Development of an Integrated Model for Chemical-Mechanical Planarization (CMP)

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Content

• Background on CMP research at Berkeley
• Modeling work and roadmap
• A Comprehensive Material Removal Model
• Experimental Validation
• Conclusions & Future Work

Acknowledgements

Researchers: Serdar Aksu, Uday Ayyagari, Andrew Chang, Edward Hwang, Sunghoon Lee, Jianfeng Luo, Zhoujie Mao

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Major Thrusts of Research at Berkeley

• Integrated model of CMP ✔
  • mechanical elements (abrasive size, shape, dist’n, pad characteristics- hardness and roughness, pressure, velocity, etc.)
  • chemical elements integration
  • validation/software “packaging” for CAD
• AE-based process feedback and optimization
• Consumable/surface design ✔
• Metrology (scatterometry) for profile development
• Environmental modeling
Polishing and CMP

Lapping process
- Workpiece
- Lapping plate
- Abrasive particle (10-150µm)
- Abrasive slurry
- Soda lime glass surface by lapping

CMP process
- Workpiece
- Polishing plate
- Polishing pad
- Abrasive particle (less than 0.1µm)
- Silicon wafer surface by CMP

100µm
Characteristics of slurry film thickness

- Wafer
- Slurry
- Polishing pad

Direct contact

Semi-direct contact

Hydroplane sliding

Friction coefficient

Hersey number ($= \frac{\text{Viscosity} \cdot \text{Velocity}}{\text{Pressure}}$)

Striebeck curve

Direct contact

Semi-direct contact

Hydroplane sliding

Elasto-hydrodynamic lubrication

Hydrodynamic lubrication

Film thickness
Mechanical and Chemical Material Removal Effects vs Slurry Film Thickness

Effect of gap on CMP - material removal

• Material removal per sliding distance

Preston’s equation:

\[
\frac{\Delta h}{\Delta t} = C \cdot P \cdot V = C \cdot P \cdot \frac{\Delta s}{\Delta t}
\]

\[
\frac{\Delta h}{\Delta s} = C \cdot P
\]

(C=Preston’s coefficient
P = pressure, V=velocity,
h=removed height, s=sliding distant
t= time)
Scale effects – Abrasives/Pad

- UR100 from Rodel

Abrasives Pad

![Image of abrasives pad with labeled components: Abrasive particle (<0.1 μm), End fibrils, Vertically oriented pores, Urethane impregnated polyester felt, 100 μm, 400 μm, 1500 μm distances.]

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Mechanical Aspects of the Material Removal Mechanism in Chemical Mechanical Polishing (CMP)
CMP Parameters

**Input Parameters**
- **Pad**
  - Fiber Structure
  - Conditioning
  - Compressibility
  - Modulus
- **Slurry**
  - pH
  - Oxidizers
  - Buffering Agents, Abrasive
  - Concentration
  - Abrasive Geometry and
  - Size Distribution
- **Wafer Geometry and Materials**
- **Process**
  - Pressure
  - Velocity
  - Temperature
  - Slurry Flow
  - Polish Time

**Output Parameters**
- **Material Removal**
- **WIWNU**
  - (Within-Wafer Non-Uniform Material Removal)
- **WIDNU**
  - (Within-Die Non-Uniform Material Removal)
- **Surface Quality**
  - Roughness
  - Scratching
### CMP Modeling Roadmap
**Objectives from Industrial Viewpoint - VMIC 2001**

- Models are not reliable enough to be used as verification of process

- Usefulness of modeling is the ability to give feedback for “what-if” scenarios (predicting “polishability” of new mask designs) in lieu of time-consuming DOE tests

- Models should give some performance prediction for realistic, heterogeneous pattern effects

- Models should predict not only wafer scale phenomena but also have some capability to capture feature/chip scale interaction
Roadblocks for Modeling

• Multi-scale (wafer-, die-, feature-level) interactions must be integrated for global CMP modeling to be useful

