Fundamental Study of Interfacial Phenomena and Modeling for CMP Consumables Design

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Outline

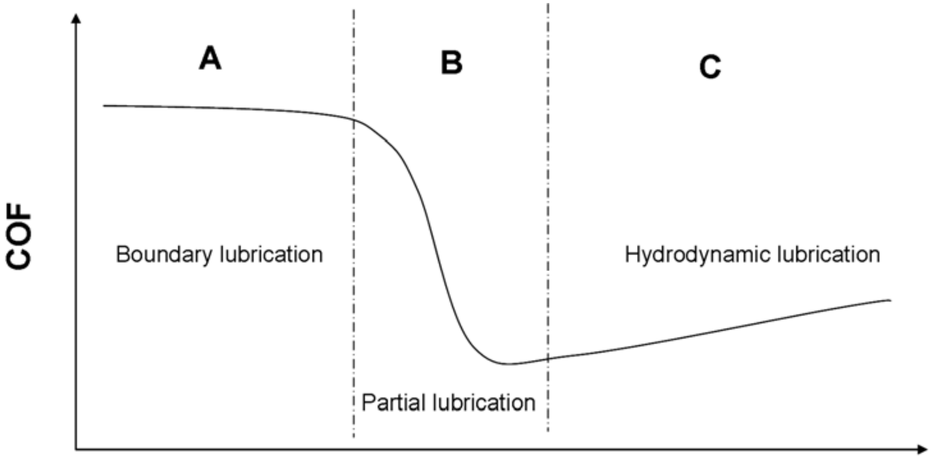
- Part 1: Interfacial Phenomena
  - Lubrication regime
  - CMP interaction
  - Summary

- Part 2: Modeling
  - CMP modeling
  - Application to design of consumables
  - Summary

INTERFACIAL PHENOMENA FOR CMP CONSUMABLES DESIGN

Contact condition

Stribeck Curve

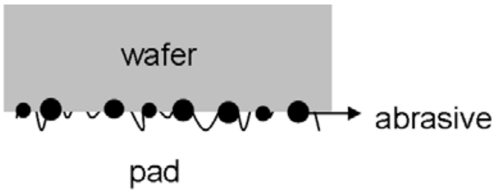


Viscosity*Velocity/pressure

↓

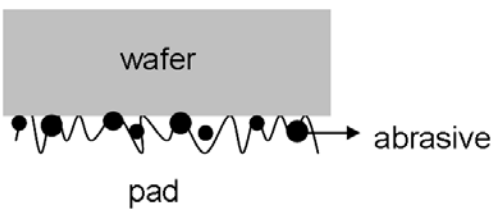
Sommerfeld number

"A" regime



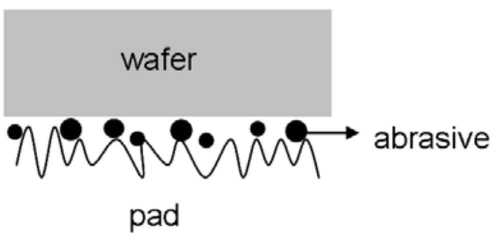
Boundary lubrication

"B" regime



Mixed lubrication
elastohydrodynamic lubrication

"C" regime



Hydrodynamic lubrication

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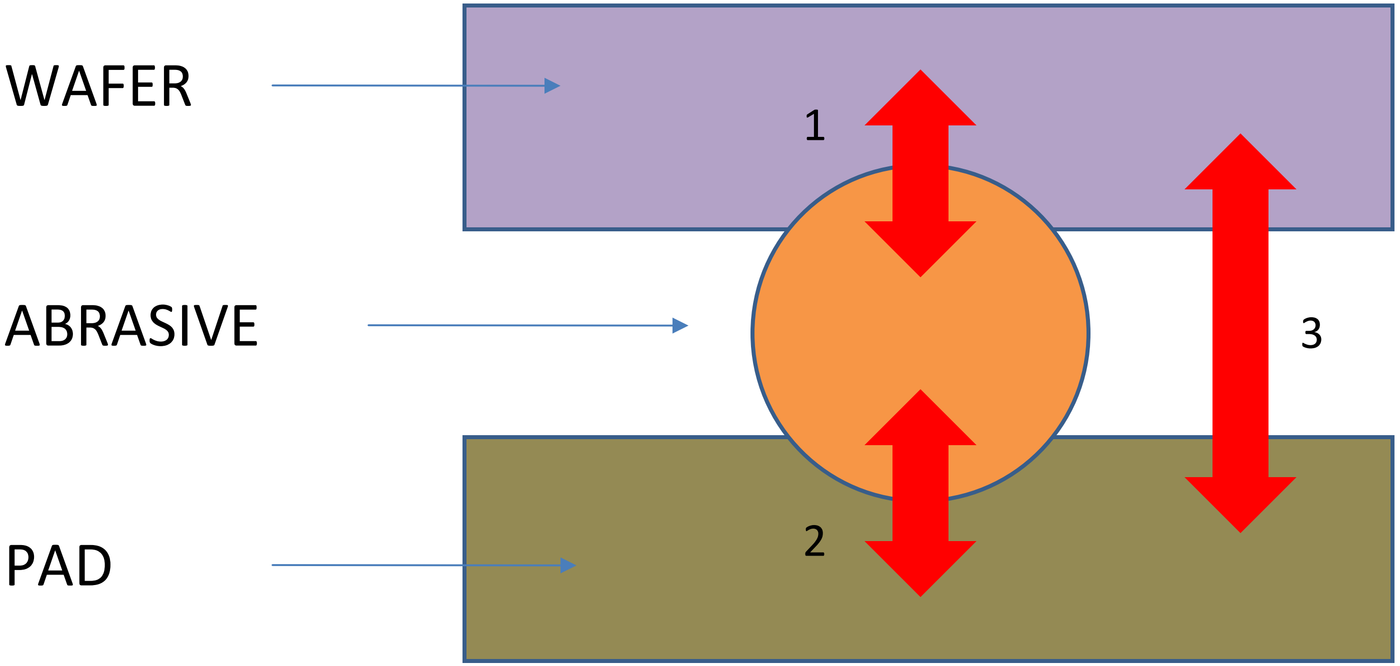
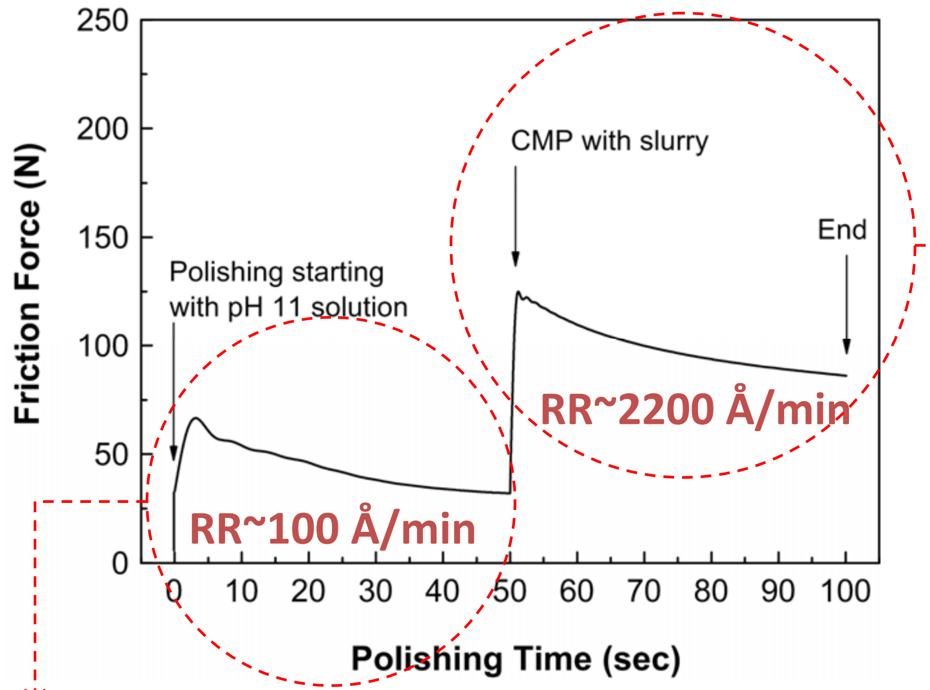
Wafer-Abrasive-Pad Interaction

