A Novel Figure-of-Merit for Characterizing Resist Performance

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Outline

• Introduction
  – Lithographic Uncertainty Principle

• Theory
  – $K_{LUP}$: A Novel Figure-of-Merit for Resists

• Characterization of Acid Diffusion

• Results on 193nm immersion
  – Model resists
  – Requirements on $K_{LUP}$

• Progress in performance of EUV resists
  – Use $K_{LUP}$ to monitor performance improvement

• Conclusions
Introduction
Lithographic Uncertainty Principle

Dose

Acid Diffusion Length

Shot Noise Statistics = Photons/ Pixel

Ultimate Resolution

Line Edge Roughness

Acid Diffusion Length

LUP
Introduction
Lithographic Uncertainty Principle

\[ LWR \propto \frac{1}{\sqrt{\text{Dose}}} \]

R. Brainard et al. 3rd EUVL Symposium, 2004
**Lithographic Uncertainty Principle**

\[
LWR_{corr\_dose} \propto \left( \frac{1}{L_D} \right)^{3/2} \frac{ILS \cdot MTF_{diff}}{Dose} \cdot \sqrt{\frac{Dose}{hv \cdot d}}
\]

- **Best LER**
- **100nm 1:1 lines**


\[
D: \text{resist thickness}
\]

at \(L_D = 0.3 \times p\)
Introduction

Lithographic Uncertainty Principle

\[ MTF_{\text{diff}} = \frac{1 - \exp\left(-2\pi^2 \left(\frac{L_D}{p}\right)^2\right)}{2\pi^2 \left(\frac{L_D}{p}\right)^2} \]

- \( L_D \): acid diffusion length
- \( p \): pitch

\[ EL = 0.4 \times EL_{\text{opt}} \text{ at } L_D = 0.3 \times p \]

Theory

\[ LWR_{\text{corr \_ dose}} \propto \left( \frac{1}{L_D} \right)^{3/2} \frac{\text{MTF}_{\text{diff}}}{ILS \cdot MTF_{\text{diff}}} \]

\[ MTF_{\text{diff}} \propto \frac{EL}{NILS} \]

\[ LWR_{\text{corr \_ dose}} = LWR \cdot \sqrt{\frac{\text{Dose}}{h \nu \cdot d}} \]

\[ \text{NILS} \propto p \cdot ILS \]

\[ K_{LUP} = \sqrt{\frac{\text{Dose}}{h \nu \cdot d}} \cdot EL \cdot LWR \cdot \frac{(L_D)^{3/2}}{p} \]

NOTE: \( K_{LUP} \) will depend on Absorbance and Quantum Efficiency
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Acid Diffusion Characterization

Exposure on ASML XT:1250Di, NA 0.85, 6% att. PSM, Annular 0.93/0.69σ

Plot EL/NILS and fit with $MTF_{\text{diff}}$ with $L_D$ as only variable.

\[
MTF_{\text{diff}} = \frac{1 - \exp\left(-2\pi^2\left(\frac{L_D}{p}\right)^2\right)}{2\pi^2\left(\frac{L_D}{p}\right)^2}
\]

Acid Diffusion Characterization

Method verification: Increasing PEB, increases image blur due to acid diffusion
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KLUP results on 193nm resists – through pitch

As expected KLUP shows flat behavior through pitch and NILS

\[ KLUP = \sqrt{\frac{Dose}{h \nu \cdot d}} \cdot EL \cdot LWR \cdot \left(\frac{L_D}{p}\right)^{3/2} \]

<table>
<thead>
<tr>
<th>( p ) (nm)</th>
<th>( \lambda ) (nm)</th>
<th>( \nu ) (s(^{-1}))</th>
<th>( E_s ) (mJ/cm(^2))</th>
<th>( d ) (nm)</th>
<th>( EL )</th>
<th>( LWR ) (nm)</th>
<th>( L_d ) (nm)</th>
<th>( KLUP )</th>
<th>NILS</th>
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<td>300</td>
<td>193</td>
<td>1.6E+15</td>
<td>12.9</td>
<td>150</td>
<td>0.24</td>
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<td>1.60</td>
<td>1.22</td>
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**KLUP results on 193nm resists - processing**

KLUP is not affected by processing conditions such as SB/PEB settings.

\[
KLUP = \sqrt{\frac{Dose}{h \nu \cdot d}} \cdot EL \cdot LWR \cdot \frac{(L_D)^{3/2}}{p}
\]