• Linkage of models to upstream (deposition, etc.) and downstream (lithography, etc.) processes

• Models need to address defectivity

• New materials, consumables (pad, slurry, etc.) modeling and characterization
# Literature Review of Modeling of CMP

<table>
<thead>
<tr>
<th></th>
<th>MRR Water Level</th>
<th>Feature Level</th>
<th>Die Level</th>
<th>Non-uniformity</th>
<th>Abrasive</th>
<th>Slurry/Water usage</th>
<th>Slurry/Water usage</th>
<th>Abrasive</th>
<th>Slurry/Water usage</th>
<th>Energy</th>
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<td>Preston, 1927</td>
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<td>Various (10) incl. Burke, Runnels, Zhao</td>
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Past 2-D Material Removal Rate (MRR) Models

- **Experimental Model** [1]: Preston’s Equation
  \[ \text{MRR} = K_e P_0 V + \text{MRR}_0 \]
  where \( K_e \) an all-purposed coefficient, \( \text{MRR}_0 \) a fitting parameter, \( P_0 \) down pressure, and \( V \) the relative velocity.

- **Analytical Model Considering Wafer-Pad Contact Area** [2]: Zhao’s Equation
  \[ \text{MRR} = K_e (P_0 - P_{th})^{2/3} V \]
  where \( P_{th} \) a fitting parameter. 
  Active abrasive number is proportional to contact area. Contact area \( \propto P_0^{2/3} \)

*All with an all purpose factor \( K_e \) to represent the roles and interactions of other input variables except the down pressure and velocity

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2. Zhao et. al., 1999, Applied Physics
Motivations for a Comprehensive Material Removal Model

- Identify the most important input parameters related to Slurry Abrasives, Wafer, and Polishing Pad except the down pressure $P_0$ and velocity $V$

- Investigate the interactions between the input parameters

- Develop material removal rate formulation to consider the roles of the input parameters and their interactions

- Model as a basis for process design and optimization (including environmental impacts)
Consumable Parameters including: Slurry Abrasive Concentration, Abrasive Size Distribution, Slurry Oxidizer Type and Concentration, PH, Pad Topography and Pad Material (Hardness and Young’s Modulus), Wafer Materials and Process Parameters including Down Pressure, Relative Velocity, Slurry Temperature and so on.

Mechanical Model
- Model of Wafer Properties
- Model of Pad Properties
- Model of Slurry Abrasive Properties

Chemical Model
- Chemical-Pad Interaction Model
- Chemical-Slurry Abrasive Interaction Model

Mechanical-Chemical Interaction Model:
- Competition between Mechanical Removal and Passivation
- Enhancement of Mechanical Elements (Indentation, Leading Edge Area) on Passivation
- Chemical-Pad Interaction Model
- Chemical-Slurry Abrasive Interaction Model

Inputs and Outputs
- Wafer Surface Hardness Model
- MRR
- Material Removal by a Single Active Abrasive
- Number of Active Abrasives
- Force Applied on Abrasives
- Abraded Material-Chemical Interaction (Dissolution) Model
- Wafer-Chemical Interaction: Passivation Rate Model
- Sub-Model not Included in Current Model or Unimportant Relationship
- Sub-Model included in Current Model or Important Relationship

Strong Relationship Included in Current Model
Weak Relationship Included in Current Model
- Sub-Model
- Model Output
Chemical Aspects of CMP

• Chemical and electrochemical reactions between material (metal, glass) and constituents of the slurry (oxidizers, complexing agents, pH)
  – Dissolution and passivation
• Solubility
• Adsorption of dissolved species on the abrasive particles
• Colloidal effects
• Change of mechanical properties by diffusion & reaction of surface
Interactions between Input Variables

Four Interactions: Wafer-Pad Interaction; Pad-Abrasive Interaction; Wafer-Slurry Chemical Interaction; Wafer-Abrasive Interaction

Framework Connecting Input Parameters with Material Removal Rate

Basic Equation of Material Removal: \( MRR = N \times Vol \)

