Immersion & EUV Lithography: Two Pillars to Sustain Single-Digit Nanometer Nodes

Burn J. Lin

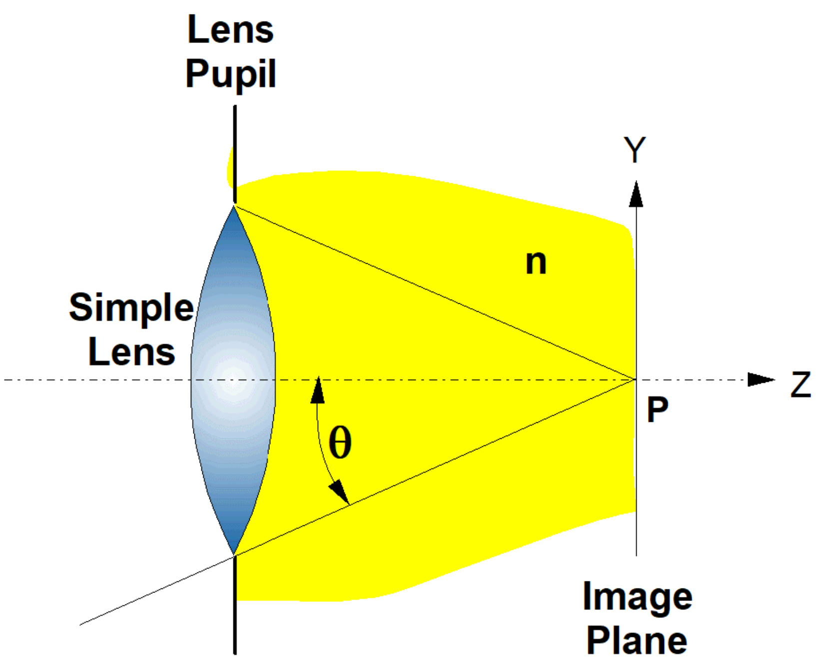
National Tsing Hua University

Resolution & DOF Scaling Equations

$$Half\ Pitch = k_1 \frac{\lambda_0}{n \sin\theta}$$

$$DOF = k_3 \frac{\lambda_0}{n \sin^2(\theta / 2)}$$

DOF = Depth of Focus



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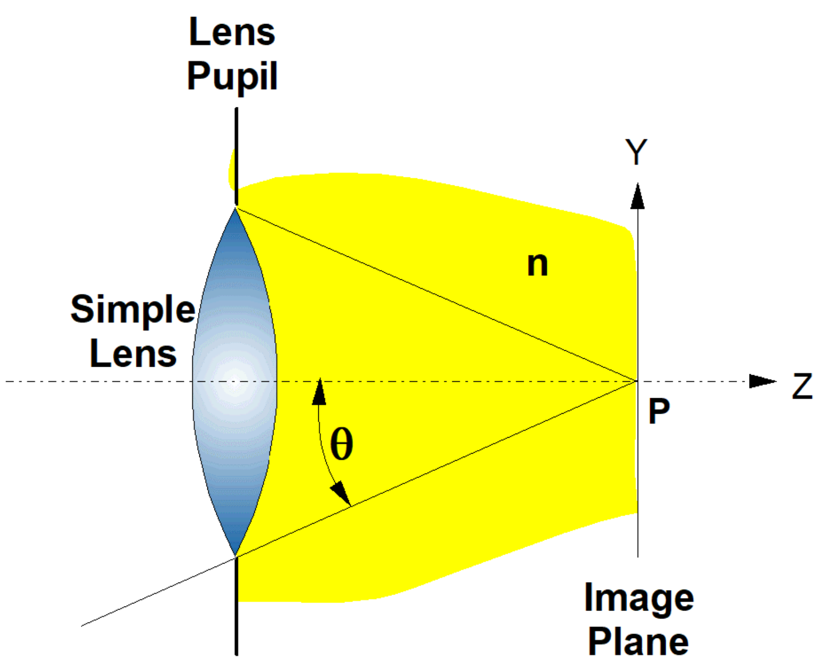
Four Ways to Improve Resolution

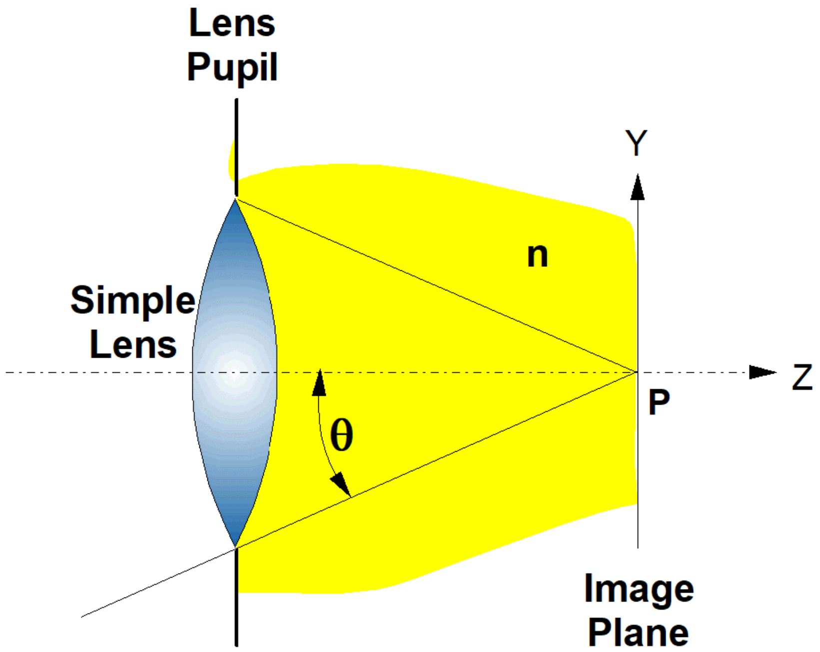
$$HP = k_1 \frac{\lambda_0}{n \sin\theta}$$



1. Increase $\sin\theta$
2. Reduce λ_0
3. Reduce k_1
4. Increase n

Today's Topics

$$HP = k_1 \frac{\lambda_0}{n \sin \theta}$$



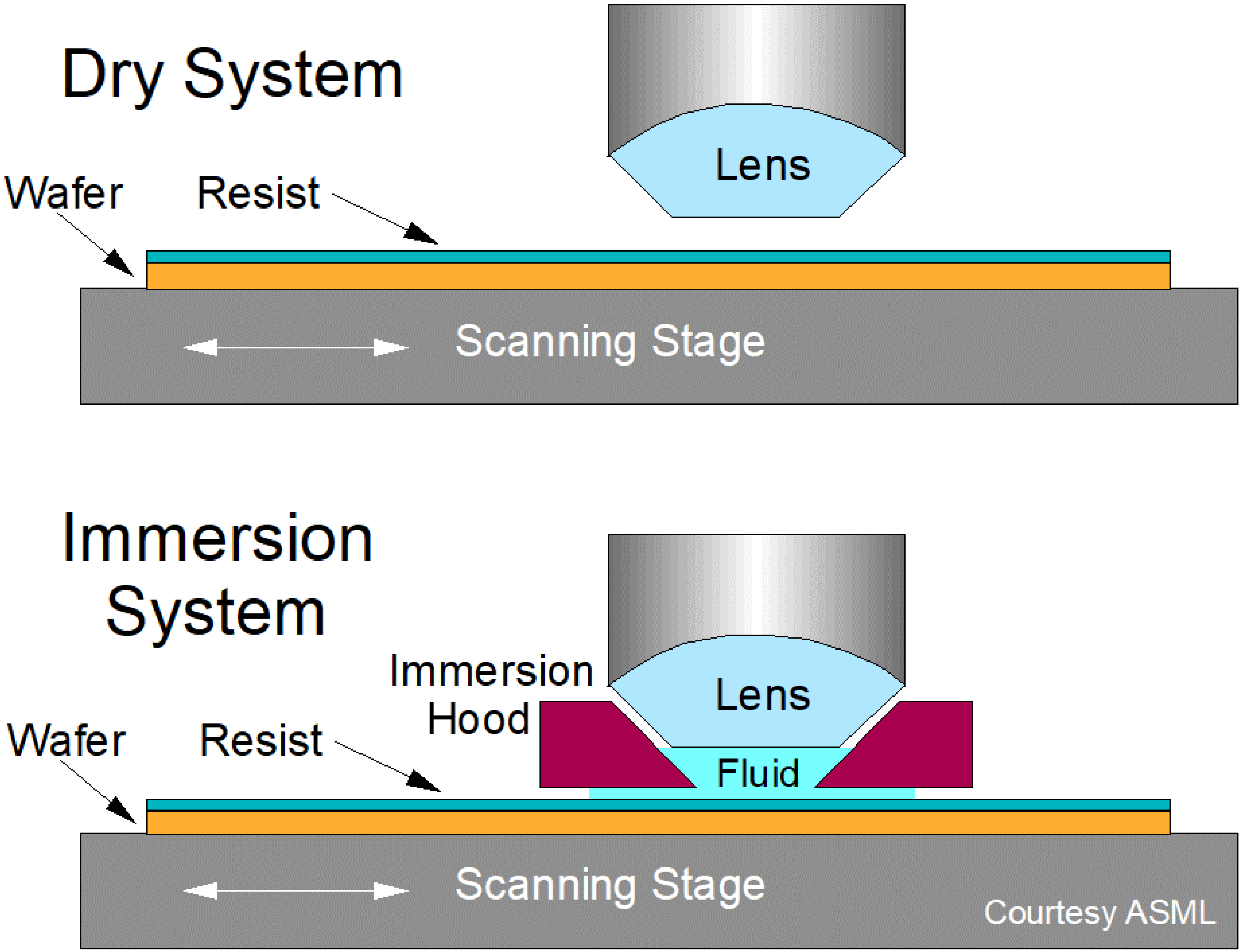
1. Immersion lithography
   - Increase *n*

2. EUV lithography
   - Reduce wavelength

Immersion Lithography

- Increase *n*

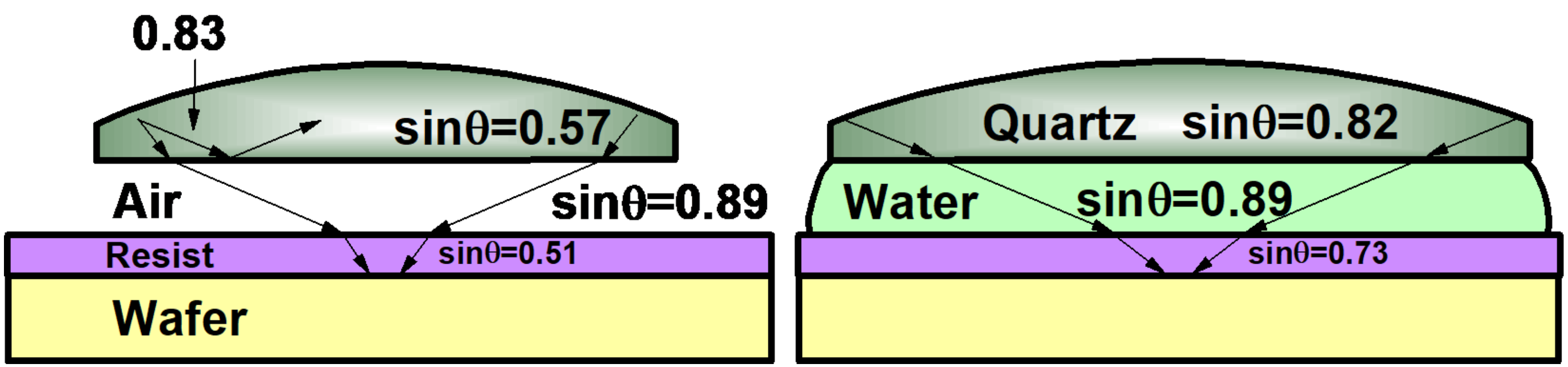
Dry & Immersion Systems



Advantages of ArF immersion over Dry F_2

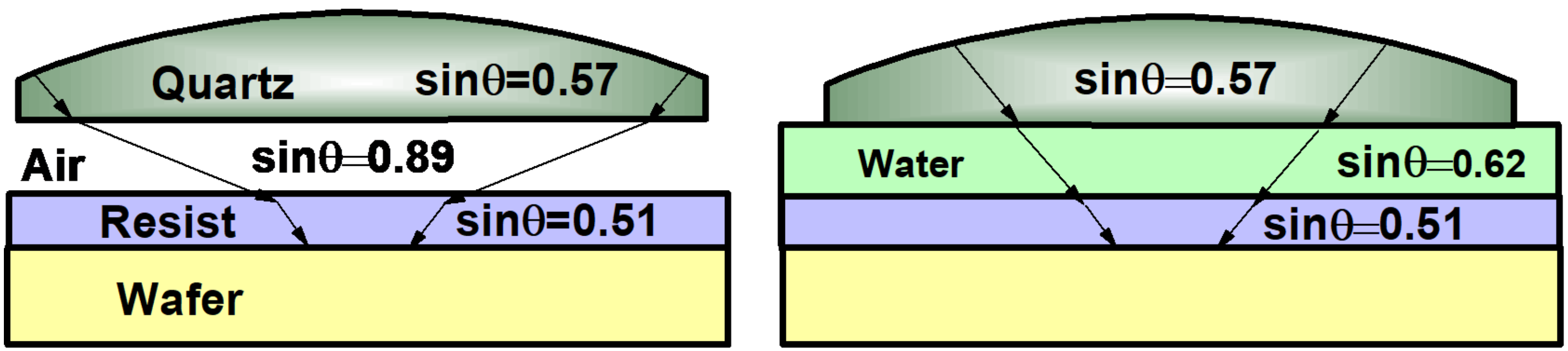
1. 134 nm vs. 157 nm overtakes dry F_2 by another generation.
2. No problem with CaF_2 quality and quantity.
3. No resist absorption and etch resistance issues.
4. No N_2 purging concern.
5. No hard pellicle issue.

