Course: EE6601 / Advanced Wafer Processing

School: School of Electrical and Electronic Engineering

Lithography – Advanced Lithography

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Advanced Lithography – Lesson Overview

Advanced lithography:

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

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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)

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

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 $NA > 1$

⇨ $k_1 < 0.3$ achievable
CD: Critical Dimension

$NA = n \sin\theta$

Improvement in Resolution - Depth of Focus (DOF) Issue

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

DOF decreases as
$\boldsymbol{\lambda} \downarrow$

DOF decreases as
$\boldsymbol{k_2} \downarrow$

DOF decreases as
$\boldsymbol{NA} \uparrow$

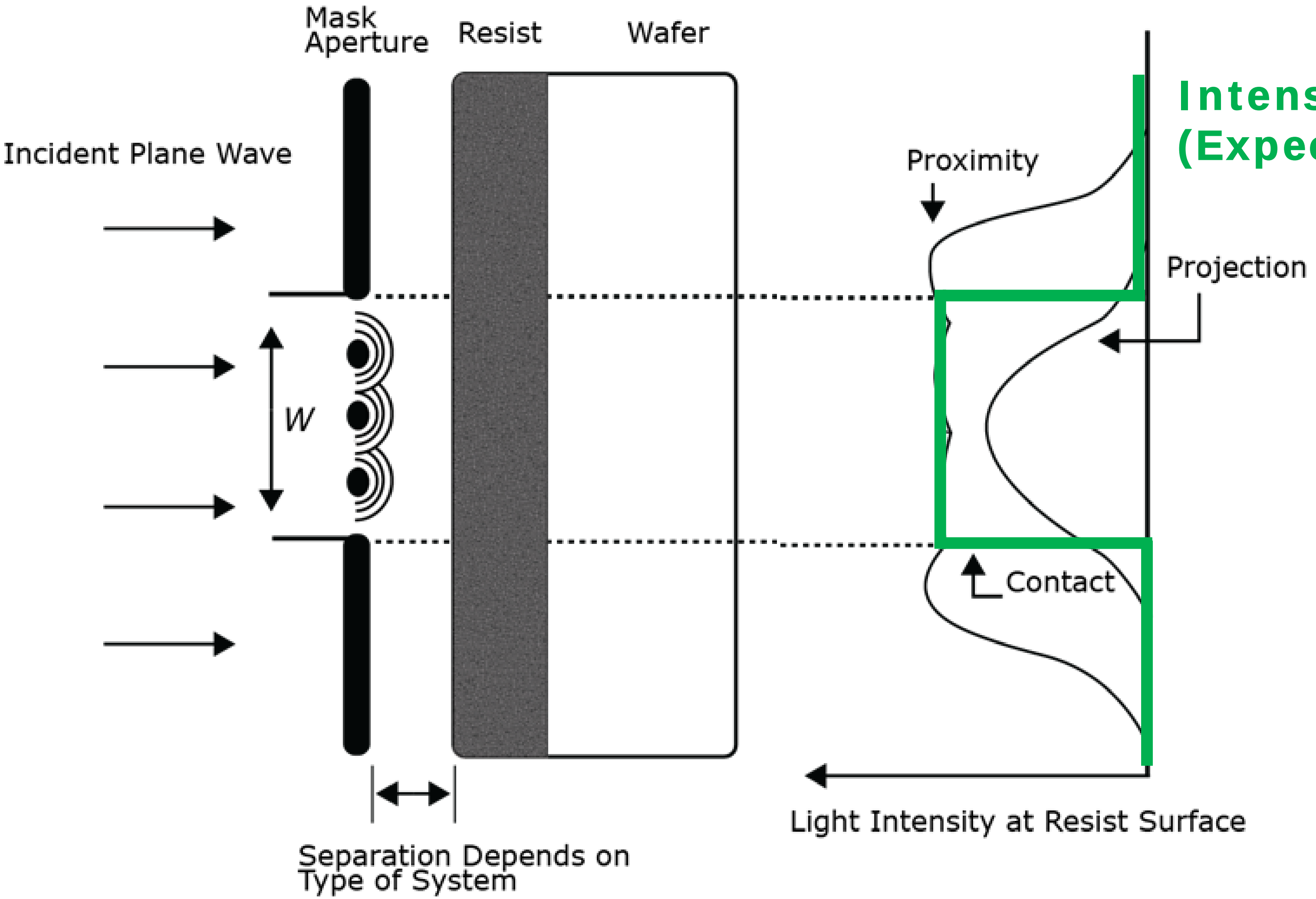
Nevertheless, wafers are made of PLANAR (very flat surface) with Chemical Mechanical Polishing (CMP) which allow the lithography systems to work with smaller DOF, resolving DOF issue.

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 to 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).

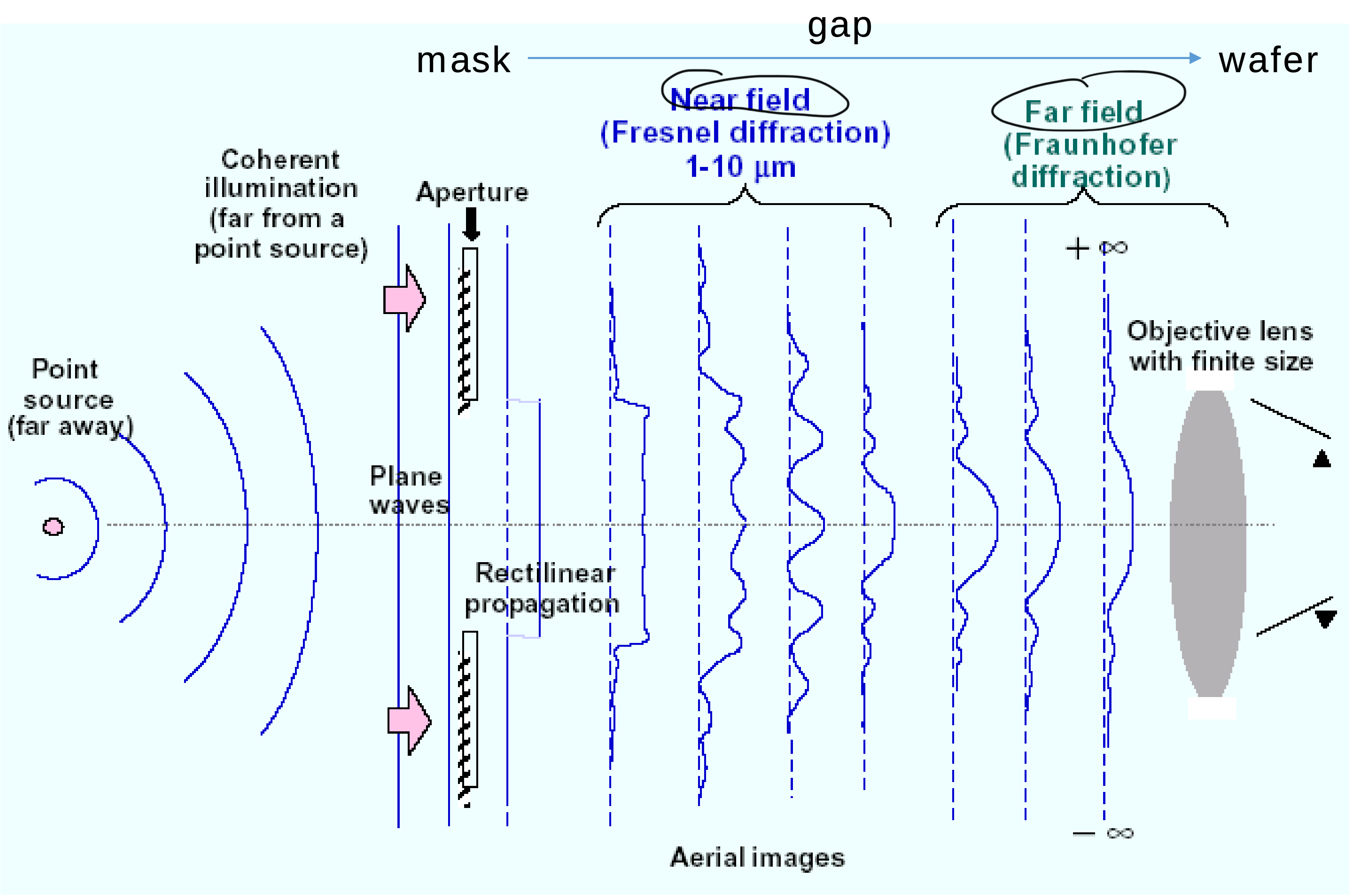
Diffraction in Lithography (Cont'd.)



