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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<td>TECHNOLOGY NODE</td>
<td>180nm</td>
<td>130nm</td>
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<td>70nm</td>
<td>50nm</td>
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<tr>
<td>FEOL Particle Size (nm)</td>
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<td>FEOL Particles (#/cm²)</td>
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<td>0.051</td>
<td>0.052</td>
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<tr>
<td>BEOL Particle Size (nm)</td>
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<td>BEOL Particles (#/cm²)</td>
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<td>Surface Roughness (nm)</td>
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<td>0.12</td>
<td>0.1</td>
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<td>Critical surface metals (*10⁹)</td>
<td>9</td>
<td>7</td>
<td>4.4</td>
<td>2.5</td>
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<tr>
<td>Organics (*10¹³ atoms/cm²)</td>
<td>7.3</td>
<td>6.6</td>
<td>5.3</td>
<td>4.1</td>
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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

$\text{v}(\text{cm/s})$

Distance From Tank Wall (cm)

Intensity (W/cm$^2$)

$\text{Streaming Velocity vs. Acoustic Power}$

$\text{f} = 760 \text{ kHz}$

$\text{v}(\text{cm/s})$

Intensity (W/cm$^2$)

$1 \text{ M Hz}$

$850 \text{ kHz}$

$760 \text{ kHz}$

$360 \text{ kHz}$
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:**
  \[
  \delta_{ac} = \left( \frac{2v}{\omega} \right)^{1/2}
  \]
  - 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:**
  \[
  \delta_H = 0.16 \left( \frac{v}{U_x} \right)^{1/7} \cdot x
  \]
  - in water, \( u=4\text{m/s} \), at center of the wafer,
  \( \delta_H=2570\mu\text{m} \)


**Velocity Profile in a Boundary Layer**

\[ y = 0 \sim 2500 \text{ micron} \quad \text{and} \quad y = 0 \sim 10 \text{ micron} \]

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

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

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

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

\begin{align*}
\text{drag force} (0.5 \text{ micron particle}) & \quad \text{green line} \\
\text{drag force} (1 \text{ micron particle}) & \quad \text{blue line}
\end{align*}
## 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 (1μm particle)**
- **Drag Force (0.1μm particle)**

**I = 7.75 W/cm²**

- Frequency (kHz)
- Boundary layer thickness (micron)
- Streaming Velocity (m/s)
- Drag Force (N)

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**Northeastern University**

**Microcontamination Research Lab**
**Ratio of Removal/Adhesion Moment (RM)**

- **RM:**

  $$RM = \frac{\text{Removal moment}}{\text{Adhesion resisting moment}}$$

  $$RM = \frac{F_d(1.399R-\delta)+F_{dl}\cdot a}{F_a\cdot a}$$

- 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/cm\(^2\), \( U_{ac} = 4 \text{m/s}, d_{ac} = 0.63 \text{um} \))
- Drag Force (Hydrodynamic Flow, \( U = 4 \text{ m/s}, d_h = 2750 \text{um} \))
- Double layer force
- Van der Waals Force, PSL/SiO\(_2\)
- Van der Waals Force, SiO\(_2\)/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 $\text{SiO}_2$, $\text{Si}_3\text{N}_4$, $\text{Al}_2\text{O}_3$, 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

SC-1, Electrical double layer force is repulsive force

- 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

Particles > 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

![Bar graph showing defects and cleaning conditions](image)
Key Results from Preliminary Research

- 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>100nm, acoustic flow drag force is dominated;
  - 30nm<d<100nm, drag force and electrical double layer force are on same level;
  - d<30nm, 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.