Working Principle I
Medium Coupling Higher Spatial Frequency to Improve Resolution



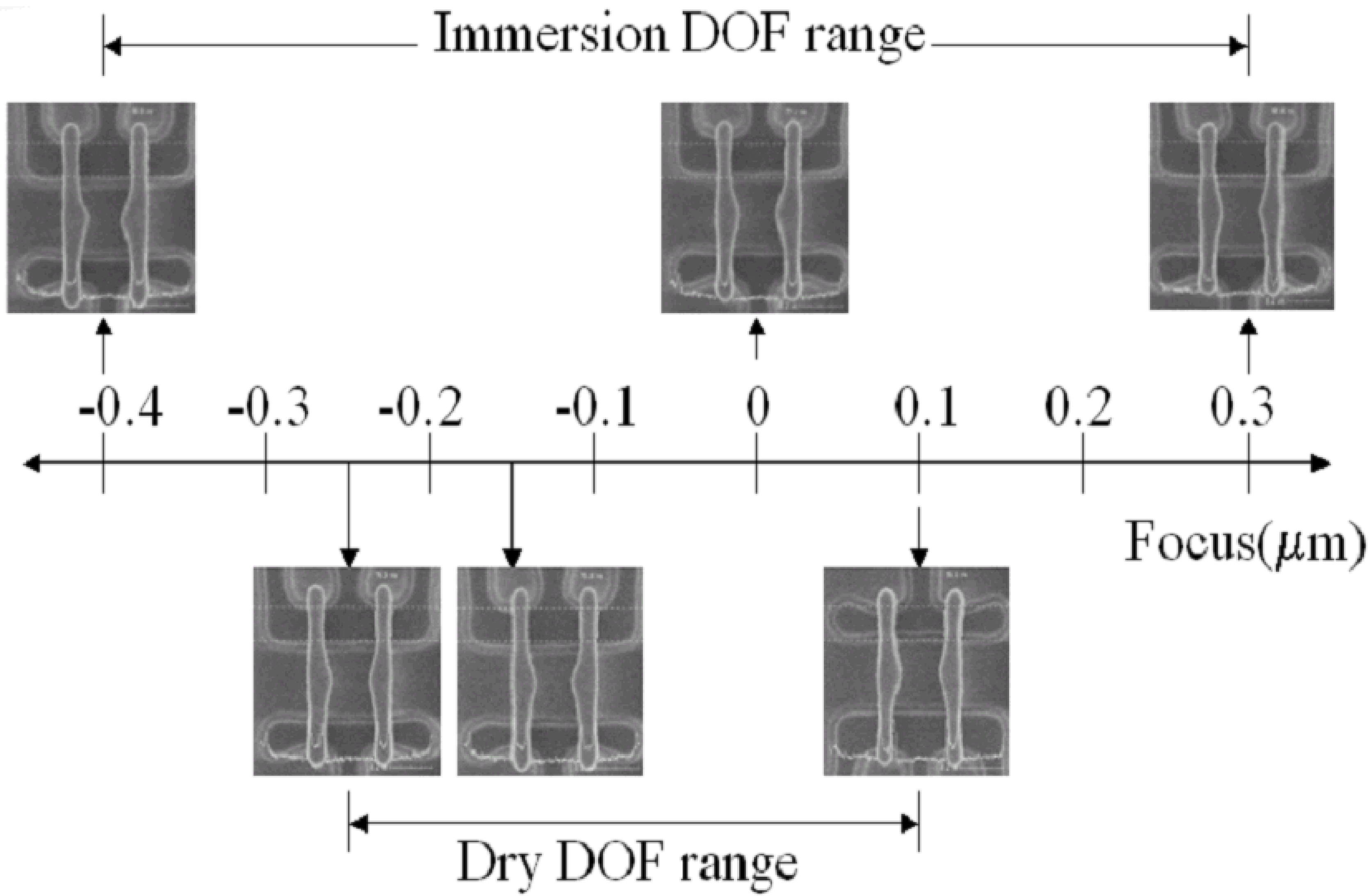
$n_{quartz} = 1.56$, $n_{water} = 1.44$, $n_{resist} = 1.75$.

Working Principle II
Preserving Incident Angle in Media for DOF

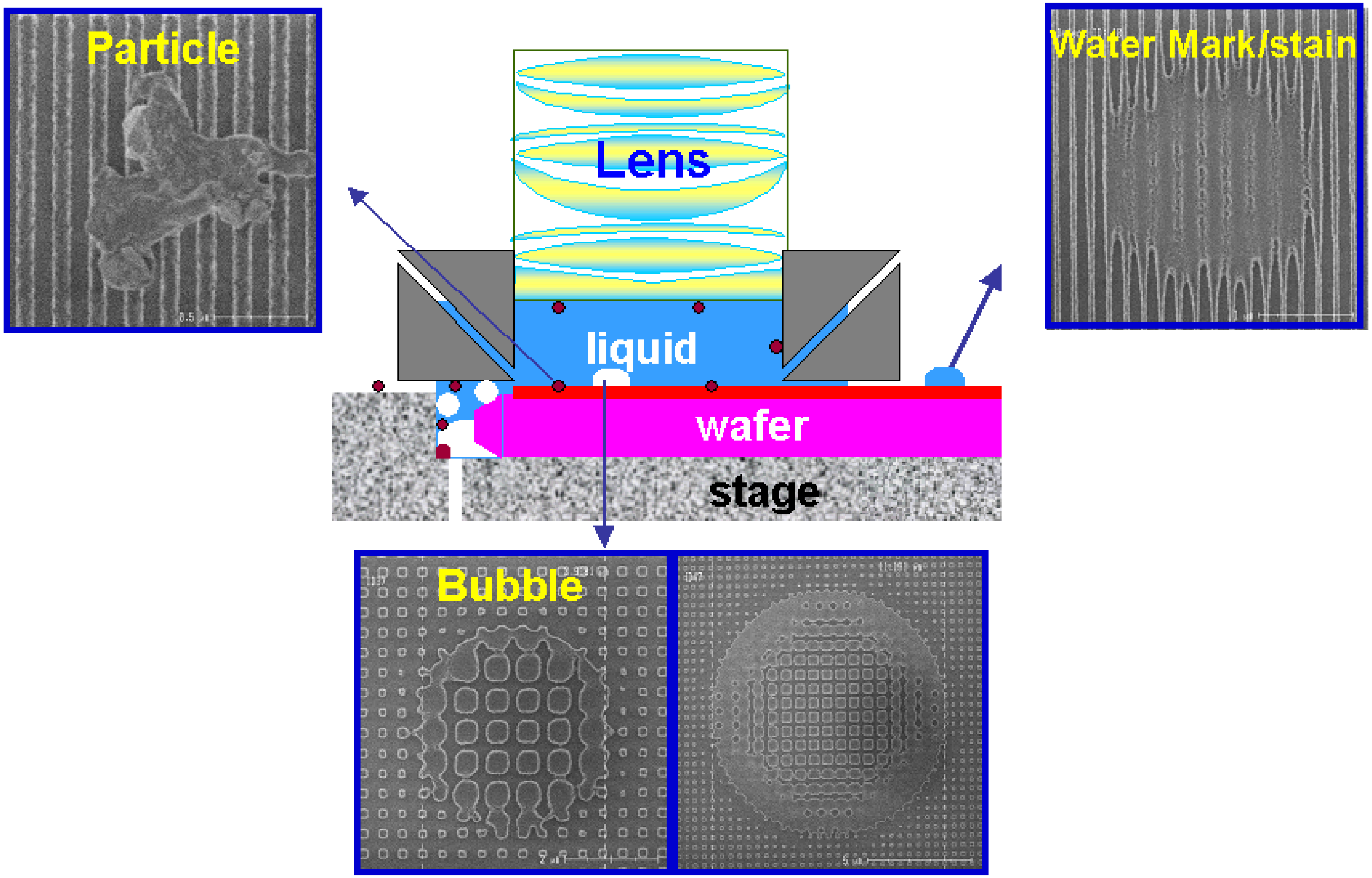


$n_{quartz} = 1.56$, $n_{water} = 1.44$, $n_{resist} = 1.75$.

DOF of Poly Image on Active Layer

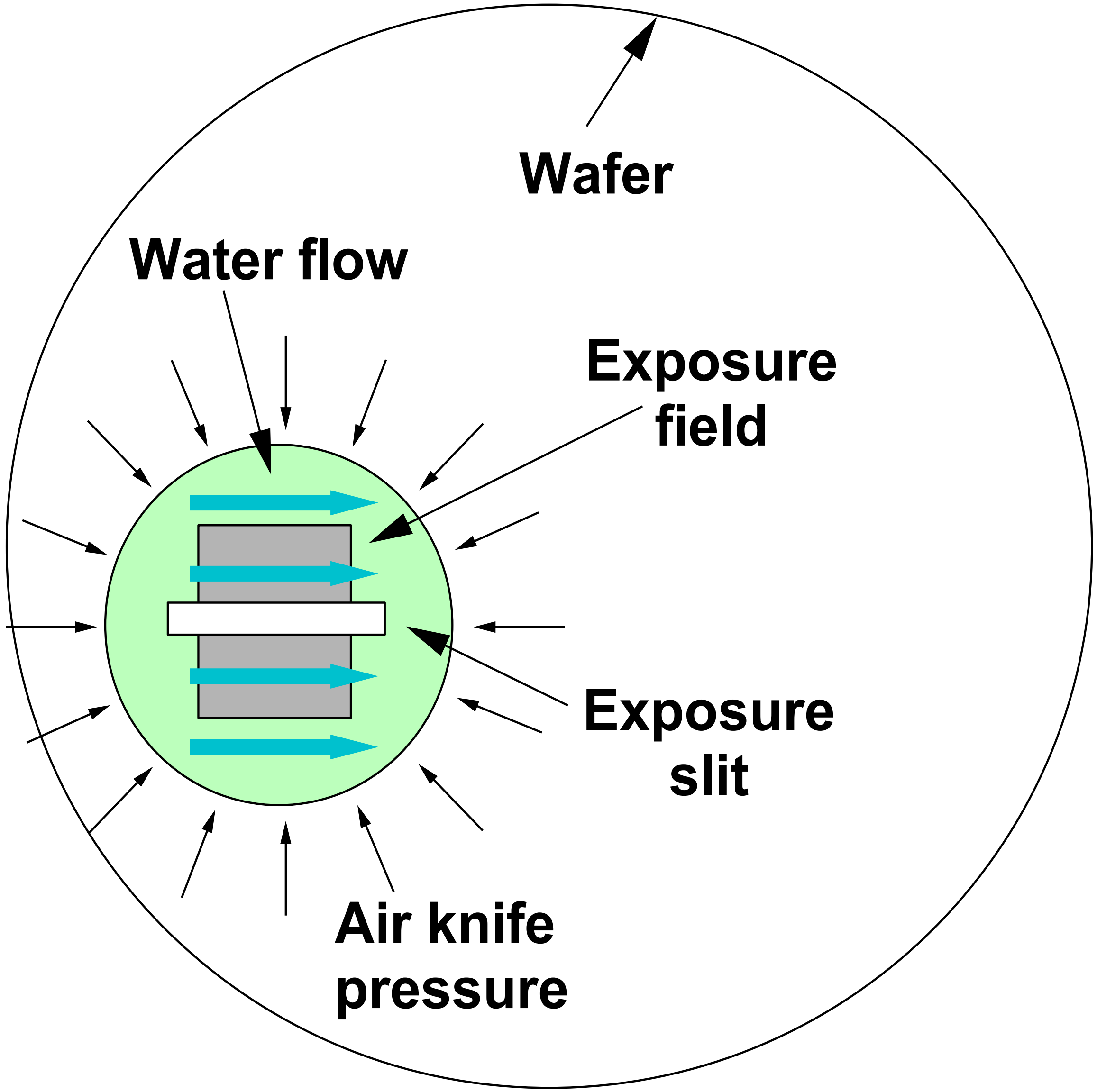


(J.H. Chen)