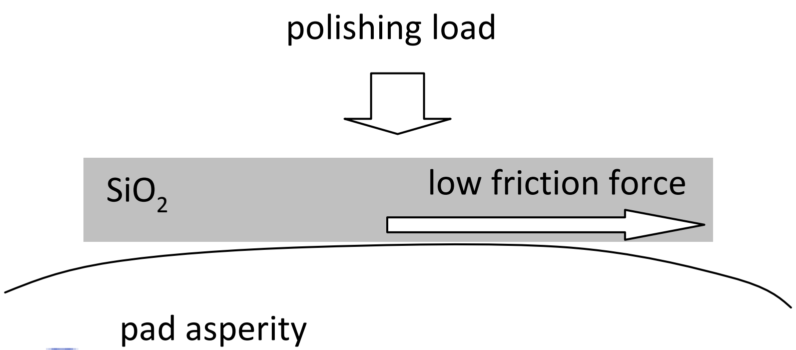


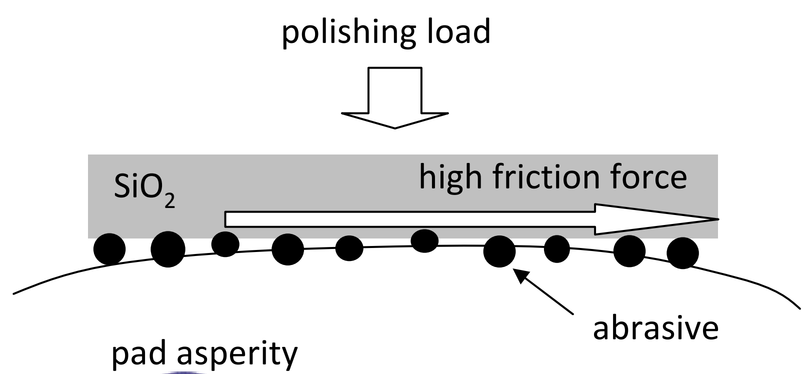
Wafer-Abrasive-Pad Interaction



(a) without abrasives

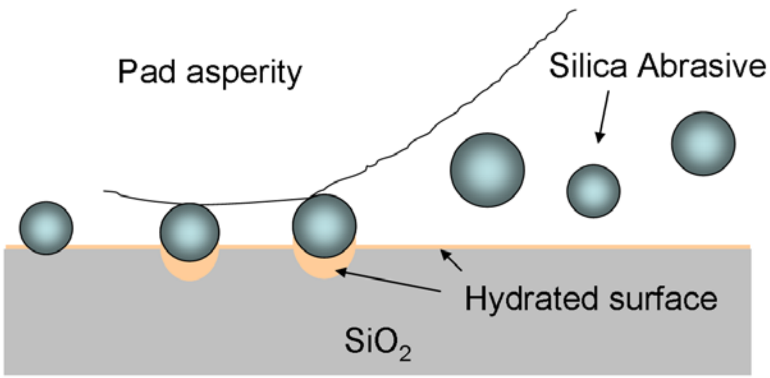
(b) with abrasives





Interaction between silica-, ceria abrasive and oxide film surface

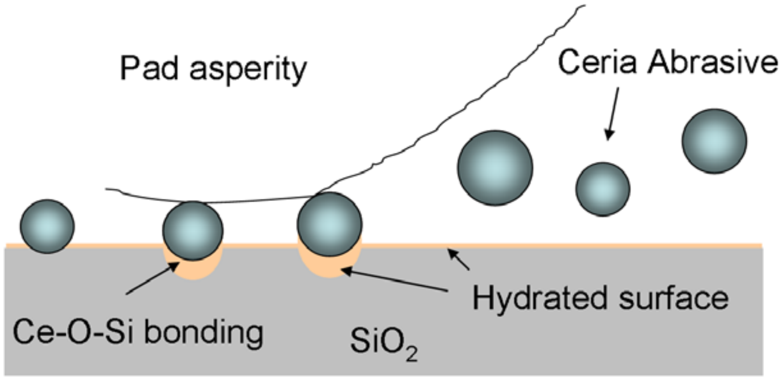
silica-based slurry



1. Formation of a little hydrated surface in alkaline slurry
2. Indentation of silica particles on SiO_2 film surface
3. Plastic deformation of SiO_2 film surface with friction force
   Formation of hydrated surface around deformation region
   (Si-O-Si bonds breaking)
4. Simultaneously plowing of abrasive

Minoru Tomozawa, Solid State Technology, pp. 169-175, 1997.

ceria-based slurry



1. Formation of a little hydrated surface in neutral slurry
2. Indentation of ceria particles on SiO_2 film surface
3. Plastic deformation of SiO_2 film surface with friction force
   Formation of hydrated surface around deformation region
   (Si-O-Si bonds breaking with Ce-O-Si bonding)
4. Simultaneously plowing of abrasive

L. Cook, Journal of Non-Crystalline Solids, 120 (1990), 152-171
T. Hoshino, Journal of Non-Crystalline Solids, 283 (2001), 129-136

