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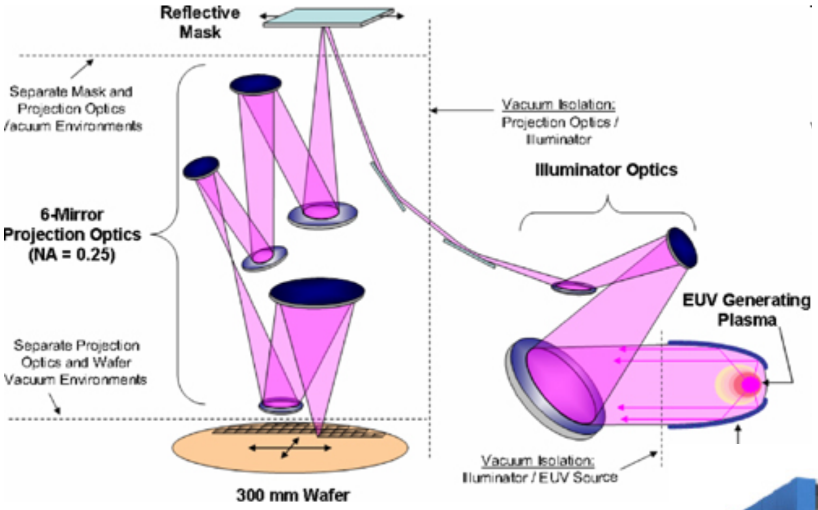
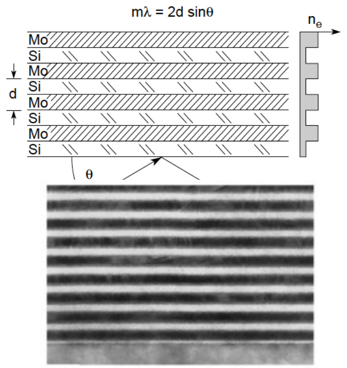
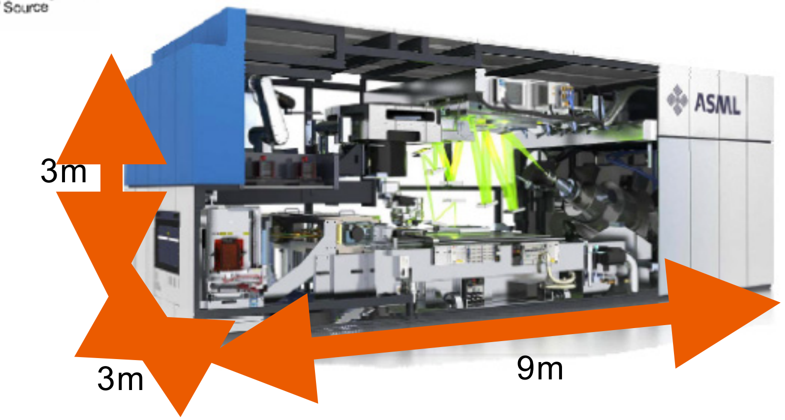
Pushing the resolution limits of photolithography: *Understanding the fundamentals of the EUV resists*

EUV Lithography

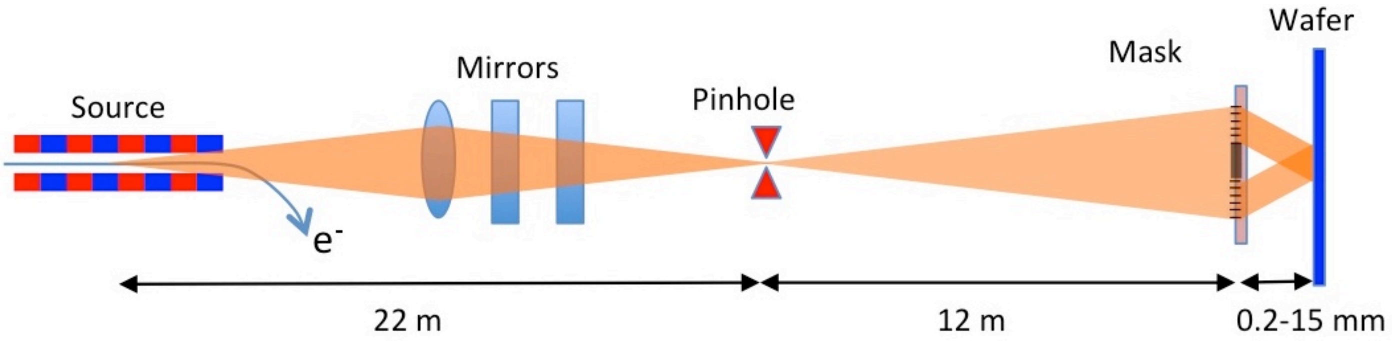




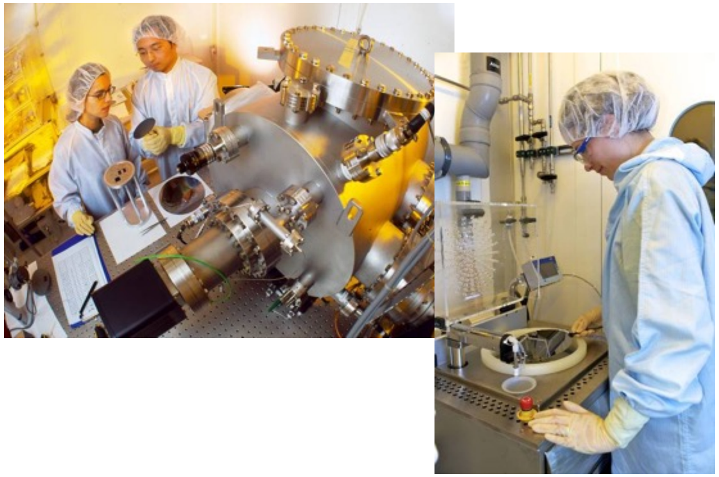
- EUV lithography:
    - Reflective optics and mask
    - Plasma source
- EUV in high-volume production delayed mainly due to source power
- Planned for HVM production in 2018



XIL-II: EUV-IL @ Swiss Light Source, PSI



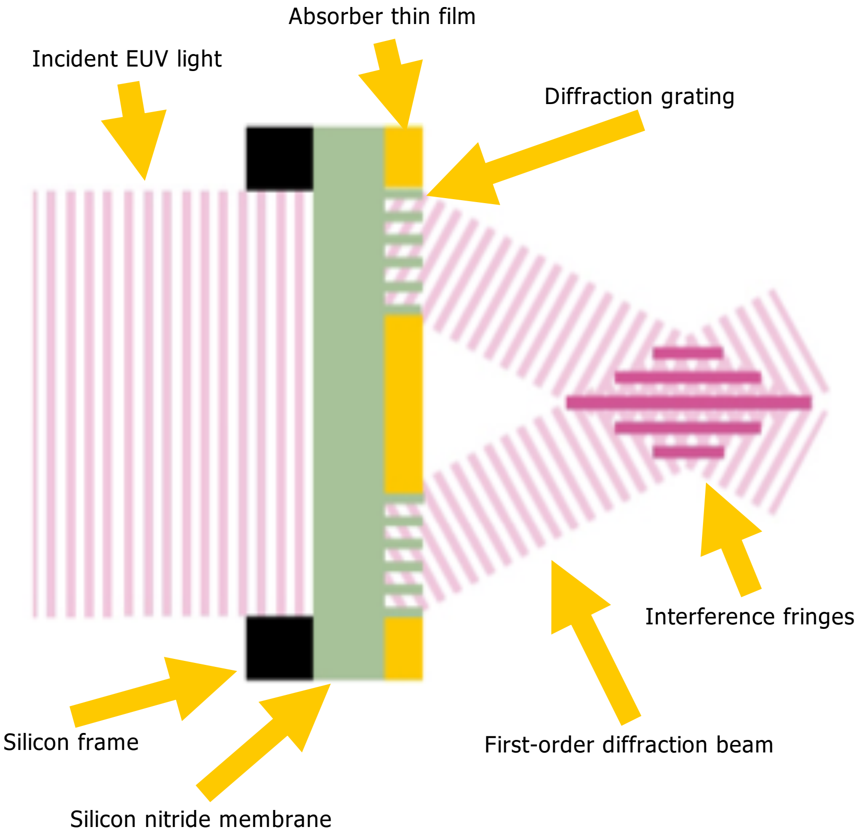
- Undulator source+ Switchable mirror+ pinhole
  - High brightness
  - High spatial coherence
  - 4% bandwidth
  - tunable wavelength (λ=2.5-18 nm)
- On-site cleanroom
  - Spin-coater, wet-bench, hot-plates, microscope, developer, optical thickness measurement



