Critical defect size on the extreme ultraviolet (EUV) mask and cleaning process for its removal

Min-Su Kim\textsuperscript{a}, Hye-Rim Ji\textsuperscript{b}, In-Seon Kim\textsuperscript{b}, Hye-Keun Oh\textsuperscript{b}, Jin-Ho Ahn\textsuperscript{c} and Jin-Goo Park\textsuperscript{a,†}

\textsuperscript{a}Department of Materials Engineering, Hanyang Univ., Ansan, KOREA
\textsuperscript{b}Department of Applied Physics, Hanyang Univ., Ansan, KOREA
\textsuperscript{c}Department of Materials Science and Engineering, Hanyang Univ., Seoul, KOREA

\textsuperscript{†}+82(0)31 400 5226
jgpark@hanyang.ac.kr
Hanyang Univ., Ansan, 426-791, KOREA
Critical defect size on 16 nm EUVL mask
Ultra fine particle removal by megasonic cleaning
Introduction
Scaling Scenario: Lithography

G. Chung, “Partnership to build a better future, and leading edge collaboration”, SPCC (2012)
Issue of contaminated particles on EUV mask

- **EUV mask defects**

Fine particles on EUV mask can be printed !!

→ Particles should be removed without damage on EUV mask

- **Effect of contaminated particle**

![Diagram of EUV mask layers with particle effects](image-url)

TaBO/TaBN A-L

Ru C-L

Mo-Si M-L

Substrate

λ=13.5nm

Mask

Wafer
Research Objective

Critical defect removal from Ru surface

Investigation of critical defect size
- Effect of defect size on 16 nm HP node EUV mask

Effect of megasonic cleaning on ultra fine particle
- Boundary layer thickness, drag force with particle size

Megasonic cleaning for ultra fine particle removal
- PRE & pattern damage test
Critical defect size on EUV mask
### Experimental procedure [Critical defect size]

#### Conditions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wavelength</strong></td>
<td>13.5 nm</td>
</tr>
<tr>
<td><strong>Illumination</strong></td>
<td>Dipole</td>
</tr>
<tr>
<td><strong>Coherence (σ_r−σ_c)</strong></td>
<td>0.1–0.8</td>
</tr>
<tr>
<td><strong>Numerical Aperture</strong></td>
<td>0.33</td>
</tr>
<tr>
<td><strong>Target CD (at wafer)</strong></td>
<td>16 nm</td>
</tr>
<tr>
<td><strong>Target CD (at mask)</strong></td>
<td>64 nm</td>
</tr>
<tr>
<td><strong>Reduction (Mask : wafer)</strong></td>
<td>4:1</td>
</tr>
</tbody>
</table>

#### Position of defect on EUV mask

1. Space b/w absorber pattern
2. On the absorber pattern
3. Left side of absorber pattern
4. Right side of absorber pattern

#### Defect materials

Sn / TaN / W / SiO<sub>2</sub> / C
CD variation w/ defect position

- CD variation w/ defect position
  - Space > Right side > Left side > Absorber
CD variation w/ defect size

- Critical defect $\rightarrow$ 10% CD error
- CD error is drastically increased with increasing defect size
  $\rightarrow$ Sn > TaN > W > SiO$_2$
• Critical defect size is in inverse proportion to extinction coefficient
• 10 % CD error caused by 23 nm ~30 nm particles @ 16 nm HP node EUV mask
  ➔ Below 30 nm particles should be removed
  ➢ Cleaning process is required to remove ultra fine particles
Megasonic cleaning for 30 nm particle removal
Experimental procedure [Cleaning test]

- **Particle removal & pattern damage test w/ megasonic cleaning**

**Sample preparation**
- Standard silica particles (30, 137 nm)
- 2 cm X 2 cm Ru wafer
- Wet deposition & 1day aged
- PR line pattern (200 nm)

**Megasonic cleaning**
- 1, 2 MHz megasonic (Durasonic, Korea)
  - MS power ~ 10 W
  - Cleaning time ~ 30 sec
- DIW, dNH$_4$OH (pH10), H$_2$-DIW (1 ppm)