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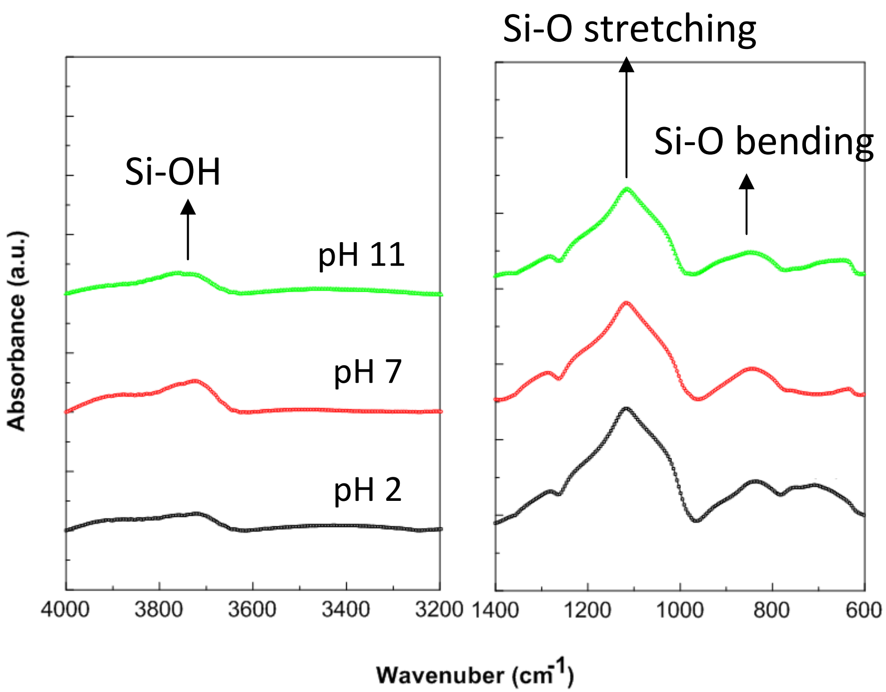
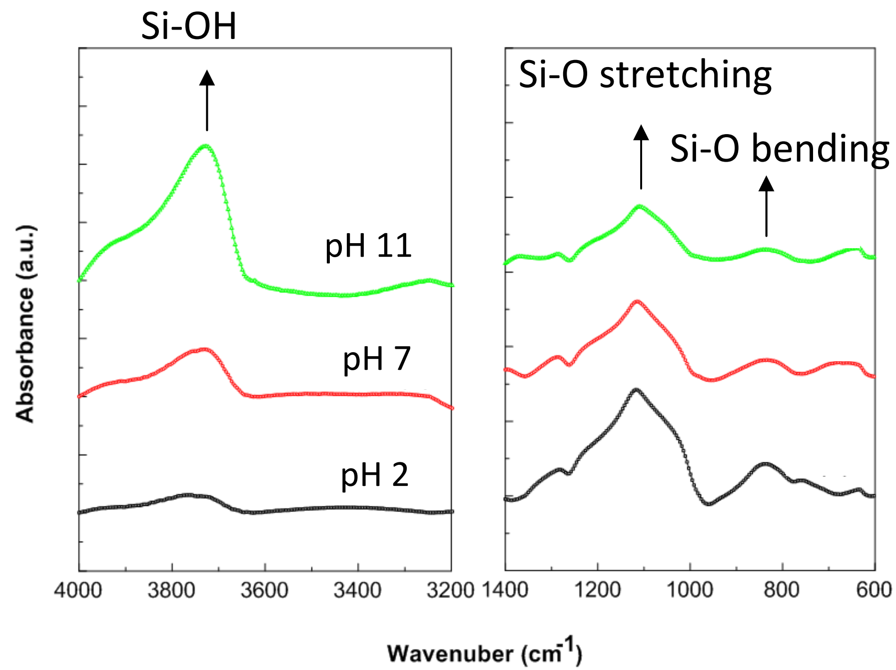
Formation of hydrated layer after CMP

Silica-based slurry



Ceria-based slurry



Low hydration

- Same material

High hydration

- Strong chemical reaction between abrasive and SiO_2 film

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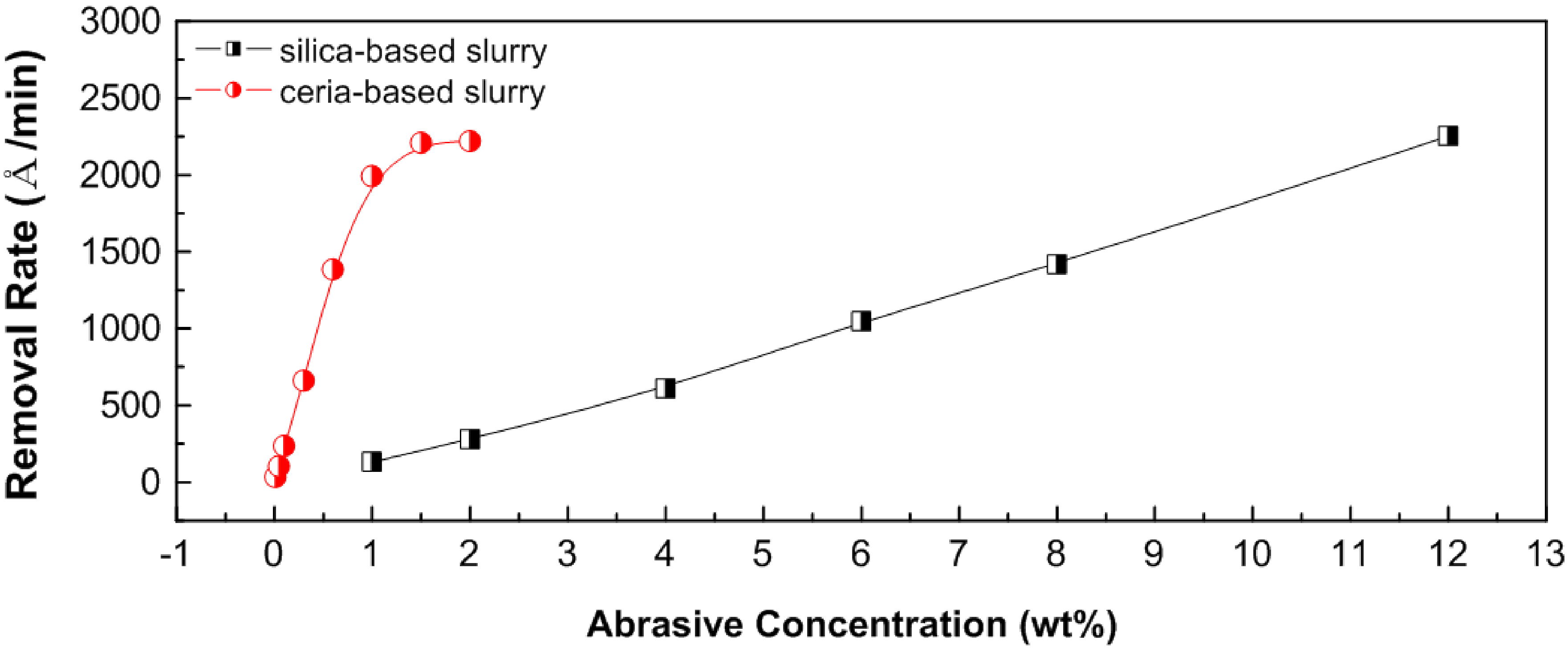
Abrasive particles in slurry



- The number of abrasive particles played an important role in material removal.
- The ceria slurry has high MRR efficiency in spite of low abrasive concentration and neutral environment of slurry.

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Schematic of active abrasive particles

