Nanometer Scale Patterning and Processing

Spring 2016

Lecture 15

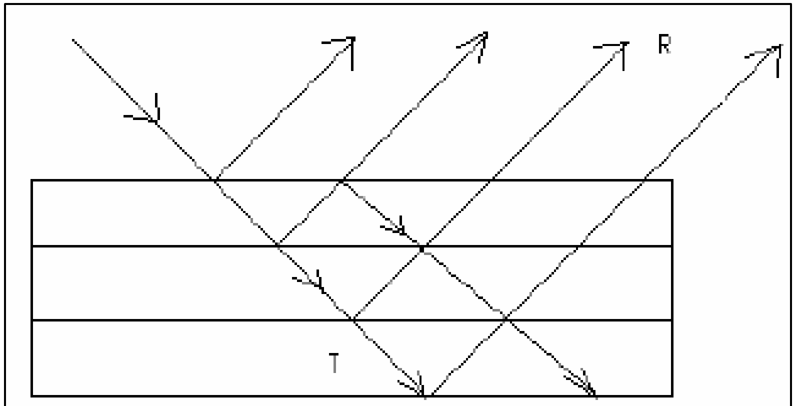
Extreme UV (EUV) Lithography – Optics, Mask, Resist, and Contamination Control

Extreme UV (EUV) lithography

1. Overview, why EUV lithography?
2. EUV source (hot and dense plasma).
3. Optics (reflection mirrors).
4. Mask (absorber on mirrors).
5. Resist (sensitivity, LER, out-gassing).
6. Contamination control.

Optics for EUV lithography (EUVL): overview

- All solids, liquids, and gasses absorb 13.5nm photons, so no longer refracting lens.
- A beam of EUV light is absorbed in 100nm of H_2O.
- Even worse, conventional optical devices will not reflect EUV light.
- EUVL uses concave and convex mirrors coated with multiple layers of molybdenum and silicon -- this coating can reflect nearly 70 percent of EUV light at 13.5nm.
- The other 30 percent is absorbed by the mirror.
- Without the coating, light would be almost totally absorbed before reaching the wafer.
- The mirror surfaces have to be nearly perfect - even small defects in coatings can destroy the shape of the optics and distort the printed pattern in resist.

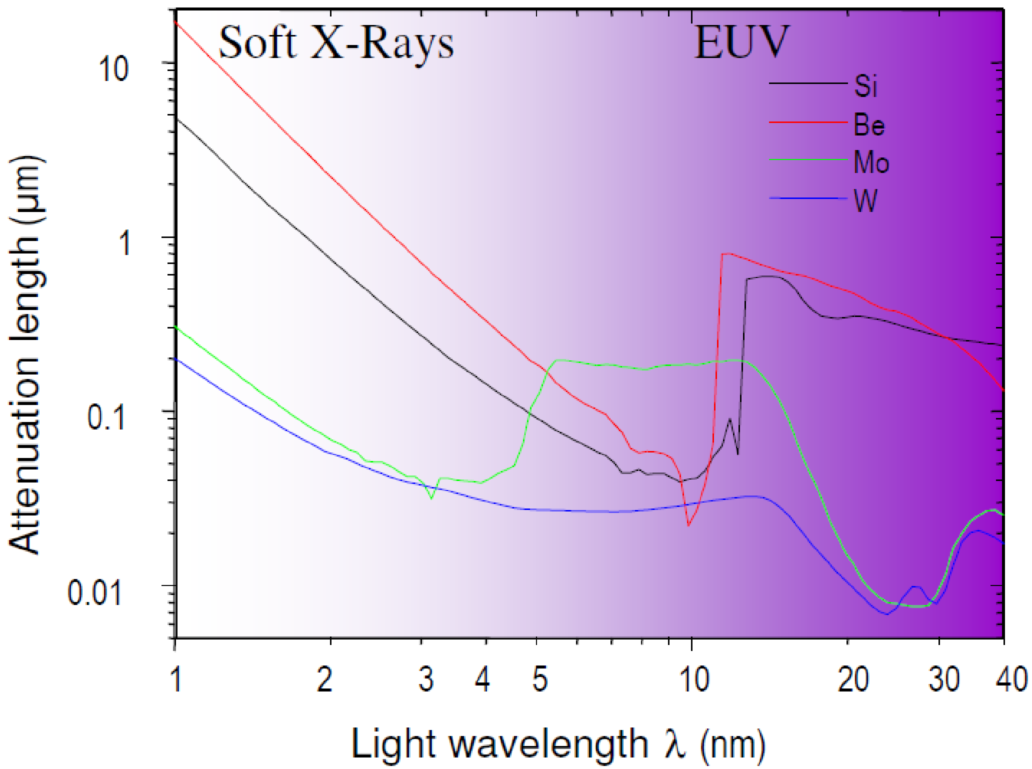


Multiple reflections

If the thicknesses and compositions of all films are carefully controlled, the reflected light will *constructively* interfere resulting in the brightest possible reflection.

Why Si/Mo and 13.5nm?

Absorption in solids for EUV and soft x-rays

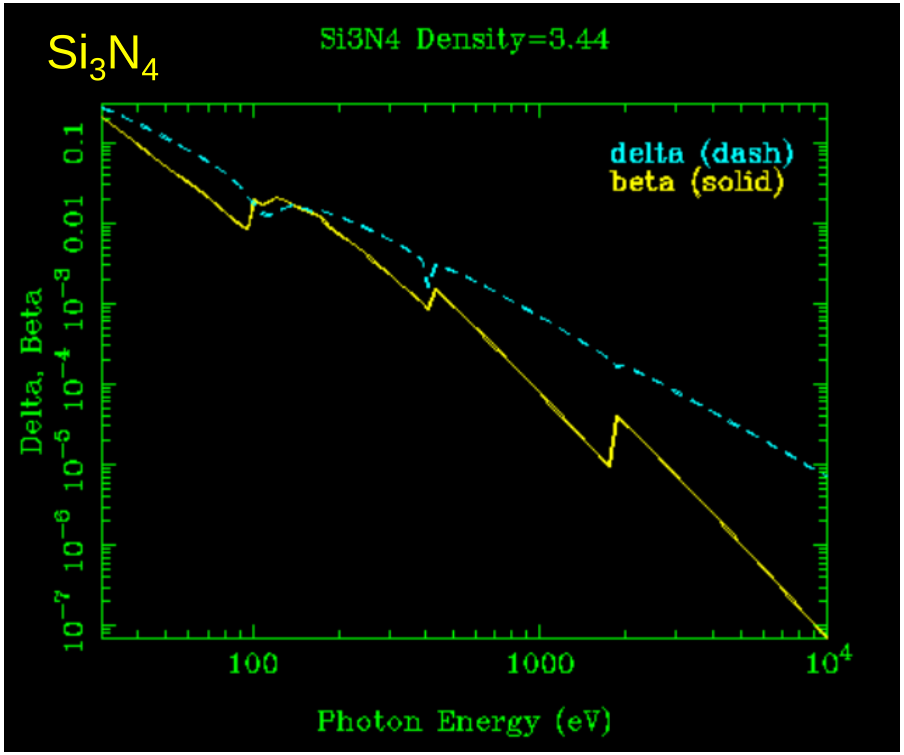


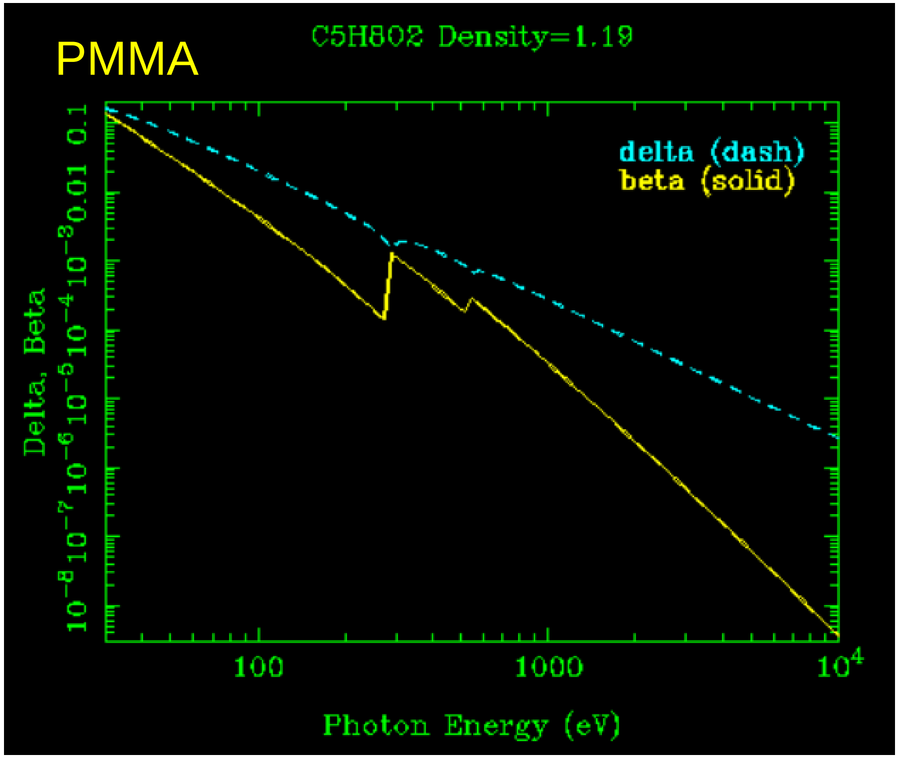
For high reflection, the absorption should be low (i.e. attenuation length should be large). So Mo, Si, Be are good candidates at ~10-15nm.

- Mo/Si ~40 layer pairs ~70% reflectance where Mo and Si are most transparent.
- Mo/Be has higher reflectance (at λ=11nm) but narrower; and more importantly, Be is toxic.
- Multi-layer coating is more difficult to control for shorter wavelength. Till now mirror for λ=4.7 nm has been fabricated, though less reflectivity and narrower bandwidth.

