Cleaning Efficiency Improvement Solutions for FEOL CMP

Business of Cleans / SPCC Conference

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**CMP Mechanism and Cleaning Challenges**

- Three-body interaction: Wafer, Pad, Slurry
- Slurry: Complex suspensions containing abrasive particles, stabilizing agents and inhibitors
- Pad & abrasive remove inhibitor(a) from high pressure areas
- Remaining inhibitor(a) protects low areas.
- After polish layer cleared from stop layer, inhibitor(b) protects stop area and inhibitor(a) represses dishing of oxide in trenches
- Polishing by-products (chemical reactants, agglomerated slurry and pad/conditioner debris) are present on wafer after polish and needs to be removed during post-CMP cleans

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**Bulk Polish**

**Clearing and Overpolish**
Particle removal: interaction force between the particle and the substrate has to be eliminated by shear force:
- Fluid shear flow, Brush scrub, Megasonic cleaning, Fluid jet

Chemical etching is used to assist with breaking the particle-surface bond
- Undercut on the substrate and/or wet etch of the particle

After breaking the bond, the particle has to be removed away from the surface to prevent re-attachment
Post CMP Cleaning Trends

- What stays the same? Key Post CMP Clean Technologies

**Chemical Mechanical Buff with Soft Pad**
- Highest shear force Chemical Clean
  - Goal: High PRE
  - Break particle-surface bond

**Double Sided Brush Scrub**
- High shear force Chemical Clean
  - Goal: High PRE
  - Break particle-surface bond

**Non-Contact Cleans: Megasonic or Fluid Jet**
- Low shear force Chemical Clean
  - Goal: Low adder
  - No re-contamination

**Marangoni Dry**
- Surface tension gradient based drying
  - Goal: No adders
  - No watermarks

**Post CMP Wet Clean (SPM)**
- Aggressive Chemical Clean
  - Goal: Ce ion removal, Organics removal

Dehydration process:
\[ \text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2 \rightarrow \text{H}_2\text{SO}_5 \text{ (Caro's acid) + H}_2\text{O} \]

Formation of atomic oxygen
\[ \text{H}_2\text{SO}_4 + \text{H}_2\text{O}_2 \rightarrow \text{H}_3\text{O}^+ + \text{HSO}_4^- + \text{O} \]
Post CMP Cleaning Trends

- **What’s Different? Clean Technologies’ Implementation**
  - Decrease in the critical particle size drives more stringent cleaning efficiency requirements
    - Wide adoption of Chemical Mechanical Buff
      - “Easy to clean” applications now require cleaning efficiency improvements
      - PreClean™ initially adopted for FEOL; adopted in HVM for BEOL in 2018; great interested for WMG in 2019
    - Advanced metrology techniques
  - Novel Cleaning Chemistries drive HW compatibility specifications
  - Post CMP Wet Clean elimination: SPM replacement
  - Custom approaches and system flexibility requirements
    - Multiply films exposed require optimized module sequence and recipe structure
    - Tool box of Cleaning Options, which can be easily used based on specific applications and issues
Particle Removal

- **Adhesion moment**
  - Function of adhesion force (van der Waals), particle geometry
  - Proportional to particle radius

- **Removal Moment:**
  - Function of shear force, double layer interactions, particle geometry
  - Proportional to square of particle radius

\[ MR = \frac{\text{Removal (Drag) Moment}}{\text{Adhesion Moment}} \]

For \( MR > 1 \), a certain % of particles can be removed

Smaller particles are more difficult to remove
Cleaning Efficiency Comparison on “Easy to Remove” Particles for Individual Cleaner Modules

Cleaning Efficiency = \( \frac{(\text{Pre} - \text{Post})}{\text{Pre}} \)

All modules run with < 2.0 wt% NH₄OH

Challenge wafers: Spin-on SiN particles on TEOS film

Contact Clean methods demonstrate high particle removal efficiency
Brush shear force is sufficient to remove >99% of the particles
Cleaning Efficiency Comparison on Post CMP Defects

Brush shear force is NOT sufficient to remove strongly attached particles
Adding Chemical Mechanical buff in PreClean module improves defects >100X
Adding Megasonic tank clean does not improve defects

Polisher: Asahi Ce slurry / VP50xx pad / PreClean: Acidic Clean Chemistry / BKM pad / Meg:DIW, BB1:acidic clean, BB2:DIW
Why Non-Contact Clean is Needed?