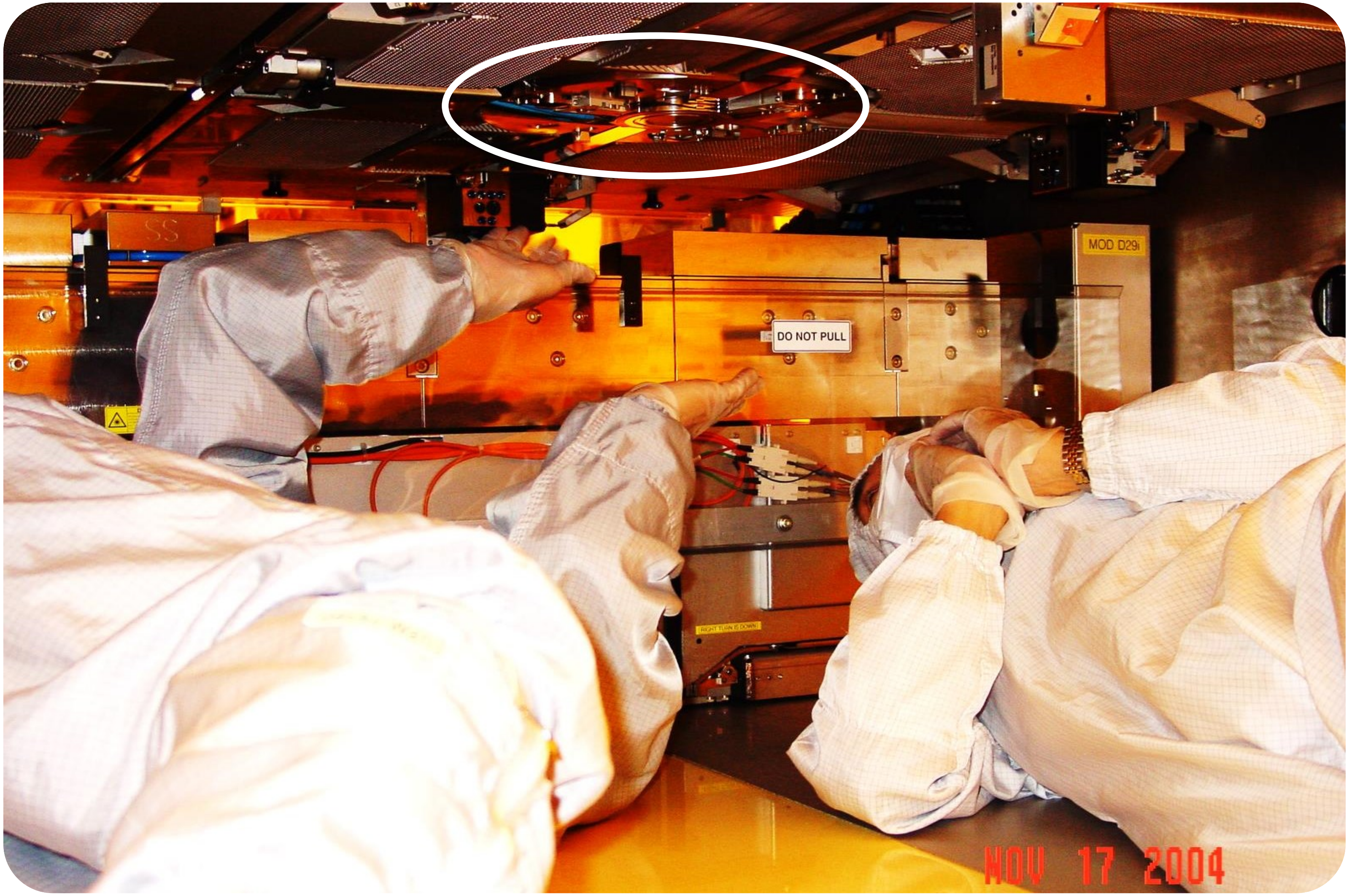


Major defects in immersion lithography, particles, water stains, and bubbles. (C.Y. Chang)

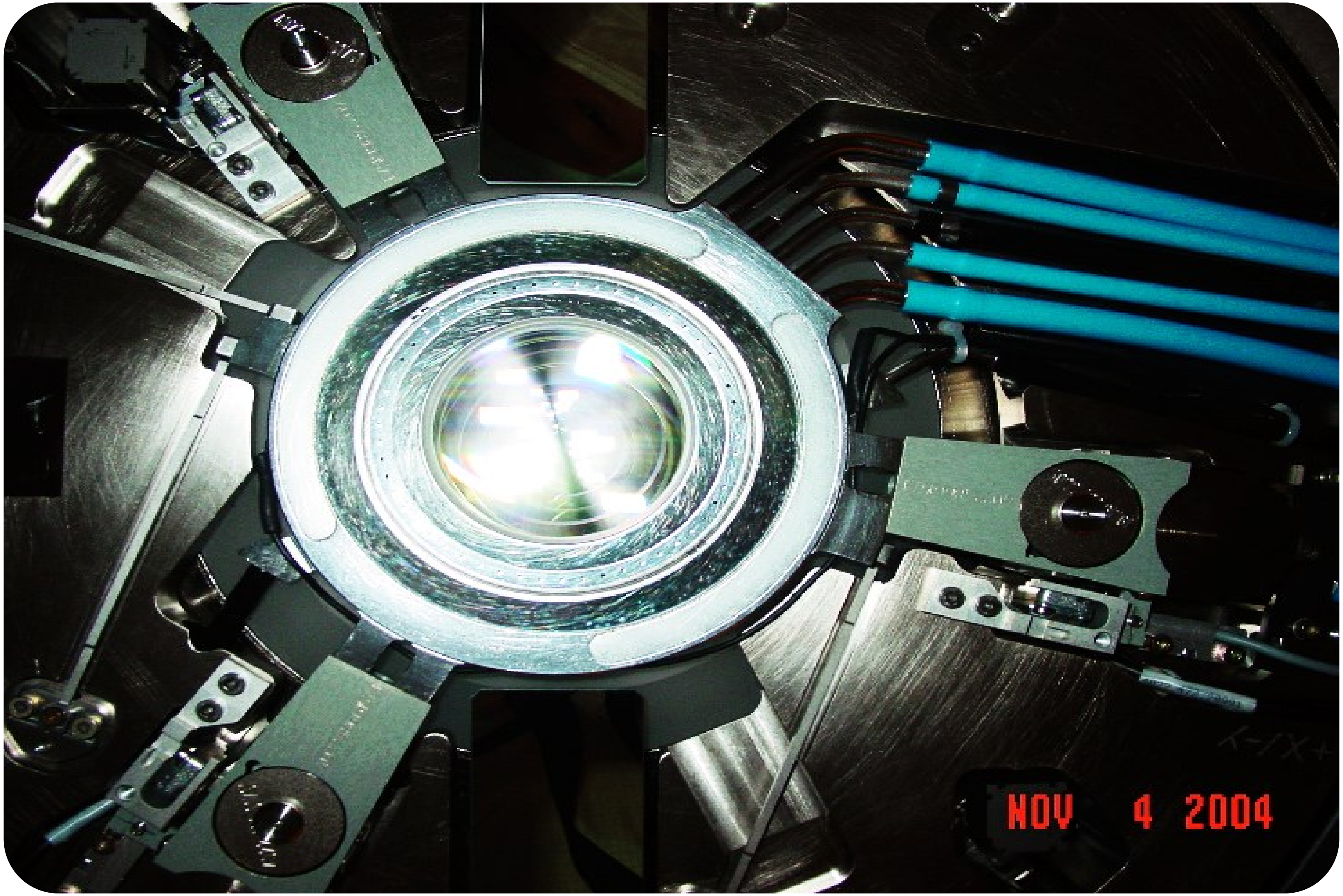
Conceptual Configuration of Immersion Hood



