CMP Modeling as Part of Design for Manufacturing

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Outline

• Modeling objectives and perspective
• CMP process model development
• Short review
• Towards design for manufacturing (DFM)
# Levels of Flexibility - Design to Manufacturing

<table>
<thead>
<tr>
<th>Level</th>
<th>Feature Prediction, Control, and Optimization</th>
<th>Design</th>
<th>Manufacturing</th>
<th>Finishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level I</td>
<td>Feature prediction, control, and optimization in an iterative design and process planning environment</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Level II</td>
<td>Feature prediction, control, and optimization through the selection of a manufacturing plan in an &quot;over-the-wall&quot; design-to-manufacturing environment</td>
<td>Low</td>
<td>High</td>
<td>High -&gt; low</td>
</tr>
<tr>
<td>Level III</td>
<td>Feature prediction and control through limited adjustments to a pre-established manufacturing process</td>
<td>Low</td>
<td>Limited</td>
<td>High -&gt; low</td>
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<tr>
<td>Level IV</td>
<td>Feature prediction for finishing process planning, finishing tool trajectories and sensor-feedback strategies</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Software driven

Hardware driven
Modeling Roadmap for maximum impact

- Minimum cost/CoO
- Maximum production
- Maximum flexibility
- Maximum quality
- Minimum environmental & social impact
- Broaderest integration
  *
  *
  *
- Through software

Include "islands of automation" and existing models
Include supply chain with constraints (e.g., "quality gates")

Extend to "social impact" constraints (green, sustainability, health, safety, etc.)

Through software

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Is there need for this?

Design

Manf’g

Design

Manf’g
What you see depends on where you are standing!

Source: Y. Granik, Mentor Graphics

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What’s your world view?

Process

Design

Process

Design

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Components of Chemical Mechanical Planarization

- Mechanical Phenomena
- Chemical Phenomena
- Interfacial and Colloid Phenomena
Scale Issues in CMP

Material Removal

Active Abrasives

Chemical Reactions

critical features

Mechanical particle forces

Particle enhanced chemistry

Pores, Walls

Grooves

Tool mechanics, Load, Speed

Pad

Mechanism

Layout

Scaling Issues

From E. Hwang, 2004

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An overview of CMP research in Berkeley

Physical models of material removal mechanism in abrasive scale

- Doyle
- Talbot
- Dornfeld

Chemical reactions vs. Mechanical material removal mechanism vs. Electrochemical material removal mechanism

- Abrasive type, size and concentration
- Pad asperity density/shape
- Pad mechanical properties in abrasive scale

Models of WIDNU
- Better planarization efficiency
- Better control of WIWNU
- Smaller WIWNU
- Small dishing & erosion
- Reducing scratch defects
- Reducing "Fang"
- Reducing slurry usage
- Uniform pad performance thru it's lifetime
- Longer pad life time
- Ultra low-k integration
- E-CMP

Models of WIWNU
- Better control of WIWNU
- Smaller WIWNU

MIT model
- Pattern
- Topography
- Pad properties in die scale
- Slurry supply/flow pattern in die scale
- Wafer scale pressure NU
- Wafer scale velocity profile
- Wafer bending with zone pressures
- Slurry supply/flow pattern in wafer scale
- Pad groove

Test
- Fabrication technique
- Fabrication
- Pad design
CMP Modeling History in SFR/FLCC*

Before SFR/FLCC

- Preston's Eqn. \( MRR = CPV \)
- Combined eqn. \( R = \tau CM/(C+M) \)

SFR/FLCC

- Luo (SFR) \( MRR = N \times Vol \)
- Choi (FLCC) \( MRR = \) Tribo-electro-chemical model

Now

- Interfacial/colloidal effects

DfM/MfD

- Computational efficiency
- Flexible in scale
- Process links

* According to Dornfeld

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Interactions between Input Variables