Brushes scrubbing removes but also adds particles

Source of adders: Loose particles suspended in liquid boundary layer on wafer surface

Non-Contact Clean after brush scrub reduces adders by 50%

Non-Contact Clean benefits:
- When used before contact clean, Non-Contact Clean prevents media loading
- When used after the brush, Non-Contact Clean reduces re-contamination from brush

**Post = Pre - Removed + Added**

- **Pre = 3459**
- **Post = 453**
- **Removed = 3129**
- **Added = 121**

**Oneway Anova**

<table>
<thead>
<tr>
<th>Level</th>
<th>Number</th>
<th>Mean</th>
<th>Std Error</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1/SC1 Dryer</td>
<td>33</td>
<td>102.727</td>
<td>11.858</td>
<td>78.814</td>
<td>126.64</td>
</tr>
<tr>
<td>FinalClean/SC1</td>
<td>12</td>
<td>48.583</td>
<td>19.604</td>
<td>8.928</td>
<td>88.24</td>
</tr>
</tbody>
</table>
Ce Slurry Cleaning Challenge

- Ceria abrasive have significant surface chemical action during SiO₂ film polish

Slurry particle contamination remains high after conventional Brush Scrub

Nano-Particles (<50nm size) cause patterning issues at subsequent level (shorts, opens)
Advanced Metrology Techniques Needed to Detect Nano-Ceria

- ICP-MS Ce detection is a sensitive method to quantify Ce particle contamination below the SP5/SP7 sensitivity limits

- VPD ICP-MS analysis is a 3-step process:
  - Decomposition of oxide layer using HF vapor:
    - $\text{SiO}_2 + 6\text{HF} \rightarrow \text{H}_2\text{SiF}_6 + 2\text{H}_2\text{O}$
    - $\text{H}_2\text{SiF}_6 \rightarrow \text{SiF}_4 + 2\text{HF}$
  - Trace metals in oxide layer form water soluble fluorides; these are collected by scanning process
    - $\text{Fe}_2\text{O}_3 + 6\text{HF} \rightarrow 2\text{FeF}_3 + 3\text{H}_2\text{O}$
    - Cerium fluorides has poor flexibility. Specialty acid blend is used to ensure complete collection of Ce-containing compounds
  - Post scanning, VPD droplet is collected and analyzed by ICP-MS

Combination of laser scattering techniques (SP5/SP7) and ICP-MS is used for Ce Cleans development
### Integrated Ceria Cleaning Solution

- Applied Materials is developing an integrated (within CMP cleaner) ceria cleaning solution *to eliminate post-CMP wet cleaning*

### Comparison

<table>
<thead>
<tr>
<th>Challenges of Current Industry POR (post CMP wet clean process)</th>
<th>Benefits of Integrated non-SPM/non-HF Ceria Cleaning Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>• SPM long <strong>process time:</strong> ~3min/wafer -&gt; ~20wph/chamber -&gt; 240wph/system (12 chambers/system)</td>
<td>• Eliminates need for post-CMP wet clean: cycle time, fab space &amp; SPM/HF CoC</td>
</tr>
<tr>
<td>• Additional <strong>integration step</strong> required longer <strong>cycle time &amp; fab floor space</strong></td>
<td>• Avoids additional handling and facilities requirements of SPM for CMP systems</td>
</tr>
<tr>
<td>• <strong>Hazard / Toxic</strong> of hot SPM/HF required additional <strong>handling &amp; facilities requirements</strong></td>
<td></td>
</tr>
<tr>
<td>• <strong>Cost of Hot SPM Usage</strong> SPM CoC = raw material + waste treatment + handling within the fab</td>
<td></td>
</tr>
</tbody>
</table>

**Applied is focused on an Integrated non-SPM/non-HF Ceria Cleaning Solution**
Non-HF Solution is Needed to Replace SPM Cleans

HF is a poor choice for post CMP ceria removal

~70A TOX removal is needed to reduce Ce concentration to <1E9 atoms/cm² with HF scrub
Ce Slurry Cleaning Challenge for High Oxide Removal CMP

Post CMP Piranha Clean can dissolve Ceria particles

Piranha Wet bench

AMAT approach: replace chemical reaction with chemically assisted high shear force cleaning

\[ MR = \frac{\text{Removal(Drag) Moment}}{\text{Adhesion Moment}} \]

For \( MR > 1 \), a certain % of particles can be removed

\[ F_D \] – The Drag force
\[ F_A \] – the Adhesion force
\[ F_L \] – the Lift force
\[ F_t \] – the tangential friction

Liquid Flow field

**Chemical Reaction:**

\[
2 \text{Ce} O_2 + H_2 O_2 + 3 H_2 SO_4 \rightarrow \text{Ce}_2 (SO_4)_3 + O_2 + 4H_2O
\]

Peroxide acts as a reducer in an acidic media and as an oxidizer in a basic media. In SPM, ceria is reduced by peroxide.