Refractive index at EUV

n=1-δ-iβ (δ, β<<1), n is close to 1, so low reflection

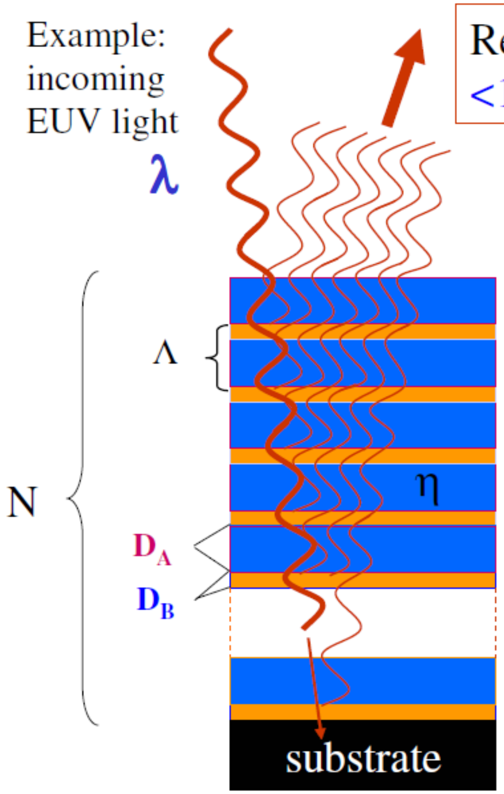




- Refractive index is closer to 1.0 for shorter wavelength. So no "optics" for x-ray.
- For λ=13.5nm, photon energy = 92 eV, so δ, β is not negligible, making reflective optics possible.
- Amplitude reflection $r=(n_1-n_2)/(n_1+n_2)$ for normal incidence at each interface.

http://www-cxro.lbl.gov/, lots of information there

Multilayer EUV mirrors – Bragg reflectors

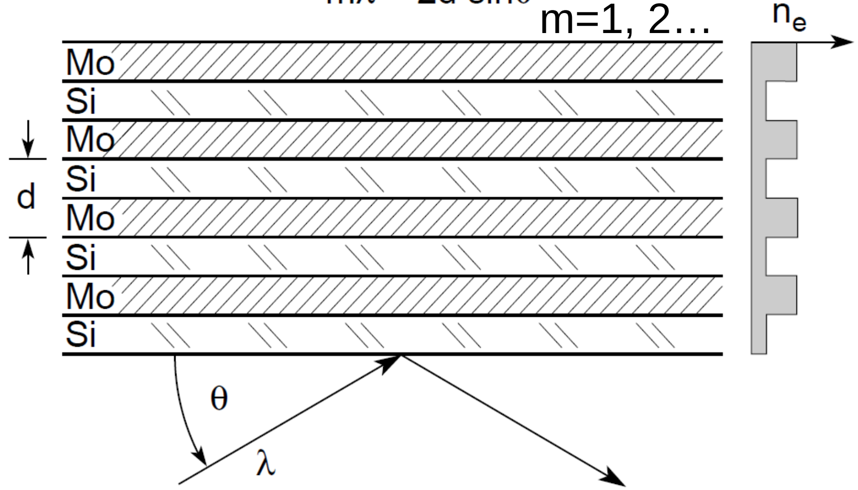


Reflected EUV EM-waves "in phase"
<1% per interface → ~70% in total

$\Lambda = D_A + D_B$ = bi-layer period
λ = radiation wavelength

The period $\Lambda \approx$ ½ wavelength(for normal incidence)
Layer thicknesses ≈ ¼ wavelength

$m\lambda = 2d \sin\theta$

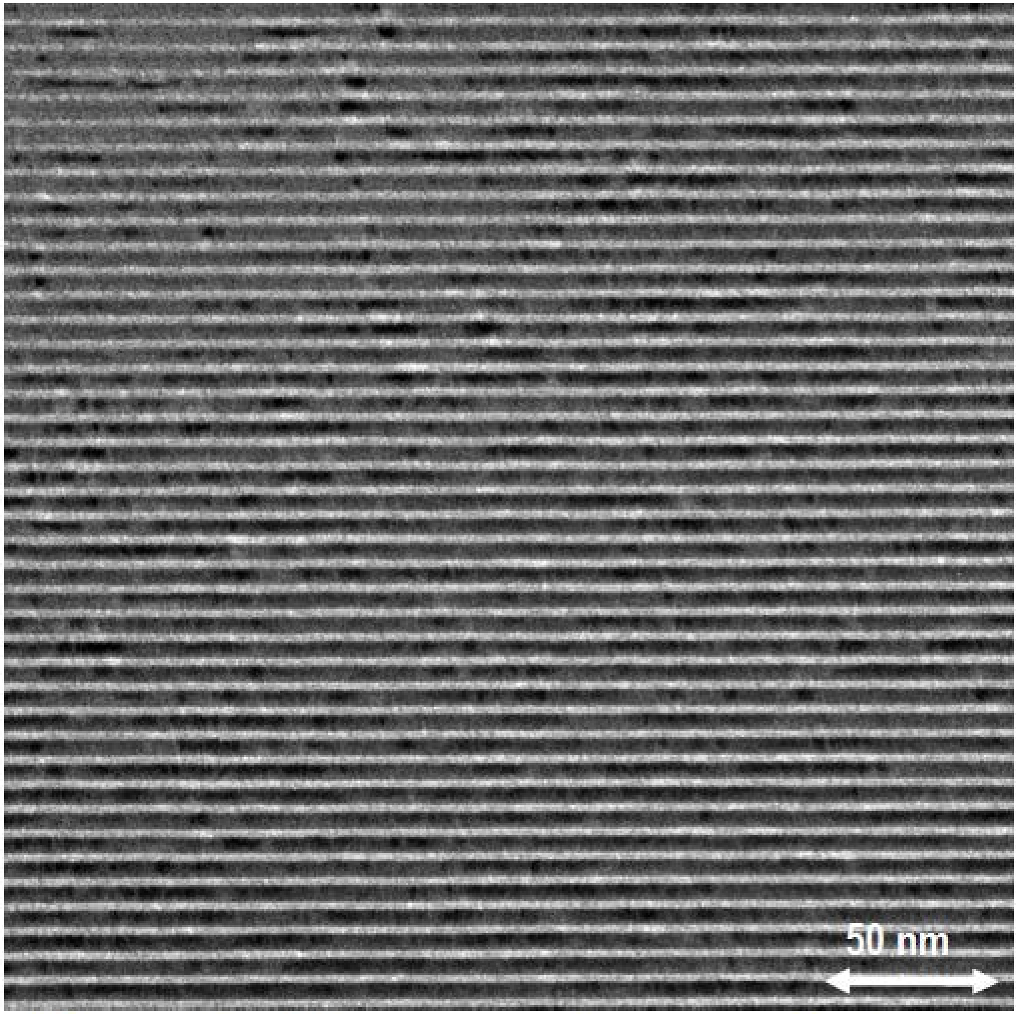


Amplitude reflection $r=(n_1-n_2)/(n_1+n_2)$ for normal incidence at each interface.

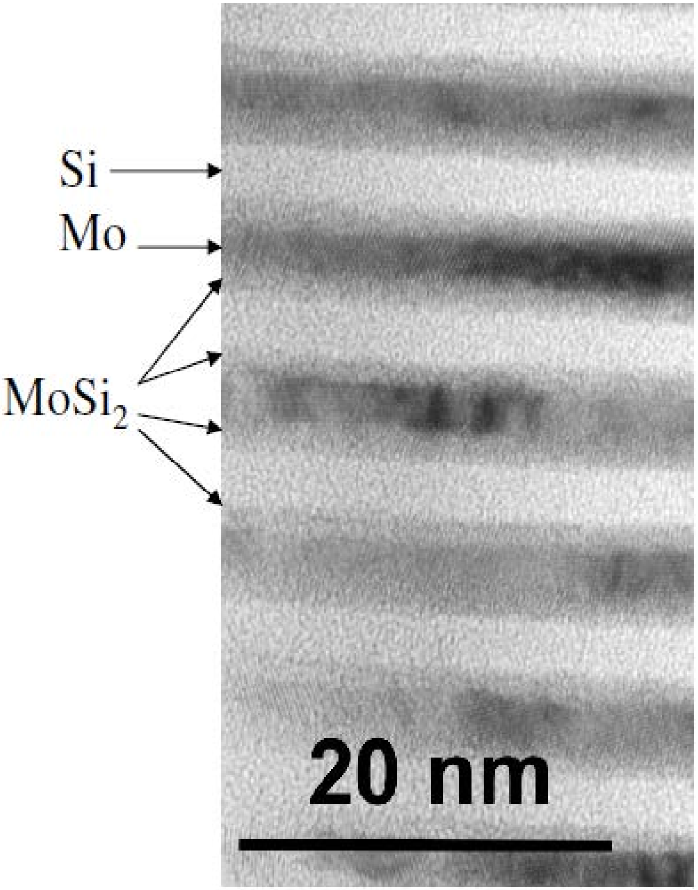
- The mirror is aspheric
- For normal incidence, if $D_A \sim D_B$, then each layer ~3.4nm for λ=13.5nm.
- Since the angle of incidence changes across the mirror, so do the required Mo/Si layer thicknesses.
- Acceptable surface roughness: 0.2nm RMS, corresponding to a phase shift error of 10°.