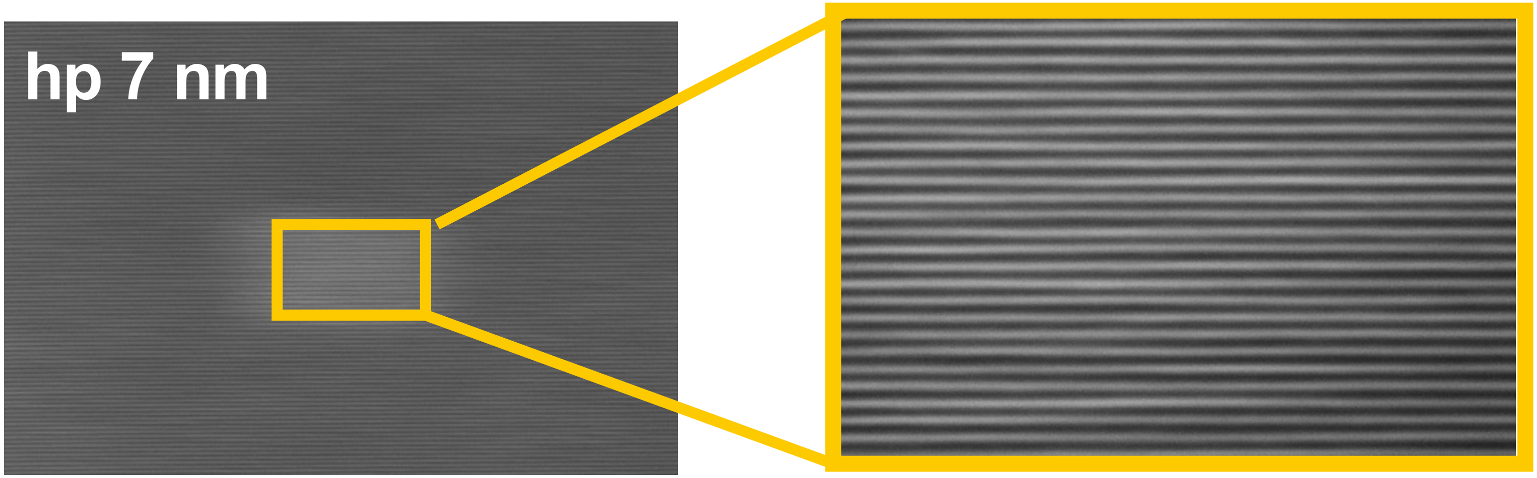
EUV interference lithography

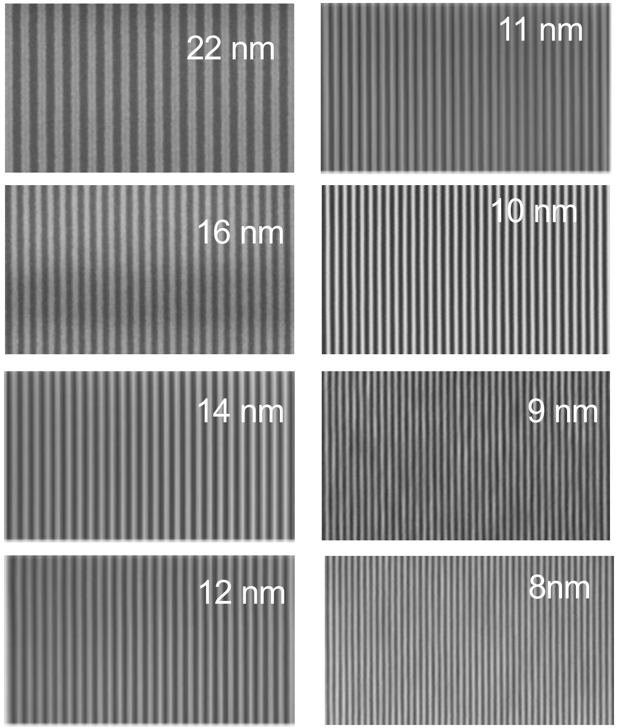
CONCEPT:

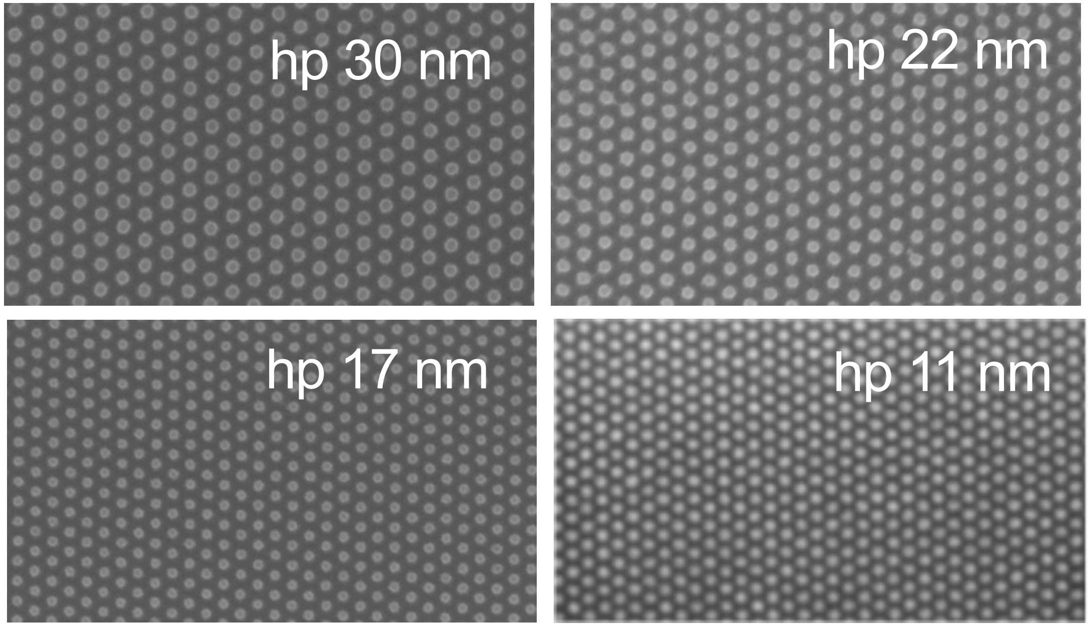
- EUV: 13.5 nm wavelength
  - Spatially coherent
  - Temporal coherence: $\Delta\lambda/\lambda=4\%$
- Diffractive transmission gratings:
  - Metal gratings written with EBL
  - on Si_3N_4 membranes (~100 nm)
- diffracted beams interfere
- interference pattern printed in resist



Record resolution in photolithography



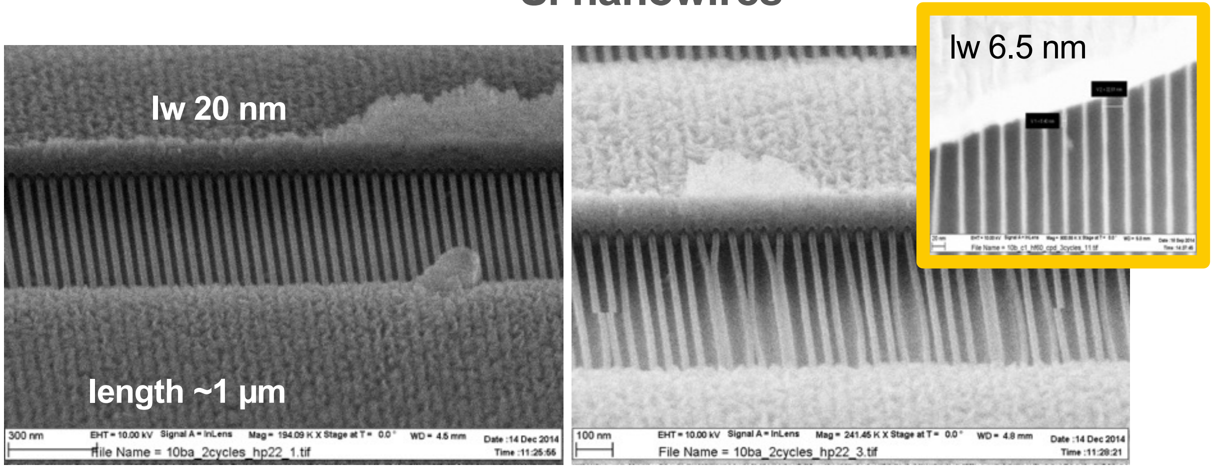




Science with EUV-IL

- EUV resist development
- Nanoimprint stamps
- Fluidic confinement structures
- Plasmonics and Metamaterials
- Polymer grafting
- Biomaterials
- Catalysis
- Templated assembly
- Cell growth templates
- Nanomagnetism
- Fresnel Zone Plates
- etc.