We laid under to see the lens bottom

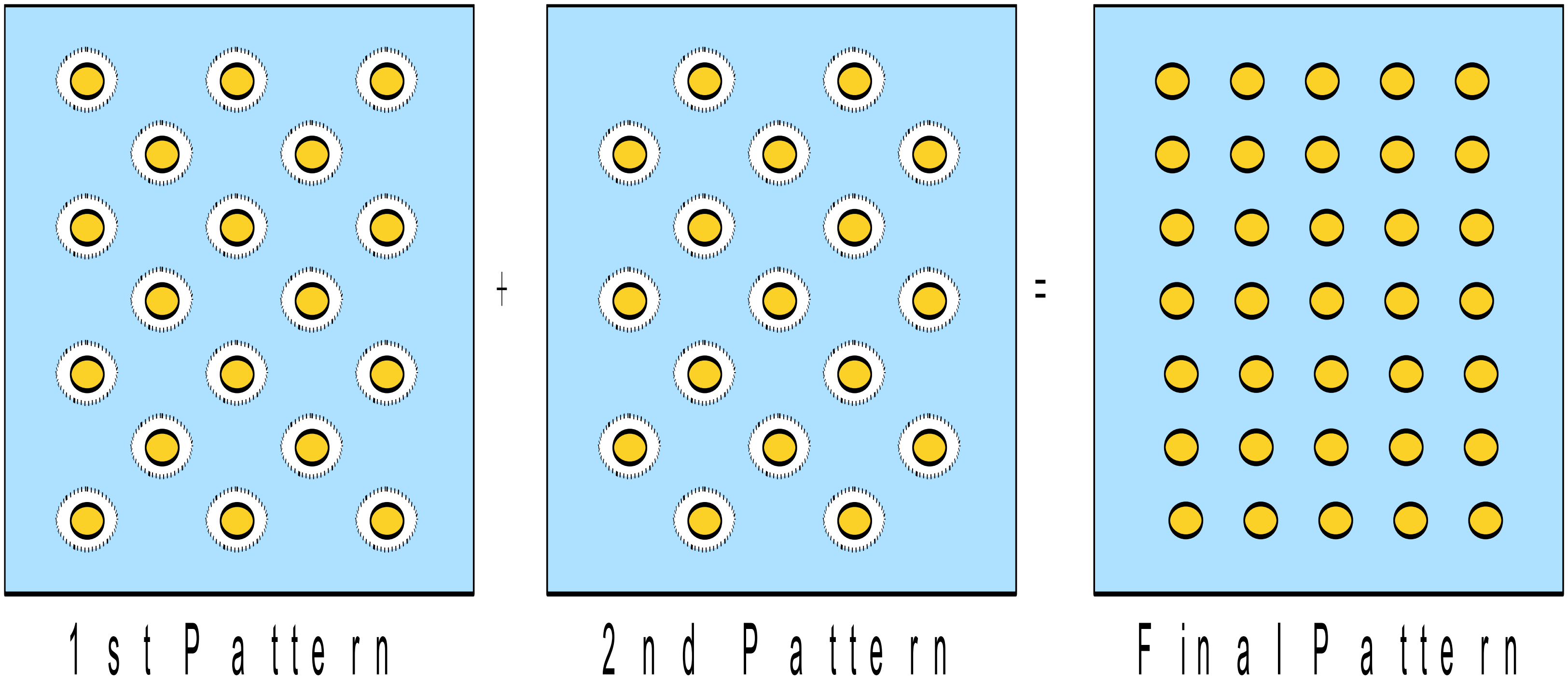


Lens Bottom - with Immersion Hood

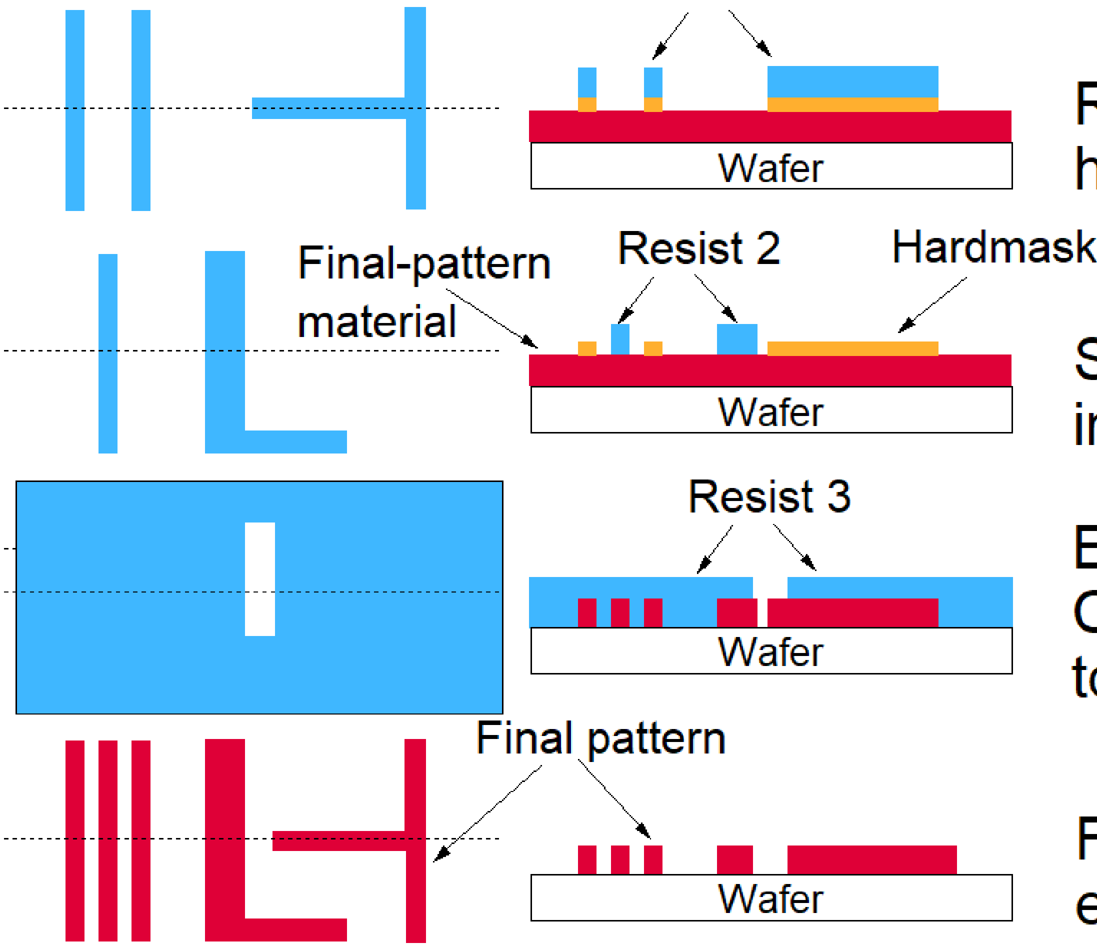


Issues for Designers

Pitch Splitting Increases Density



Triple Patterning
Pitch Splitting + End Cutting



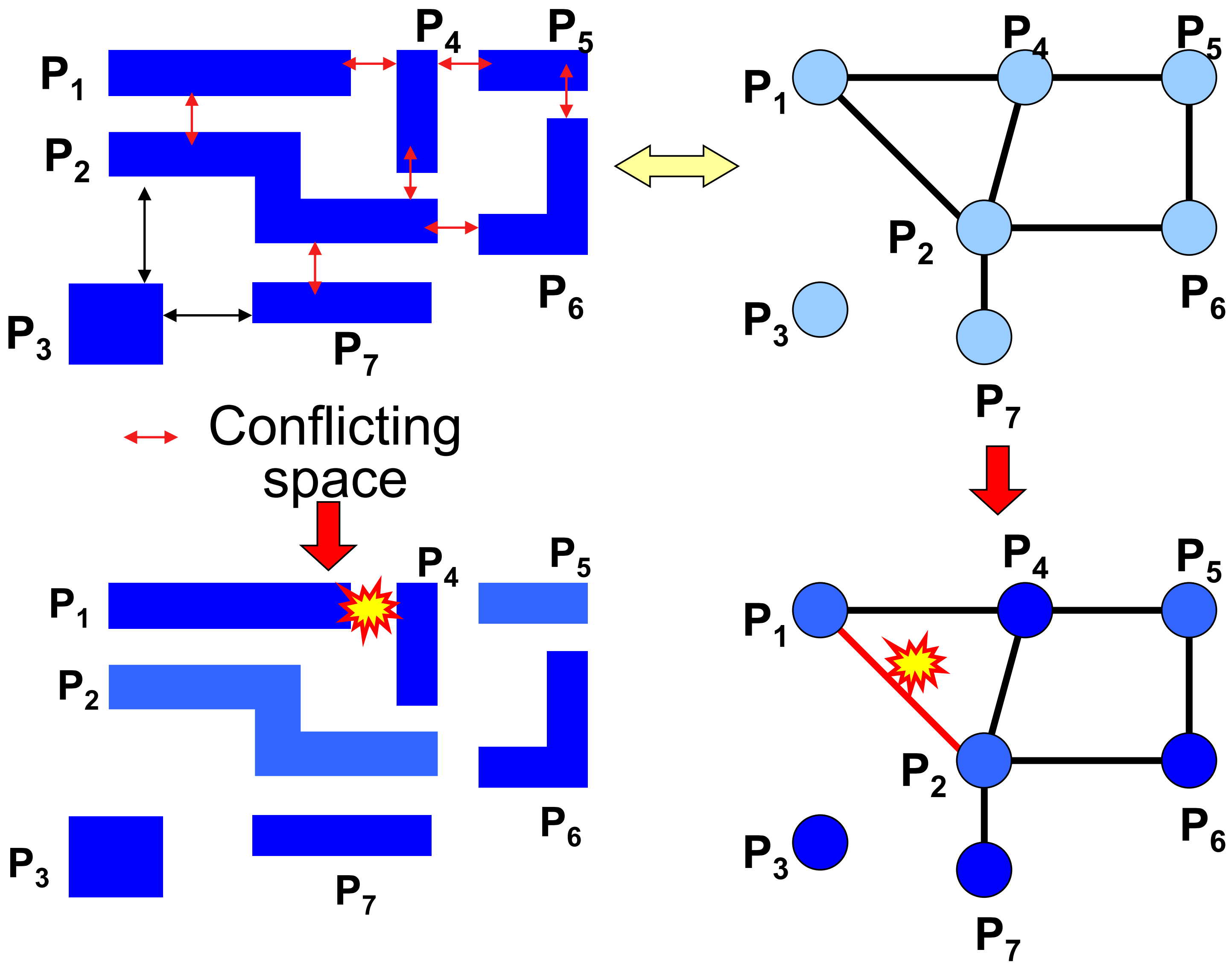
Resist-1 and etched hardmask images

Strip resist 1, coat and image resist 2

Etch final-pattern layer. Coat and image resist 3 to cut line end.

Final pattern from the end-cutting resist mask.

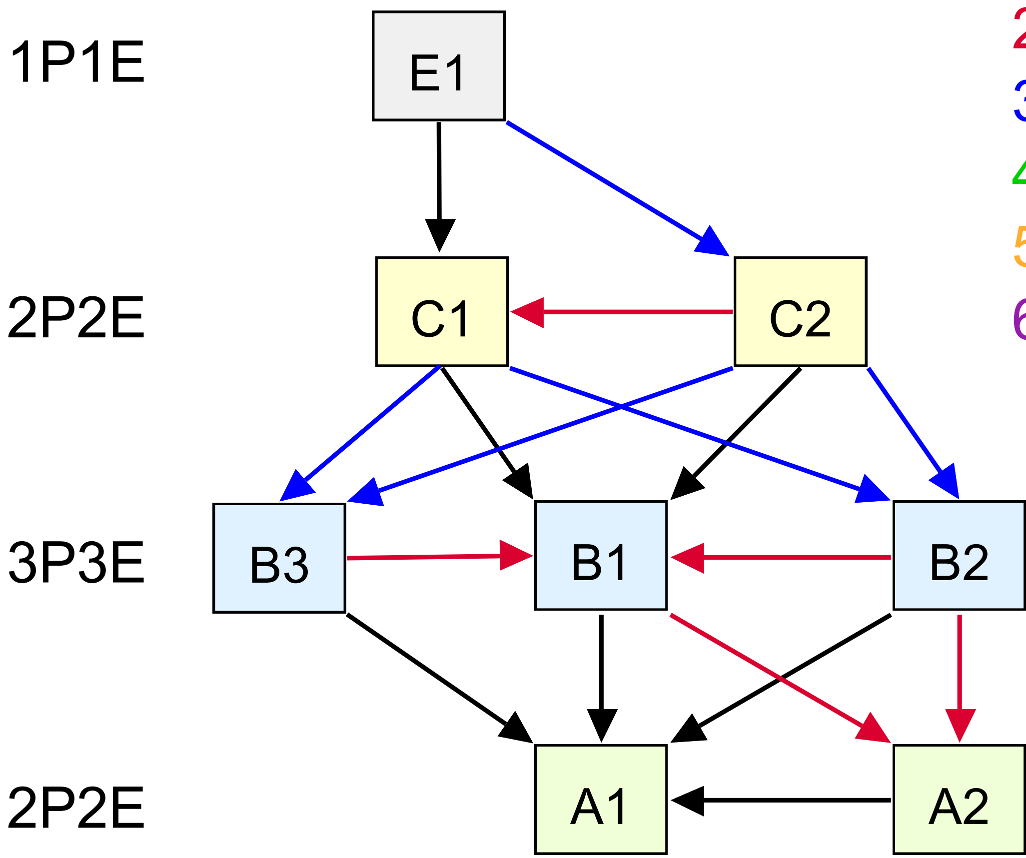
Issue I: G-Rule Violations



Issue II

Higher-Order Overlay Errors

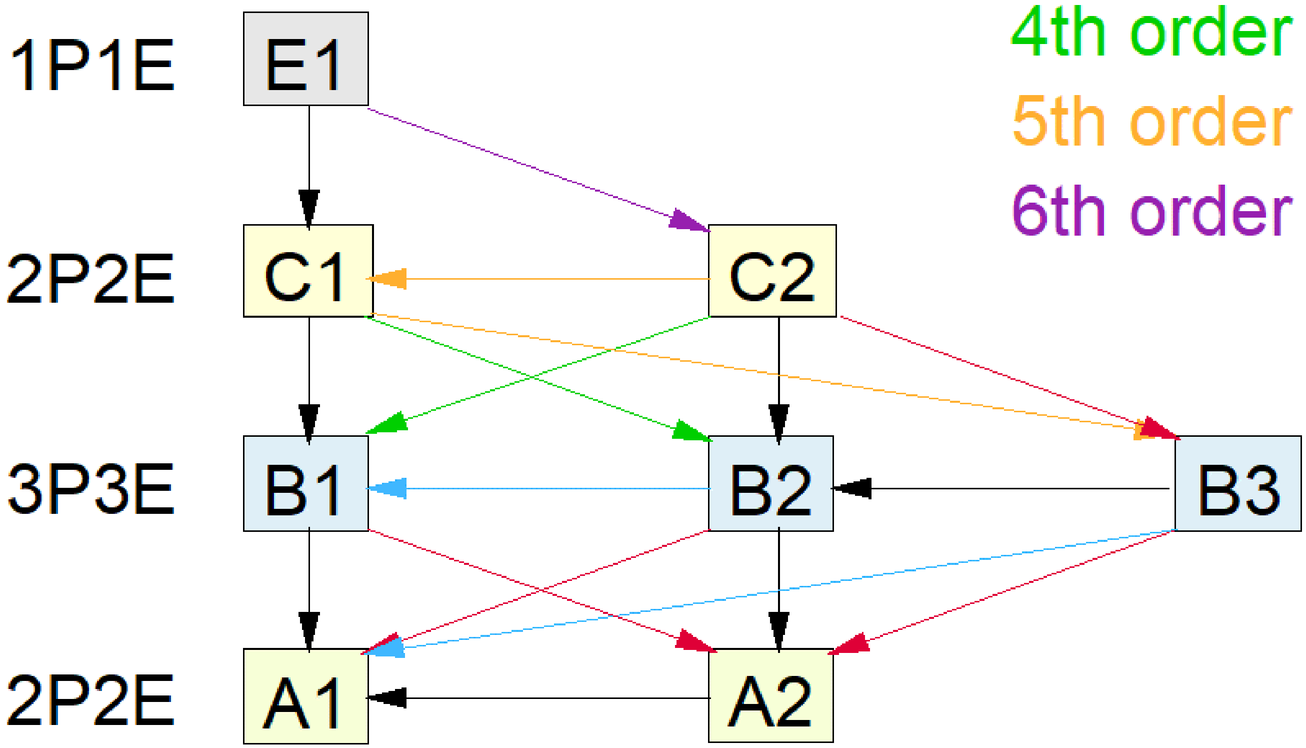
1P1E Aligned to 3 Layers
1st to 3rd Order Overlay Errors



Direct align 1.5%
2nd order 2.1%
3rd order 3%
4th order 4.2%
5th order 6%
6th order 8.4%

6th Order Overlay Error Can Happen

Direct align	1.5%
2nd order	2.1%
3rd order	3.0%
4th order	4.2%
5th order	6.0%
6th order	8.4%



