Framework for Modeling of Pattern Dependencies in Multi-Step Cu CMP Processes

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Motivation: Pattern Dependent Problems in Cu CMP

Cu Dishing and Oxide Erosion lead to:
- Higher line resistance.
- Surface Non-Uniformity
- Possible shorting of adjacent lines on higher metal levels.

GOALS:
- Identify the key layout dependencies of dishing and erosion.
- Predict the amount of dishing and erosion for any layout, for a given polish process.
- Design around dishing and erosion.
- Minimize dishing and erosion.
Outline

■ Model Formulation
  ❏ Modeling Approach
  ❏ The Three Intrinsic Stages in Cu CMP
  ❏ Model Parameters

■ Model Calibration
  ❏ Calibration Mask Set
  ❏ Calibration Methodology

■ A Typical Cu CMP Process

■ Summary
Modeling Approach

- Identify the **intrinsic stages** in Cu CMP.
- Construct **Removal-Rate Diagrams (RR-diagrams)** for each intrinsic stage.
- Formulate the **model equations** from the RR-diagrams.
- Develop a methodology for calibrating the model i.e. extracting model parameters (unknowns) for a given process.
The Three Intrinsic Stages in Cu CMP

Stage 1: Bulk copper removal

Stage 2: Barrier removal

Stage 3: Overpolish

Overpolish occurs due to:
- Recess caused by electroplating.
- Non-uniform removal rate across the wafer.
- Non-uniform pattern within a die (pattern meaning pattern density, line width and line space).

Oxide Erosion
Cu Dishing
Stage 1: Removal of Overburden Cu

- **Time Phases:**
  - $t_a < t_b < t_c$

- **Removal Rate Equation:**
  \[ \frac{K_{Cu}}{1 - \rho_{Cu}} \]

- **Step Heights:**
  - $H_{ex}$: Local step height above which the pad does not contact the down area.
  - $H_I$:

- **Processes:**
  - **Cu up-area**
  - **Cu down-area**
**Stage 3: Overpolish**

- \( D_{ss} \) is steady-state Cu dishing.
- \( d_{\text{max}} \) is maximum Cu dishing.
- \( \Psi_s \) is the edge rounding factor.

\[
K_{Cu} = \frac{\Psi_s K_{ox}}{1 - \rho_{Cu}}
\]

- \( \rho_{Cu} \) is the removal rate.

**Dishing Height**

- \( d_{\text{max}} \) is the maximum dishing height.
- \( D_{ss} \) is the steady-state dishing height.

**Cu Removal Rate**

- \( K_{Cu} \) is the Cu removal rate.
- \( K_{ox} \) is the oxide removal rate.

**Oxide Erosion**

- \( \Delta t \) is the time difference.

- \( t_a \) is the start time.
- \( t_b \) is the steady-state time.

- \( \text{No dishing and erosion} \) when \( t_a < t_b \)

- \( \text{Cu Dishing} \) when \( t_a < t_b \)

- \( \text{Cu Dishing} \) when \( t_a < t_b \)

- \( \text{More Cu Dishing} \) when \( t_b + \Delta t > \text{steady-state time} \)
Model Parameters

- The model parameters are:
  - $K_{\text{ox}}$, $K_{\text{Cu}}$, $K_b$: These are blanket removal rates.
  - $d_{\text{max}}$, $H_{\text{ex}}$, $\Psi_s$: These are the pattern dependent parameters.
  - Planarization Length: It depends on the polish process parameters.

$\Psi_s$ is a function of line space and polish process parameters.

- $d_{\text{max}}$ is an increasing function of line width.
Model Parameters

\[ d_{\text{max}} = f(\theta_p, l_w, l_s) \]  \hspace{1cm} (Eq. 1)

OR

\[ d_{\text{max}} = g(\theta_p, l_w, \rho_{Cu}) \]  \hspace{1cm} (Eq. 2)

\[ H_{ex} = u(\beta_p, l_w, l_s) \]  \hspace{1cm} (Eq. 3)

OR

\[ H_{ex} = v(\beta_p, l_w, \rho_{Cu}) \]  \hspace{1cm} (Eq. 4)

\[ \Psi_s = w(\alpha_p, l_s) \]  \hspace{1cm} (Eq. 5)
Outline

Part 1

- Formulation of Mathematical Model
  - Modeling Approach
  - The Three Intrinsic Stages in Cu CMP
  - Model Parameters

✔ Model Calibration
  - Calibration Mask Set.
  - Calibration Methodology.

- A Typical Cu CMP Process

- Summary
Calibration Mask Set

- Wide range of pitch and density structures on M1.
- Electrical (resistance) test structures.
- Multi-level effects of M1 on M2.
Calibration Methodology

**PART 1**

- Measured dishing and Erosion
- Layout details
- Process details: $K_{ox}$, $K_{Cu}$, $K_b$, etc.

**PART 2**

- Estimate $t_2$ subject to the given constraints.

**PART 3**

- Estimate $H_{ex}$ subject to the given constraints.

Initial guess $PL, d_{max}, d_0, t_3$ and $\Psi_s$

Are the dishing and erosion errors minimized?

Yes

Output: $PL, d_{max}, d_0, t_3$ and $\Psi_s$

No

Modify the initial guesses of $PL_3, d_{max}, d_0, t_3$, and $\Psi_s$
A Typical Cu CMP Process: 2 Step Polish Process

**POLISH STEP 1**
- Slurry 1
- Down Force 1
- Table Speed 1
- Pad 1

\[ K_{Cu(1)} > K_{b(1)} > K_{ox(1)} \]

**POLISH STEP 2**
- Slurry 2
- Down Force 2
- Table Speed 2
- Pad 2

\[ K_{Cu(2)} < K_{b(2)} < K_{ox(2)} \]

At the end point time, we might have the following extreme scenarios:

**High Cu density structure:**
- Overpolish Stage.
- Dishing and Erosion present.

**Low Cu density structure:**
- Barrier Removal Stage.
- No dishing and erosion.
For the high Cu density structure, we have the following scenario:

- Dishing = d₁
- Erosion greater than zero.

- Dishing = d₂ (d₂ < d₁).
- Increased Erosion.
A Two Step Polish Process (cont).

For the low Cu density structure, we have the following scenario:

Zero pre-dishing; Barrier not yet cleared.

Dishing = -d_2; Barrier has just being cleared.
Summary

■ Model for pattern dependencies in copper CMP developed.
  □ Model captures three intrinsic stages of Cu CMP processes.
  □ Model exploits the dependence of removal rate on local step-height.
  □ Preliminary results show that the model explains the pattern and time trends observed in experimental data.

■ Model parameter extraction methodology proposed.

■ Framework for extending the model to multi-step polish process proposed.

■ Future work: Relating the model parameters to the polish process parameters like down force, table speed, pad elasticity, etc.

■ Our ultimate goals include:
  □ Prediction of oxide (or more generally dielectric) thicknesses and Cu thicknesses across an entire chip (after CMP), for a given process.
  □ Designing around dishing and erosion.
  □ Minimizing dishing and erosion.