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



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Optical Enhancement Technique

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

Phase Shift Mask (PSM)

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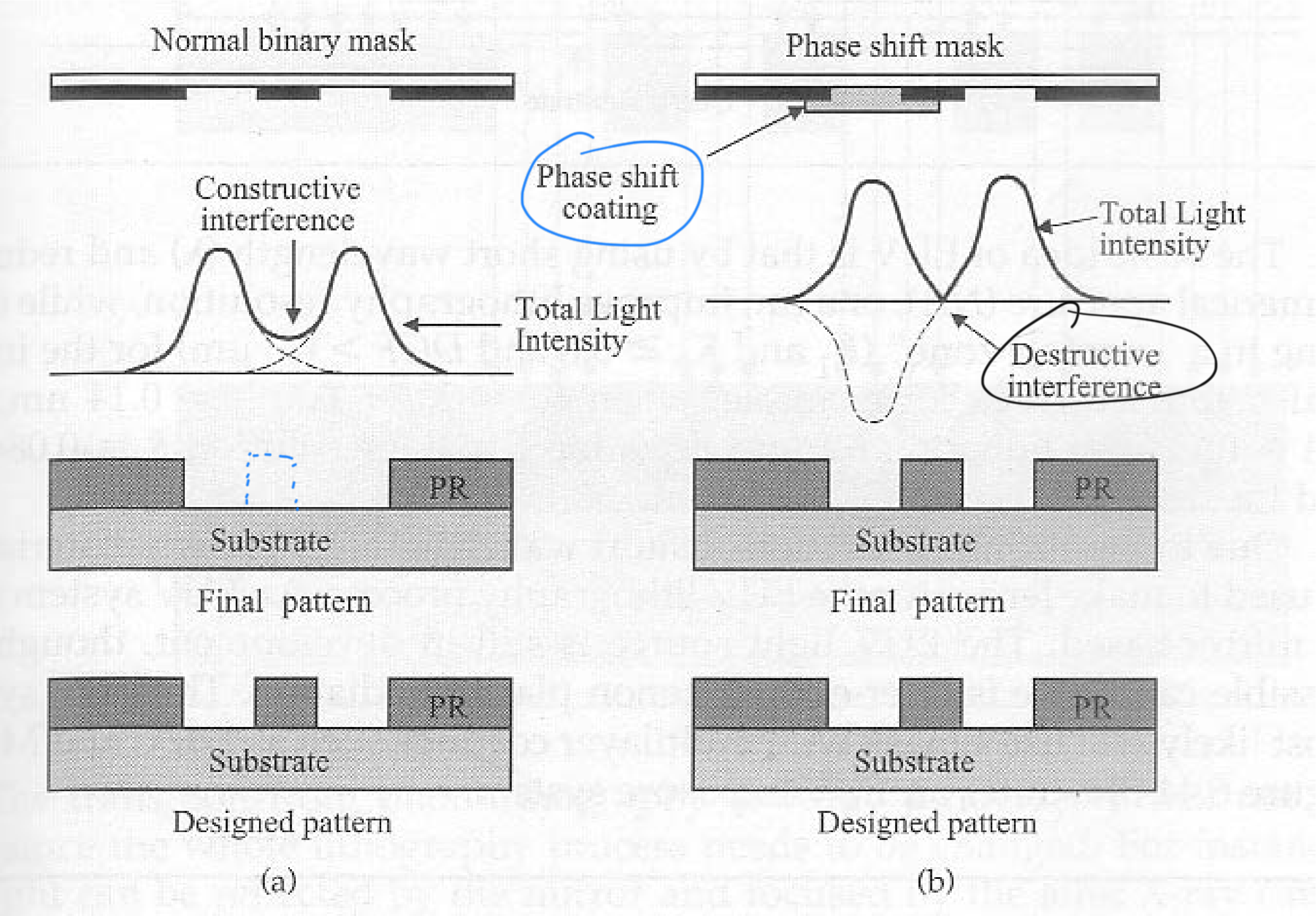


Phase-Shift Mask (PSM) is a method used to overcome problems associated with light diffraction through small openings patterned on the reticle.

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

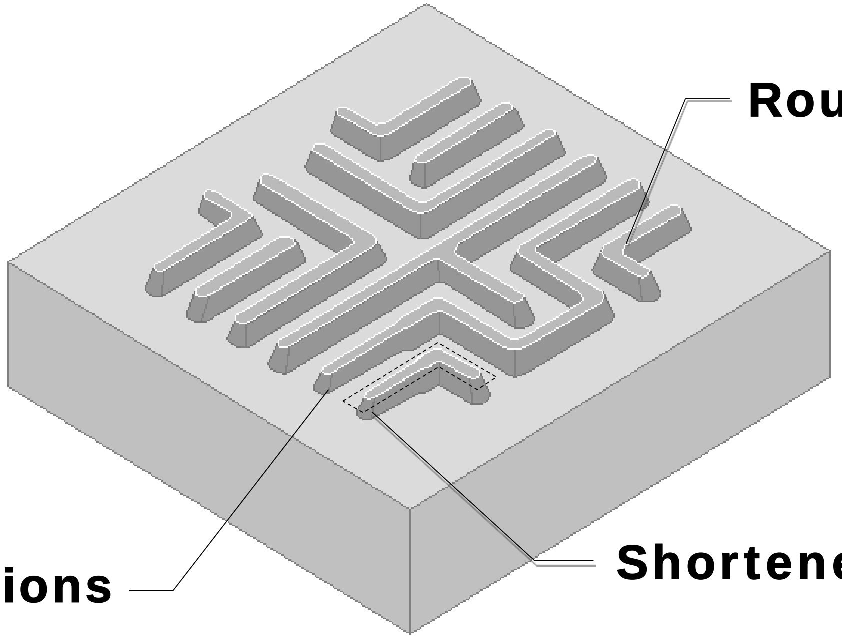
RV

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.

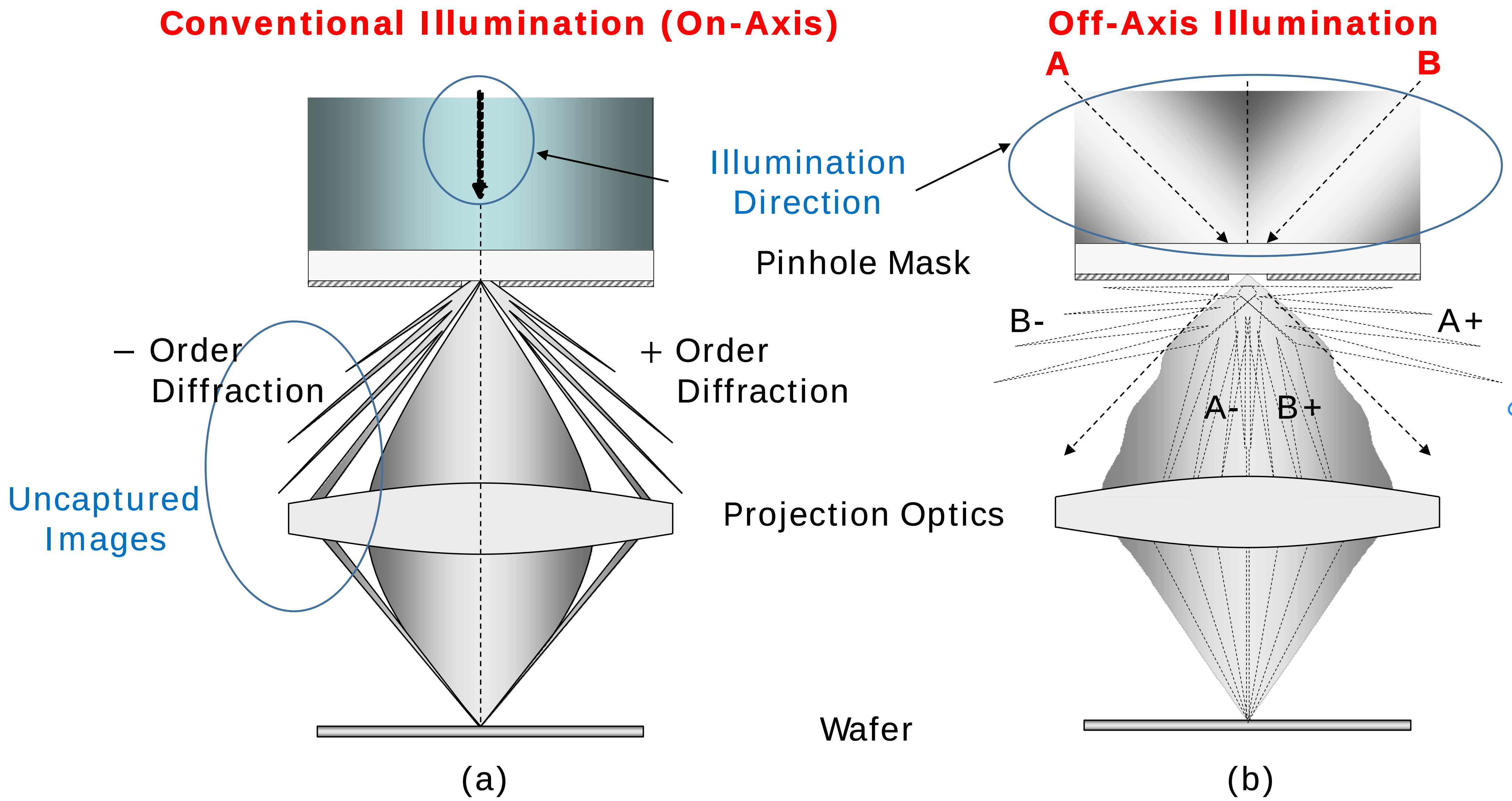
The approach involves adding extra features to the mask, usually at corners where features are sharp, to compensate for the high-frequency information lost due to diffraction effects.



