Characteristics of Spatial Endpoint Uniformity of CMP for Reduced Consumables and Improved Yield

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Task A4-2:
Sensors and Control for CMP Waste Reduction

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Impact of Sensors and Controls for CMP

Manufacturing Metrics:

- Single CMP tools now run around 63% of capacity (40 wafers/hour) where 2-3 hours of an 8 hour shift are spent performing metrology to achieve better endpoint and uniformity.

- Availability of in-situ sensors and controls may: increase production by 40-60%, eliminate 1-2 test wafers per hour (5-6K wafers per year, per machine), eliminate 3-4 reworked wafers per hour (9K per year),

- Single CMP tool may consume $275,000 of slurry per year [1] and produce 27,500 gallons of waste slurry that requires treatment & resources.

- CMP tools now account for 30% to 40% of total water consumed by fabs [2].

- reduce processing times and effectively reduce slurry and water by at least 10-15%.

ESH Metrics:

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<tr>
<th>Goals / Possibilities</th>
<th>Usage Reduction</th>
<th>Emission Reduction</th>
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<tbody>
<tr>
<td></td>
<td>Energy</td>
<td>Water</td>
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<td>In-situ sensors and controls for CMP</td>
<td>10 -15%</td>
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<td>Chemicals</td>
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<td>&gt; 15% reduction in slurry</td>
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<td>PFCs</td>
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<td>Other Hazardous Wastes</td>
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<td>&gt; 15% reduction in pads</td>
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Example: CMP Sequence Capture with IR Camera

- Examining Factors in Wafer-level Uniformity
- Developing In-situ Spatial Endpoint Detection
- Results:
  - Gathered data from Cu polish experimental designs
  - Correlated radial dependence of oxide removal rate with IR images
  - IR thermography not suitable in-situ, spatial endpoint detection
  - IR thermography does provide visibility into CMP and is suitable for developing thermal models.
  - Examined new in-situ reflectance based sensor that measures spatial endpoint

Acknowledgements: Kai Yang and Darrel Erb at AMD Submicron Development Center and Jian-Yu Lai, Jason Melvin and Prof. Chun at MIT

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Spatial Variation in Wafer Level Removal Rate and Endpoint Non-Uniformity

- Clearing may occur from outside to inside
- Endpoint non-uniformity increases dishing and erosion
- Lack of spatial endpoint information often results in the re-work of wafers to remove remaining material
Why Does Material Removal Vary with Radial Position?

Temperature along \((q)\) and removal rate at \((r)\) are related spatially through the relative velocities and force between the pad & wafer.

Relationship can be observed in comparing Preston’s removal rate \(R(r)\) equation with that for the change in temp. due to polish (at bottom).

\[
R(r) = -k_p \cdot (F_N(r) / A) \cdot V(r)
\]

Changes in temperature \(\Delta T\) measured spatially across the pad are effected by:

- Differences in Force Across Wafer
- Differences in Relative Velocities
- Changes in the coefficient of friction when transitioning from one material to another (at endpoint).

\[
\Delta T(q) \propto (\Delta E = P(r, q) \cdot \Delta t = c_f \cdot (F_N(r)) \cdot V(r, q) \cdot \Delta t)
\]

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Spatial Mapping Between Pad and Wafer Positions

- Measured pad positions map to sets of intersecting wafer radii.
- Contributions of each wafer radius to measure pad position depend upon spatial uniformity (e.g. relative velocities or force).
Goal of Sensor Development: **Controlling Uniformity**

Oxide Thickness (angstroms)

Polish time: 20 sec.

Polish time: 60 sec.

Polish time: 180 sec.

