PHYSICAL CLEANING OF SUBMICRON TRENCHES AND VIAS

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OUTLINE

- Motivation
- Goals and Objectives
- Applications
  - Blanket Wafer Megasonic Cleaning
  - Rinse of Submicron Trenches by Parallel Oscillating Flow
  - Rinse of Submicron Trenches by Normal Oscillating Flow
- Key Preliminary Research Results
The International Technology Roadmap for Semiconductors (2000 update)

- Technology generation is changing every three years;
- Nano feature size requires submicron trench with high aspect-ratio.
Interconnect: Then and Now!!

1961
Aluminum Interconnect
4 Transistors, 1 Level Metal

After ~37 years
Copper Interconnect
40 Million Transistors, 6 Levels Metal

Increases in
chip functionality
chip performance

Need for
submicron multilevel interconnects

Need for
cleaning submicron high aspect-ratio trenches
## Surface Preparation Technology Requirements -- Long Term**

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<tbody>
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<td></td>
<td>TECHNOLOGY NODE</td>
<td>180nm</td>
<td>130nm</td>
<td>100nm</td>
<td>70nm</td>
<td>50nm</td>
<td>35nm</td>
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<td>FEOL Particle Size (nm)</td>
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<td>50</td>
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<td>FEOL Particles (#/cm$^2$)</td>
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<td>130</td>
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<td>70</td>
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<tr>
<td>BEOL Particles (#/cm$^2$)</td>
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<tr>
<td>Surface Roughness (nm)</td>
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<td>Critical surface metals ($*10^9$)</td>
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<td>7</td>
<td>4.4</td>
<td>2.5</td>
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<td>Organics ($*10^{13}$ atoms/cm$^2$)</td>
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<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 cleaning techniques for micro and nano scale trenches and vias with high aspect ratios.
- Use physical modeling to study the mechanism contaminant removal process in submicron deep trenches.
- Identify and control the key cleaning parameters for effective cleaning and high rinsing efficiency.
- Study the macro and micro features of the cleaning fluid interaction with a patterned wafer to identify the effect of cleaning fluid direction.
Approach

- Fundamental Approach
- Time-dependent analysis of the trench cleaning process to determine, understand and predict:
  - Cleaning Mechanism
  - Cleaning Efficiency, F\{AR, W, D, etc.\)
  - Cleaning tank Geometry (single, batch, etc.)
  - Optimum cleaning conditions
  - Technology limits with shrinking trench width
Approach

- **Fundamental Approach**
- **Key Trench Cleaning Parameters**
  - flow frequencies
  - velocity (pressure) amplitude
  - trench width
  - Trench aspect ratio
  - Trench shape or geometry
  - Cleaning liquid surface tension
  - Trench surface energy (hydrophilic or hydrophobic)
  - Flow direction with respect to the trench
  - Effect of Pressure amplitude on damage
Experimental and Modeling of Rinsing of Potassium Chloride Using Megasonic Rinse

- Incompressible, viscous, and laminar fluid.
- A megasonic beam is generated by an immersed transducer at the bottom of the tank.
- Realistic megasonic tank geometry.
- No overflow

Megasonic tank geometry
The Effect of Megasonic Rinse

- The agreement between experiment and simulation is good.
- The physical model and the modeling technique used is accurate enough to simulate acoustic streaming and mass transfer.
- The megasonic rinse flow dramatically reduces the rinsing time.

![Graph showing the effect of megasonic rinse on surface concentration over time](image)
Copper Removal by Dissolution

- first-order dissolution $k_1=2.7\times10^{-2}$/sec
- no redeposition

The numerical results fit well with the experimental results of TXRF measurements of Cu removal from Si(111) during immersion in room-temperature SC-1 solution.
Trench Geometry

Patterned Wafer
submicron multilevel interconnects

Channel

D

Cavity

W

Geometry
Numerical results are in excellent agreement with Perkins’ experimental results.

\[ t/T = n \quad t/T = n+0.6 \quad t/T = n+0.7 \quad t/T = n+0.9 \]

\( \text{Re}_s=42, \text{Re}_p=136, \text{St}=0.147 \)
The Enhancement of Mass Transport from Trench by Using Oscillating Flow

Ions Concentration vs. time, Aspect ratio = 5:1 & 1:1

- With same average velocity, oscillating flow rinse has higher efficiency than steady flow rinse.

- Deep trench (AR=5:1) cleaning is difficult than shallow trench (AR=1:1) cleaning.