TEM images of EUV mirrors

TEM of a Mo/Si EUV mirror, N=50, Λ=6.8 nm



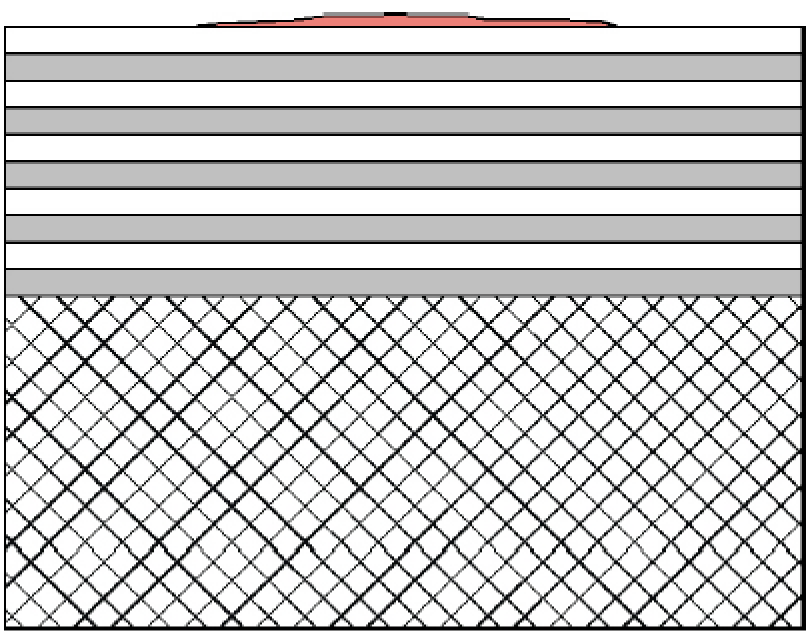
HR TEM reveals interfacial $MoSi_2$



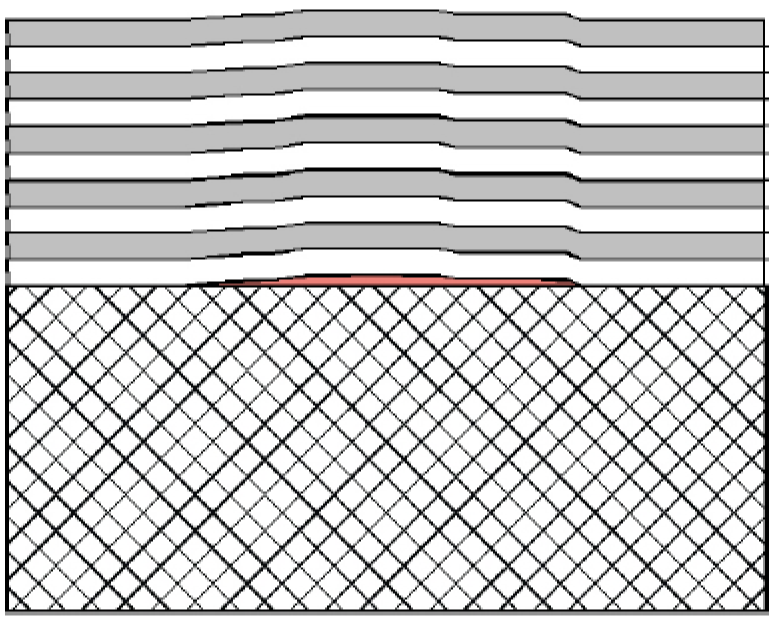
Deposited by magnetron sputtering

EUV mask blank defects

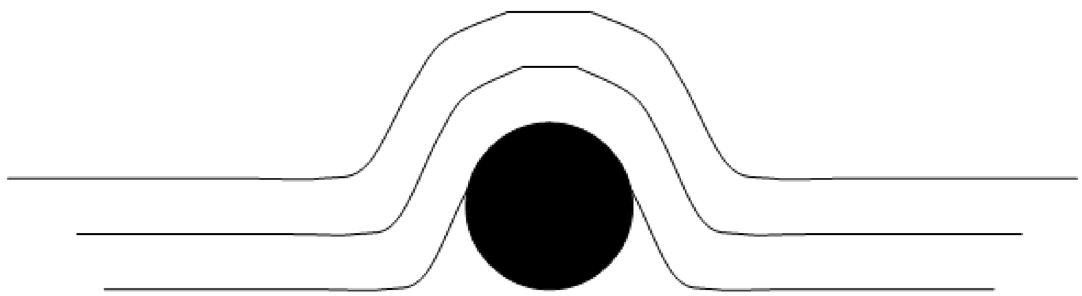
Amplitude Defect



Phase Defect

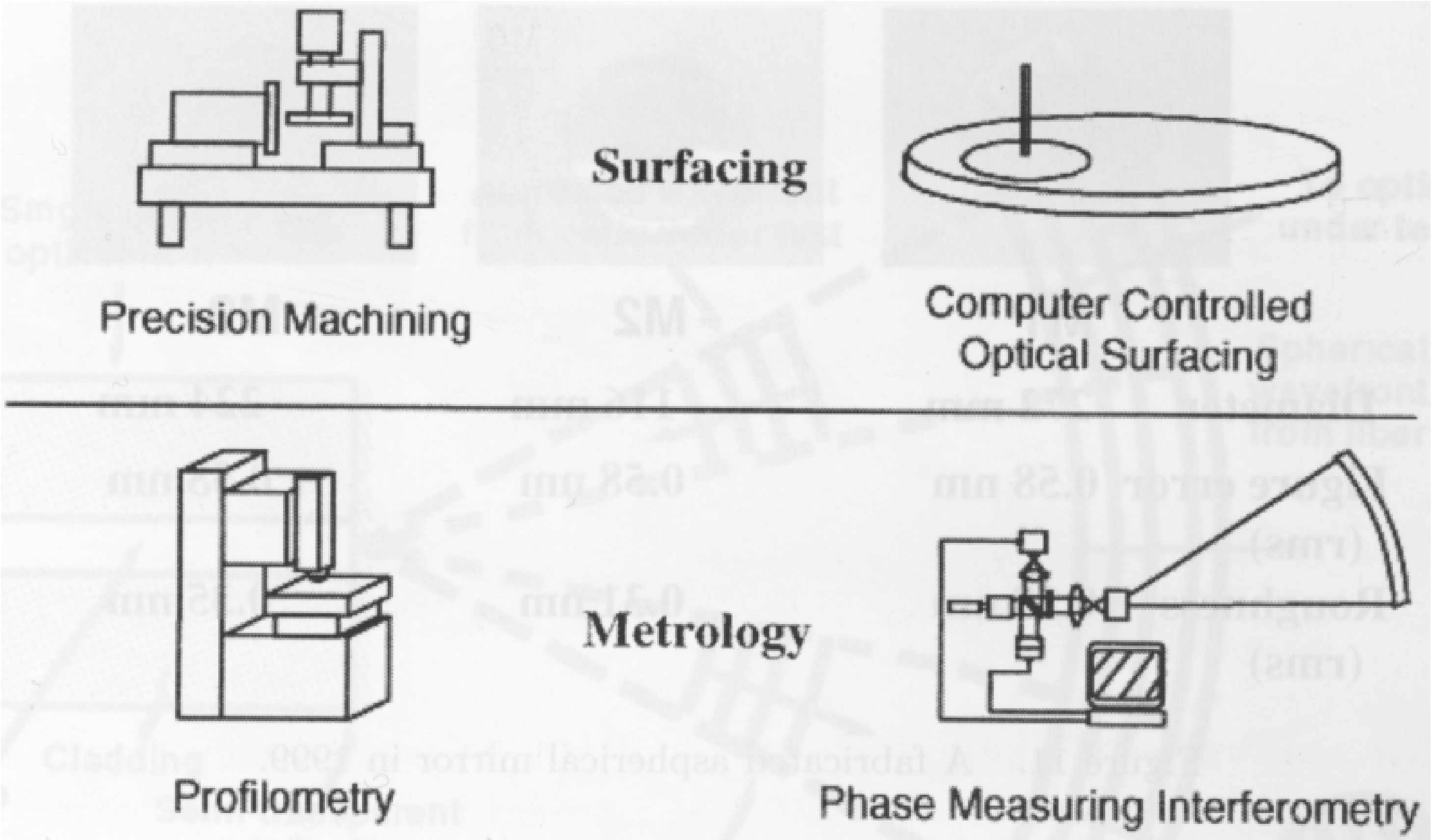


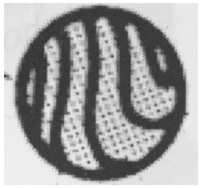
A defect in mirror has a large effect!



- As the multilayer is deposited over a particle on the substrate, the multilayer is distorted, and the distorted region becomes wider as more layers are added.

