NANO AND MICROSCALE PARTICLE REMOVAL

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OUTLINE

- Goals and Objectives
- Approach
- Preliminary Results
  - Acoustic Streaming and Boundary Layer
  - Particle Removal Mechanism
  - Double layer
  - Effect of Particle Size and Flow Frequency
- Key Preliminary Research Results
# Surface Preparation Technology Requirements -- Long Term

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<tbody>
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<td>TECHNOLOGY NODE</td>
<td>180nm</td>
<td>130nm</td>
<td>100nm</td>
<td>70nm</td>
<td>50nm</td>
<td>35nm</td>
<td>35nm</td>
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<tr>
<td>FEOL Particle Size (nm)</td>
<td>90</td>
<td>82.5</td>
<td>60</td>
<td>50</td>
<td>35</td>
<td>25</td>
<td>18</td>
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<tr>
<td>FEOL Particles (#/cm²)</td>
<td>0.064</td>
<td>0.06</td>
<td>0.064</td>
<td>0.051</td>
<td>0.052</td>
<td>0.052</td>
<td>0.052</td>
</tr>
<tr>
<td>BEOL Particle Size (nm)</td>
<td>180</td>
<td>165</td>
<td>130</td>
<td>100</td>
<td>70</td>
<td>50</td>
<td>36</td>
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<td>0.051</td>
<td>0.052</td>
<td>0.052</td>
<td>0.052</td>
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<tr>
<td>Surface Roughness (nm)</td>
<td>0.15</td>
<td>0.14</td>
<td>0.12</td>
<td>0.1</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Critical surface metals (*10⁹)</td>
<td>9</td>
<td>7</td>
<td>4.4</td>
<td>2.5</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Organics (*10¹³ atoms/cm²)</td>
<td>7.3</td>
<td>6.6</td>
<td>5.3</td>
<td>4.1</td>
<td>--</td>
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</tr>
</tbody>
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** ---- The International Technology Roadmap for Semiconductors, 2000**
Goals and Objectives

- Develop an effective nanoscale particle removal technique using acoustic streaming.
- Provide a fundamental understanding of the removal mechanism that will be experimentally verified.
- Experimentally measure particle removal of particles in the size range of 10-100 nm from semiconductor wafers.
- Evaluate effect of streaming flow frequency, velocity amplitude and particle size and particle/substrate composition on the removal efficiency experimentally and numerically.
Approach

- **Fundamental Approach**
- **Experimental and modeling approach to determine, understand and predict:**
  - Particle Removal Mechanism
  - Cleaning Efficiency, $F(R, V, F_{ad}, \text{etc.})$
  - Cleaning tank Geometry (single, batch, etc.)
  - Optimum cleaning conditions
  - Cleaning technology limits with shrinking particle and defect size
Approach

**Fundamental Approach**

**Key Particle Removal Parameters**
- flow frequency
- velocity (pressure) amplitude
- Particle size
- Particle composition
- Particle shape
- Particle deformation and contact area
- Double layer effect on removal
- Cleaning liquid surface tension
- Surface and particle surface energy (hydrophilic or hydrophobic)
MEGASONIC CLEANING

- Megasonic sound wave:

\[ \nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \]

\[ p(x, t) = p_0 \sin(kx - \omega t + \Phi) \]

\[ u(x, t) = u_0 \sin(kx - \omega t + \Phi) \]

- Megasonic power intensity:

\[ I = \frac{p_0^2}{2 \rho c} \]

Megasonic Cleaning Mechanism
ACOUSTIC STREAMING

**Streaming Velocity vs. Acoustic Power**

Distance From Tank Wall (cm) vs. Intensity (W/cm²)

- f = 760 kHz

- I = .77W/cm²
- I = 1.55W/cm²
- I = 2.33W/cm²
- I = 3.10W/cm²
- I = 3.88W/cm²
- I = 4.65W/cm²
- I = 5.43W/cm²
- I = 6.20W/cm²
- I = 6.97W/cm²
- I = 7.75W/cm²

**Streaming Velocity vs. Acoustic Power**

- 1 M Hz
- 850k Hz
- 760k Hz
- 360k Hz
PARTICLE REMOVAL

- Nano-scale particles will be a challenge to current cleaning techniques.