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



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

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What is Immersion Lithography (IML)?

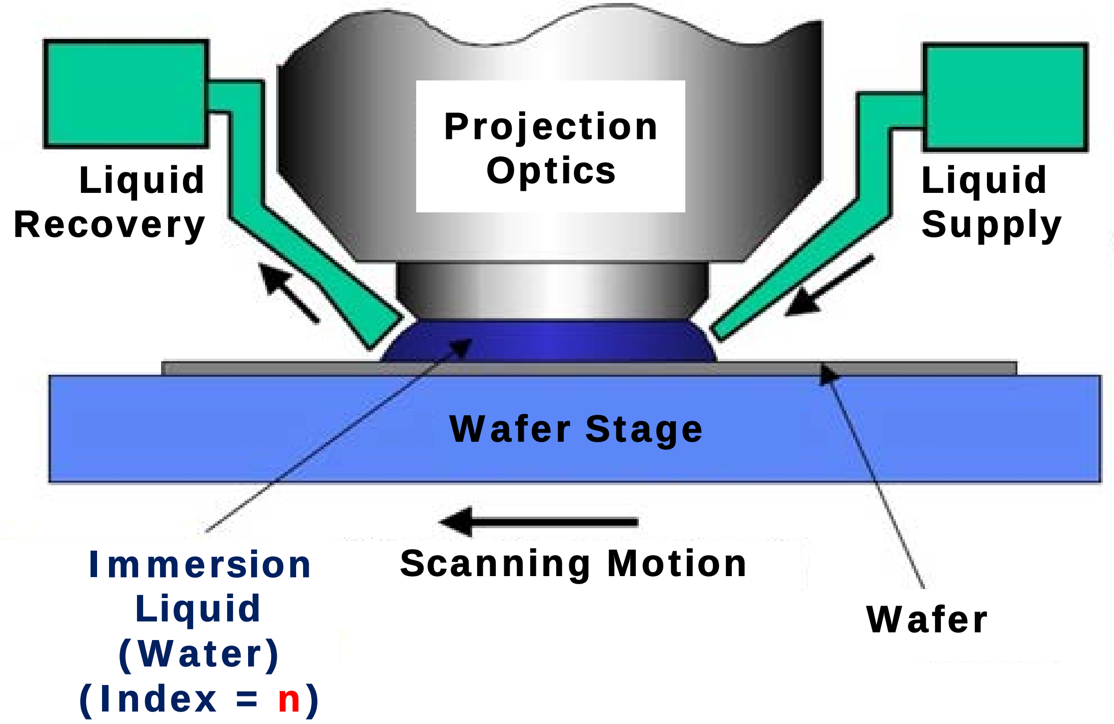
- **Approach 1:**
  - $\boxed{\text{Same lens column design}}$
  - Maintain resolution
  - Improve Depth of Focus (DOF)
- **Approach 2:**
  - $\boxed{\text{Modified lens column}}$: Hyper-NA (> 1.0)
  - Improve resolution
  - Lower DOF

design

NA ↑

W_{min} ↓

Resolution ↑



Immersion Lithography – Depth of Focus

Approach 1: Lens of same NA as in air

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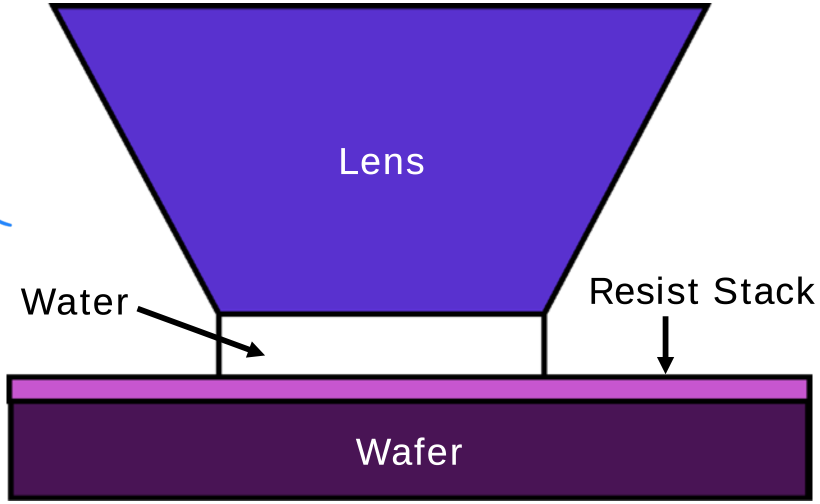
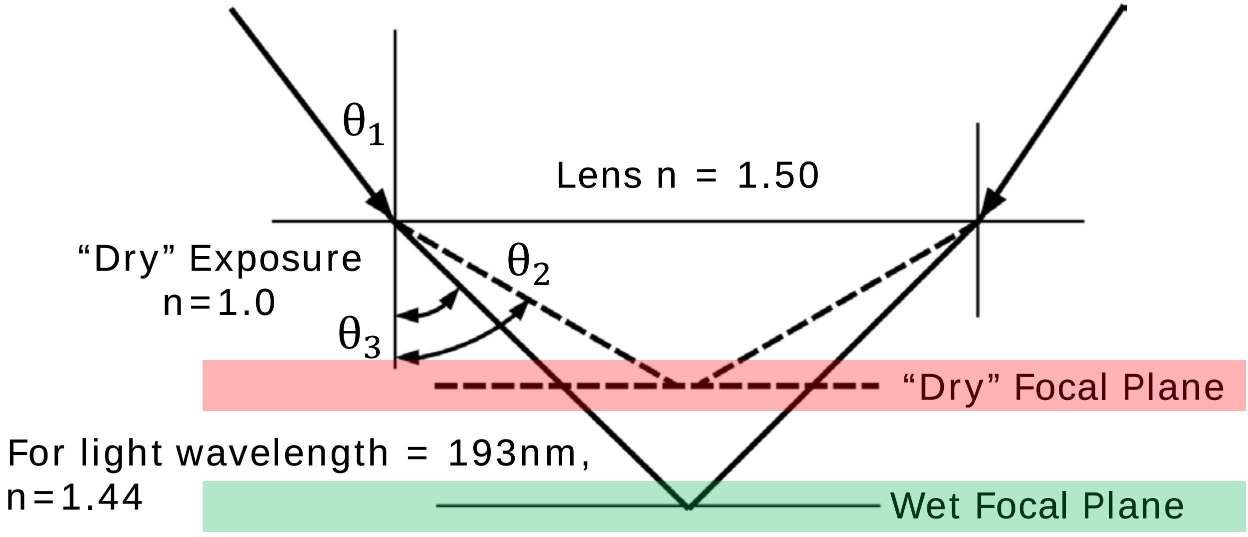




$$W_{min} = k_1 \frac{\lambda}{(NA)}$$ (Maintained)