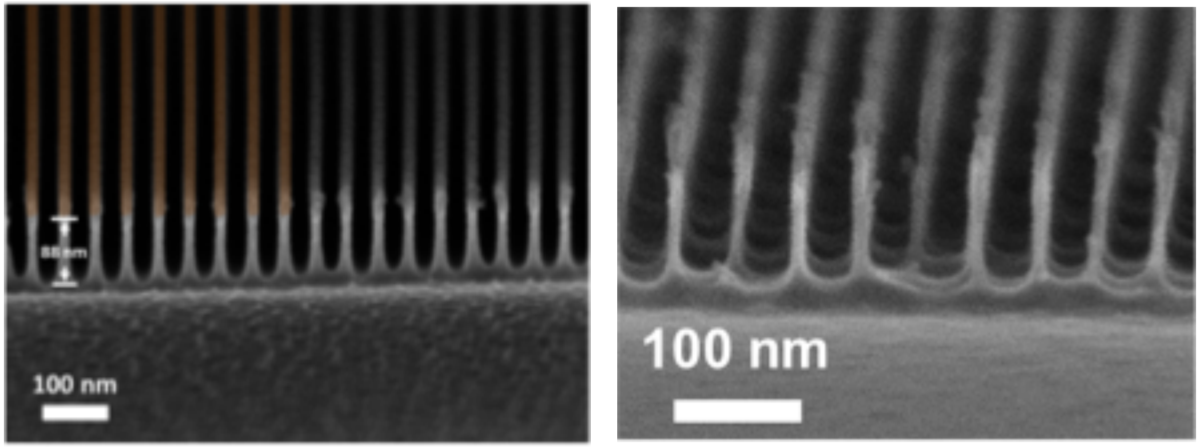
Si nanowires



Si fins

16 nm

11 nm

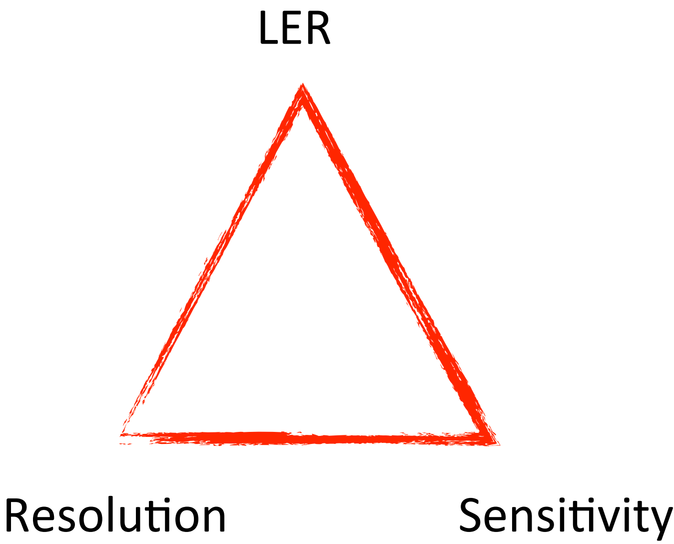


Height 88 nm

EUV resists

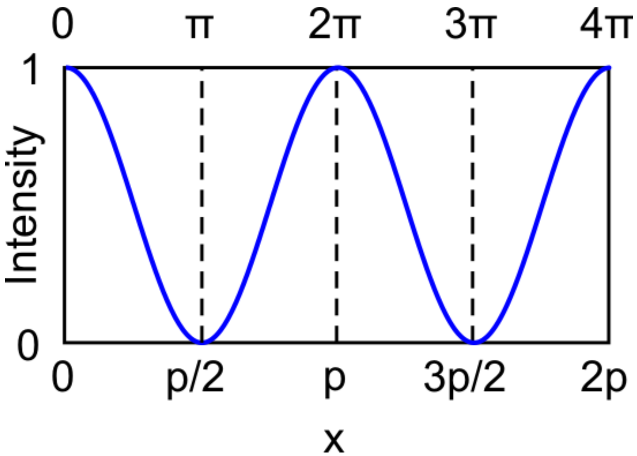
- A major challenge is EUV resists with the best performance
  - Resolution, HP (nm)
  - Sensitivity, dose (mJ/cm^2)
  - Line edge roughness, 3σ (nm)

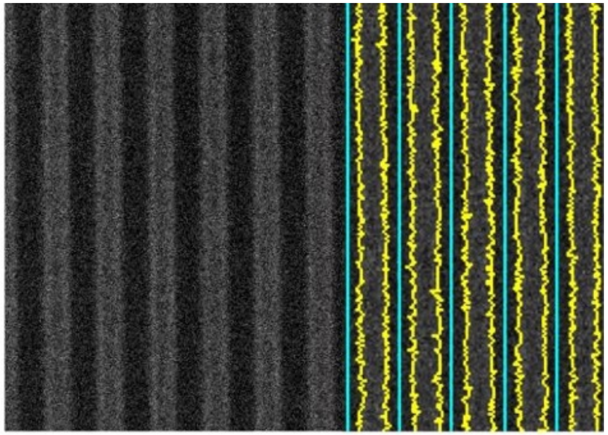
- XIL is a powerful method in development of EUV resists
  - High resolution and well defined image, pitch independent.
  - Enabling research before tools are available.
  - Low-cost
  - Flexible: outgassing, contamination


