Material Challenges for EUVL

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AVS: Material Opportunities for Semiconductors

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Challenges

- **Source**
  - *High thermal load multilayers*
  - *In situ tin removal*

- **Optics**
  - *Spectral filters*
  - *Robust capping layers*

- **Mask**
  - *High efficiency pellicle*

- **Defects**
  - *Roughness*

- **Resist**
  - *Photon harnessing*
  - *Materials stochastics*
Multilayers
Multilayer mirrors required to build up adequate near normal reflectivity

\[ d = \frac{\lambda}{2\sin\theta} \]
Multilayer Defects
Buried (phase) defects lead to intensity variations at wafer

Modeled aerial image of 60-nm wide, 1-nm tall isolated defects through focus (25-nm steps)
NA=0.35, σ = 0.5, Ideal optic
Sub-half-nm defect tolerance at 22-nm half pitch

NA = 0.35, \( \sigma = 0.5 \), Centered defect

\[ \frac{\lambda}{2NA^2} = 55 \text{ nm} \]

Data courtesy of E. Gullikson, Berkeley Lab
Near-quarter-nm defect tolerance at 16-nm half pitch

NA=0.45, σ = 0.5, Centered defect

- 30 nm defocus
+ 30 nm defocus

Data courtesy of E. Gullikson, Berkeley Lab
Mask Roughness
**Mask sources of LER**

- **Absorber**
- **LER**
- **Multilayer with replicated surface roughness (RSR)**

### Equation

\[ \Delta \theta = 2h \left( \frac{2\pi}{\lambda} \right) \]
Imaging transforms phase roughness to intensity speckle

230 pm RSR

In focus
\( \sigma = 0.5 \)

Contrast = 0.9%
Imaging transforms phase roughness to intensity speckle

230 pm RSR

50-nm defocus
$\sigma = 0.5$

Contrast = 6%
Imaging transforms phase roughness to intensity speckle

230 pm RSR

50-nm defocus
\[ \sigma = 0.3 \]

Contrast = 9%
Wafer print demonstration

Correlation = 61%, Correlated LER = 3.4 nm

Position along length of line

Edge deviation (nm)
## Model-based roughness specifications

<table>
<thead>
<tr>
<th>Configuration</th>
<th>RSR limit (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22-nm, disk 0.5, 0.32 NA</td>
<td>46</td>
</tr>
<tr>
<td>16-nm, quad, 0.32 NA</td>
<td>77</td>
</tr>
<tr>
<td>16-nm, annular, 0.42 NA</td>
<td>77</td>
</tr>
</tbody>
</table>

Hydrogen Atom

53 pm
Conformal growth of layers with random roughness

Individual layer roughness = total roughness/sqrt(N_{Layers})
Interlayer roughness
38% more tolerant

![Graph showing RMS speckle contrast vs. defocus (nm) for fully conformal and conformal random thickness conditions. The graph indicates that the fully conformal condition has a higher RMS speckle contrast compared to the conformal random thickness condition for the same defocus values.]
**Model-based interlayer roughness specifications**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Single layer roughness* (pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22-nm, disk 0.5, 0.32 NA</td>
<td>7</td>
</tr>
<tr>
<td>16-nm, quad, 0.32 NA</td>
<td>12</td>
</tr>
<tr>
<td>16-nm, annular, 0.42 NA</td>
<td>12</td>
</tr>
</tbody>
</table>

* Assume 80 layers
Photoresist
Simultaneously meeting resolution, sensitivity, and LER crucial issue for EUV resists

22-nm half pitch - 2016
17-nm half pitch - 2019
13-nm half pitch - 2022

All three requirements must be met and balanced for any technology or it will not work.

Resolution

Acid diffusivity, activation energy, photon statistics, quantum efficiency, outgassing

LER

Sensitivity

Resolution

2013 ITRS Roadmap

“RLS” Tradeoff

10 mJ/cm²
15 mJ/cm²
20 mJ/cm²

1.3 nm
1.0 nm
0.8 nm
EUV photons 14x more energetic than 193nm photons

Thickness = 22nm, absorption = 4.2\( \mu \text{m}^{-1} \), dose = 20mJ/cm\(^2\)
LER/sensitivity trends

![Graph showing LER vs. Sensitivity](image-url)
CA resists surpassing 16-nm HP

Resist A: 30 mJ/cm²

Resist B: 20mJ/cm²

Resist C: 22mJ/cm²
Time averaged photon image → Poisson absorption image → Released acid image