$$NA = n \sin \theta$$

Improvement in DOF

$$\delta = \frac{nk\lambda}{(NA)^2}$$

Approach 2: Modified NA

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

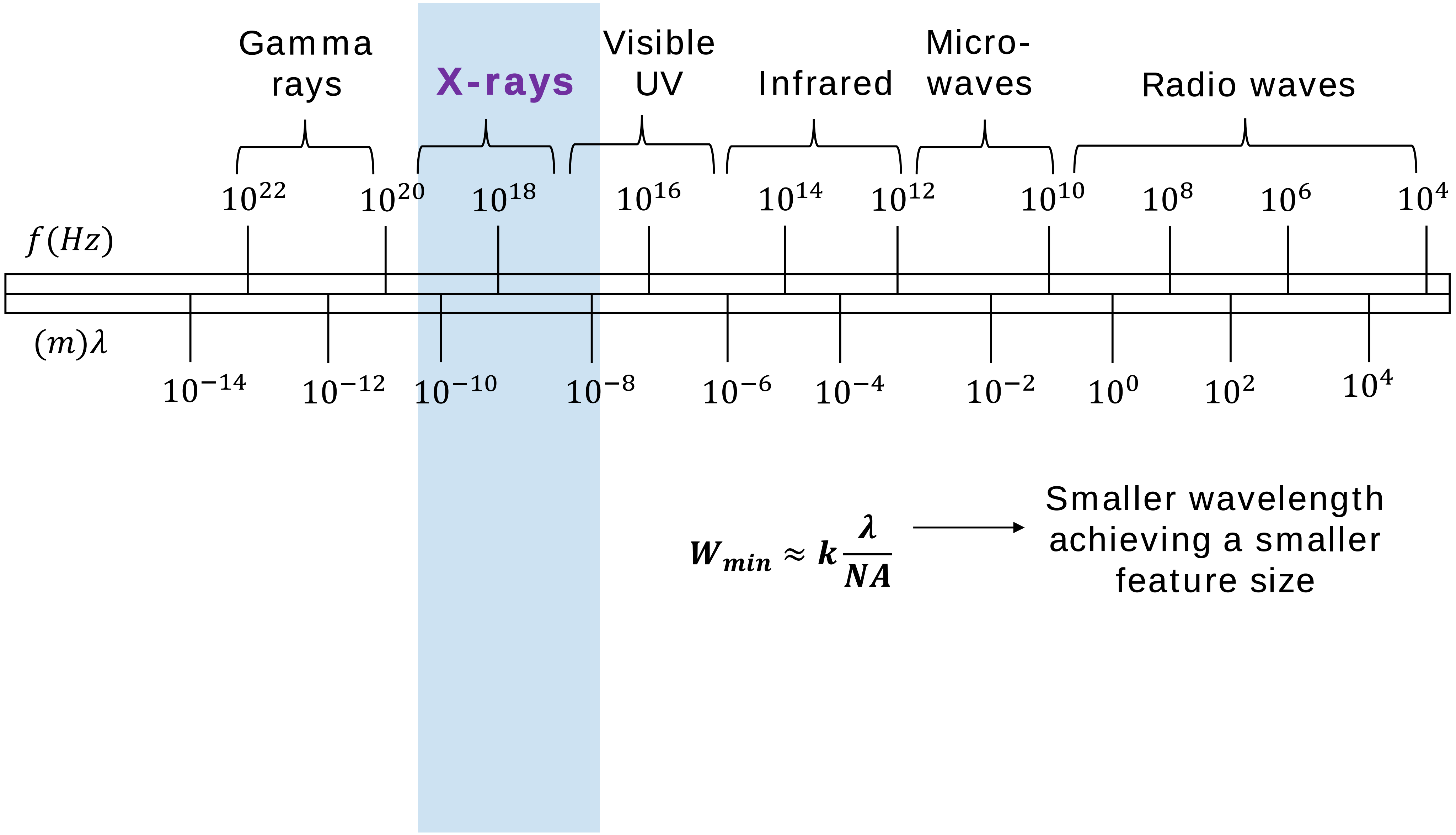
Higher resolution: $\downarrow W_{min} = \dfrac{k_1 \lambda}{NA} = \dfrac{k_1 \lambda}{n \sin\theta}$