<table>
<thead>
<tr>
<th>SB/PEB (°C)</th>
<th>p (nm)</th>
<th>λ (nm)</th>
<th>( \nu ) (s(^{-1}))</th>
<th>( E_s ) (mJ/cm(^2))</th>
<th>d (nm)</th>
<th>EL</th>
<th>LWR (nm)</th>
<th>( L_d ) (nm)</th>
<th>KLUP</th>
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<td>150</td>
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<td>35.7</td>
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<td>120/115</td>
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<td>8.3</td>
<td>37.0</td>
<td>1.34</td>
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<td>130/115</td>
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<td>11.9</td>
<td>150</td>
<td>0.18</td>
<td>8.3</td>
<td>33.1</td>
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<td>110/130</td>
<td>200</td>
<td>193</td>
<td>1.6E+15</td>
<td>16.5</td>
<td>150</td>
<td>0.13</td>
<td>6.5</td>
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<td>1.40</td>
</tr>
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<td>193</td>
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<td>14.8</td>
<td>150</td>
<td>0.15</td>
<td>7.5</td>
<td>39.6</td>
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<td>130/130</td>
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<td>11.8</td>
<td>150</td>
<td>0.16</td>
<td>8.1</td>
<td>37.0</td>
<td>1.27</td>
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</table>
KLUP results on 193nm resists – polymer type

KLUP may vary across polymer types and is a measure to identify true resist improvements.

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

<table>
<thead>
<tr>
<th>PAG</th>
<th>( p ) (nm)</th>
<th>( \lambda ) (nm)</th>
<th>( \nu ) (s(^{-1}))</th>
<th>( E_s ) (mJ/cm(^2))</th>
<th>( d ) (nm)</th>
<th>( EL )</th>
<th>( LWR ) (nm)</th>
<th>( L_d ) (nm)</th>
<th>KLUP</th>
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<tr>
<td>Polymer C</td>
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<td>1.6E+15</td>
<td>19.1</td>
<td>150</td>
<td>0.24</td>
<td>7.7</td>
<td>33</td>
<td>1.28</td>
</tr>
<tr>
<td>Polymer D</td>
<td>300</td>
<td>193</td>
<td>1.6E+15</td>
<td>16.5</td>
<td>150</td>
<td>0.28</td>
<td>6.5</td>
<td>32</td>
<td>1.13</td>
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</table>
What $K_{\text{LUP}}$ do we want?

- $K_{\text{LUP}}$ should be low. Target for $K_{\text{LUP}}$ is dictated by NILS $\Rightarrow K_{\text{LUP}}/\text{NILS}$
- The better your optical contrast, the more you impact you can suffer from the resist process.

$$K_{\text{LUP}} = \sqrt{\frac{\text{Dose}}{h \nu \cdot d} \cdot EL \cdot LWR \cdot \left(\frac{L_D}{p}\right)^{3/2}}$$

For optimal LWR, $L_D = 0.3 \times p$ and $EL = 0.4 \times EL_{\text{opt}}$

1.20NA water immersion lithography; annular illumination

1.65NA high-index immersion lithography; C-Quad illumination

<table>
<thead>
<tr>
<th>$p$ (nm)</th>
<th>$\lambda$ (nm)</th>
<th>$\nu$ (s$^{-1}$)</th>
<th>$E_s$ (mJ/cm$^2$)</th>
<th>$d$ (nm)</th>
<th>$EL$</th>
<th>$LWR$ (nm)</th>
<th>$L_d$ (nm)</th>
<th>$K_{\text{LUP}}$</th>
<th>NILS</th>
<th>$K_{\text{LUP}}/\text{NILS}$</th>
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<td>1.6E+15</td>
<td>16.5</td>
<td>150</td>
<td>0.28</td>
<td>6.5</td>
<td>32</td>
<td>1.13</td>
<td>2.79</td>
<td>0.40</td>
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<tr>
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<td>193</td>
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<td>32</td>
<td>1.13</td>
<td>2.79</td>
<td>0.40</td>
</tr>
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</table>

- 193nm: $K_{\text{LUP}}$ target for 32nm half pitch is $\sim$4X lower than current resist performance
$K_{LUP}$ results on 193nm resists – PAG loading