LER

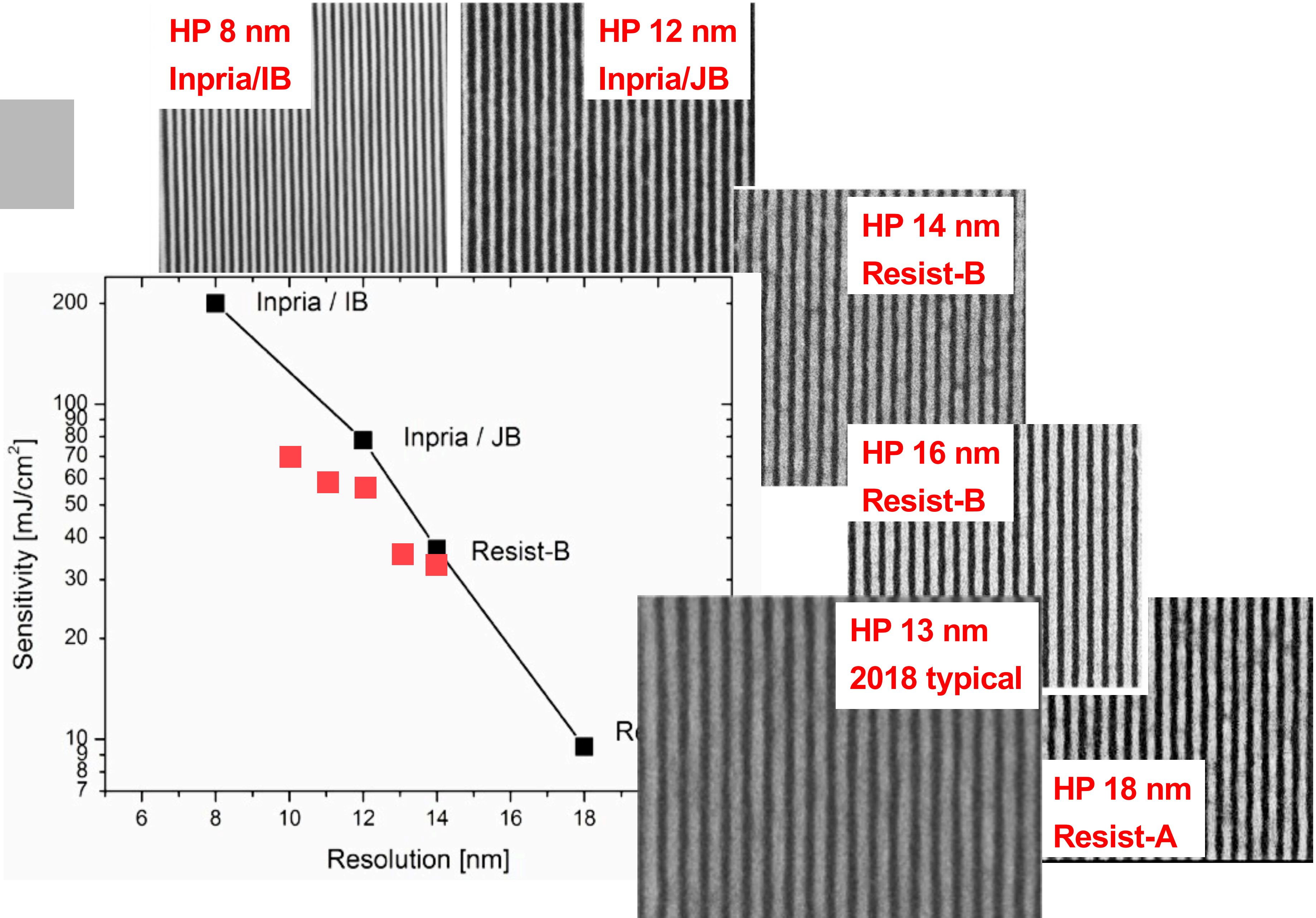
Resolution

Sensitivity



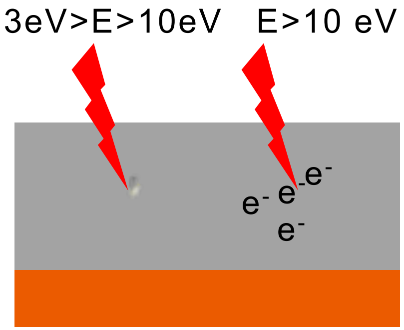


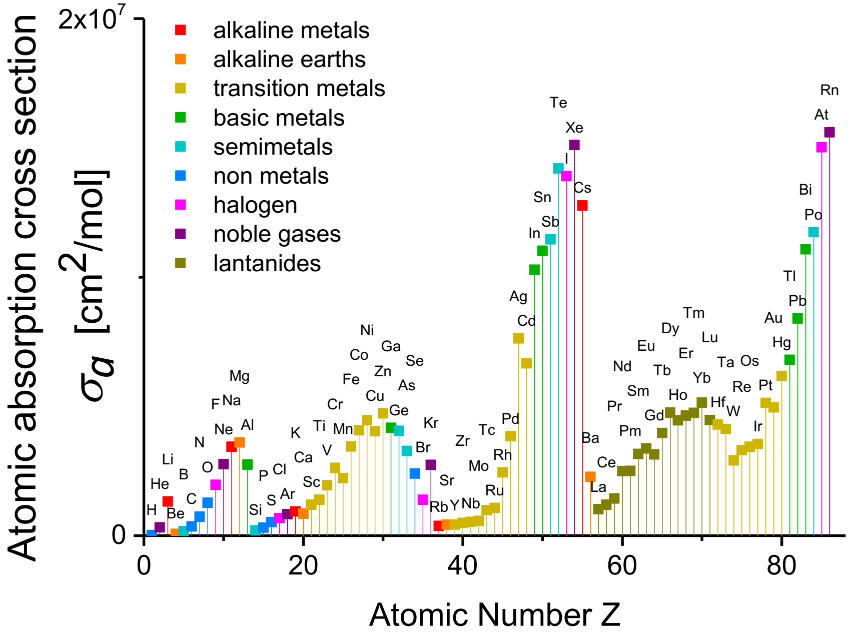
EUV resists: State of the art @ SPIE 2013



How does EUVL work?

- Absorption mechanism
- Secondary electrons:
  - How many are generated?
  - How do they interact?
  - How many of them are “useful” electrons?
  - What are the loss mechanisms?
  - How far they travel?
- Chemical reactions:
  - How many acids are generated?



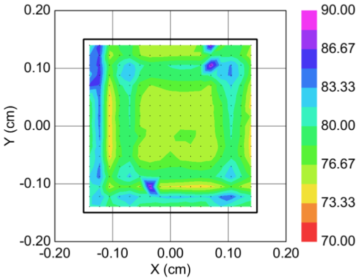


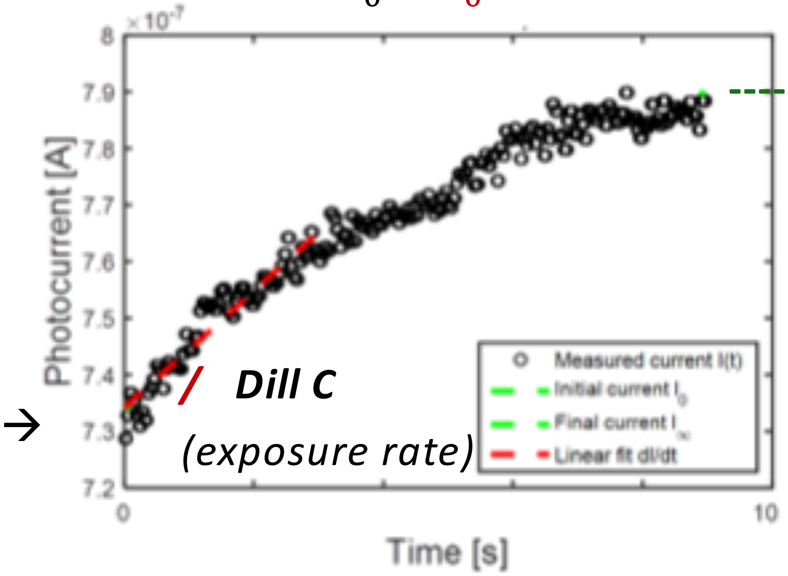
Method:

$$T_X = \frac{\Phi}{\Phi_0} = \frac{I}{I_0} = e^{-\alpha d}$$

Resist thickness *d* measurement:

- Woollam M2000 spectroscopic ellipsometer
- 250-1000 nm spectral range
- focusing probe (Φ 30 μm), automatic stage
- Cauchy + B-spline ellipsometric model





Dill B

(unbleachable)

↑

Dill A = B – α

(bleachable)

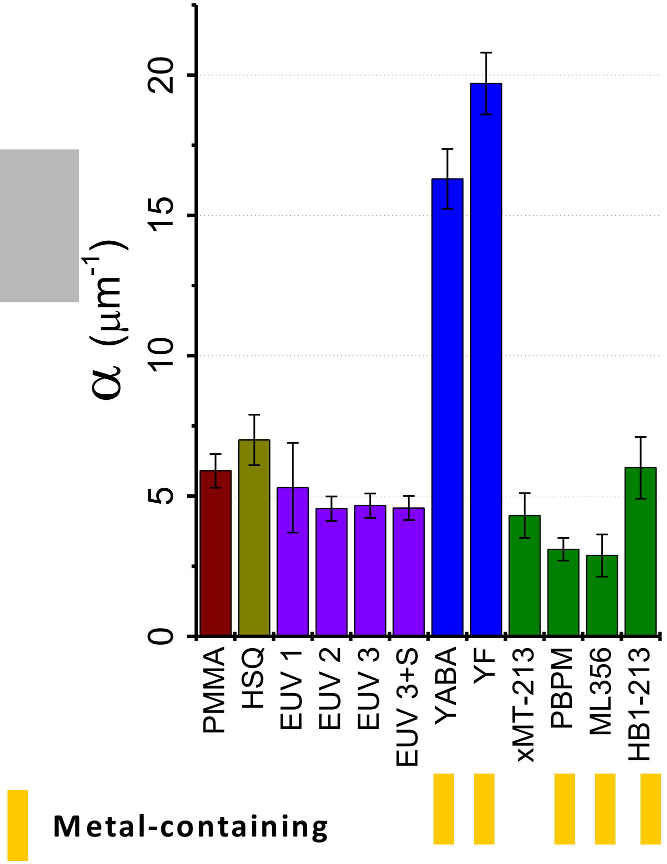
↓

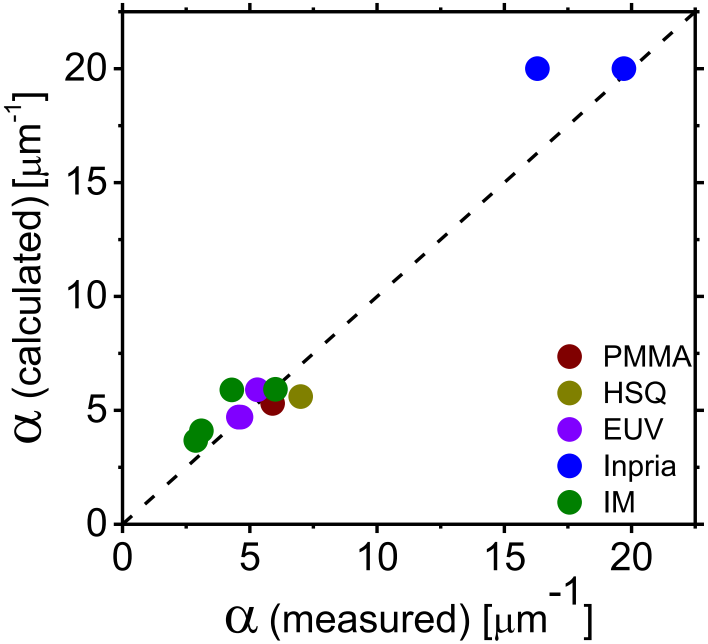
α →

Dill C

(exposure rate)

Absorption coefficient of EUV resists





Previous studies:

For PMMA, $\alpha_{PMMA} = 5\ \mu m^{-1}$ [1][2] (transmission).
For most organic polymers, calculated $\alpha \approx 3 - 5\ \mu m^{-1}$ [3].

EUV backbone polymers, $\alpha \approx 2.1 – 4.4\ \mu m^{-1}$ [2] (grazing angle reflectivity).
Fluorinate EUV resists $\alpha = 6.54\ \mu m^{-1}$ [4] (transmission).

† PMMA: formula $C_5O_2H_8$, density 1.2 g/cm^3.

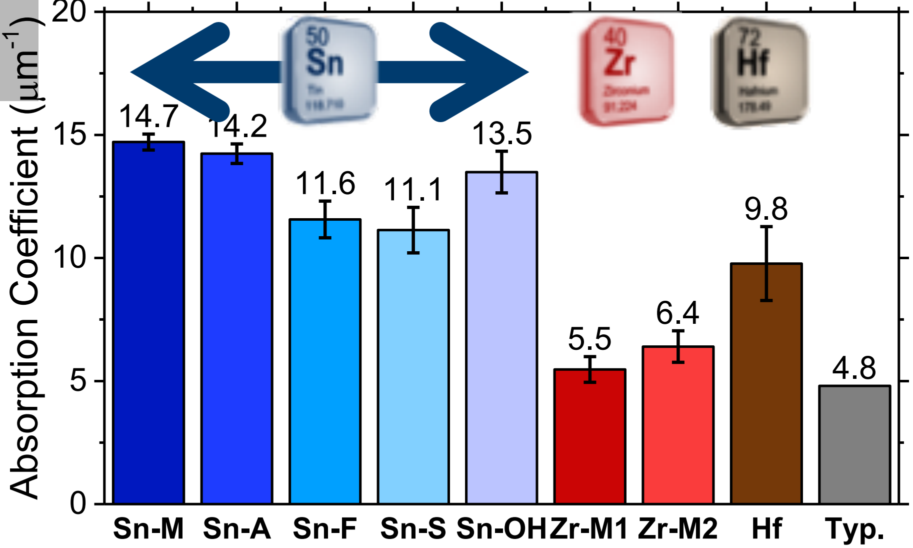
‡ HSQ: formula $Si_8O_{12}H_8$, density 1.4 g/cm^3.
* Source: Manufacturer.

