k_2 are constant , $n = 1$ (for air)

Again, like the case of resolution, we used k_2 factor as an experimental parameter. It has no well-defined physical meaning.

Depth of Focus for Projection Photolithography

$$DOF = \delta = \pm k_2 \frac{\lambda}{(NA)^2}$$

- Large NA gives smaller depth of focus.
- This is also true for the camera. A cheap camera takes photos that are always in focus no matter where the subject is. This is because it has small lenses.



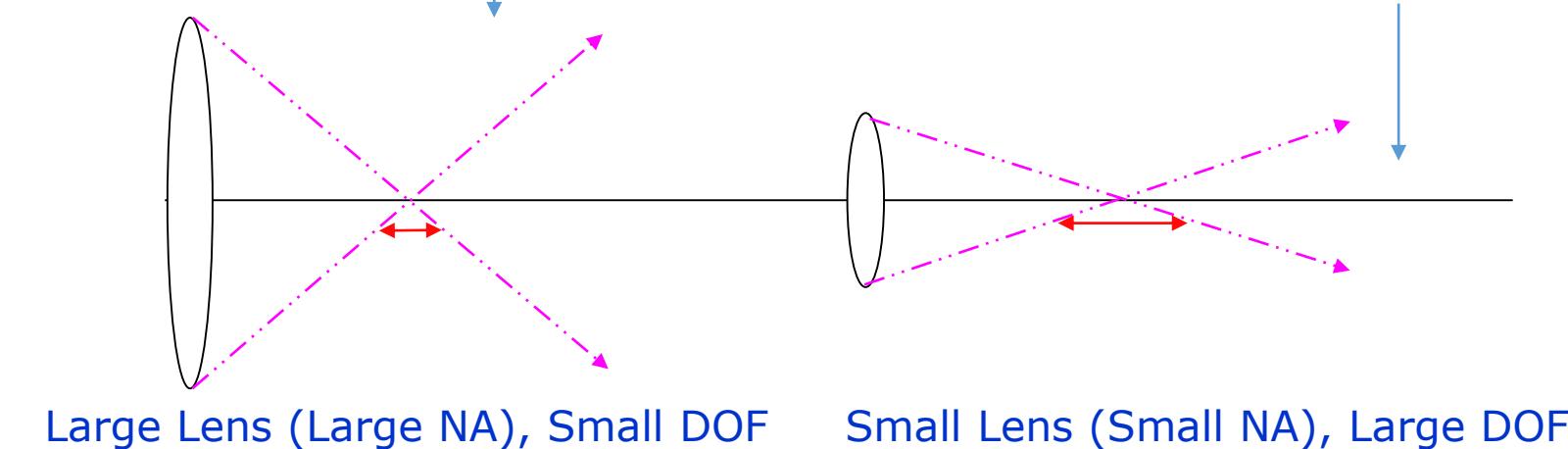
Small DOF
(Background Blurred)

What one need here is a telephoto lens at its widest aperture.



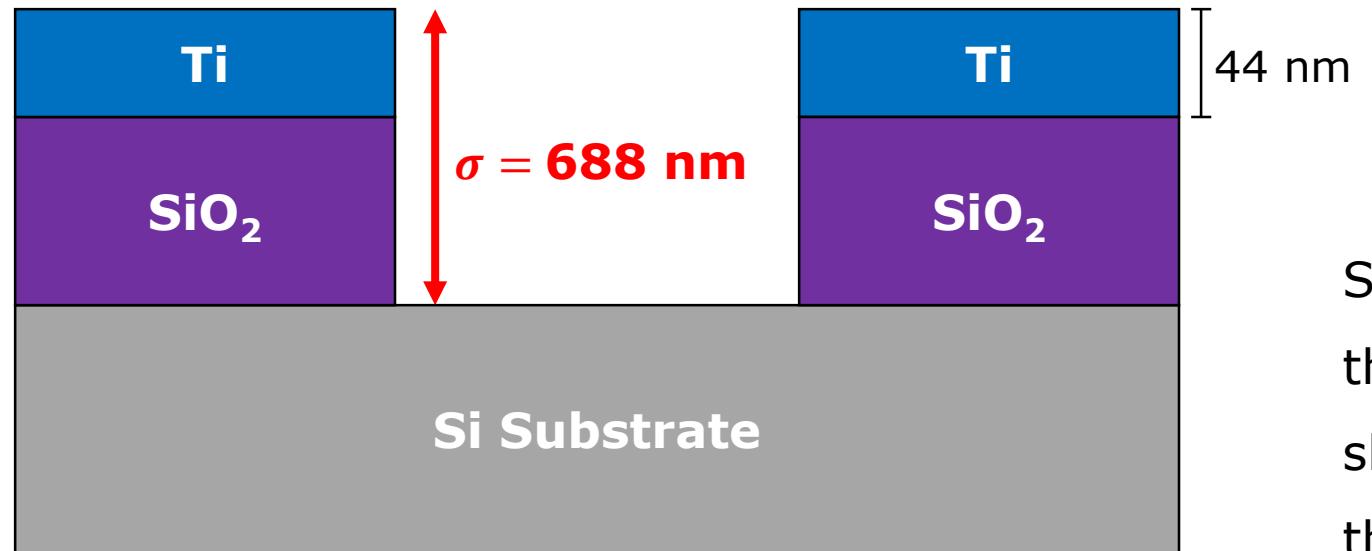
Large DOF

A small aperture was used to ensure the foreground stones were as sharp as the ones in the distance.



Practice Question 3

We need to perform lithography patterning on a structure illustrated below using a step-and-repeat aligner ($NA = 0.6$, $k_2 = 1$). The exposure source is excimer laser (248 nm). To obtain a sharp image, what is the maximum thickness of the SiO_2 layer?



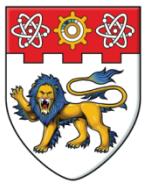
$$\sigma = \frac{k_2 \lambda}{(NA)^2}$$

$$\sigma = 688 \text{ nm}$$

Since titanium has a thickness of 44 nm, the total thickness of titanium and SiO_2 should not exceed 688 nm. Therefore, the SiO_2 layer should be $\leq 600 \text{ nm}$.



Pause and
try out this
question



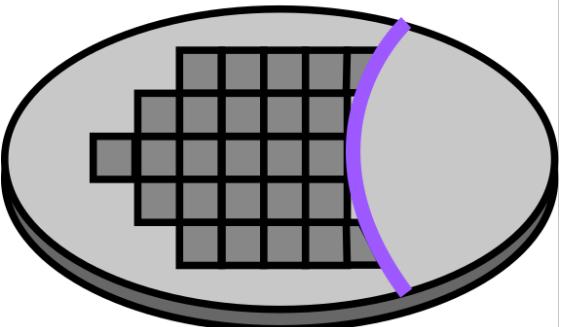
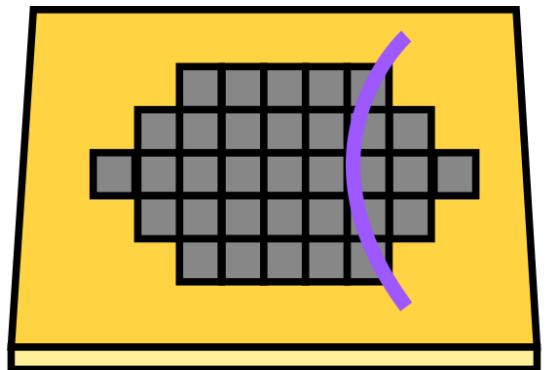
Mask and Reticle

Mask and Reticle for Lithography

Mask
Single Exposure:
 1:1 Mask

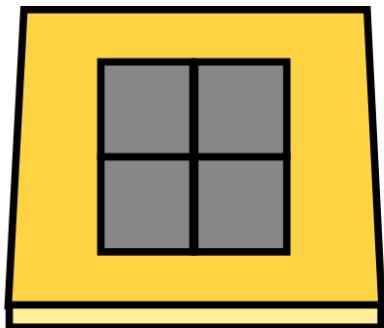
Pattern for a Complete Wafer

Same Size Pattern



Scanner

Wafer



Reduction Stepper

Reticle
Multiple Exposure:
 Reticle (Typically 4:1)

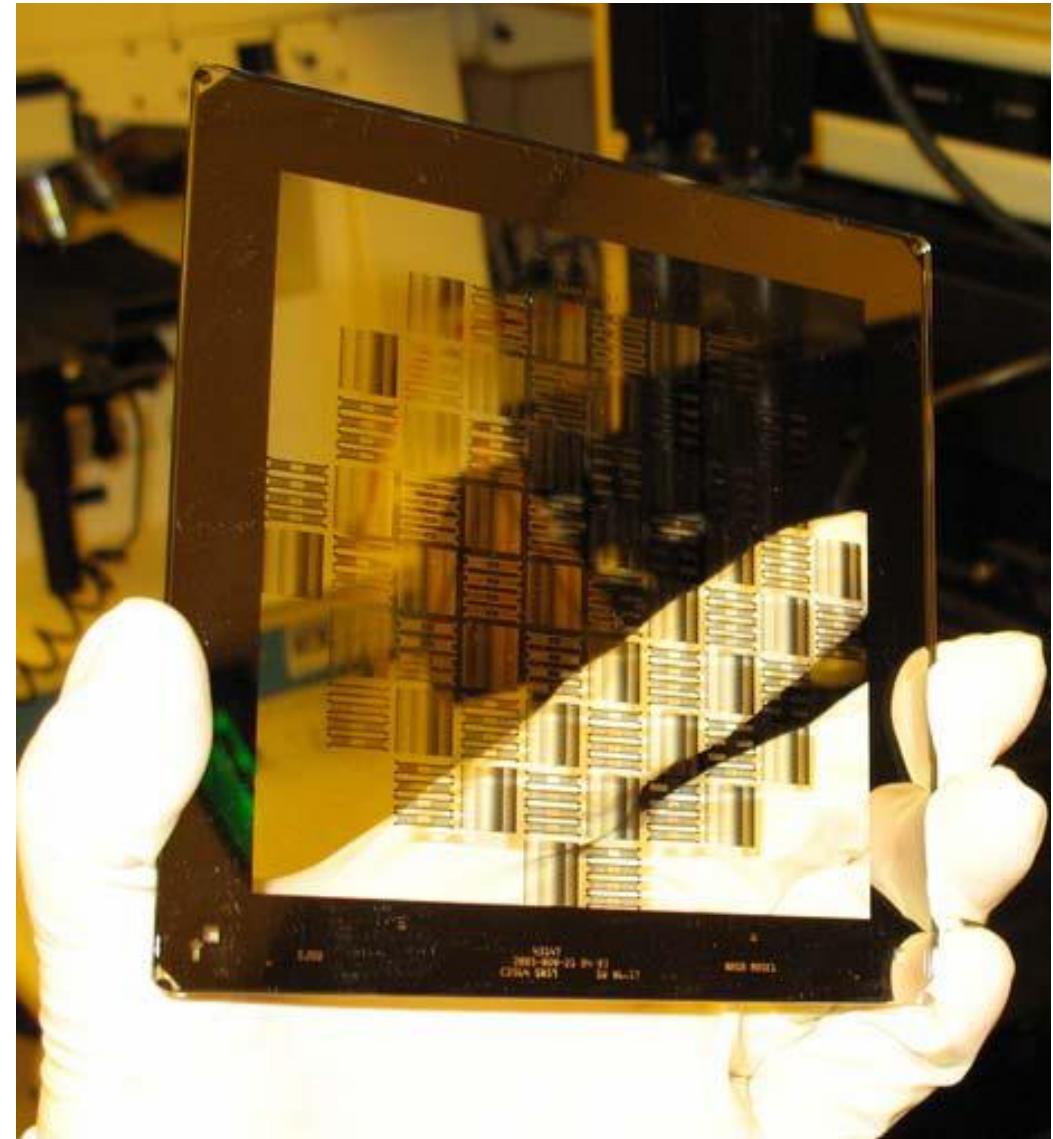
Pattern for Only Part of the Wafer

Reduced Size Pattern

Achieve Higher resolution

Mask and Reticle – Required Properties

- Flat and highly polished
- One surface of glass is patterned with opaque chromium
- High degree of transparency for optimal usage, better exposure, higher transmitted power to PR



Lithography Technology – Summary

Lithography technology:

- Lithography aligners can be single exposure or multiple exposures.
- The resolution of lithography determines the smallest feature size it can print, whereas the depth of focus determines the range of tolerable focus error.
- Masks are used in single exposure aligners, whereas reticles are used in multiple exposure aligners.



Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

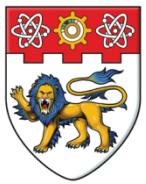
Lithography – Resist Technology

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Resist technology:

- Chemistry of resist
- Metrics of resist
- Advantages and disadvantages of positive and negative resist

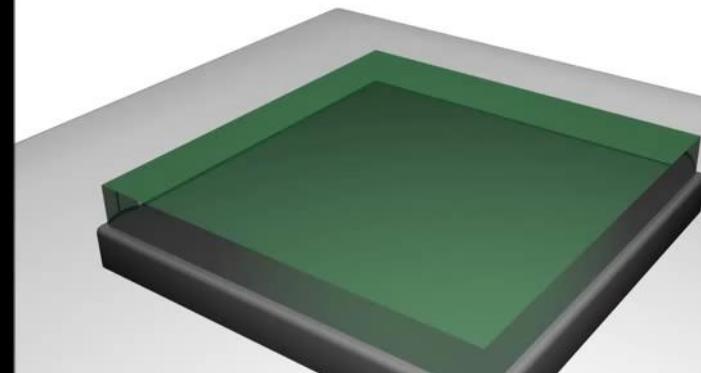


Chemistry of Resist

Positive and Negative Photoresist/ Resist

Positive Resist

Case 1: Positive photoresist deposited on substrate



P. Falcaro et al. *Chem.Soc.Rev.* 2014 DOI: 10.1039/C4CS00089G

Exposed region becomes **more soluble**



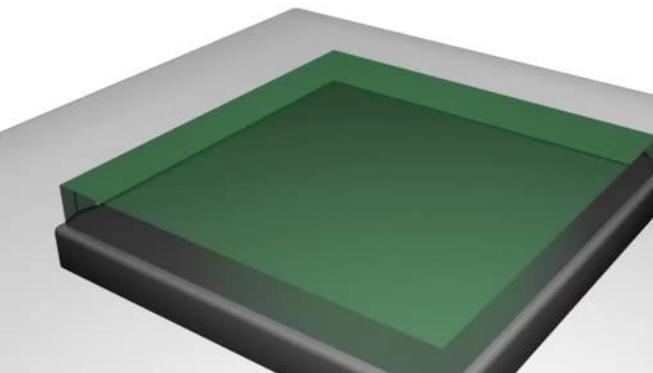
Wash away **exposed** region



Pattern formed on substrate is the **same as the mask**

Negative Resist

Case 2: Negative photoresist deposited on substrate



P. Falcaro et al. *Chem.Soc.Rev.* 2014 DOI: 10.1039/C4CS00089G

Exposed region becomes **less soluble**



Wash away **unexposed** region



Pattern formed on substrate is the **opposite from the mask**

Positive and Negative Photoresist/ Resist (Cont'd)

Types of photoresist:

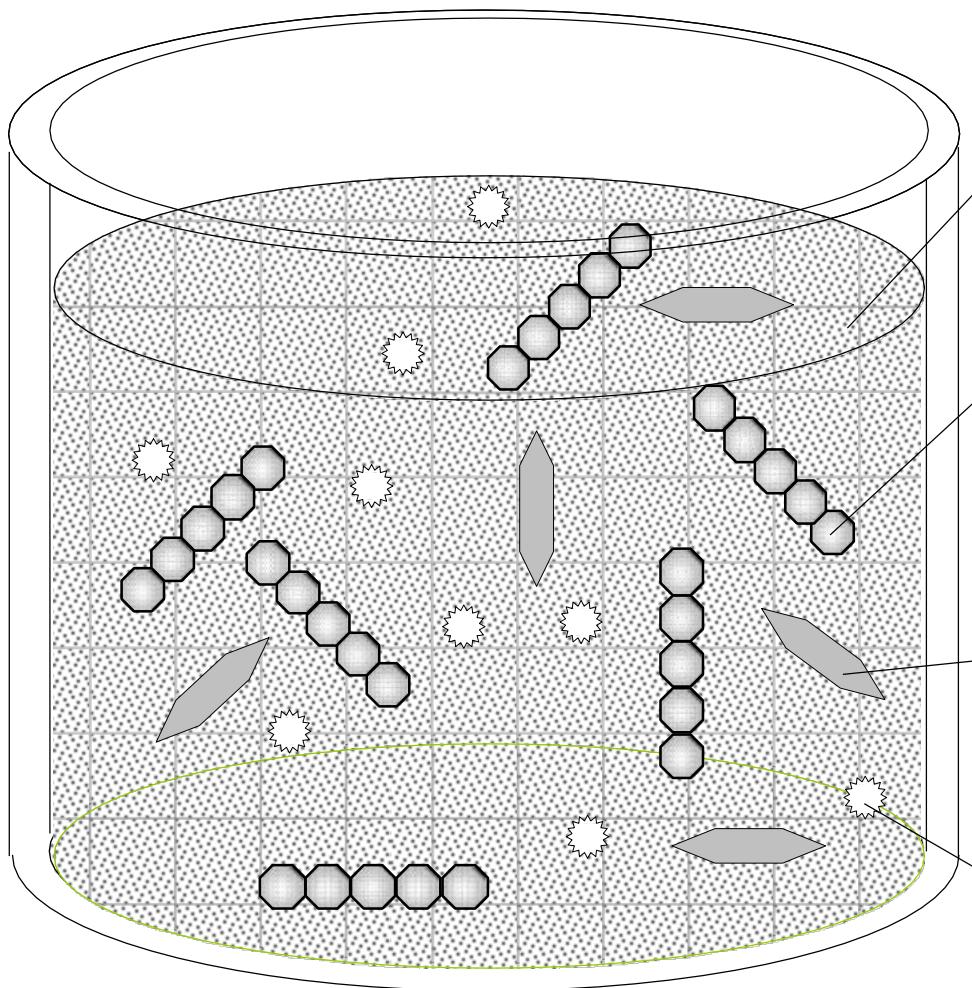


**Pause and
read
carefully**

Positive Resist	Negative Resist
Exposed region becomes more soluble	Exposed region becomes less soluble
Exposed areas are removed and unexposed areas remain after *resist development	Exposed areas remains and unexposed areas are removed after *resist development
Patterns formed on the wafer are the same as those of the mask	Patterns formed on the wafer are opposite as those of the mask

*Resist development: A process to remove soluble region, will be discussed.

Components of Resist



Solvent:

Gives resist its flow characteristics

Resin:

Mix of polymers used as binder;
gives resist its mechanical and
chemical properties

Sensitisers:

Photosensitive component of
the resist material

Additives:

Chemicals that control
specific aspects of resist
material

Components of Resist (Cont'd)

Main components for lithographic capability:

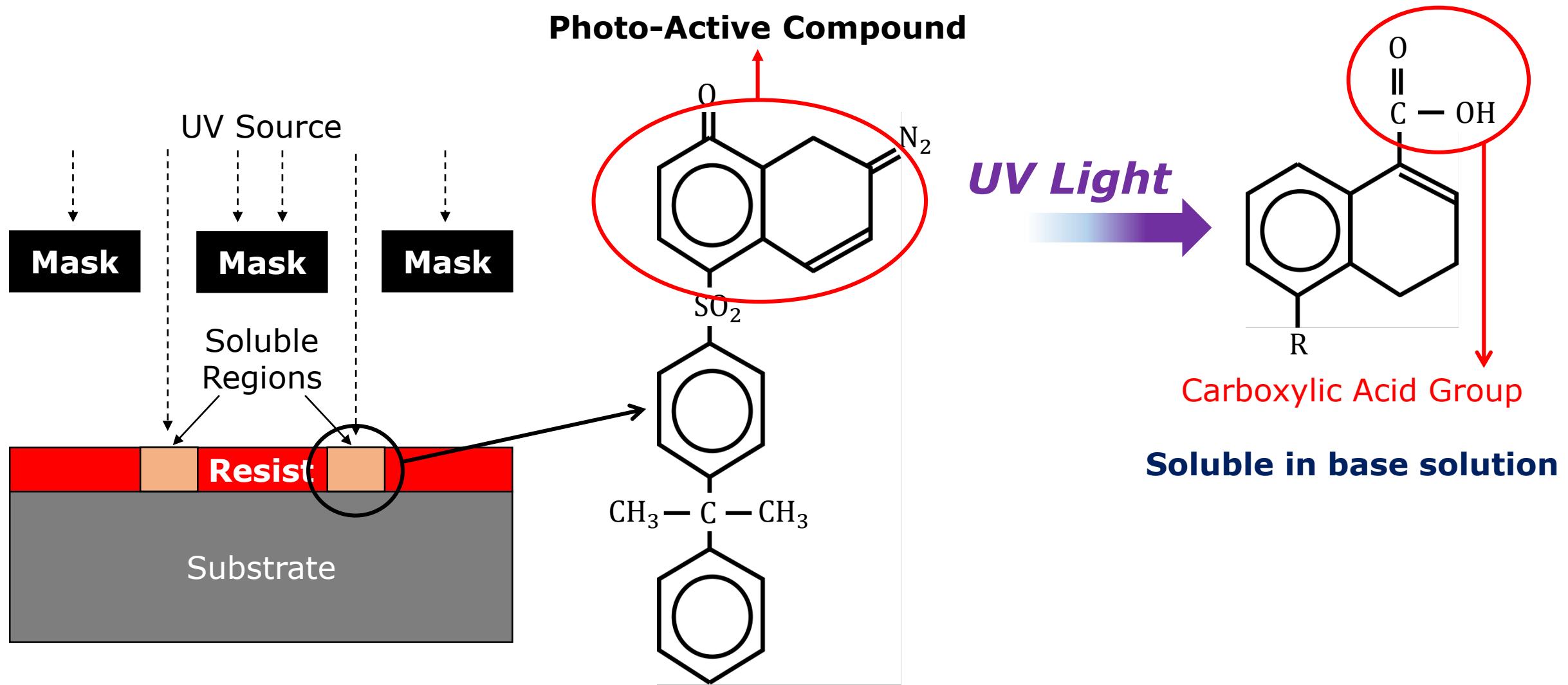
- Resin: Not opaque at λ
 - Give resist mechanical and chemical properties (reaction to developer, etc.)
- Sensitiser
 - Photo active compound/ group (PAC/ PAG) at λ
- Solvent
 - Keeps resist in liquid state
 - Allows spin coating of the resist
 - Solvent content determines viscosity and hence, the **thickness**
- Additives
 - Capability for further process: Etch resistivity/ implant blocking capability

Chemistry of Positive and Negative Resist

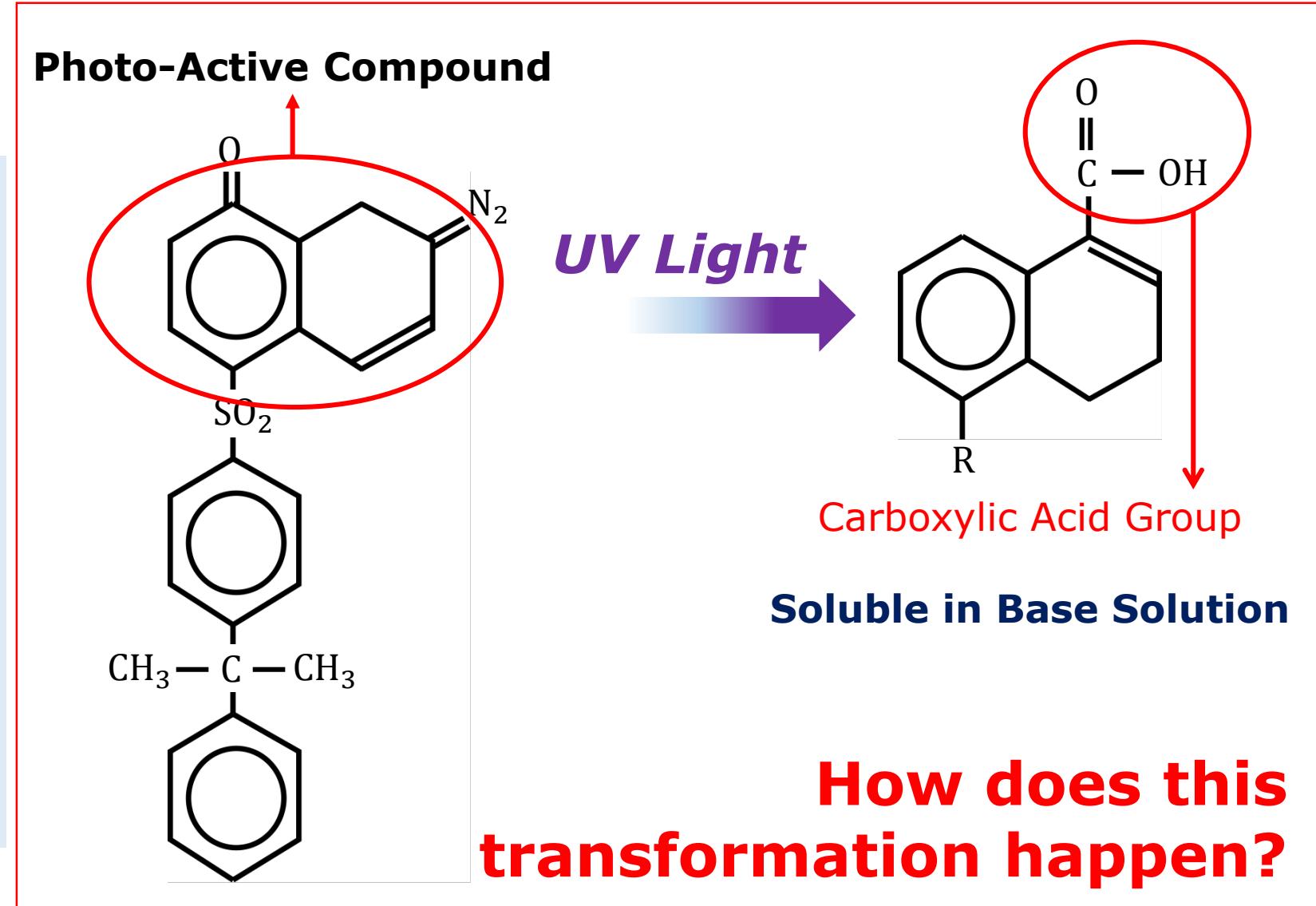
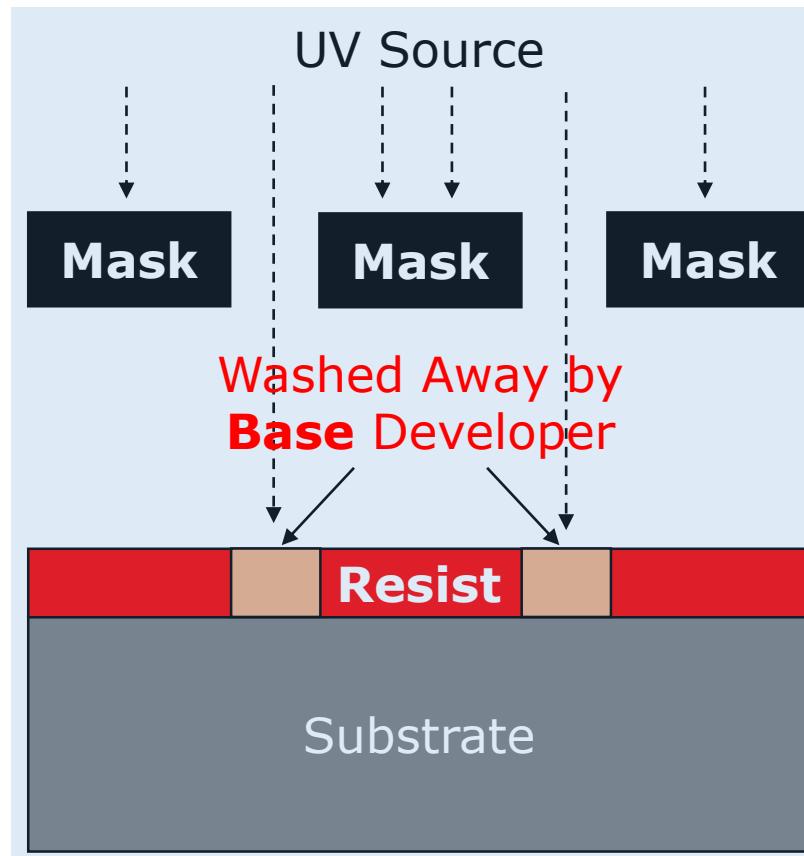
- Positive optical resist
 - **Resin** (Novolac resin)
 - **Sensitiser/ dissolution inhibitor** (PAC = Diazoquinones)
 - **Solvent** (Propylene Glycol Methyl Ether Acetate (PGMEA), N-Methyl Pyrrolidine (NMP), N-butyl acetate, xylene, etc.)
 - **Developer:** Hydroxides (TMAH, KOH, NaOH, etc.)
- Negative optical resist
 - **Resin** (Cyclised synthetic rubber resin)
 - **Sensitiser** (PAC = Bisarylzide)
 - **Solvent** (Aromatic solvent)
 - **Developer** (Organic solvents)

Positive and negative resist have different types of developer due to different photochemical reactions.

Positive Resist

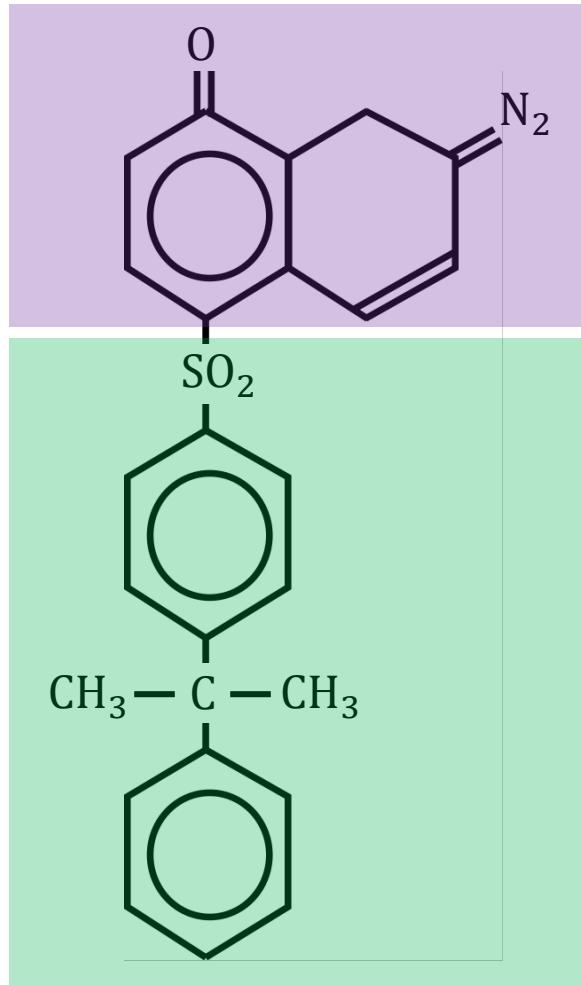


Positive Resist



How does this transformation happen?

Chemistry in Positive Resist - DQN

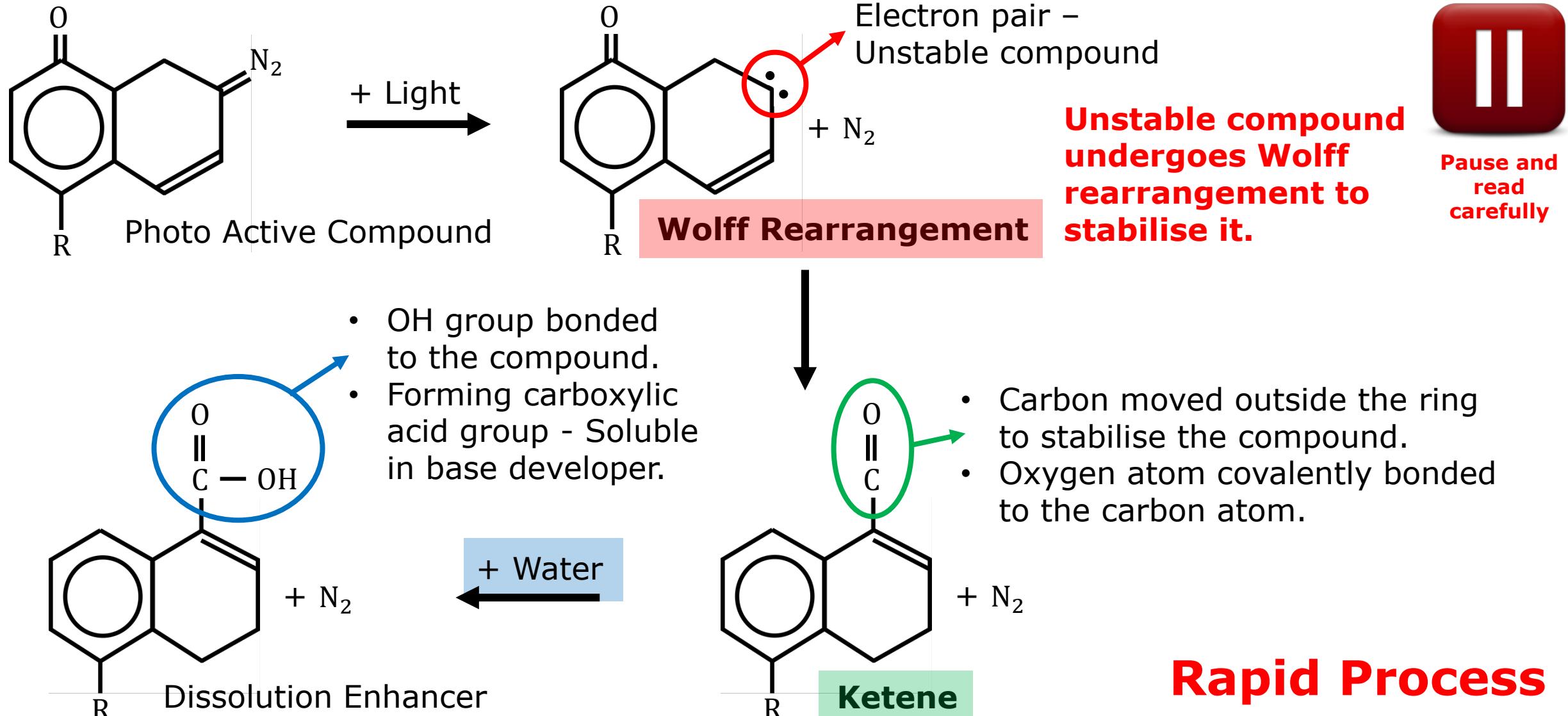


Diazoquinone (DQ) – Photoactive compound.

