Evaluation of resist performance with EUV interference lithography

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Outline

- EUV interference lithography
  - Basics of EUV-IL
  - XIL-II: EUV-IL @ PSI
    - Versatile and high-resolution patterning with EUV-IL
- Evaluation of EUV-CARs
- First patterning results with BEUV
- Conclusions and outlook
**EUV Interference Lithography**

**XIL-II beamline as Swiss Light Source (SLS)**
- EUV lithography: 13.5 nm wavelength
- Undulator source:
  - Spatially coherent
  - Temporal coherence: $\Delta \lambda / \lambda = 4\%$
- Diffractive transmission gratings: Metal gratings written on $\text{Si}_3\text{N}_4$ membranes with EBL
- Diffracted beams interfere
- Interference pattern printed in resist

**Advantages:**
- No proximity effect ($e^{-}$ mean-free-path $< 1$-$3$ nm)
- No depth of focus: Mask-to-wafer $= 1$-$10$ mm
- High resolution:
  - Theoretical limit $= 3.5$ nm
  - Current limit $< 10$ nm (world record in photon based lithography)
- Large area: up to $5 \times 5$ mm$^2$
- Step and repeat: up to $80 \times 80$ mm$^2$ with stitching
- High throughput: typically $10$ s: 10’000x e-beam
- Quality, reproducibility: enabling industrial operation
- Versatile structures

$11$ nm hp lines and $19$ nm hp dots exposed in HSQ
V. Auzelyte et al., J. Micro/Nanolith. MEMS MOEMS 8, 021204 (2009).
On-site clean room:
- Spin-coater, wet-bench, hot-plates, microscope, developer, optical thickness measurement
- In clean room environment with amine filters.
2D periodic patterns by multiple beam interference

- Two-dimensional periodic patterns for 3-, 4- and 6-beam interference
Phase-control

- Grating positions determine relative phase between interfering waves
- Shift $\Delta r$ perpendicular to the grating lines enables phase control by additional phase shift $\Phi$

\[ \sum_{n}^{N} U_{0,n} \exp(i(k_{x,n}(x - \Delta_{x,n}) + (k_{y,n}(y - \Delta_{y,n}) + k_{l,n}z))) \]


Phase-controlled EUV-IL: 4 beams

• 4-beam interference:
Phase-controlled EUV-IL: 6 beams

- 6-beam interference:

Hexagonal dots array       honeycomb       kagome

Kagome nanostructures

PMMA                               HSQ
Quasicrystals (Penrose tilings)

5-beam interference

8-beam interference:

- Quasiperiodic patterns for photonics and alignment markers
- LIL is good but has low resolution
- E-beam is high resolution but pattern generation is difficult and only mimics the quasiperiodicity
- With EUV-IL; high resolution for alignment markers. high quality or shorter operation wavelength for photonics

A. Langner et al., Nanotechnology 23, 105303 (2012).
Other interference schemes

Non-diffracting EUV-Bessel beams:

Incoherent multiple-beam lithography:

Holographic fabrication of Fresnel Zone plates
Record resolution in photon-based lithography

8 nm half-pitch: The smallest patterns ever written with photons!

Both with Inpria and HSQ
Evaluation with Resist-A

HP=30 nm  HP=22 nm  HP=20 nm  HP=18 nm  HP=16 nm

Thickness=35 nm  PAB: 105° C/90 s  PEB: 90° C/90 s  Dev: 2.38% TMAH/30s
Resist-B

HP=22 nm  HP=20 nm  HP=18 nm  HP=16 nm

LER [nm]

Dose [mJ/cm²]

CD [nm]

Dose [mJ/cm²]

Thickness=30 nm
PAB: 130 ° C / 60 s
PEB: 100 ° C / 60 s
Dev: 2.38% TMAH/ 30s
Inorganic resists

HP=30 nm  HP=22 nm  HP=16 nm

HSQ(TMAH)

HSQ(351)

Inpria(IB)

Inpria(JB)

hp=22nm

CD [nm]

LER [nm]

Dose [mJ/cm²]

Yasin Ekinci, PSI
Status of EUV resists

 Demonstrated. For sub-16 nm sensitivity is assumed to be hp independent as for >16 nm
 Not clearly demonstrated. But has great potential, or requires process optimization for LER or pattern collapse.
Patterning with $\lambda=6.5$ nm

First patterning results with BEUV or deep EUV or hard EUV

$\lambda=13.5$ nm

$\lambda=6.5$ nm

Note: These results are preliminary and not conclusive yet.
Conclusions & Outlook

- EUV-IL is a powerful tool for academic research:
  - versatile nanostructures, high resolution, high throughput, large area.
  - It gets really exciting in sub-10 nm.