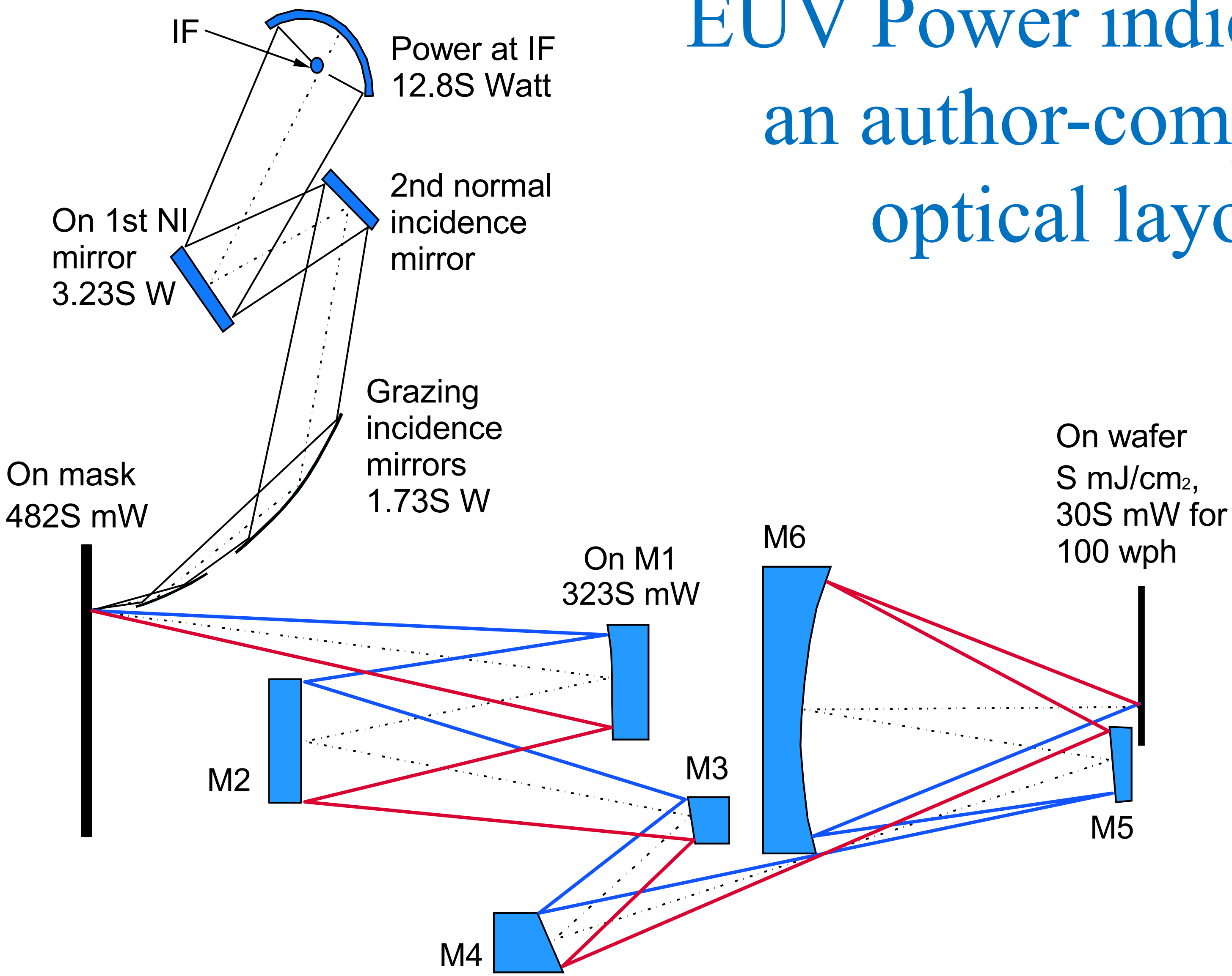
EUV Lithography

Dramatic Reduction of Wavelength

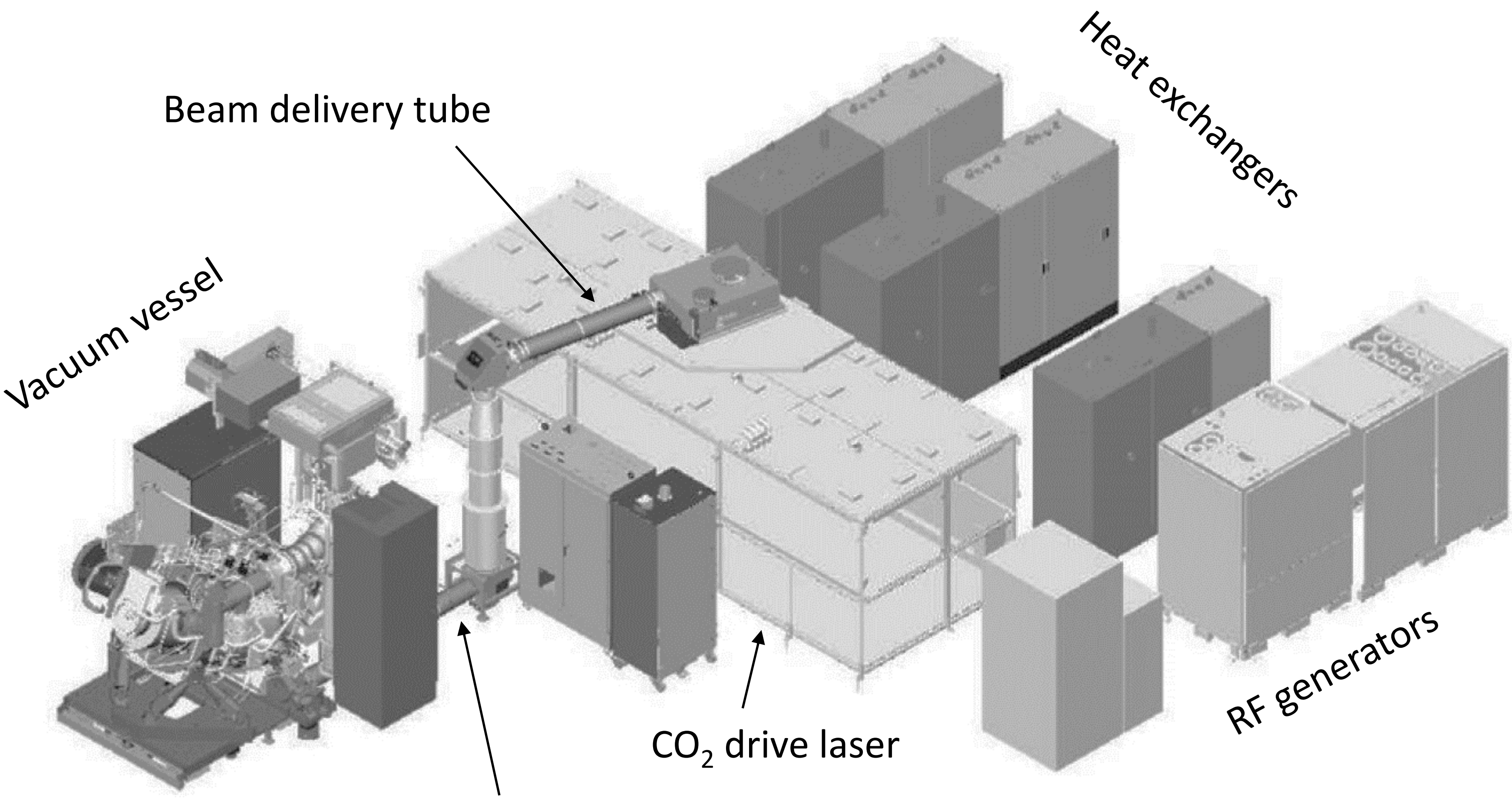
EUV Lithography

1. λ: 13.5 nm, 10% of 134 nm ArF H_2O imm λ.
2. No transparent material for lens,
   $\therefore$ An all-reflective system is required.
3. No reflective material either, until 40 layer-pairs to boost reflectivity to 67%.
4. It operates in a vacuum environment.
5. Atomic level of surface accuracy and quality.
6. Subatomic level of metrology precision.

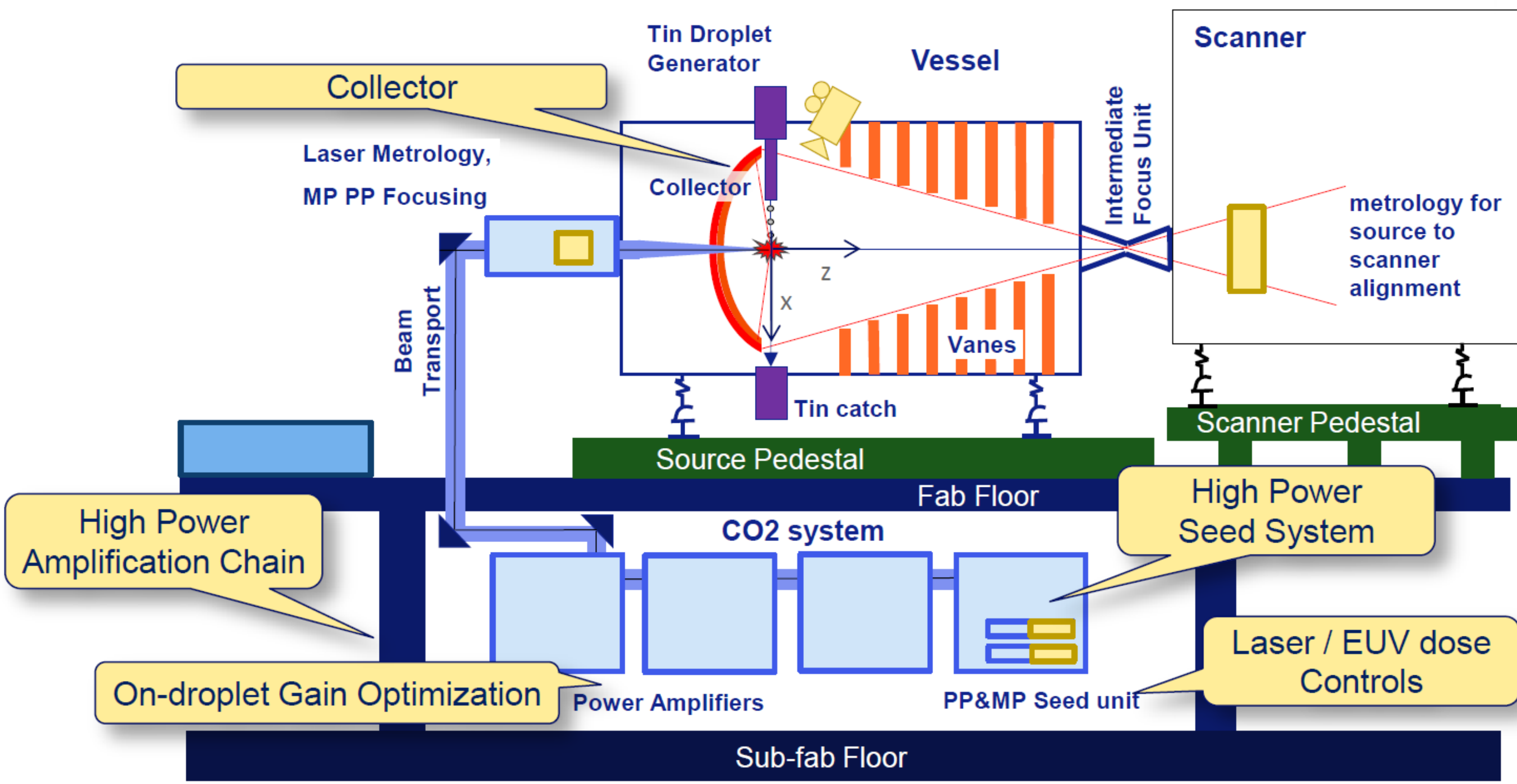
EUV Power indicated on an author-composed optical layout



