Control technology of EUV Optics Contamination:
Modeling, mitigation and cleaning for lifetime extension

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Outline

1. **Introduction**
   Requirement for optics lifetime

2. **Modeling** - Two sources of contamination -
   1. Model for Carbon Growth
   2. Model for Oxidation

3. **Mitigation & Prevention**
   1. Environmental control
   2. Capping Layer Development

4. **Cleaning**
   1. Oxidation cleaning
   2. Atomic hydrogen cleaning

5. **Summary**
Contamination related issues in EUV Lithography

**Illumination Optics**
- Plasma assisted contamination growth

**Projection Optics**
- Carbon Growth, Oxidation

**Mask**
- Particle, Carbon Growth

**Collector Optics**
- Erosion

**Source**
- Plasma Debris

**Mechanics**
- Outgassing from vacuum component

**Resist**
- Resist Outgassing

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June. 11-12, 2008
EUVL Workshop
## 2007 EUV Critical Issues Ranking

### Critical Issue

<table>
<thead>
<tr>
<th>Critical Issue</th>
<th>Rank*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliable high power source &amp; collector module</td>
<td>1.2</td>
</tr>
<tr>
<td>Resist resolution, sensitivity &amp; LER met simultaneously</td>
<td>2.1</td>
</tr>
<tr>
<td>Availability of defect free masks</td>
<td>2.8</td>
</tr>
<tr>
<td>Reticle protection during storage, handling and use</td>
<td>4.1</td>
</tr>
<tr>
<td>Projection and illuminator optics quality and lifetime</td>
<td>4.8</td>
</tr>
</tbody>
</table>

*Significant concern: Timing and cost / business case for EUVL development

*) Average of 20 steering committee member votes
Requirement and approach for Projection Optics Lifetime

- Requirement for production tool
  - Lifetime > 30,000 hours
  - Reflectivity loss < 1.6%

- Condition
  - under unbaked vacuum (H₂O, HC)
  - Outgassing from resist materials
  - EUV irradiation: I_{EUV} ≤ 10 mW/mm²

- Approach
  - Modeling:
    Understanding of contamination growth
  - Mitigation
    Environmental control & Capping layer development
  - Cleaning
    Oxidation or Reduction
Modeling

1. Model for Carbon Growth

2. Model for Oxidation
Two degradation mechanism of EUVL mirror

- Carbon growth on surface
  - Reduction of contaminants from vacuum components and resist
  - Cleaning technologies are known.
- Oxidation of subsurface
  - Oxidation resistant Capping layer
  - Novel cleaning technology is required

EUV photon

$C_xH_y$ ~ $1 \times 10^{-9} \text{ Pa}$

$H_2O$ ~ $1 \times 10^{-7} \text{ Pa}$

~ $10 \text{ mW/mm}^2$


\[
\frac{dc_{\text{sur}}}{dt} = \frac{1}{4} n_{\text{av}} S - \frac{c_{\text{sur}}}{\tau_{\text{des}}} - \sigma_{PD} I_p c_{\text{sur}} - \sigma_{PR} I_p c_{\text{sur}} - \sigma_{ED} I_p c_{\text{sur}} - \sigma_{ER} I_p c_{\text{sur}}
\]

Rate equation model was applied to atomic oxygen formation on Ru as the measure of surface oxidation.

Nishiyama et al. SPIE 2006
Fundamental understanding of Ru oxidization from surface chemistry

Helbert Over et al. Science 297

Chemistry of water molecule adsorbed on Ru and RuO2

Residence time of H₂O on Ru surface can be evaluated from TPD data

Dissociative attachment has a large cross section on Ru

Ted Madey et al. EUVL Symposium 2004
Pressure and EUV dependences of H$_2$O-induced oxidation rate

Growth rates are linear with contaminant pressure and EUV intensity in typical experimental conditions.

Contaminant pressure and EUV intensities are good scaling parameters for lifetime estimation.

Nishiyama et al. SPIE 2006
Pulse width & repetition rate dependence of growth rate

Average power = 5 mW/mm², H₂O pressure = 2 x 10⁻⁶ Torr

Growth rate decreases when repetition rate becomes low and pulse width becomes short.