Fabrication and measurement of aspheric mirror

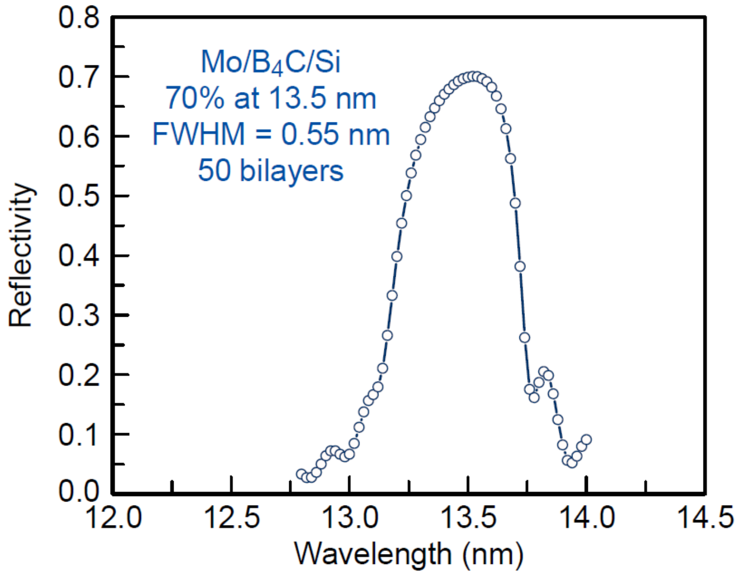


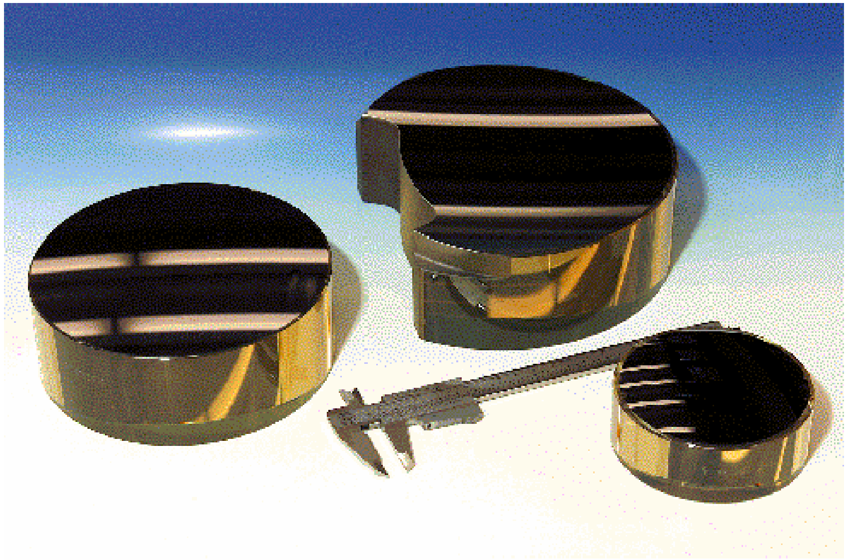


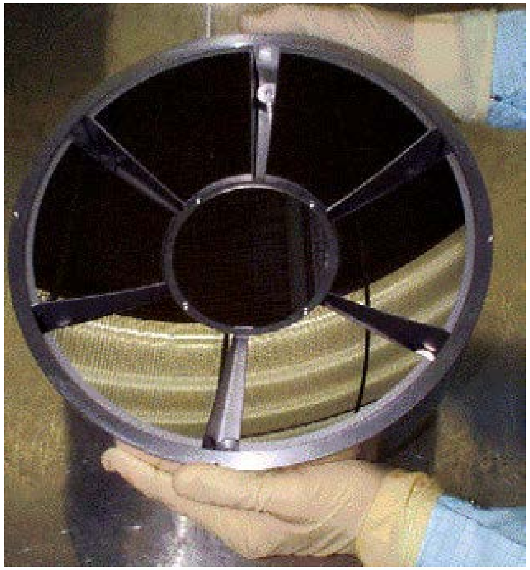
Interference fringe pattern

- Mirror accuracy sub-1nm globally, GREAT engineering achievement.
- Analyze the interference fringe, compare it pixel-by-pixel with the calculated interference fringe pattern for an ideal perfect mirror.
- Analyzing the Fourier transformed pattern rather than the wave front directly gives improved accuracy.

Prototype EUV mirrors





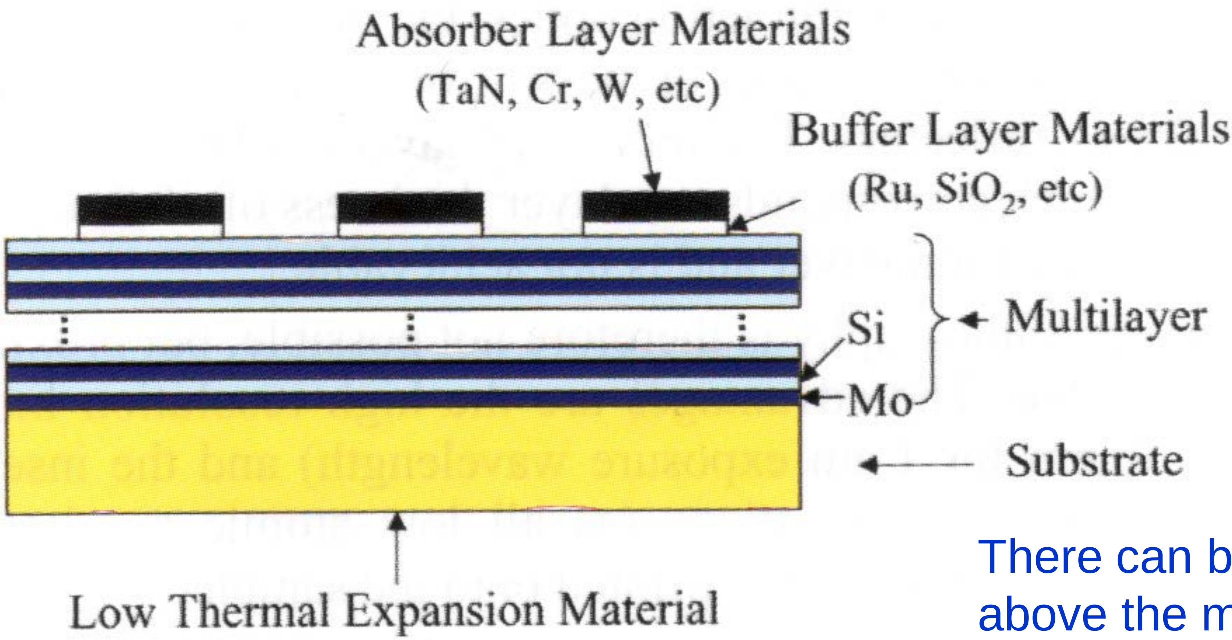


Condenser optic

Extreme UV (EUV) lithography

1. Overview, why EUV lithography?
2. EUV source (hot and dense plasma).
3. Optics (reflection mirrors).
4. Mask (absorber on mirrors).
5. Resist (sensitivity, LER, out-gassing).
6. Contamination control.

Mask for EUV lithography



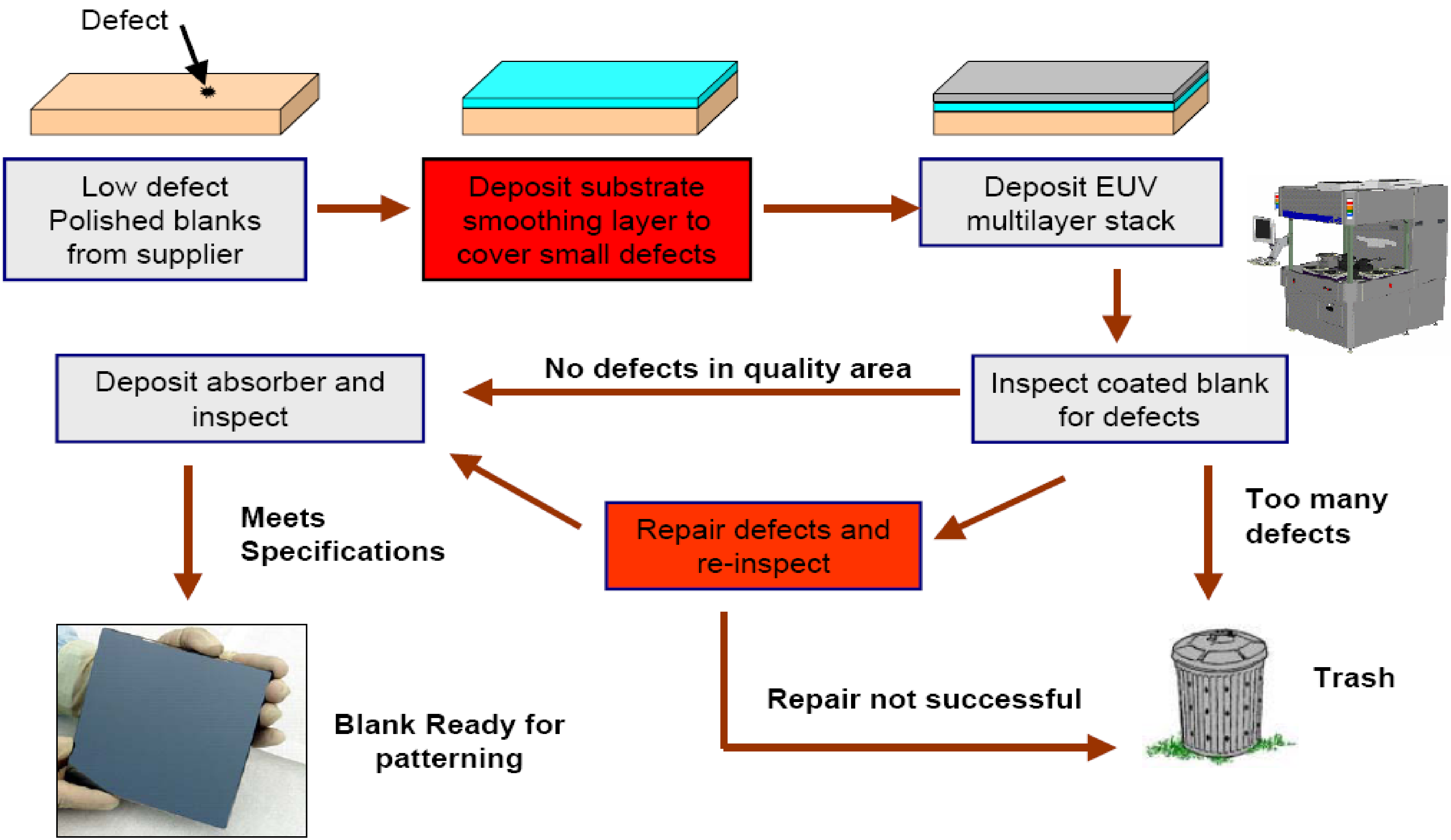
(TiO_2 doped SiO_2 amorphous glass from Corning)

There can be a capping layer (11nm Si) above the multilayer, to protect the multilayer during the following mask-making processes.