- $K_{LUP}$ decreases with increasing PAG loading due to increasing resist absorbance (see paper for further details).
- This approach will require thinner resist and transfers the problem to etch.

\[
K_{LUP} = \sqrt{\frac{Dose}{h \cdot \nu \cdot d \cdot EL \cdot LWR \cdot (L_d)^{3/2}}}
\]

<table>
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<tr>
<th>PAG loading</th>
<th>$p$ (nm)</th>
<th>$\lambda$ (nm)</th>
<th>$\nu$ (s$^{-1}$)</th>
<th>$E_s$ (mJ/cm$^2$)</th>
<th>$d$ (nm)</th>
<th>$EL$ (nm)</th>
<th>$LWR$</th>
<th>$L_d$ (nm)</th>
<th>$K_{LUP}$</th>
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<td>3wt%</td>
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<td>193</td>
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<td>150</td>
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<td>2.04</td>
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<td>6wt%</td>
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<td>1.6E+15</td>
<td>14.2</td>
<td>150</td>
<td>15.0</td>
<td>8.3</td>
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<td>1.34</td>
</tr>
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<td>9wt%</td>
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<td>193</td>
<td>1.6E+15</td>
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<td>150</td>
<td>14.6</td>
<td>8.0</td>
<td>36</td>
<td>1.03</td>
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<td>12wt%</td>
<td>200</td>
<td>193</td>
<td>1.6E+15</td>
<td>7.8</td>
<td>150</td>
<td>15.6</td>
<td>8.7</td>
<td>34</td>
<td>0.96</td>
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</tbody>
</table>
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- Conclusions
EUV resists

- Exposures were performed by EUV interference lithography on the SLS beam line at the Paul Scherrer Institut (Switzerland).
- $K_{\text{LUP}}$ has been quantified for a series of EUV resist samples that have been received from one resist vendor over a 16 month period.
- $K_{\text{LUP}}$ enables an objective evaluation of the improvement in resist performance during this time frame.
EUV Resist Performance Q2 2005

40nm L/S

32.5nm L/S

30nm L/S

25nm L/S

8.3mJ/cm²

Not Available

Not Available

Not Available

Not Available
EUV Resist Performance Q4 2005

40nm L/S  32.5nm L/S  30nm L/S  25nm L/S

13.7mJ/cm²
EUV Resist Performance Q2 2006

40nm L/S 32.5nm L/S 30nm L/S 25nm L/S

10.6mJ/cm²

Not Available
EUV Resist Performance Q4 2006

40nm L/S  32.5nm L/S  30nm L/S  25nm L/S

15.5mJ/cm²
### EUV resist performance monitor

#### Data Table

<table>
<thead>
<tr>
<th>date</th>
<th>$p$ (nm)</th>
<th>$\lambda$ (nm)</th>
<th>$\nu$ (s$^{-1}$)</th>
<th>$E_s$ (mJ/cm$^2$)</th>
<th>$d$ (nm)</th>
<th>$EL$ (s$^{-1}$)</th>
<th>LWR (nm)</th>
<th>$L_d$ (nm)</th>
<th>$K_{LUP}$</th>
<th>NILS</th>
<th>$K_{LUP}$/NILS</th>
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<td>0.70</td>
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<td>21</td>
<td>0.12</td>
<td>4.1</td>
<td>0.03</td>
</tr>
</tbody>
</table>

• **EUV**: $K_{LUP}$ target for 32nm half pitch is $\sim$3X lower than current resist performance

At 0.25NA; 0.5$\sigma$ Conventional
Conclusions

• $K_{\text{LUP}}$ is a valuable figure-of-merit for assessing resist performance
• Objective metric for comparing different resist platforms when simultaneously optimizing for photospeed, LWR and resolution
• Helpful to focus discussions on what resist performance improvement is needed
• $K_{\text{LUP}}$ for state-of-the-art EUV resists is $\sim3X$ from requirements for 32nm half pitch
• $K_{\text{LUP}}$ for state-of-the-art 193nm resists is $\sim4X$ from requirements for 32nm half pitch
  - Better maturity of 193nm resists is compensated by better NILS for EUV
• Model does not include development effects, post-processing, profile information, ...
Acknowledgements

- Resist suppliers for providing samples
- Akimasa Soyano (JSR Micro) for preparing 193nm resist model samples
- Harun Solak and Yasin Ekinci (Paul Scherrer Institut) for assistance with the interference EUV exposures
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