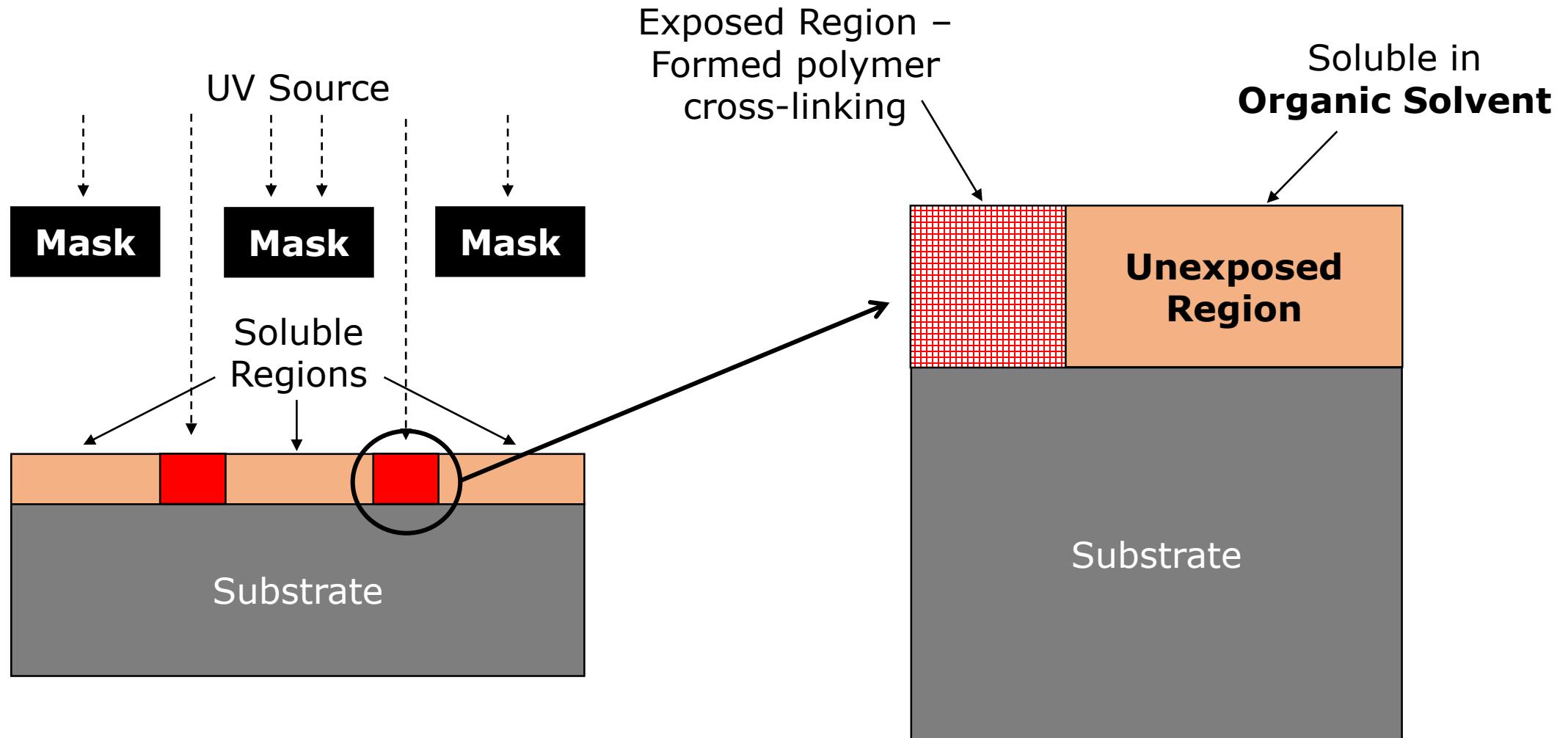
**Novolac (N) – Two CH₃ and one OH groups,
dissolves easily in aqueous solution.**

DQN

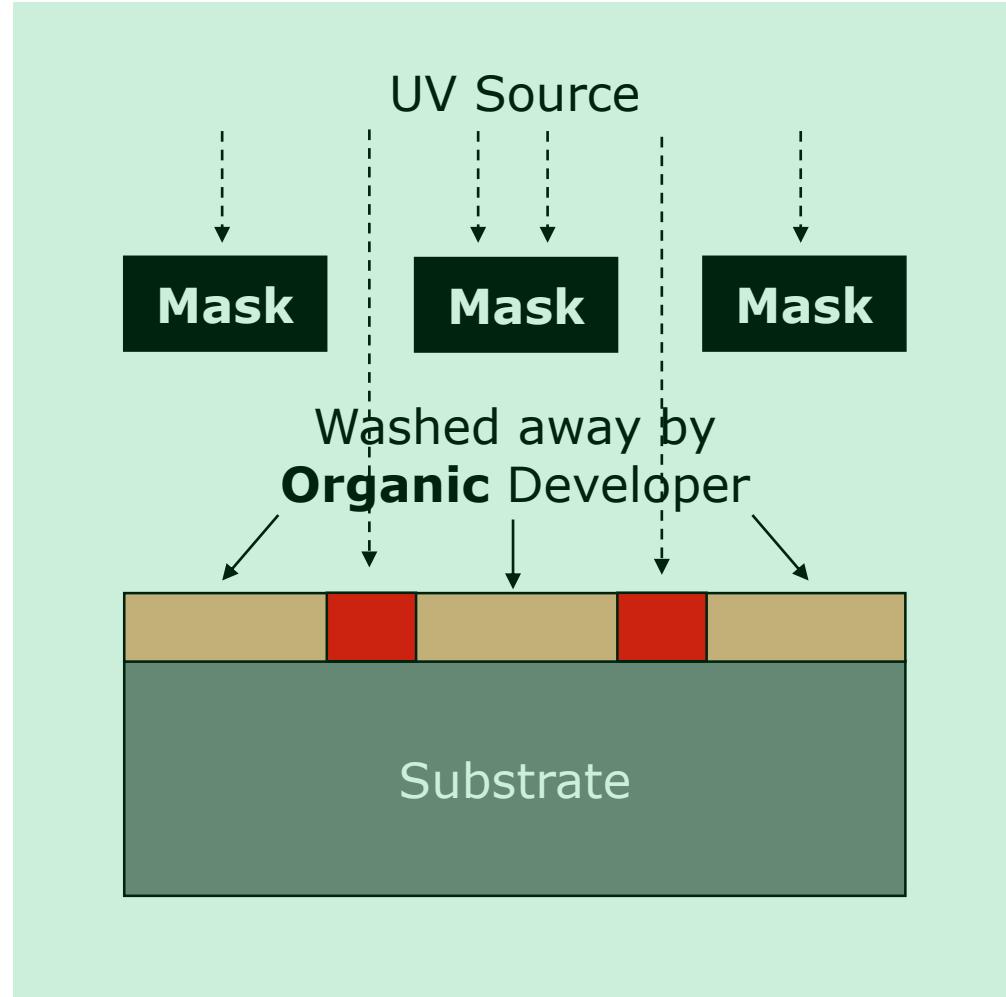
Photochemical Reaction in Positive Resist



Negative Resist



Negative Resist



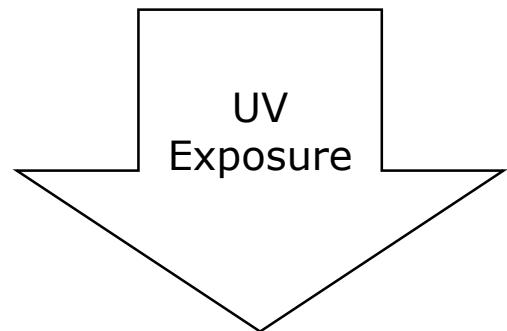
Reactions of Positive and Negative Resist



Pause and
read
carefully

Positive Resist

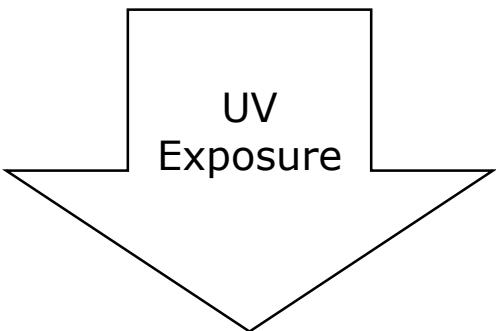
Diazoquinones (DQ)
Insoluble in developer



Carboxylic Acid
Soluble in Developer

Negative Resist

Natural Rubber-Based Polymer (Polyisoprene)
Soluble in Developer



Alkaline Developer (KOH)

Organic Developer

Practice Question

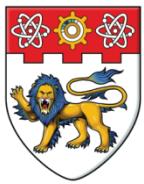
Fill in the blanks.



Pause and
try out this
question

When **positive** resist is exposed to UV source, the light-sensitive chemical in the resist converted into **(carboxylic acid)** groups, which is soluble in **(base)** developer.

When **negative** resist is exposed to UV source, the light-sensitive chemical in the resist forms **(polymer cross-links)**, where the unexposed region can be washed away by **(organic)** developer.



Metrics of Resist

Metrics of Resist

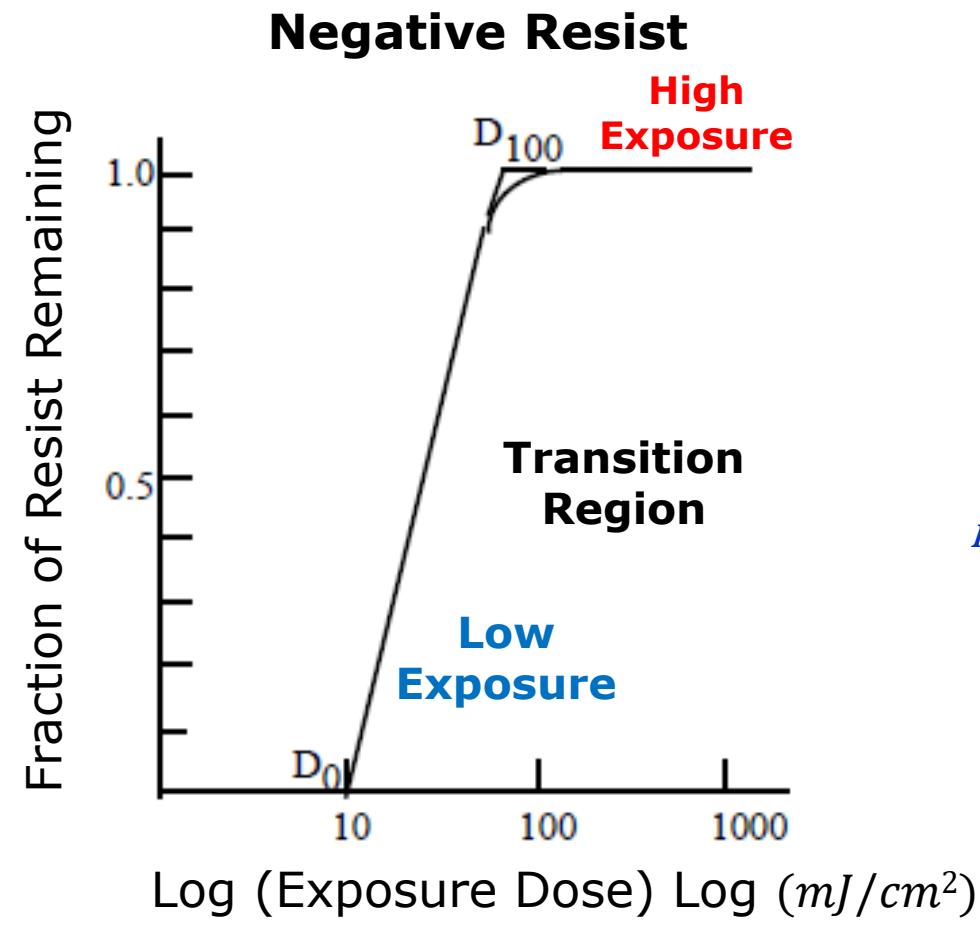
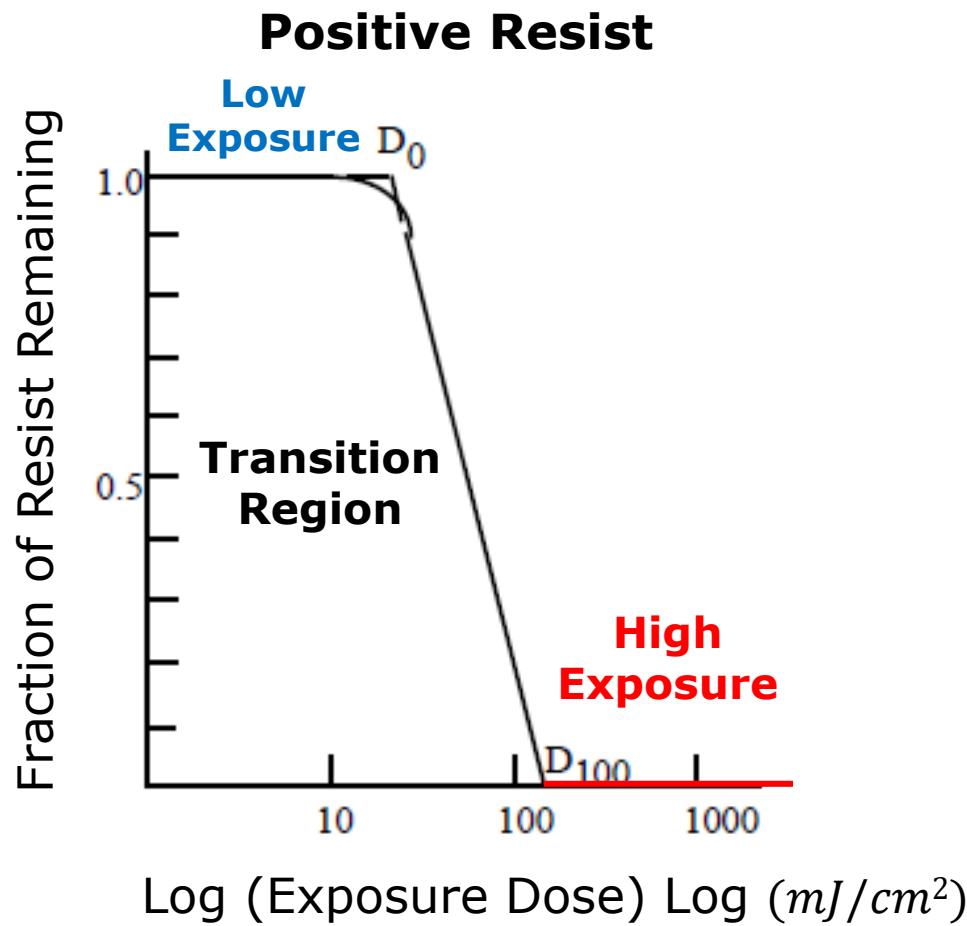
- Adhesion
- Photo activity
- Resolution ←
- Contrast ←
- Viscosity ←
- Sensitivity
- Etch resistance
- Thermal stability

Resolution and Contrast of Resist

- Resolution: How fine a line the resist can reproduce from an aerial image
- Resolution of resist is determined by:
 - Contrast, thickness, and proximity effects
 - Swelling and contraction after development
- Contrast: Ability of resist to distinguish between transparent and opaque regions of the mask
 - Measured by exposing the resist of given thickness to varying radiation dose and measuring dissolution rate

Contrast Curve

- The contrast curve of the resist presents the fraction of remaining resist as a function of exposure dose (mJ/cm^2).



$$mJ/cm^2 = \\ mW/cm^2 \times sec$$

Contrast of a Resist

Contrast, γ , can be defined as:

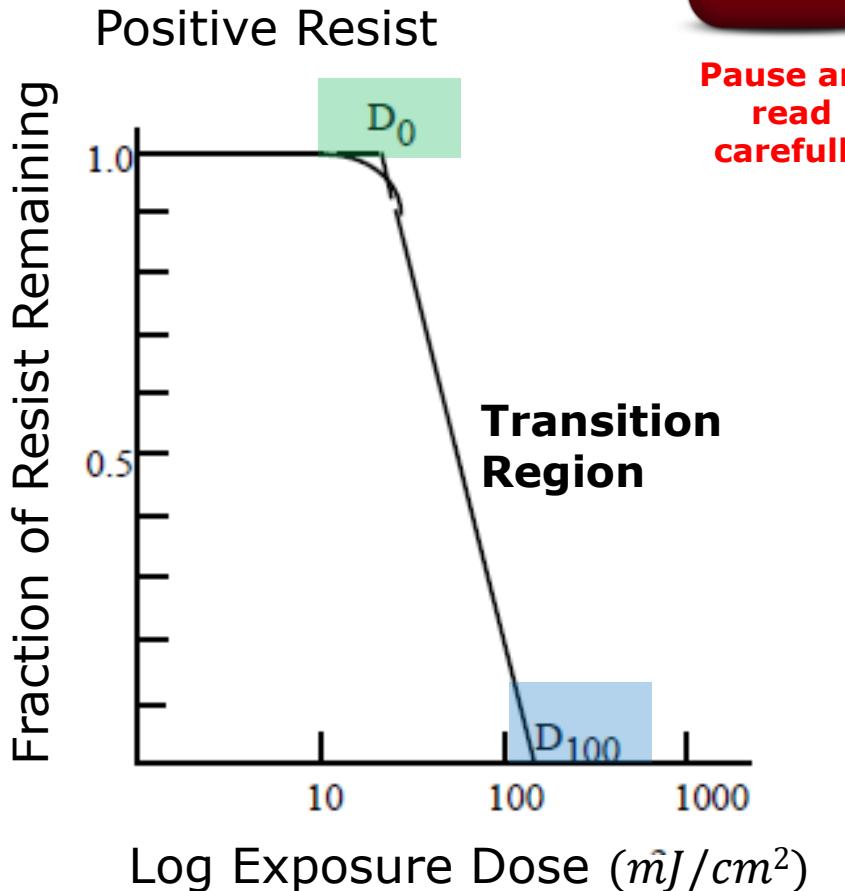
$$\gamma = \left[\log_{10} \frac{D_{100}}{D_0} \right]^{-1}$$

D_{100} : Lowest energy dose where **all of the resist is removed**

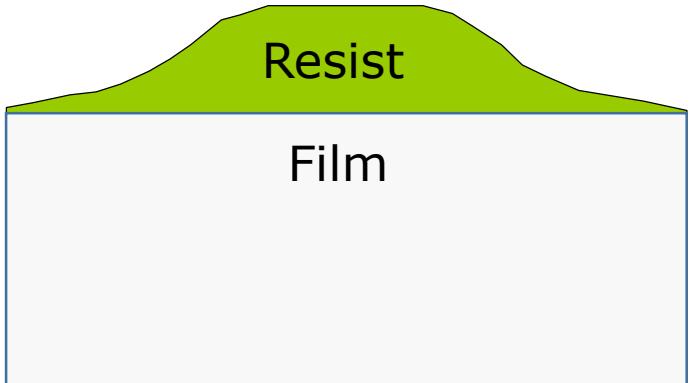
D_0 : Lowest energy dose to **begin to drive the photochemistry**

Contrast

- Measures the **ability** of the resist **to distinguish** between **transparent** and **opaque regions** of the mask
- Higher ability to distinguish → **Higher contrast** → **Sharper edge**

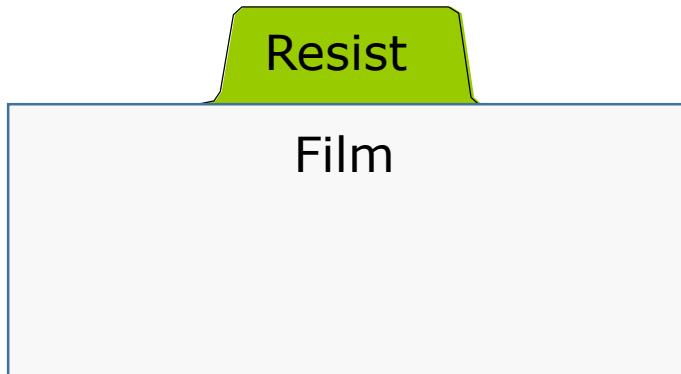


Resist Contrast



Low Resist Contrast

- Sloped walls
- Swelling
- Poor contrast



High Resist Contrast

- Sharp edges
- No swelling
- Good contrast

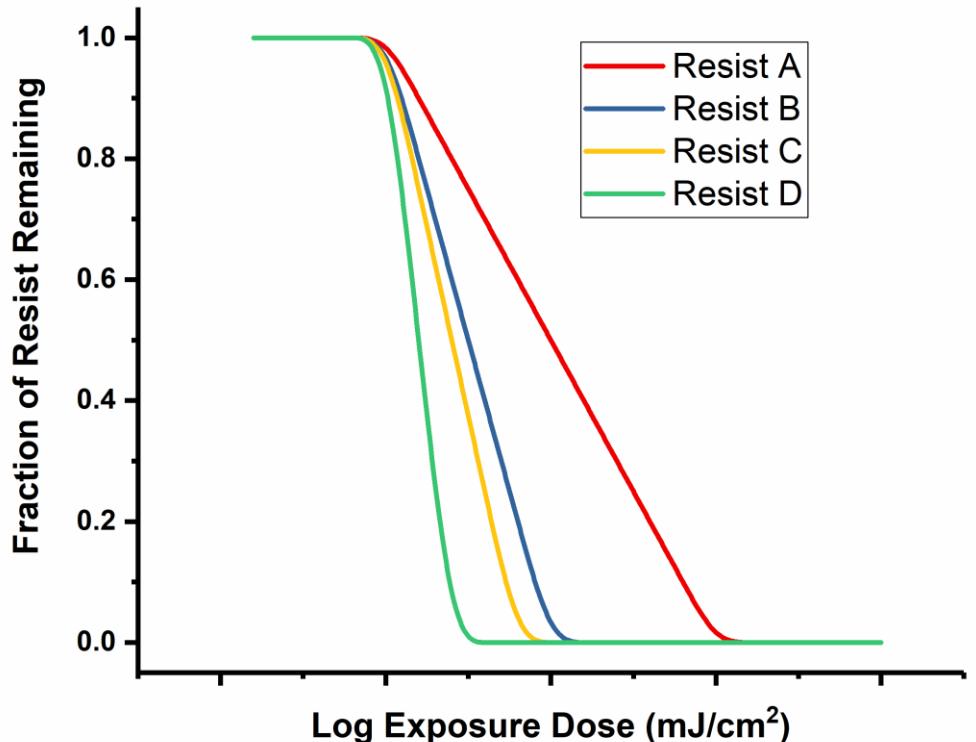
Practice Question 1

The fabrication process of a device requires resist that is capable of **achieving sharp edges.**



Pause and try out this question

Which of the following resists is the most suitable for this purpose?



Resist D:

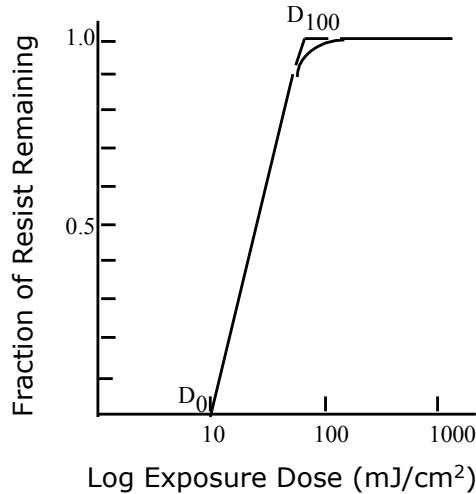
- It has the steepest contrast curve, indicating high contrast value.
- The high contrast value indicates ability to form sharp edges.

Practice Question 2

Figure shows a contrast curve of a photoresist.



**Pause and
try out this
question**



1. What type of photoresist is this?
2. Using the estimated values of D_0 and D_{100} from the figure, determine the contrast value γ .
3. What happens of the exposure dose is at a point between D_0 and D_{100} ?
4. Discuss whether the resist contrast should be high or low.

Practice Question 2



Pause and
read
carefully

1. Negative Resist

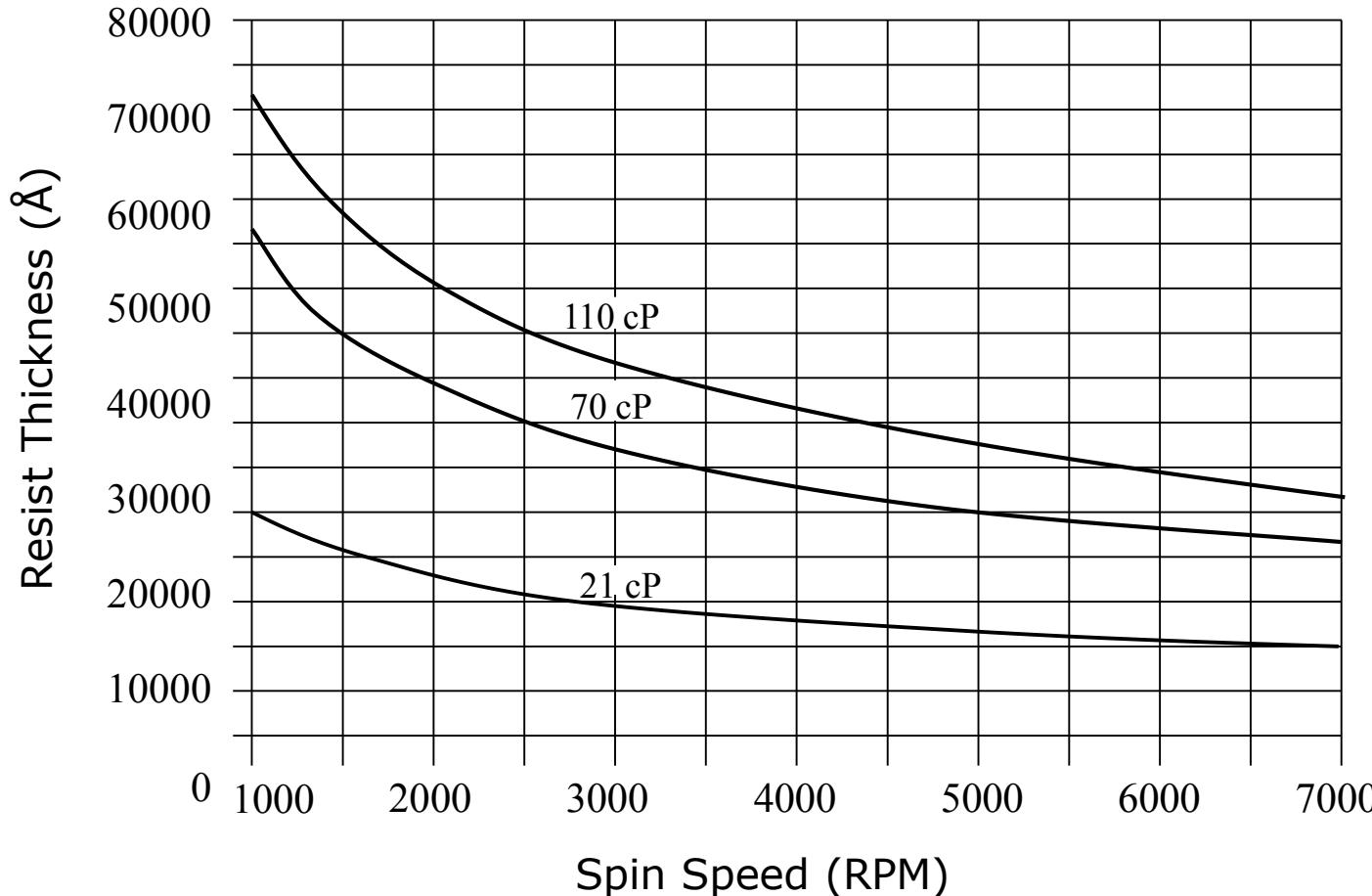
$$2. \gamma = \left[\log_{10} \frac{D_{100}}{D_0} \right]^{-1} = 1 / [\log_{10} \frac{90}{10}] = 1.05$$

3. Blurred (not sharp) pattern transfer

4. The higher the contrast of the resist, the sharper the line edge. Resist contrast represents the sharpness of the transition from exposure to non-exposure in photoresists. The higher the contrast, the sharper the edge.

Resist Viscosity

Spin speed curve of IX300 (thick DNQ resist) for different viscosity.



Solvent:

- Keeps photoresist in liquid state
- Allows spin coating of the photoresist
- Solvent content determines resist viscosity and hence, the **thickness**

Thinner Resist

$$I_R \cong \frac{\text{viscosity} \times \text{solid content (\%)} }{\sqrt{\text{spin speed}}}$$

Higher Spin Speed

Practice Question 3

An experiment in a spin coating process shows that a final resist thickness of 320nm is obtained when spun at 3000 rev/min.



**Pause and
try out this
question**

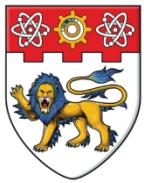
- a) Estimate the spin speed, if a 270nm thick coating of the same resist is required.
- b) If the maximum practical spin speed is 4000 rev/min, how would you re-formulate the resist to meet the above required resist thickness of 270nm?

a) Resist Layer Thickness, $I_R \approx \left[\frac{\text{viscosity} \times \text{solid content} (\%)}{\sqrt{\text{spin speed}}} \right]$

$$270 = \frac{\sqrt{3000}}{\sqrt{\text{spin speed}_1}} \times 320$$

Therefore new spin speed = 4214 rev/min

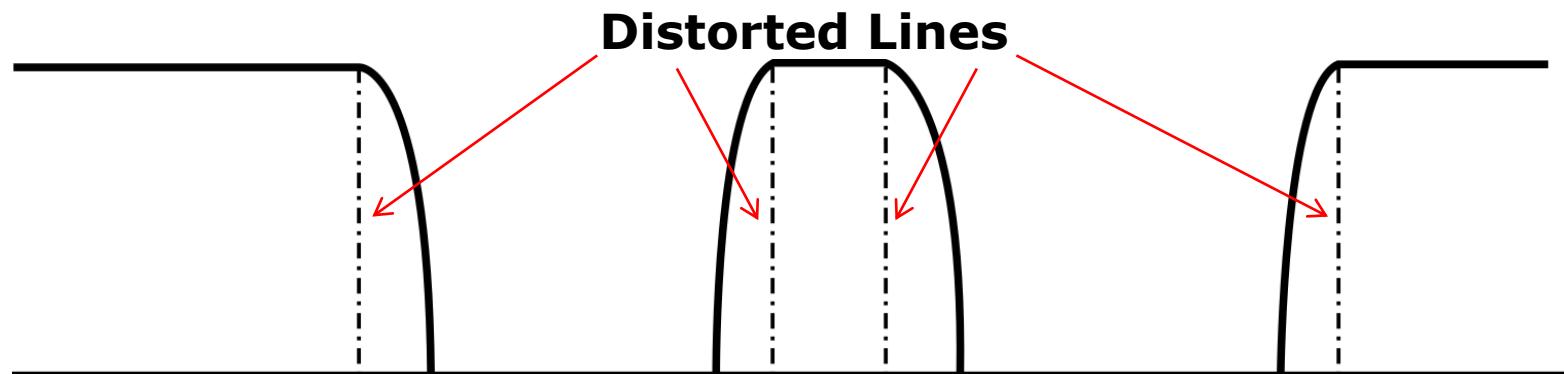
- b) If the max speed is restricted to 4000 rev/min, the viscosity and/or the solid content of the resist need to be increased in value.



Advantages and Disadvantages of Positive and Negative Resist

Advantages and Disadvantages of Using Negative Resist

Advantages	Disadvantage
Well established	
Shorter exposure time as compared to positive resist, higher throughput	Solvent-induced swelling <ul style="list-style-type: none">• Broadening of linewidth during development phase• Not suited to features $< 2\mu m$



Developed Negative Resist:

Dashed Lines Indicate Mask Pattern – **Solvent-Induced Swelling**

Advantages and Disadvantages of Using Positive Resist



Pause and
read
carefully

Advantages	Disadvantage
Does not suffer from swelling	Lower throughput:
Better resolution	Requires much larger energy
Thick resist available (for etching)	and longer exposure time

**Etching will be discussed
in the coming lecture**

Advantages and Disadvantages of Resists



**Pause and
read
carefully**

Advantages	Disadvantage
Well established	
Shorter exposure time as compared to positive resist, higher throughput	<p>Solvent-induced swelling</p> <ul style="list-style-type: none"> • Broadening of linewidth during development phase • Not suited to features $< 2\mu m$

Negative Resist

Advantages	Disadvantage
Does not suffer from swelling	
Better resolution	
Thick resist available (for etching)	Lower throughput – requires much larger energy and longer exposure time

Positive Resist

Resist Technology - Summary

Resist technology:

- Positive resist forms carboxylic groups after photochemical reaction with UV light, enabling it to be dissolved in the base developer.
- Negative resist forms polymer cross-linking after photochemical reaction with UV light, preventing it from dissolving in the organic developer.
- The important metrics of resist include resolution, contrast, and viscosity.

Practice Question 1



For the next nine statements, choose the type of photoresist, positive (+) or negative (-), that matches the accompanying statement.

**Pause and
try out this
question**

- a) + - Undergoes a chemical change when exposed to UV light.
- b) + - The exposed regions become crosslinked and hardened.
- c) + - The exposed regions become soluble and soft.
- d) + - The resulting pattern is exactly the same as the mask.
- e) + - The resulting pattern is opposite of the mask pattern.
- f) + - Swells up during the develop process, which limits Critical Dimensions.
- g) + - Has the best resolution of the two types of resists.
- h) + - The dominant resist type for use in VLSI processing.
- i) + - The preferred resist for use in submicron lithography.

Practice Question 2

An optical lithography system has an exposure power of 0.3 mW/cm^2 . The required exposure energy for Resist A is 10 mJ/cm^2 , and for Resist B is 130 mJ/cm^2 .



Pause and
try out this
question

- a) Compare the wafer throughput for Resist A and Resist B. Assume negligible time for setting up the wafers.
- b) Identify the type of photoresists for Resist A and Resist B. State the reason for your answers.

Answers:

- a) Time taken for Resist A = $10/0.3 = 33 \text{ sec}$ – faster throughput
Time taken for Resist B = $130/0.3 = 433 \text{ sec}$ – lower throughput
- b) Resist B is likely to be a positive resist. Require much larger energy, and longer exposure time, thus lower throughput. Resist A is likely to be a negative photoresist.



Course: EE3013 Semiconductor Devices and Processing
School: School of Electrical and Electronic Engineering
Etching – Wet Etching

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Lesson Objectives - Etching

At the end of this lesson on etching, you should be able to:

- Explain the fundamental concepts of wet and dry etching
- Identify the factors determining the etch rate in wet and dry etching
- Explain the techniques to improve the etch rate in wet and dry etching

Standard Process Iteration

Three main categories in semiconductor fabrication process:

Lithography

Patterning of substrate
(silicon wafer)

Etching

Removal of materials
from the substrate

Deposition

Deposit materials
(metal/ non-metal)
on the substrate

Etching Techniques

Etching can be done either in “**wet**” or “**dry**” method:

Wet etching

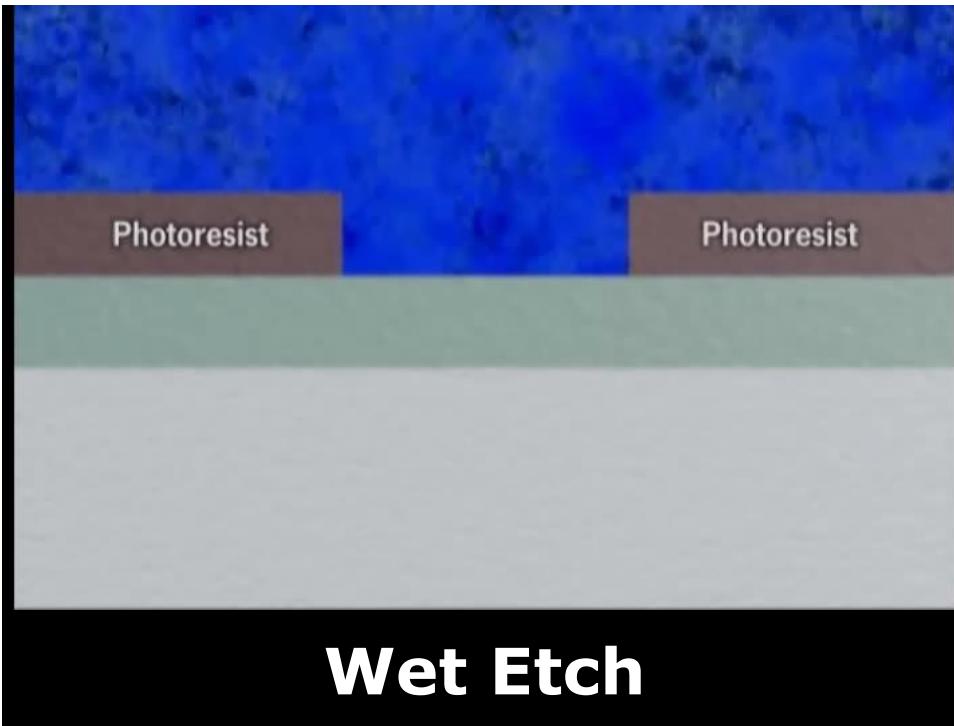
- Wet etching is a process whereby materials are removed by liquid etchants.
- Wet etching is fast, cheap and simple, but harder to control. Hence, it is not popular in nanofabrication.