- The most widely used cleaning techniques:
  - non-contact method (megasonic cleaning)
  - contact cleaning method (brush scrubbers)

- The two basic elements that need to be understood are:
  - Particle Adhesion
  - Particle Removal
**Boundary Layer Thickness**

- **Acoustic boundary layer thickness:**
  \[ \delta_{ac} = \left( \frac{2v}{\omega} \right)^{\frac{1}{2}} \]
  - in water, \( f=850\text{KHz} \), \( \delta_{ac}=0.61\mu\text{m} \)
  - \( f=760\text{KHz} \), \( \delta_{ac}=0.65\mu\text{m} \)
  - \( f=360\text{KHz} \), \( \delta_{ac}=0.94\mu\text{m} \)

- **The hydrodynamic boundary layer thickness:**
  \[ \delta_{H} = 0.16 \left( \frac{v}{Ux} \right)^{\frac{1}{7}} \cdot x \]
  - in water, \( u=4\text{m/s} \), at center of the wafer,
  \( \delta_{H}=2570\mu\text{m} \)
Velocity Profile in a Boundary Layer

\[ y = 0 \sim 2500 \text{ micron} \]

\[ y = 0 \sim 10 \text{ micron} \]

**Velocity Profile**  \( x = 4 \text{ inch}, \ U = 4 \text{m/s} \)

- Laminar flow
- Turbulent flow
- Acoustic Flow (\( f = 800 \text{kHz} \))
Drag Force Distribution on a Particle

\[ F_D = C_D \rho \frac{u_i^2}{2} A_i \]

- \( f = 800 \text{ kHz}, \quad I = 7.75 \text{W/cm}^2, \quad U_{ac} = 4.08 \text{ m/s} \)
- Acoustic boundary layer thickness = 0.63 micron

\[ u(y) \text{ (m/s)} \]

- Drag Force (0.5 micron particle)
- Drag Force (1 micron particle)
Effects of Frequency

Acoustic Flow Properties

- Acoustic, f=360KHz
- Acoustic, f=760KHz
- Acoustic, f=850KHz
- Boundary layer thickness (micron)
- Streaming Velocity (m/s)
- Drag Force (1 um particle)
- Drag Force (0.1 um particle)

Frequency (k Hz)

Boundary layer thickness (micron)

Streaming Velocity (m/s)

Drag Force (N)

I = 7.75 W/cm²
**Ratio of Removal/Adhesion Moment (RM)**

- **RM:**
  
  \[ RM = \frac{\text{Removal moment}}{\text{Adhesion resisting moment}} \]
  
  \[ RM = \frac{F_d (1.399 R - \delta) + F_{dl} \cdot a}{F_a \cdot a} \]

- When RM >1, most particles are removed.

Rolling removal mechanism
Removal Percentage vs. Moment Ratio (Silica Removal Experiment)
Effect of Particle Size on Adhesion and Removal Forces

Forces vs. Particle Diameter  \( U = 4 \text{ m/s} \)

- Drag Force (Acoustic Flow, 800kHz, 7.75W/cm², \( U_{ac} = 4 \text{ m/s}, d_{ac} = 0.63 \text{ um} \))
- Drag Force (Hydrodynamic Flow, \( U = 4 \text{ m/s}, d = 2750 \text{ um} \))
- Double layer force
- Van der Waals Force, PSL/\(\text{SiO}_2\)
- Van der Waals Force, \(\text{SiO}_2/\text{SiO}_2\)

- Drag force, electrical double layer force, and adhesion force all increase with particle size.

