PHYSICAL CLEANING OF SUBMICRON TRENCHES AND VIAS

Ahmed A. Busnaina
William Lincoln Smith Professor and Director of the Microcontamination Research Laboratory
Northeastern University, Boston, MA 02115-5000
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
- 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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<td></td>
<td>180nm</td>
<td>130nm</td>
<td>100nm</td>
<td>70nm</td>
<td>50nm</td>
<td>35nm</td>
<td>25nm</td>
<td>18nm</td>
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<td>FEOL Particle Size (nm)</td>
<td>90</td>
<td>82.5</td>
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<tr>
<td>FEOL Particles (#/cm²)</td>
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<td>BEOL Particles (#/cm²)</td>
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<tr>
<td>Surface Roughness (nm)</td>
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<td>0.1</td>
<td>0.08</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>
<td>--</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.
Copper Removal by Dissolution

- first-order dissolution 
  \( k_1 = 2.7 \times 10^{-2}/\text{sec} \)
- 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
Numerical results are in excellent agreement with Perkins’ experimental results.

\[
\begin{align*}
t/T &= n \\
t/T &= n + 0.6 \\
t/T &= n + 0.7 \\
t/T &= n + 0.9
\end{align*}
\]

(Re_s = 42, Re_p = 136, 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.
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.
Enhanced Mixing in Oscillating Flow Rinse

- 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.
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

[Graph showing the effect of frequency on cleaning efficiency for Aspect Ratio 5:1]

Aspect Ratio = 1 : 1

[Graph showing the effect of frequency on cleaning efficiency for Aspect Ratio 1:1]
EFFECT OF STROUHAL NUMBER ON CLEANING EFFICIENCY

Strouhal Number:

\[ St = \frac{fW}{U_p} = \frac{\text{Oscillation}}{\text{Velocity}} \]

AR = 1:1, D = 1 mm, W = 1 mm, Time = 1.0 s
AR = 1:1, D = 100 um, W = 100 um, Time = 0.1 s
AR = 5:1, D = 5 mm, W = 1 mm, Time = 1.0 s
AR = 5:1, D = 500 um, W = 100 um, Time = 0.1 s
NO OPTIMUM STROUHAL NUMBER FOR SUBMICRON TRENCHES

Strouhal Number: $St = \frac{fL}{U_p} = \frac{Oscillation}{Velocity}$

![Graphs showing ion in the bulk cavity vs. time for different frequencies and trench widths.]

- **D=W=1 micron, $u_{p,avg}=15$ cm/s**
  - $f=2000$ KHz, $St=4.244$
  - $f=800$ KHz, $St=1.698$
  - $f=200$ KHz, $St=0.4244$
  - $f=20$ KHz, $St=0.0424$
  - $f=2$ KHz, $St=0.0042$

- **D=W=0.5 micron, $u_{p,avg}=15$ cm/s**
  - $f=20$ KHz, $St=0.0212$
  - $f=200$ KHz, $St=0.212$
  - $f=2000$ KHz, $St=2.12$
The Enhancement of Mass Transport from Trench by Using Oscillating Flow

Cleaning Efficiency:

- Normal flow >> Parallel flow
- Oscillating flow >> Steady flow

Parameters:
- \( u_{avg} = 15 \text{ cm/s} \)
- \( AR=5:1, W=1\text{mm}, D=5\text{mm} \)

Legend:
- Parallel direction, Steady flow
- Parallel direction, Oscillating flow (20kHz)
- Normal direction, Steady flow
- Normal direction, Oscillating flow (20kHz)
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.