Dry etching

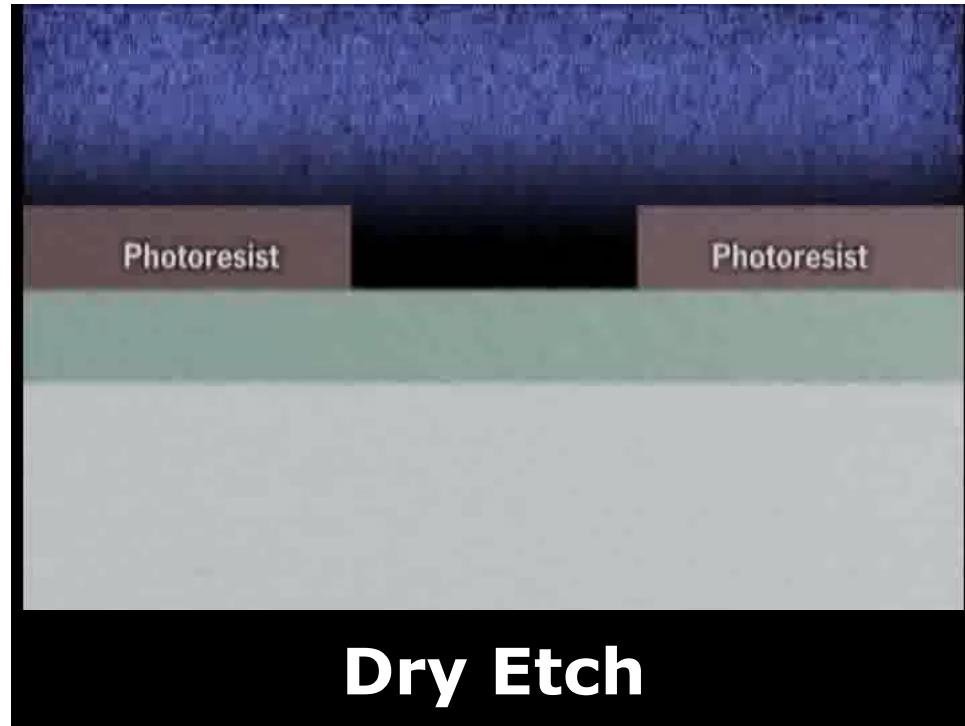
- Dry etch uses gas phase etchants in plasma.
- In comparison, dry etching is slower, requires sophisticated equipment, but easier to control.
- It works for many dielectric materials and some metals (Al, Ti, Cr, Ta, W, etc.).

Two types of **Etch Profile**: **Isotropic** and **Anisotropic**

Isotropic Etching

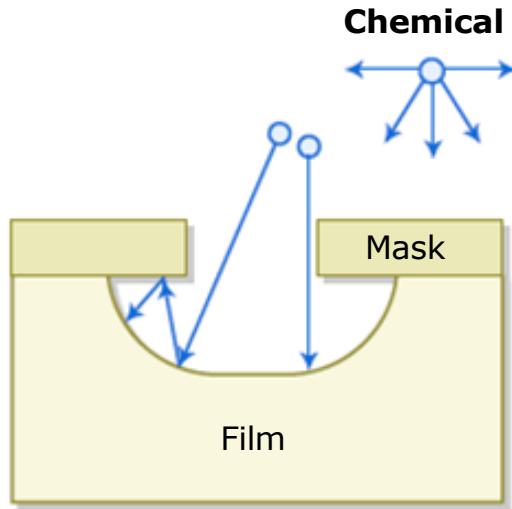


Anisotropic Etching



Types of Etch Profile

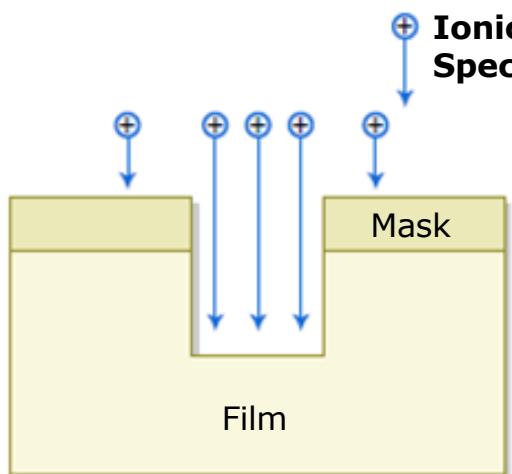
Chemical



Isotropic etching

Attacks the materials equally in all directions and results in the undercut of the mask. Thus, the obtained feature size will be larger than the mask design.

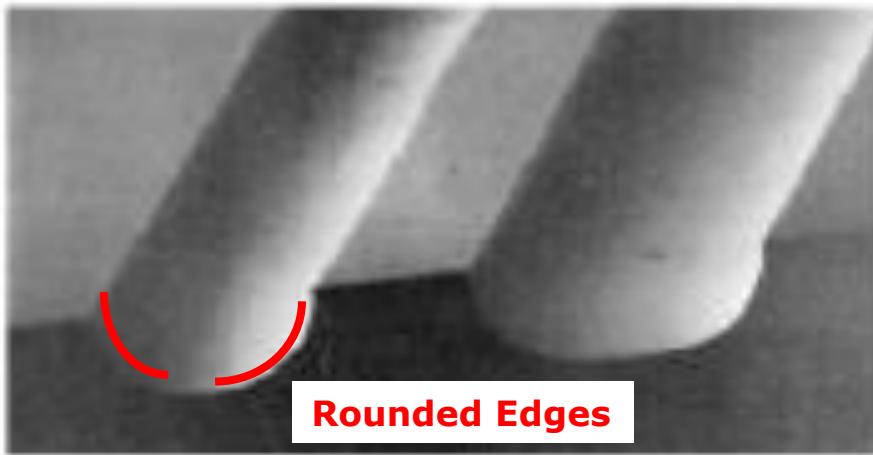
Ionic Species



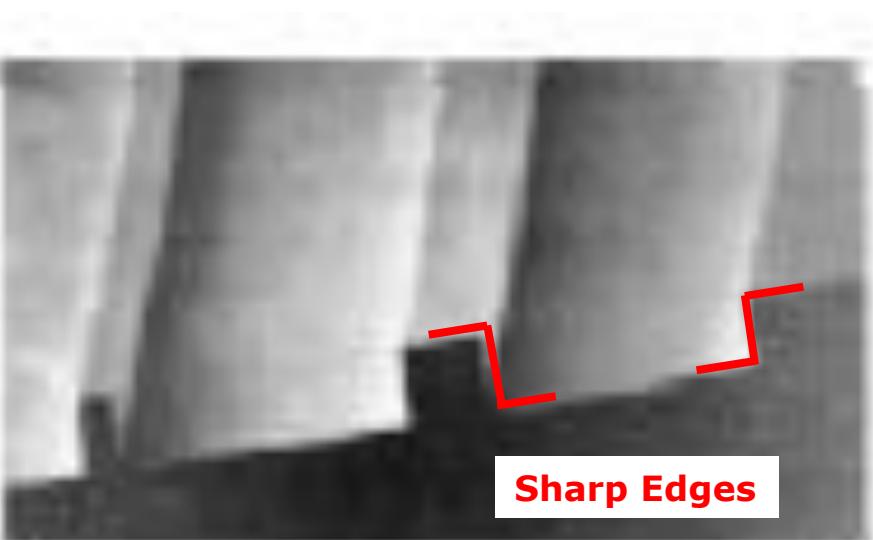
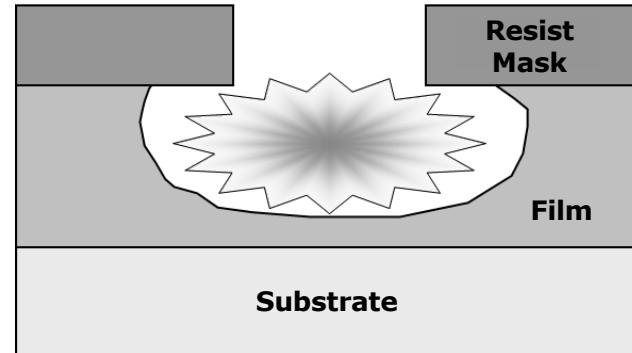
Anisotropic etching

Etching rate is faster in vertical directions than horizontal directions, forming straight edge features.

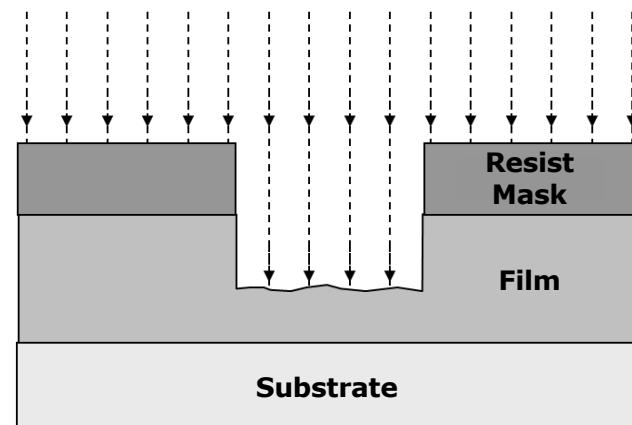
Isotropic and Anisotropic Etching Profiles



Isotropic etch:
Etches in all directions at the same rate



Anisotropic etch:
Etches in only one direction



Figures of Merit: Degree of Anisotropy

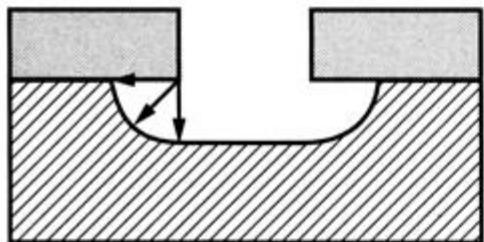
In most etching techniques, there is a mixture of isotropic and anisotropic features.



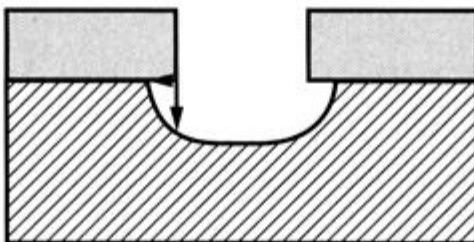
**Pause and
observe
carefully**

Degree of Anisotropy: $A = 1 - \frac{R_L}{R_V}$

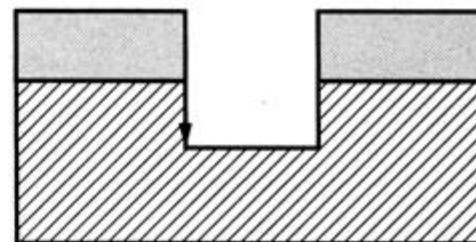
Where R_L is the lateral and R_V is the vertical etch rates respectively.



Isotropic



Anisotropic



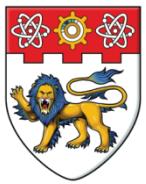
Completely Anisotropic

Isotropic: $A=0$



Anisotropic: $A=1$

**Increasing Degree of
Anisotropic**



Wet Etching

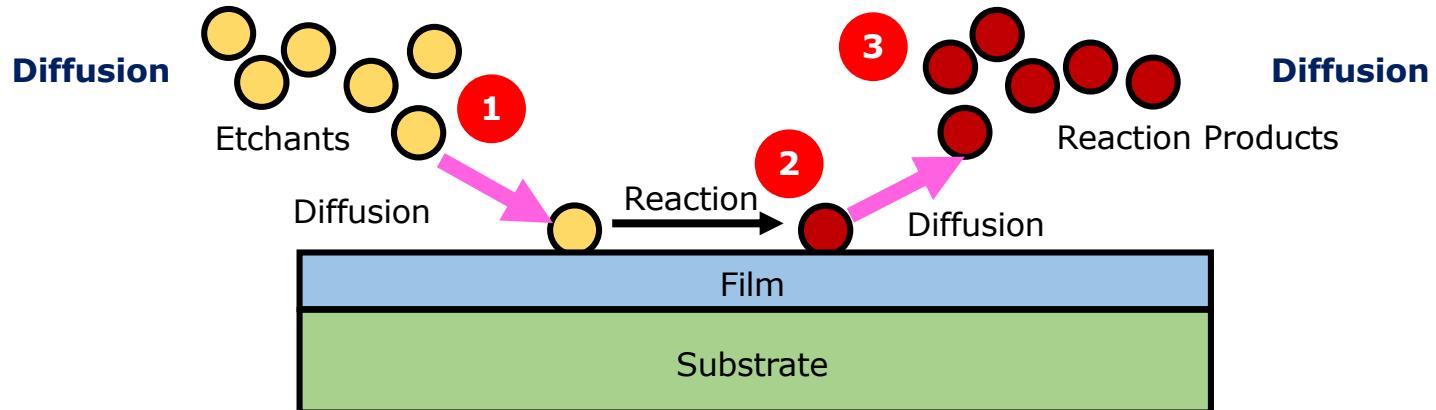
Wet Etching Processes

Etching comprises of 3 sub-processes:

1. Etchants diffuse to the reacting surface
2. Chemical reaction at the surface
3. Removal of the products from the surface through diffusion



**Pause and
observe
carefully**



- It is desirable to have a large, uniformed and well-controlled etch rate.
- The overall etch rate is determined by the slowest sub-process, which is called a **rate-limiting step**.
- The possible rate-limiting step in wet etching can either be step **(1), (2) or (3)**.

Practice Question 1

Select the most suitable technique to accelerate the corresponding sub-process.



Pause and attempt this question

Sub-Process in Wet Etching	Technique to Accelerate Sub-Process
(1) Etchants diffuse to the substrate surface	Etchant agitation / Etching in elevated temperature
(2) Chemical reaction at the surface	Etchant agitation / Etching in elevated temperature
(3) Removal of the products from the surface through diffusion	Etchant agitation / Etching in elevated temperature

Etchant agitation: Etching in an ultrasonic bath

Etchant agitation can effectively improve the diffusivity of etchants, hence accelerating process (1) and (3).

By etching in elevated temperature, the reaction rate between etchants and substrate's surface can be effectively improved, hence accelerating process (2).

Silicon Etching Process by HF and HNO₃

Silicon can be etched away by a mixture of **HNO₃** and **HF**, coupled with a diluent (water or acetic acid).

HNO₃ oxidises Si to form SiO₂.

HF will etch away the formed SiO₂.

Silicon Etching Process by HF and HNO₃

Local anodisation, oxidising the silicon (**holes** are required to start this process)



- Combines with (OH)⁻ to form the hydroxide: $Si^{2+} + 2OH^- \rightarrow Si(OH)_2$
- Subsequently liberates hydrogen to form SiO₂: $Si(OH)_2 \rightarrow SiO_2 + H_2$
- Hydrofluoric acid (HF) is used to dissolve SiO₂: $SiO_2 + 6HF \rightarrow H_2SiF_6 + H_2O$
where H_2SiF_6 is soluble in water
- The holes required for the initial oxidation is given by: $HNO_2 + HNO_3 \rightarrow 2NO_2^- + 2h^+ + H_2O$
 $2NO_2^- + 2H^+ \rightarrow 2HNO_2$



Pause and
observe
carefully

The overall reaction is: $Si + HNO_3 + 6HF \rightarrow H_2SiF_6 + HNO_2 + H_2O + H_2$

The by-products after etching are typically gaseous or water soluble for ease of removal.

Practice Question 2 – Buffered HF

The overall reaction of the Si etching is shown:



From the overall reaction, explain why the etch rate will decrease with time.

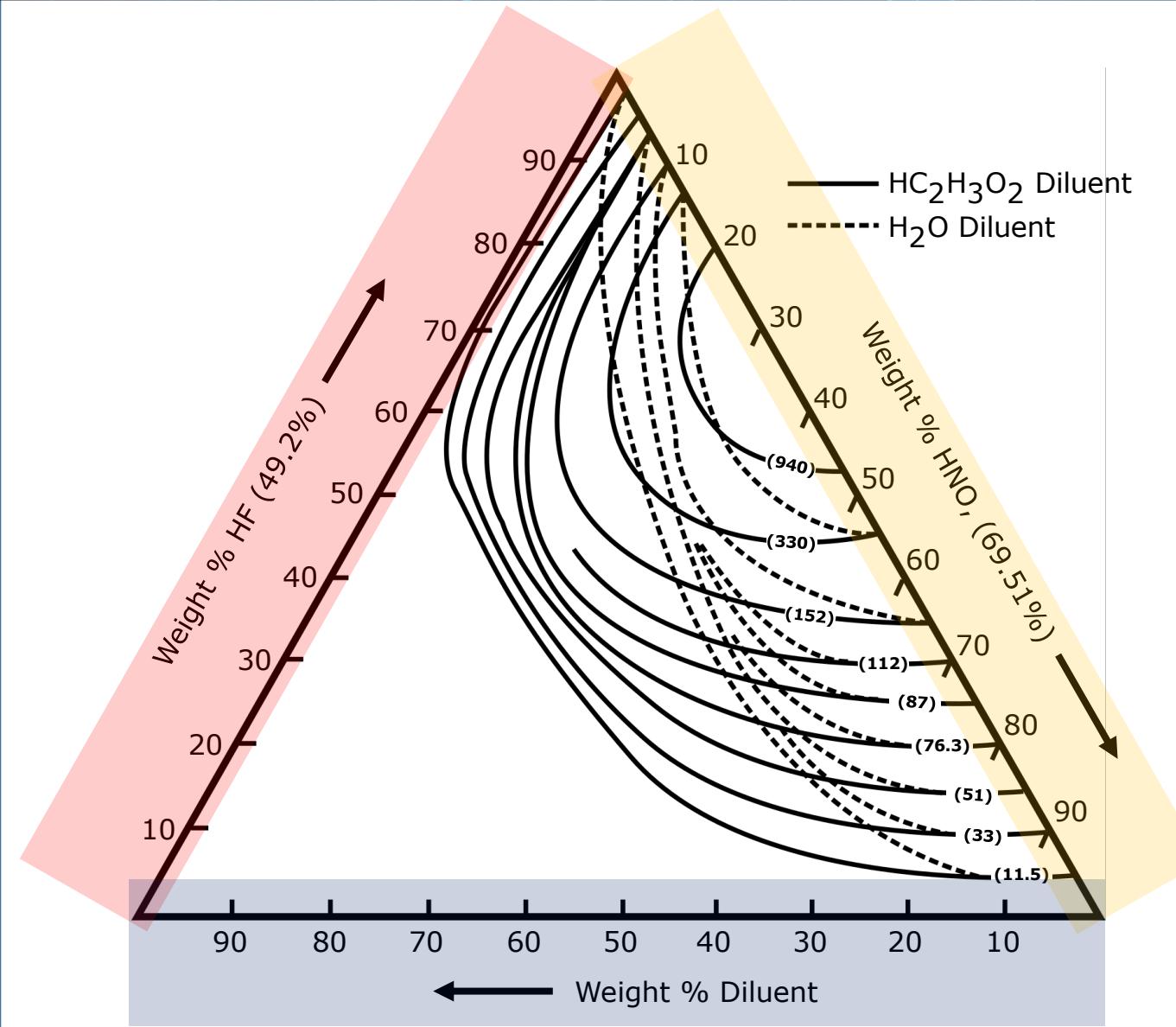


Pause and
try out this
question

Solution:

- In regular Si etching, SiO_2 etching reaction consumes HF and causes the reaction rate of SiO_2 etching to decrease.
- Buffered HF (NH_4F) is used to provide consistent etch rate by maintain HF concentration. $\text{NH}_4\text{F} \rightarrow \text{NH}_3 \uparrow + \text{HF}$

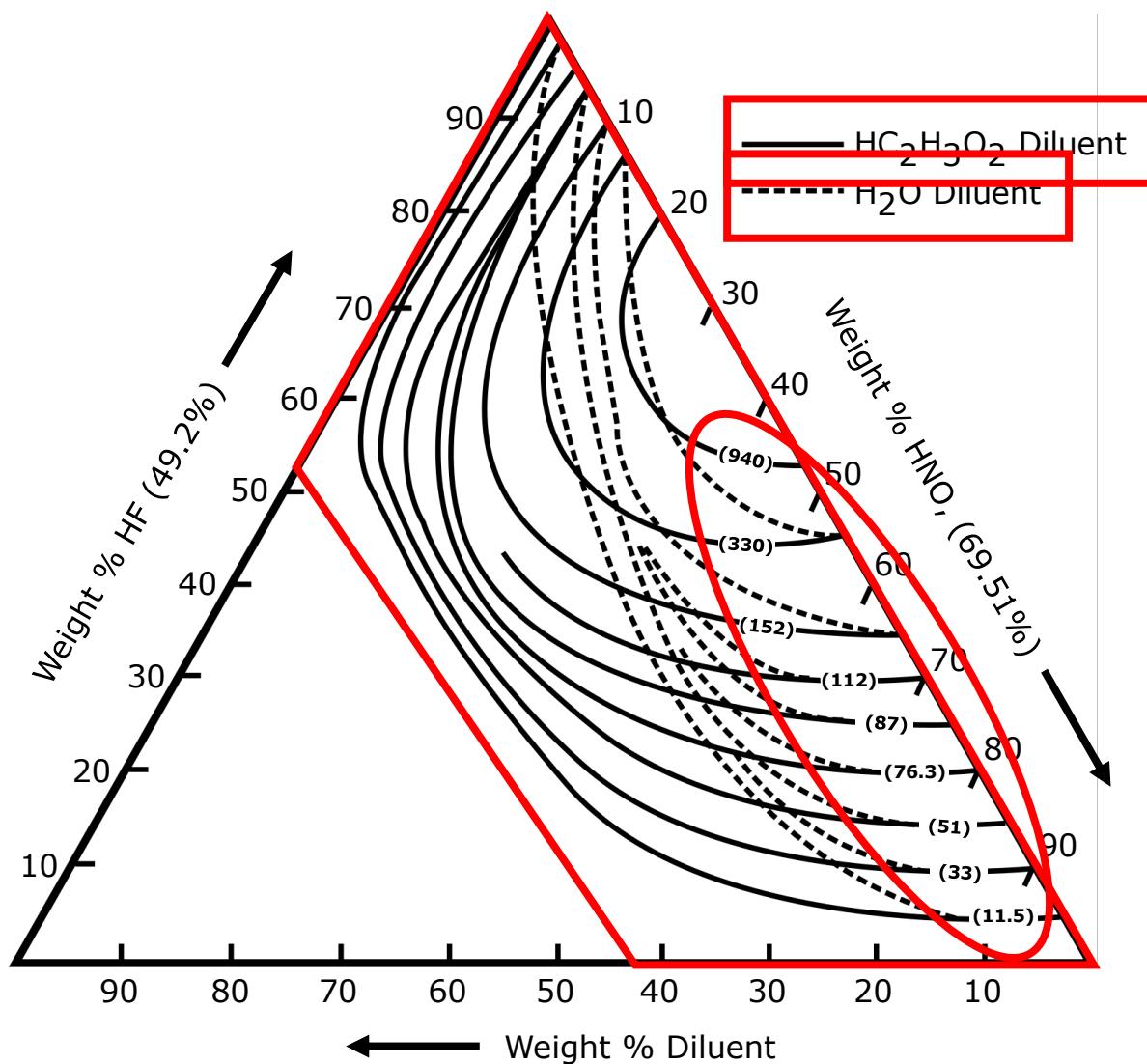
Introduction to Iso-Etch Curve



The silicon etch rate is determined under different concentrations of HNO₃, HF and diluent:

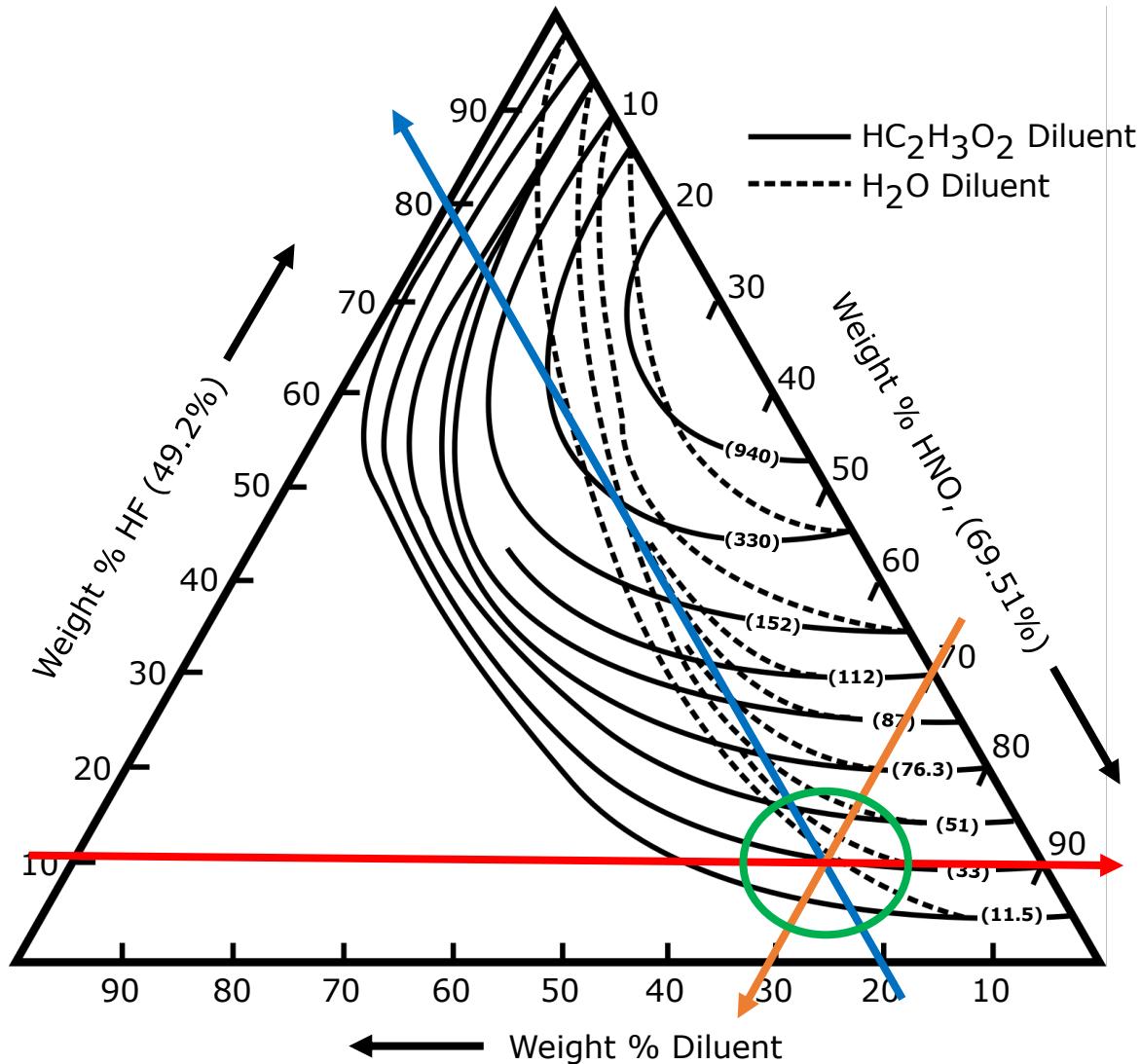
- **Concentration of HF**
- **Concentration of HNO₃**
- **Concentration of diluent. The diluent is usually water or acetic acid**

Introduction to Iso-Etch Curve



- The contour lines indicate the etch rate of Si at specific concentrations.
- The numbers in the bracket indicate the Si etch rates in $\mu\text{m}/\text{min}$.
- The solid lines indicate the etch rates when acetic acid diluent is used.
- The dash lines indicate the etch rates when water diluent is used.

Determining the Si Etch Rate From Iso-Etch Curve



How to determine the Si etch rate using the Iso-etch curve?

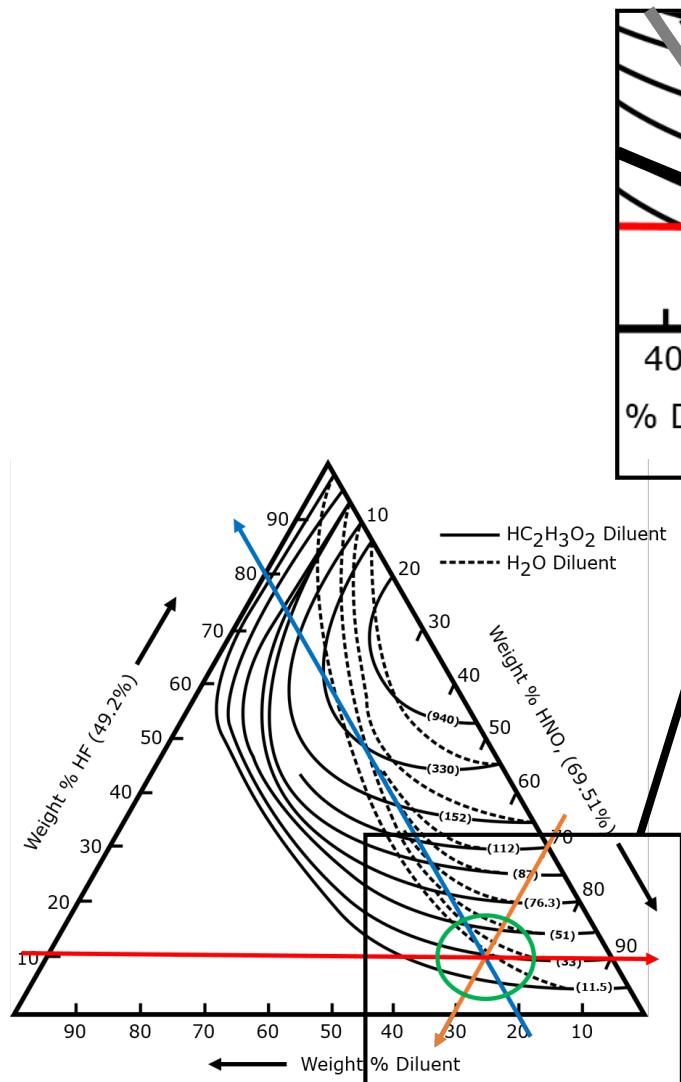
For example, if a mixture of 10% HF, 70% HNO₃, and 20% water diluent is used as Si etchant:

1. Draw a line of such from 10% HF axis
2. Draw a line of such from 70% HNO₃ axis
3. Draw a line of such from 20% diluent axis
4. Intersection point of these three lines falls at 11.5 µm/min curve of the dash line (water diluent). Therefore, the Si etch rate is 11.5 µm/min



Pause and observe carefully

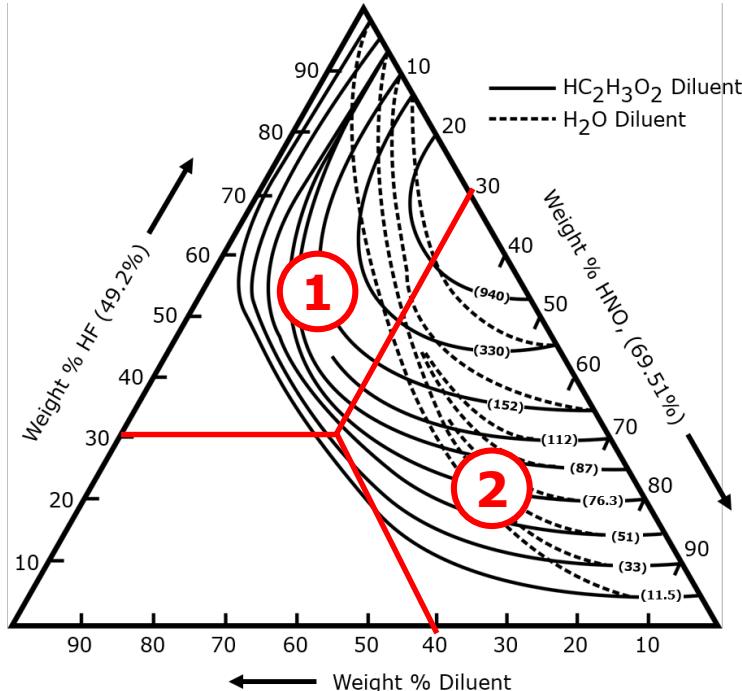
Water vs Acetic Acid as Diluent



- Acetic acid (CH_3COOH) is frequently substituted for water as the diluent.
 - It has a lower dielectric constant than water.
 - It also produces less dissociation of the HNO_3 , and yields a higher oxidation power for the etching process.
- 33 $\mu\text{m}/\text{min}$ if acetic acid is used**
10% HF, 70% HNO_3 , 20% CH_3COOH
- 11.5 $\mu\text{m}/\text{min}$ if water is used**
10% HF, 70% HNO_3 , 20% H_2O



Pause and
observe
carefully



HNO_3 oxidises Si to form SiO_2
HF etch away the SiO_2

Region 1:

**High HF concentrations, low HNO_3 concentration,
insufficient HNO_3 to oxidise the Si for HF to etch**

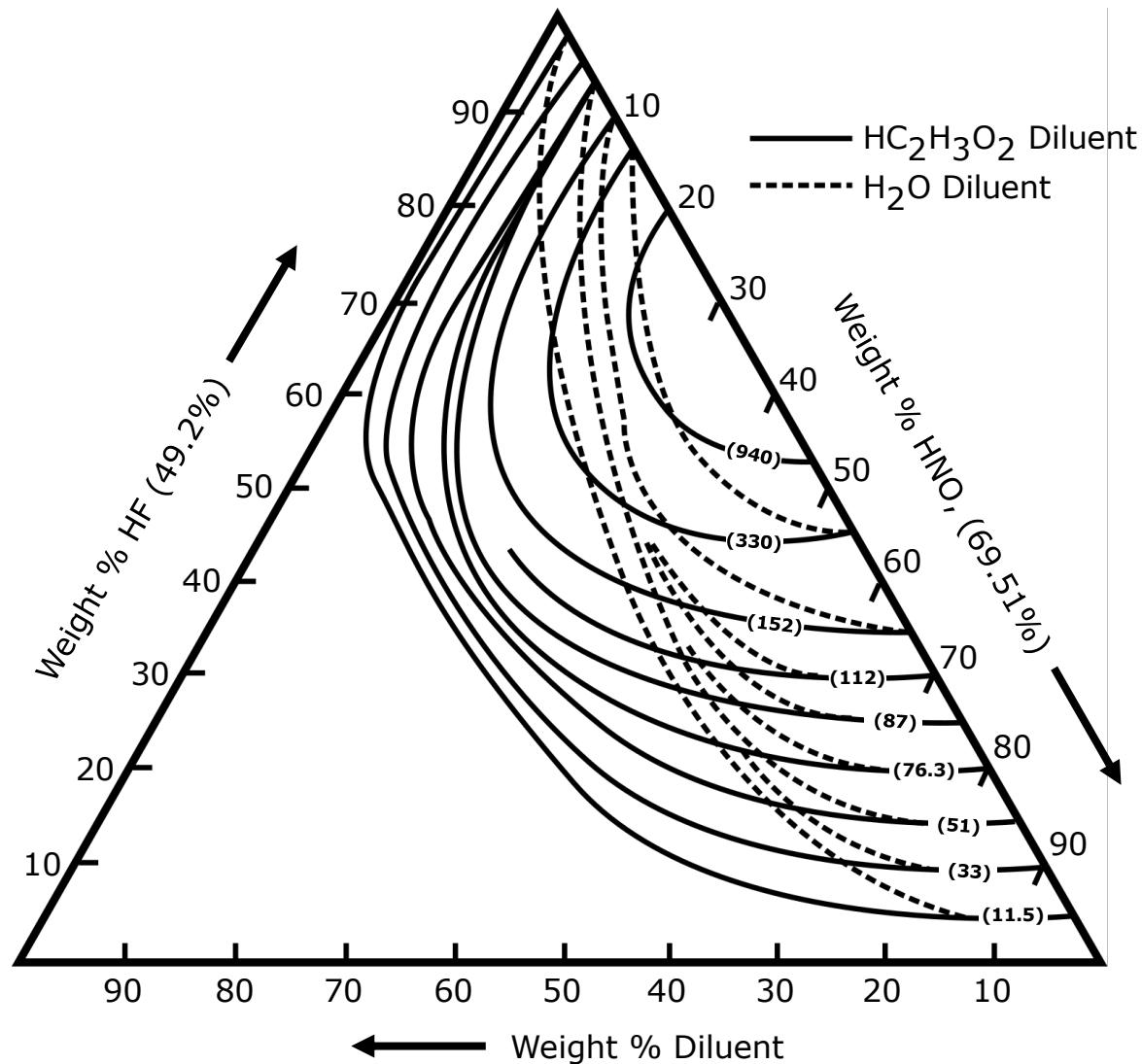
- Reaction limited by HNO_3
- The HNO_3 concentration controls the etch rate
- Etch rate is limited by oxidation, less oxide is formed on Si

Region 2:

**High HNO_3 concentrations, low HF concentration,
insufficient HF to etch away the silicon oxide
formed by HNO_3**

- Reaction limited by HF
- Ability of HF to remove the SiO_2 controls the etch rate
- Etch rate limited by reduction, more oxide is formed on Si

Practice Question 3



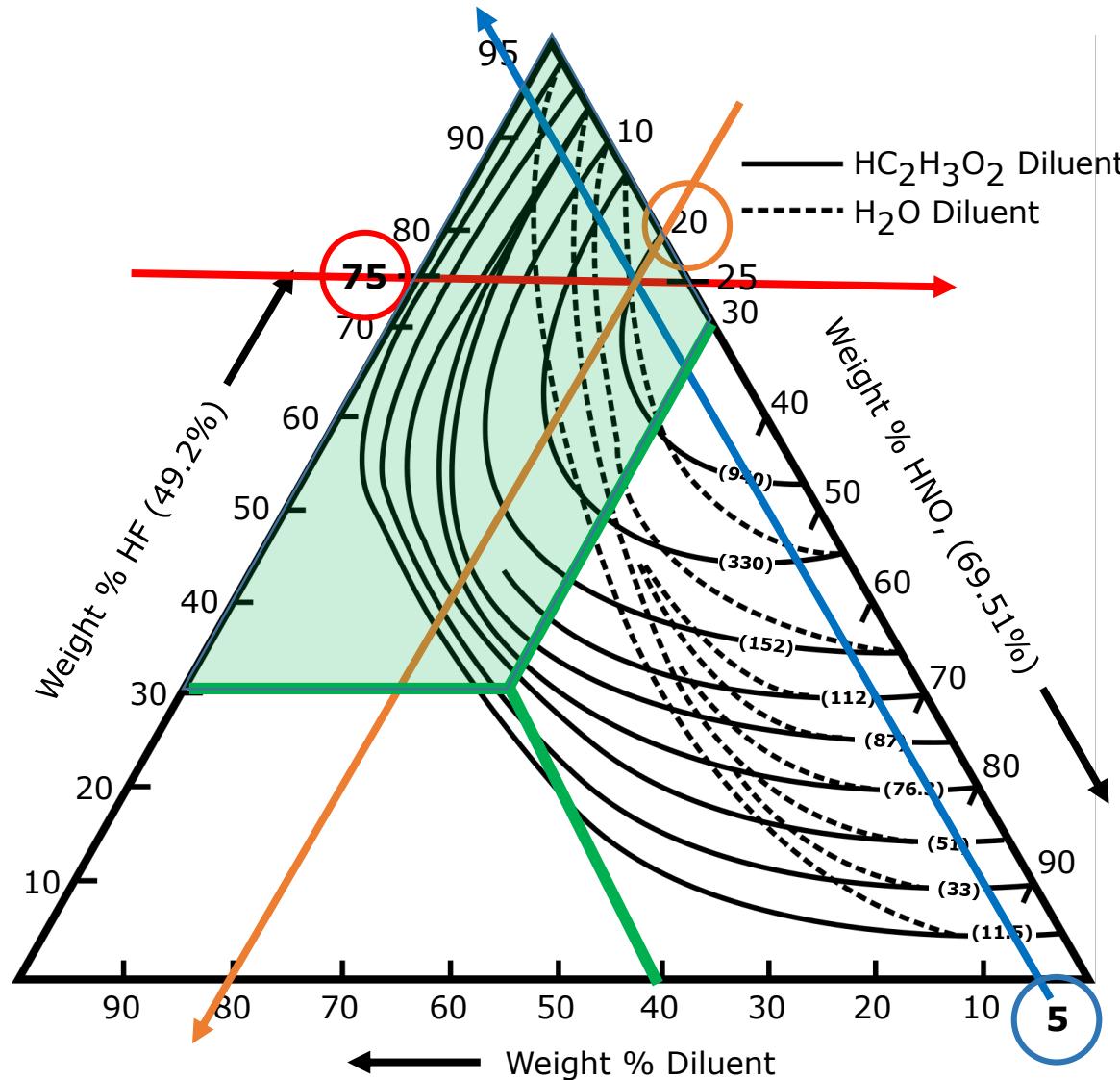
**A mixture of 75% HF,
20% HNO₃, and 5% H₂O
is used as an etchant for Si.**

- a) What is the etch rate?
- b) Which is the possible limiting factor for this etchant? (HF or HNO₃ concentration?)
- c) 5% water in the mixture is replaced with acetic acid as the diluent. What is the new etch rate?