$u_{\text{avg}} = 15 \text{ cm/s}, W = 1 \text{ mm}$
STEADY FLOW RINSE MECHANISM

- Steady flow induces a vortex (or more than one vortex for high aspect ratio trenches) inside the cavity.
- There is no convection between the vortex and the main flow.
- The transport of contaminant happens by diffusion only, which may take a long time depending on the trench size.
External oscillating flow stimulates the vortex destruction and regeneration.

Contaminants are dragged out of cavity by the expanded vortex.

The vortex oscillating mechanism significantly enhances the mixing.

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Physical Cleaning Of Submicron Trenches

Enhanced Mixing in Oscillating Flow Rinse

- Oscillating Rinse Flow:
  - $u_s = 0$ cm/s
  - $u_p = 47$ cm/s
  - $u_{avg} = 15$ cm/s
  - $f = 2000$ Hz

- Geometry:
  - $D/W = 5:1$
  - $W = 1$ mm $D = 5$ mm

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C-ion #/cm$^3$

- $1.5E+12$
- $1.4E+12$
- $1.2E+12$
- $1E+12$
- $8E+11$
- $6E+11$
- $4E+11$
- $2E+11$
- $1E+11$
- $1E+10$
- $1E+09$
- $1E+08$
- $1E+07$
- $1E+06$

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OSCILLATING FLOW RINSE MECHANISM

$t/T = 1.0$

$t/T = 1.5$

$t/T = 1.8$
How does the Frequency of Oscillating Rinse Flow Effect the Cleaning Efficiency?

Aspect Ratio = 5 : 1

Aspect Ratio = 1 : 1

Parallel Flow
- $AR = 5:1$, $D=5\text{mm}$, $W=1\text{mm}$
- $u_p = 47.1 \text{ cm/s}$, $u_{avg} = 15 \text{ cm/s}$

Steady Flow
- $f=20\text{Hz}$, $St=0.133$
- $f=200\text{Hz}$, $St=1.33$
- $f=2000\text{Hz}$, $St=13.3$
- $f= 20\text{kHz}$, $St=133.3$

$D=W=1\text{mm}$, $u_{avg}=15\text{cm/s}$
EFFECT OF STROUHAL NUMBER ON CLEANING EFFICIENCY

Strouhal Number:

\[ St = \frac{fW}{U_p} = \frac{\text{Oscillation}}{\text{Velocity}} \]
NO OPTIMUM STROUHAL NUMBER FOR SUBMICRON TRENCHES

Strouhal Number: \[ St = \frac{fL}{U_p} = \frac{\text{Oscillation}}{\text{Velocity}} \]

D=W=1 micron, \( u_{p,\text{avg}} = 15 \text{cm/s} \)

D=W=0.5 micron, \( u_{p,\text{avg}} = 15 \text{cm/s} \)

\begin{align*}
\text{D=W=1 um, } u_{p,\text{avg}} &= 15\text{cm/s} \\
\text{D=W=0.5um, } u_{p,\text{avg}} &= 15\text{cm/s} \\
\text{f=2000 KHz, } St &= 4.244 \\
\text{f= 800 KHz, } St &= 1.698 \\
\text{f= 200 KHz, } St &= 0.4244 \\
\text{f= 20 KHz, } St &= 0.0424 \\
\text{f= 2 KHz, } St &= 0.0042
\end{align*}
The Enhancement of Mass Transport from Trench by Using Oscillating Flow

Cleaning Efficiency: Normal flow >> Parallel flow
Oscillating flow >> Steady flow
A Relevant Experimental Verification
Copper Electroplating Using Acoustic Streaming

Filling of 0.3x1.0 µm trenches at 4 mA/cm²

with sonication off

Voids

with sonication on
(0.7MHz, 7.5 W/cm²)

Complete gap fill
Key Results from Preliminary Research

- Oscillating flow rinse is more efficient than steady flow rinse for both shallow (AR=1:1) and deep trenches (AR=5:1 or larger).

- When oscillating flow is used to clean trenches, the oscillating flow frequency, velocity and the size of the cavity have a major effect on the cleaning efficiency.

- Normal rinse flow shows orders of magnitudes higher cleaning efficiency than the parallel flow for both steady and oscillating flow rinse.

- For submicron trenches, higher frequency consistently gives higher cleaning efficiency. This is due to the very short diffusion time at that length scale.

- Complete gap fill in 0.3um trench copper electroplating by using acoustic streaming (0.7MHz) is due to the acoustic enhanced convection in submicron trench geometry.