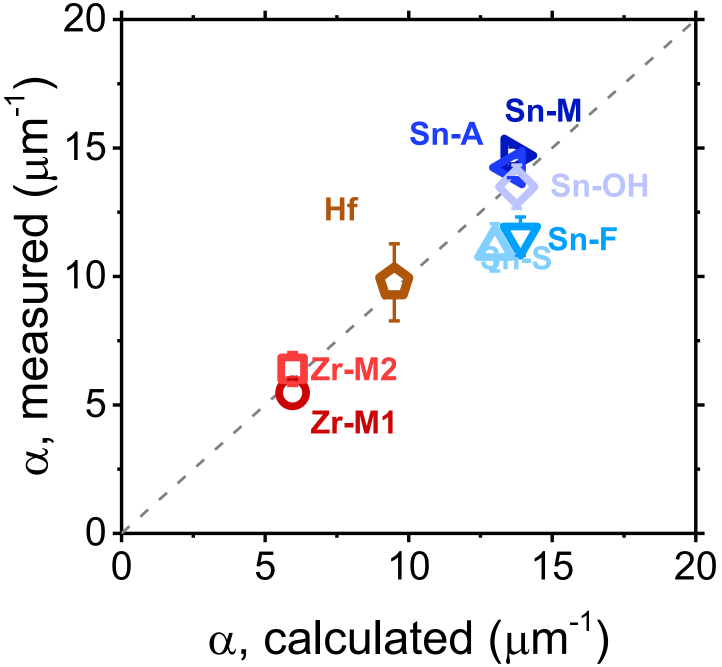
[1] G. D. Kubiak et al., Journal of Vacuum Science & Technology B 10, 2593 (1992).
[2] Y.-J. Kwark et al., J. Vac. Sci. Technol. B 24, 1822 (2006).

[3] N. N. Matsuzawa et al., Microelectronic Engineering 53, 671 (2000).

[4] A. Sekiguchi et al., Proc. of SPIE Vol. 9422 94222L-1.

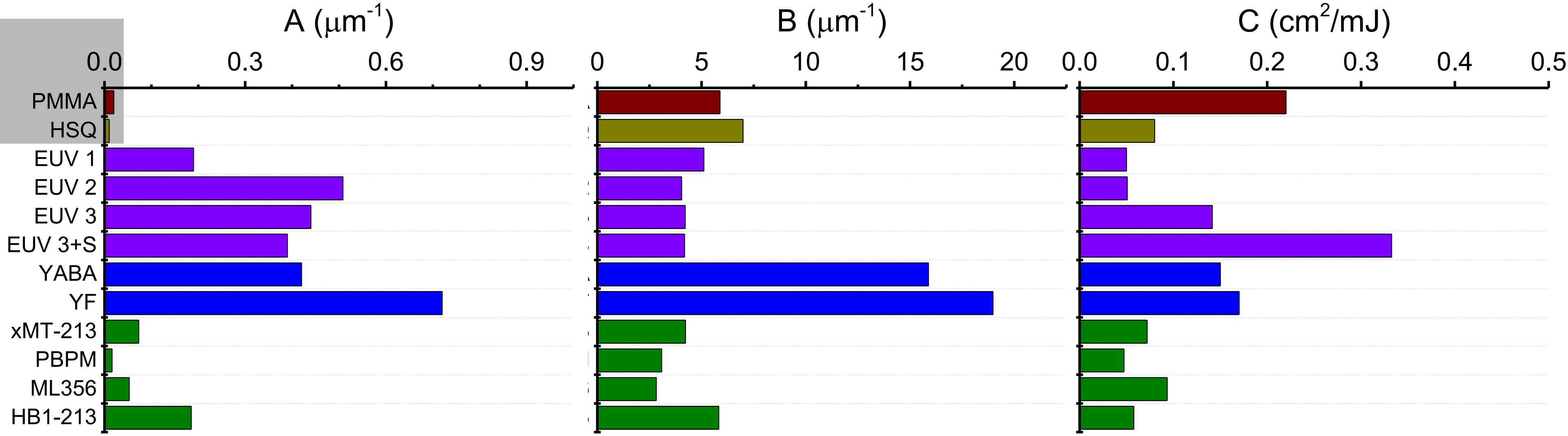
Absorption of metal-based photoresists





The actual absorption α can be to substantially different than predicted, thus affecting the real sensitivity and lithographic performance.

Results: Dill Parameters



A

bleachable coefficient

- A > 0
- A << α for EUV resist

B

unbleachable coefficient

- B ≈ α at EUV

C

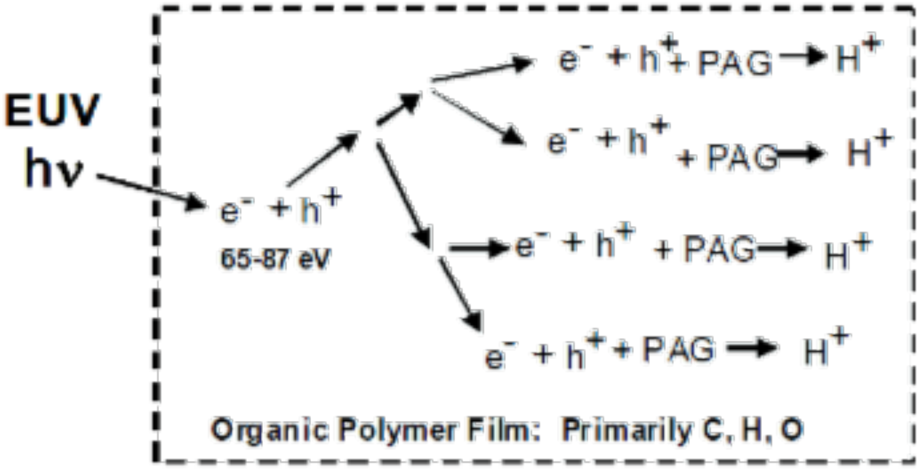
exposure rate constant

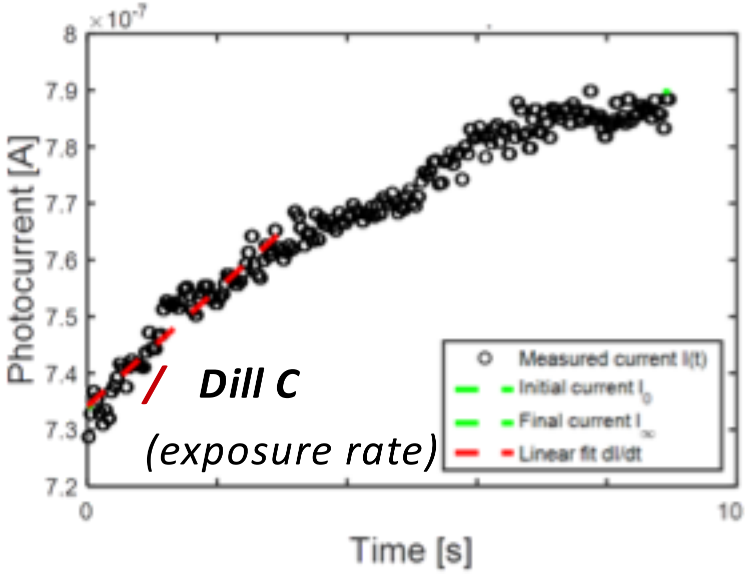
- UV 0.022 ≈ 0.008 cm2/mJ [1]
- DUV ≈ 0.005 cm2/mJ [2]
- higher in EUV 3+S

[1] MicroChemicals, Optical Properties of Photoresists. Application Note, 2013.

[2] Y.-S. Sohn et al., JVST B 19(6), 2077 (2001).