Spatial position across wafer

radius (r)

Spatial removal rate sensors enable controls

Carrier head allows for differential pressures in four zones to improve uniformity

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Two Approaches to Measure Spatial Endpoint and Removal Rate

**IR Thermography**

- **Pros:**
  - Not dependent upon material properties
  - Can be used with almost any CMP machine

- **Cons:**
  - Signal to noise highly dependent upon slurry transport and available viewing position on pad
  - Cost of sensor high but steadily decreasing

**Fiber Optic Reflectance**

- **Pros:**
  - Spatial resolution, signal-to-noise is fantastic
  - Low cost sensor

- **Cons:**
  - Limited to copper wafers
  - Installation may be limited to particular equipment
  - Special pads with fitted windows are used
8-inch Copper CMP Experiments at MIT

- MIT dual platen CMP tool (right)

- Illustrations of how optical reflectance and IR thermography are used during copper polish (below)

Acknowledgements: Prof. Jung-Hoon Chun and Jason Melvin in MIT Mechanical Engineering Dept.
MIT 8-inch Copper Experiments:  
*Partial Clearing Case*

- Experimental Conditions for 8-inch Copper Polish:
  - Matched table and carrier velocities: 60 rpm
  - Pressure: 6 psi
  - Slurry flow rate: 250 ml/min
  - Duration: 250s

- Resulting in a partially cleared wafer:
In-situ Reflectance Sensor for Copper

Measures spatial thickness of copper on wafer through a window in pad

Acknowledgements: Prof. Jung-Hoon Chun and Jason Melvin in MIT Mechanical Engineering Dept.
Principal component analysis (PCA): How does it work?

- PCA uses eigenfunction decomposition to maximize the information content of a given data set.
- Correlations captured by PCA may not necessarily be the desired correlations – resulting in much cause-effect related analysis.

1. Raw Measured Data (the outcome of each experiment is a datapoint)

   $X = [x_1, x_2]$

2. Mean-center $X$ to matrix $M$ (subtract the mean of each channel)

   $M = [x_1 - E(x_1) \quad x_2 - E(x_2)]$

3. Eigenfunction Decomposition of Covariance Matrix

4. Rotate to New Coordinates:

   $z_1 = MV_1$
   $z_2 = MV_2$

Transform to New Basis
PCA Based IR Thermography Measurements and Comparison with Reflectance Sensor

IR Thermography Results:
• Most significant variation occurs in center of wafer occurs from 125 to 177 sec.
• Coincidence or correlation with pad variation?
• Resembles score for PCA #3, both seeing global endpoint?
• Results inconclusive, until better S/N can be achieved

Reflectance Measurements

IR Camera Measurements (PCA #1)

Corresponds with center region of wafer

Most significant variation in center 0-25 mm ring

Most significant variation in pad positions corresponding to center of wafer

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PCA Based IR Camera Measurements and Comparison with Reflectance Sensor

IR Thermography Results:
- Most significant variation occurs in center of wafer occurs from 140 to 180 sec.
- Coincidence or correlation with pad variation?
- Resembles score for PCA #1, both seeing global endpoint?
- Results inconclusive, until better S/N can be achieved

Reflectance Measurements

IR Camera Measurements (PCA #3)

Corresponds with outer region of wafer

Loading for PCA #3

Score for PCA #3

Most significant variation in pad positions corresponding to outer regions of wafer

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MIT 8-inch Copper Experiments: *Complete Clearing Case*

- Experimental Conditions for 8-inch Copper Polish:
  - Matched table and carrier velocities: 60 rpm
  - Pressure: 6 psi
  - Slurry flow rate: 250 ml/min
  - Duration: 350s

- Resulting in a fully cleared wafer:
In-situ Reflectance Sensor for Copper
Measures spatial thickness of copper on wafer through a window in pad

Acknowledgements: Prof. Jung-Hoon Chun and Jason Melvin in MIT Mechanical Engineering Dept.