Nishiyama et al. SPIE 2006
Modeling for Carbon growth on EUV mirror
Mass Dependence of deposition rate

Tested contaminant molecules

<table>
<thead>
<tr>
<th>Organic gas</th>
<th>B.T. / °C</th>
<th>M.W.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buthane</td>
<td>-1</td>
<td>58</td>
</tr>
<tr>
<td>Buthanol</td>
<td>117</td>
<td>74</td>
</tr>
<tr>
<td>Methyl propionate</td>
<td>79</td>
<td>88</td>
</tr>
<tr>
<td>Hexane</td>
<td>69</td>
<td>86</td>
</tr>
<tr>
<td>Perfluoro octane</td>
<td>97</td>
<td>438</td>
</tr>
<tr>
<td>Decane</td>
<td>174</td>
<td>142</td>
</tr>
<tr>
<td>Decanol</td>
<td>231</td>
<td>158</td>
</tr>
<tr>
<td>Methyl nonanoate</td>
<td>214</td>
<td>172</td>
</tr>
<tr>
<td>Diethyl benzene</td>
<td>183</td>
<td>134</td>
</tr>
<tr>
<td>Dimethyl phtalate</td>
<td>283.7</td>
<td>194</td>
</tr>
<tr>
<td>Hexadecane</td>
<td>287</td>
<td>226</td>
</tr>
</tbody>
</table>

Aoki et al. EUVL Symposium 2005

Heavier molecules show larger carbon deposition rates.

This fact should be explained by the adsorbate mass dependence of residence time.
Insufficiencies in theoretical modeling

Non-linear dependences on pressure and intensity were observed in carbon deposition rate.

*Nakayama et al. SPIE 2008*

Current surface models have not counted followings;

- Interface reaction of oxidation
- Surface change in carbon growth

![Diagram showing reaction and surface changes](image)
Mitigation

1. Environmental control
   1. Reduce contaminant levels [HC and water]
   2. Active blending of oxidation preventing gas

2. Capping Layer Development
   1. Oxidation resistant capping layer
Difference of degradation speed with vacuum condition

ES1 : Ultra High Vacuum
3.7x 10^{-7} Pa

ES2 : O-ring sealed vacuum
4.5 x 10^{-5} Pa

\( \frac{R}{R_0} \) vs Dose (J/mm²)

H₂O+EUV oxidation was suppressed by high background chamber. Prevention of oxidization by background gas was suggested.

Kakutani et al. EUVL Symposium 2005

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Mitigation by mixing of methanol

Small amount of methanol in ambient background gas mitigate H2O+ EUV oxidization

Shannon Hill et al. SPIE 2006
Condition: H₂O:1 × 10⁻⁴Pa EUV: 180J/mm² 16mW/mm²

Reflectance relative change

Light dose/(J/mm²)

😊 C-Cap, Nb-Cap, Pt/Ru-Cap
😊 Ru/B₄C-Cap, Ru/SiO₂(2)-Cap
😊 Ru/SiO₂(1)-Cap, SiO₂-Cap, Rh-Cap

Matsunari et al. EUVL Symposium 2005
Capping Layer Screening

Ruthenium capping layer still a leading candidate for oxidation protection.

Sasa Bijt et al.
EUVL Symposium 2004

TiO$_2$-capped MLs are extremely stable in air and under accelerated lifetime testing

Sasa Bijt et al.
EUVL Symposium 2005

ΔR = - 0.3%
Cleaning Technology

1. Oxidation cleaning for carbon
   • O₃, O, EUV + O₂

2. Reductive cleaning for carbon and oxide
   • Atomic hydrogen
Atomic-H Cleaning of Carbon Contamination

Reflectivity recovery

As sputtered: 62.4%
C contamination: 58.9%
Atomic H cleaning: 61.9%

Oizumi et al. SPIE 2005
Atomic-H Cleaning of Oxide Layer

Reduction of Ru oxide

Before H-treatment
(Ru Oxide)

After H-treatment
(Ru Metal)

Reflectivity recovery

As sputtered : 62.3%
Oxidation : 59.6%
Atomic H cleaning: 62.0%

Nishiyama et al. EIPBN 2006
Carbon cleaning of patterned mask

Cleaning rate = 0.37 nm/min

5 min → H-treatment → 30 min

Electron dose on carbon deposition (×10^{15} cm^{-2})

- 2.000
- 4.000
- 8.400
- 12.000
- 16.000

Thickness (nm)

- 1.4
- 2.8
- 5.6
- 8.4
- 11.2
Repeated carbon cleaning

...which is removable: no cumulative effect after repeated cleaning and exposure

Conclusion

- No reflectance degradation due to in-situ cleaning observed.

Hans Meiling et al. SPIE 2006
Summary

- Optics contamination and lifetime is a big concern in EUVL technology
- **Modeling**
  - Models for carbon growth and oxidation are proposed.
  - Lifetime scaling on contaminant-pressure and EUV-intensity are carried out.
- **Mitigation:** Two approaches are developing.
  1. Vacuum environmental control
  2. Capping layer development
- **Cleaning:** Two methods are developing
  1. Oxidization removal for carbon contamination
  2. Reductive removal for carbon and oxide layer by atomic hydrogen
- There are still remaining more than one-order-of-magnitude lack in satisfying optics lifetime (without cleaning). Further efforts and total approaches are necessary.