RLS optimization

$K_{LUP}$ to understand trends

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Resist screening with interference lithography at PSI
LER vs sensitivity trend

30nm L/S resolution
EUV resist screening with interference litho and on the ASML EUV ADT (NA=0.25, $\sigma=0.5$)

Similar trend LER vs sensitivity on the ADT
EUVL resist challenges - RLS

Sensitivity
- Acid Diffusion
  - Length = Pixel Size
- Shot Noise Statistics
  - = Photons/Pixel
- Resolution
- Line Width
- Roughness

Acid Diffusion Length

\[
K_{LUP}(A, \Phi) = \sqrt{\frac{E_s}{h \nu d}} \cdot EL \cdot LWR \cdot \frac{(L_d)^{3/2}}{p}
\]


Use this approach for:
- Quantitative understanding of variation of effect of resist composition parameters
- Comparison of Resists: Alternative Platforms monitor the performance of resists
Physical meaning of $K_{\text{LUP}}$

$$K_{\text{LUP}} = \sqrt{\frac{E_s}{h \nu \cdot d} \cdot EL \cdot LWR \cdot \frac{(L_d)^{3/2}}{p}}$$

- The $K_{\text{LUP}}$ formula can be re-arranged to

$$LWR = \frac{K_{\text{LUP}}}{p \cdot \sqrt{\frac{h \nu \cdot d}{E_s \cdot L_d^3}}}$$

- Lower $K_{\text{LUP}}$ is better

- Factor of two reduction in $K_{\text{LUP}}$ means
  - Resist prints same features at same dose with but with half LWR
  - OR
  - Resist prints same features with similar LWR, but at sizing dose divided by 4

- Shot noise – deprotection statistics
- Interdependent parameters!
Outline

• Introduction
  – What is $K_{LUP}$?

• Effect of Film Thickness

• Effect of PAG Loading

• Polymer-bound PAG Resists

• Conclusion
Effect of film thickness

\[ K_{LUP} \cdot \sqrt{A} \cdot \Phi = \text{Constant} \]

Therefore,

\[ K_{LUP} \propto \frac{1}{\sqrt{d}} \]

- \( K_{LUP} \) behavior versus thickness as expected
  - \( K_{LUP} \) scales with \( \frac{1}{\sqrt{d}} \)

- Important consequence:
  Any future reduction in resist thickness will have to be compensated by a similar increase in effective absorbance (effective = leading to acid creation) in order to decrease \( K_{LUP} \)
Effect of film thickness on Sizing Dose and LWR

- LWR increases drastically upon reducing resist thickness
- Dose to size decreases with reducing resist thickness

Interference litho exposures
• Increase in LWR with decreasing film thickness is consistently found
• Increase is more drastic than expected just from shot noise scaling when based on incident dose
• Shot noise scaling is applicable when absorbed dose is considered (as done in $K_{LUP}$)
• Need to increase absorbance for EUV resists
  • Increase F content
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PAG Loading – Motivation

- Increasing PAG loading for KrF/ArF increases Absorbance ($A$)
  - Make more efficient use of photons
  - Decrease Sizing Dose
  - Higher Acid density $\Rightarrow$ Less Acid shot noise resulting in better LWR
- But too high loading leads to loss of pattern profile (in 193nm)
- Increasing PAG loading for EUV does not increase Absorbance ($A$),...
- ..., but does increase the acid quantum yield ($\Phi$)
  - Make more efficient use of photons
  - Decrease Sizing Dose
  - Higher Acid density $\Rightarrow$ Less Acid shot noise resulting in better LWR
PAG loading: A way to improve $K_{LUP}$

- Series of conventional model resists
- $K_{LUP}$ decreases with increasing PAG loading due to larger acid generation efficiency

<table>
<thead>
<tr>
<th>PAG loading</th>
<th>$p$ (nm)</th>
<th>$\lambda$ (nm)</th>
<th>$E_s$ (mJ/cm$^2$)</th>
<th>$d$ (nm)</th>
<th>$EL$ (nm)</th>
<th>$LWR$ (nm)</th>
<th>$L_d$ (nm)</th>
<th>$K_{LUP}$</th>
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<td>25%</td>
<td>90</td>
<td>13.4</td>
<td>13.3</td>
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<td>50%</td>
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<td>13.9</td>
<td>80</td>
<td>0.242</td>
<td>10.6</td>
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<td>100%</td>
<td>90</td>
<td>13.4</td>
<td>15.8</td>
<td>80</td>
<td>0.252</td>
<td>8.5</td>
<td>14.8</td>
<td>0.50</td>
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<tr>
<td>150%</td>
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<td>80</td>
<td>0.233</td>
<td>6.8</td>
<td>14.6</td>
<td>0.39</td>
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</table>
• Resist absorbance at EUV is governed by the chemical composition of the matrix, not by PAG (as in KrF and ArF)
• In EUV, increasing PAG loading reduces LWR, but does not cause sloped profiles
X-sections as function of PAG loading

- Profiles deteriorate at increasing PAG loading by top-rounding, sloped profiles and top-loss. All is caused by increased absorbance.
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Why polymer-bound PAGs?

- Suppress phase separation between PAG and polymer
  - Would allow for increase of PAG concentration
    » Lower **Sizing Dose**
    » Lower **LWR**

- Improve PAG uniformity
  » Lower **LWR**

- Suppress acid diffusion
  - Better **resolution** capabilities
Assessment of Polymer-Bound PAG resists

- $K_{LUP}$ has been determined for three EUV resists using EUV interference lithography
  - Polymer-bound PAG + blended PAG
  - Anion-bound PAG platform
  - Cation-bound PAG platform

- Apart from the PAG the three formulations are similar: same backbone and same acid labile group

- Lithographic performance of three resists are compared to EUV reference resist MET-2D
Assessment of Polymer-Bound PAG resists

<table>
<thead>
<tr>
<th></th>
<th>p (nm)</th>
<th>λ (nm)</th>
<th>ν (s⁻¹)</th>
<th>$E_s$ (mJ/cm²)</th>
<th>d (nm)</th>
<th>EL (nm)</th>
<th>LWR (nm)</th>
<th>$L_d$ (nm)</th>
<th>$K_{LUP}$</th>
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<td>0.24</td>
<td>4.8</td>
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Observations:
- $LWR$ of novel resist concepts is considerably improved
- Lower $L_d$ gives larger $EL$ as a bonus
- The novel materials B and C show substantially larger sizing doses
- Yet, novel materials exhibit significantly lower $K_{LUP}$ values
• Polymer-bound PAG resists show very promising results
  - EUV-C exhibits lowest $K_{\text{LUP}}$ so far
  - Blend-A and EUV-B show intermediate results
Conclusions

- Scaling of resist film thickness <80nm can only be maintained if resist absorbance can be sufficiently increased
  - For EUV this may become problematic

- For EUV resists PAG loading should be maximized (while avoiding phase separation)
  - No negative impact observed on profile, exposure latitude or resolution
  - Larger acid concentration improves LWR

- Polymer-bound PAG resists offer an attractive path for achieving high PAG loading
  - These materials show best $K_{\text{LUP}}$ performance thus far

- $K_{\text{LUP}}$ is a useful metric for understanding resist performance and comparing different formulations

- RLS improvement by
  - Increasing polymer absorbance
  - Increasing Quantum yield
  - Post processing to reduce LWR