Pushing the resolution limits of photolithography:

*Understanding the fundamentals of the EUV resists*

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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
- **Undulator source** + Switchable mirror + pinhole
  - High brightness
  - High spatial coherence
  - 4% bandwidth
  - Tunable wavelength ($\lambda=2.5$-18 nm)

- **On-site cleanroom**
  - Spin-coater, wet-bench, hot-plates, microscope, developer, optical thickness measurement
**CONCEPT:**

- EUV: 13.5 nm wavelength
  - Spatially coherent
  - Temporal coherence: $\Delta \lambda / \lambda = 4\%$
- Diffractive transmission gratings:
  - Metal gratings written with EBL on Si$_3$N$_4$ membranes (~100 nm)
- diffracted beams interfere
- interference pattern printed in resist
Record resolution in photolithography

hp 7 nm

22 nm
16 nm
14 nm
12 nm
11 nm
10 nm
9 nm
8 nm

hp 30 nm
hp 22 nm
hp 17 nm
hp 11 nm
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

lw 20 nm

length ~1 µm

Si fins

lw 6.5 nm

16 nm

11 nm

Height 88 nm
A major challenge is EUV resists with the best performance:
- Resolution, HP (nm)
- Sensitivity, dose (mJ/cm²)
- 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
EUV resists: State of the art @ SPIE 2013

HP 8 nm Inpria/IB
HP 12 nm Inpria/JB
HP 14 nm Resist-B
HP 16 nm Resist-B
HP 13 nm 2018 typical
HP 18 nm Resist-A

Graph showing sensitivity [mJ/cm²] vs. resolution [nm] for various resist materials.
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?
Resist thickness \(d\) measurement:
- Woollam M2000 spectroscopic ellipsometer
- 250-1000 nm spectral range
- focusing probe (\(\Phi 30 \mu m\)), automatic stage
- Cauchy + B-spline ellipsometric model

\[
T_x = \frac{\Phi}{\Phi_0} = \frac{I}{I_0} = e^{-\alpha d}
\]

\(\alpha, d\)

\(\uparrow\) Dill B (unbleachable)
\(\downarrow\) Dill A = \(B - \alpha\) (bleachable)
\(\alpha \rightarrow\) Dill C (exposure rate)
Absorption coefficient of EUV resists

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

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

Absorption of metal-based photoresists

The actual absorption $\alpha$ can be substantially different than predicted, thus affecting the real sensitivity and lithographic performance.
Results: Dill Parameters

A (µm\(^{-1}\))

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<thead>
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<tbody>
<tr>
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<td>0.0</td>
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<td>0.3</td>
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<td>EUV 2</td>
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<td>EUV 3</td>
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B (µm\(^{-1}\))

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C (cm\(^2\)/mJ)

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Ableachable coefficient

- A > 0
- A << α for EUV resist

Unbleachable coefficient

- B ≈ α at EUV

Exposure rate constant

- UV 0.022 ≈ 0.008 cm\(^2\)/mJ [1]
- DUV ≈ 0.005 cm\(^2\)/mJ [2]
- higher in EUV 3+S

Role of *Dill parameter C* in CAR

\[ PAC(t) = PAC_0 e^{-I_C t} \]

\[ QY = \frac{\#PAG}{\#abs.\ ph.} = C \frac{N_A h c}{\alpha \ln 10 \lambda M_M / \rho} \]

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
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

Torok et al,

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

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

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
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:

Intensity profile
In resist and substrate

Secondary electron density
In resist and substrate with 3 nm blur

SED = I(z) * exp [-λz]

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:
    $r = f(z, E) = e^r f c(E \times SED(z))$

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

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 \( \rightarrow \) 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:

\[
\begin{align*}
\text{Optical Density} & \quad \text{Energy (eV)} \\
0.0 & \quad 280 \\
0.5 & \quad 285 \\
1.0 & \quad 290 \\
1.5 & \quad 295 \\
2.0 & \quad 300 \\
2.5 & \quad 305 \\
3.0 & \quad 310
\end{align*}
\]

\[
\begin{align*}
\text{Optical Density} & \quad \text{Energy (eV)} \\
0.0 & \quad 280 \\
0.5 & \quad 285 \\
1.0 & \quad 290 \\
1.5 & \quad 295 \\
2.0 & \quad 300 \\
2.5 & \quad 305 \\
3.0 & \quad 310
\end{align*}
\]
Acknowledgments

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Material vendors

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Swiss Nanoscience Institute
European Commission
Various companies

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

Thank you for your attention!