Threshold develop

Reaction diffusion

Deprotection image

Multivariate Poisson Propagation Model, Gallatin SPIE 2005; Naulleau, Gallatin JVST 2010
<table>
<thead>
<tr>
<th></th>
<th>Resist A</th>
<th>Resist B</th>
<th>Resist C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measured LWR @ 16 nm (nm)</strong></td>
<td>3.1</td>
<td>4.8</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Modeled Photon limited LWR (nm)</strong></td>
<td>2.1</td>
<td>2.7</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Estimated material limited LWR (nm)</strong></td>
<td>2.3</td>
<td>4.0</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>Modeled material limited LWR (nm)</strong></td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

* Use Multivariate Poisson Propagation Model, SPIE 2005, JVST 2010 …
Use ~11-nm resist blur determined from measured LER PSD
Use supplier provided resist absorptivity = 0.0042 nm⁻¹
**Includes acid, PAG, and Quencher random variables based on assumed typical material parameters
**Optimal blur** = \(0.5 \times \text{half pitch}\)
For contacts, smaller blur is better

16-nm contact photon-limited CDU
Shrinking photon count big problem for future nodes

half pitch (HP) = 11-nm
Blur (pixel size) = 5 nm (0.5HP)
Absorptivity = 0.0042 nm\(^{-1}\)
(typical polymer resist value)

Only 30 photons absorbed!
Shrinking photon count big problem for future nodes

half pitch (HP) = 11-nm
Blur (pixel size) = 3 nm (0.25HP)
Absorptivity = 0.0042 nm\(^{-1}\)
(typical polymer resist value)

Only 12 photons absorbed!
What would it take to enable 20-mJ/cm$^2$ with 14-nm contacts?
A potential future resist

- Assume absorptivity of 0.02 nm\(^{-1}\)
A potential future resist

• Assume absorptivity of $0.02 \, \text{nm}^{-1}$
A potential future resist

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• Assume QE of 6
A potential future resist

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A potential future resist

• Assume absorptivity of 0.02 nm\(^{-1}\)
• Assume QE of 6
• Assume PAG loading of 0.5/nm\(^3\)
A potential future resist

- Assume absorptivity of $0.02\,\text{nm}^{-1}$
- Assume QE of 6
- Assume PAG loading of $0.5/\text{nm}^3$

<table>
<thead>
<tr>
<th>%PAG</th>
<th>TPS-PFBS (Sulfonium, S⁺)</th>
<th>Good</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>OS-S1</td>
<td>Good</td>
</tr>
<tr>
<td>7.5</td>
<td>OS-S1</td>
<td>Good</td>
</tr>
<tr>
<td>10</td>
<td>OS-S1</td>
<td>Good</td>
</tr>
<tr>
<td>15</td>
<td>OS-S2</td>
<td>315</td>
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<tr>
<td>20</td>
<td>OS-S3</td>
<td>318</td>
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<tr>
<td>25</td>
<td>OS-S4</td>
<td>377</td>
</tr>
<tr>
<td>30</td>
<td>OS-S5</td>
<td>501</td>
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<tr>
<td>40</td>
<td>OS-S6</td>
<td>961</td>
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<tr>
<td>50</td>
<td>OS-S7</td>
<td>1248</td>
</tr>
<tr>
<td>60</td>
<td>OS-S8</td>
<td>1248</td>
</tr>
<tr>
<td>70</td>
<td>OS-S8</td>
<td>1246</td>
</tr>
</tbody>
</table>

0.7/\text{nm}^3

A potential future resist

• Assume absorptivity of 0.02 nm\(^{-1}\)
• Assume QE of 6
• Assume PAG loading of 0.5/nm\(^3\)
• Acid blur = 3 nm, electron blur = 2 nm
A potential future resist

- Assume absorptivity of 0.02 nm\(^{-1}\)
- Assume QE of 6
- Assume PAG loading of 0.5/nm\(^3\)
- Acid blur = 3 nm, electron blur = 2 nm

Would enable 20 mJ/cm\(^2\) for 14-nm contacts
Summary

• **Biggest remaining EUV challenge is source power**

• **Multilayer materials challenges include defects and roughness**

• **Future photoresist materials will need to be more absorbing**
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