**Evaluation of PRE & pattern damage**
- Optical Microscope (LV100D, Nikon, Japan)
  - For 137 nm silica particle & pattern damage
- AFM (XE-100, Parksystem, Korea)
  - For 30 nm silica particle

**PR vs Poly Si pattern collapse force**
- AFM tip
  - NSC 15 (40 N/m) for poly Si
  - NSC 18 (3.5 N/m) for PR

**OM image of PR pattern 200 nm**
- Comparison of collapse force
  - PR @ 200 nm ≈ Poly Si @ 35 nm

- Pattern collapse force were measured to justify the deviation between PR and Poly Si pattern
  
  ➔ Evaluation of pattern damage by MS cleaning
Mechanism of Megasonic Cleaning

- **Bubble oscillation + microstreaming (stable cavitation)**

  - Bubble oscillation + microstreaming (stable cavitation)
  - By Laplace pressure
  - Particles could be removed by the force induced bubble oscillation with microstreaming

- **Bubble collapse (transient cavitation)**

  - Bubble collapse (transient cavitation)
  - When bubble collapse, it cause liquid jet or shock wave
  - Removal of contaminated particles and generation of pattern damage

Boundary layer thickness in acoustic field

**Boundary layer thickness in ultrasound field**

\[
\delta = \sqrt{\frac{\mu}{2\pi f \rho}}
\]

Where, \( \rho \) is liquid density, \( \mu \) is viscosity of liquid, \( f \) is frequency.

- Boundary layer thickness is decreased with increasing frequency in acoustic field
  - High freq. is more effective to remove small particles
- Resonant bubble size is also decreased
  - Bubble collapse force would be decreased
- Boundary layer thickness grows in proportion to \( x^{1/2} \)

**Resonant bubble size @ frequency**

\[
\rho P_0 4\pi R_0^2 R_0^3 - 3\gamma P_0^2 R_0 - 6\gamma P_0 \sigma + 2P_0 \sigma = 0
\]

Where, \( P_0 \) equilibrium pressure, \( R_0 \) resonant bubble radius, \( f \) frequency, \( \gamma \) ratio of specific heat, \( \sigma \) density of liquid.

- 1 MHz \( \approx 0.4 \) µm
- 2 MHz \( \approx 0.3 \) µm

**Resonant bubble size**

1 MHz \( \approx 3.7 \) µm
2 MHz \( \approx 2.0 \) µm

**Boundary layer thickness in boundary layer theory**

\[
\delta(x) = 5 \sqrt{\frac{\nu x}{U_\infty}}
\]

Where, \( \nu \) is kinematic viscosity, \( U_\infty \) is velocity of outer flow, \( x \) is position.


---

Drag force on particles by fluid flow

- Instantaneous fluid particle velocity
  \[ U = \sqrt{\frac{I}{\rho C}} \]
  Where, \( I \) is intensity of incident acoustic waves
  \( \rho \) is viscosity of liquid
  \( C \) is frequency


- Drag force on the particles
  \[ F_D = 1.7009 \cdot (3\pi\mu d V_p) \]
  Where, \( d \) is diameter of particle
  \( V_p \) is fluid velocity at center of particle

  V. Kapila et al., Proc. of SPIE, 5992 (2005) 59923X-1

- Drag force by fluid flow @ 1 MHz MS
  \( \rightarrow 137 \text{ nm silica particle is about } 10 \text{ times} \) larger than 30 nm particle

- Drag force to vdW force ratio
  \( \rightarrow 137 \text{ nm silica particle is about } 2 \text{ times} \) higher than 30 nm particle

- More difficult to remove fine particle
Result of PRE w/ silica particle size

- 137 nm silica particles were almost removed @ 1 MHz 3 W 10 sec
- PRE of 30 nm silica particles was about 80 % despite high MS power 10 W
  → Drag force by acoustic streaming @ 30 nm silica particle is much lower than 137 nm silica particles
- PRE of 30 nm silica particles was over 95 % @ 1 MHz 10 W 30 sec
Comparison of PRE between 30 nm & 137 nm silica particles

- 137 nm silica particle → 1 MHz MS 3 W 10 sec
- 30 nm silica particle → 1 MHz MS 5 W 30 sec