Pause and
try out this
question

Practice Question 3



A mixture of 75% HF, 20% HNO₃, and 5% H₂O is used as an etchant for Si.

- a) What is the etch rate?

The etch rate is 330 μm/min.

- b) What is the possible limiting factor of this etchant? (HF or HNO₃ concentration?)

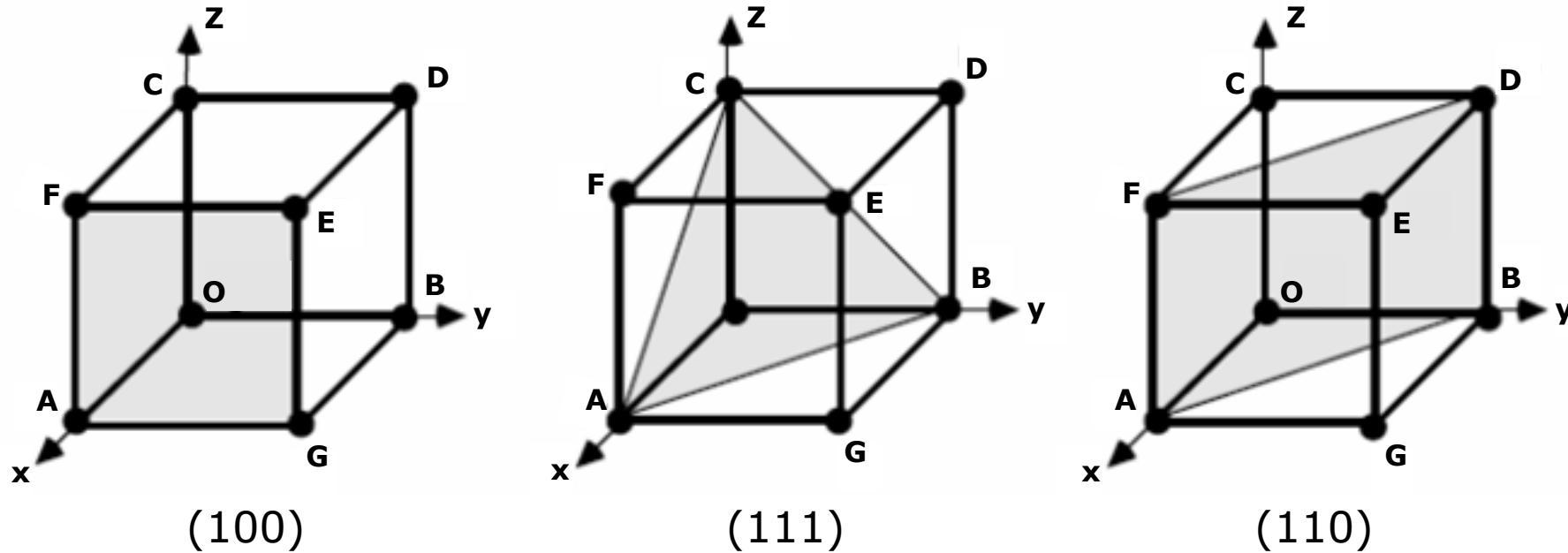
The reaction is limited by HNO₃ concentration, which corresponds to oxidation rate of the Si.

- c) 5% water in the mixture is replaced with acetic acid as the diluent. What is the new etch rate?

The new etch rate is 940 μm/min.

Orientation Dependent Etching

Silicon Wafer Crystal Orientation



Different Si atomic planes have different etch rates in KOH etchant.

Orientation Dependent Etching

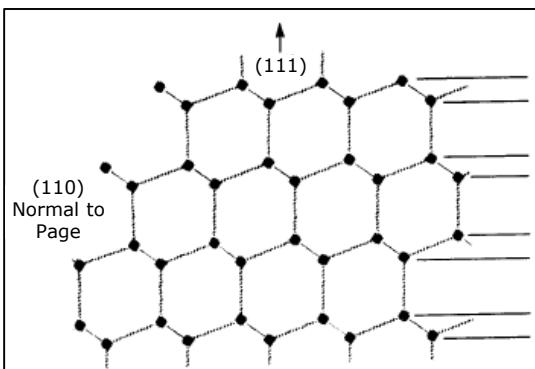
Some etchants dissolve a given crystal plane of a semiconductor faster than other planes.

Example: KOH in water and isopropyl alcohol.

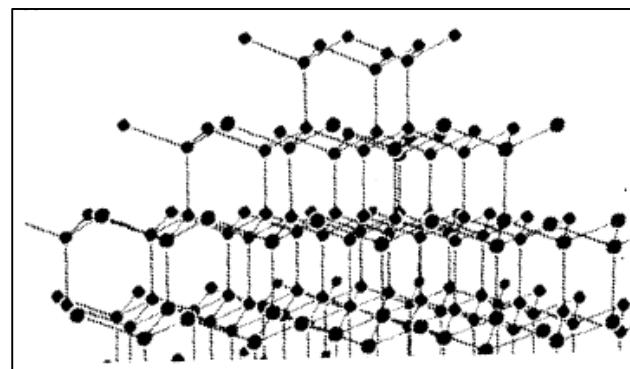
Etching rate for Si: 0.6 $\mu\text{m}/\text{min}$ for (100) plane

0.1 $\mu\text{m}/\text{min}$ for (110) plane

0.006 $\mu\text{m}/\text{min}$ for (111) plane



(110)



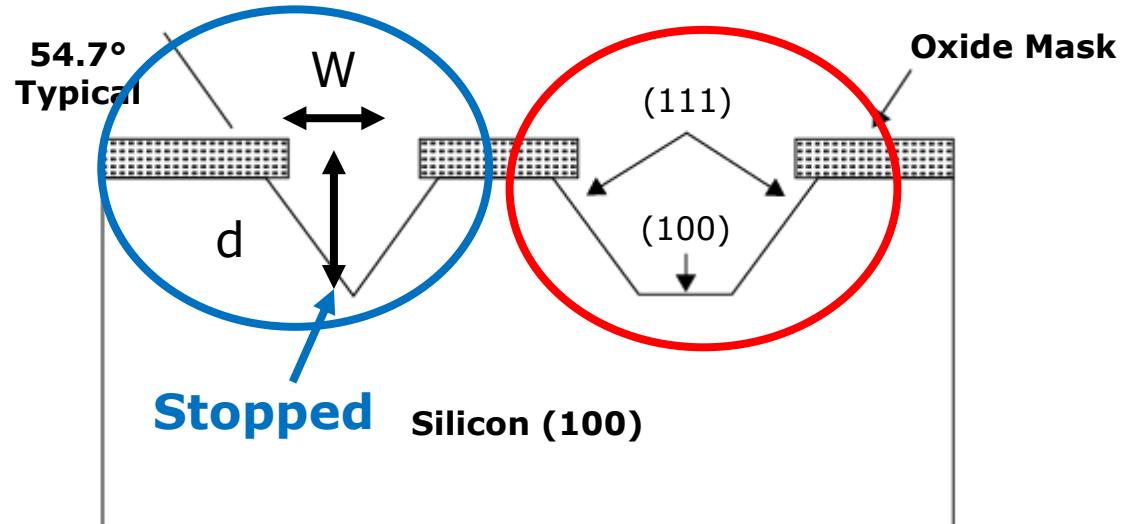
(111)

- Si (111) plane is closely packed \rightarrow Slowest etching
- (111) plane of Si oxidises faster than other planes, thus the surface is covered faster with oxide, which blocks further dissolution

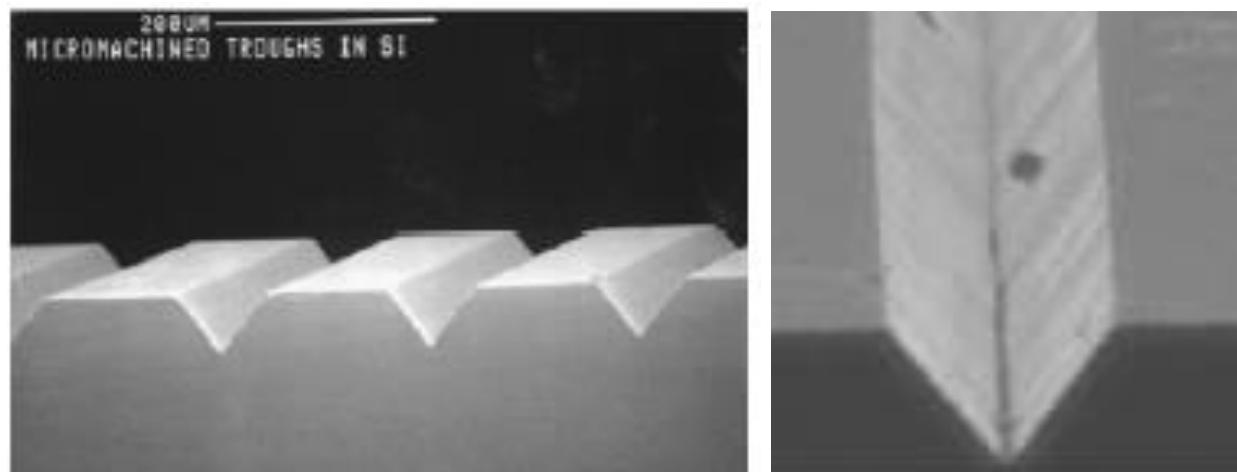
Orientation Dependent Etching (Cont'd.)

- Through an oxide mask, KOH etching of Si forms (111) planes at the side walls
- Since (111) has a slow etch rate, it forms a self-stopping V-groove. (111) plane makes an angle of 54.7° with (100) naturally, the width (W) of the defined image approximately determines the depth (d) following the relation:

$$d \approx \frac{W}{2} \tan 54.7 \approx 0.7 W$$



V-Shaped Groove Formation in the (100) Silicon with Anisotropic Etching



Practice Question 4

Compare the etching characteristics of (100) and (111)-oriented silicon wafers. Give at least two applications of orientation dependent etching.

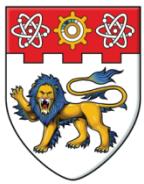


Pause and
try out this
question

Some etchants dissolve a given crystal plane of a semiconductor faster than other planes. Etching speed changes from one crystal plane to another crystal plane when they are in a different orientation group. Especially (111) phase of Si has more atoms per unit area compared to (100) plane, thus making more difficult to etch (111) plane than the (100) plane, therefore slower etching rate on the (111) plane.

Applications of orientation dependent etching:

- Chemical machining of semiconductor materials
- V shaped and vertical groove cutting
- Wafer defect investigation (crystal defects)



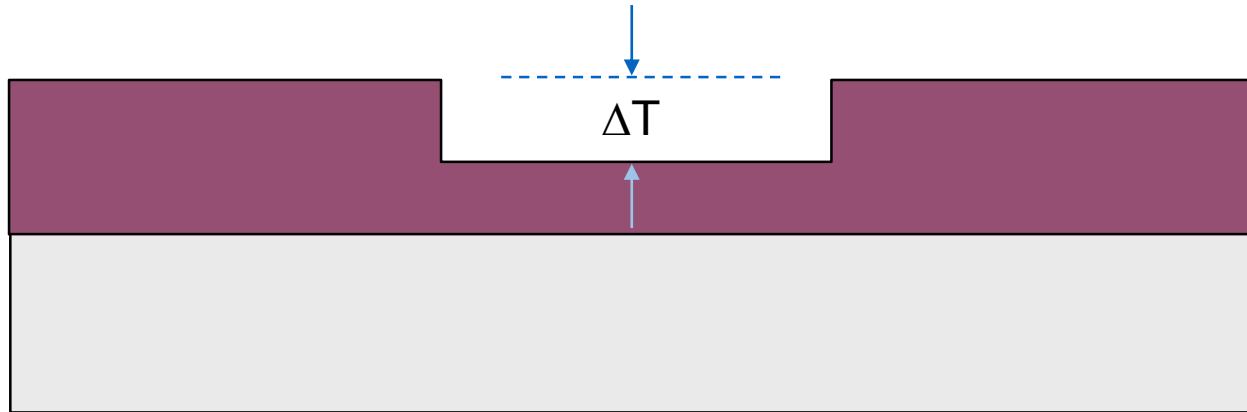
Etch Parameters

Some Etch Parameters

- Etch rate
- Undercut and over-etch
- Selectivity

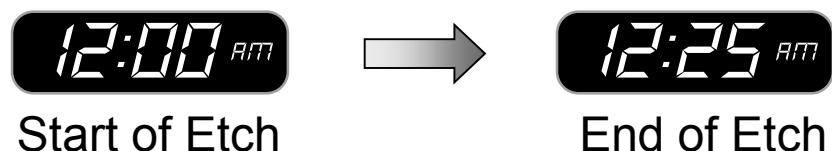
Etch Rate

ΔT = Change in Thickness

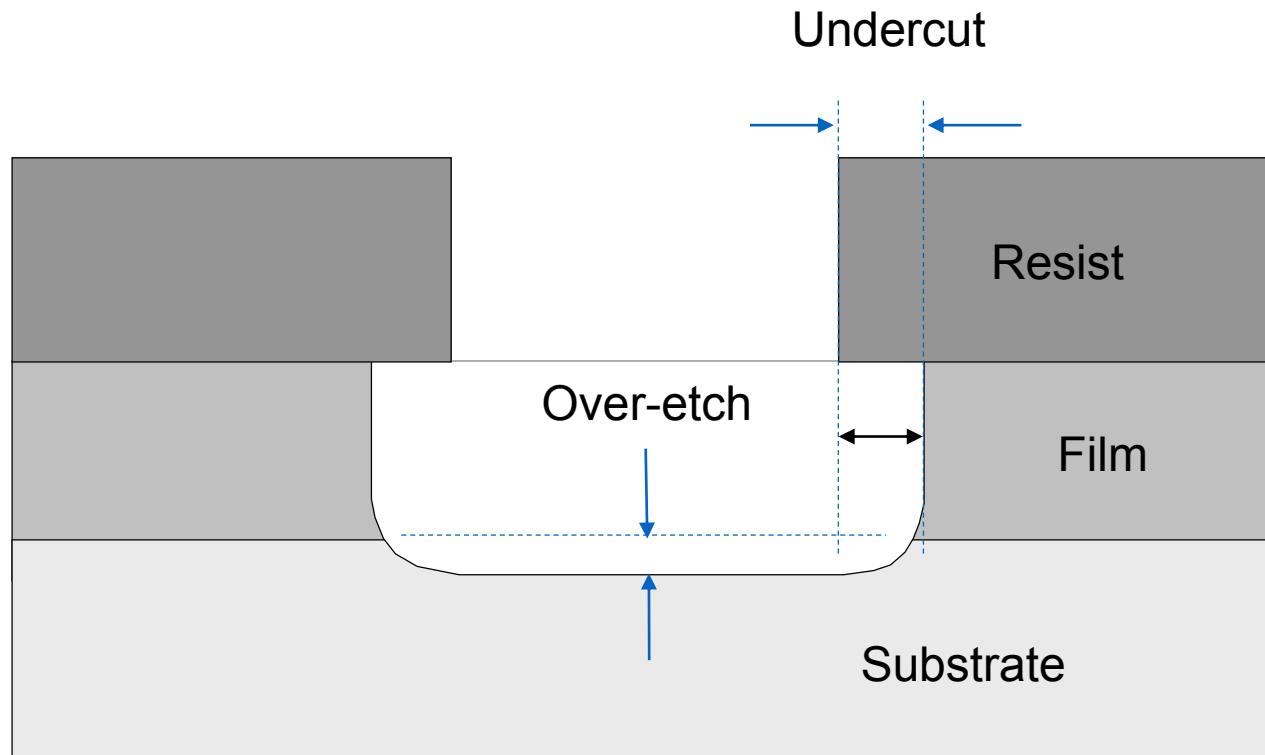


$$\text{Etch Rate} = \frac{\Delta T}{t}$$

t = Elapsed Time during Etch



Etching Undercut and Overetch

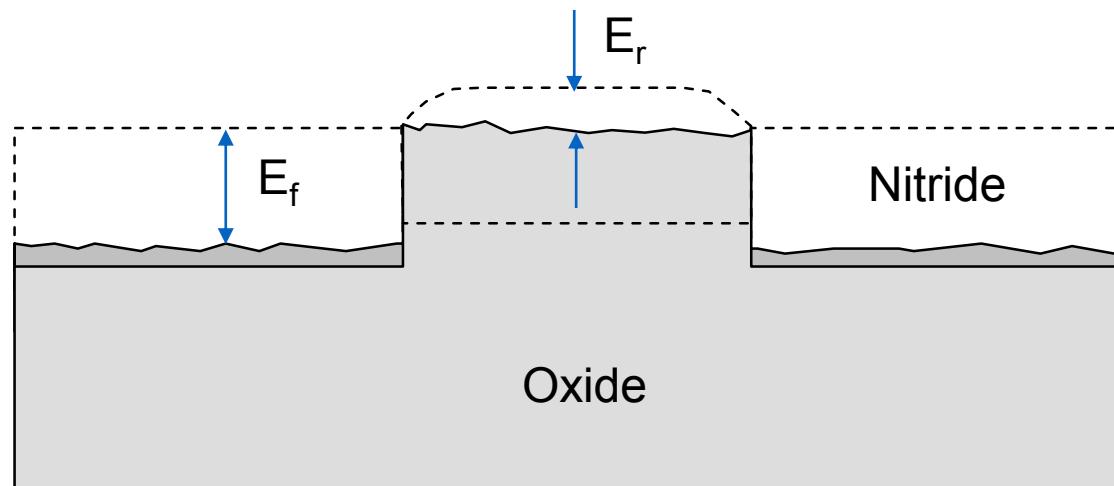


Etch Selectivity

Selectivity is the ratio of the etch rates between the different materials, especially the material that needs to be etched as compared to the material that we do not want to remove.
 $(E_f$: high etch rate; E_r : low etch rate)

$$S = \frac{E_f}{E_r}$$

HIGH SELECTIVITY MEANS THAT ETCHING ONLY OCCURS ON THE DESIRED LAYER!



Etch Selectivity (Cont'd.)

What affects selectivity?

- **Impurity type and/ or concentration**
- **Material composition**

Examples:

Impurity concentration:

Etchant:

KOH:water:isopropyl alcohol of 7:19:4

Etch Rates:

- **0.94 $\mu\text{m}/\text{cm}^{-3}$** n/p-doped Si of **10¹⁴ to 10¹⁸ cm^{-3}**
- **0.02 $\mu\text{m}/\text{cm}^{-3}$** n/p-doped Si of **10¹⁸ to 10²⁰ cm^{-3}**

Application:

Highly doped n/p layer inserted intentionally as etch stop.

Material composition:

Etchant:

Nitric Acid:H₂O₂ of 10:1

Selectivity:

In GaAs/ AlGaAs compound, the etch selectivity in removing GaAs is 95.

Application:

Often used in GaAs technology.

Practice Question 1

$0.6\mu\text{m}$ of SiO_2 is to be etched; the rate is $0.2 \mu\text{m}/\text{min}$.

If etch selectivity of the oxide relative to **mask** is 24:1, the SiO_2 is slightly over-etched for 3.6 minutes. **What is the minimum thickness of the mask?**



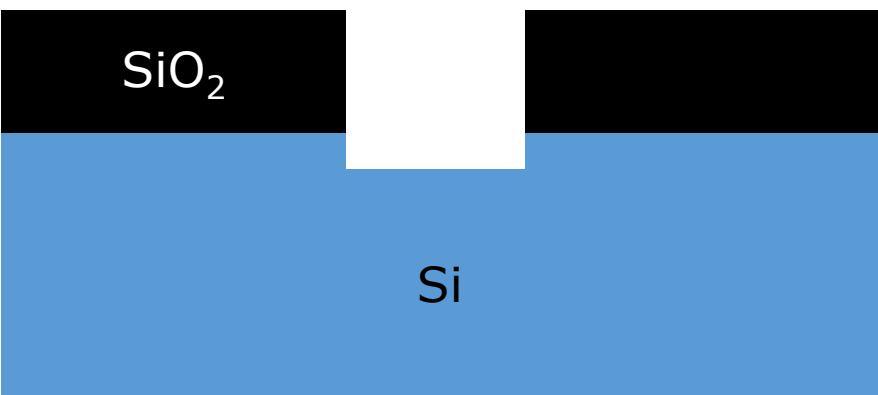
Pause and
try out this
question

Solution:

$$S = \frac{r_{oxide}}{r_{mask}} = \frac{24}{1} = \frac{0.2\mu\text{m}/\text{min}}{\text{Thickness}/3.6\text{min}}$$

$$\text{Mask thickness} = \frac{0.2 \times 3.6}{24} = 0.03$$

Mask should be at least $0.03\mu\text{m}$ thick.



How thick is a $0.035\mu\text{m}$ mask after 3.6 minutes of etching?

$$t_{mask}(3.6) = 0.035 \mu\text{m} - \frac{0.2}{24} \times 3.6 = 5 \text{ nm}$$

Etch Rate of Mask Etch Time

Lesson Summary - Etching

Comparison:

- Wet etching usually yields isotropic etching profile; whereas dry etching usually yields anisotropic etching profile.
- Wet etching uses wet chemical etchant; whereas dry etching uses ionic/ plasma etchant.

Wet Etching:

- Wet etching uses chemical etchants to etch away the target materials.
- In wet etching of Si, HNO_3 is used to oxidise Si into SiO_2 ; and HF is used to etch away the formed SiO_2 .
- The etching rate of Si depends on its crystal orientation for certain etchants.

Practice Question 2

Determine if the statements below are true or false.



- | | | |
|---|-------|--|
| a) Isotropic etches at the same rate in all directions (for $A = 0$) | True | Pause and try out this question |
| b) Anisotropic etch is more likely to cause underetching | False | |
| c) Wet chemical etching normally produces isotropic profiles | True | |
| d) Anisotropic etches in only one direction (for $A = 1$) | True | |
| e) Anisotropic etches perpendicular to the wafer surface | True | |
| f) Low lateral etching is a characteristic of isotropic etch | False | |
| g) Vertical sidewalls are a characteristic of isotropic etch | False | |
| h) Higher packing density in ULSI chips is achievable due to anisotropic etch characteristics | True | |

Practice Question 3

Define etch selectivity. Does wet etching have good or poor selectivity? What does high selectivity mean? State and explain the selectivity formula.



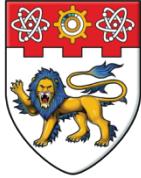
Pause and
try out this
question

Selectivity represents how much faster one film etches than another film under the same etch conditions. It is the ratio of the etch rates between the different materials, especially the material that needs to be etched compared with the material that we do not want to remove.

Wet etching has good selectivity. High selectivity means that etching only occurs on the desired layer.

$$S = \frac{E_f}{E_r}$$

(E_f : High etch rate; E_r : Low etch rate)



Course: EE3013 Semiconductor Devices and Processing
School: School of Electrical and Electronic Engineering
Etching – Dry Etching

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Etching can be done either in “**wet**” or “**dry**” method:

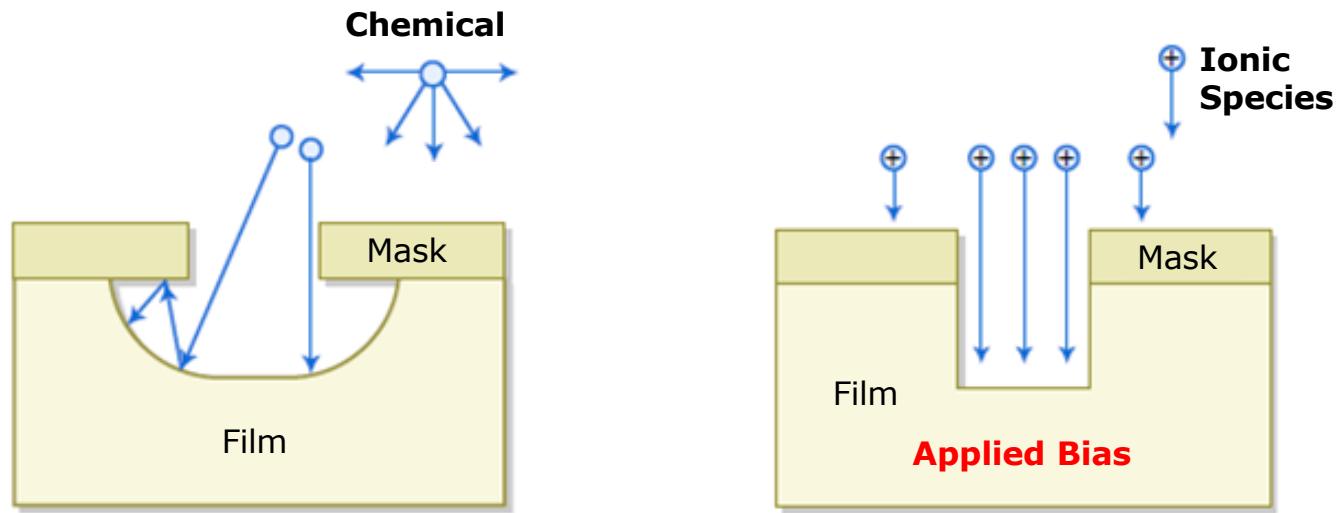
Wet etching

- Wet etching is a process whereby materials are removed by liquid etchants.
- Wet etching is fast, cheap and simple, but harder to control. Hence, it is not popular in nanofabrication.

Dry etching

- Dry etch uses gas phase etchants in plasma.
- In comparison, dry etching is slower, requires sophisticated equipment, but easier to control.
- It works for many dielectric materials and some metals (Al, Ti, Cr, Ta, W, etc.).
- Since the gas phase etchants in plasma are used in dry etching, dry etching is sometimes called plasma etching.

Anisotropy in Dry Etching



- Since ionic species are present in the plasma driven by an applied bias, it can result in directional etching.
- Therefore, anisotropic profile can be achieved by dry etching technique.

Why Dry Etching?

General Etch Requirement:

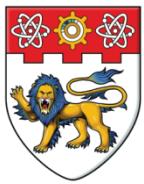
- Achieve desirable profile (slope or vertical)
- Minimal undercut
- Uniformity and reproducibility

Can be achieved by dry etching.

Dry Etching – Lesson Overview

Dry etching:

- Plasma generation and processes
- Plasma interaction with the substrate
 1. Physical interaction (sputter etching)
 2. Physical + chemical interaction (reactive ion etching)
- Factors controlling the plasma etch rate
- Plasma damage and general issues in etching



Plasma Generation and Processes

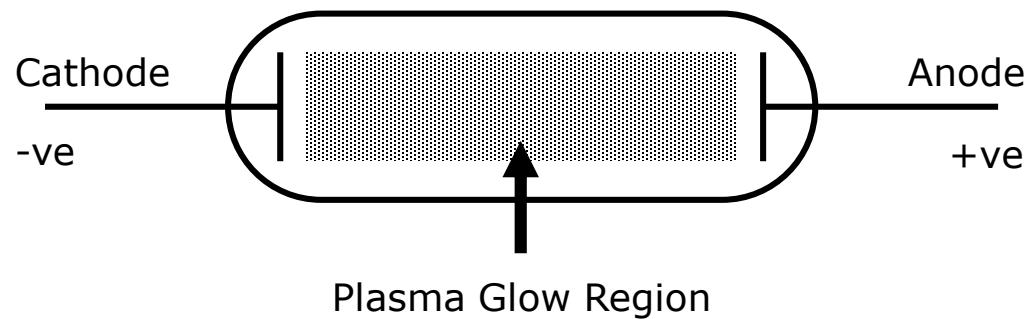
Dry Etching (Plasma)

What is a Plasma?

- An ionised gas with about equal amounts of positive ions and negatively charged particles
- Usually electrons, positive ions, and a small amount of negative ions
- It has a neutral charge in macroscopic sense

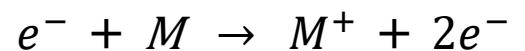
Plasma Generation

- A neutral gas is placed within a tube with a DC potential applied across two electrodes.
- The released electrons accelerate toward the positive electrode or anode, and along the way undergo a series of elastic and inelastic collisions, and the plasma is therefore formed.
- Kinetic energy is conserved in elastic collisions. An electron has a smaller mass than an atom, the energy transfer is negligible and the electron will simply change direction.
- All other types of electron collision are inelastic and will result in ionised species or excited neutral species in the plasma.