**Graphical Representation:**

- \( F_U(z) \) – Substrate
- Substrate:
  - \( F_D \) – The Drag force
  - \( F_A \) – the Adhesion force
  - \( F_L \) – the Lift force
  - \( F_t \) – the tangential friction

**Equation:**

\[ MR = \frac{\text{Removal(Drag) Moment}}{\text{Adhesion Moment}} \]
## Integrated Ceria Cleaning Solution

<table>
<thead>
<tr>
<th>Split</th>
<th>Brief conditions</th>
<th>SP5 @45nm</th>
<th>Ceria Particles (defect review/classification)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4 (No Buff)</td>
<td>Polish &amp; Brush Box w/ Range of Cleaning Chemistries</td>
<td>20,000 to 50,000</td>
<td>&gt;200 (est.)</td>
<td>Chemistries can help, but not sufficient</td>
</tr>
<tr>
<td>5</td>
<td>Polish w/ Platen Buff w/ Chem Y</td>
<td>180 to 280</td>
<td>Did not measure</td>
<td>High PRE Buff makes significant improvement</td>
</tr>
<tr>
<td>6</td>
<td>Polish w/ PreClean w/ Chem Y</td>
<td>215</td>
<td>4</td>
<td>PreClean Shows Similar Performance to Platen Buff</td>
</tr>
<tr>
<td>7</td>
<td>Polish w/ PreClean w/ Chem X</td>
<td>127</td>
<td>None Found</td>
<td>Chemistries in PreClean can impact performance</td>
</tr>
</tbody>
</table>

**Notes:**
1. 4 (No Buff) Polish & Brush Box w/ Range of Cleaning Chemistries
2. 5 Polish w/ Platen Buff w/ Chem Y
3. 6 Polish w/ PreClean w/ Chem Y
4. 7 Polish w/ PreClean w/ Chem X

**Diagram:**
- Chemical Buff Significantly Improves Defects
- Split 6 Previous BKM PreClean w/ Chem Y
- Split 7 CnF PreClean w/ Chem X

**Legend:**
- Co Particles
- Other Particles

**Additional Information:**
- Versum STI24xx / Nexplanar 60YY Polish
Non-SPM Clean Performance

- **Ce Ion Concentration by VPD ICP-MS**

  - **Target:** <1E9 atoms/cm² surface Ce

  - **Graph:**
    - Split 7: New Approach PreClean + Chem X
    - Split 6: Previous BKM PreClean + Chem Y

- **Defects by SP5**

  - **Means and Std Deviations**
    | Level               | Number | Mean   | Std Dev  | Std Err Mean | Lower 95% | Upper 95% |
    |--------------------|--------|--------|----------|--------------|-----------|-----------|
    | Split 7: New Approach PreClean + Chem X | 3      | 0.9933 | 0.090185 | 0.05207     | 0.7693    | 1.2174    |
    | Split 6: Previous BKM PreClean + Chem Y | 4      | 1.4350 | 0.235867 | 0.11793     | 1.0597    | 1.8103    |

**Key Points:**

- **10-15X improvement in Ce ion surface concentration with new approach**
- **50% improvement in defect performance on TEOS**
Addressing Post CMP Cleaning Challenges in LK Prime™ System

- Cleaner: 5x Side-by-Side Cleaner Stations
  - Megasonics
    - Provides physical force to remove contamination form the features
    - Provides full wafer immersion tank for bevel contamination removal
  - PreClean
    - Provides means to perform chemical buff in a dedicated slurry-free module
    - Vertical buff enables effective contamination removal off the surface
    - Enable cleaning of top surface of the wafer bevel
  - Two consecutive brush boxes provide high particle removal efficiency and precise brush pressure control
  - Vapor Dryer provides defect-free drying of hydrophilic, hydrophobic and mixed surfaces
  - Cleaner Chemical Flexibility enables particle undercut and lift-off
    - HF-compatible brush box enables SiO₂ substrate etching
    - Proprietary chemicals often include particle etch capability
# AMAT CMP Defect Improvement Tool Box

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<tr>
<th>Module</th>
<th>Feature</th>
<th>Benefit</th>
<th>Mechanism</th>
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<tr>
<td>HCLU</td>
<td>Chemical Rinse during polish to clean transition</td>
<td>Improved defectivity for Poly / Si CMP</td>
<td>Improved wetting on hydrophobic films (Poly, BDIII)</td>
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<td>PreClean</td>
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**Ready to Engage to Develop/Optimize a BKM for Customers (i.e., your wafers and consumables)**
Chemical Rinse in HCLU: Poly CMP