- **N**
  - Slurry Abrasive Weight
  - Concentration C
  - Average Abrasive Size \( X_{avg} \)
  - Proportion of Active Abrasives

- **Vol**
  - Force F & Velocity
  - Active Abrasive Size \( X_{avg-a} \)
  - Wafer Hardness \( H_w \) / Slurry Chemicals & Wafer Materials

- **X_{avg}**
  - Fraction of Active Abrasives: \( 1 - \phi \frac{(g - X_{avg})}{\sigma} \) where \( g \) is the minimum size of active abrasives

- **\( \phi \)**
  - Pad Topography & Pad Material
  - Abrasive Size Distribution

- **\( g \)**
  - Down Pressure \( P_0 \)

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Modeling of Pad and Wafer Interaction

**Pad Surface:**
- Rough and all asperities are in contact with wafer

**Wafer Surface**
- Smooth in comparison with pad surface

**Pad Material:**
- Young’s Modulus E

**Wafer Material**
- Rigid-body in comparison with pad
Modeling of Pad-Abrasive Interactions on the Contact Area: Fraction of Active Abrasives

Stage 1
Abrasive number \( n \propto \frac{C}{X_{\text{avg}}^3} \)

Stage 2

Stage 3

Stage 4: Final ‘Stable’ Contact with Closely Packed Abrasives
Interaction Between Wafer and Abrasive: Material VOL Removed by a Single Abrasive

Model of Material Removed by a Single Abrasive
Material Removal Rate as Functions of Down Pressure and Abrasive Size Distribution

\[
MRR = N \times Vol = K_1 \{1 - \phi (1 - K_2 P_0^{1/3})\} P_0^{1/2} V.
\]

Fraction of Active Abrasive:
\[
1 - \phi \left( \frac{g - X_{avg}}{\sigma} \right) \quad \text{where } g \text{ is the minimum size of active abrasives}
\]

\[
MRR = N \times Vol = K_3 \frac{C}{X_{avg}^3} \{1 - \phi (X_{avg} - g) / \sigma \} \quad X_{avg-a}^2
\]
Experimental Verification of Pressure Dependence of Material Removal Rate (MRR) (I)

MRR = N Vol = K₁ \{1 - φ(1 - K₂ P₀^{1/3})\} P₀^{1/2}.

Advantage over Preston’s Eq. MRR = Kₚ P₀ + MRR₀:

What input variables and how they influence Kₑ is predicable

SiO₂ CMP Experimental Data from Zhao and Shi, Proceedings of VMIC, 1999
Experimental Verification of Pressure Dependence of Material Removal Rate (MRR)(II)

$k_2$ is a function of consumable factors including abrasives and polishing pad but independent of slurry chemicals. This agrees well with the model prediction.
Abrasive Size Distribution Dependence of MRR: Particle Size Distribution [1]

Five Different Kinds of Abrasive (Alumina) Size Distributions for Tungsten CMP

<table>
<thead>
<tr>
<th>Abrasive Size Distribution</th>
<th>Mean Size (µm)</th>
<th>Standard Deviation (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKP50</td>
<td>0.29</td>
<td>0.070222</td>
</tr>
<tr>
<td>AKP30</td>
<td>0.38</td>
<td>0.118959</td>
</tr>
<tr>
<td>AKP15</td>
<td>0.60</td>
<td>0.210633</td>
</tr>
<tr>
<td>AA07</td>
<td>0.88</td>
<td>0.288768</td>
</tr>
<tr>
<td>AA2</td>
<td>2.00</td>
<td>1.056197</td>
</tr>
</tbody>
</table>

A abrasive Size Distribution Dependence of MRR: Experiment Results [1] VS. Model Predictions

\[ y = 325.1x^{-0.6411} \]

\[ y = 314.77x^{-0.6695} \]

\[ (X_{\text{avg}}, \sigma) \]

\[ (0.29 \mu\text{m}, 0.07022 \mu\text{m}) \]

\[ (0.38, 0.118959) \]

\[ (0.60, 0.210633) \]

\[ (0.88, 0.288768) \]

\[ (2.0, 1.056197) \]