Polish time: 35 sec.
Polish time: 258 sec.
Polish time: 300 sec.
PCA Based IR Thermography Measurements and Comparison with Reflectance Sensor

IR Thermography Results:

- Most significant variation in 25-75mm region occurs from 260 to 300 secs.
- Coincidence or correlation with pad score variation?
- Resembles score for PCA #3, both seeing global endpoint?
- Results inconclusive, until better S/N can be achieved

Reflectance Measurements

IR Camera Measurements (PCA #1)

Corresponds with 25-75 mm region of wafer

Most significant variation in pad positions corresponding to 25-75 mm of wafer

Most significant variation in the 25-75 mm ring

Red = 0 to 25mm
Green = 25mm to 50mm
Blue = 50mm to 75mm
Magenta = 75mm to 100mm

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**Thermal Modeling of CMP**

- **Hypothesis:** Most the thermal energy associated with polish is transferred via heat through pad and slurry
- **Approach:**
  - Energy balance formulation
  - Experimental verification
  - Model of thermal dynamic behavior

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### Energy In

- Approx. power
- \( \approx 300 \text{ W} \)
- Chemical Energy
- \( \approx 20 \text{ mW} \)
- Chemical Energy

### Energy Out

- Initial Condition: at room temp 21 deg. C
- Mechanical Energy
- Conduction into Head \( \approx 0 \text{ W} \)
- Convection via Slurry Flow \( \approx 260 \text{ W} \)
- Conduction thru Table \( \approx 41 \text{ W} \)
- Radiation to Environment \( \approx 0.4 \text{ mW} \)

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Pad Heating is a Dynamic Process

• Each pad position experiences heating and cooling cycle

Position:
• Pad begins polish against wafer
• Pad leaves contact with wafer
• Pad begins to cool under flow of slurry
• Pad continues to cool
• Pad concludes cooling cycle

Thermal Cycle for One Pad Revolution
Pad Heat Dynamics: HSPICE Model and Simulation

- Heat dynamics modeled and simulated using HSPICE
- \( q_f \) is the heat flow created during contact with wafer during polish
- \( R_1 \) is resistance presented by the pad (and some slurry contained in pores)
- \( R_s \) is resistance presented by slurry flowing over the pad
- \( C_t \) is thermal capacitance associated with energy stored within the pad

**HSPICE Circuit Representation**

- \( q_f \) heat generated during polish
- \( T_{pad} \) pad temp
- Switch:  A | B
- Heat Current Source vs. Time
- \( T_{room} \) room temperature

**graphs**
- \( q_f \): heat generated during polish
- \( T_{pad} \): pad temp

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HSPICE Simulation vs. Experimental Pad Temperatures

- Top plot:
  HSPICE simulation predicted pad temperature

- Bottom plot:
  Experimentally measured temp (in red)
  Fitted step response with time constant, 19.3s (in blue)
Conclusions

• Advances in in-situ sensors for CMP will have significant environmental and economic impact on processing

• Spatial endpoint is shown using optical reflectance sensor and will be used to demonstrate run-by-run uniformity control this summer

• Spatial endpoint is theoretically possible using IR thermography but requires improvement in signal-to-noise to be useful

• IR thermography may be useful for providing greater visibility into the CMP polishing fundamentals and pad conditioning effects

• Dynamic thermal model for CMP is simulated and validated against experimental data
Appendix – Extra slides for Q&A

• What is the IR camera measuring?
• Results from prior AMD experiments (~1998)
What is the IR Camera Measuring?

Question:
• Does the IR camera measure heat in the pad or from flow of slurry?

Experiments:
• Sequences indicate slurry under head heats to 32 °C and flows over the pad which is at 38 °C
• Changes in measured temp. on order of 0.1 seconds is due to slurry
Results of IR Based Copper Endpoint at AMD

- Experiments conducted with AMD to examine copper endpoint detection
- Endpoint detected spatially at various stages of clearing (shown below)
- T-squared endpoint signal shown to provide a global estimate of clearing

**Case 1: Polish stopped during clearing**

- During post-polish inspection an outer ring approx. 1-2 inches had cleared

**Case 2: Polish through endpoint into the barrier layer**

- Complete clearing of copper

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PCA Applied to AMD Thermal Measurements

- Note that PCA seems to capture variation on areas of the pad associated with outer regions of the wafer during the partial clear.
- Overall, the measured signals did not provide sufficient signal-to-noise and repeatability to be used as an in-situ spatial endpoint sensor.
- Further analysis required.

Case 1: Polish stopped during clearing

![Diagram showing wafer with copper outer ring cleared down to barrier metal.](image)