Ionisation

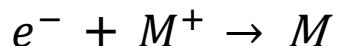
- Electron impact ionisation (**inelastic collisions**)
- The primary electron **removes an electron** from the atom, **producing** a positive **ion** and two electrons
- Example:



Where *M* is the gas molecule

Recombination

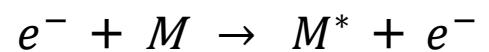
- Inverse process of ionisation
- An **electron coalesces with a positive ion** to form a neutral atom
- Example:



Where *M* is the gas molecule

Excitation

- **Energy provided** to atoms **enables the electron to jump** to a **higher energy level** within the atom with a corresponding quantum absorption of energy, but insufficient to ionise the atom
- It can result from both electron impact excitation or photo excitation
- Example:

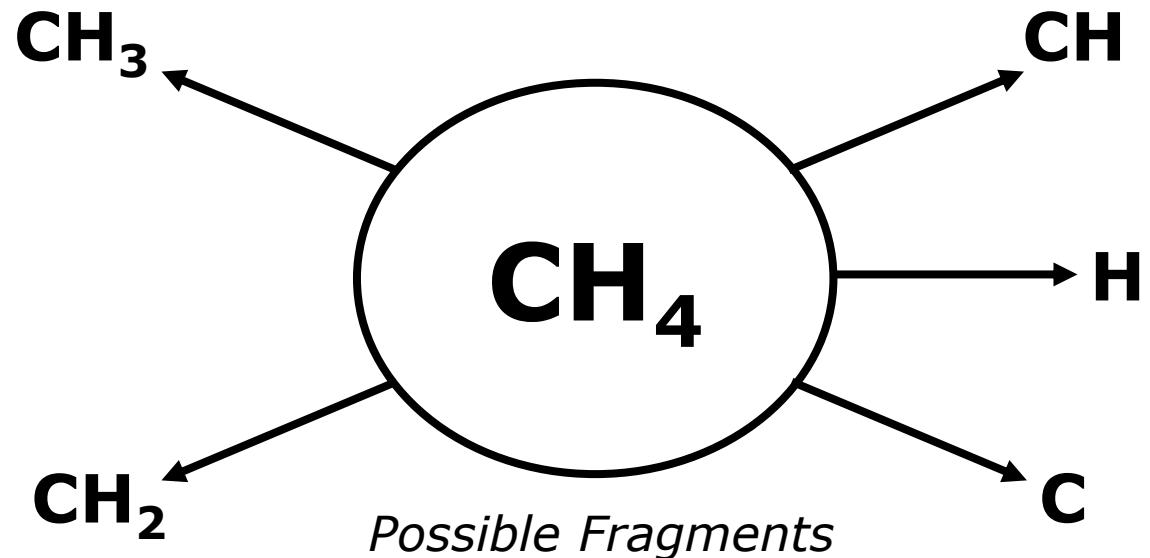


Relaxation

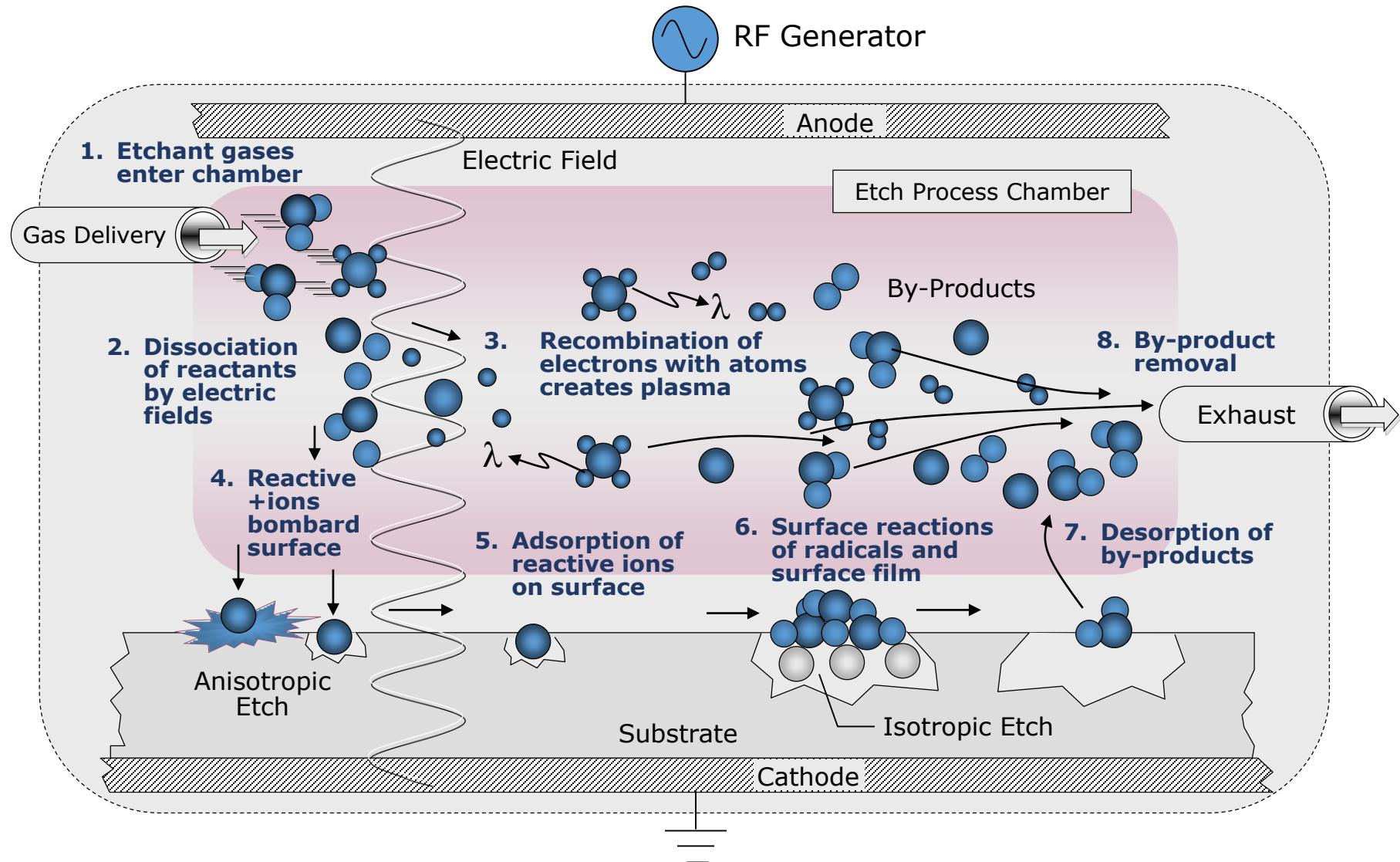
- Inverse process of excitation
- The **excited states are rather unstable** and the electron configuration soon **returns to the ground state** in one or several transitions, with lifetimes varying from nanoseconds to seconds
- Each transition is accompanied by the **emission of a photon** of various specific energy $h\nu$

Plasma Processes: Dissociation of Gas Molecules

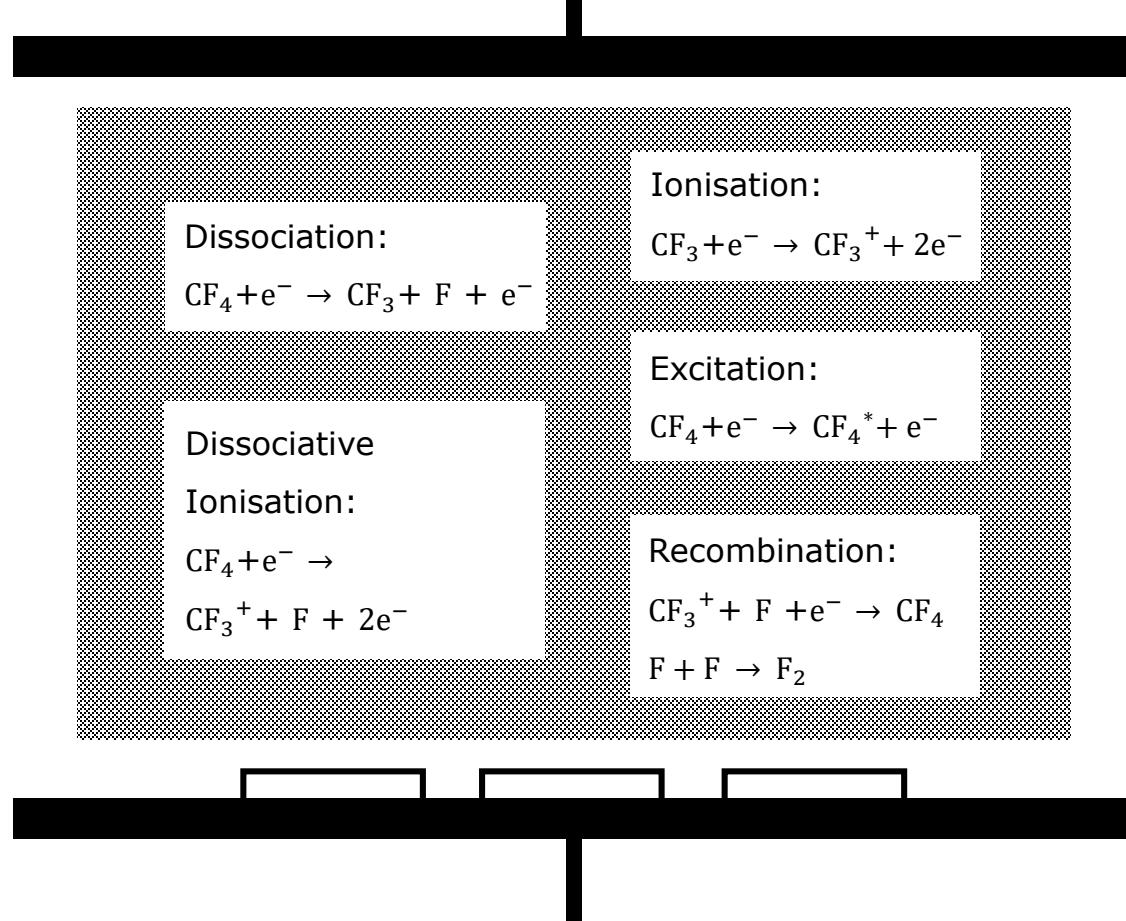
- As the energy of plasma electrons is much higher than the chemical bond energy, molecules in a plasma are essentially randomised, breaking down into all conceivable fragments.
- For example, a plasma of methane (CH_4) can be expected to include the fragments of CH_3 , CH_2 , CH , H , and C .

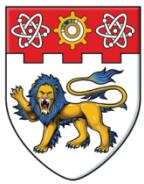


Plasma Processes



Etching Gas: CF_4





Plasma Interaction with the Substrate

Plasma Interaction with the Substrate (Outline)

Plasma interaction with the substrate:

- **Physical interaction (sputter etching)**
- Physical + chemical interaction (reactive ion etching)

Interaction of Plasma with the Surface

Types of plasma interactions:

- **Physical** — Surface bombarded with energetic ions. The ions' loss of kinetic energy on the surface dominates the interaction. E.g.: Argon (inert gas) plasma etching
- **Physical & Chemical** — In addition to physical etching, chemical erosion by the bombarding ions contribute to etching process. E.g.: CF_4 (reactive gas) plasma etching

Physical Interaction with the Surface – Argon Plasma

Argon gas is usually used for physical plasma etching:

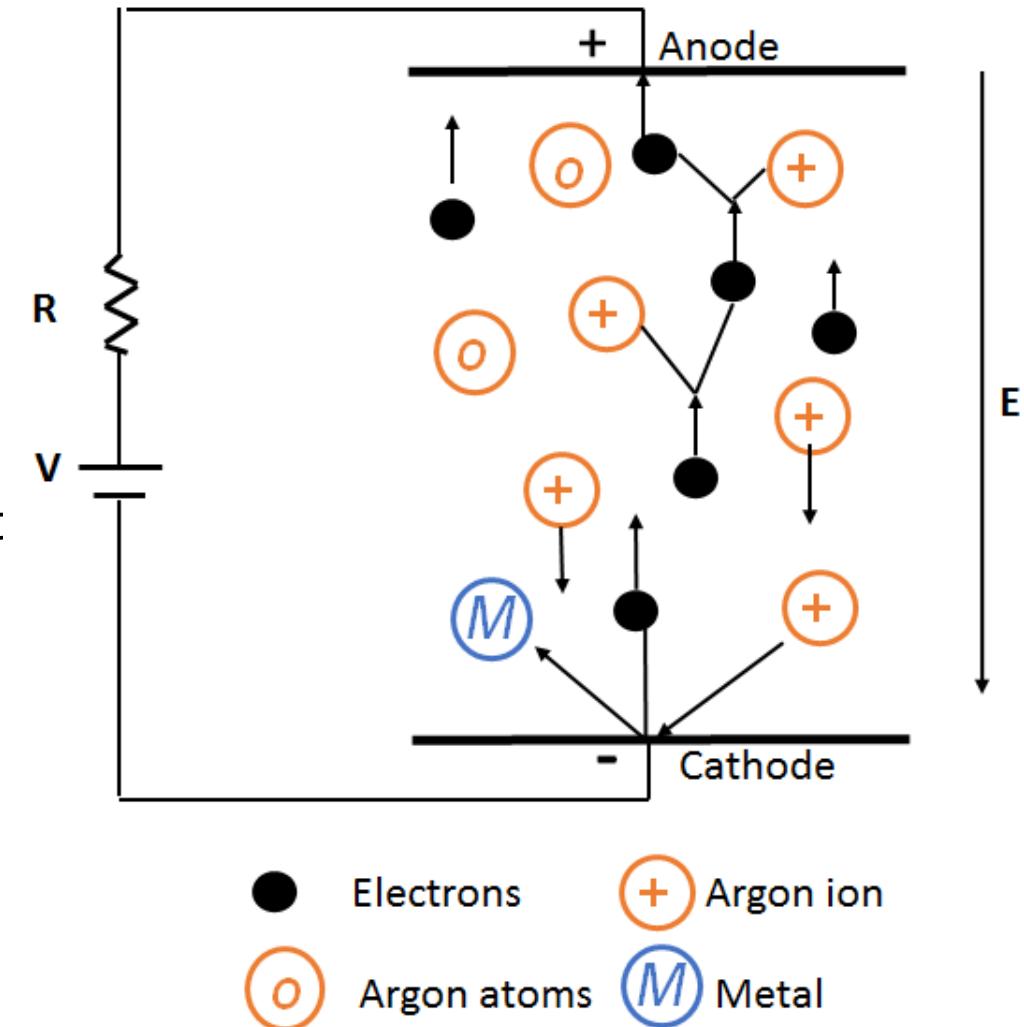
- Argon is an inert gas
- Relatively heavy gas for momentum transfer
- High energy bombardment to sputter away the surface

Such physical plasma etching can also be called sputter etching.

Sputtering Etching (Physical)

Sputter etching:

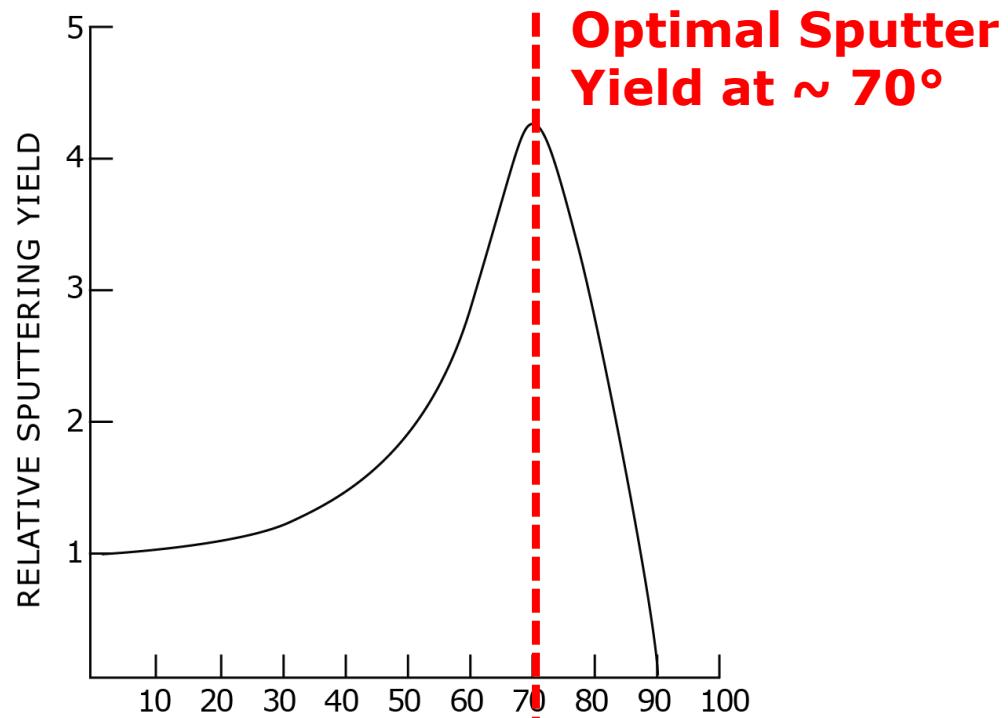
- **High particle energy** ($>500\text{eV}$) **noble gas ions** (Ar^+) created by DC/RF power to remove the target surface
- Operating pressure: 0.01 to 0.1 torr
- Interaction is **purely physical**, with **no chemical reaction** between the gas ion and the target
- Due to the vertical bombardment of ions onto the target surface, **good anisotropy** can be achieved
- **Poor selectivity** (no differentiation between different target elements)



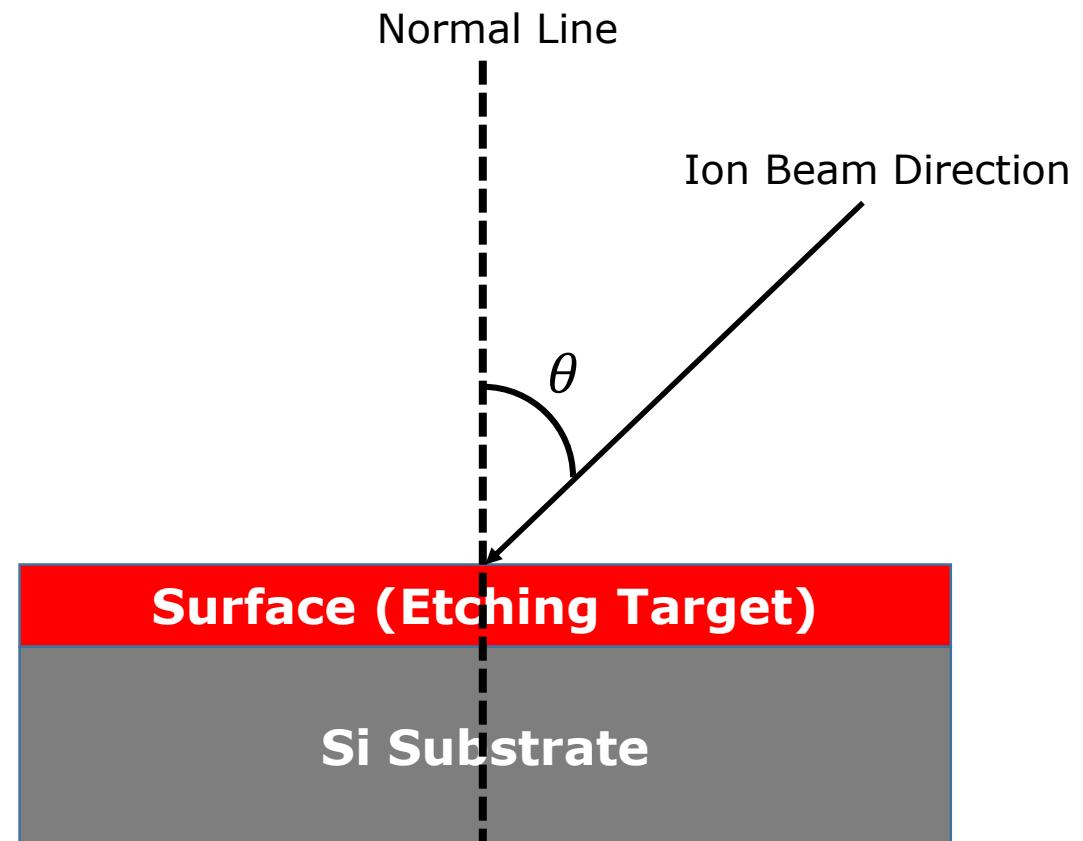
Sputtering Etching (Physical): Sputter Yield

Sputter yield:

- Ratio of the **number of ejected target atoms per bombarding ion** at a given energy
- Yield depends on the angle of ion flux



A typical curve of relative sputtering yield versus incident angle, θ , of the ion flux.



Plasma Interaction with the Substrate (Outline)

Plasma interaction with the substrate:

- Physical interaction (sputter etching)
- **Physical + chemical interaction (reactive ion etching)**

Interaction of Plasma with the Surface

Types of plasma interactions:

- **Physical** — Surface bombarded with energetic ions. The ions' loss of kinetic energy on the surface dominates the interaction. E.g.: Argon (inert gas) plasma etching
- **Physical & Chemical** — In addition to physical etching, chemical erosion by the bombarding ions contribute to etching process. E.g.: CF_4 (reactive gas) plasma etching

How do we achieve a combination of physical and chemical interaction between the surface and ions in a plasma etching system?

- Reactive ions (CF_4) is used to replace argon ions as the etchant
- Two etching mechanisms involved: physical and chemical mechanisms

Physical etching mechanism: Ion bombardment induced momentum transfer.

Chemical etching mechanism: Formation of volatile etch products between reactive etchants and target surface.

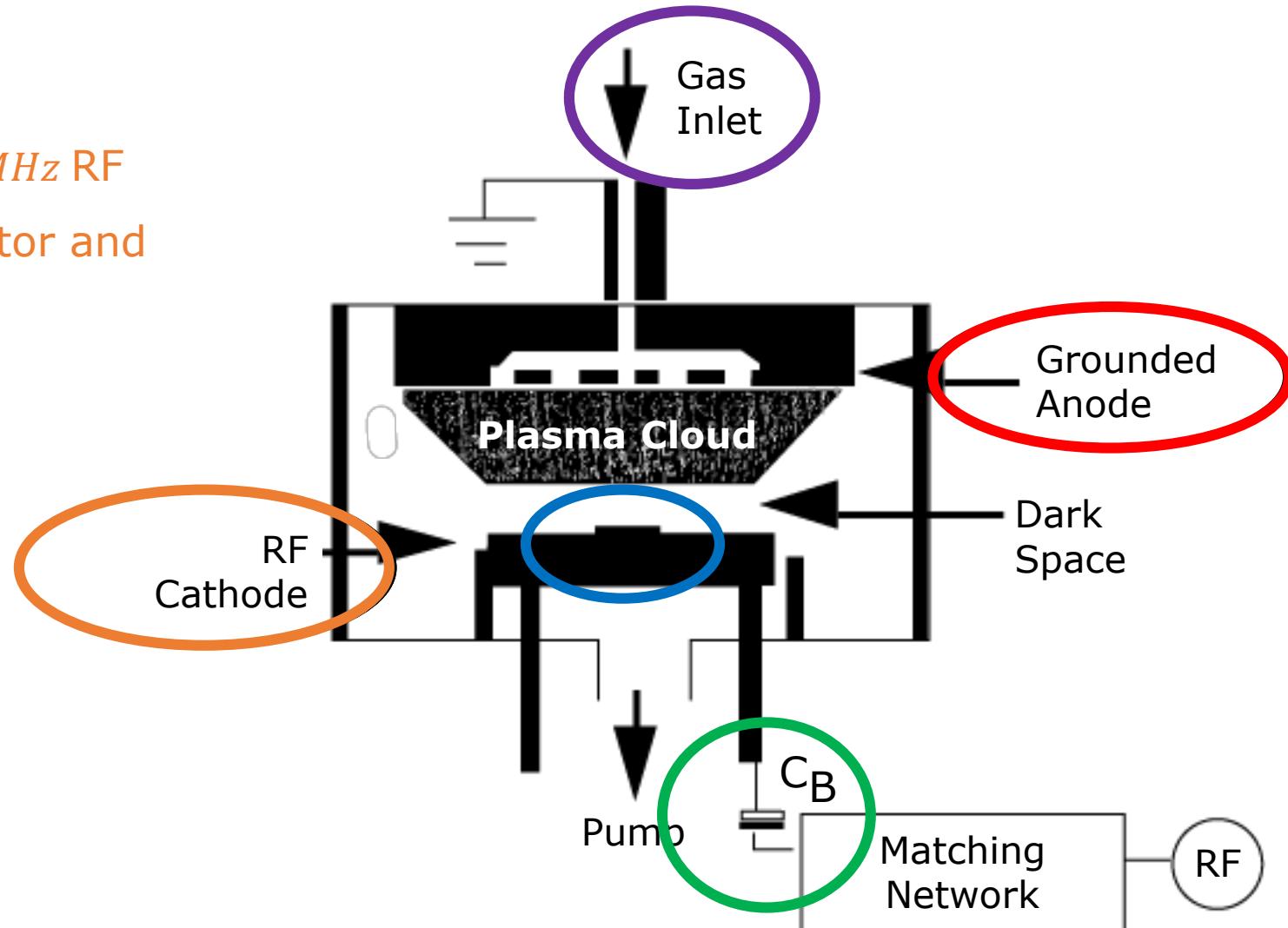
Since reactive ions are used as the etchant, such technique is usually called **Reactive Ion Etching (RIE)**.

Reactive Ion Etching: Parallel Plate RIE Reactor

- RIE uses one or more reactive gases as the etchants.
- Operating pressure: 10 mtorr – 100 mtorr to confine the plasma between two parallel plates.
- Substrates are normal to the gas flow and the RF field, resulting in a high degree of anisotropy because ions strike perpendicularly onto the surface.

Basic Theory of A Parallel Plate RIE System: Basic Components

- Two parallel electrode plates
- Top electrode plate is grounded
- Bottom electrode is driven by a 13.56 MHz RF generator, connected through a capacitor and an impedance matching circuit
- The function of the capacitor is to block the electrode from discharging through the power supply
- The sample (substrate) is placed on the bottom electrode
- Etch gas is fed into the etch chamber which is kept under a vacuum evacuated environment

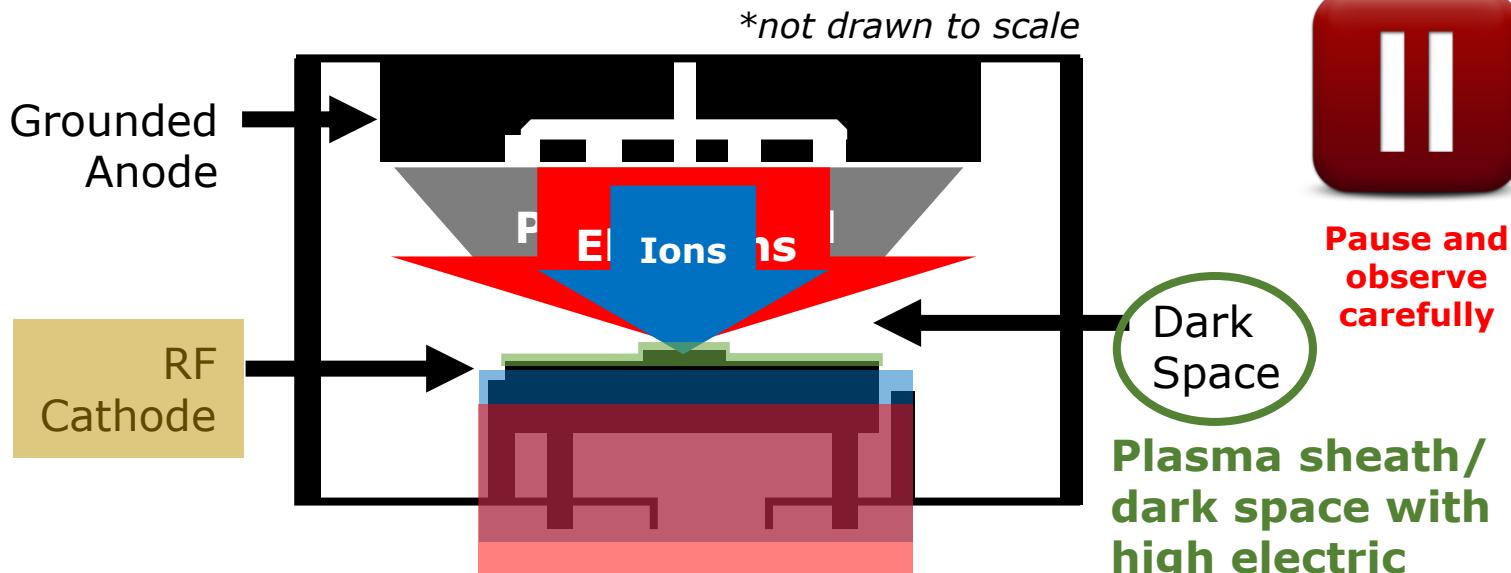


Basic Theory of A Parallel Plate RIE System: Operating Principles

1. Electrons in chamber gained energy by applied RF power.

2. When the bottom electrode is positive, many highly mobile electrons are accelerated towards the electrode, causing a significant accumulation of negative charge.

3. When the bottom electrode is negative and heavy, immobile ions accelerate towards it. However, only relatively few of these ions strike the electrode as compared to the number of electrons in the previous cycle. Hence, in a steady state, this electrode is negative biased, and therefore is called a cathode.



4. A high electric field region is then formed around the cathode. This region is known as the plasma sheath, or the dark space, where ion acceleration takes place before bombarding the electrode.

5. **Ions are accelerated** in dark space before bombarding the substrate.

Basic Theory of A Parallel Plate RIE System: Plasma Potential

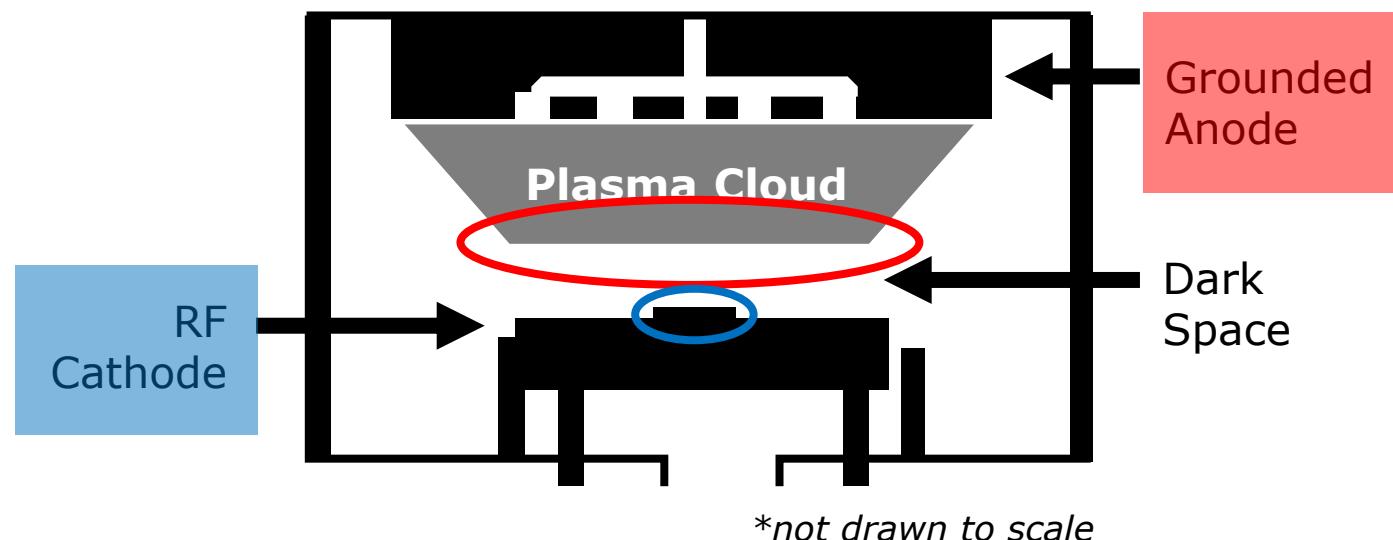
- The plasma potential is determined by the expression: $|V_c| = V_a \left(\frac{A_a}{A_c} \right)^4$
- V_c = potential difference between the powered electrode (cathode) and the plasma
- V_a = potential difference between the ground electrode (anode) and the plasma

$$\frac{A_a}{A_c} = \text{ratio of the respective electrode areas}$$

Why must the anode area be bigger than the cathode area?

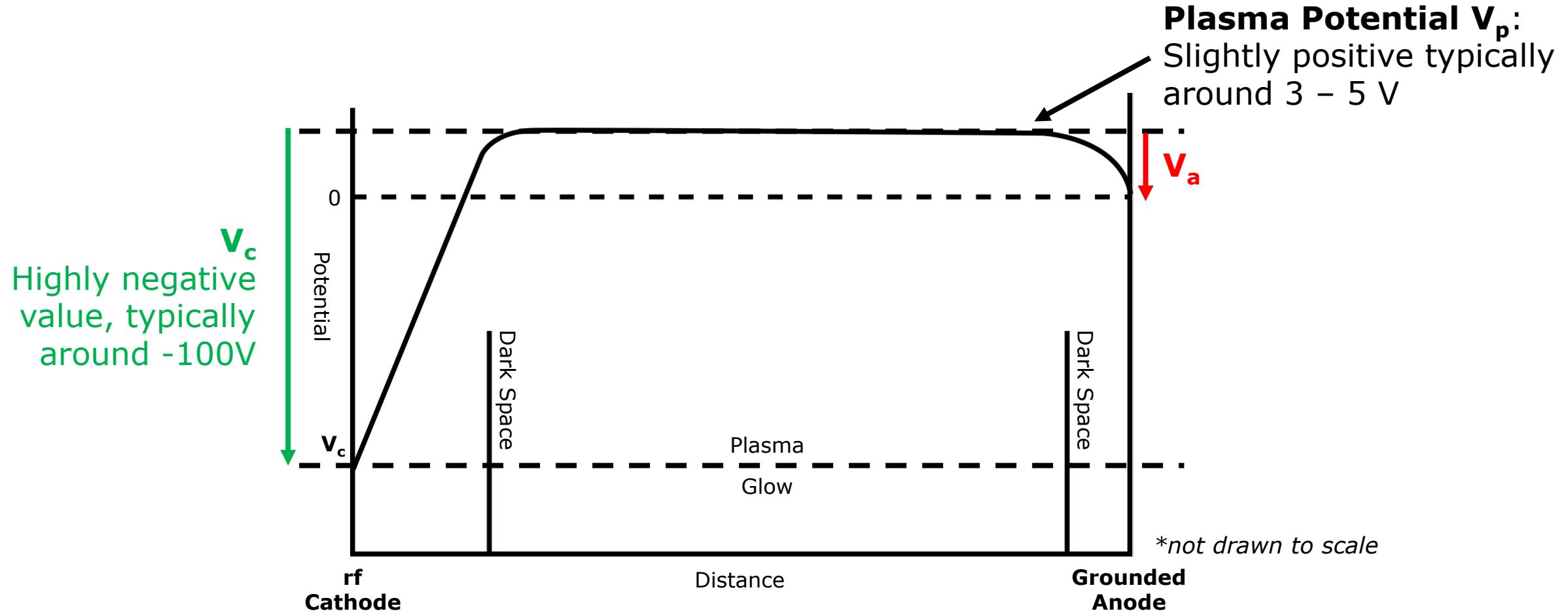
$$\uparrow |V_c| = V_a \left(\frac{A_a}{A_c} \right)^4 \uparrow$$

This will increase the energy of the bombarding ions, hence increasing the etch rate.



Basic Theory of A Parallel Plate RIE System: Plasma Potential

- The potential distribution between the electrodes is shown in the following graph:



- The acceleration of ions by the high field region (dark space) in RIE system yields high energy ion bombardment on the substrate, resulting in the physical etching on the substrate.

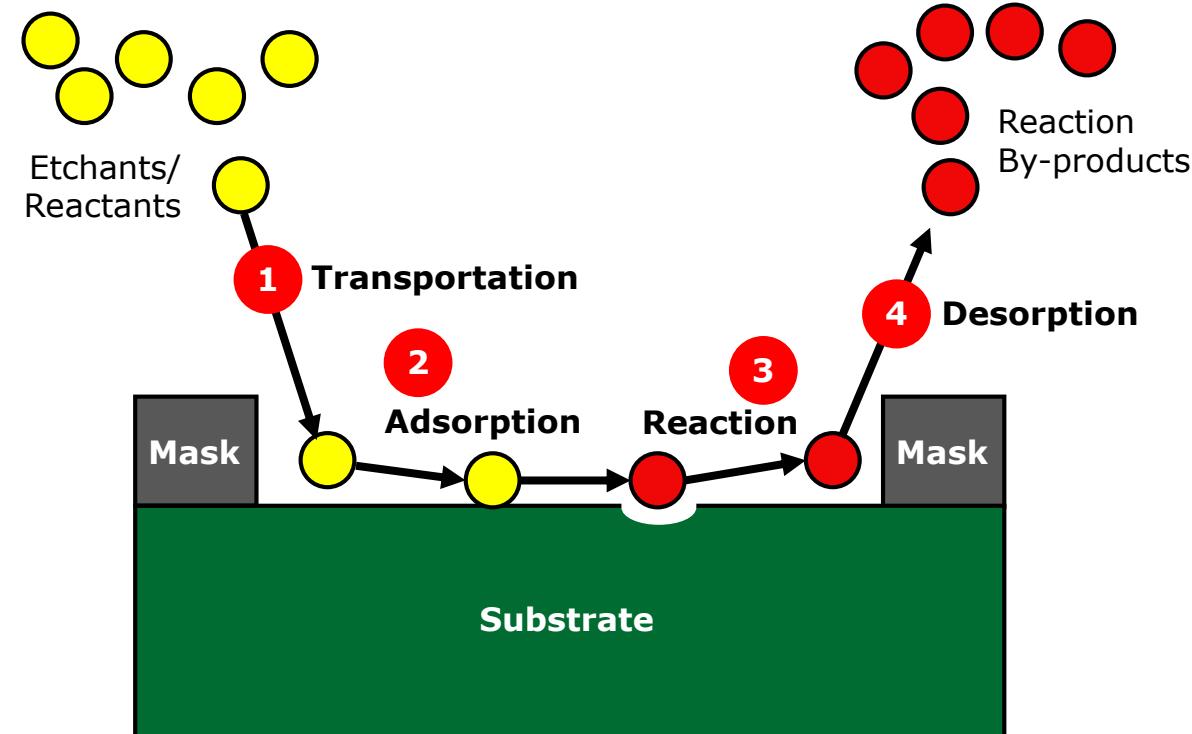
Next, let us look at the chemical interaction between reactive etchants and the substrate in RIE system.

RIE Mechanism

Four steps are involved in reactive ion etching mechanisms:

- 1. Transportation:** The etchant (positive ions) accelerates to the substrate surface.
- 2. Adsorption:** The etchant chemisorbs onto the surface of the substrate.
- 3. Reaction** with the substrate and the formation of the volatile by- product (gaseous form).
- 4. Desorption** of the volatile by-product away from the substrate.

The possible rate-limiting step in dry etching can either be step **(1), (2), (3), or (4)**.



Etch Rate-Limited Conditions

Transportation-limited condition: The rate of etchant transportation is significantly slower than the etchant-substrate reaction rate. The rate of step (1) and (4) determines the overall etch rate in dry etching.

Reaction-limited condition: The rate of etchant-substrate reaction rate is significantly slower than the rate of etchant transportation. The rate of step (2) and (3) determines the overall etch rate in dry etching.

Gases Used to Etch Films in Wafer Fabrication

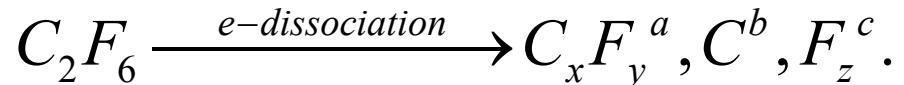
Film	Etch Gases
Si	CF ₄ , CF ₄ – O ₂ , CF ₃ Cl, CCl ₄ , SF ₆ – O ₂ , NF ₃ , ClF ₃
SiO ₂	C ₂ F ₆ , C ₃ F ₈ , CF ₄ – H ₂ , CHF ₃
Si ₃ N ₄	CF ₄ – O ₂ , C ₂ F ₆ , C ₃ F ₈ , CF ₄ – H ₂
Organics	O ₂ , O ₂ – CF ₄ , O ₂ – SF ₆
Al	CCl ₄ , CCl ₄ – Cl ₂ , BCl ₃ , BCl ₃ – Cl ₂ , SiCl ₄
W, WSi ₂	CF ₄ , C ₂ F ₆ , SF ₆

- For etching of Si-based films, fluorocarbon (C_XF_Y)-based chemistry is used
- For etching of organic films, oxygen-based chemistry is used.
- For etching of metal lines, chlorine-based or fluorine-based chemistry is used.