NA ↑

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

X-Ray Lithography

X-Ray Lithography

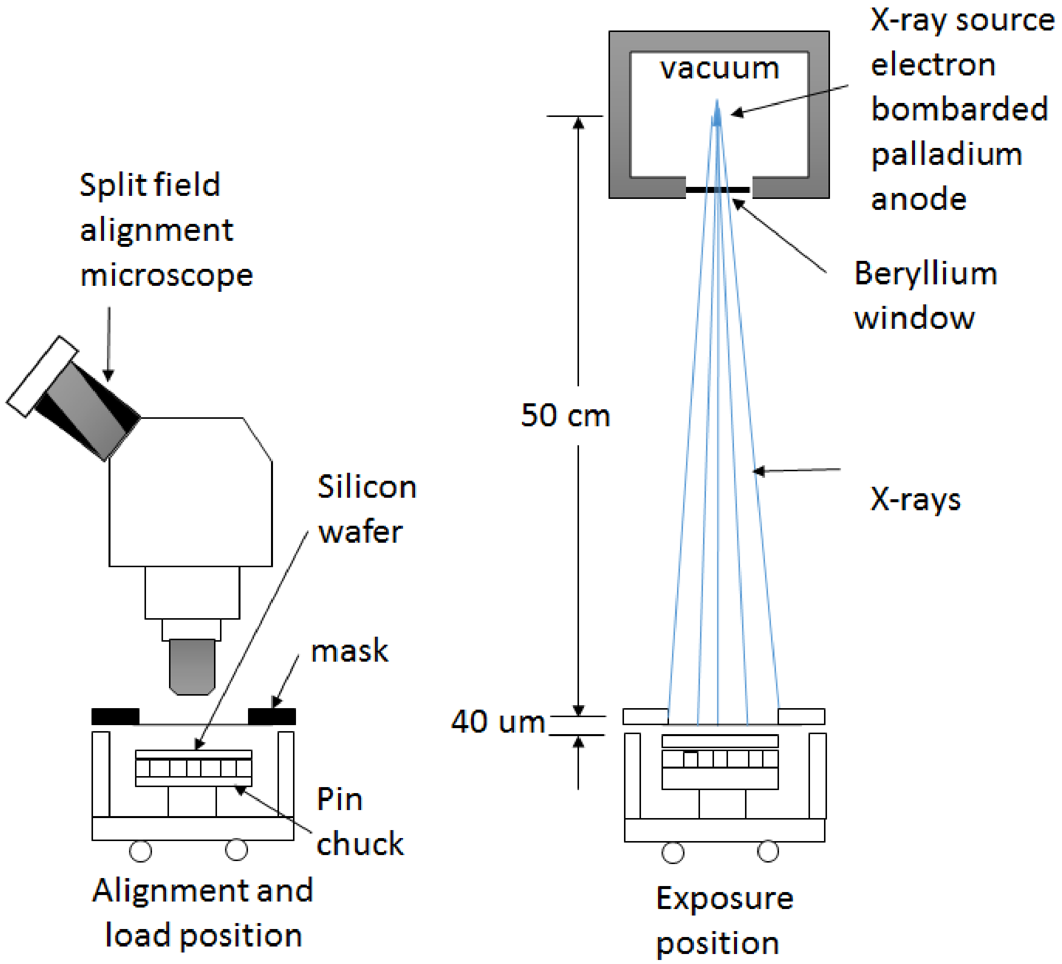


$$W_{min} \approx k\frac{\lambda}{NA} \longrightarrow$$

Smaller wavelength achieving a smaller feature size

Schematic of an X-Ray Lithography System

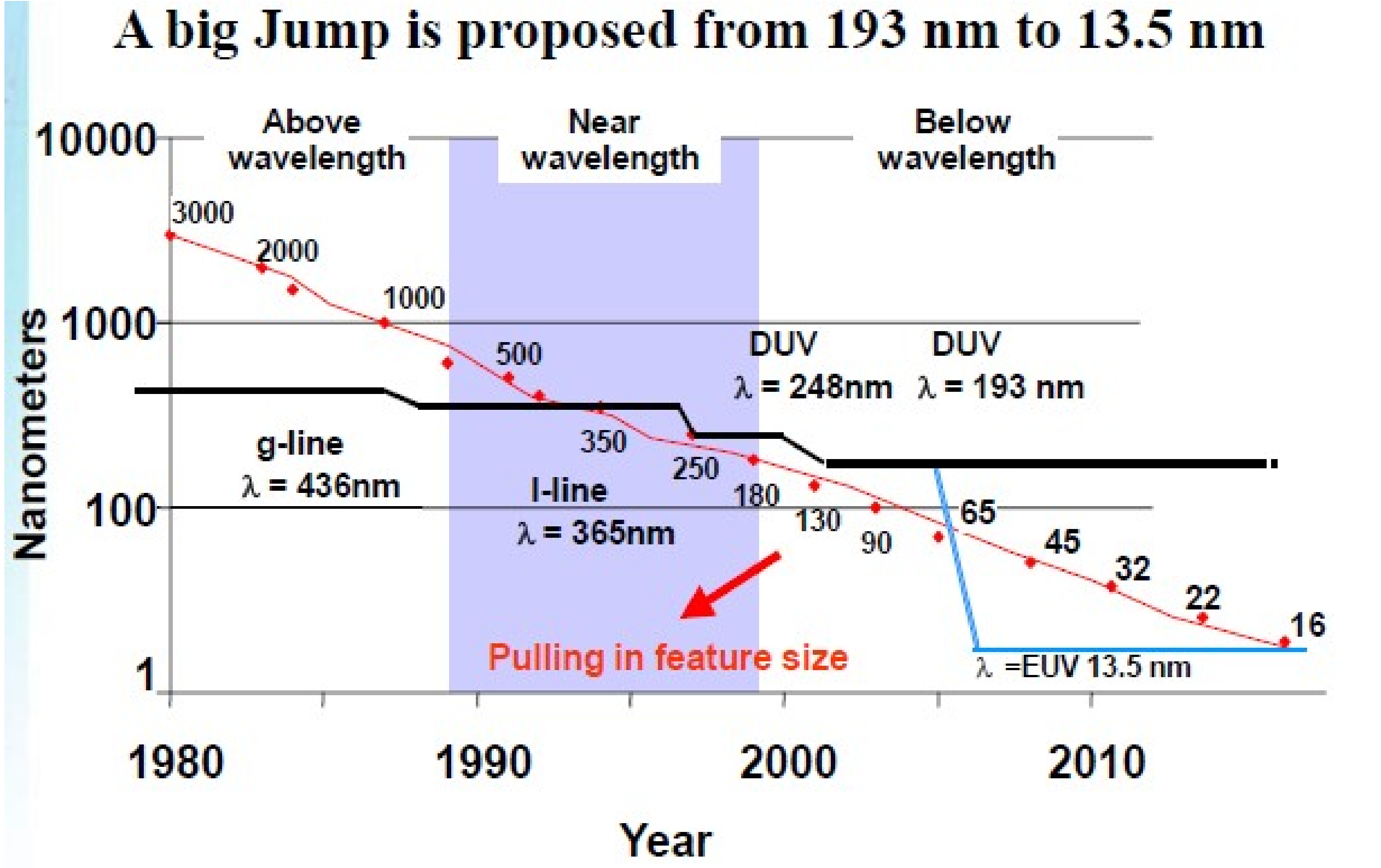
- λ ~ 1 nm (extremely short wavelength for high resolution)
- X-rays are produced by synchrotron radiation in a high energy electron storage ring.
- Contamination becomes less of a concern because X-rays will penetrate most dust particles (low atomic number).
- No need for vacuum (little absorption of 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 (< 30nm) due to small λ.



EUV Lithography

Extreme UV Lithography (EUV)

- The next great debate in lithography is the need to move to the next wavelength, 13.5 nm or extreme ultraviolet (EUV).



EUV -- Challenges of Introducing a New Litho Wavelength

Immersion (ArFi)	EUV
Water in Scanner	High Vacuum
Materials Interactions	New Wavelength (13.5nm)
Hyper-NA (>1)	Reflective Optics
Same Wavelength	New Mask
Same Masks	No Pellicle
Same Resists	New Resists

- Immersion presented many challenges, but many elements ported for dry ArF
- EUV is a significantly more challenging endeavour, requiring more innovative comprehensive solutions

Extreme UV Lithography (EUV)

- Considerable challenges for the further extension of 193 nm lithography beyond 40 nm half-pitch memory designs in both the development of high-index materials to drive NA beyond 1.35, and in further extension of low-k1 technology through double patterning.

EUV

- Light source with λ = 13.5 nm
- 13.5nm light is absorbed by all materials
- Purely reflecting optics system including mask
- Each mirror consists of multilayers of Mo and Si and can both be used for reduction (usually 4x) and as mask
- Supports Resolution Enhancement Techniques
- Vacuum Operation
- Recent demonstration in an EUV system has showed that 200 nm features can be patterned as 35 nm on wafer
- Strong support from many manufacturers
- EUV system will cost 40M USD

Extreme UV Lithography (EUV)

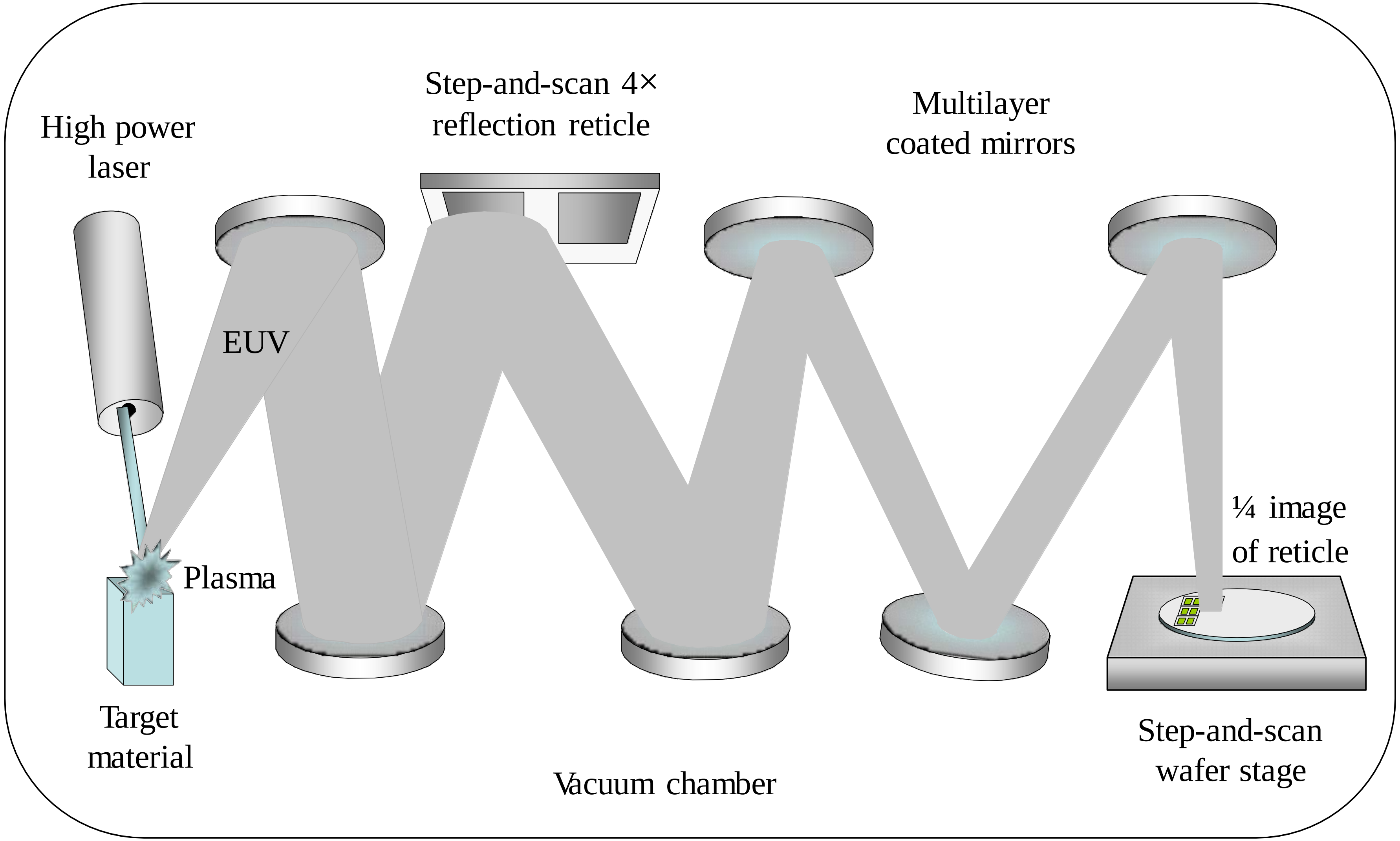
<u>How EUV Works:</u>

- **Uses light of extremely short wavelength (~13.5nm).**
  - **Principle of High Harmonic Generation (HHG)**
  - **focuses a conventional laser into a gas to produce high harmonics of the fundamental laser frequency.**
- **Images are produced by reflecting light off a series of mirrors, off a mask, then off another series of mirrors onto a wafer.**
  - **Mirrors are used in place of lenses due to high absorption at short wavelengths.**
- **The reflection process reduces the patterned image 4X.**
- **Shorter EUV wavelength has better resolution than conventional DUV.**
- **Features down to 35nm can be printed.**