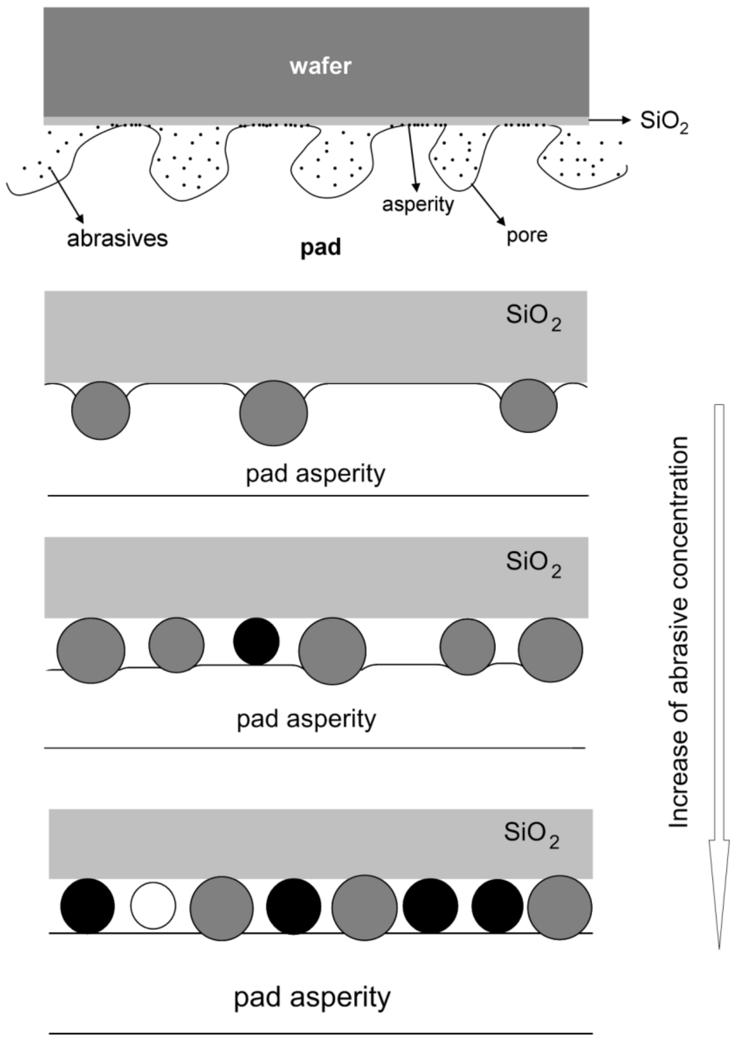
Microscopic contact

in mixed lubrication

Contact at low abrasive concentration

Transition

Contact at high abrasive concentration

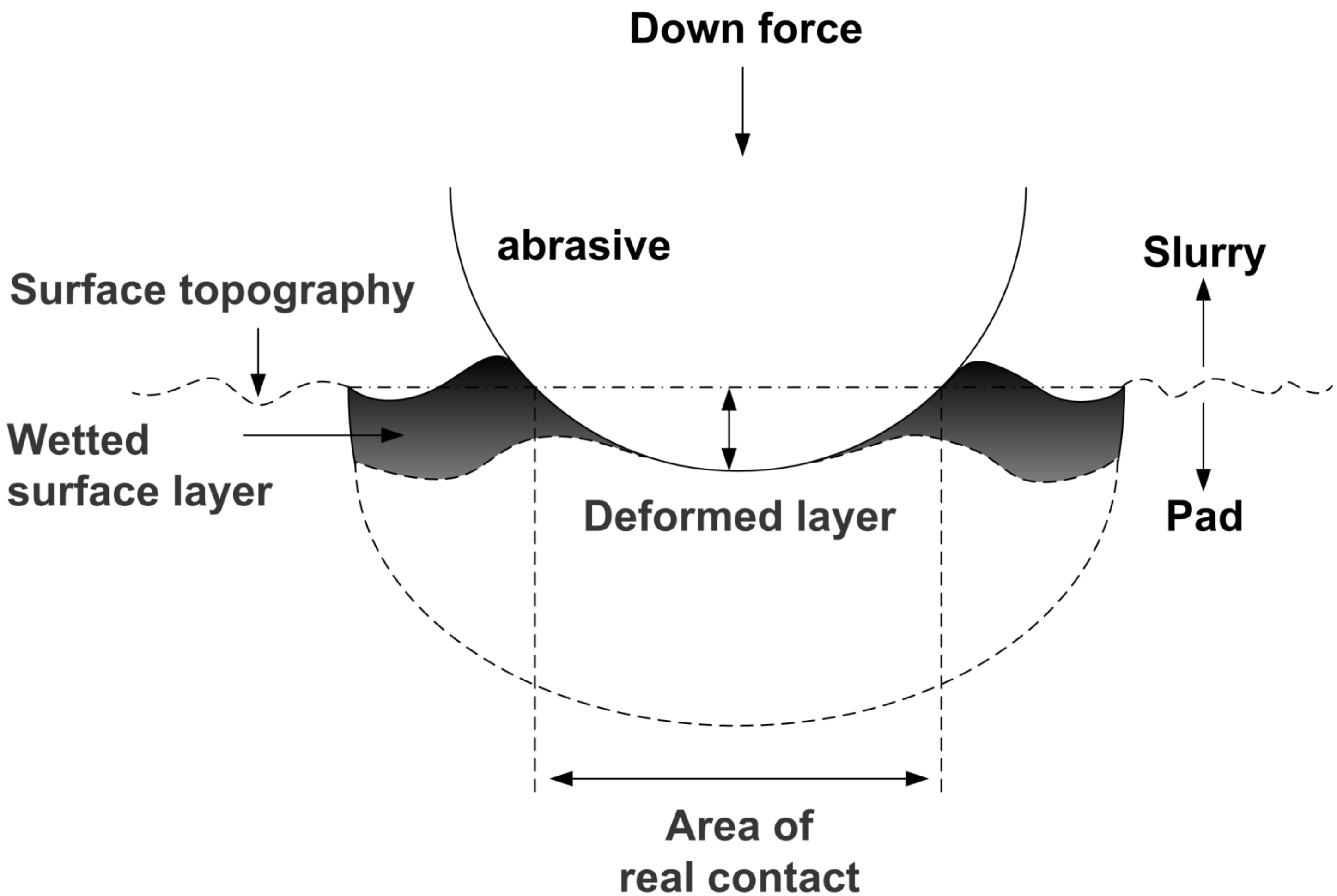


Active abrasive with two-body abrasion

Active abrasive with three-body abrasion

Inactive abrasive

Abrasive and Pad Interaction



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Basic material removal model

Material removal rate

$$= \rho_w * N * Vol_{removed} + C_{chemical\ action}$$

$$\begin{pmatrix} \rho_w = \text{material density of wafer } \textit{(constant)} \\ N = \text{number of active abrasive} \\ Vol_{removed} = \text{volume removed by a single abrasive } \textit{(constant)} \\ C_{chemical\ action} = \text{material removal amount by chemical } (\textit{constant}) \end{pmatrix}$$

- Active abrasive: cause mechanical material removal
- Asperity distribution of pad means the probability of the number of active abrasive
- Material removal rate $\propto$ Number of active abrasive (N)