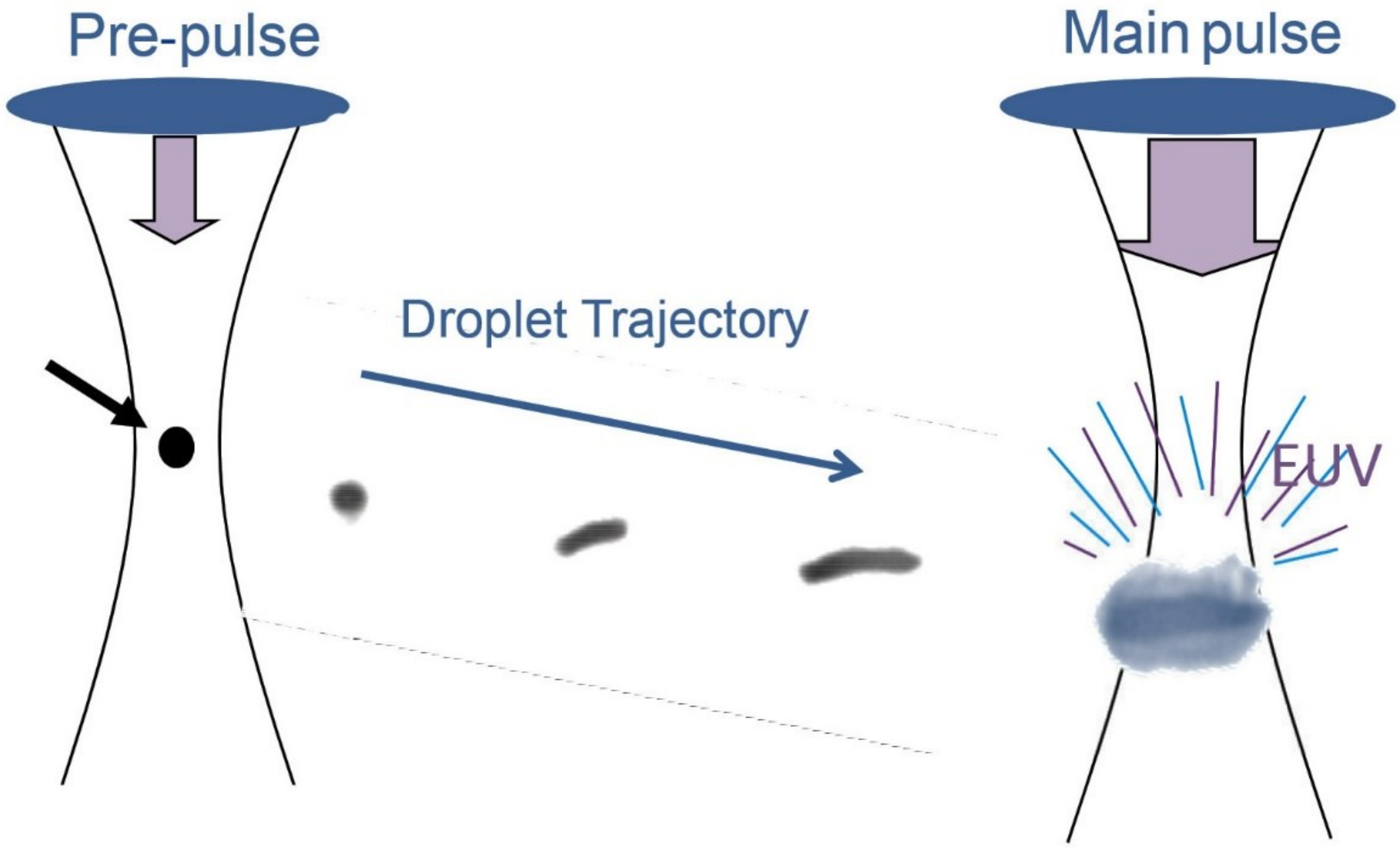
EUV Source of the ASML NXE3100



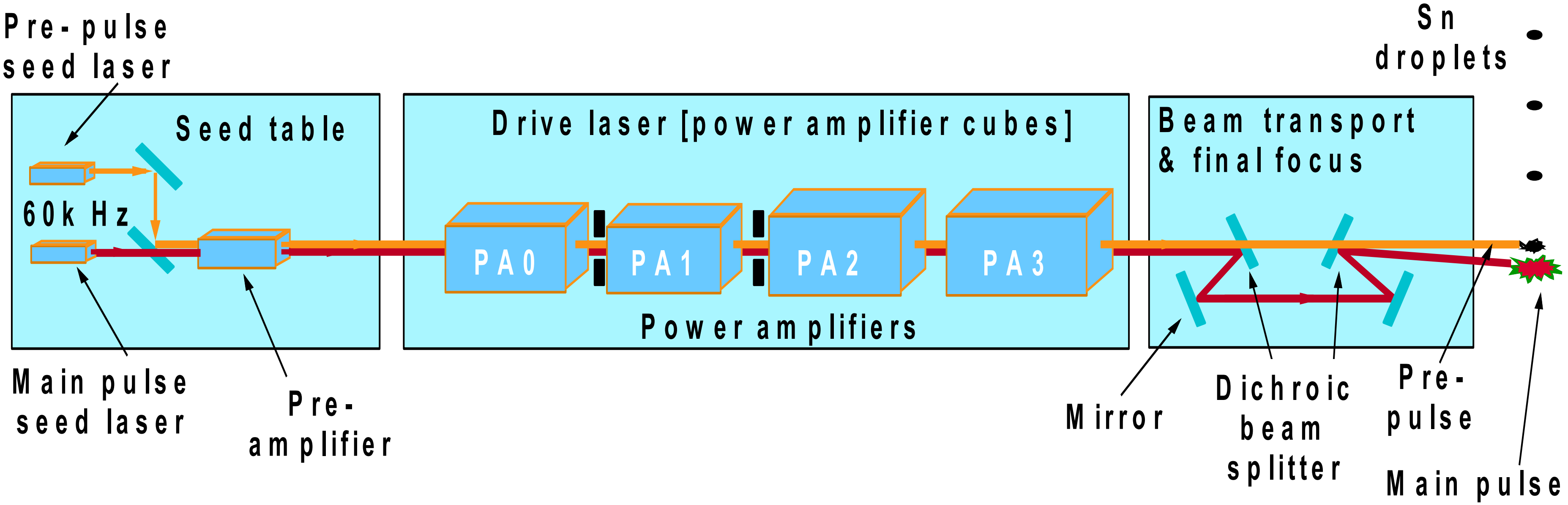
Sn LPP MOPA Architecture for ASML NXE3300



Pre-pulse Technique to Increase EUV Conversion Efficiency



Generation of Pre- & Main-Pulses



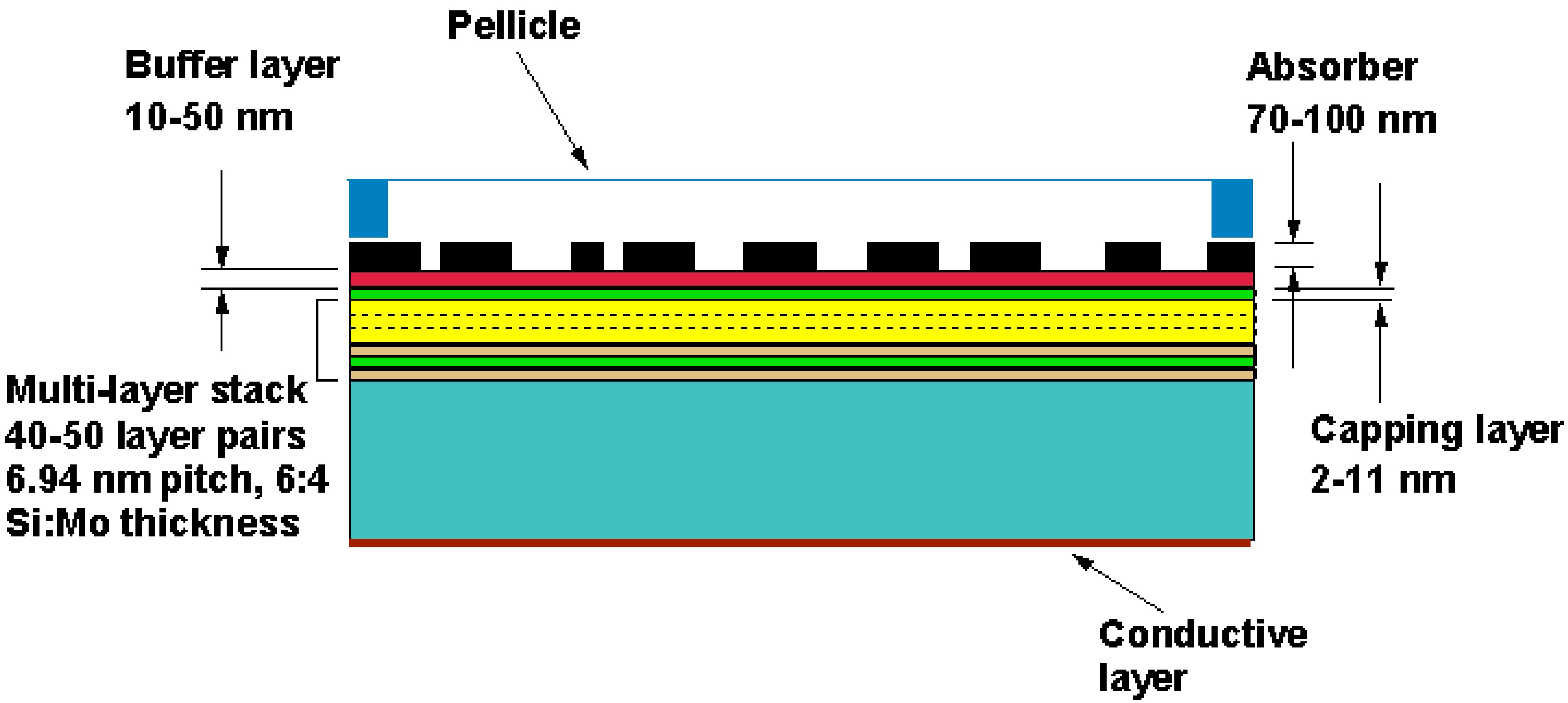
EUV MASK

Pellicle

Absorber Thickness

Flatness and Roughness

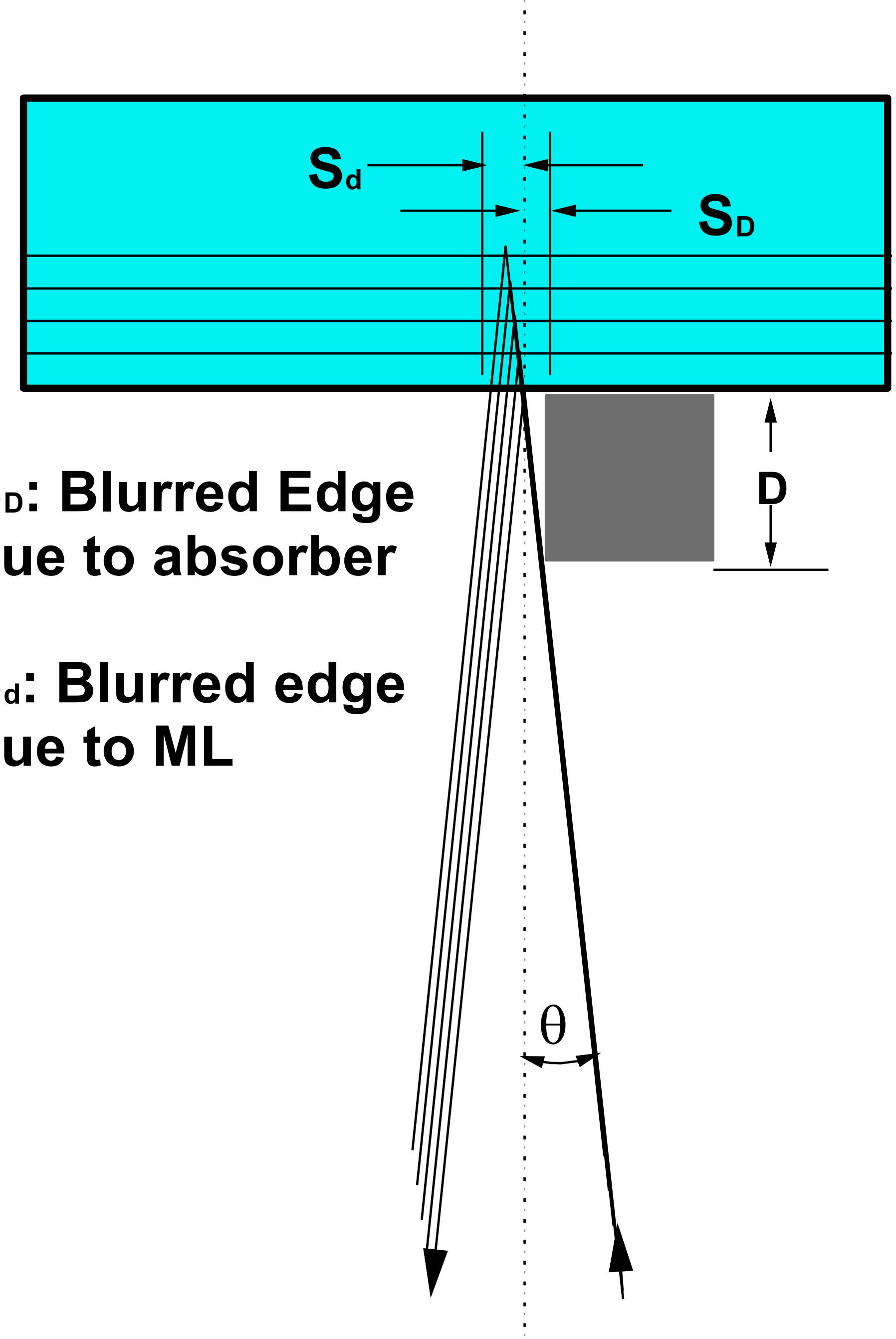
Configuration of EUV Mask



EUV Mask Pellicle

- Has to be thin, homogeneous, strong, inert.
- EUV power penalty about 20% in 2 paths.
- Has to withstand
  - High speed scanning of mask
  - Uneven thermal stress from EUV image and attached foreign particle
  - Radiation damage
  - Chemical damage
- Cost penalty