Typical thickness

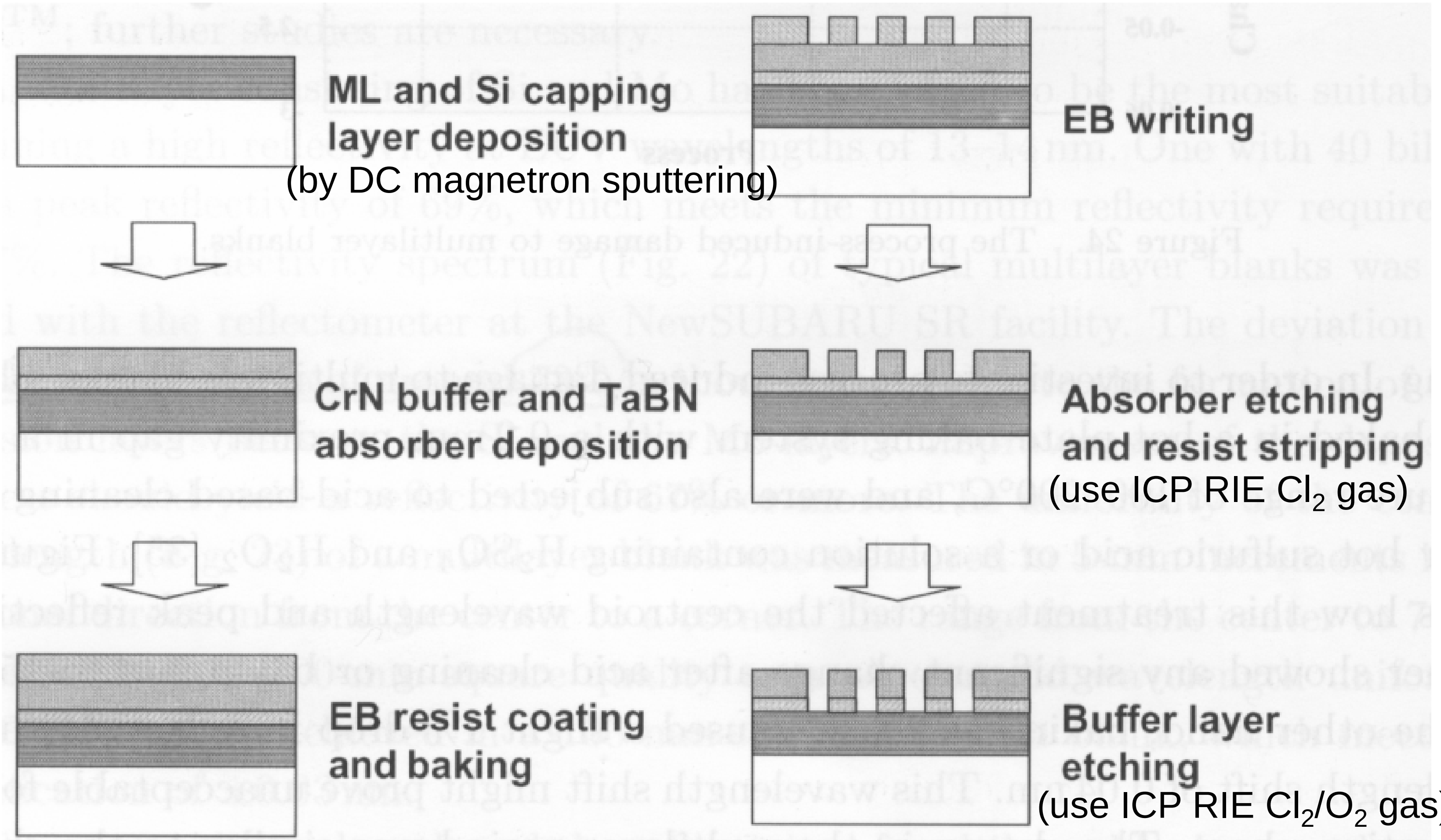
Absorber	Absorber Thickness (nm)	Buffer layer	Buffer layer thickness (nm)	Total height (nm)
Cr	70	SiO2	80	150
TaN	100	SiO2	90	190
TaBN	50	Cr	50	100

EUV mask fabrication: multi-layer mask blank fabrication



PURDUE
UNIVERSITY

EUV mask fabrication: pattern by e-beam lithography



Defects easy to print into resist, so NO defect is allowed in a completed mask.

Many defects can be repaired by local heating, focused ion beam milling….

Extreme UV (EUV) lithography

1. Overview, why EUV lithography?
2. EUV source (hot and dense plasma).
3. Optics (reflection mirrors).
4. Mask (absorber on mirrors).
5. Resist (sensitivity, LER, out-gassing).
6. Contamination control.

Resist for EUV lithography

Resist requirements:

- High Sensitivity (so allowing weak sources)
- High resolution (for small feature sizes)
- Low LER (line edge roughness)
- Minimal out-gassing (contaminate optics)

Most conventional resists are patternable at EUV.

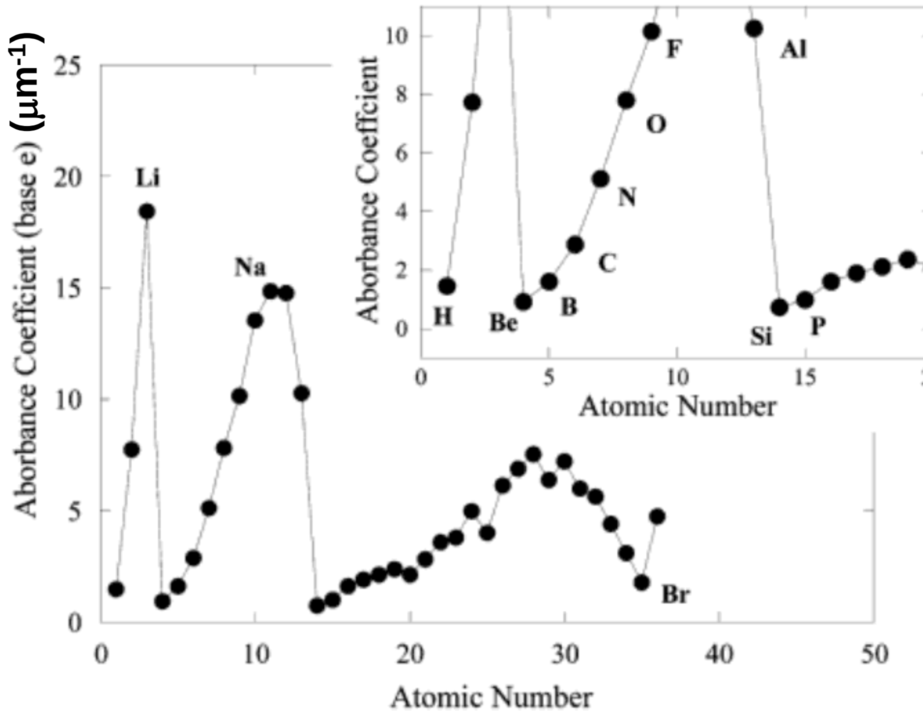
Table 4. Specification of EUV resist for 32-nm node.

Item	Target
Resolution, gate	15 nm
Resolution, half pitch	50 nm (32nm?)
LER (3σ)	1.5 nm
Sensitivity	2–5 mJ/cm^2
Absorbance	1.1 μm^{-1}
DOF	$\geq$0.2 μm
Outgassing	1×10^{-6} pa

Absorbance in EUV

- The EUV absorbance in organic materials occurs by inner-shell electrons and is therefore - differently from optical lithography - independent of molecular structure.
- The absorption of molecules is then equal to the sum of the atomic absorptions.
- The strongest absorbing atoms in resists and PAGs are F > O >> N > C, Cl, S, H.

(PAG: photo-generated acid,
for chemically amplified resist)



PMMA has highest resolution, but too slow (low sensitivity)

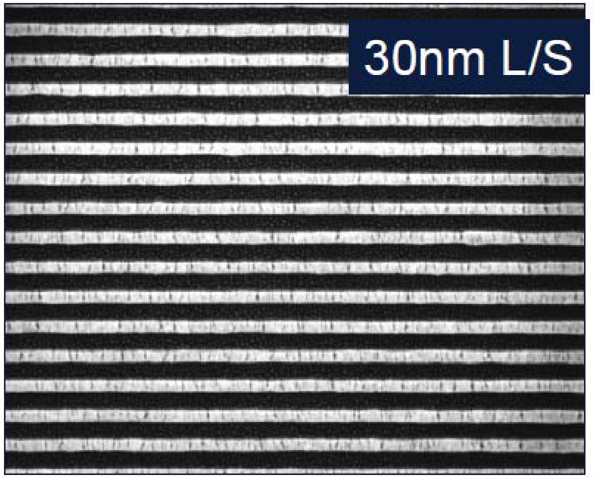
PMMA

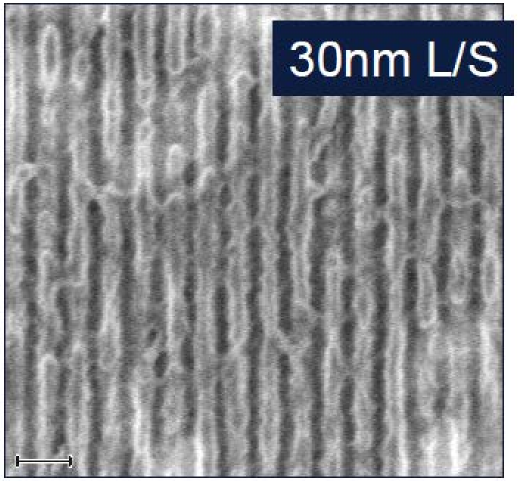
Non-CA Resist

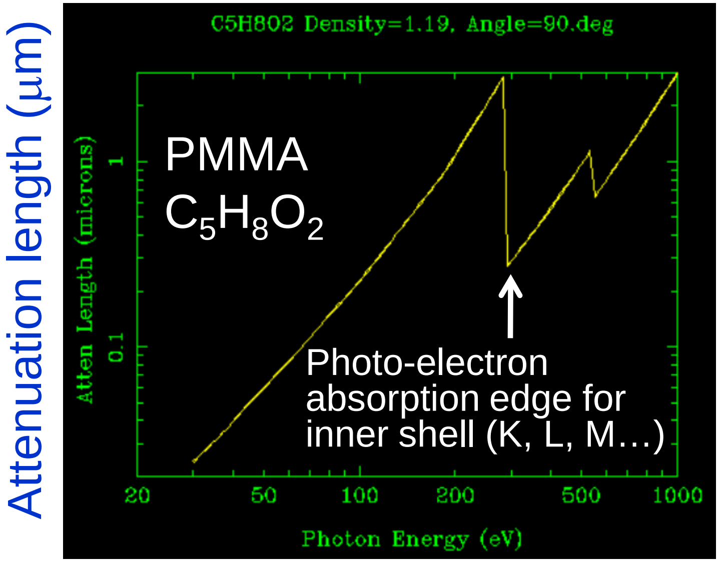
CA: chemically amplified
L/S: line/space

State of the art

CA Resist







Another issue for PMMA and most other resists is the low penetration depth (order 100nm, need ~200nm) into resist at 13.5nm(92eV).

So might (or not) need a bi-layer resist process (top for lithography, bottom layer for pattern transfer).