*For reference only

RIE Mechanism: Plasma Etching of Silicon/ Silicon Oxide

- In the case of RIE of SiO_2 in C_2F_6 plasma, the dissociation process may produce:



- Both carbon and fluorine can act as active etching species in this case, with carbon responsible for reaction with O_2 and fluorine with silicon.
- The following etching mechanisms are proposed ($ads = adsorption$):

Chemisorption: $\text{C}_x\text{F}_y^a, \text{C}^b, \text{F}_z^c \rightarrow (\text{C}_x\text{F}_y)_{ads}, (\text{C})_{ads}, (\text{F}_z)_{ads} [+electrons],$

Reaction: $(\text{C}_x\text{F}_y)_{ads}, (\text{C})_{ads}, (\text{F}_z)_{ads} + \text{SiO}_2 \rightarrow w(\text{SiF}_4)_{ads}, (\text{CO}_z)_{ads},$

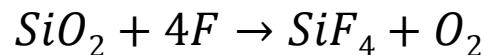
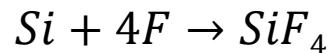
Desorption: $w(\text{SiF}_4)_{ads}, (\text{CO}_z)_{ads} \rightarrow w(\text{SiF}_4)_{gas}, (\text{CO}_z)_{gas}.$

Where w, x, y and z here is equal to 1 or 2;

a, b and c can be either positively or negatively charged.

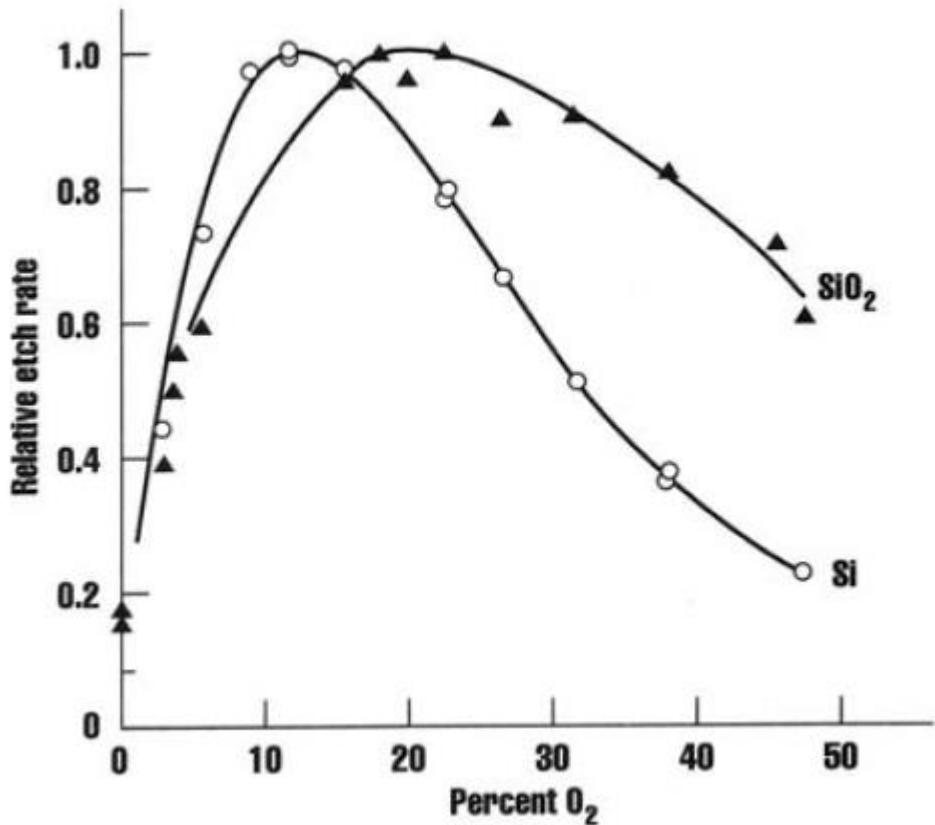
Plasma Etching of Silicon/ Silicon Oxide (Cont'd)

- When only CF_4 is used as the feed gas in RF plasma etch, no etching of Si or SiO_2 occurs.
- Etching starts after O_2 is added to the feed gas.
- Atomic F is the active etchant for Si and SiO_2 through the formation of the volatile SiF_4 and O_2 :



How does the O_2 content affect the etch rate?

Tailoring Gas Composition for RIE (Addition of O₂ Gas)



Etch Rate of Si and SiO₂ in CF₄ / O₂ Plasma

- Oxygen is added to CF_x plasma to increase the amount of reactive F species:
$$\text{CF}_2 + \text{O} \rightarrow \text{COF} + \text{F}$$
 (Highly probable due to the presence of O₂)
- Oxygen reacts with CF₃ and CF₂. Hence reducing the recombination rate of F and prevents the formation of the unreactive CF₄.
$$\text{CF}_2 + 2\text{F} \rightarrow \text{CF}_4$$
 (Less probable due to the above formation of **COF**)
- However, the etch rate will decrease if more O₂ is introduced, due to the dilution of CF₄ concentration.

Practice Question 1

Decide the appropriate effect in terms of increase (\uparrow), or decrease (\downarrow), if the electrode size of the RF generator in a plasma etch system is decreased.



Pause and
try out this
question

- a)   Ion energy
- b)   DC bias
- c)   Etch rate
- d)   Selectivity

Practice Question 2

What type of gas chemistry is generally chose for silicon plasma etching?



Pause and
try out this
question

- a) Fluorocarbon
- b) Hydrocarbon
- c) Silicon/carbon-based gases
- d) Noble gases

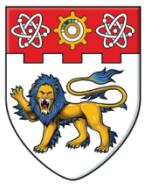
Practice Question 3

Why does the addition of O_2 change the etch rate in a CF_4 -based plasma etch.



Pause and
try out this
question

Oxygen is added to CF_4 plasma to increase the amount of reactive F species.
(O reacts with CF_3 and CF_2 and hence reduces the recombination of F)



Factors Controlling Plasma Etch Rate

Factors Controlling Plasma Etch Rate

- Steady state pressure
- Average residence time
- Throughput/ gas load

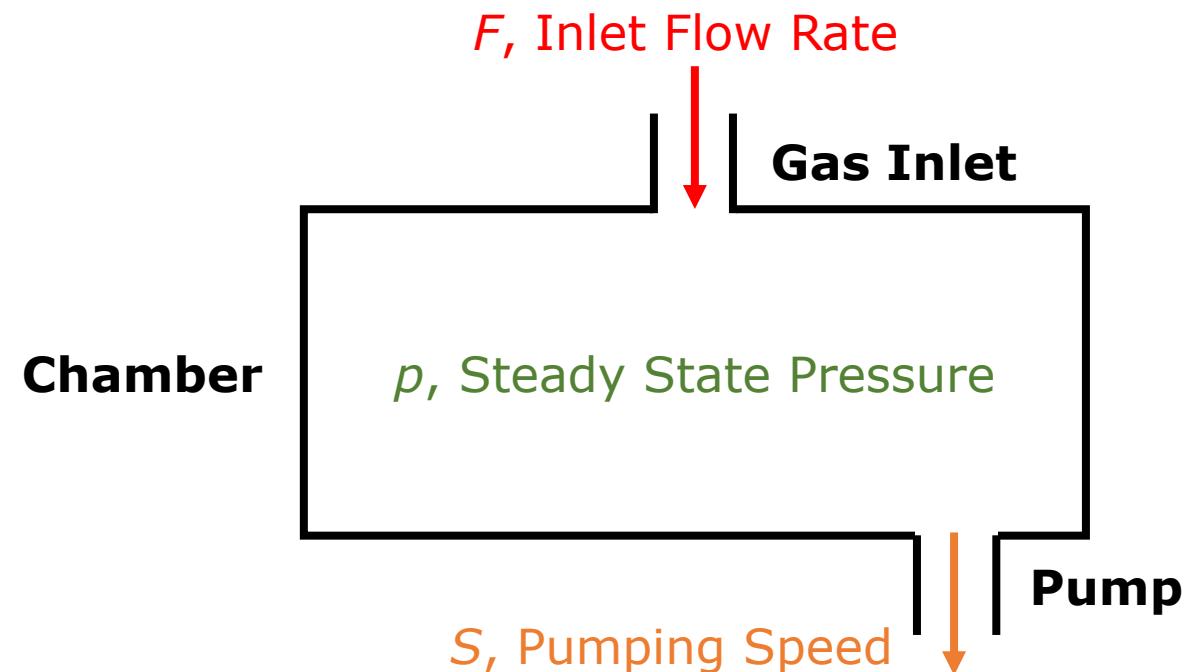
Factors Controlling Plasma Etch Rate: Steady State Pressure

The **steady state pressure (p)** in the system can be expressed as:

$$p = \frac{F \cdot 760}{S} \text{ Torr}$$

Where F and S are the **inlet flow rate** and **pumping speed** in the same units (litre/second) ($1 \text{ atm} = 760 \text{ torr}$).

Pumping speed S measures the volume of gas passing through the pump per second.

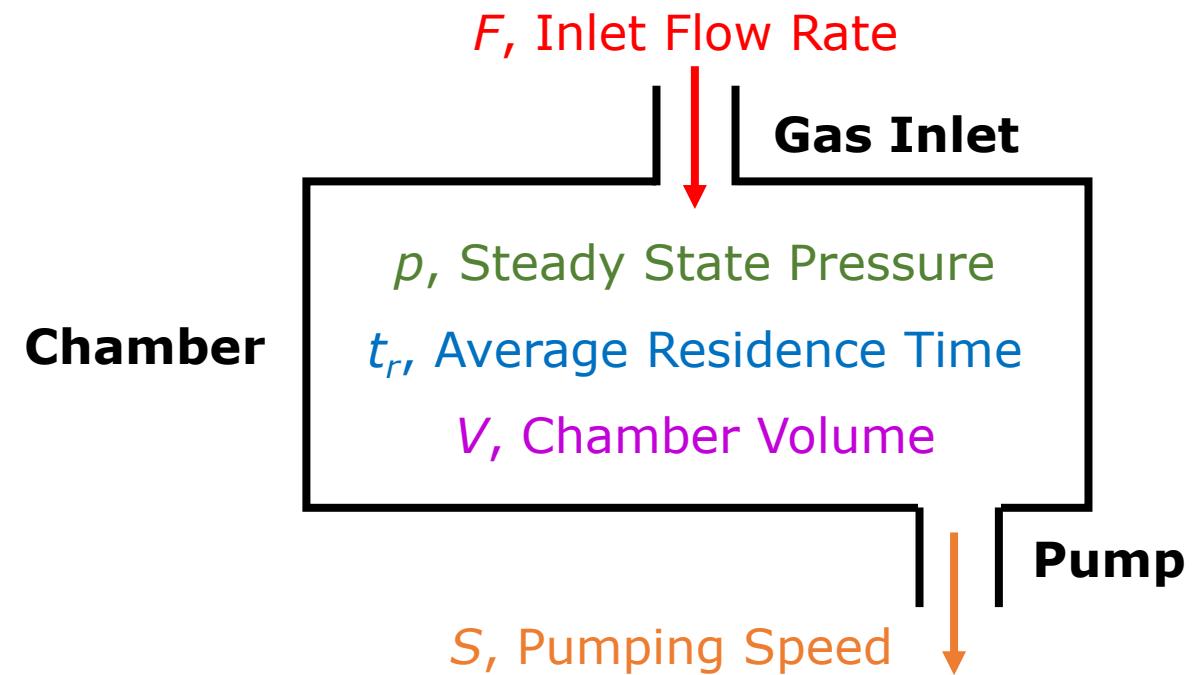


Flow rate and residence time:

- The **flow rate (F)** of the feed gas and the **reactor pressure (p)** determine the **residence time (t_r)** of the average molecule of the plasma.
- Residence time of a gas molecule is the **average time it remains in the process chamber before being pumped away.**
- Average residence time, t_r (in seconds)

$$t_r = \frac{V \cdot p}{760 \cdot F}$$

Where V is the **chamber volume**.



Factors Controlling Plasma Etch Rate: Average Residence Time

By substituting: $p = \frac{F \cdot 760}{S} \text{ Torr}$

Into: $t_r = \frac{V \cdot p}{760 \cdot F}$

We obtain: $t_r = \frac{V}{S}$

- For a constant S , t_r does not vary with the changing pressure brought about by the change in flow rate (F). Hence, we should not assume that increasing F will increase the residence time and the corresponding etch rate.

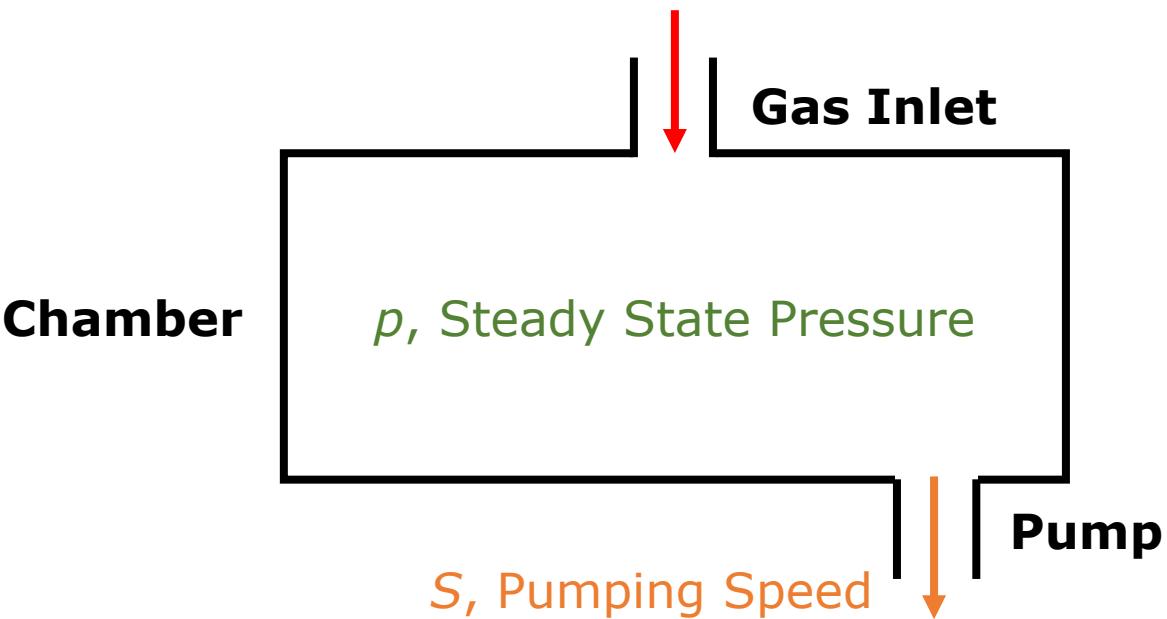
- **Throughput** or the gas load Q , equals to pS
(pressure times the pumping speed):

$$Q = pS$$

- Hence, it is **proportional to the flux of molecules** passing through the pump.
- Units for throughput is torr litre/second (lt/s), but standard cc per minute (sccm) is more commonly used. Standard referring to standard temperature ($^{\circ}\text{C}$) and standard pressure (1 atm, or 760 torr)

$$1 \text{ sccm} = \frac{10^{-3} [\text{litres}] \times 760 [\text{torr}]}{60 [s]} = 0.01266$$

$$1 \text{ torr litre / s} = 78.9 \text{ sccm}$$



Practice Question



Pause and
try out this
question

A conventional 13.56 MHz parallel plate reactive ion etching (RIE) system was deployed to etch SiO_2 film with C_2F_6 plasma. The cathode plate of the RIE system has a diameter of 20 cm and a chamber volume of 20 litres. The etching was carried out at a cathode potential (V_c) of -450 V with a C_2F_6 flow rate of 25 m per second and a radio-frequency (RF) power of 100 W. The average residence time of the plasma is 1 second.

Determine:

- a) The power density of this process
- b) The anode diameter, assuming the anode potential (V_a) of 15 mV
- c) The etch pressure of the chamber
- d) The speed of the pump
- e) Suggest ways to improve etch rate of the system

Practice Question

a) The power density of this process:

Power density = RF power/ cathode area

$$\frac{100W}{\pi \left(\frac{20cm}{2} \right)^2} = 0.318 W/cm^2$$

b) The anode diameter, assuming the anode potential (V_a) of 15 mV:

$$|V_c| = V_a \left(\frac{A_a}{A_c} \right)^4 \quad \sqrt[4]{\frac{V_c}{V_a}} A_c = A_a \quad \sqrt[4]{\frac{450}{0.015}} 20^2 = (D_a)^2$$

$$D_a = 72.5 \text{ cm}$$

Practice Question

c) The etch pressure of the chamber:

$$t_r = \frac{V \cdot p}{760 \cdot F}$$

$$p = \frac{760(0.025)(1)}{(20)}$$

$$p = 0.95 \text{ Torr}$$

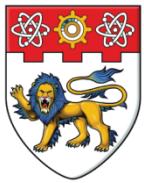
d) Calculate the speed of the pump:

$$t_r = \frac{V}{S}$$

$$S = \frac{20}{1} = 20 \text{ litre/s}$$

e) Suggest ways to improve etch rate of the system:

- Use higher RF power/ higher cathode potential
- Increase anode area



Plasma Damage and General Issues in Etching

Plasma Damage

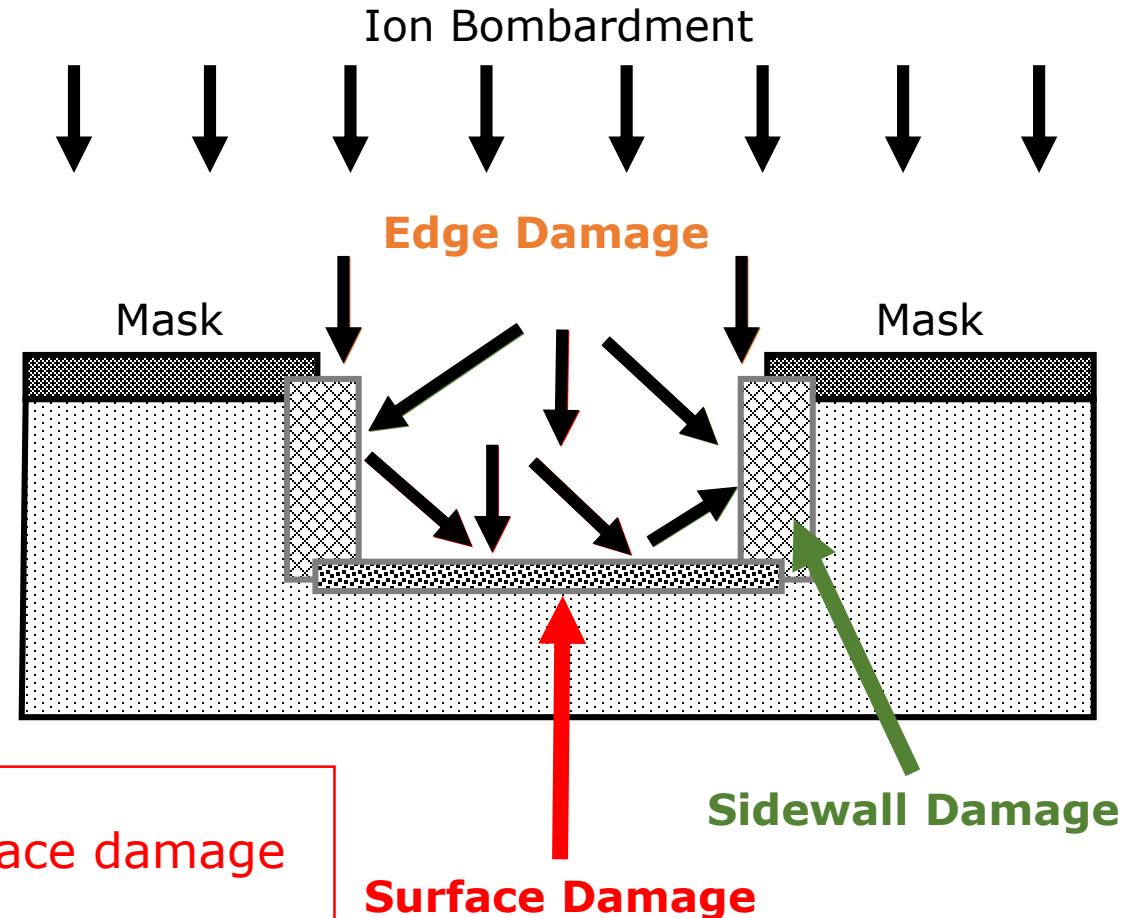
Plasma damage:

- High ion fluxes of 10^{15} ion/cm^2 are delivered at energies of **300 to 700 eV** in plasma etching.
- The **high ion bombardment energy** causes **damage to the material**, and considerable **degradation** to the electrical and optical properties of devices.
- The degree of damage is **highly dependent on the accelerating potential and the mass of the ion species**.

Plasma Damage

For materials near to patterned edges, the rebound ions, sputtered material and chemical reactants may also cause damage to the edge.

The principal source of surface damage may result directly from the ion flux.



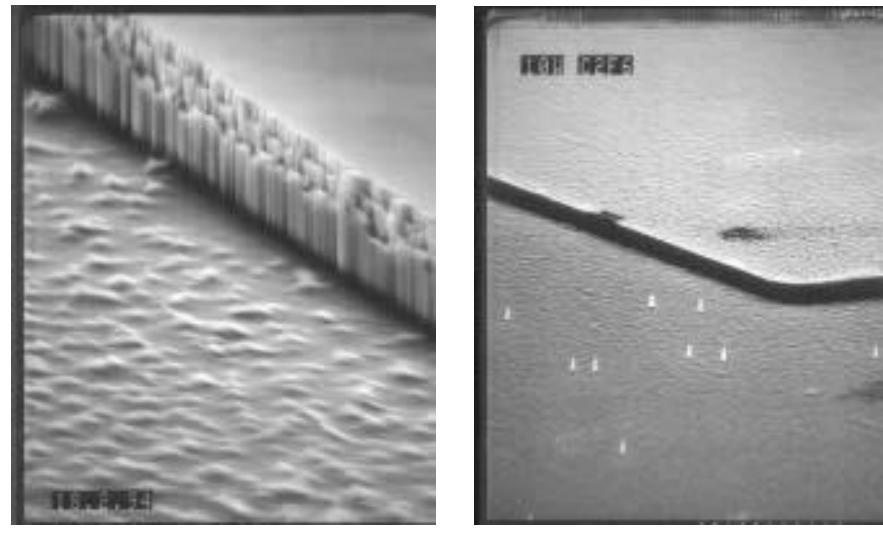
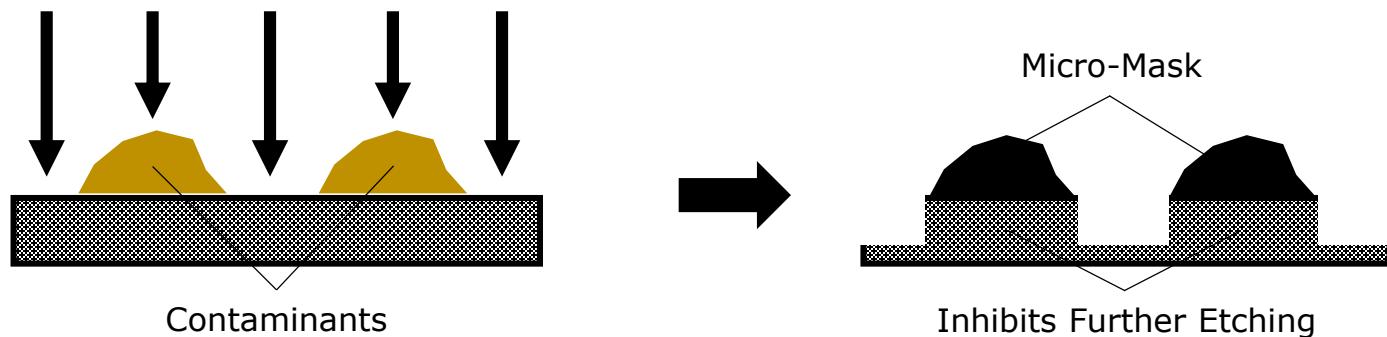
Sidewalls suffer damage from the direct bombardment by directional ions and reactive radicals, and possibly deposition and ricocheting particles from the bottom surface.

Plasma Damage

- Plasma damage has been observed to:
 - a) Reduce the carriers mobility of semiconductors
 - b) Deactivate dopants
 - c) Increase the resistivity
- Annealing of samples using a RTP (Rapid Thermal Processor) or furnace at temperatures in the range of 450 to 800°C for a few seconds to a few minutes may partially or totally remove the damage.

Surface Contamination

- Contaminants such as fingerprints, dust particles, etc., may contaminate the semiconductor by leaving behind non-volatile by-products.
- These contaminants may deposit on the semiconductor surface and act as micro masks during the etching of the semiconductor.
- These micro-masks could inhibit the subsequent etching of the semiconductor and also cause the etched surface to be rough.



(a)

(b)

- a) A rough surface due to contamination.
- b) A reasonably clean surface has been obtained from the sample exposed to low power C₂F₆.

General Issues Associated with Etching

- **Uniformity:** Across wafer
- **Etching rate:** Fast enough to be practical, and slow enough to be controllable
- **Selectivity:** Should be high
- **Anisotropy:** Directional dependence of etch rate
- **By-products:** Volatile or otherwise, easily removed

Practice Question 1

Define the following terms:

- (a) Etch selectivity
- (b) Anisotropy in etching



Pause and
try out this
question

Why are they important in microfabrication?

Practice Question 1

a) Etch selectivity:

- **Selectivity is the ratio of the etch rates between different materials, especially the material that needs to be etched compared with the material that we do not want to remove.**
- Smaller geometries require thinner layers of resist. High selectivity is necessary in most advanced processes to ensure critical dimension and profile control. The smaller the feature size of the process, the higher selectivity is needed.

b) Anisotropy in etching:

- **Anisotropy in etching is the ratio of vertical etching rate over horizontal etching rate.**
- With smaller geometries, the etch profiles have higher aspect ratios. It is difficult to get etchant chemicals in and reaction by-products out of the high aspect ratio openings. To overcome this, it is desirable to have directionality to drive the plasma into the high aspect ratio openings.



**Pause and
read
carefully**

Wet Etching	Dry Etching
Simple, inexpensive equipment	Elaborated equipment required (Higher cost)
Large batch process possible	
No proper etchant for specific materials (Si_3N_4)	Anisotropic etching (High downwards etching)
Minimum etching dimension is relatively large	Minimum etching dimension is small
Undercutting in isotropic etching	Less lateral etching, less undercutting

Lesson Summary - Etching

Dry Etching

- Dry etching uses ionic (plasma) etchants to etch away the target materials.
- Plasma generation involves ionisation, recombination, excitation, relaxation and dissociation processes.
- Sputter etching uses inert ions (argon), whereas reactive ion etching uses reactive ions (C_2F_6).
- The operation of an RIE system is governed by the plasma potential and the area of the electrodes.
- Important parameters in dry etching include etchant gas flow rate, average residence time of the etchant gas, steady state pressure of the system chamber, and pumping speed of the etching system's pump.
- Plasma etching may cause sidewall damage, surface damage, and edge damage on the substrate.

Practice Question 2

Determine if the statements below about dry etch processes are either true or false



Pause and
try out this
question

- a) Etch profiles of directional etch systems are generally isotropic. False
- b) Dry etch provides good CD (critical dimension) control. True
- c) Dry etch creates minimal resist lifting. True
- d) Etch uniformity of dry etch is inferior to wet etch. False
- e) Dry etch processes use less chemicals than wet etch processes. True
- f) Plasma-induced damage is more common in wet etch processes. False
- g) The complexity and cost of dry etch equipment is higher. True

Practice Question 3

- a) Describe the basic components of a plasma dry etch system.
- b) Explain what is a reactive plasma and how it is generated in a DC glow discharge?
- c) What are the advantages and disadvantages of reactive ion etching versus sputter etching? Cite an example of when one might want to use sputter etching rather than RIE?
- d) In the plasma of a RIE system, consider an argon atom that is ionized during a collision in the plasma. Over a given mean free path, one of the particles will achieve a much higher speed. Explain, with a diagram, how does that affects the potential (voltage) of the plasma relative to that of either electrode?
- e) What are the general issues associated with etching?



Pause and
try out this
question

Practice Question 3



Pause and
read
carefully

- a) The basic components of a dry etch system include a reaction chamber where the etching takes place, an RF power supply to ignite the plasma, a gas flow control system and a vacuum system to remove etch-by products and gases.
- b) Reactive plasma describes a discharge process in which ionization and fragmentation of gases take place and produce chemically reactive species. Such species are reactive both in gas phase and with solid surface. These reactive species are used to interact and etch or remove the surfaces that are not masked by the lithography pattern. Electron collision are inelastic and will result in ionized species or excited neutral species in the plasma via ionization, relaxation, recombination, etc
- c) RIE gives more selectivity; sputtering etches almost everything, at about the same rate. Use sputter etching when etching multilayer stack of different materials on the substrate, when etching substrate a little doesn't matter.

Practice Question 3



Pause and
read
carefully

d) Over a given mean free path, electron achieves a much higher speed and thus travels much farther than the ion. Since most of these particles are created in the plasma, more electrons than ions leave the plasma and as a result, the plasma is at a positive potential relative to either electrode.

e)

- **Uniformity:** Across wafer
- **Etching rate:** Fast enough to be practical, and slow enough to be controllable
- **Selectivity:** Should be high
- **Anisotropy:** Directional dependence of etch rate
- **By-products:** Volatile or otherwise, easily removed



Course: EE3013 Semiconductor Devices and Processing

School: School of Electrical and Electronic Engineering

Deposition - Physical Vapour Deposition

Learning Objectives

At the end of this lesson on deposition, you should be able to:

- Describe the properties of a high-quality thin film.
- Explain the fundamental concepts in Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD).
- Explain the advantages and possible limitations of PVD and CVD techniques, and ways to improve them.

Standard Process Iteration

There are three main categories in semiconductor fabrication process:

Lithography

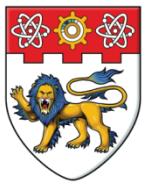
Patterning of substrate
(Silicon wafer)

Etching

Removal of materials
from the substrate

Deposition

Deposit materials
(metal/ non-metal)
on the substrate

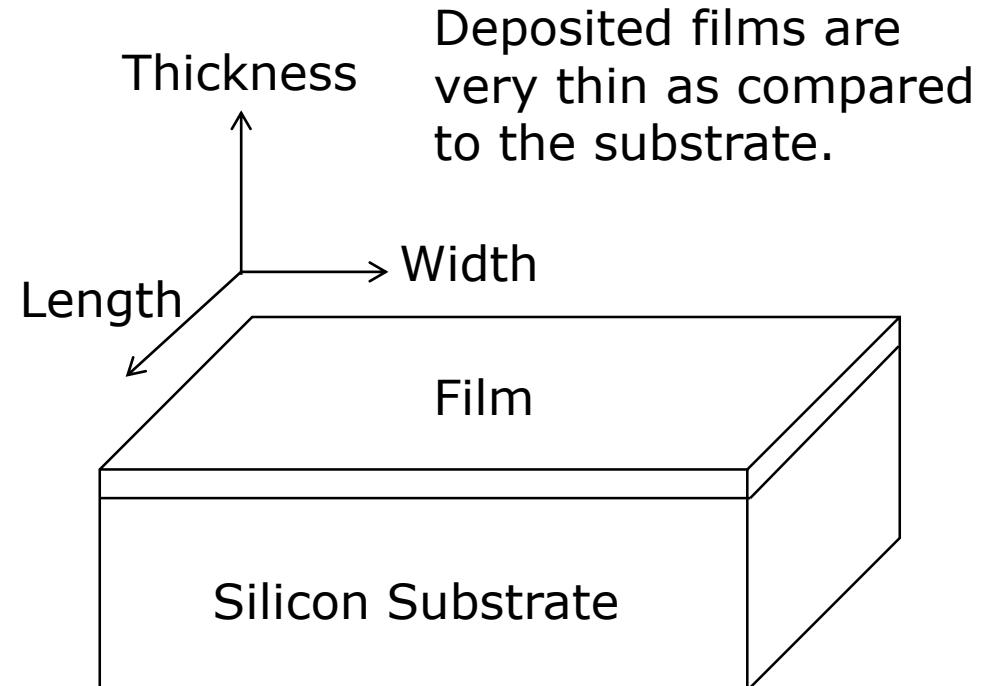


Thin Film Deposition

Thin film: Thickness typically $< 1000 \text{ nm}$

Special properties of thin films: Different from bulk materials

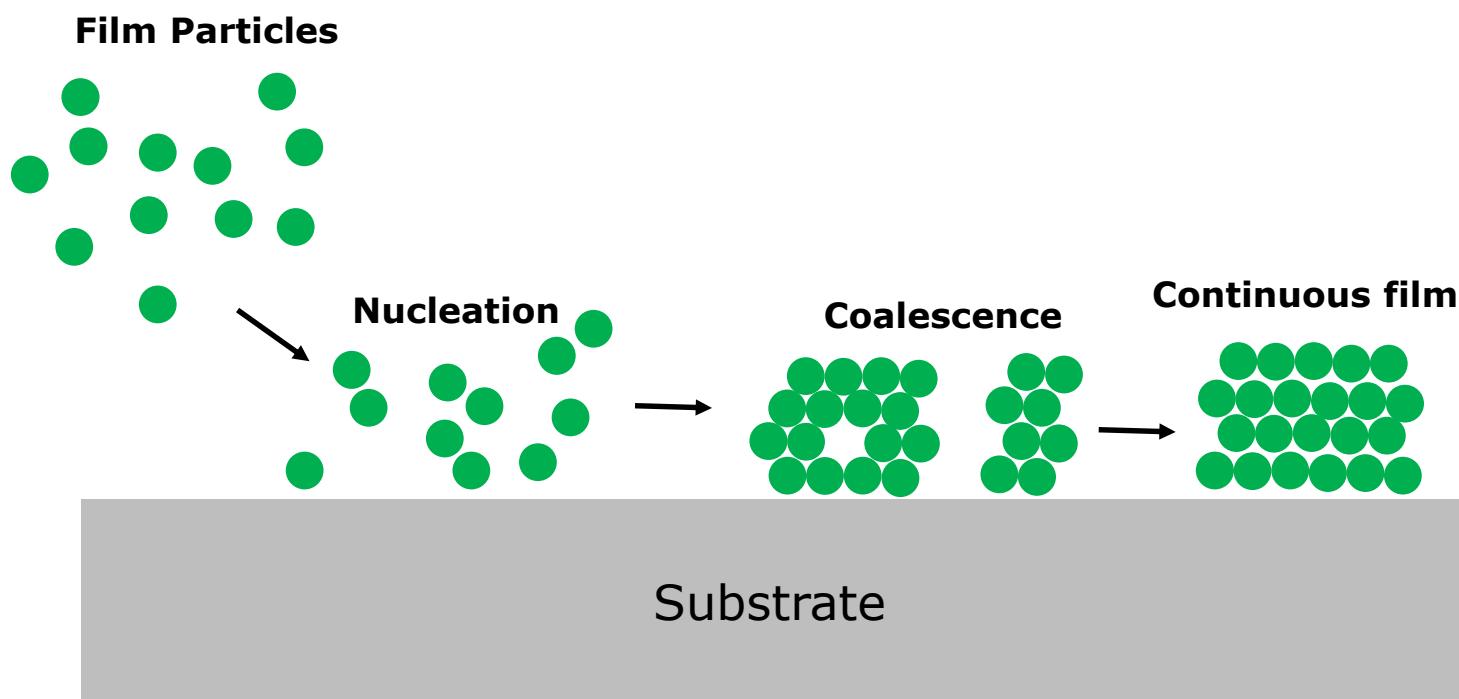
- Not fully dense
- Under stress
- Different defect structures from bulk materials
- Strongly influenced by surface and interface effects