Abrasives Size Distribution Dependence of MRR: MRR as a Function of Concentration and Abrasive Size Distribution

MRR Saturation at Concentration 10% for Smaller Abrasives

- $X_{\text{avg}} = 2\mu m$
- $X_{\text{avg}} = 0.88\mu m$
- $X_{\text{avg}} = 0.6\mu m$
- $X_{\text{avg}} = 0.38\mu m$
- $X_{\text{avg}} = 0.28\mu m$

$y = 18.825x^{0.6756}$

$y = 18.584x^{0.6884}$

Linear Relationship Holds for Larger Abrasives

Relationship between Standard Deviation and MRR Based on Model Prediction

- Std dev influenced
- Size influenced

- Xavg = 0.29um
- Xavg = 0.38um
- Xavg = 0.60um
- Xavg = 0.88um
- Xavg = 2um
# Java Implementation of CMP Optimization Software based on the Material Removal Model

![Image of CMP Optimization Software](image.png)

The image above represents the Java implementation of CMP (Chemical Mechanical Planarization) optimization software based on the Material Removal Model. The software is used to optimize the CMP process for semiconductor manufacturing, ensuring uniformity and reduction of defects on the wafer surface.

### Example Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down Press.</td>
<td>0.19, 1.907, 1.020, 0, 0</td>
</tr>
<tr>
<td>Contact Press.</td>
<td>0.203, 2.904, 0.020, 0, 0</td>
</tr>
<tr>
<td>Active Abrast.</td>
<td>0.221, 2.705, 0.020, 0, 0</td>
</tr>
<tr>
<td>Orientation</td>
<td>0.302, 0.417, 1.020, 0, 0</td>
</tr>
</tbody>
</table>

### Material Properties

- **Patterned Wafer**
  - G1: 0.42
  - P2: 0.106
- **Blunter Wafer**
  - G1: 0.42
  - P2: 0.106

### Process Parameters

- **A abrasive Average Size:** 8 nm
- **A abrasive Size Deviation:** 12 nm
- **Pad Topography Constant:** 1/1000

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"Design" of consumables - Pad Example

Prototype surface, 20X

Prototype surface, 55X

Design software interface for prototype pad surface; geometry of individual elements, pitch and mechanical properties are Variable, courtesy of J. F. Luo, LMA, 2001
Basic Framework of the CMP Optimization Software
Preprocessor: Machine Setup

Machine Setup Dialog

Machine Type:
- Applied: Mira Mesa
- Applied: Reflection
- Ebatech
- LAM
- Strasbaugh
- Other

Machine Geometry Parameters:
- Head Diameter: 8 inch
- Platen Diameter: 600 mm
- Center Offset: 100 mm

Process Parameters:
- Down Pressure (psi): 7
- Platen Velocity (rpm): 90
- Head Velocity (rpm): 20

Retaining Ring Parameters:
- Ring Width: 10 mm
- Ring Pressure (psi): 6

OK
Cancel
Preprocessor: Consumable Setup

Slurry

Pad
Preprocessor: Wafer Setup
Postprocessor: Interface Pressure Distribution
Postprocessor: Velocity Distribution
Postprocessor: Down Pressure Dependency of MRR
Postprocessor: WIWNU: Function of Pressure Distribution, Velocity Distribution and Pressure Dependency of MRR
Postprocessor: WIDNU: Function of Pattern Density and Pressure Dependency of MRR
Conclusions

• A comprehensive model is developed to explain the material removal mechanism in CMP

• The roles and interactions of polishing pad, slurry and wafer are being identified using this comprehensive model

• MRR formulations considering the integrated effects of input variables are developed and verified

Future Work

• Further experimental verification of the model needed

• Model-based process optimization (e.g. using Java)

• Process “design” capabilities (e.g. pad, abrasive, chemistry)