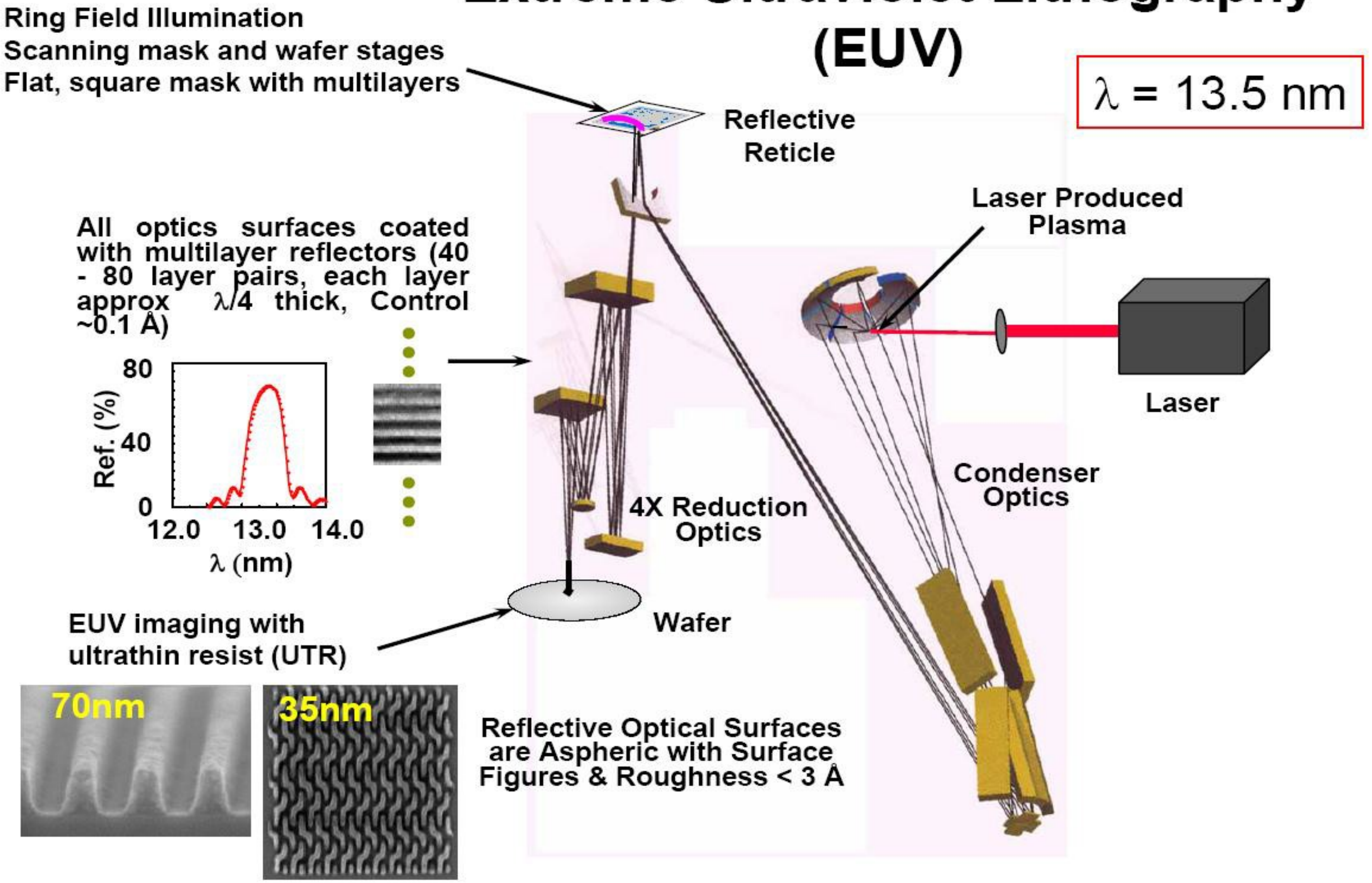
Challenges for EUV:

- source power
- optics lifetime
- resist sensitivity
- mask defectivity

Concept for Extreme Ultraviolet Lithography

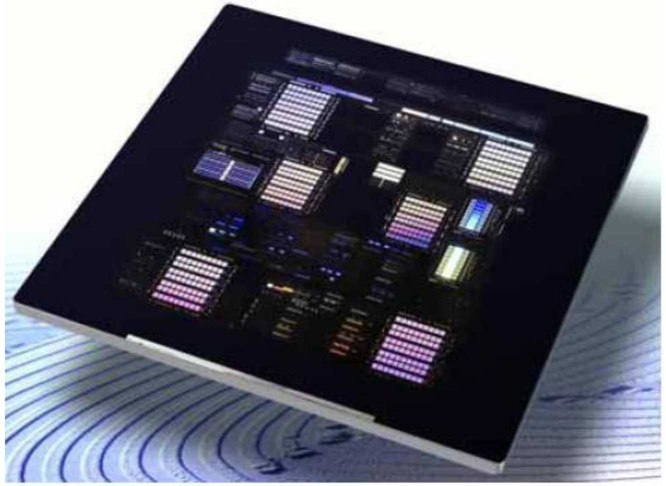


Extreme Ultraviolet Lithography (EUV)

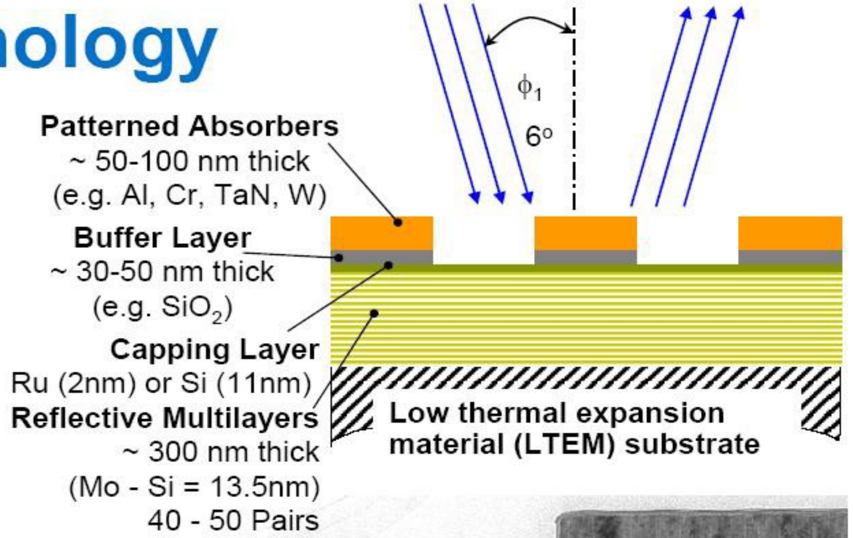


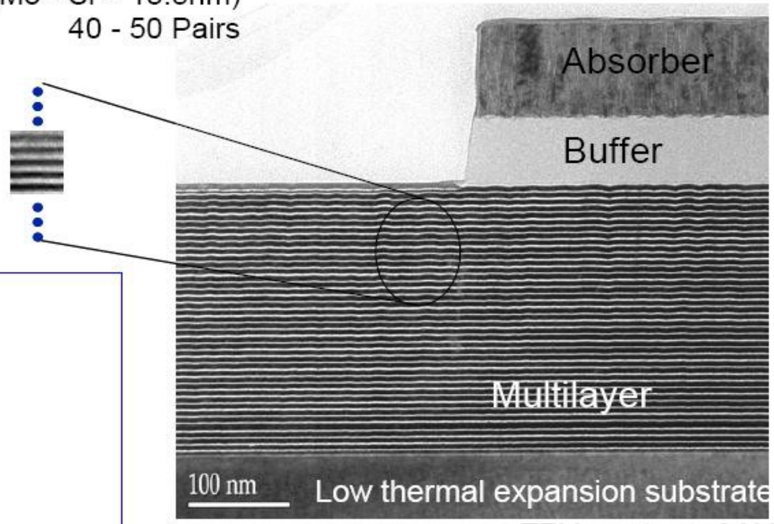
HectorSematech

EUV Mask Technology



Full Field 6” EUV Mask with 100-nm node CMOS
Multilayers: Mo - Si
Absorber Stack: Cr/SiON
120 mm x 104 mm field size
(Courtesy of P. Mangat & S. Hector, Motorola)