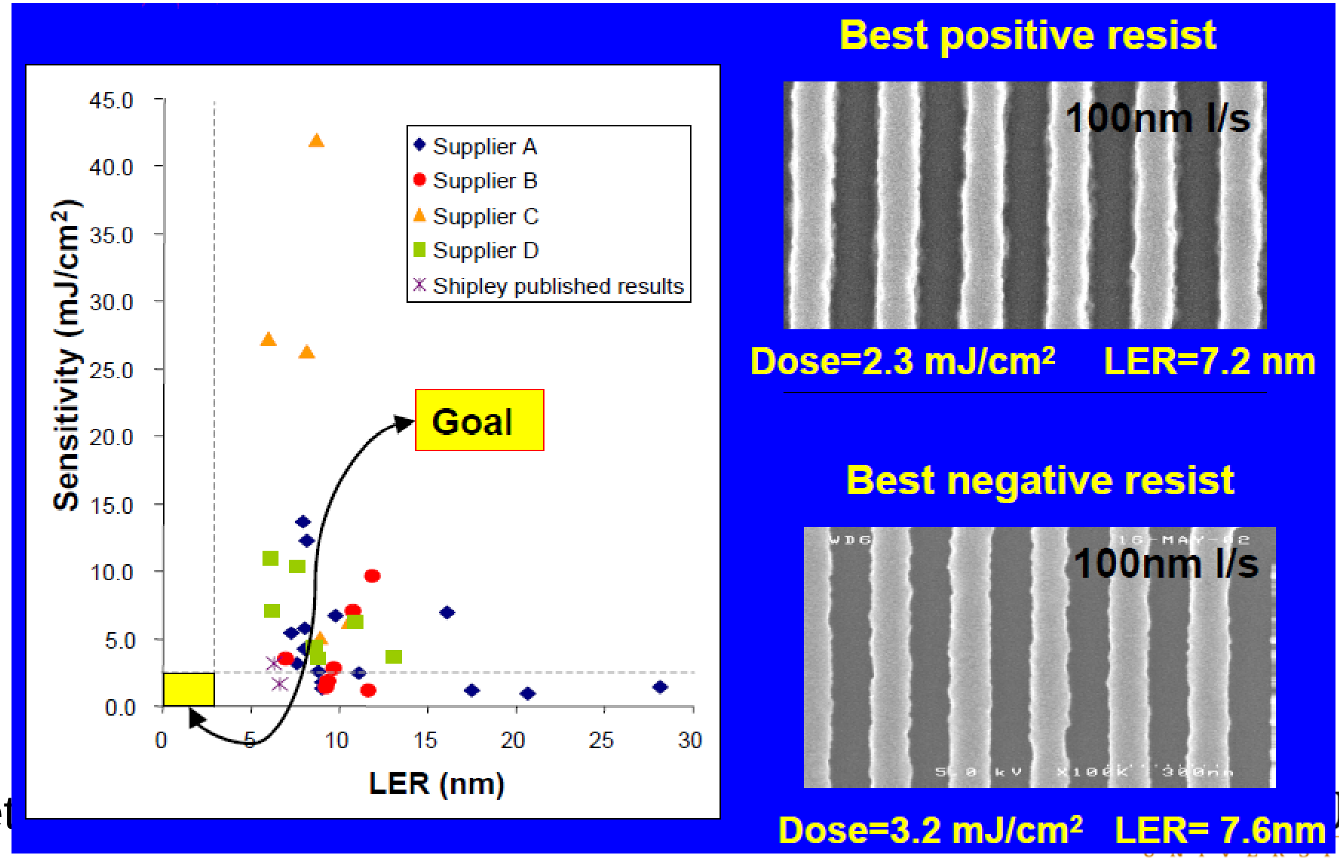
Resist LER (line edge roughness)

LER is due to:

- Shot (statistical) noise. At EUV, photons have high energy, therefore low counts and high LER due to statistical photon number fluctuation.
- Shot noise needs to be compromised with resist sensitivity. High sensitivity (fewer photons per exposure) leads to high shot noise. Roughly LER$\propto$(dose)$^{-1/2}$.
- Uncontrolled diffusion of photo-acid (also limit resolution).
- Scattering of secondary electrons in resist and substrate (leads to image blur).

For 32nm node, need
Sensitivity: 2-5mJ/cm^2
LER: 1.5nm

2mJ/cm^2$\rightarrow$1.36 photon/nm^2(!!)

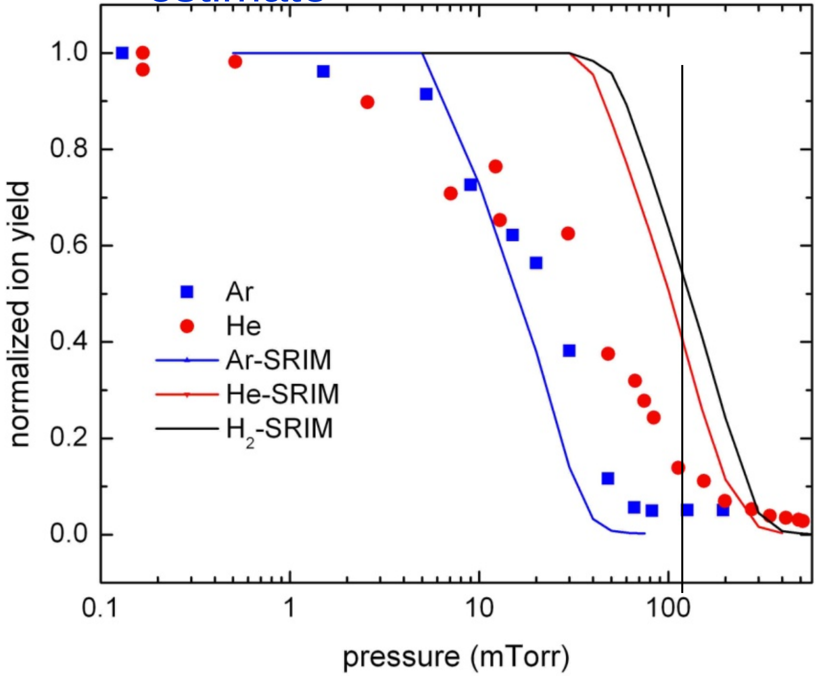


Contamination and damage to EUV optics

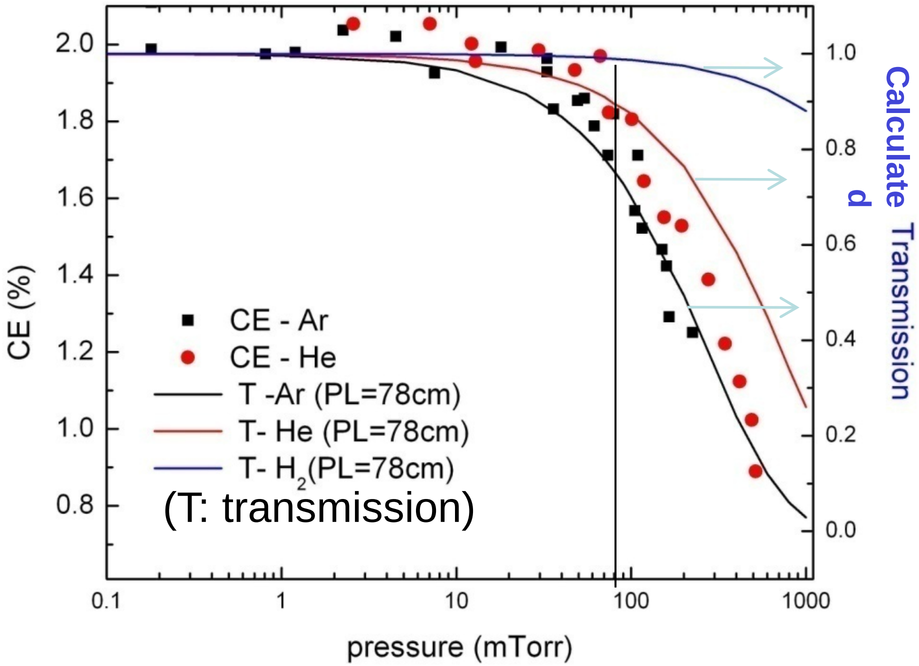
- Debris with low velocity will deposit to the mirrors, causing contamination. (debris for Sn or Li source, not for Xe gas source)
- Debris with high velocity could damage the optics by sputtering material off the lenses.
- Many methods have been tried to manage high energy debris particles:
  - Gas stopping
  - Magnetic stopping
  - Gas plus magnet
- Contamination of lens (due to resist out-gassing…): EUV irradiation leads to photochemical reactions that cause hydrocarbons to adsorb to the mirror and mask, reducing mirror's reflectivity.
- Contamination removal methods includes:
  - UV (λ>185nm) irradiation in ozone atmosphere at 150^{o}C.
  - Synchrotron radiation.
  - DUV (deep UV, λ=172nm) radiation (simple and efficient).

Gas stops ions, but also stops EUV photons

Ion yield at 10˚, 15 cm Faraday cup *vs.* SRIM estimate



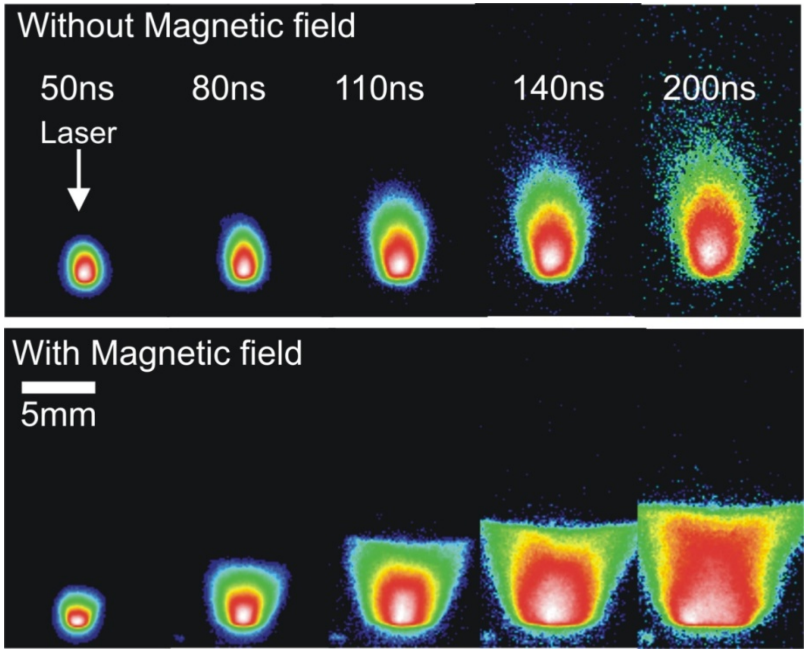
Conversion efficiency (CE) at 45˚, 78 cm



For instance, for He gas at 100mTorr, 80% ions are stopped at 15cm from source, with CE dropped from 2% to 1.6% at 78cm from source.