  Real contact area

J. Luo and D.A. Dornfeld;
IEEE Transactions on Semiconductor Manufacturing, vol.14(2), pp.112-133. 2001.

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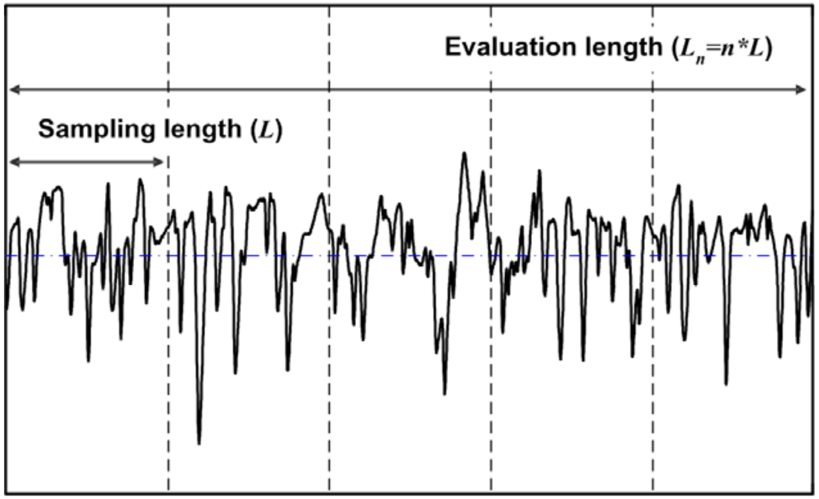
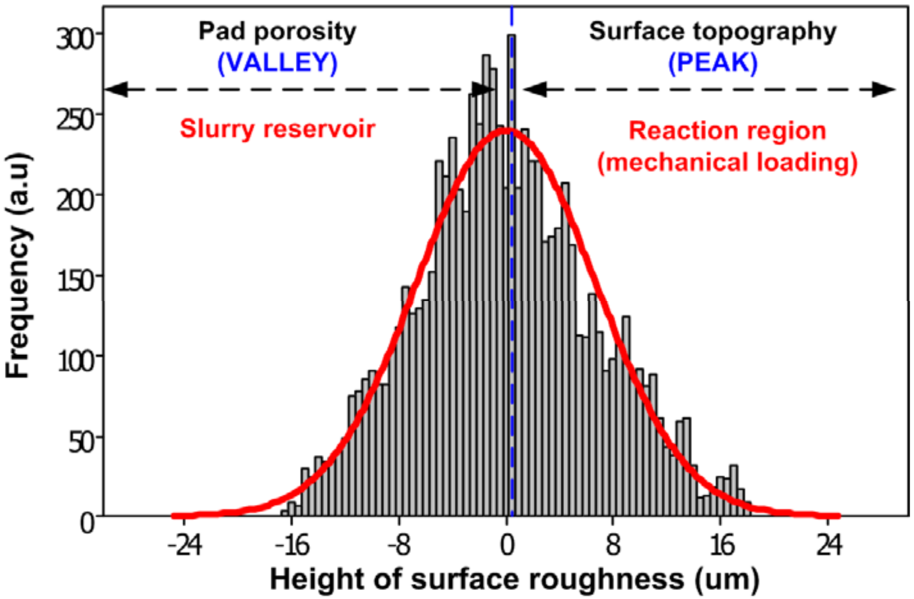
Histogram analysis of asperity height





- Pad surface topography = peak area + valley area

Peak area
= Reaction region (mechanical loading)
= active layer of pad top layer
= multiple direct contacts with abrasives
= the most rapid wear during the polishing

Valley area
= space for slurry reservoir
= ability to retain polishing slurry

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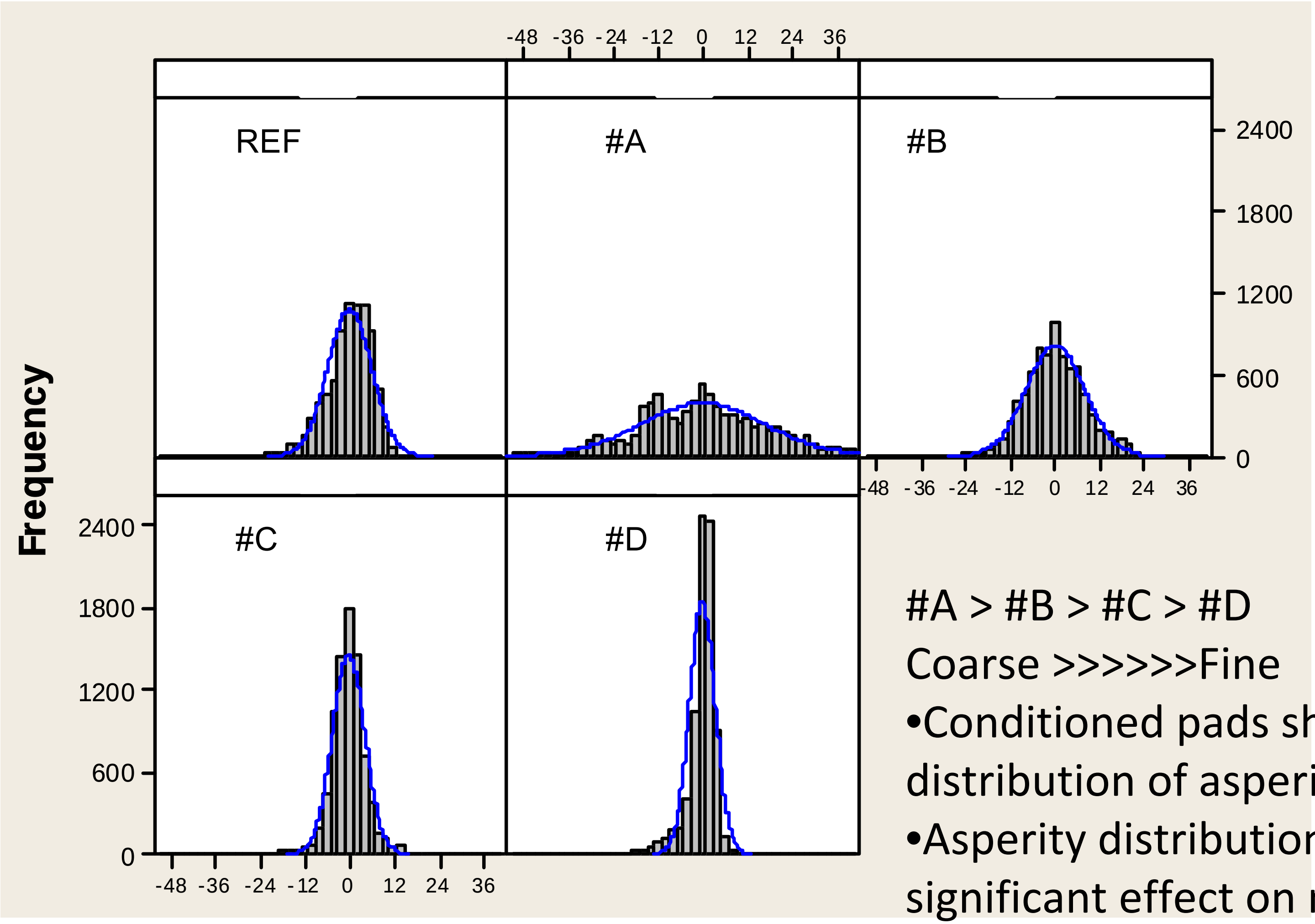
Asperity height distribution of conditioned pad



#A > #B > #C > #D

Coarse >>>>>>Fine

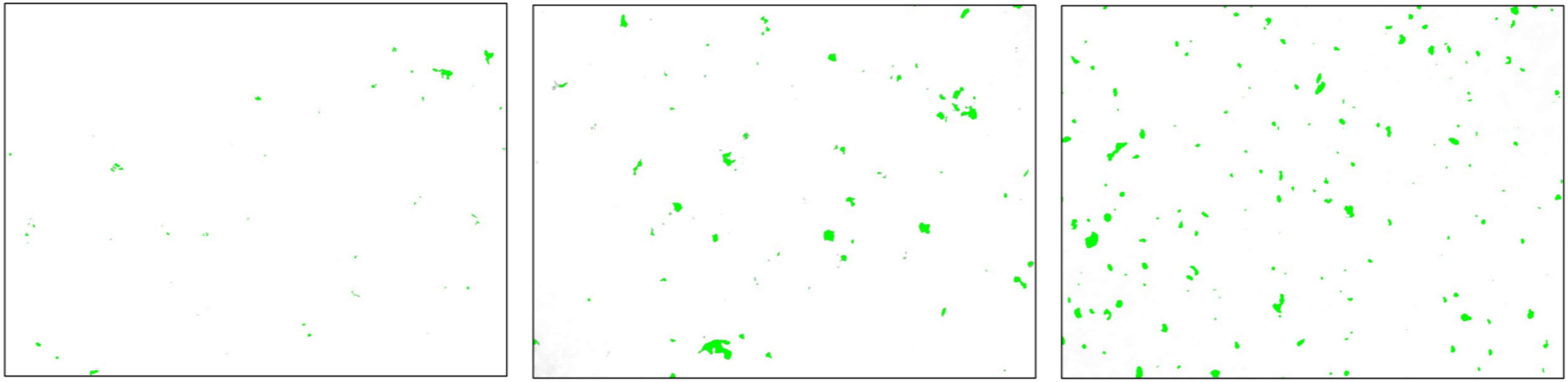
•Conditioned pads show variable distribution of asperity height.