Role of *Dill parameter C* in CAR





Dill C

(exposure rate)

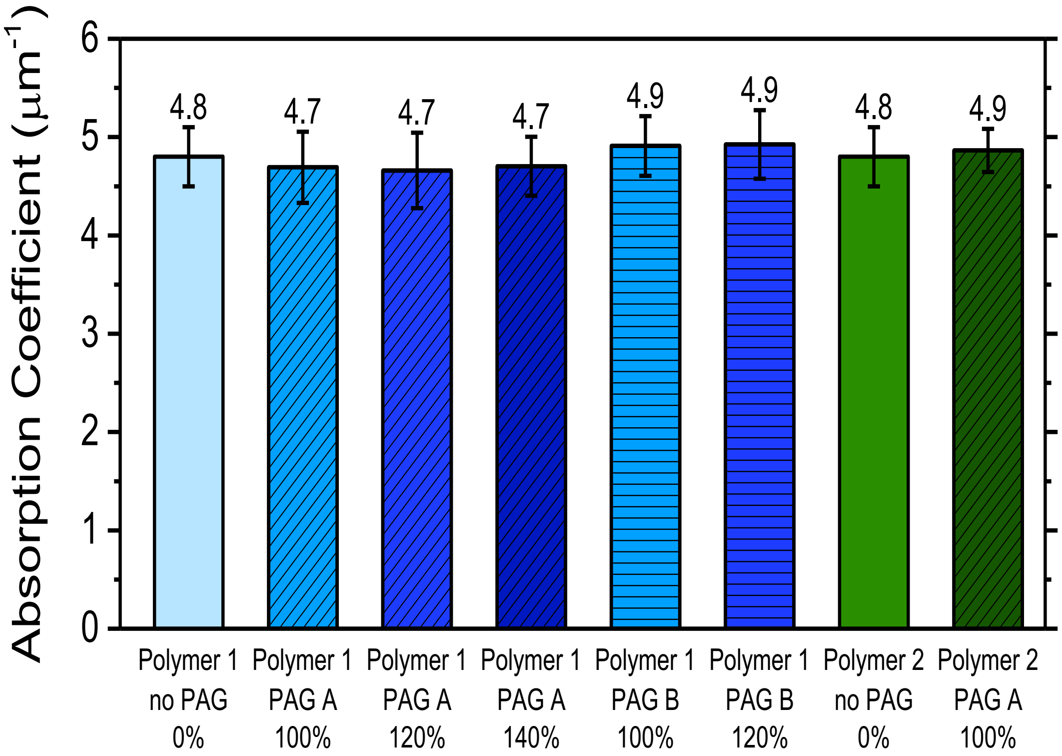
$$PAC(t) = PAC_0\, e^{-ICt}$$

$$QY = \frac{\#PAG}{\#abs.ph.} = C\,\frac{N_A hc}{\alpha \ln 10\, \lambda\, M_M/\rho}$$

[1] C. Mack et al., Applied Optics 27(23), 4913 (1988)

EUV CARs: Absorption

1. effect of PAG loading
2. effect of PAG molecule
3. effect of backbone polymer

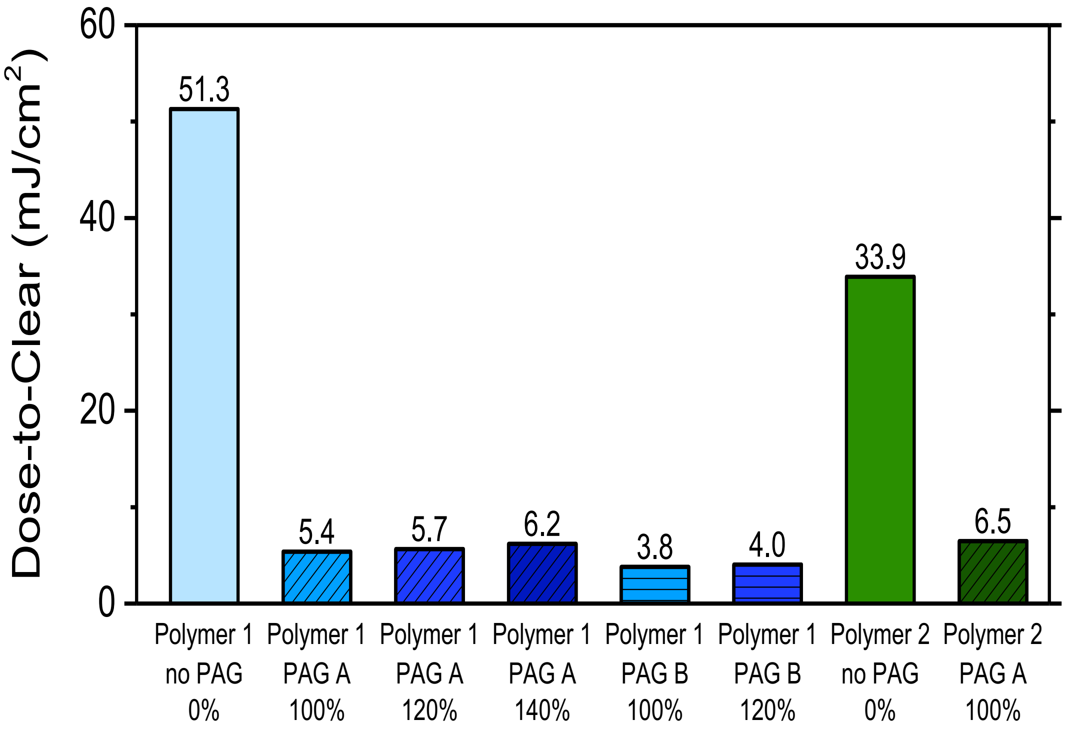


No significant changes due to different components of the resists

Because they are similar organic molecules

EUV CARs: Sensitivity

Dependence on PAG loading, PAG type and backbone polymer type

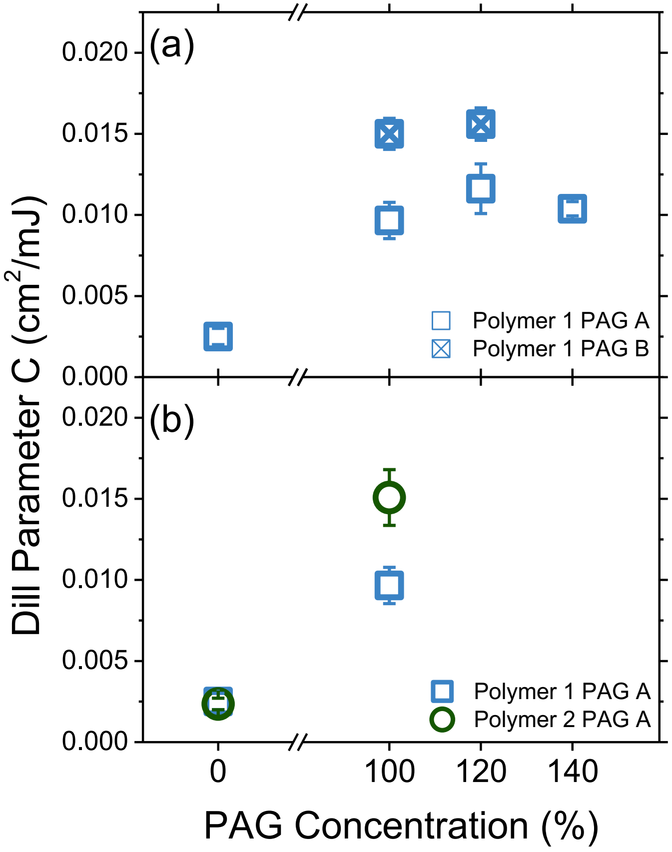


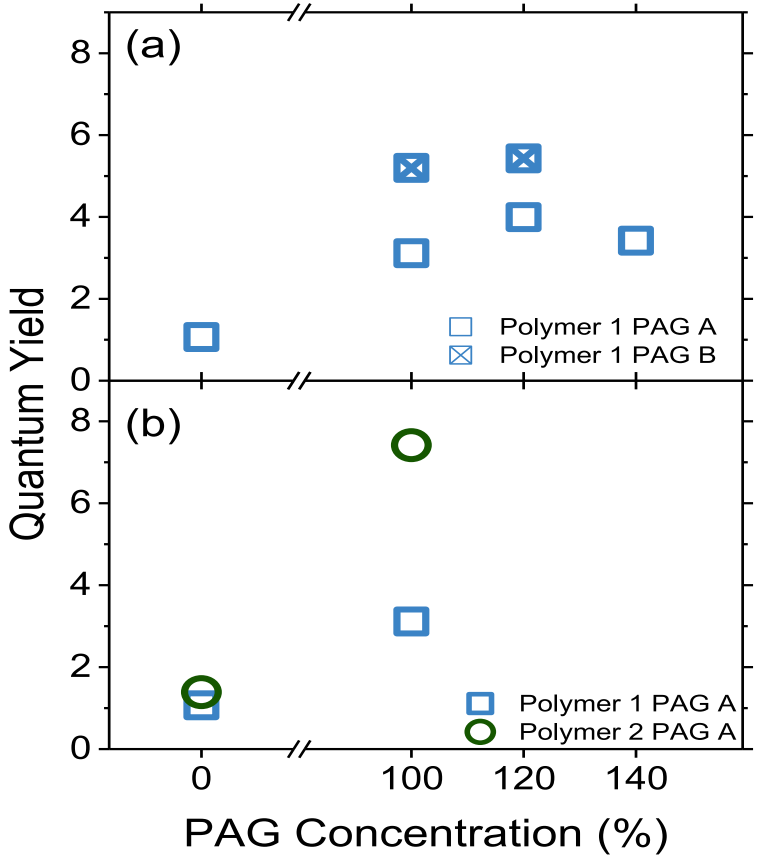
PAGs makes the resist much more sensitive as expected