- Acting as removal forces,
  - \(d>100\text{nm}\), acoustic flow drag force is dominated;
  - \(30\text{nm}<d<100\text{nm}\), drag force and electrical double layer force are on same level;
  - \(d<30\text{nm}\), electrical double layer force is dominated;
At the pH of water, silica, PSL, PVA, and W particles are all negatively charged.

The high negative zeta potentials are measured at high pH solution for SiO$_2$, Si$_3$N$_4$, Al$_2$O$_3$, tantalum pentoxide, tungsten, polyvinyl alcohol (PVA), and also for Si and PSL.

Using a high pH cleaning solution, electrical double layer force occurs as a strong repulsion between the particle and the substrate.
Using DI water only, the removal of nano-size particles (10-100 nm) can be best accomplished using acoustic streaming at frequencies larger than 1.3 MHz.
**Effects of Frequency on RM**

DI water, Electrical double layer force is negligible  

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>RM no $F_{el}$ (1µm SiO$_2$/SiO$_2$)</th>
<th>RM no $F_{el}$ (0.1µm SiO$_2$/SiO$_2$)</th>
<th>RM no $F_{el}$ (1µm PSL/SiO$_2$)</th>
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<tbody>
<tr>
<td>$10^1$</td>
<td>$10^6$</td>
<td>$10^5$</td>
<td>$10^4$</td>
<td>$10^3$</td>
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<tr>
<td>$10^2$</td>
<td>$10^7$</td>
<td>$10^6$</td>
<td>$10^5$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$10^8$</td>
<td>$10^7$</td>
<td>$10^6$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$10^4$</td>
<td>$10^9$</td>
<td>$10^8$</td>
<td>$10^7$</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>

SC-1, Electrical double layer force is repulsive force

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>RM (1µm SiO$_2$/SiO$_2$)</th>
<th>RM (0.1µm SiO$_2$/SiO$_2$)</th>
<th>RM (1µm PSL/SiO$_2$)</th>
<th>RM (0.1µm PSL/SiO$_2$)</th>
</tr>
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<td>$10^1$</td>
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| The smaller the particles, the higher frequency acoustic flow is needed. |
| Soft particles (PSL) are more difficult to remove than hard particle (silica), needing almost an order of magnitude higher frequency. |
Fast Single Wafer Post-CMP Cleaning
Single versus Batch

The Removal Efficiency of Al2O3 particles

Particulate > 0.2 micron

Before Dep
After Dep
After Cleaning

10 min Batch
10 min Batch
20 min Batch
20 min Batch
1 min Single
1 min Single
Complete removal of silica particles down to 100nm is achievable by using a single wafer megasonic cleaning with DI water only.
Megasonic Cleaning of Polished TOX Wafers Using SC1

Defects #

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature</th>
<th>150 W</th>
<th>540 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 min</td>
<td>30°C</td>
<td>600</td>
<td>1000</td>
</tr>
<tr>
<td>10 min</td>
<td>30°C</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>5 min</td>
<td>60°C</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>10 min</td>
<td>60°C</td>
<td>100</td>
<td>200</td>
</tr>
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</table>

Legend:
- 150 W
- 540 W
Megasonics induced acoustic streaming is essential to the removal of submicron and nano-size particles.

As the frequency increases, the acoustic boundary layer thickness decreases and streaming velocity increases thereby increasing the removal (drag) force.

Using DI water, the removal of nano-size particles (10-100 nm) can be best accomplished using acoustic streaming at frequencies larger than 1.3 MHz.

Utilizing the electrical double layer force as a repulse force, by using basic chemistry, removal of 10nm silica particle can be accomplished using megasonic cleaning above 800 kHz.

Acting as removal forces,
- $d>100\text{nm}$, acoustic flow drag force is dominated;
- $30\text{nm}<d<100\text{nm}$, drag force and electrical double layer force are on same level;
- $d<30\text{nm}$, electrical double layer force is dominated;

Soft particles (such as Polystyrene Latex PSL) are more difficult to remove than hard particle (silica), because of adhesion induced deformation, needing almost an order of magnitude higher frequency.