- EUV-IL is a powerful tool for resist evaluation for future technology nodes:
  - cost-effective, pitch-independent aerial image, High resolution
  - different wavelengths (BEUV).

- Current status of EUV resist development
  - Resist A: 18 nm hp resolution with $\approx 10 \text{ mJ/cm}^2$ sensitivity: LER improvements necessary (1) with thicker resist using pattern collapse mitigation and (2) line smoothing strategies
  - Resist B: 16 nm hp resolution with $\approx 30 \text{ mJ/cm}^2$ sensitivity
  - For 16 nm hp sensitivity less than 30 mJ/cm$^2$ should be feasible

- With decreasing HP: pattern collapse becomes the limiting factor
- Going from EUV to BEUV: resist development is necessary.

Acknowledgments: We thank the resist suppliers: Inpria, Shin Etsu, and JSR. Thanks to Todd R. Younkin for discussions.

Thank you for your attention!
## Resist comparison

<table>
<thead>
<tr>
<th>Resist name</th>
<th>Substrate</th>
<th>PAB</th>
<th>Thickness</th>
<th>PEB</th>
<th>Developer/Time</th>
<th>Sensitivity</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resist-A</td>
<td>Si/Underlayer</td>
<td>105°C / 90s</td>
<td>35 nm</td>
<td>90°C / 90s</td>
<td>TMAH 0.26N / 30s</td>
<td>9.5 mJ/cm² ±1.1 mJ/cm²</td>
<td>18 nm</td>
</tr>
<tr>
<td>Resist-B</td>
<td>Si/Underlayer</td>
<td>130°C / 60s</td>
<td>30 nm</td>
<td>110°C /60s</td>
<td>TMAH 25% /30s</td>
<td>30 mJ/cm²</td>
<td>&lt;16 nm</td>
</tr>
<tr>
<td>Inpria(X15JB)</td>
<td>Si/O₂ Plasma</td>
<td>80°C / 120s</td>
<td>20 nm</td>
<td>80°C / 120s</td>
<td>TMAH 25% /120s</td>
<td>80 mJ/cm²</td>
<td>&lt;16 nm</td>
</tr>
<tr>
<td>Inpria(XE15IB)</td>
<td>Si/O₂ Plasma</td>
<td>80°C / 180s</td>
<td>20 nm</td>
<td>80°C / 60s</td>
<td>TMAH 25% /30s</td>
<td>163 mJ/cm²</td>
<td>&lt;&lt; 16nm</td>
</tr>
<tr>
<td>HSQ(TMAH)</td>
<td>Si</td>
<td>No</td>
<td>35 nm</td>
<td>No</td>
<td>TMAH 2.6N / 60 s</td>
<td>229 mJ/cm²</td>
<td>&lt;16 nm</td>
</tr>
<tr>
<td>HSQ(351)</td>
<td>Si</td>
<td>No</td>
<td>35 nm</td>
<td>No</td>
<td>351 /30 s</td>
<td>659 mJ/cm²</td>
<td>&lt;&lt;16 nm</td>
</tr>
</tbody>
</table>
Resist-A: Thinner resist for 16 nm hp

HP=16 nm, through dose

![Image of resist patterns and graphs showing CD and LER vs. dose for different hp and thicknesses.]
Reproducibility tests

Resist-A: Shelf-life

![Graph showing CD vs. Dose for different resist and dose conditions.](image)
Dose calibration

Patterned area

Blanket exposure areas

Blanket exposure areas

Dose to clear for Resist-A

Thickness [normalized]

0 1 2 3 4 5 6 7 8 9 10

Dose [mJ/cm²]
Sub-10 nm patterning with 2. order diffraction

Grating parameters:

- Support Si,N$_x$
- Mask grating
- Photon stop

Fill factor f = hw/p

Results for various hp values:
- hp=20nm
- hp=11nm
- hp=8nm
- hp=7nm
- hp=9nm
- hp=6nm

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