•Asperity distribution has a significant effect on material removal behavior during CMP process

Analysis of area of real contact

As-received pad | Conditioner A | Conditioner B

0.27% | 0.89% | 1.45%



Randomly distributed asperities

Uniformly distributed asperities

- Pad conditioning process has a strong effect on distribution of pad asperity height.
- High real contact area can ensure stable material removal and low stress planarization.

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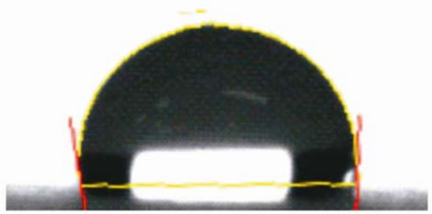
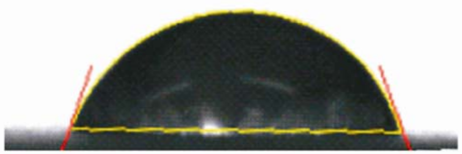
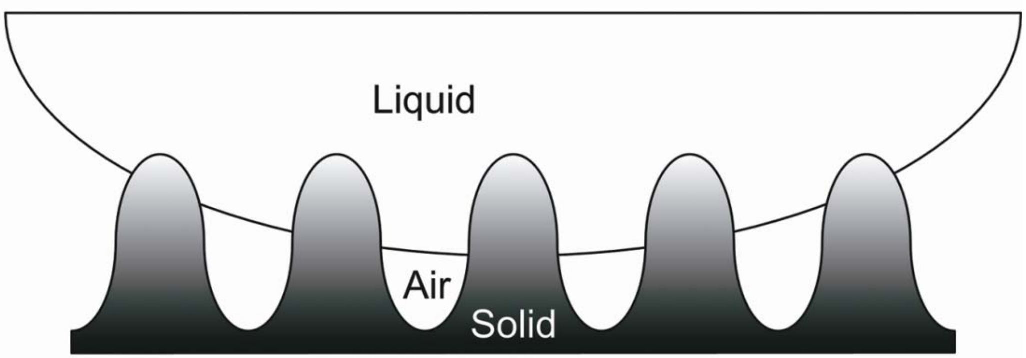
Analysis of contact angle



Pad A
; large deviation of
asperity height



Pad B
; small deviation of
asperity height



(b)

1. Contact angle $\propto$ Roughness

Higher roughness value
> Thicker gap between peak/valley
> More air trap inside topography

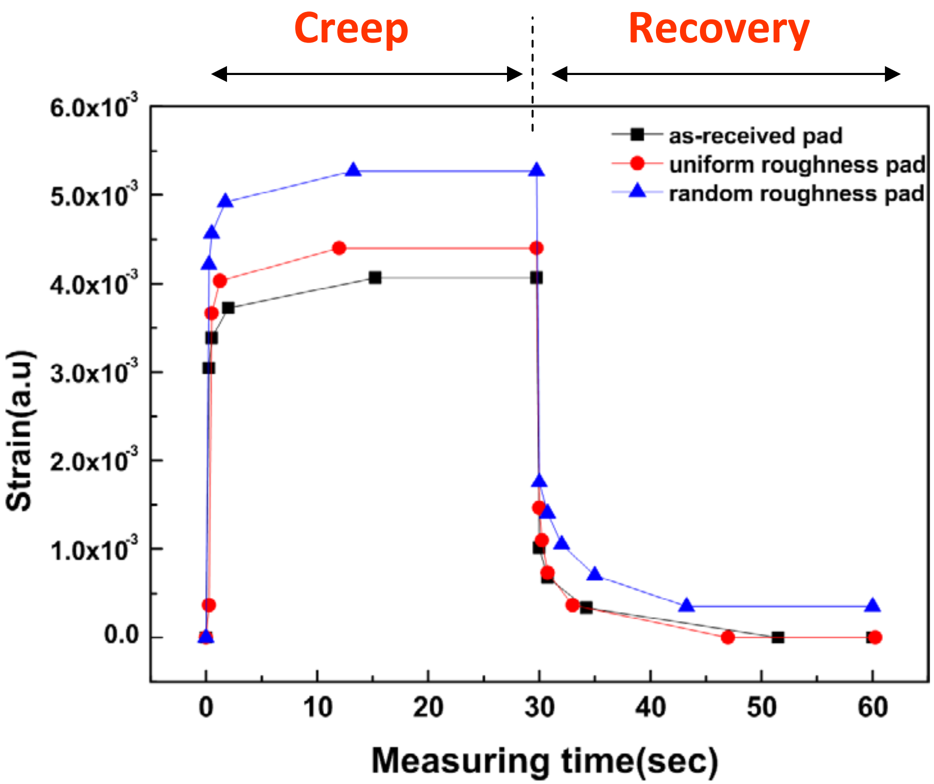
….. Higher contact angle

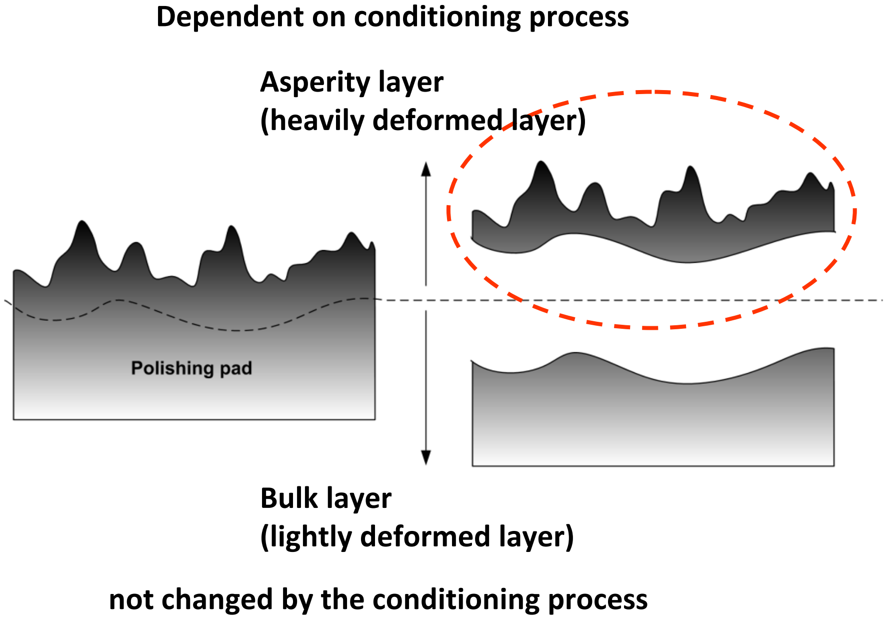
2. Contact angle $\propto$ Uniformity of Roughness

Randomly distributed asperities
… Higher contact angle

\>\>\>\>
Makes pad more hydrophobic and MRR lower

Analysis of viscoelastic deformation





Xie, Thesis of Doctor, 2007

- Strain: Randomly distributed asperities > uniformly distributed asperities
- Small and uniform deformation = more stable against creep and recovery
- Deformation of asperity layer can be strongly influenced by pad conditioning process regardless of same pad.