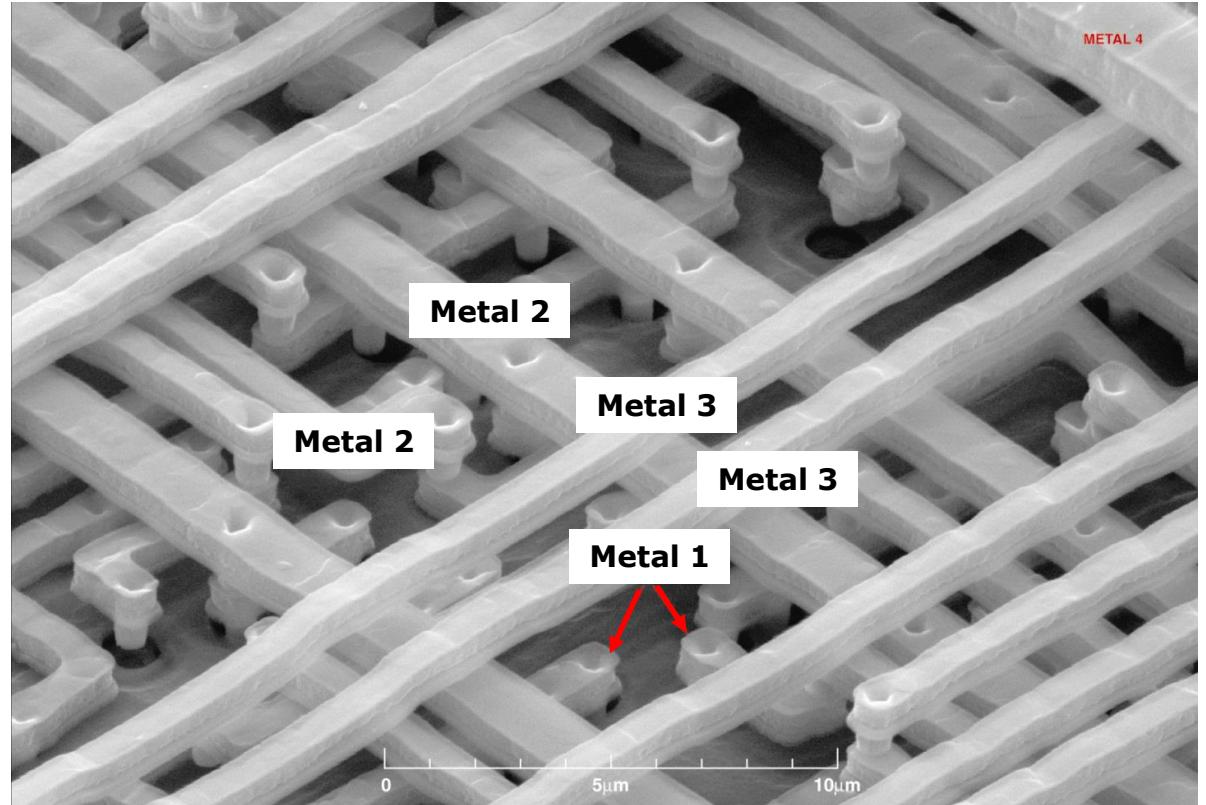
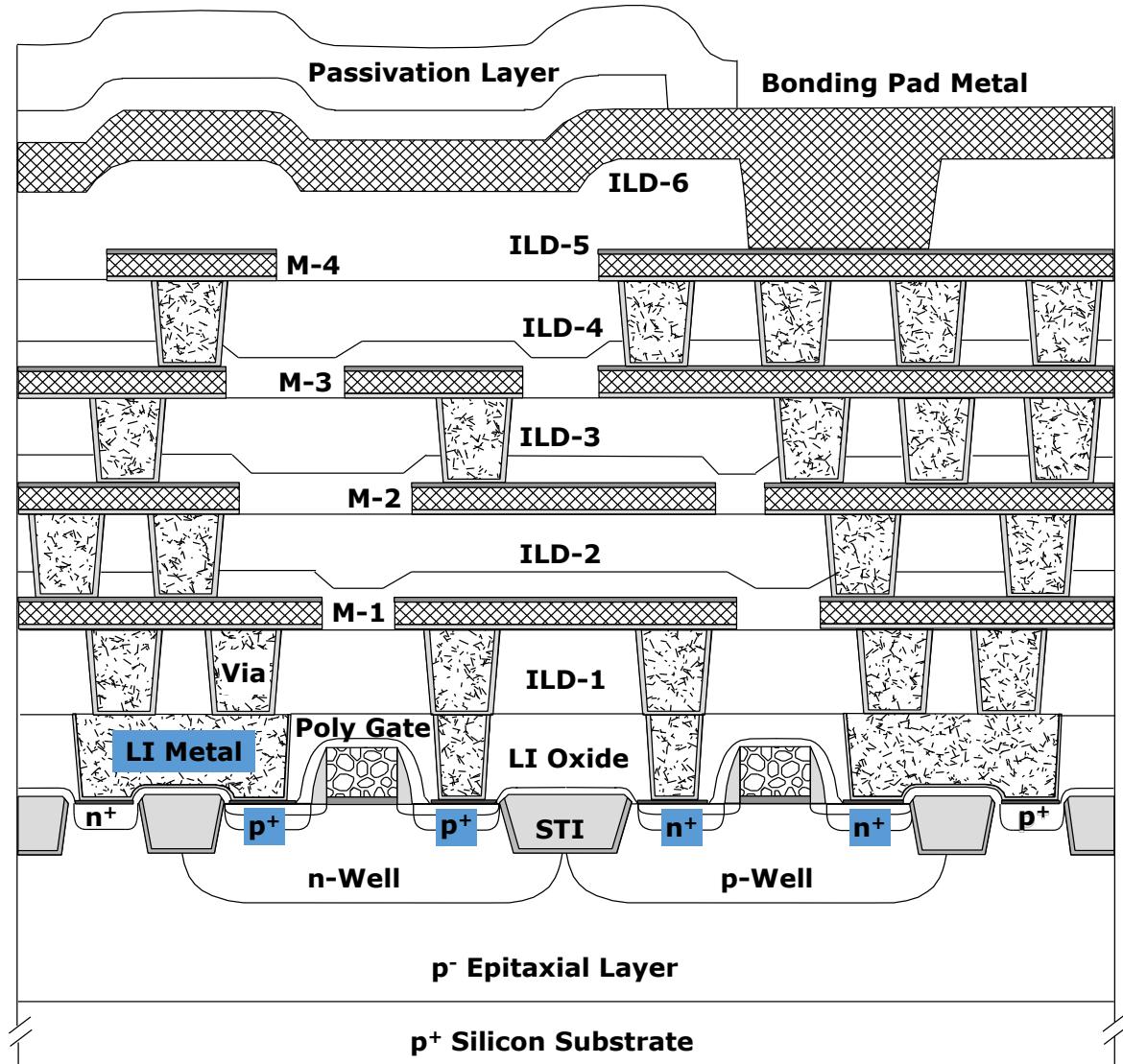
Mechanism in Thin Film Deposition

Here are the **typical steps** to deposit thin films:

1. Emission of particles from source (heating, high voltage, etc.)
2. Transport of particles to substrate
3. Condensation of particles on substrate



Multilevel Metallisation on a Wafer



Deposition of the high-quality thin film is needed for multilevel metallisation.

Two main deposition methods used today:

- **Physical Vapour Deposition (PVD)** (no chemical reaction involved)

The vapour of thin film materials is created inside the chamber, and condensation occurs on wafer surface leading to the deposition of a solid thin film.

E.g. Evaporation and sputter deposition are most commonly used for metals.

- **Chemical Vapour Deposition (CVD)** (involves chemical reaction)

Reactant gases are introduced into the chamber, and chemical reactions occur on wafer surface leading to the deposition of a solid thin film.

E.g. APCVD, LPCVD, and PECVD, which are most commonly used for dielectrics and Si.

General Characteristics of Thin Film Deposition

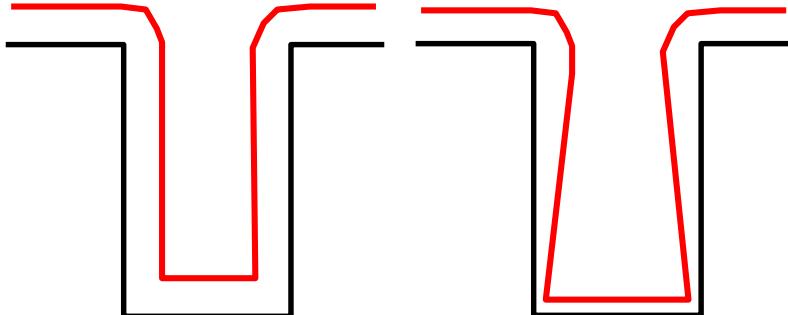
Quality of Film:

- Physical and chemical properties
- Electrical property: Breakdown voltage
- Mechanical properties: Film stress and substrate adhesion
- Optical properties: Transparency and refractive index
- Composition
- Film density and defect (pinhole) density
- Texture
- Impurity level and doping
- Conformality (step coverage)
- Trench/ hole filling

Will be further discussed in this lesson

Step Coverage

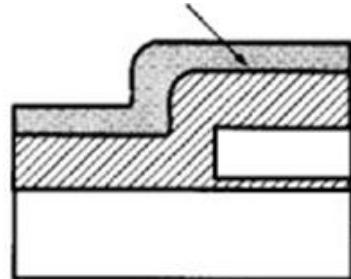
Good Step Coverage



Poor Step Coverage

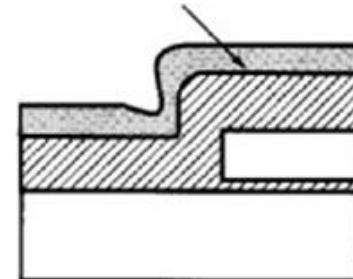
The step coverage of a deposition is its conformality in filling a hole/ trench. Good step coverage film is needed for electrical connection.

Metal



(a)

Metal

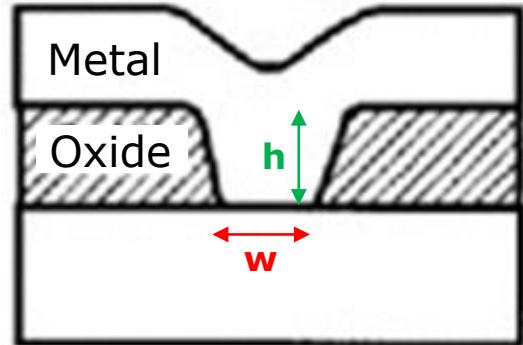


(b)

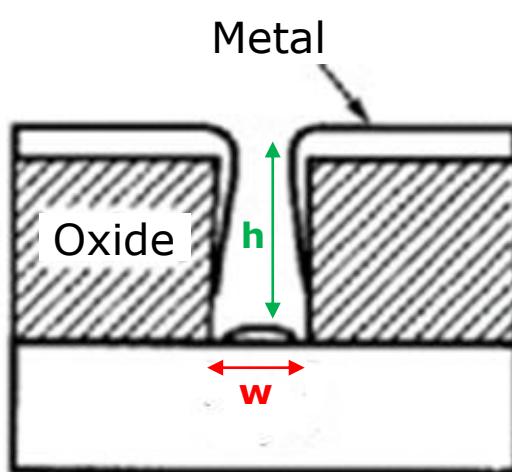
For example, in depositing metal in non-planar topography:

- Figure (a): Conformal step coverage, with a constant thickness on horizontal and vertical surfaces
- Figure (b): Non-conformal step coverage, thinner for vertical surfaces

Trench/ Hole Filling



Low Aspect Ratio Trench



High Aspect Ratio Trench

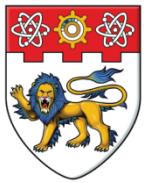
Aspect ratio (AR):

$$\text{AR} = \text{height}/\text{width}$$

$$\text{AR} = h/w$$

It is generally more difficult to fill higher aspect ratio trenches, as the filling may have poor step coverage due to poor conformality.

Hence, it is important to understand the thin film deposition techniques to produce high-quality thin films.



Thin Film Deposition Methods: Physical Vapour Deposition (Evaporation)

In PVD, chemical reactions are not involved. There are **two types of PVD**:

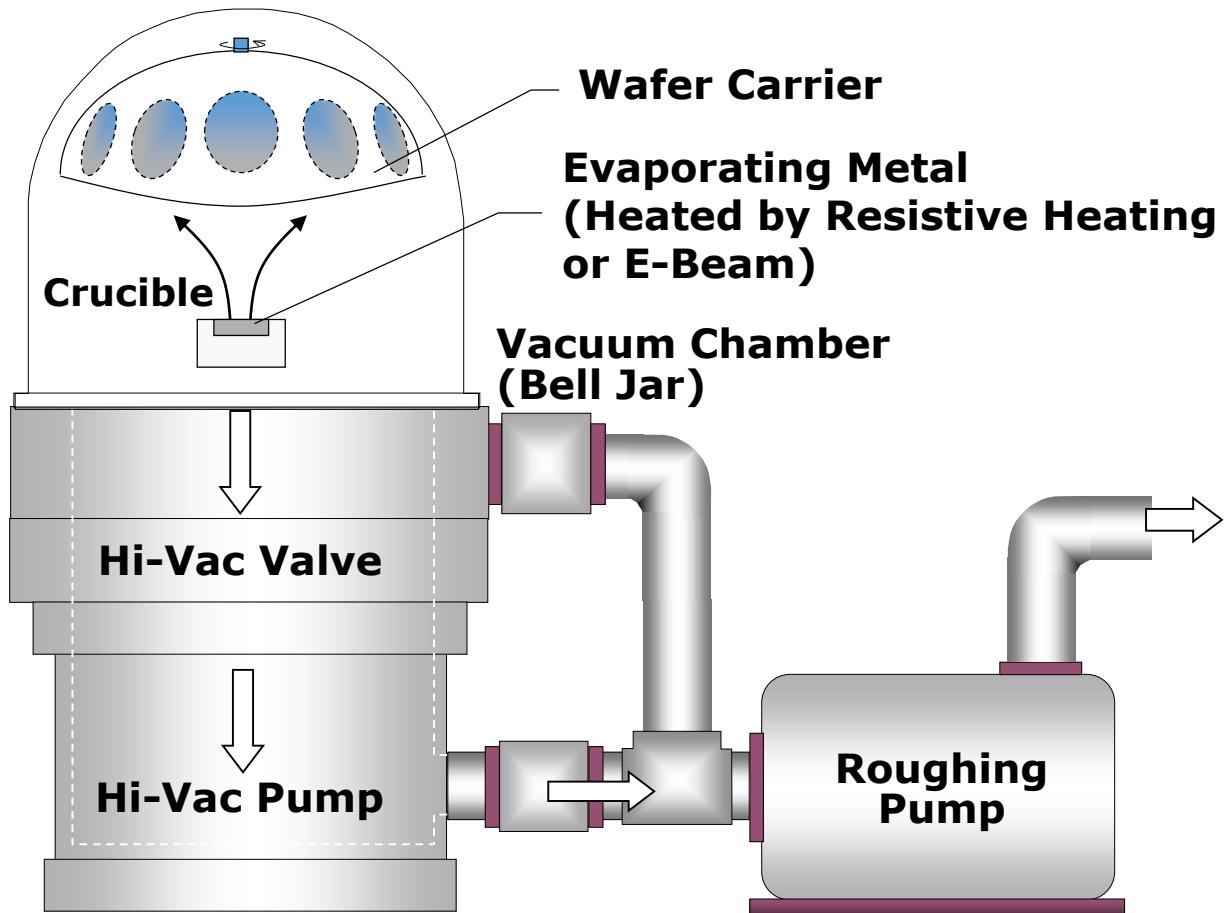
Evaporation:

- Material source is heated to high temperature in a vacuum either by thermal or e-beam methods.
- Material is vapour transported to target in a vacuum.
- Film quality (density) is often not as good as sputtered film.
- The film thickness can be monitored precisely using a quartz balance.

Sputter deposition: (*There is also sputter etching as discussed earlier*)

- Material is removed from the target by momentum transfer.
- Gas particles (often Argon) are ionised by plasma, ions strike the target and remove (sputter away) the atoms in the target.
- Sputtered atoms are condensed on the substrate.
- It involves energetic bombardment of ions.
- The as-deposited film is denser due to higher energy of the sputtered atoms.

Evaporation (Also Called Vacuum Deposition)



- In evaporation, the source material is heated in a high vacuum chamber ($P < 10^{-5}$ Torr), hence, the name vacuum deposition.
- High vacuum is required to minimise collisions of source atoms with air molecules.
- Heating is done by resistive or e-beam sources.
- Surface interactions are physical and can be very fast ($> 1 \mu\text{m}/\text{min}$ is possible, but film quality may suffer. For R&D, it is typically $0.1 \sim 1\text{nm/sec}$).
- It has poor conformal coverage.

Two types of evaporation:

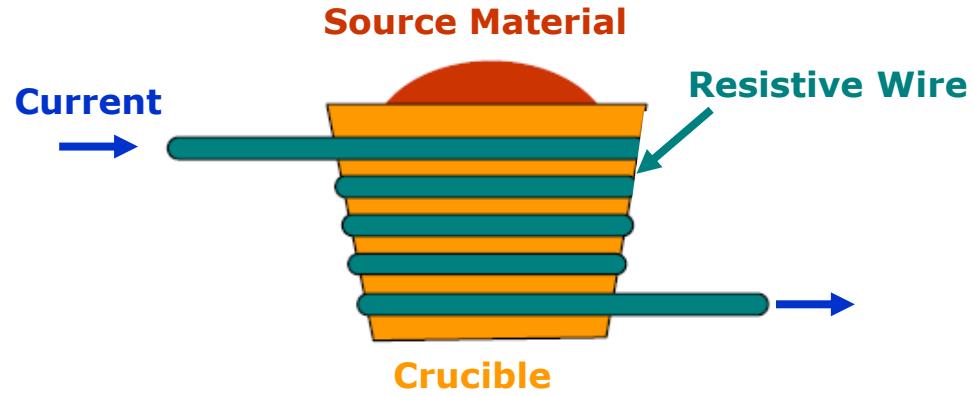
1. Thermal evaporator:

- Resistive heating
- A relatively old deposition technique

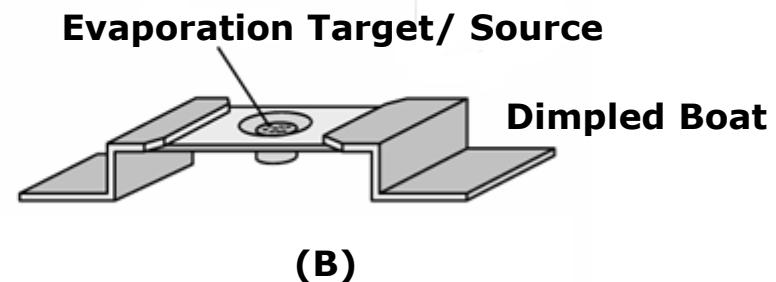
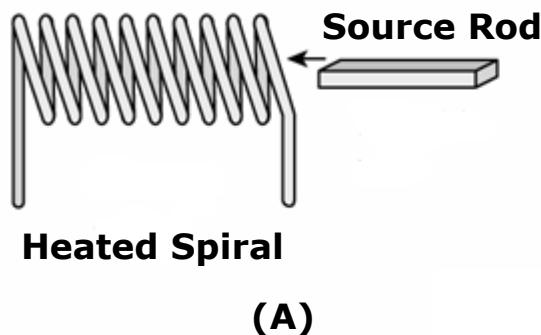
2. Electron beam evaporator:

- Heated by electron beam
- Most popular technique
- More expensive than the thermal evaporator

Thermal Evaporation

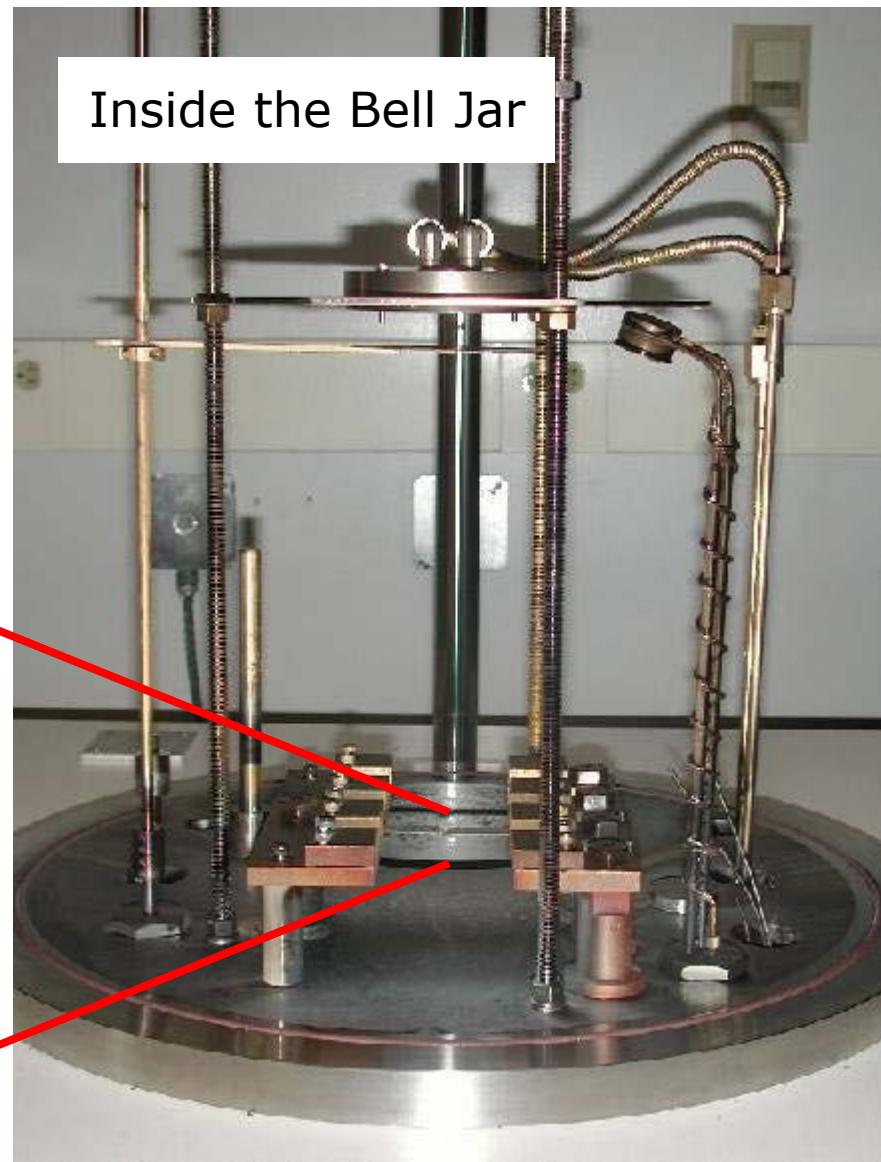
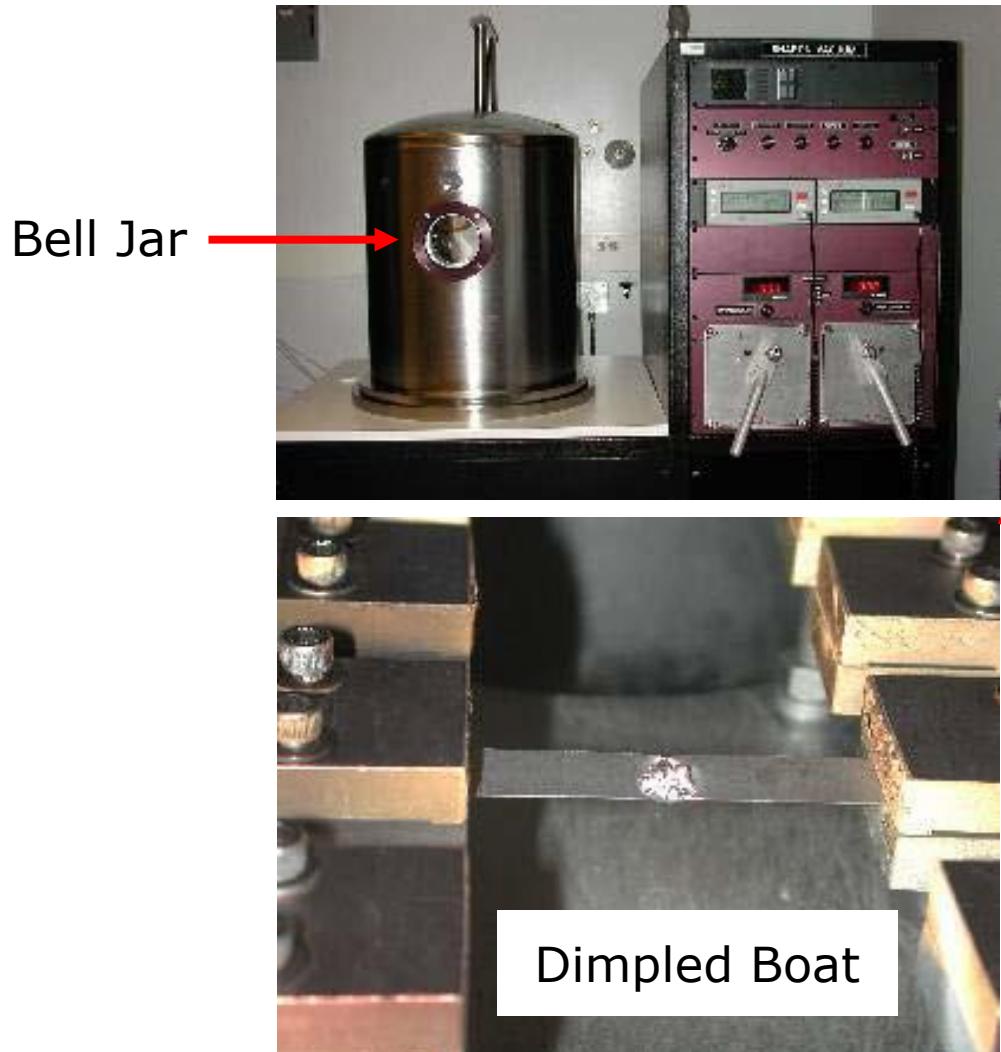


- Widespread use for materials whose vapour pressure can be reasonable at $1,600^{\circ}\text{C}$ or below
- Common evaporant materials:
Au, Ag, Al, Sn, Cr, Sb, Ge, In, Mg, and Ga

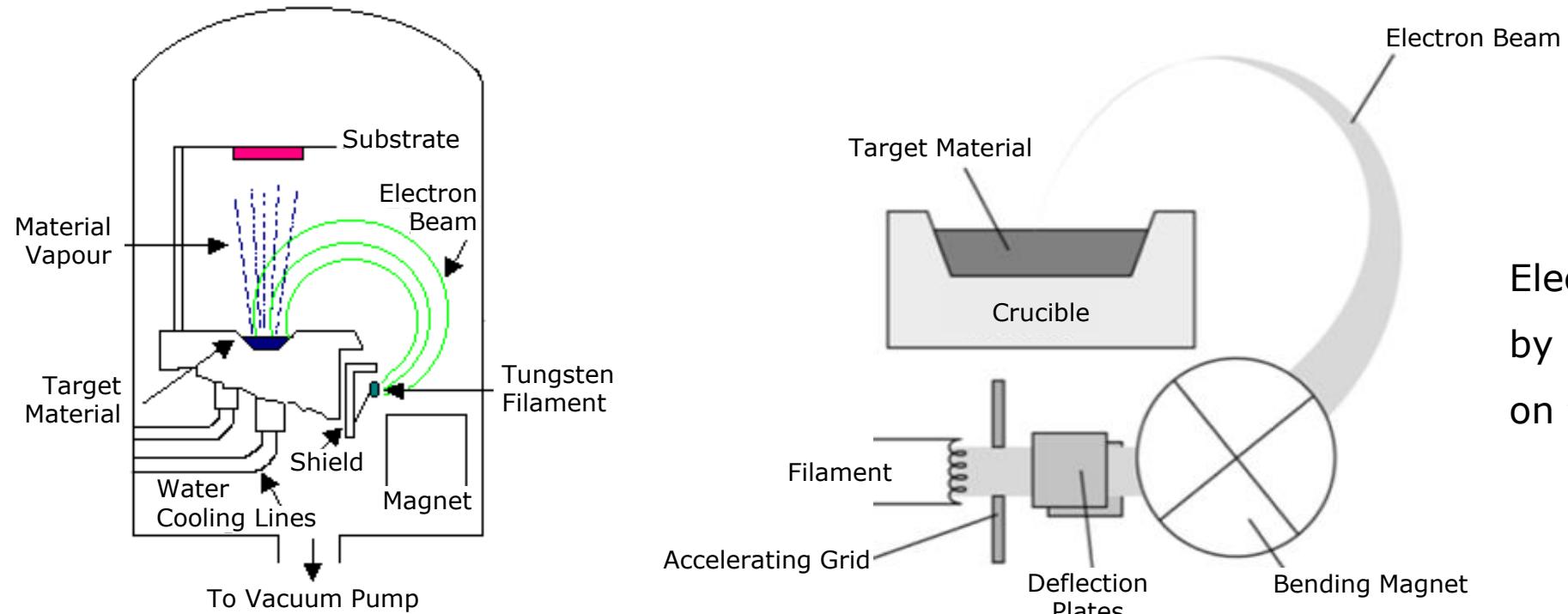


- A. Heating the source rod using heated spiral
- B. Heating the source material using a dimpled boat

Photos of Thermal Evaporator



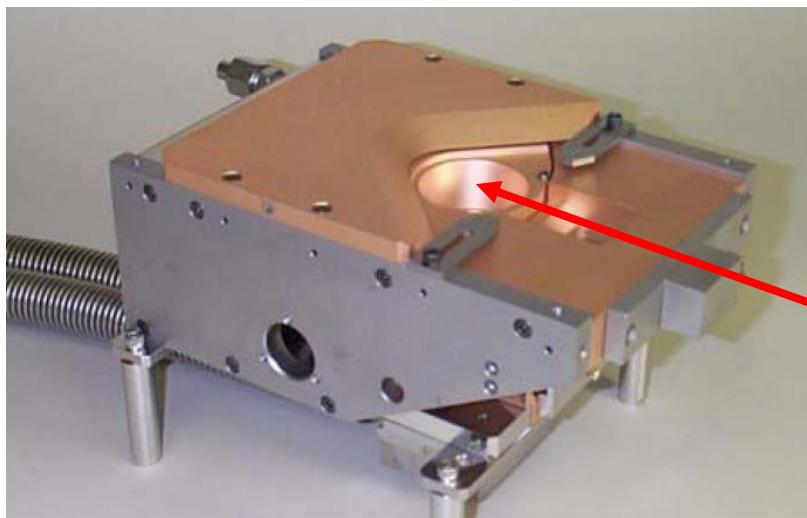
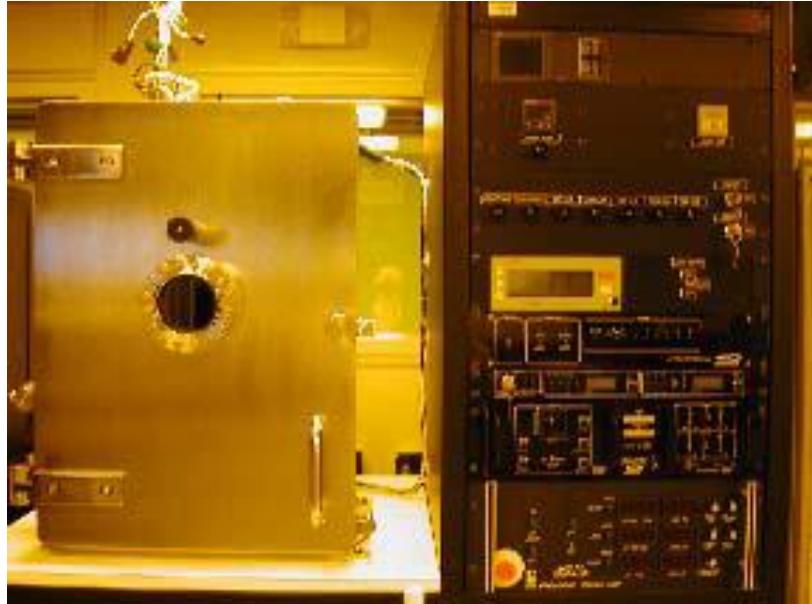
Electron Beam Evaporation



Electron beam deflected by bending magnet to hit on the target material

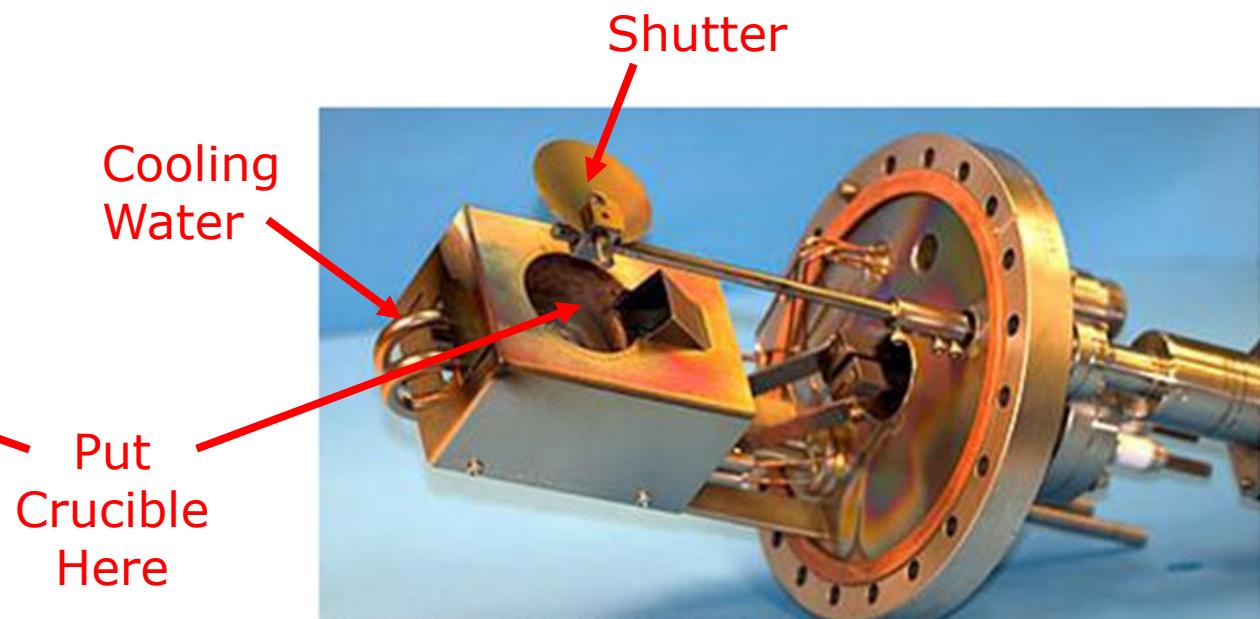
- A focused electron beam is used to heat and evaporate metals. Electrons are accelerated by DC 10kV, with a current of 10s-100s of mA, the target material temperature can be very high.
- It is suitable for high melting point metals like W, Ta, etc.
- Evaporation occurs at a highly localised point near the beam bombardment spot on the source surface, so little contamination from the crucible.

Photos of e-Beam Evaporator



Mechanical shutter:

- Evaporation is initiated by heating of target by e-beam collision, but the heating of target cannot be terminated instantly.
- A shutter is needed to terminate the deposition instantly.



Typical Boat/ Crucible Material

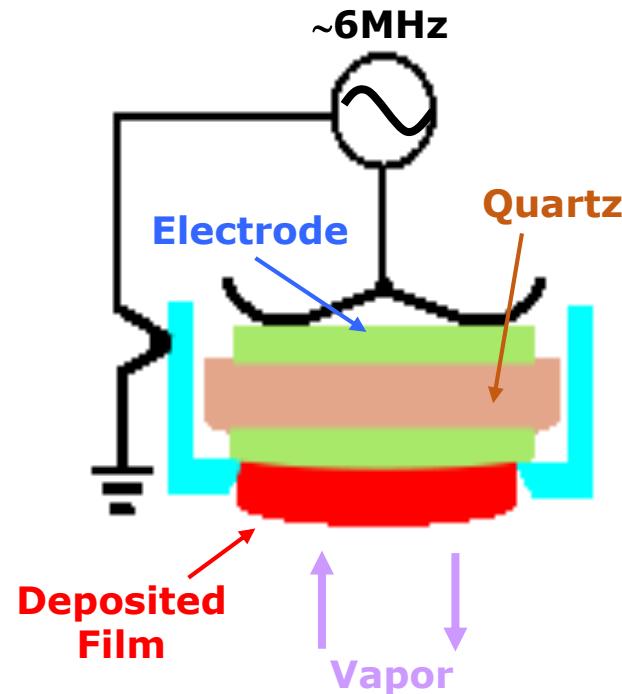
Refractory Metals	
Material	Melting Point (°C)
Tungsten (W)	3,380
Tantalum (Ta)	3,000
Molybdenum (Mo)	2,620
Refractory Ceramics	
Graphite (C)	3,799
Alumina (Al_2O_3)	2,030
Boron Nitride (BN)	2,500

Considerations: Thermal conductivity, thermal expansion, electrical conductivity, and reactivity

Graphite: Most popular, but avoid cracking the crucible due to stress/ temperature gradients

Aluminum: Tungsten dissolves in aluminum, so not quite compatible

How to Monitor Film Thickness during Evaporation?



Quartz Crystal Micro-Balance (QCM):

- QCM can monitor the thickness deposited on the wafer by measuring the shift of resonance frequency when the film is deposited on its surface.
- It can measure film thickness with a sub-Å accuracy.