More MS power & cleaning process time are required to remove fine particle
Effect of cleaning solution @ MS cleaning
Total interaction energy between particle and surface

- **Zeta-potential of particle & surface**
  - Zeta-potential is going to negative value @ high pH solution
  - Interaction energy is repulsion @ high pH solution

- **Effect of pH on interaction energy**

\[ E_{\text{net}} = E_{\text{electrostatic}} + E_{\text{van der Waals}} \]

\[ E_T = 64\pi R\varepsilon_0\varepsilon\left(\frac{kT}{e}\right)^2 \tanh^2\left(\frac{Ze\psi_0}{4kT}\right)e^{-\kappa D} - \frac{AR}{6D} \]

- \( R \): Particle radius
- \( \varepsilon \): Permittivity of medium,
- \( \varepsilon_0 \): Permittivity of free space
- \( k \): Boltzmann constant
- \( T \): Absolute temperature
- \( z \): Valance number,
- \( \kappa \): Reciprocal of Debye length,
- \( D \): Distance between surface and particle
- \( A \): Hamaker constant
- \( \psi_0 \): Zeta potential of particle and surface

- **30 nm silica particle w/ Ru surface**

- **pH 4**
- **pH 6**
- **pH 8**
- **pH 10**

**Zeta-potential (mV)**

<table>
<thead>
<tr>
<th>pH</th>
<th>Zeta-potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-60</td>
</tr>
<tr>
<td>6</td>
<td>-40</td>
</tr>
<tr>
<td>8</td>
<td>-20</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

**Total interaction energy x 10^{-20} (J)**

- **Repulsion**
- **Attraction**

- **30 nm silica particle w/ Ru surface**
**Cavitation threshold @ frequency & dissolved gas**

- **Higher frequency of MS** ⇒ **lower cavitation effect & PRE** / **higher dissolved gas concentration** ⇒ **higher cavitation effect & PRE**

→ Cavitation effect by dissolved gas: \( H_2 > NH_3 > N_2 \)
Cavitation threshold @ frequency & dissolved gas

- Cavitation threshold is lower @ 1 MHz than 2 MHz megasonic
  - Small differences in cavitation threshold w/ various dissolved gas @ 1 MHz frequency
- There is a large difference in cavitation threshold between gases @ 2MHz frequency
  - Lower cavitation effect @ all dissolved gases
PRE result @ megasonic frequency

- PRE was drastically reduced @ high frequency MS (2 MHz)
  - Cavitation threshold is much higher than 1 MHz frequency
- Degradation of bubble cavitation effect @ high frequency MS (2 MHz)
  - Bubble cavitation is a main factor in particle removal
- Cleaning solution has to be induced @ high frequency MS cleaning
Effect of pH & dissolved gas in PRE

- PRE was improved with addition of NH$_4$OH (pH 10) and H$_2$ gas (1 ppm) in DIW
  - Bubble cavitation effect is more activated by additives
- 2 MHz MS is still lower PRE than 1 MHz MS @ pH10 w/ H$_2$-DIW solution
  - Cavitation threshold is higher @ 2 MHz MS
Result of pattern damage test

- 200 nm PR pattern collapse was higher @ 1 MHz MS cleaning
  → Higher cavitation effect & large bubble size @ 1 MHz MS
- Pattern damage was obviously reduced @ 2 MHz MS despite induced additives
  → High frequency MS is suitable for damage free cleaning process
Summary

- Critical defect size on 16 nm HP node EUV mask
  - CD variation w/ defect position → Space > Right side > Left side > Absorber
  - Below 30 nm particles can be occur 10 % CD error

- Megasonic cleaning for 30 nm particle removal
  - More difficult to remove small particle → Lower drag force than large particle
  - Cavitation threshold was higher @ 2 MHz MS than 1 MHz MS
    → Additives (NH₄OH & H₂ gas) were induced to increase PRE @ high freq. MS
  - More megasonic power & cleaning process time were required @ 2 MHz MS cleaning
    → PRE was improved & pattern damage is obviously reduced as compared with 1 MHz MS
THANK YOU FOR YOUR ATTENTION!!