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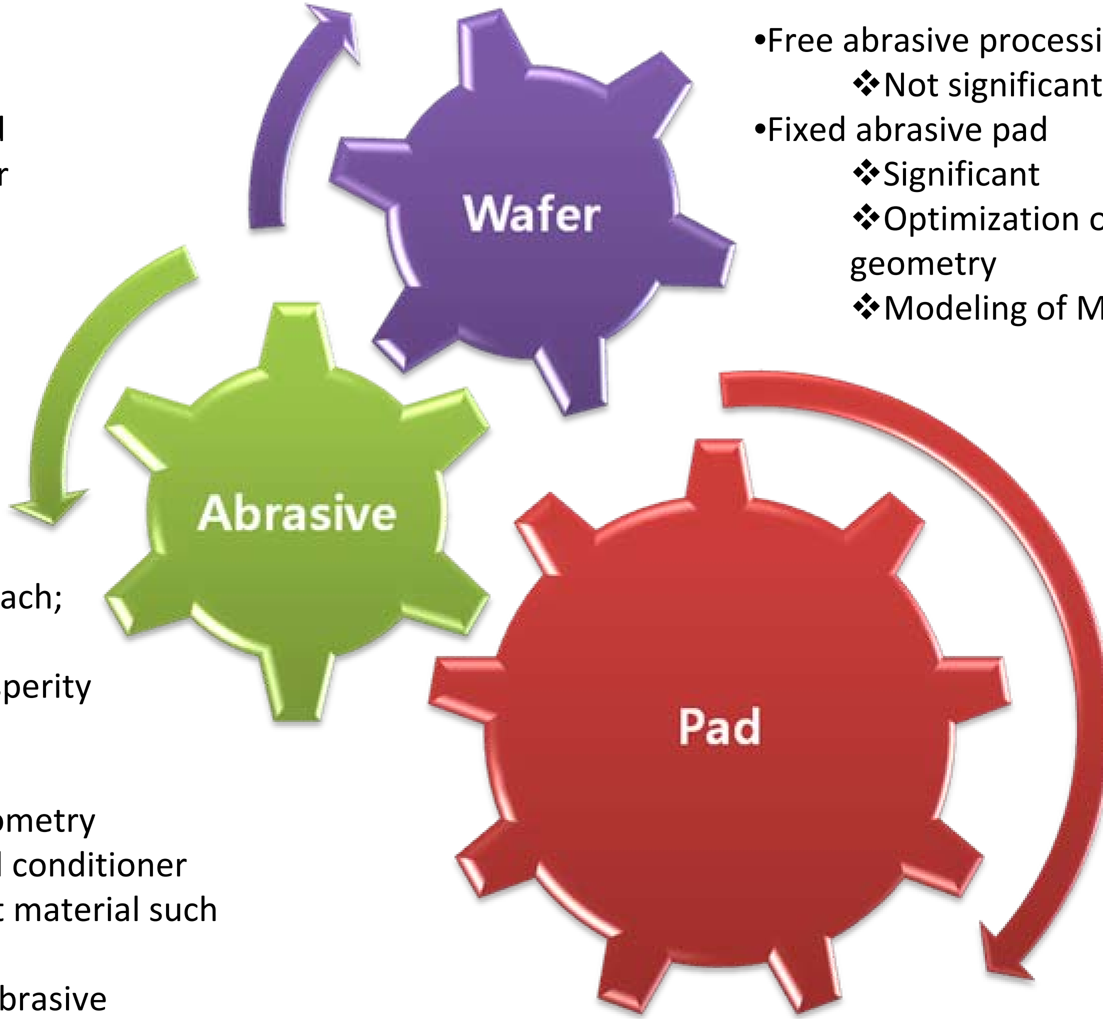
Summary and Future Work

•Hydration surface layer
•Definition of active abrasive
•Theoretical approach; simulation and modeling of active abrasive's behavior
•New abrasive particle for effective material removal

•Free abrasive processing
❖Not significant
•Fixed abrasive pad
❖Significant
❖Optimization of FAP geometry
❖Modeling of MRR



•Uniform distribution of pad asperity
•Theoretical and experimental approach; estimation of active abrasive
•Molding pad; optimization of pad asperity
•Optimization of pad groove design
•Mean residence time of slurry
•Optimization of pad conditioner geometry
•Estimation of active diamond of pad conditioner
•New pad for emerging hard and soft material such as compound semiconductor
•Simulation of slurry flow including abrasive

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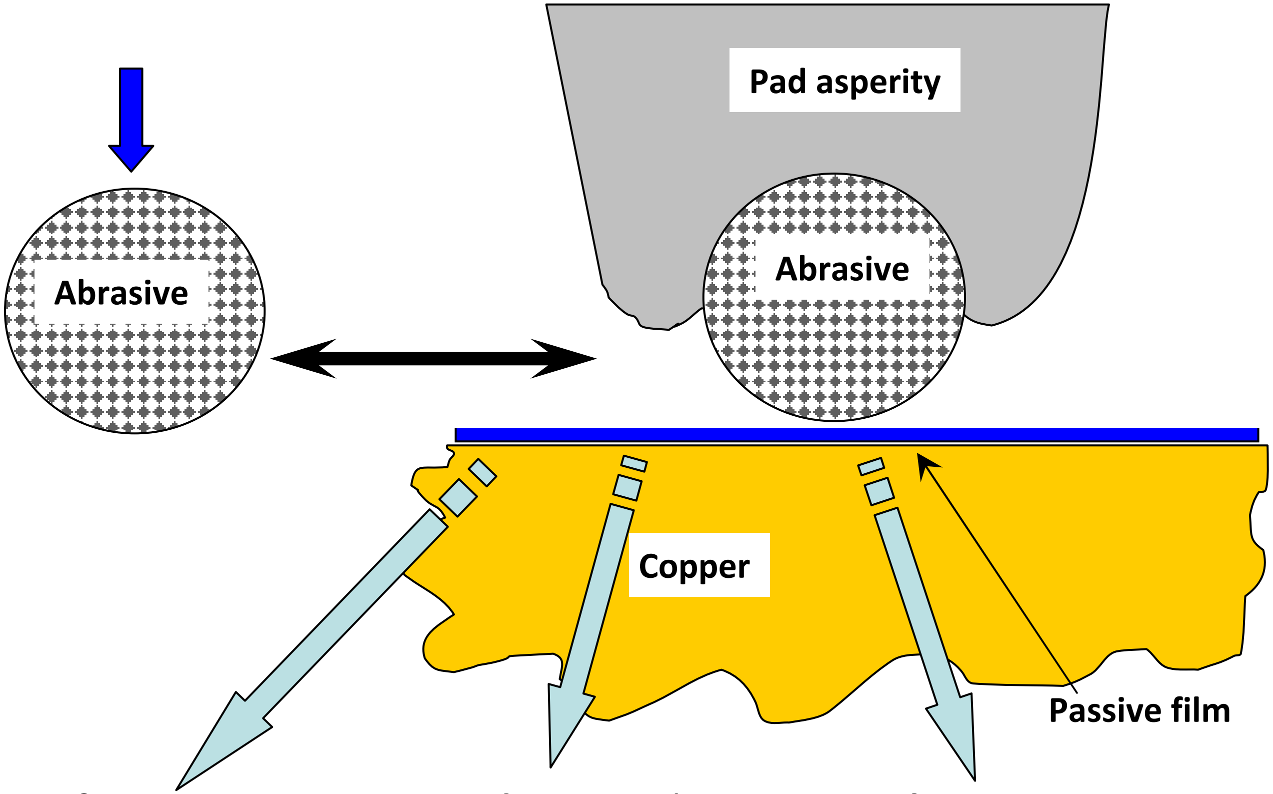
MODELING
FOR CMP CONSUMABLES DESIGN