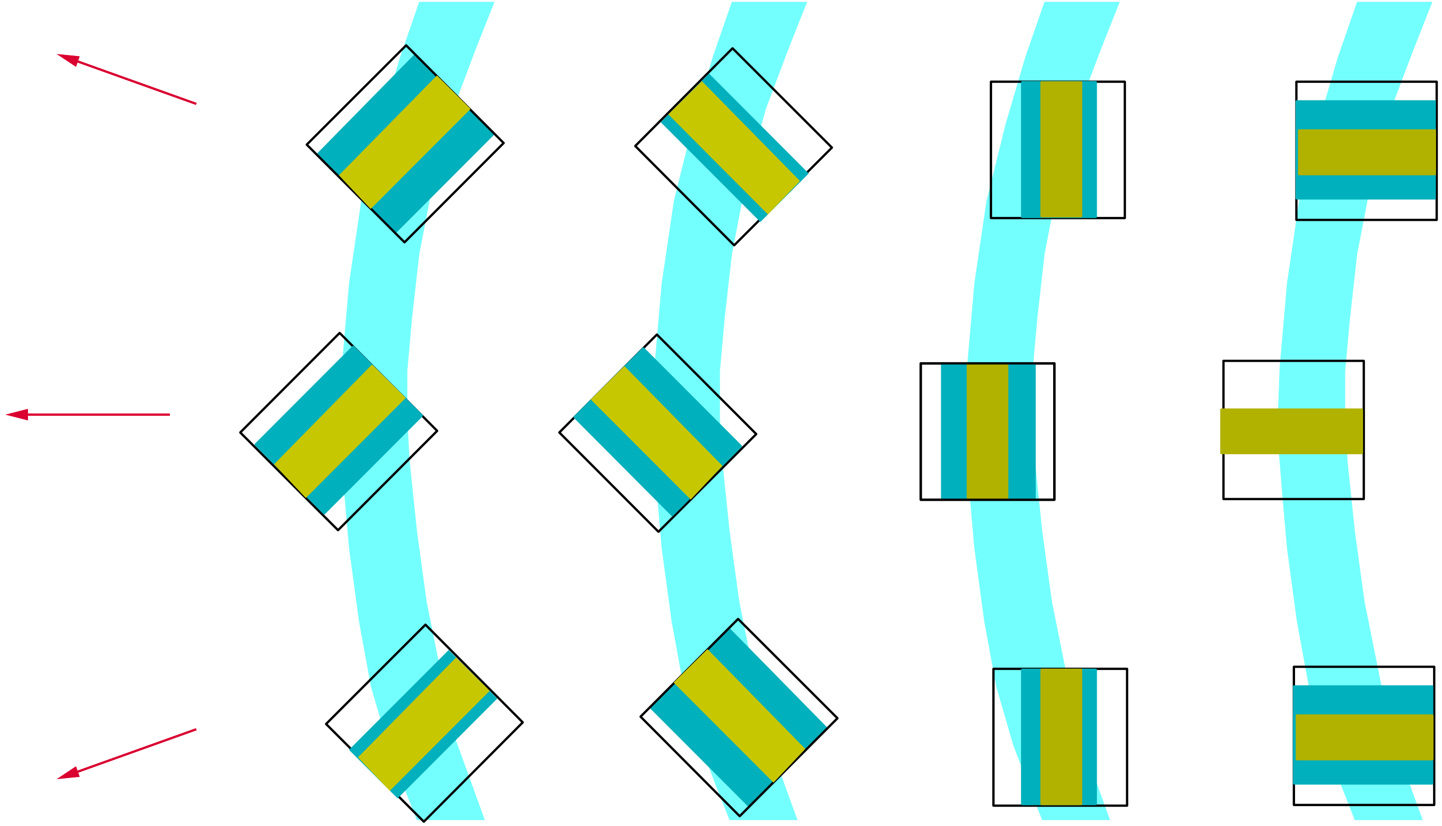
Shadow of Edges due to Finite CRAO (Chief Ray At Object)



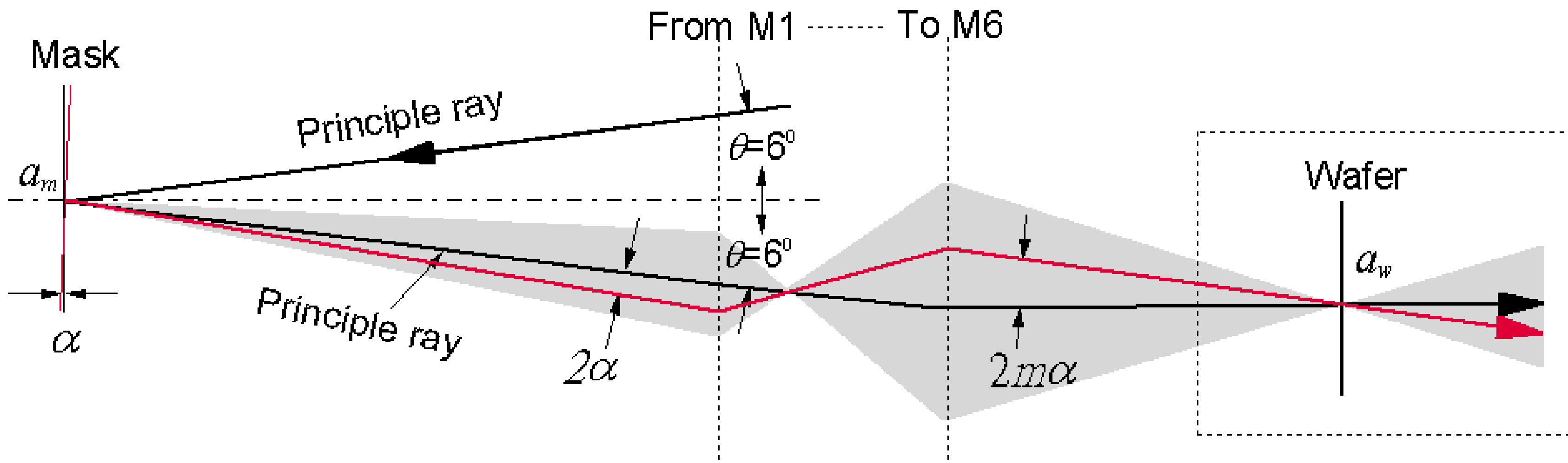
S_D: Blurred Edge due to absorber

S_d: Blurred edge due to ML

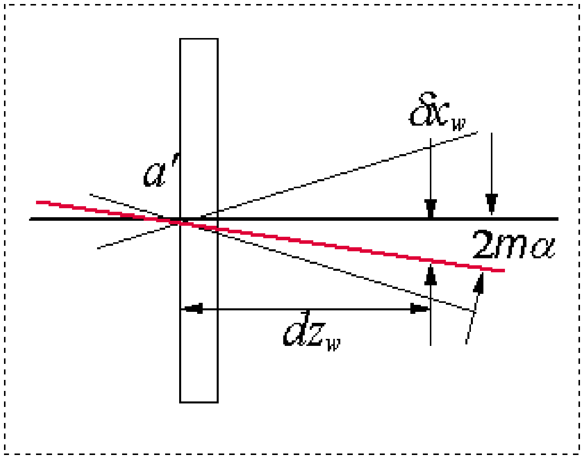
Shadow of Edges as Function of Position at the Illuminated Slit

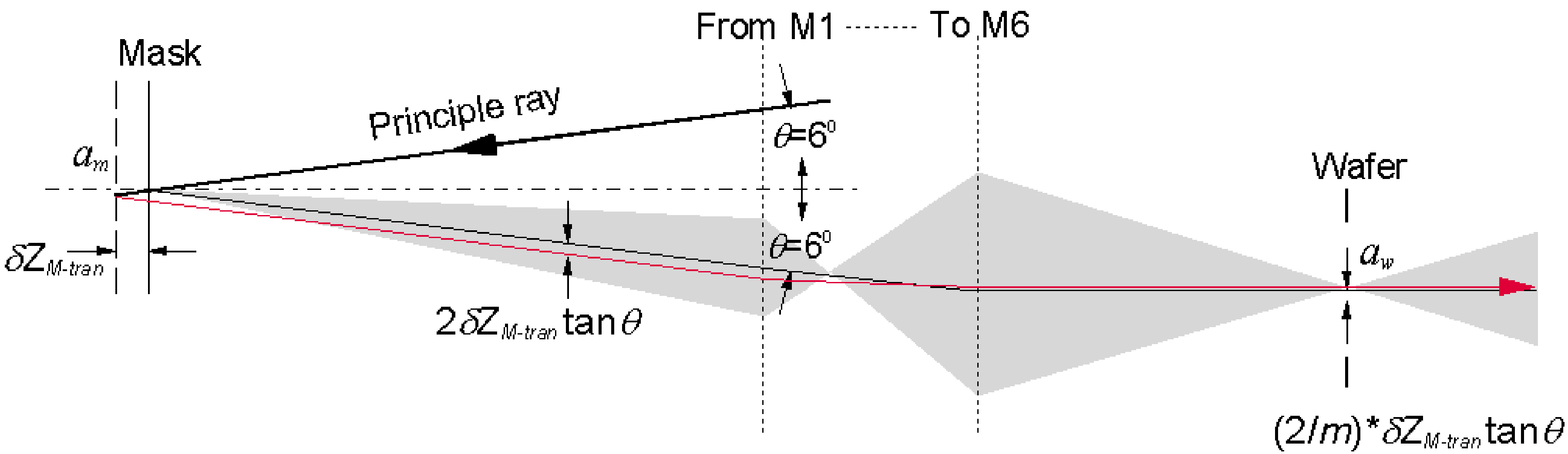


Courtesy Lorusso



A tilt of a becomes 2α due to reflection, then $2m\alpha$ due to m:1 reduction. When the wafer is in focus, no lateral shift is induced. When the wafer is out of focus by dz_W, there is a lateral displacement $\delta x_W = dz_W * 2m \sin\alpha$.



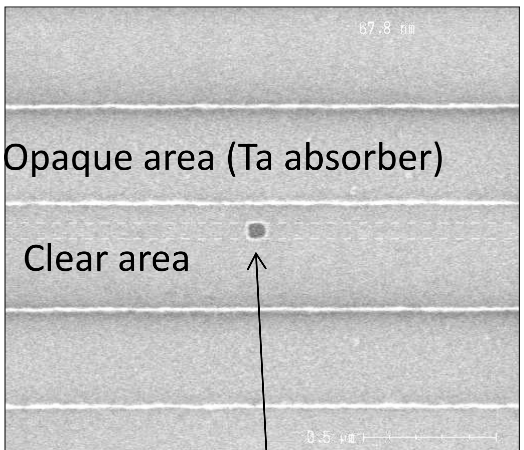


Mask longitudinal misplacement produces a lateral displacement in the image

$\therefore$ Mask flatness & roughness spec < 1 nm

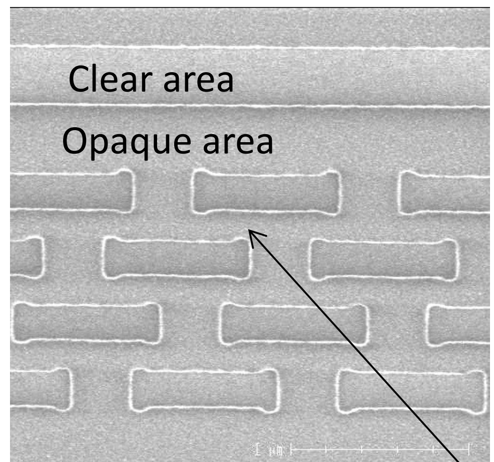
Mitigation of EUV mask blank defects by manipulating the placement of the mask pattern to cover the defect with opaque features.