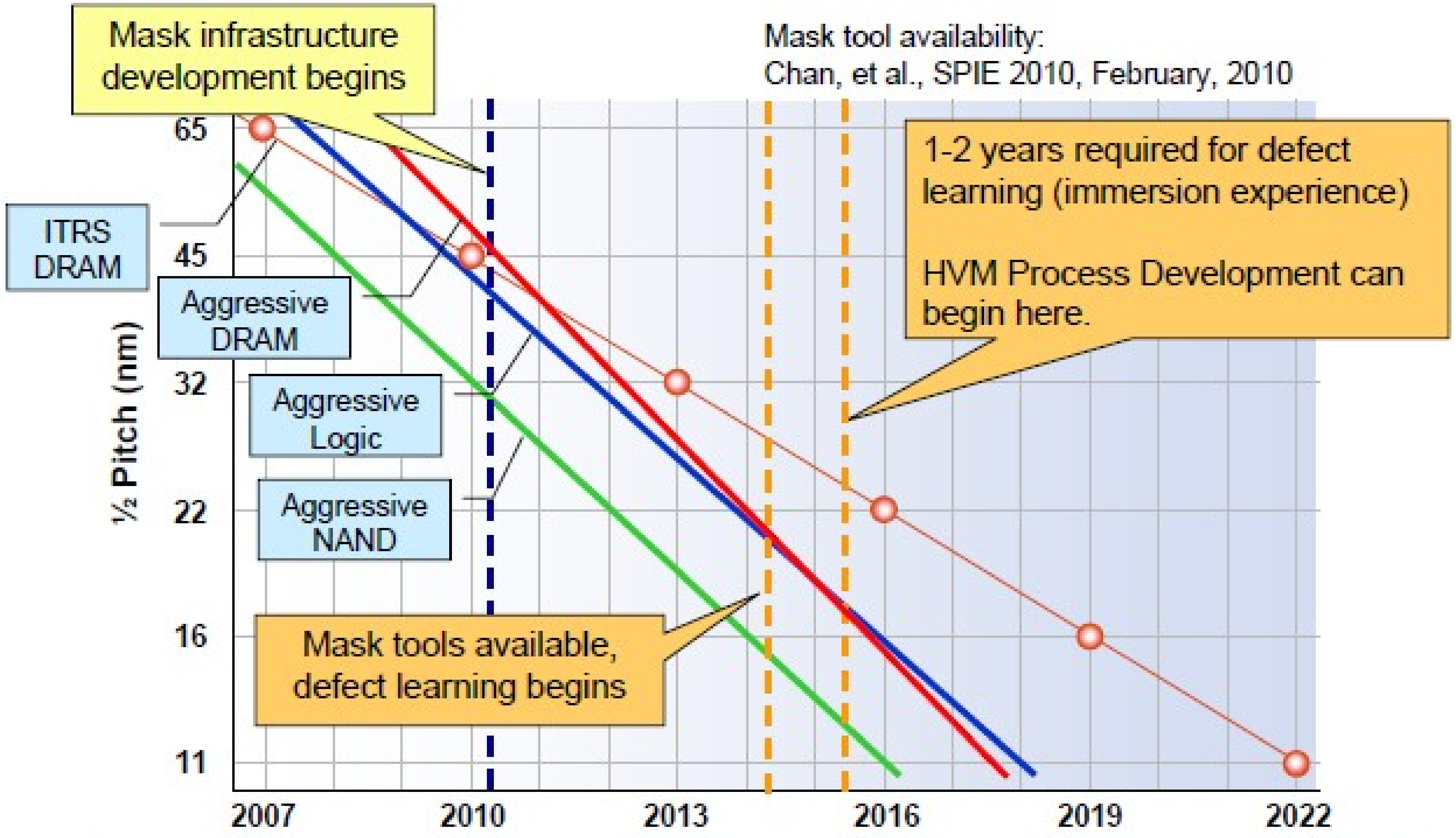


TEM courtesy of AMD

- Key challenges for EUV mask multilayers
  - High uniformity of thickness
  - No printable defects
  - Temperature stability

Hector/Sematech

EUV Infrastructure Schedule



Delays in infrastructure continue to push out adoption of EUV → increased cost and longer ROI for equipment makers

Nikon

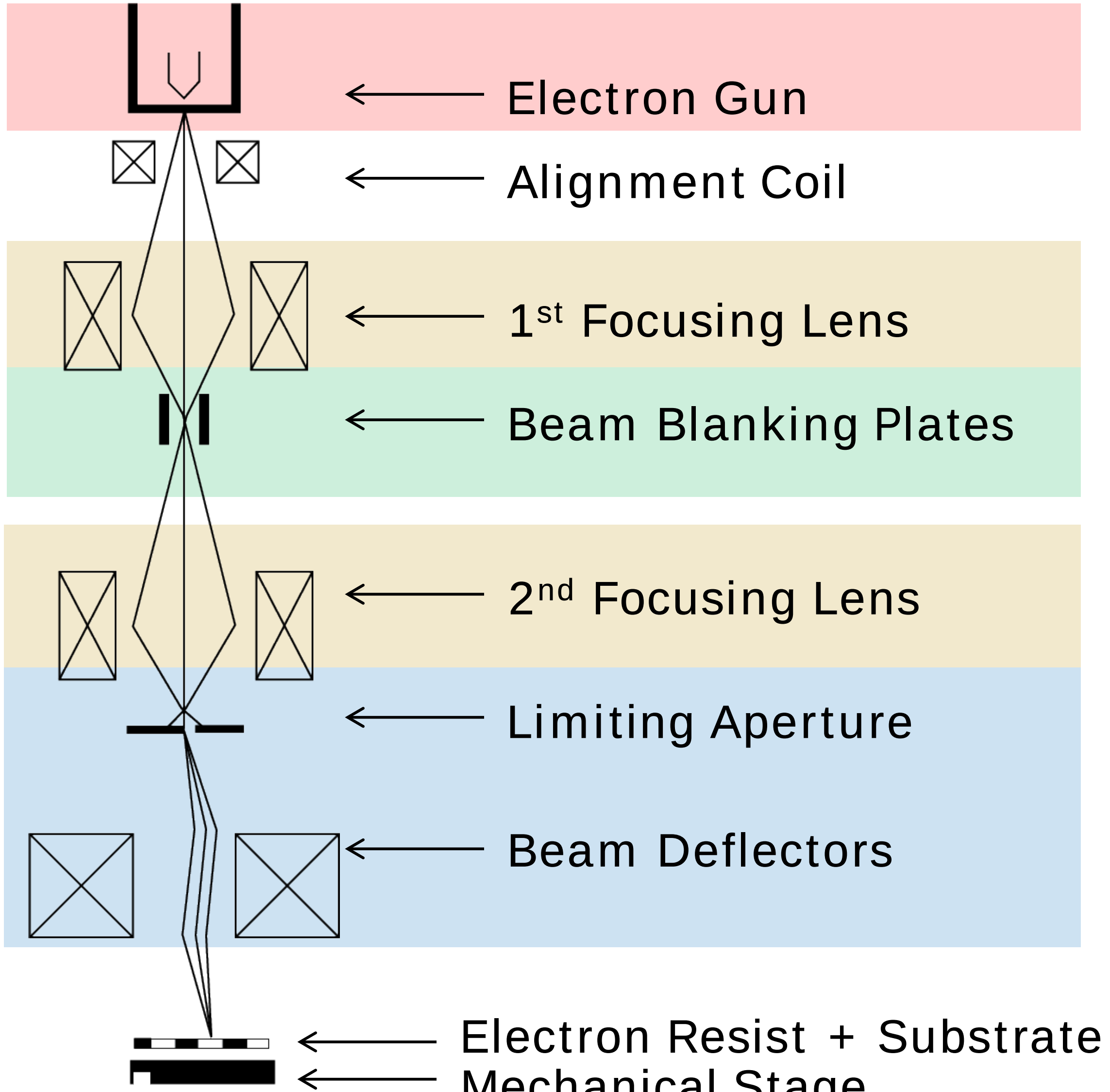
E-Beam and SCALPEL Lithography

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)

no mask



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.