Polymer 2 is more sensitive

PAG-B is more sensitive

Quantum yield





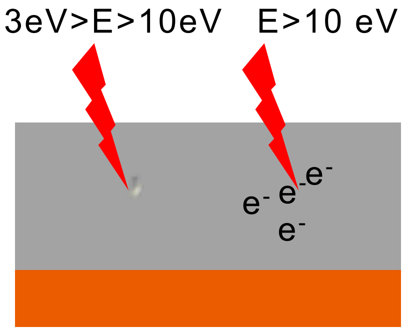
Without PAG: QY is close to 1

PAG loading has little effect: saturation regime

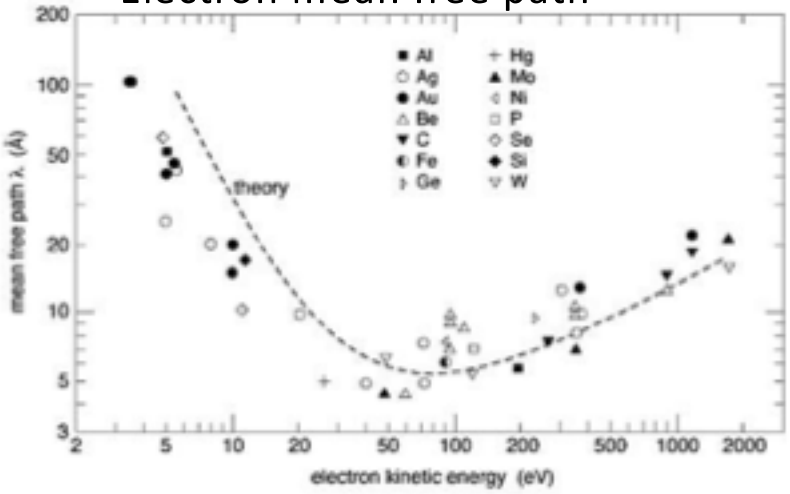
PAG B has higher QY due to higher ionizability

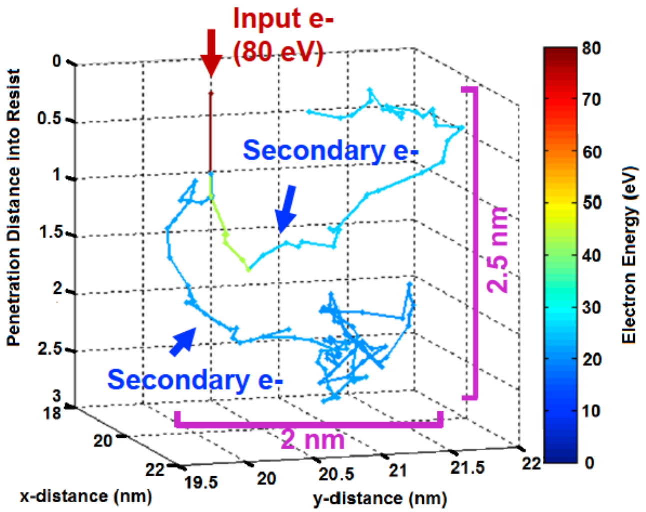
Polymer 2 increases the QY

Proximity effects in EUVL



Electron mean free path





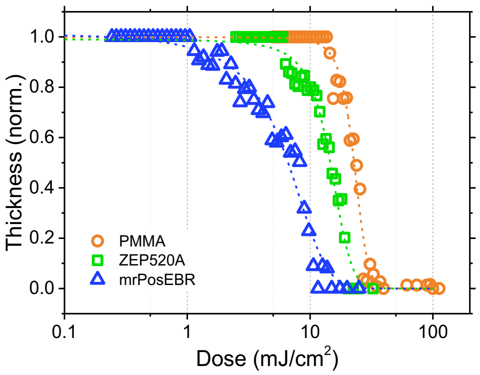
Torok et al,

J. Photopolym. Sci. Technol., Vol. 26, No. 5, 2013

How to measure the secondary electron blur?

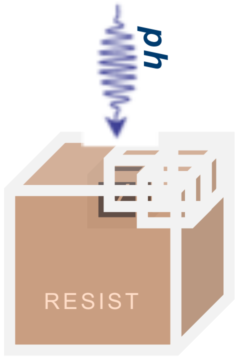
Lithographic sensitivity is the reciprocal of the Dose-to-Clear, measured from contrast curve:

$$Litho\ Sensitivity = \frac{1}{DtC} = \alpha \times (QY, QE, CA, \ldots)\ [mJ/cm^2]$$



We define ***Chemical Sensitivity*** as: $$CS = \frac{1}{\alpha \times DtC}$$

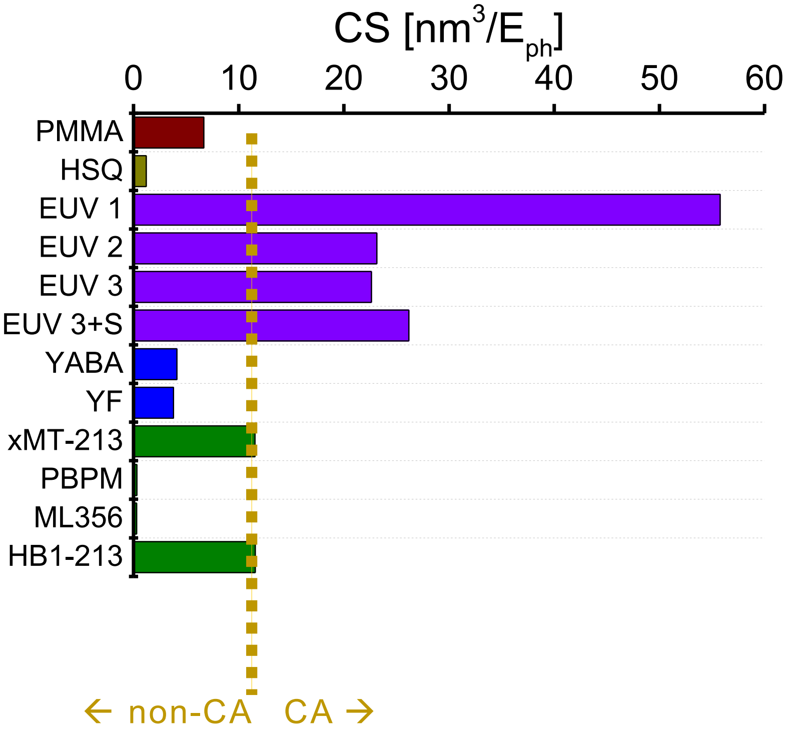
$$CS = \frac{1}{\alpha[\mu m^{-1}] \times DtC[mJ/cm^2]} = [m^3/J] = [nm^3/E_{photon}]$$

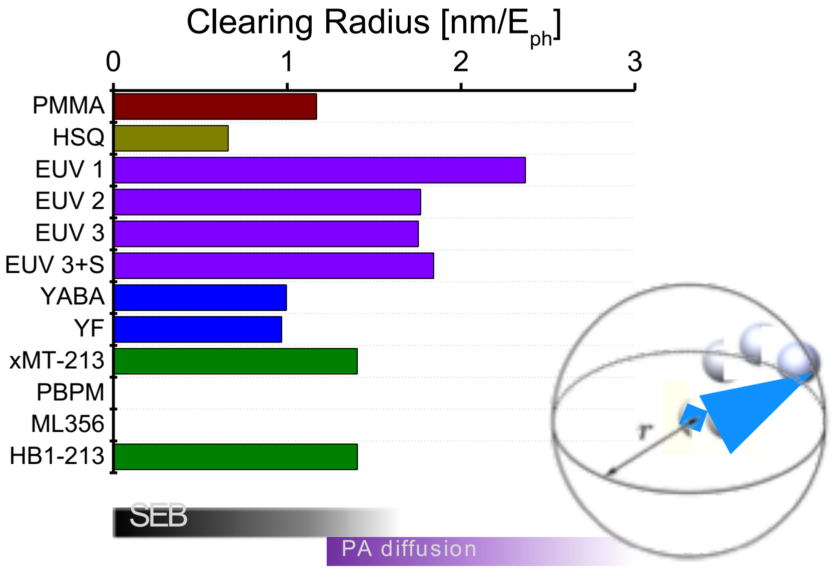


CS indicates the volume of resist cleared by each absorbed EUV photon.