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

Pad Materials/Shape Effects

Dishing and erosion

Linear Viscoelastic Pad

Pad/wafer contact modes in damascene polishing

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Effect of Pattern Density - Planarization Length (PL)

- High-density region
- Global step
- Low-density region
- Metal lines
- Planarization Length
Modeling of pattern density effects in CMP

Effective pattern density

Planarization length (window size) effect on “Up area”

< Test pattern >

< Post CMP film thickness prediction at die-scale >

< Effective density map >

a=320um

a=640um

a=1280um
Feature level interaction between pad asperities and pattern topography

Reference height (z=0)

\[ F(x, y) = K_p \times \int_0^{Z(x, y) - Z_{pad}} (\text{asperity}\_\text{density}) \times (\text{PDR}(z + dz) - \text{PDR}(z)) \times (Z(x, y) - z) \]

Feature level interaction between pad asperities and pattern topography

\[ F_{\text{tent}} = \int_{\text{die}} F(x, y) \, dx \, dy \]

\[ F_{\text{tent}} > F_{\text{die}} ? \]

- Yes: ++Z_{pad}
- No: F_{\text{tent}} < F_{\text{die}} ?
  - Yes: --Z_{pad}
  - No: Z_{pad}
Characterization of Pad Surface

Probability Density (µm⁻¹)

Asperity Height (µm)

Active asperities

(source: A. Scott Lawing, NCCAVS, CMPUG 5/5/2004)
Model for the simulation

\[ MRR(x, y) = -\frac{dz(x, y)}{dt} \propto R_a(x, y) \times \# \text{asperities} \]

New model

\[ MRR(x, y) = C^{**} \frac{R^2 R_a^{1/4} E^{3/2} V_p}{H_w^{3/2} D_p^{PD(x, y)}} \int_{z_{pad}}^{z(x, y)} \varepsilon(x, y, \delta)^{7/4} AHD(\delta) d\delta \]

Fitting parameter accounting for chemical reactions, abrasive size distribution etc.

- Abrasive particle size
- Asperity radius
- Pad/film properties
- Polishing speed
- Pad asperity height distribution

Hardness of material polished

Mean distance between asperities

Pattern density effect
Modeling Overview

**Chip Layout**
- Pattern density
- Line space
- Line width

**HDP-CVD Deposition Model**

**CMP model**

**CMP Input Thickness**

**Evolution**

**Nitride thinning**
Adding the electro-chemical effects

• Develop a transient tribo-electro-chemical model for material removal during copper CMP
  – Experimentally investigate different components of the model
• Using above model develop a framework for pattern dependency effects.

Slurry chemistry
(pH, conc. of oxidizer, inhibitor & complexing agent)

Pad properties
layers’ hardness, structure

Abrasive
Type, size & conc.

Polishing conditions
(pressure P, velocity V)

Polished material

Incoming topography

CMP Model
1. Passivation Kinetics
2. Mechanical Properties of Passive Film
3. Abrasive-copper Interaction
   Frequency & Force

Removal Rate (RR)

Planarization, Uniformity, Defects
Application: Polishing induced stress

Pressure concentrated locally (about 300 psi)
→ Risk of cracking in the sub layers
**FEM Analysis: Model**