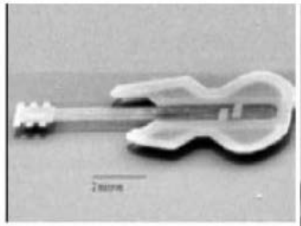
De Broglie wavelength of electrons

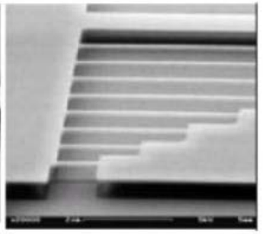
remember

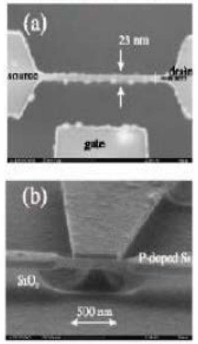
$$\lambda = \frac{h}{\sqrt{2meV}}$$

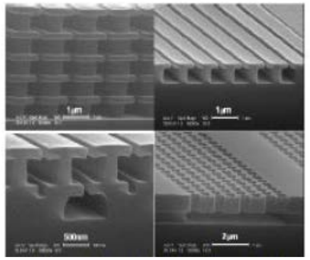
Where m is the mass of electron, e is electronic charge, h is Plank's constant.

Nanofabrication by E-Beam Lithography









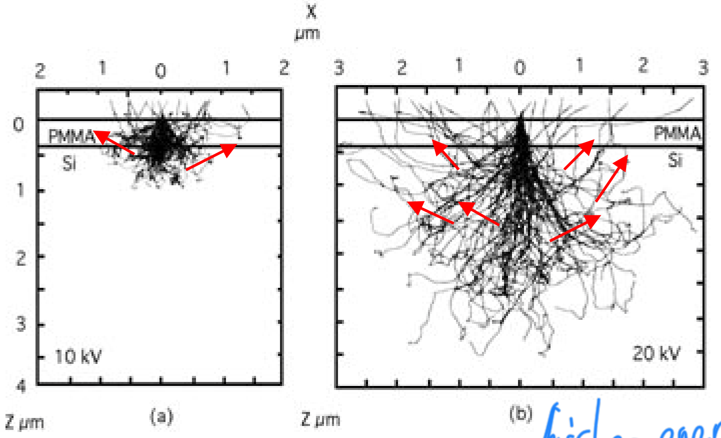
Advantages

- 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

expensive

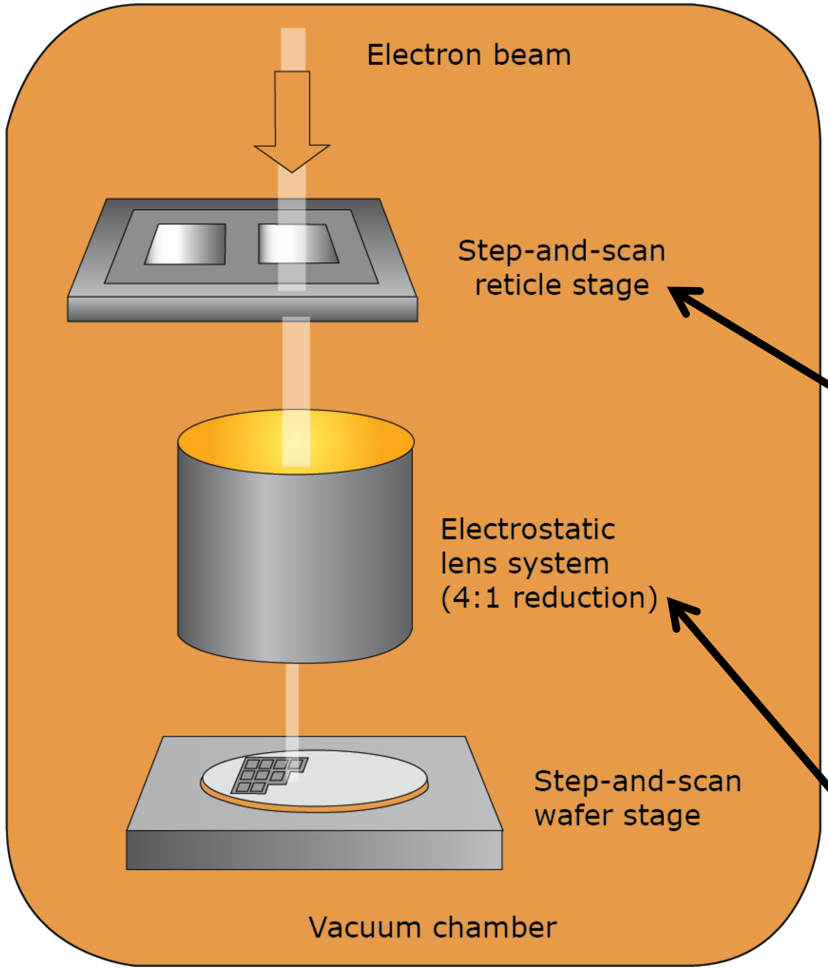
- Requires ultra-high vacuum system to drive electrons effectively
- Very sensitive to electronic and mechanical noise
- Proximity effect - resolution degrades due to backscattering of electrons within the resist surface



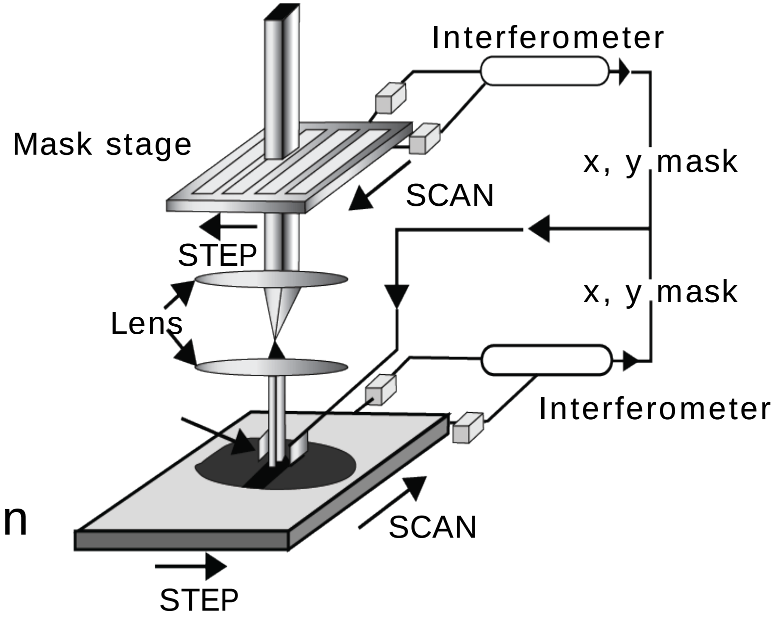
higher energy worse

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 <u>not</u> considered a viable lithography method for the next generation lithography?

a) Optical lithography

b) Extreme UV (EUV)

c) SCALPEL

d) X-ray lithography

Pause and try out this question

read carefully

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.

a) Determine the smallest feature size that is possible with this system for an allowable proximity gap of 0.6um.

b) 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

a) For smallest feature size, use 365nm (i-line),

$$W_{\min} = \sqrt{k\lambda g} = \sqrt{365x10^{-9} \times 0.6x10^{-6}}$$

$$= 4.68x10^{-7}\,m$$

b) If 436nm (g-line) is used,

$$g = \frac{(W_{\min})^2}{k\lambda} = \frac{(1.5x10^{-6})^2}{436x10^{-9}}$$

$$= 5.16x10^{-6}\,m$$

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 carefully

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)

$W_{min}^2 = k\lambda g$

$\uparrow g = \frac{W_{min}^2}{k\lambda \downarrow}$

Practice Question 4

Pause and try out this question

read carefully

What are the advantages and disadvantages for X-ray?

Advantages of X-ray lithography

- High resolution
- Reduced diffraction effect   small λ wavelength

Disadvantages of X-ray lithography

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