PURDUE UNIVERSITY

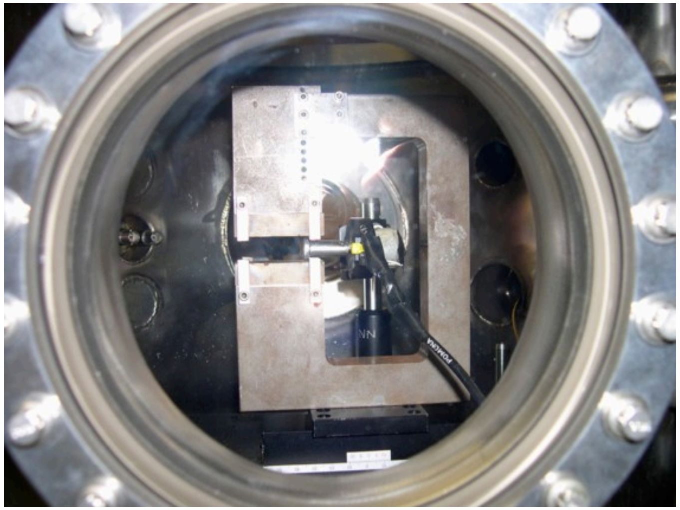
Magnetic diversion is partially effective, but not sufficient

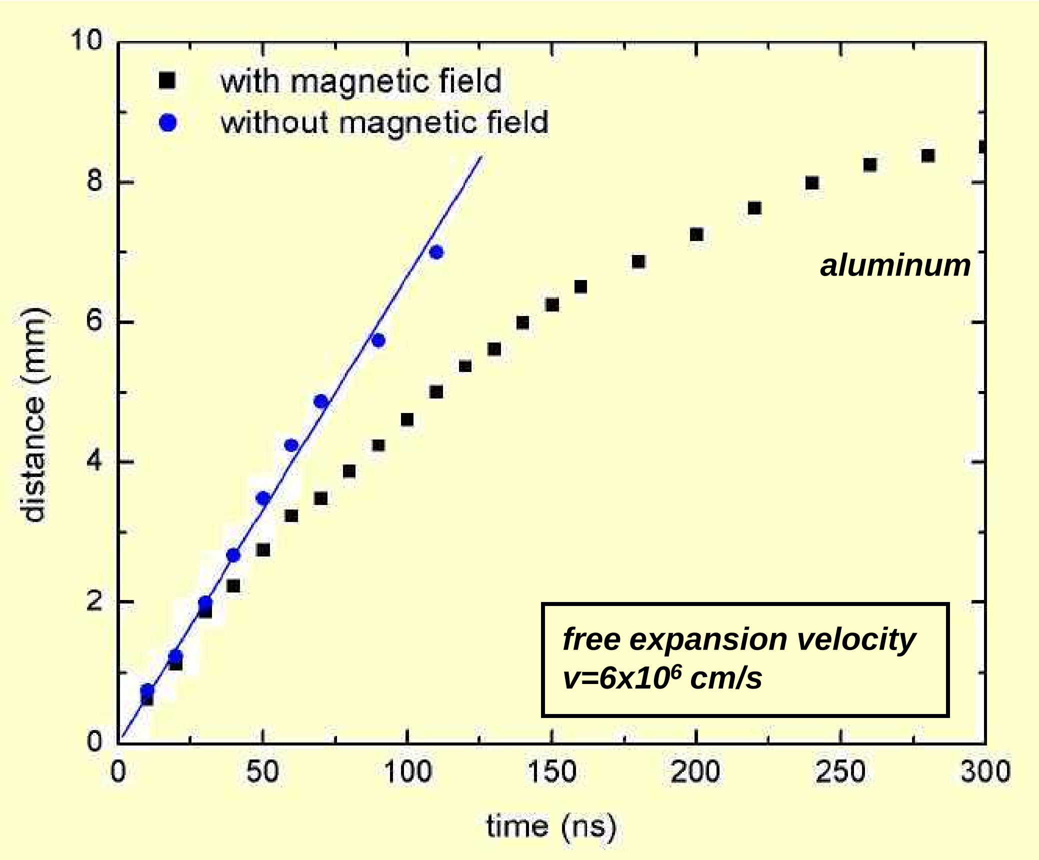


Magnetic field deflects the *moving charged* ions and clusters (debris), with no effect to photons.

Force on charge=q**v** × **B**

(q: charge, v: velocity, B: magnetic field)

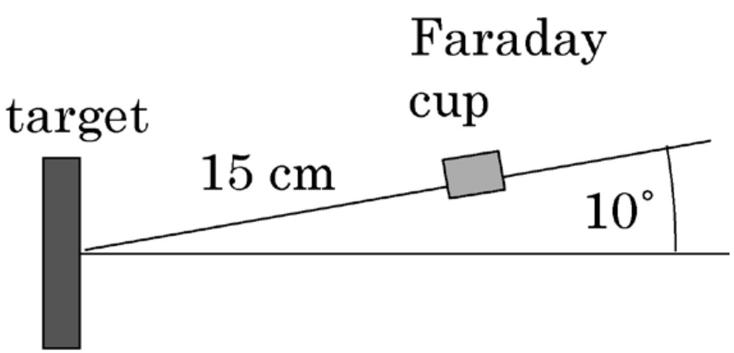


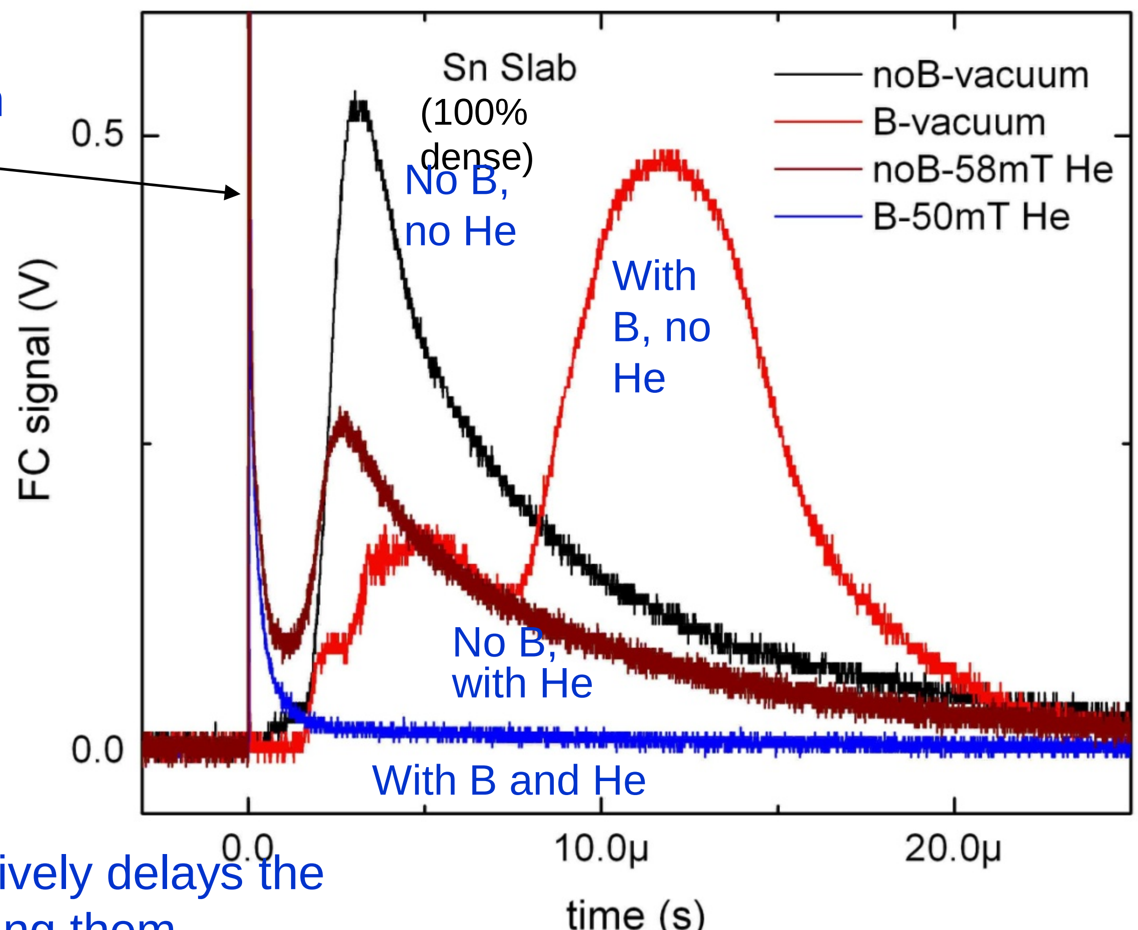


Magnetic field plus background gas is most efficient

Faraday cup time-of-flight measurements

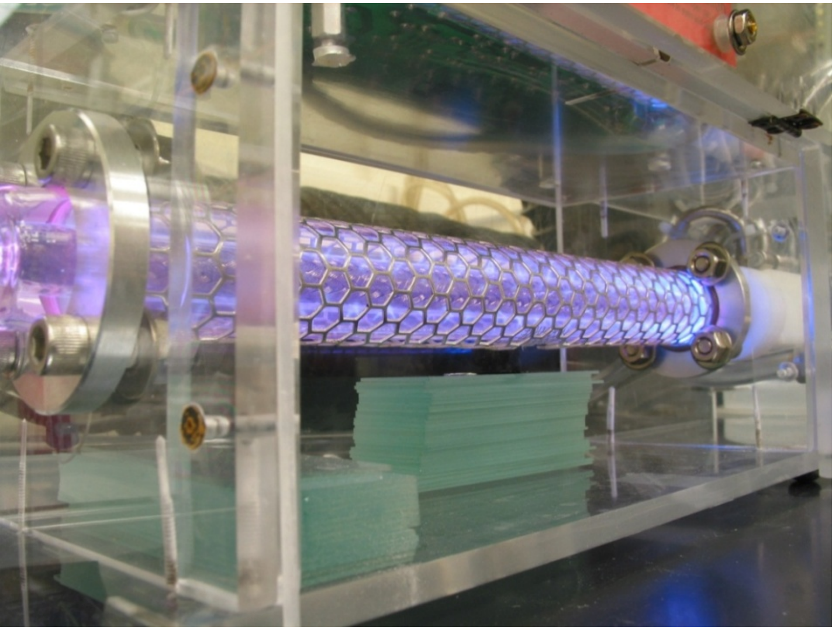
Photo-ionization peak appears when gas is present





Magnetic field alone (no He) effectively delays the arrival of ions/debris without stopping them.