- CS is thickness independent: can be compared across different resist platform.
- Larger CS indicate a higher chemical reactivity, due to chemical amplification, QY, QE, etc...
- Can be measured by measuring contrast curves and absorption

Chemical Sensitivity





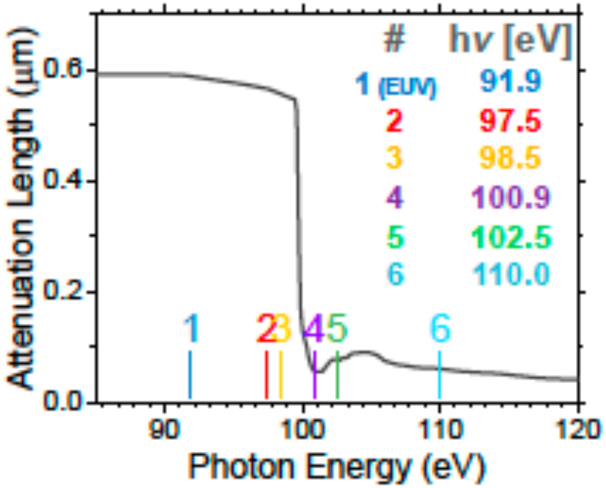
Another interpretation is derived from the radius of a sphere having the CS volume.

The clearing radius is a measure of the **total resist blur (**SE blur + PA diffusion blur + etc…):

Effect of SEB from the substrate (the theory)

Optical attenuation of Si

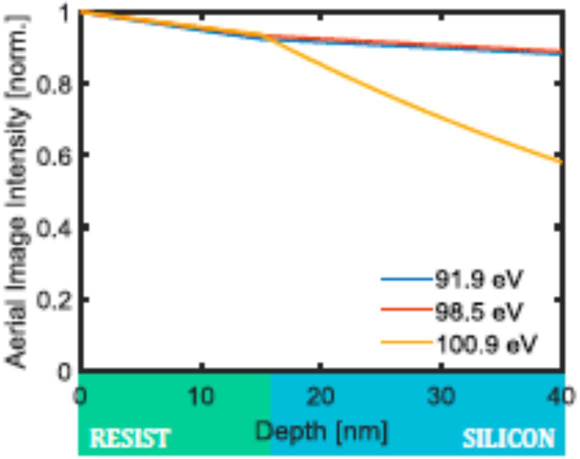
@ different energies:



$SED=I(z)* \exp[-\lambda z]$

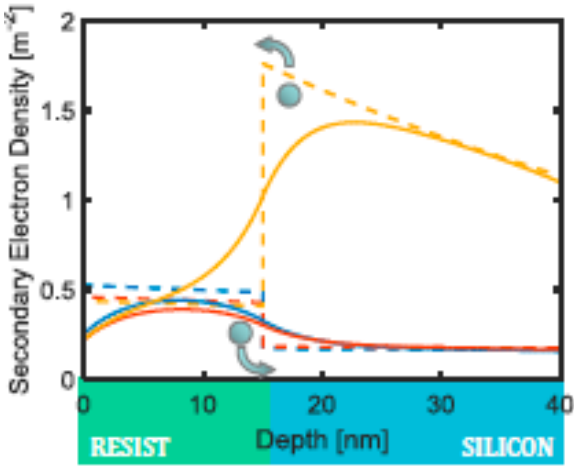
Intensity profile

In resist and substrate



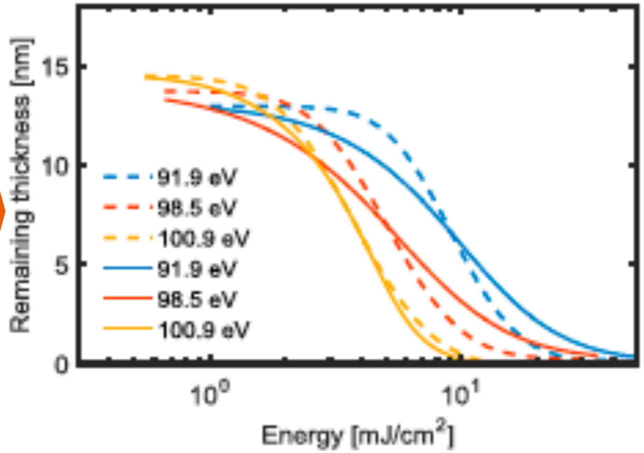
Secondary electron density

In resist and substrate with 3 nm blur



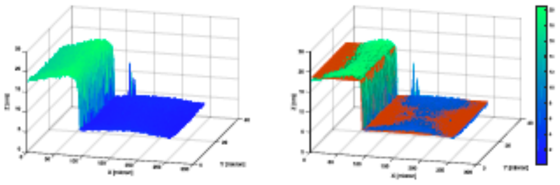
Dose-to clear curve

@ different energies

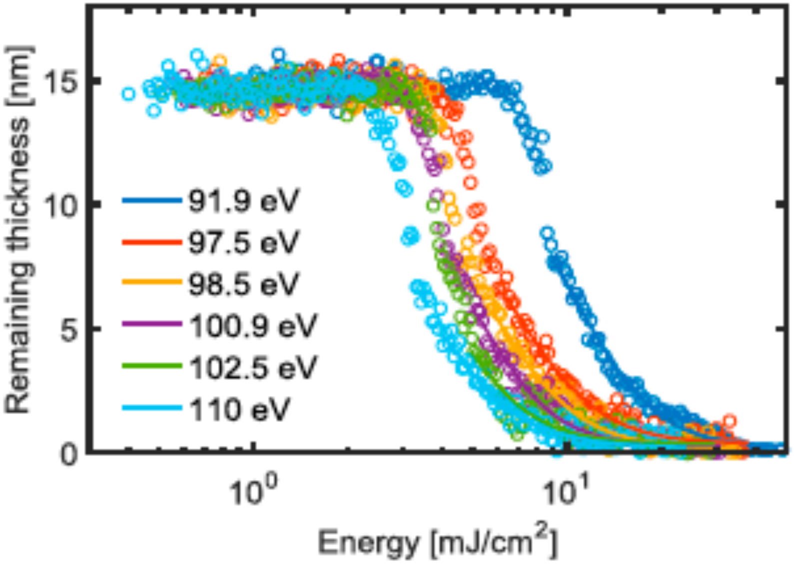


Effect of SEB from the substrate (the experiment)

- *PMMA molecular weight 50k, non-CA*
- *Thickness ≈ 15 nm, to enhance the interfacial effect*
- *200 doses x 6 photon energy*
- *All exposures on same wafer, developed at once*



- *Step measured by AFM, fitted to 2D step function*



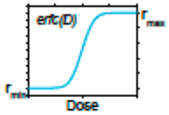
- *Development rate is the Δ thickness per unit time* [9]:

$$r = \frac{dz}{dt} \Rightarrow \int_0^{t_{dev}} dt = \int_0^{z} \frac{1}{r} dz'$$

where the development time is fixed (t_{dev} = 30 s).

- *The development rate depends on both dose and depth:*

$$r = f(z,E) = erfc\big(E \times SED(z)\big)$$



- *Numerical solve of the integral in z (no analytical sol.)*
- *In the approximation of no SEB and linear* r(E), *the developed depth varies as:*

$$z(E) = \alpha^{-1}\ln\big(1 + \alpha t_{dev}(E - E_0)\big)$$

Best fit to the data: 2.3 nm

Summary

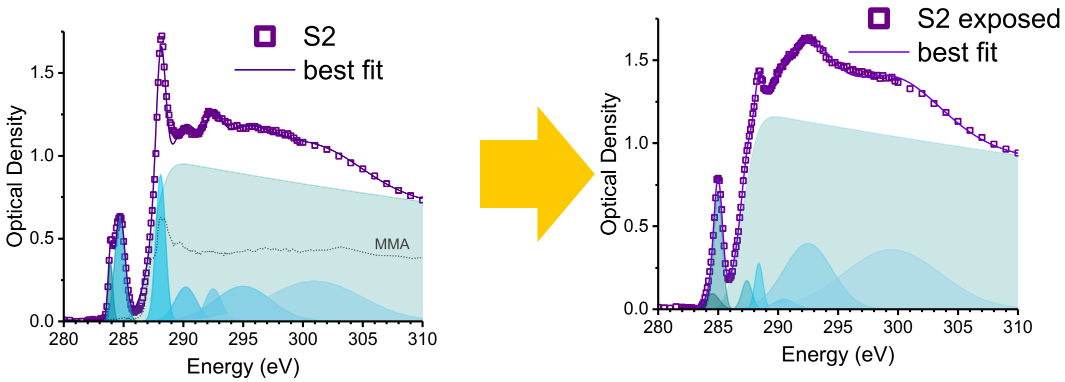
- It is good news that EUV photons can make down to 7 nm hp.
- But we need to understand the fundamentals and reaction pathways

- Macroscopic parameters → Microscopic parameters
  (dose, absorption, Dill's parameters) (SEB, QE)

- For a state-of-the-art CAR: QY is 3-8
- PAG-backbone interaction could be exploited to increase QY
- SEB: For non-CAR=~1-2 nm and for CAR=4-5 nm

- To push the resolution limits of EUV lithography
  - we need to understand the fundamentals
  - We need to employ many analytical tools

NEXAFS:



Acknowledgments

Hard work:

ALM

LMN

PSI

Material vendors

Financial support:

SNF

Swiss Nanoscience Institute

European Commission

Various companies

Advanced lithography and metrology group
www.psi.ch/sls/xil

Thank you for your attention!