Objective:
- Convert Hydrophobic poly surface to Hydrophilic as soon as possible after polish step to prevent strong bonding of residues onto surface

Strategy:
- Rinse wafer surface in HCLU with surfactant-containing cleaning chemistry

<table>
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<tr>
<th>Process</th>
<th>SP2 Maps</th>
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<th>Ave. Counts@80nm</th>
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<tr>
<td>Polish_1psi 60s HCLU 10s Chemical Rinse PreC Buff_MegB1B2</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
<td>164</td>
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<td>Polish_1psi 60s HCLU 10s DIW Rinse PreC Buff_MegB1B2</td>
<td>![Image]</td>
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<td>1654</td>
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About 10X improvement in defects from adding chemical rinse in HCLU was observed

Polish: Silica slurry polish / HCLU: acidic cleaning solution / PreClean: acidic cleaning solution
PreClean Module for Chemical Mechanical Buff

Challenge:

- Nano-Particles (<50nm size) cause patterning issues at subsequent level (shorts, opens)
- Buffing in polisher impacts TPUT

Approach:

- Move chemical buffing from polisher to cleaner
- Vertically orient to leverage one-pass chemical usage and avoid particle re-attachment and scratching

Applied’s Solution:

- Soft Pad Chemical Buff in the Cleaner

Chemical Mechanical Buff with optimized chemistry is needed for FEOL CMP
Brush Box Spray Bar CIP
Chemical Coverage Uniformity Improvement

Problem Statement
- Chemical etch (coverage) non-uniformity with brush-closed process due to brush and chemical spray interferences

Solution
- Optimized shower style spray bar

TOX Removal with Brush-Closed Process

Shower style HVM spray bar improves range by 3X
Released for LK Prime™ and LK3.0
Ozonated Water Clean for Oxide and Poly Polish Organics Reduction

Objective:
► Remove organic contamination with Ozonated Water Clean

Strategy:
► Implement DIO₃ rinse in Brush Box (BB1 or BB2)
► Supply DIO₃ through DIW rinse spray bars
► Reduce O₃ concentration to <10 ppm for brush compatibility
► Remove brushes to eliminate interactions with DIO₃ if higher O₃ concentration is needed

Status:
► Implemented in Si CMP BKM: NH₄OH + HF/DIO3
► Released for LK Prime™

Defect reduction with DIO₃ is due to reduction in surface Carbon and Si surface conversion

3x improvement observed with DIO₃
SteadyClean: Advanced Brush Torque Control

Challenge:
► For small brush gap compression processes (<0.5mm), variations in roller brushes & mechanical setup lead to unstable particle cleaning and/or short brush lifetimes.

Approach:
► Maintain consistent brush shear force on wafer surface by dynamically changing brush spacing to keep brush motor torque consistent

Benefit:
► Consistent brush PRE for stable particle defect performance and longer brush lifetimes.

Control Shear Force for Consistent Roller Brush PRE
**Vapor Dry 1.5**

- **Objective:**
  - High speed vapor drying process to support short polish times
  - More robust Drying

- **Strategy:**
  - Optimized spray bar position and angle as well as N2-IPA flow
  - Modified angle, height and spacing of spray bars to front and back

- **Status:**
  - 29 sec BKM with new bars equivalent to 52 sec BKM with old bars
  - Available on LK and LK Prime™

### Inputs
- Angle
- Height
- Distance
- N₂/IPA flow rate

### Outputs
- Defects
- Wetness
- Touch-point

Optimized IPA spray bar (VD1.5) enables high speed dry on hydrophilic substrates.
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Ready to Engage to Develop/Optimize a BKM for Customers (i.e., your wafers and consumables)
Summary

- Geometry shrinking and new material implementation in advanced nodes demand the achievement of high particle removal efficiency
- To address cleaning challenges in various nodes, Applied CMP Clean technology continues to evolve and includes broad portfolio of cleaning techniques
  - Optimized post polish rinse
  - High shear force PreClean module for high particle removal efficiency
  - Single wafer Megasonic module for improving defect removal efficiency
  - HF-compatible dual brush box module with
    - Improved chemical coverage uniformity
    - SteadyClean Brush Torque (Shear Force) Control for Consistent Roller Brush PRE
    - Ozonated Water Rinse for Organic Defect Reduction
    - BB2.0 Brush Conditioning for Extended Brush Life
  - Single wafer IPA dryer for achieving water-mark free drying at high speed (with VD1.5 option)

Optimized Solutions Require the Right Approach (Process Modules) and the Right Process (Process Engineers/Applied)