Advantages:

- Films can be deposited at high rates (up to $\sim 100 \text{ \AA/s}$)
- Low energy atoms ($\sim 0.1 \text{ eV}$) leave little surface damage
- Little residual gas and impurity incorporation due to high vacuum conditions
- Very little substrate heating

Limitations:

- Difficult to achieve accurately controlled alloy compounds
- Poor step coverage
- X-ray damage

Comparison of Thermal and e-Beam Evaporation

	Thermal	E-Beam
Material	Metal of low melting point materials	Both metal and dielectrics
Typical Evaporating Materials	Au, Ag, Al, Cr, Sn, Sb, Ge, In, Mg, Ga	Everything in 'Thermal' plus Ni, Pt, Ir, Rh, Ti, V, Zc, W, Ta, Mo, Al_2O_3 , SiO , SiO_2 , SnO_2 , TiO_2 , ZrO_2
Impurity	High	Low
Deposition rate	$1 \sim 20 \text{ \AA/s}$	$10 \sim 100 \text{ \AA/s}$
Temperature Range	$\sim 1,800^\circ\text{C}$	$\sim 3,000^\circ\text{C}$
Cost	Low	High

Thermal evaporation:

- Simple, robust, and in widespread use
- Use W, Ta, or Mo filaments to heat evaporation source
- Typical filament currents are 200-300 Amperes
- Exposes substrates to visible and IR radiation
- Contamination from heated boat/ crucible



Electron beam evaporation:

- More complex, but extremely versatile, virtually any material
- Less contamination, less heating to wafer (as only small source area heated to very high temperature)
- Exposes substrates to secondary electron radiation, where high voltage electron beam can generate X-rays
- Since x-rays will damage substrate and dielectrics (leads to trapped charge), e-beam evaporators cannot be used in MOSFET



Thin Film Deposition Methods: Physical Vapour Deposition (Sputter Deposition)

Now, let us look at sputter deposition:

Evaporation:

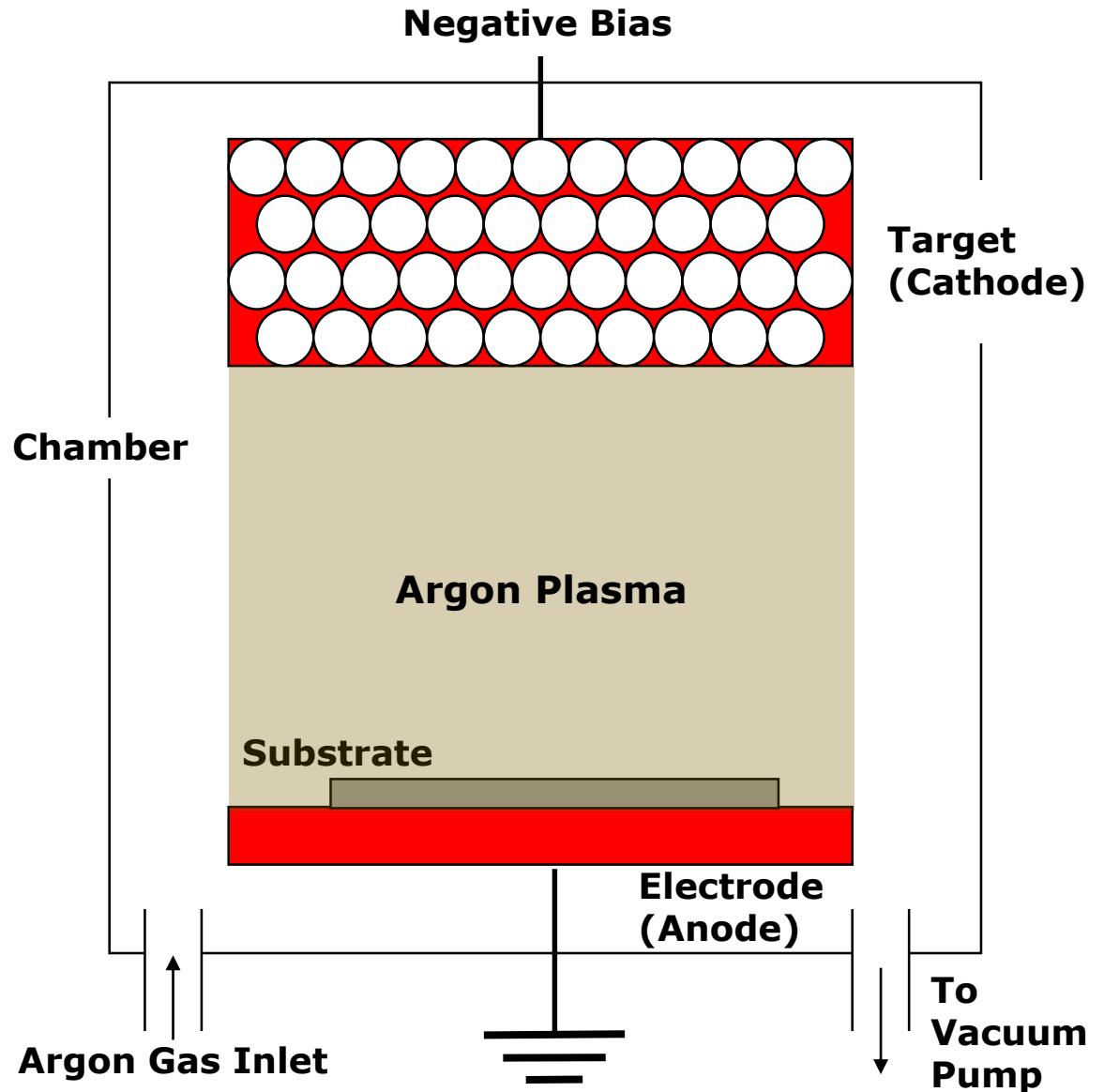
- Material source is heated to high temperature in a vacuum either by thermal or e-beam methods.
- Material is vapour transported to target in a vacuum.
- Film quality (density) is often not as good as sputtered film.
- The film thickness can be monitored precisely using a quartz balance.

Sputter deposition: (*There is also sputter etching as discussed earlier*)

- Material is removed from the target by momentum transfer.
- Gas particles (often Argon) are ionised by plasma, ions strike the target and remove (sputter away) the atoms in the target.
- Sputtered atoms are condensed on the substrate.
- It involves energetic bombardment of ions.
- The as-deposited film is denser due to higher energy of the sputtered atoms.

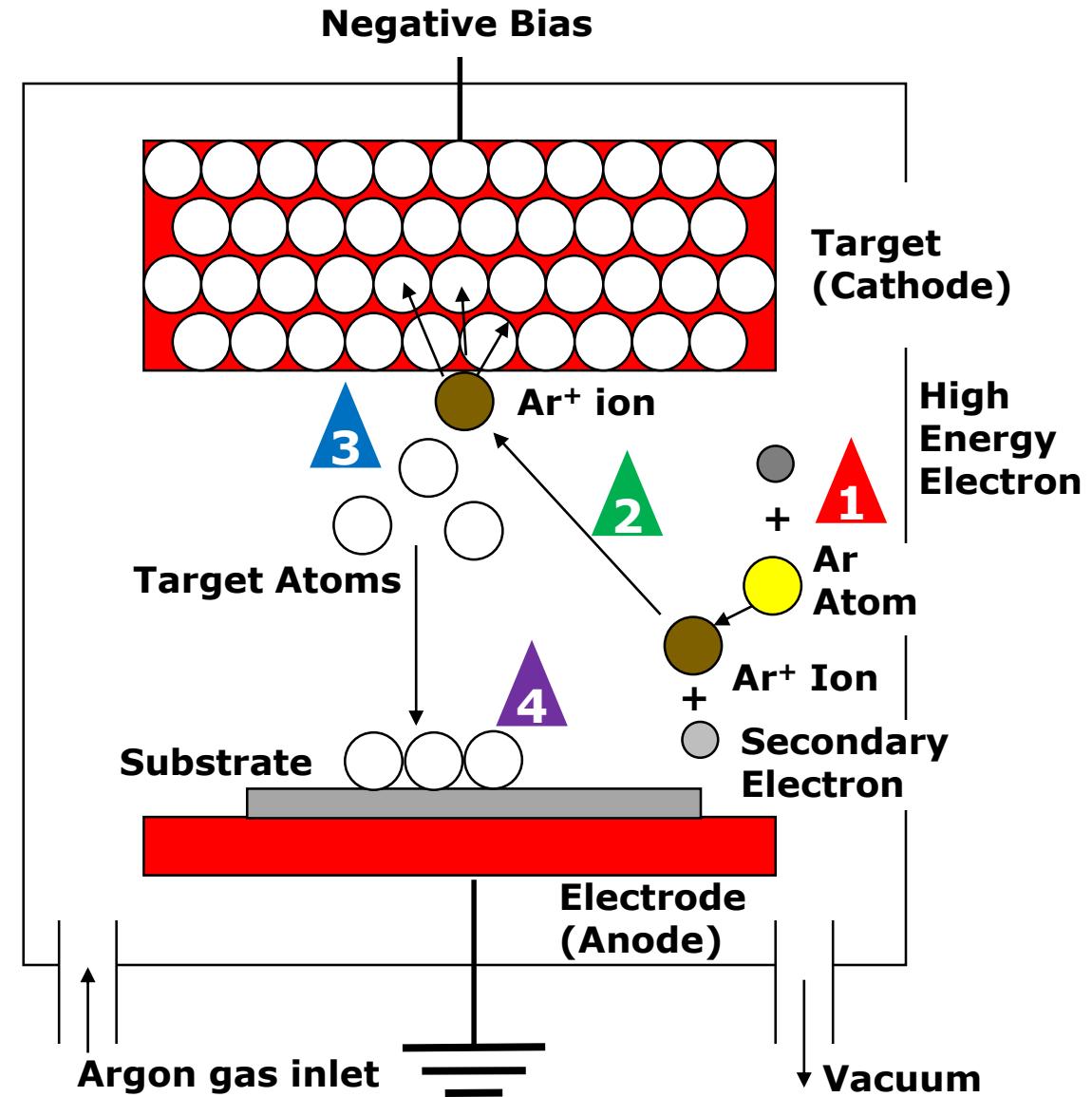
Schematic Diagram of Sputtering System

- The material to be sputtered (sputtering target) is placed in the cathode of an electrical circuit and is supplied with a high negative voltage.
- The substrate is placed on an electrically grounded anode.
- Gas is introduced into the chamber. The electrical field accelerates electrons and turn the gas into plasma.



Sputtering Process: Overview

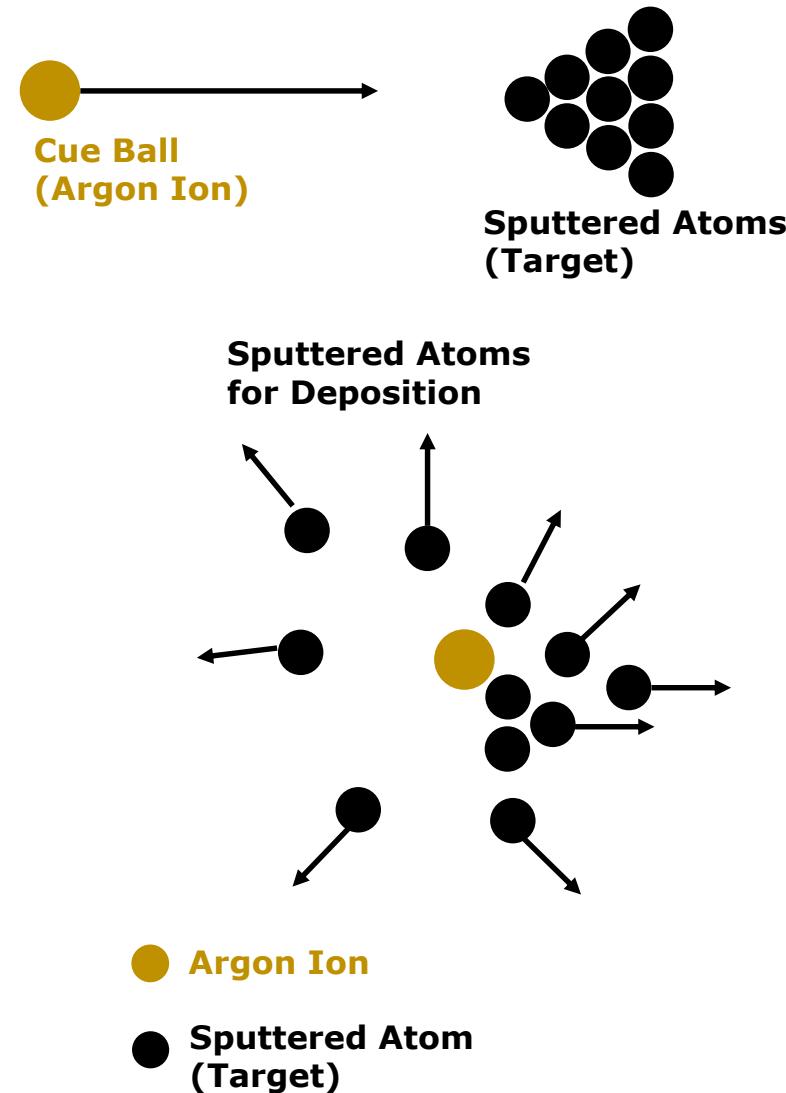
- Basically, sputtering is similar to sputter etching, where heavy and neutral ions are used to remove atoms from the target surface.
 - Heavy, chemically inert ions – argon ions are usually used.
 - The overall process of sputtering deposition can be summarised as such. Potential is applied between cathode and anode to form an argon plasma.
1. High energy electrons from the plasma collide with argon atoms to form Ar⁺ ions and secondary electrons.
 2. The Ar⁺ ions will then be accelerated towards the sputtering target through negative bias applied to the target.
 3. When high energetic Ar⁺ ions strike the target surface, the momentum of the argon transfers to the target material to dislodge one or more atoms. This is referred to momentum transfer.
 4. The ejected (sputtered) atoms move through the plasma, land on the substrate (on the anode), condense and form a thin film.



Sputtering Process: Overview (Cont'd)



Targets for Sputter Deposition



- Major process parameters include operation pressure ($\sim 1\text{-}100\text{mTorr}$), power (few 100W), voltage (-2 to -5kV for DC sputtering), and substrate bias is sometimes added.
- In addition to the semiconductor industry, a wide range of industrial products use sputtering. For example: LCD, computer hard drives, hard coatings for tools, and metals on plastics.
- It can be analogically described as the cue ball (Ar^+) striking the billiard balls (target atoms).

General Properties of Sputtering Deposition

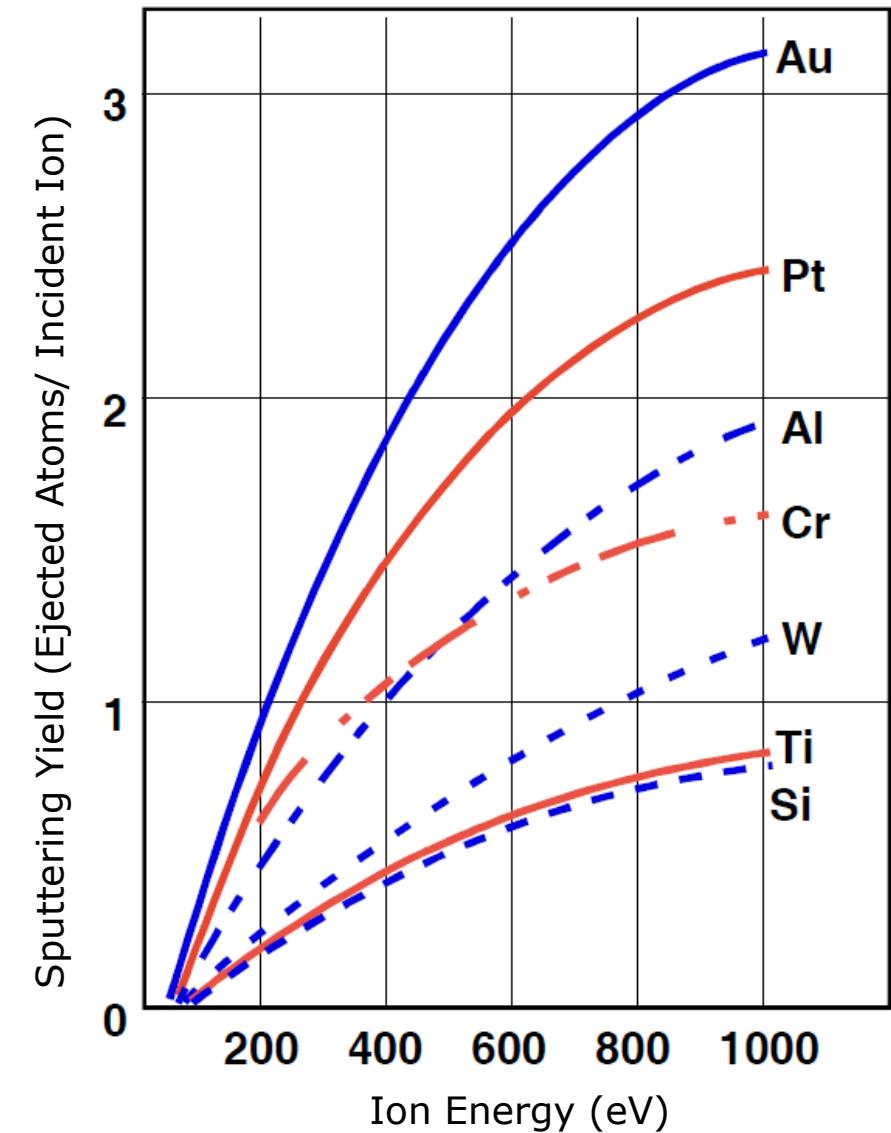
- The energy of each bombarding ion is 500-1000eV. The energy of sputtered atoms is 3-10eV. Thus, the sputtering process is very inefficient from the energy point of view as **95% of the incoming energy goes to target heating and secondary electron.**
- High rate sputter processes need **efficient cooling techniques to avoid target damage** from overheating which can cause a serious problem.
- The sputtered species, in general, are predominantly **neutral or not charged particles.**
- The energies of the atoms or molecules sputtered at a given rate are about one order of magnitude higher than those thermally evaporated at the same rate, which often leads to **better film quality.**
- However, since sputtering yields are low and the ion currents are limited, **sputter-deposition rates are invariably one to two orders of magnitude lower** compared to thermal evaporation rates under normal conditions. **Sputter yield is dependant on various factors.**

Sputter Yield

- Sputter yield is the number of sputtered atoms per bombarding (impinging) ion. The higher the yield, the higher sputter deposition rate
- The yield is rather insensitive to the target temperature except at very high temperatures where it shows an apparent rapid increase due to the accompanying thermal evaporation
- The sputter yield depends on:
 - a) Ion energy**
 - b) Ion incident angle**
 - c) Ion mass**

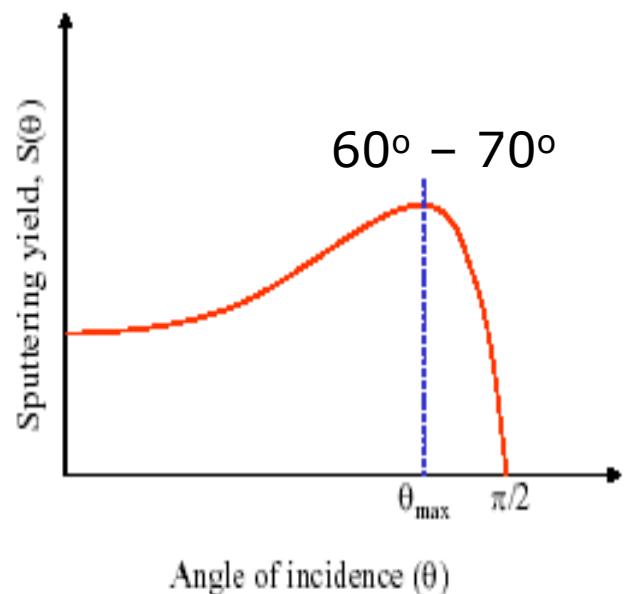
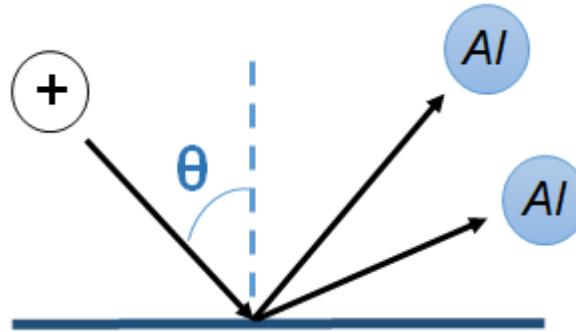
Dependence of Sputter Yield on Ion Energy

- The yield increases with the ion energy.
- For higher ion energies, the yield approaches saturation, which occurs at higher energies for heavier bombarding particles.
- Sometimes, at very high energies, the yield decreases as argon ions penetrate into sputter target (i.e. atoms beneath the target surface are unable to reach the surface to escape).

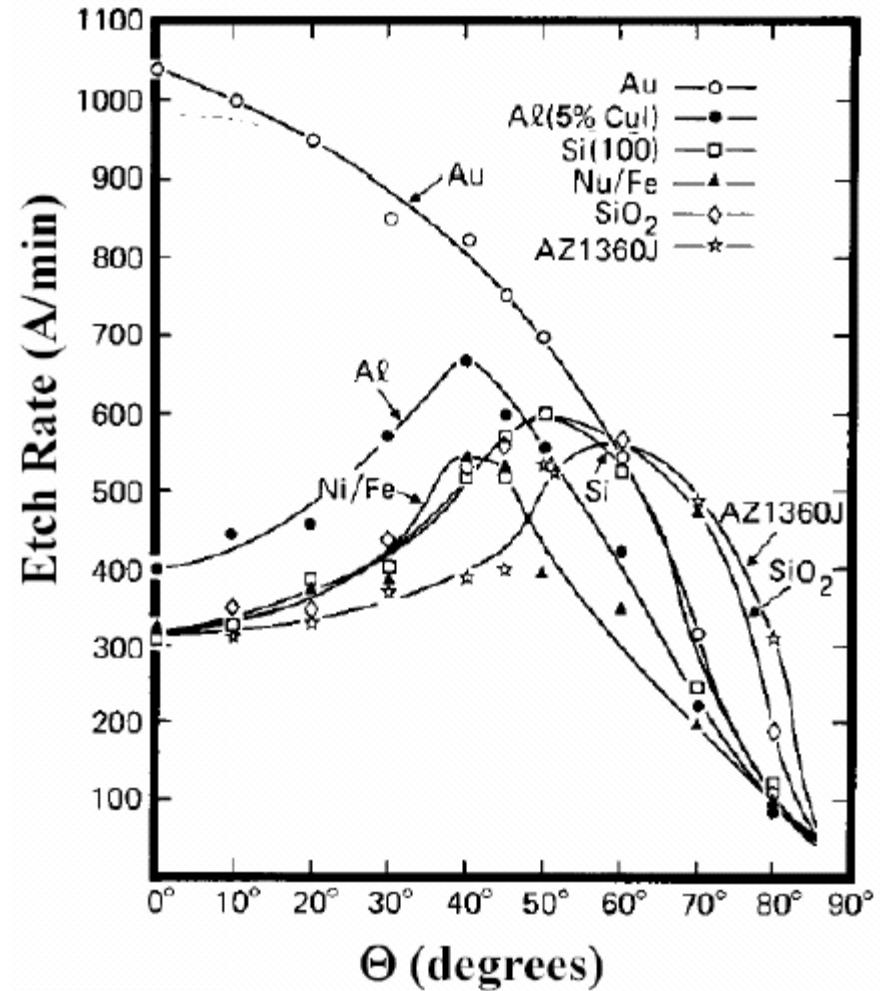


Dependence of Sputter Yield on Ion Incident Angle

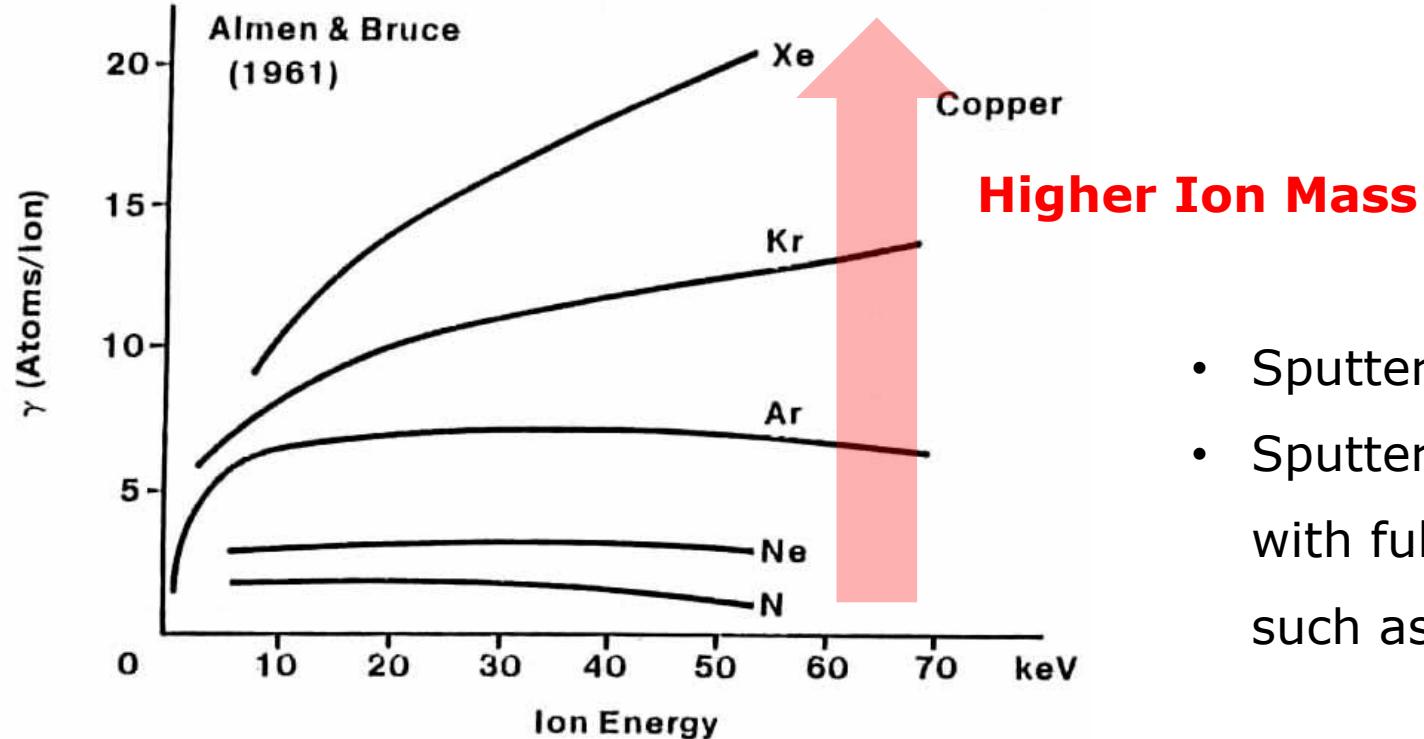
- The yield with increasing obliqueness (θ) of the incident ions
- However, at large angles of incidence, the surface penetration effect decrease the yield drastically
- An optimal angle is needed to achieve high sputtering yield



Sputter yield on Si target using Ar gas



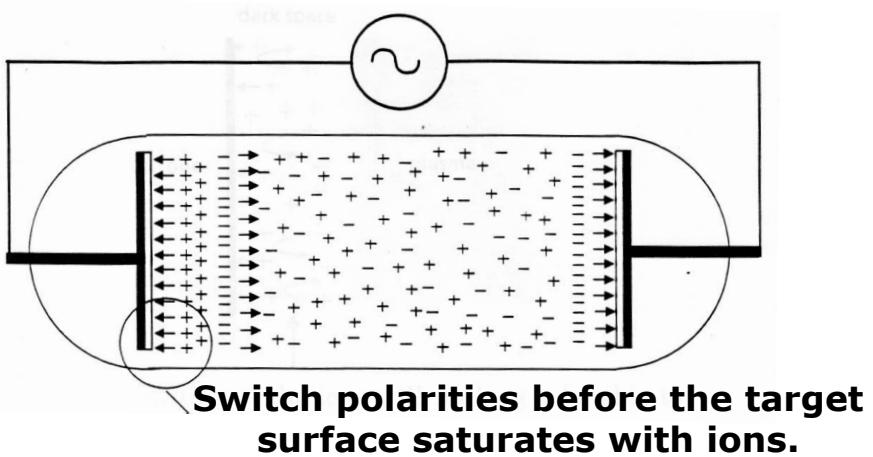
Dependence of Sputter Yield on Ion Mass



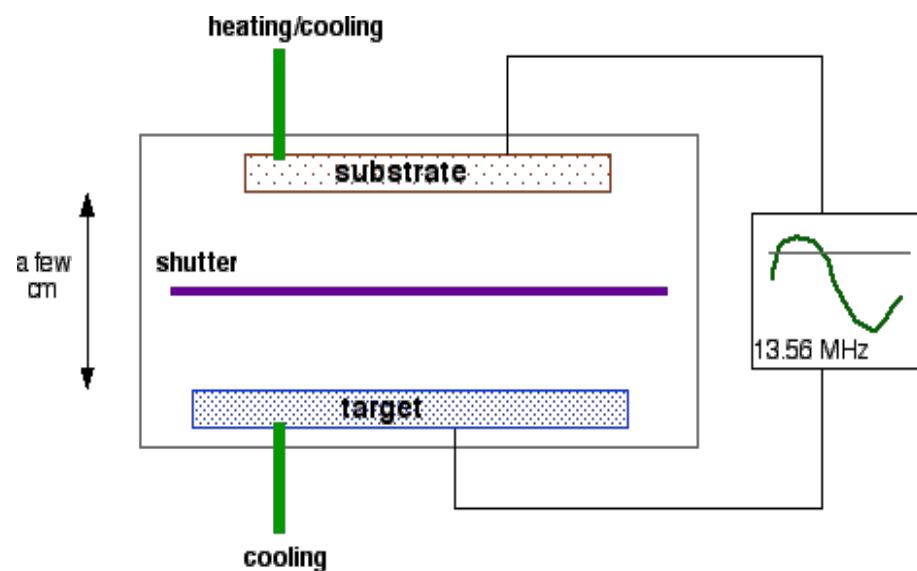
- Sputter yield increases with ion mass
- Sputter yield is at its maximum for ions with full valence shells. Noble gasses such as Ar, Kr, and Xe have large yields.

Sputtering yields of the noble gases on copper, as a function of energy.

RF (Radio Frequency) Sputter Deposition



- DC sputtering system is unable to sputter insulating/ dielectric materials.
- To resolve this issue, additional Radio Frequency (RF) potential is applied to the cathode (target) of the sputtering system.
- Positive charge (Ar^+) builds up on the cathode (target) in DC sputtering systems. Alternating potential can avoid charge build-up.
- Sputtering of insulator become possible because of the RF on the target.



Magnetron Sputter Deposition

Issues

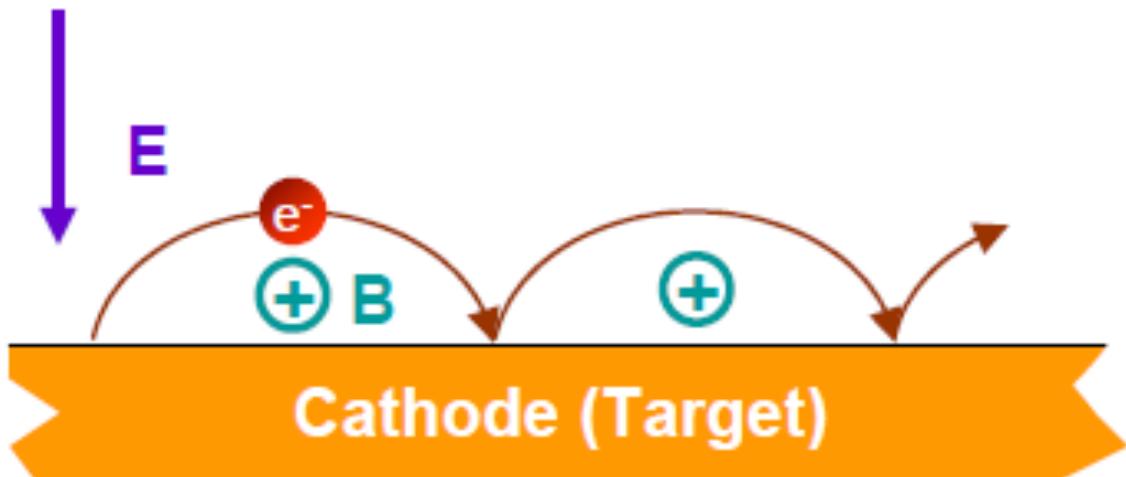
- **Low ionisation efficiency in electron-argon gas collision:** In DC & RF sputtering, the efficiency of ionisation from energetic collisions between the electrons and gas atoms is low. Most electrons lose energy in a non-ionising collisions or are collected by the electrodes. Hence, deposition rates are low.
- **Slight increase in efficacy by RF:** Oscillating RF fields only gives slight increment on the ionisation efficiency.

Solution

- **Magnets used to increase argon ionisation:** To increase deposition rates, magnets are used to increase the percentage of electrons that take part in ionisation events, increasing the ionisation efficiency.
- **The magnetic field causes electrons to move spirally:** Magnetic field is applied perpendicularly to an electric field, to trap electrons near the target surface. It will cause them to move in a spiral motion until they collide with an Ar atom.
- **The ionisation and sputtering efficiencies are increased significantly** - deposition rates increase by 10-100 \times , to 1 μm per minute.

Magnetron Sputter: High Density of Plasma Near Target

The orbital motion of electrons increases the probability of collision with neutral species and create ions.



- In magnetron sputtering, magnets are employed to capture and restrict the electrons in front of the target
- Increase the ion bombardment rate on the target, produce more secondary electrons, increases the ionisation rate in the plasma
- More ions cause more sputtering of the target which increases the deposition rate without increasing the chamber pressure
- Higher deposition rate

Advantages and Disadvantages of Sputter Deposition

Advantages:

- Able to deposit a wide variety of metals, insulators, alloys, and composites
- Able to deposit compound/ alloy thin film – the film has the same composition as the sputter target
- Better film quality (densified) and step coverage than evaporation. This is partly because adatoms are more energetic
- More reproducible deposition control – same deposition rate for same process parameters (not true for evaporation), so easy film thickness control via time
- Can use large area targets for uniform thickness over large substrates
- Sufficient target material for many depositions
- No x-ray damage

Disadvantages/ Limitations:

- Substrate damage due to possible ion bombardment
- Higher pressures 1 –100Mtorr ($< 10^{-5}$ torr in evaporation), more contaminations unless using ultra clean gasses and ultra clean targets
- The deposition rate of some materials quite low
- Most of the energy incident on the target becomes heat, which must be removed



Comparison between Evaporation and Sputtering

Properties	Evaporation	Sputtering
Rate	1,000 atomic layer/s	1 atomic layer/s
Thickness control	Possible	Easy
Materials	Limited	Almost unlimited
Contaminants	Low	High
Surface roughness	Little	High (ion bombardment)
Adhesion	Medium	Good (higher energy adatoms)
Film properties	Difficult to control	Can be controlled
Step coverage	Poor	Good
Equipment cost	Medium	Expensive

Lesson Summary - PVD

- Step coverage and trench filling are important figure of merit in a thin film deposition, where trench filling is highly dependent on the aspect ratio of the trench.
- PVD can be carried out using evaporation technique or sputtering technique.
- Evaporation technique can either be carried out using thermal evaporation or electron beam evaporation.
- For sputtering process, high energetic argon ions are used to dislodge atoms from target materials for deposition.
- Sputter yield depends on ion energy, ion mass, and the incident angle of the ion.
- RF sputtering can prevent charge accumulation on the substrate, hence, making dielectric deposition possible. However, magnetron sputtering induces spiral motion on ions, which increases the sputter yield.

Practice Question 1

Determine if the statements below are true or false.



- a) In a RF sputtering system, the Si wafer is placed on the cathode plate. False
- b) In a RF sputtering system, the target is placed on the anode plate. False
- c) In a RIE system, the Si wafer is placed on the cathode plate. True
- d) Sputter yield depends on ion incident angle. True
- e) Physical vapour deposition involves chemical reaction in the nucleation step. False

Pause and
try out this
question

Practice Question 2

In sputtering, the sputtered atoms condense and form a thin film on the wafer surface with



Pause and
try out this
question

- a) Different material composition than the target
- b) The same material composition as the plasma
- c) The same material as the target
- d) The same material composition as the incoming gas