Hydrocarbon contamination removal by 172nm excimer DUV (deep UV) lamp



DUV at this short wavelength produces oxygen radicals directly from molecular O_2, which react with oxygen gas to form ozone. The reactive ozone & DUV oxidize contaminants and they evaporate.

(Longer wavelength, e.g. 185nm, won't work)

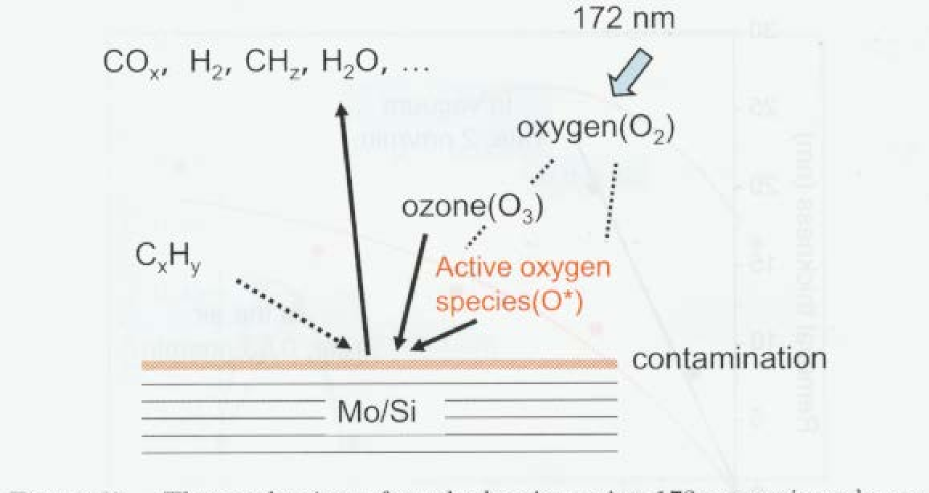


Figure 37. The mechanism of mask cleaning using 172 nm excimer lamp.

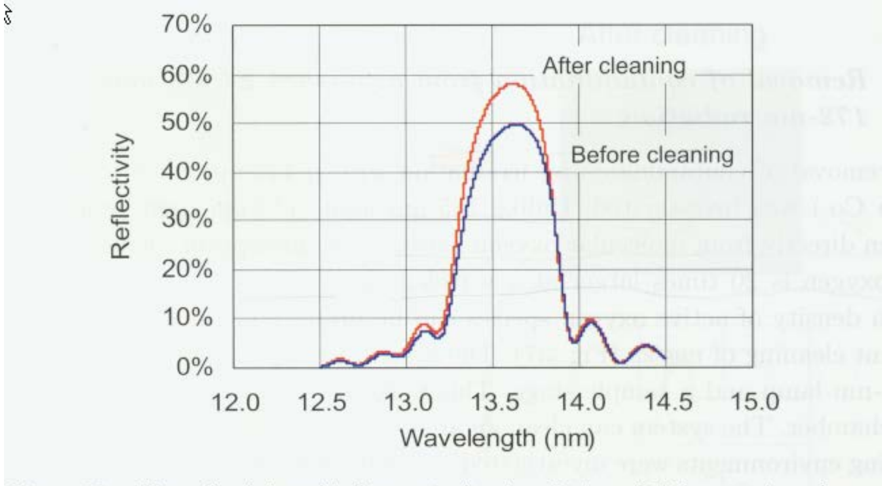


Figure 39. The reflectivity of before and after irradiation of 172 nm excimer lamp.

EUVL alpha demo systems and results

As of 2007, two alpha demo tools are at research centers

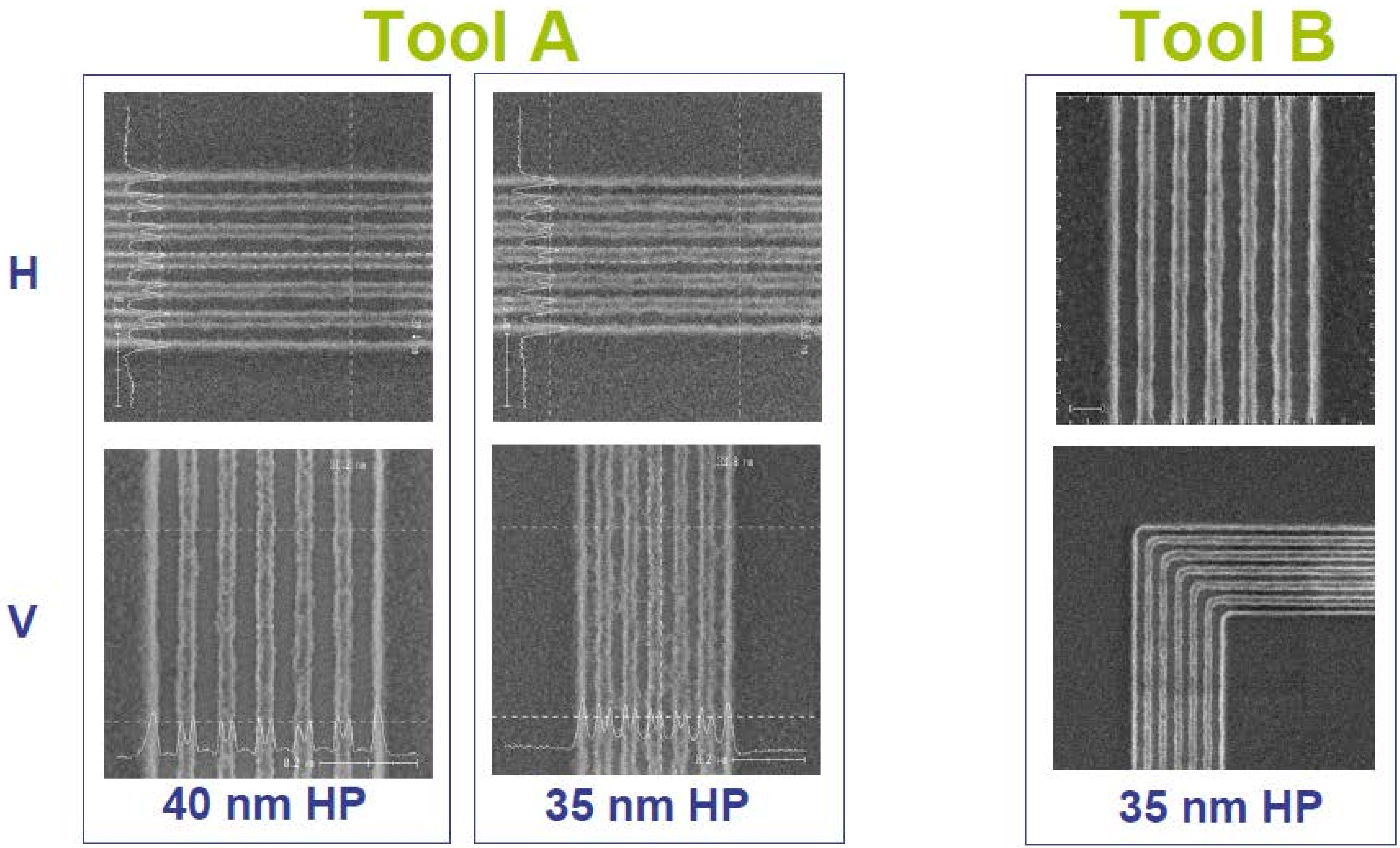
IMEC (Leuven, Belgium)

CNSE (Albany, NY, USA)

- λ 13.5 nm
- NA 0.25
- Field 26 x 33 mm^2
- Magnification 4x reduction
- Sigma 0.5
- Chief ray angle at mask is 6 degrees

- Single stage, 300mm wafer, linked to track
- ATHENA alignment sensor
- Single reticle load (no library)
- X REMA only; UNICOM
- Uses TWINSCAN technology (eg focus)
- Reflective optics
- Sn DPP source

ASML



Dose-2-clear wafer exposed

Resist: 150 nm thick MET1K (XP-4502-J), 120°C SoftBake; 60s PEB at 110°C. (recipe I-MET1K-150). Reticle: BA-EUV-Setup: 4556444N001 (Bright area).

- Resist: R&H 100, 120 nm MET-2D (~22 mJ/cm^2)
- Reticle: 40 and 35 nm coded
- Conventional illumination, fixed σ = 0.5
- Softbake: 120-130°C, 60 s, PE Bake: 110-120°C, 60-90s

Current Status (February 2016)

- To be inserted into the 10nm node, between 2017 and 2022.
  - TSMC, Intel, Samsung.
- ASML NXE:3300B: first production EUV scanner
  - NA = 0.33, 4X demagnification, 22 nm half pitch
  - 30W source power
    - Laser mechanism broke (around Jan. 30, 2014). Miaslignment?
  - 40W and 50W in lab
  - Throughput: 43 Wafer per hour for 55W source
- Investment in ASML: $1B from Intel and $1.4B from TSMC in 2012
- Current solution: triple and quadruple 193nm immersion lithography

http://semiengineering.com/euv-suffers-new-setback/
http://www.theregister.co.uk/2014/02/25/asml_euv_scanner_fails_at_tsmc_and_intel_investigates_dsa/