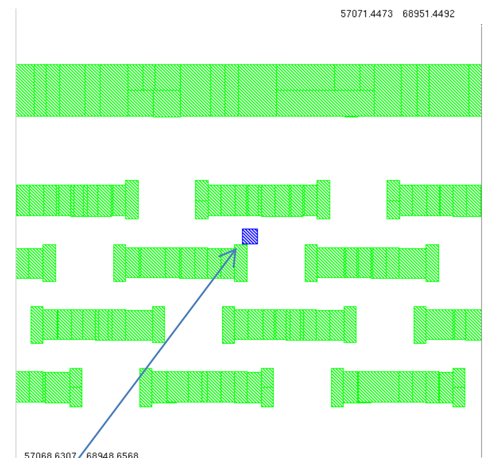
Without pattern shift



This blank defect (~70nm on mask) is in the clear area and will be printed on wafer

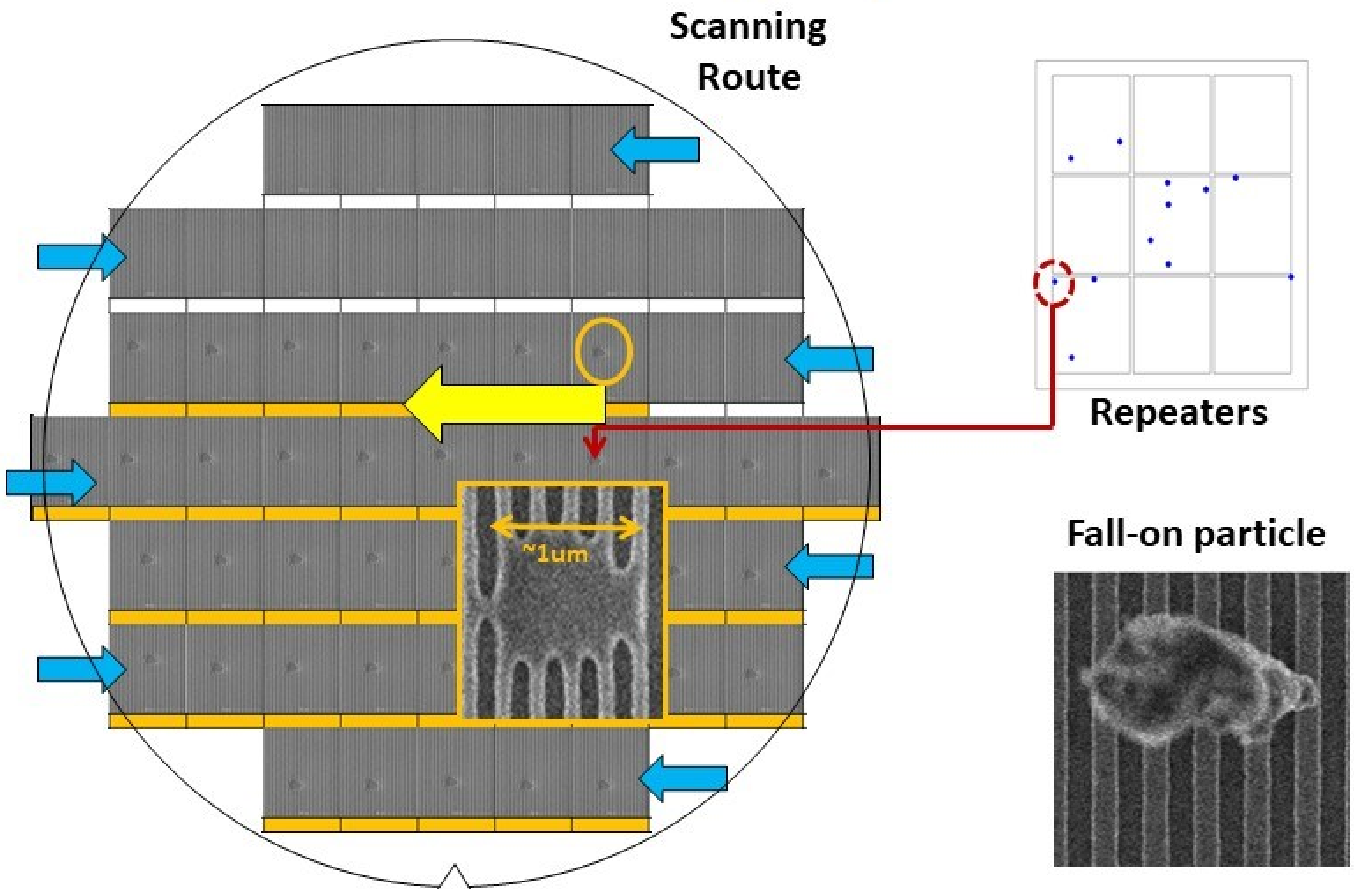
With pattern shift





After global pattern shift, a blank defect shown above is now hidden under the Ta absorber

Micrometer-size particle attached to mask during exposure



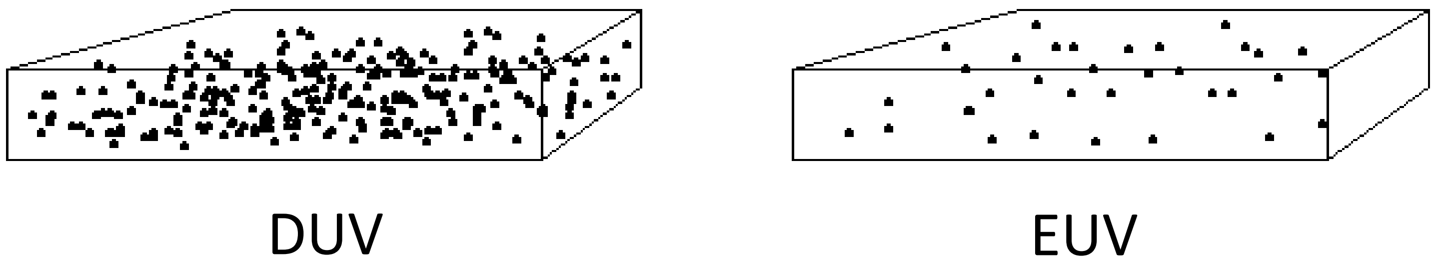
EUV RESIST

Sensitivity

Thickness

Etch Resistance

Variability of Photons for EUV & DUV



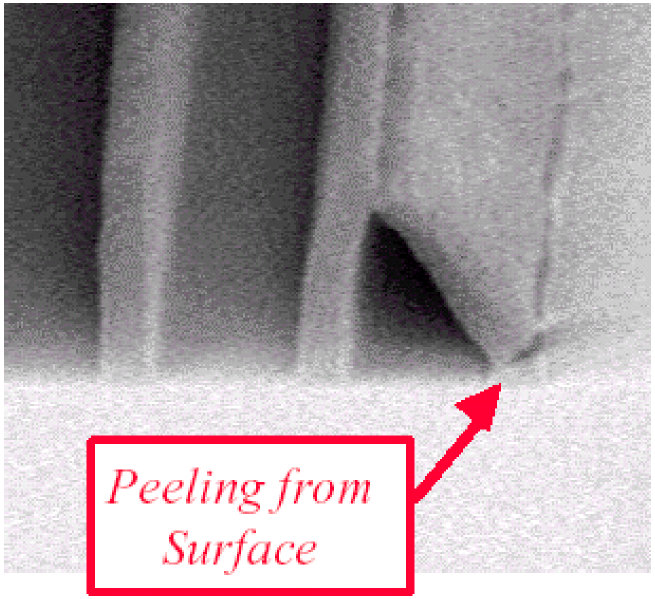
$$\frac{\text{No. of 13.5nm photons per volume}}{\text{No. of 193nm photons per volume}} = \frac{6.4\ \text{eV}}{91.8\ \text{eV}} = 1/14.3$$

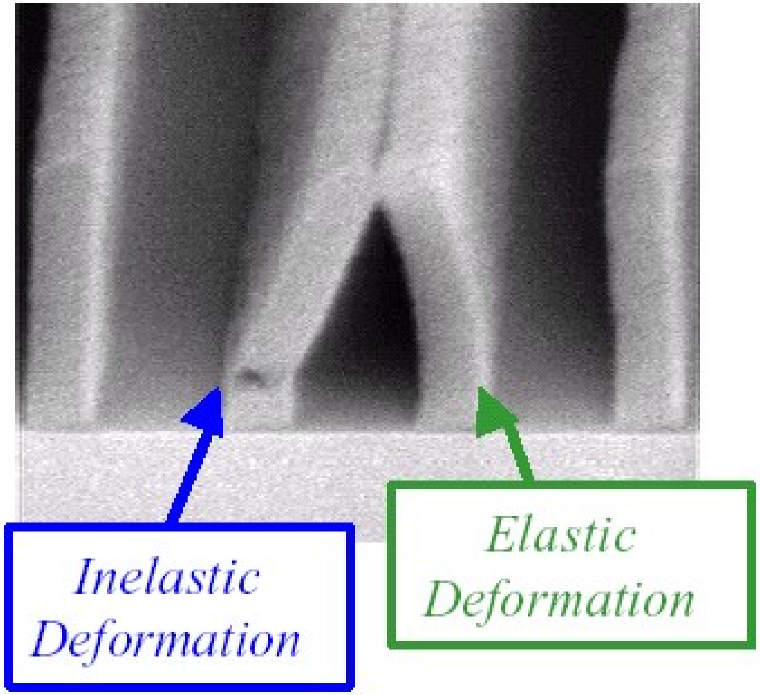
$$\frac{\text{Variability of EUV photons}}{\text{Variability of ArF photons}} = \sqrt{\frac{91.8\ \text{eV}}{6.4\ \text{eV}}} = 3.8$$

Conflicting Requirements on Resist Sensitivity

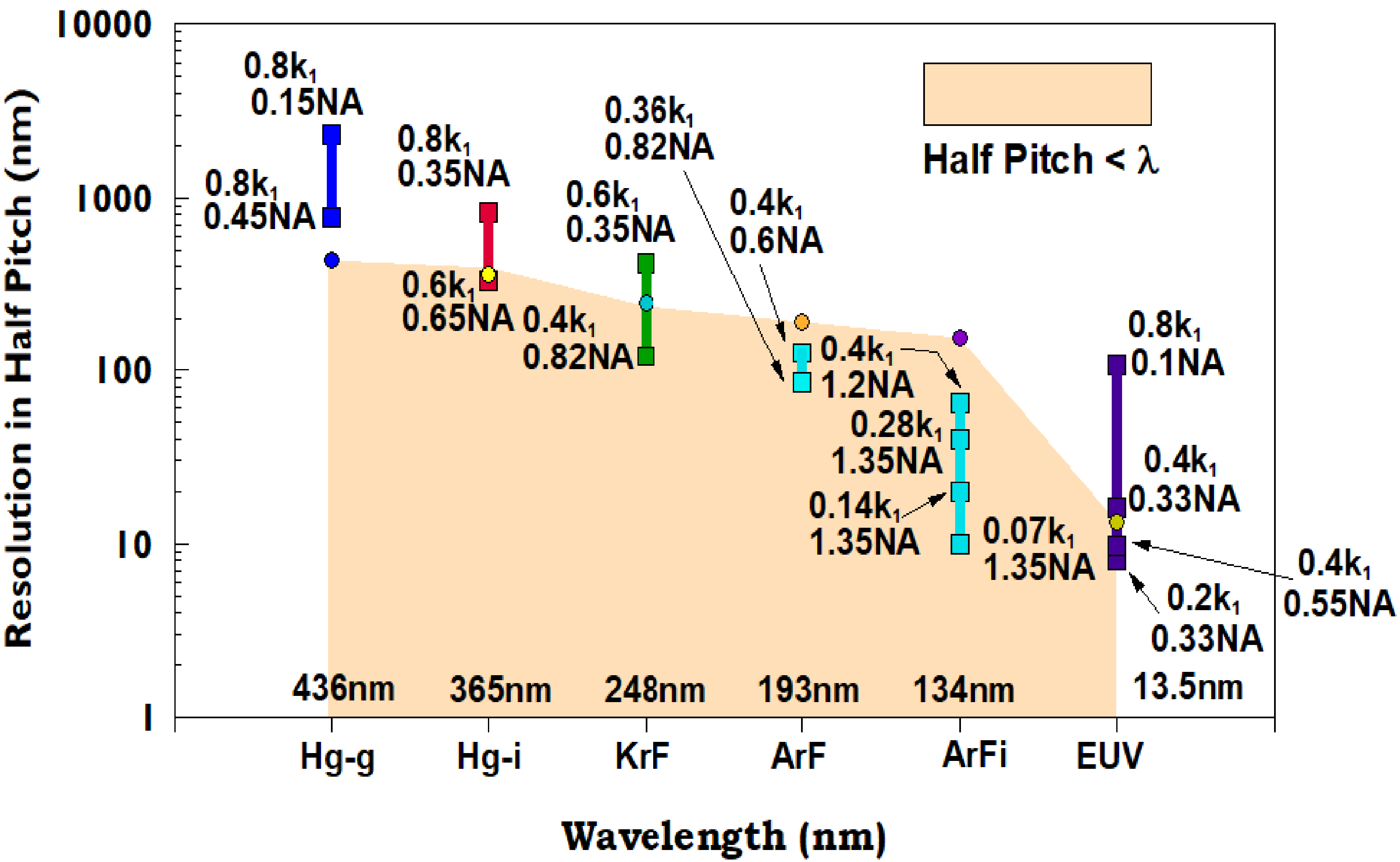
- Throughput/cost => High sensitivity
  - Smaller features => Higher sensitivity
- Stochastic phenomenon => Low sensitivity
  - Smaller features => Low sensitivity
- Low line roughness => Low sensitivity

Resist Height : Width < 3:1 to prevent collapse





Evolution of Lithography for Moore's Law
1000x linear improvement. 1Mx in density



Thank you for your attention