**BOUNDARY CONDITIONS:**
- Fixed at the bottom
- Periodic Boundary Conditions (symmetry)

**LOADS:**
- Downward Constant Pressure – 2psi
- Horizontal Shear (friction) stress – 0.7psi

**LOW-K Layer**
- \( E = 5 - 20 \text{ GPa} \);
- \( \alpha = 0.25 \)

**COPPER Layer**
- \( E = 129.8 \text{ GPa} \);
- \( \alpha = 0.34 \)

**TANTALUM Layer**
- \( E = 185.7 \text{ GPa} \);
- \( \alpha = 0.34 \)
FEM Analysis in CMP

Von Mises stresses

Step 1
Low-k: $E = 5\text{GPa}$

Step 2

Step 3
Low-k: $E = 20\text{GPa}$
Modeling Challenges

• Present methods treat CMP process as a black box; are blind to process & consumable parameters
• Need detailed process understanding
  – For modeling pattern evolution accurately
    • Present methods do not predict small feature CMP well
  – For process design (not based on just trail and error)
• Multiscale analysis needed to capture different phenomena:
  – At sufficient resolution & speed
• CMP process less rigid than other processes: possibility of optimizing consumable & process parameters based on chip design
  – MfD & DfM
• Source of pattern dependence is twofold:
  – Asperity contact area (not addressed yet)
  – Pad hard layer flexion due to soft layer compression (addressed by previous models)
Extensive test/measurements required

Model:
- captures only 1 source of pattern dependency
- coarse (resolution ~10µm)

Specific to particular processing conditions

Source: Praesegus Inc.

• Helps in dummy fill
  - Design improvement but no process optimization
• Optimization should be across process & design:
  - Need to be able to tune all the available control knobs
Pattern Related Defects

Nominal Pattern density = Area(high features) / (Total Area)

Present Approach

- \( MRR(x, y) = \frac{K}{\rho(x, y)} \)
- \( \rho(x, y) \) calculated as a convolution of a weighted function (elliptic) over evaluation window.
- Evaluation window size (R) determined empirically.

Initial topography

Non-uniform removal

Local planarization

End point

Over polishing

Low pattern density

High pattern density

erosion & dishing

residue film
Need a “GoogleEarth” view of modeling

We are here
CMP phenomena at different scales

- Pad/Wafer
- Die
- Feature/Asperity

100nm-10μm

1-10μm

Pad asperity

Abrasive Contact

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Pattern Evolution Framework

- Consumables
- Polishing Conditions

Material Removal Model

\[ RR = \frac{M_{Cu}}{\rho n F \tau} \int_{0}^{\tau} i(t_0 + t) dt \]

\[ MRR(x, y) = \frac{K}{\rho(x, y)} \]

Time step evolution

Smith feature prediction problems

Space Discretization: Data Structure

Asperity contact area (\( \mu m \))

Empirically fit, based on pad flexion (scale=mm)

Effects to Capture

• Multiscale Behavior
  – Material removal operates on different scales and contributes to the *net* material removed in the CMP process
  – Material removal at any location is affected by its position in different scales
  – Different models need to be used to capture behavior at different scales

• Far-field Effects
  – Most IC manufacturing processes are only dependant on local features
  – CMP performance depends on both local as well as far-field features
CMP Model Tree

- Tree based data structure will encapsulate both wafer features and pattern evolution at various scales

- Pad/Wafer (~m)
- Die (~cm)
- Asperity (~μm)
- Feature (45nm-10μm)
- Abrasive contact (10nm)
Data Structure

• Efficient surface representation is required
  – Mesh-based representations allow for fast processing, and have been widely used

• Need to capture repeating features
  – Use tiles/modular units
  – For “similar” features, use property inheritance from modular features

• Multiscale analysis
  – Use multiresolution meshes – allow for querying in mm/um/nm scales
  – Also support querying of far-field features along with local features
Data Structure

• Model precision vs. Level of Detail
  – Identify tradeoffs between speed of analysis and the accuracy of the models used

• Data Structure design motivated by physical considerations
  – Tree levels \( \equiv \) phenomenon scale
  – object properties \( \equiv \) physical phenomena.

• Inheritance:
  – Inherit properties from parents at higher levels of tree and from generic object at that level
Multiscale Optimization Example

- Address WIDNU at different levels depending on available flexibility:
  - Change pad hardness (tree level 1)
    - Inflexibility: scratch defects, pad supplier
  - Dummy fill (chip, array level)
    - Inflexibility: design restrictions
  - Change incoming topography (feature level)
    - Inflexibility: deposition process limitation
  - Change chemical reactions, abrasive concentration (abrasive level)

Within die non-uniformity
Nitride Thinning in STI
Thank you for your attention!