Seungchoun Choi, Shantanu Tripathi, Fiona Doyle and David Dornfeld

Mechanistic model for copper CMP



2. Mechanical response of passive films

1. Passivation kinetics: the transient oxidation rate of copper after removal of passive film

3. Abrasive-copper interaction frequency & force

All three components need to be individually estimated for modeling

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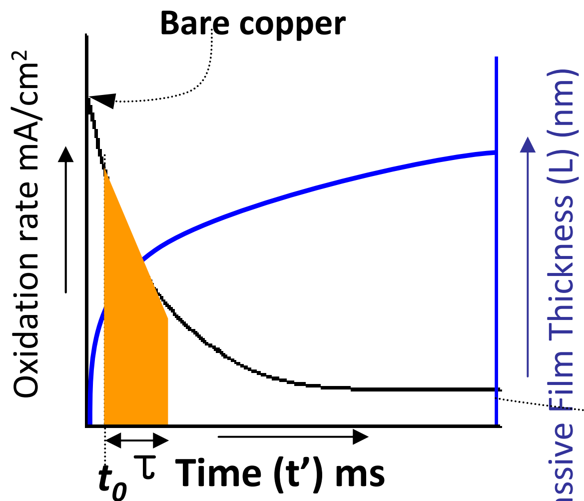
Copper CMP Material Removal Model

Passivation kinetics

- Film growth kinetics

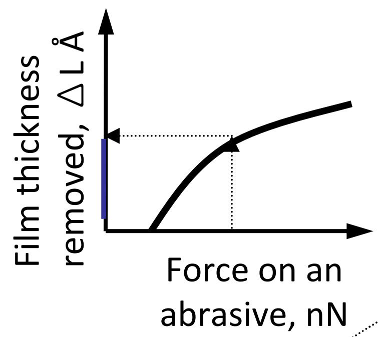


Copper: transient passivation behavior *i(t')*

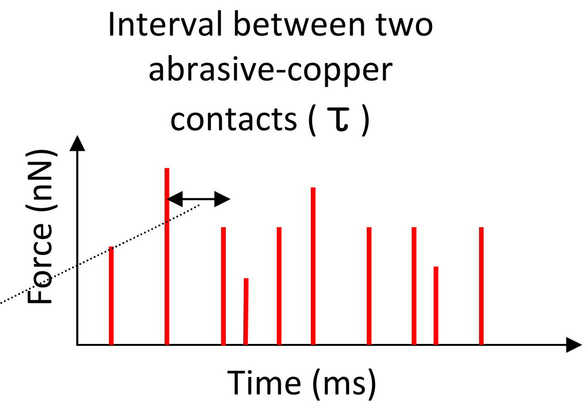
$$L(t_0+\tau)-L(t_0)=\Delta L \Rightarrow t_0$$

t_0 can be found given *L(t') (fig 1.), ΔL (fig 2.)* & *τ (fig 3.)* (since *L(t')* is concave)

Mechanical removal response of passive film



Asperity-abrasive-copper interaction force and frequency



Removal Rate (nm/s)

$$RR=\frac{M_{Cu}}{\rho nF\tau}\int_0^{\tau} i(t_0+t)\,dt$$

M_{Cu} : Atomic mass of copper
ρ : density of copper
n : # e^- transferred
F : Faraday's constant

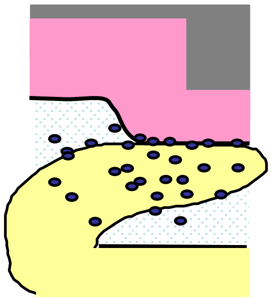
Input Parameters for Model

Frequency of Mechanical Interactions

- Elmufdi and Muldowney (2006) have measured the real contact area of asperities on a typical commercial pad using confocal reflectance interference contrast microscopy
- Real contact ratio, $Ar_{\%}$, between 1 and 10% for the usual operating CMP pressures
- Where $Ar_{\%}$ was 1%, the average asperity contact area, $\overline{Asp}_{area}$ was about 100 μm^2
- If relative pad-wafer velocity is 1 m/s, then average interval between consecutive asperity-copper contacts

$$\tau = \sqrt{\overline{Asp}_{area}} \Big/ V \cdot Ar_{\%} = 1 \text{ ms}$$

- Duration of contact = $\sqrt{\overline{Asp}_{area}} \Big/ V$ = 10 μs << 1 ms



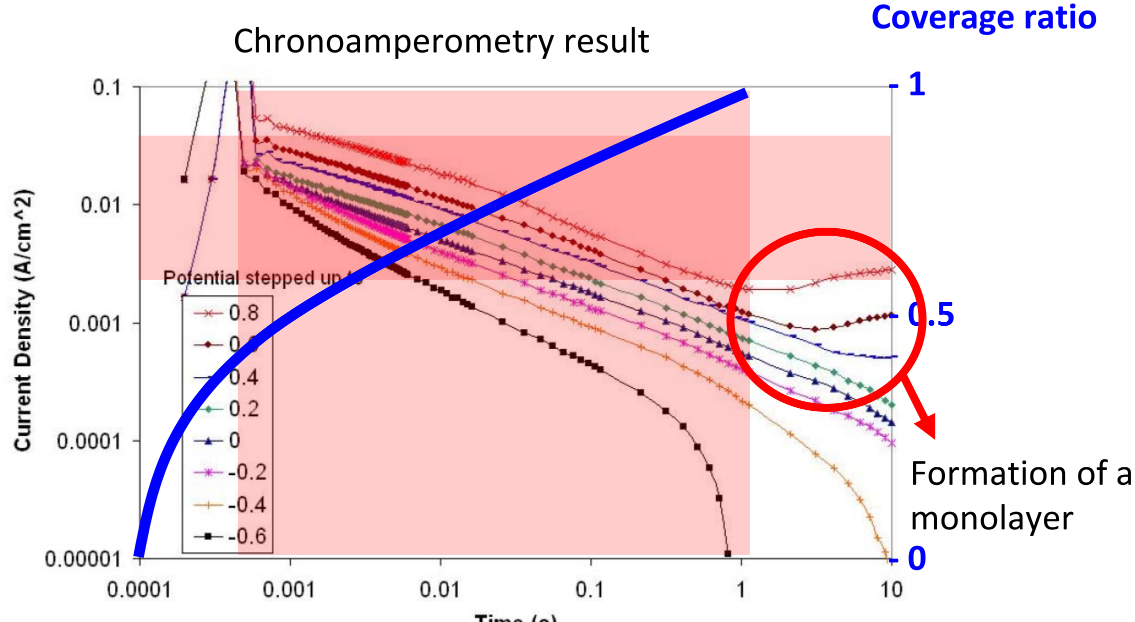
sum abrasive-Cu and asperity-Cu contacts

Protective Film Formed on Cu Surface During Cu CMP in Acidic Slurry Containing BTA

- For intervals between two asperity copper contacts of 1 to 10ms, this corresponds to removal of a copper layer of 0.1 to 1Å thick per interaction => less than one atomic layer of copper (1.4Å)
- Removal due to both dissolution between the two interactions and removal of oxidized copper film by the interaction
- Typical copper removal rates during CMP are in the range of 50 to 600 nm/min.

•There exists only a portion of monolayer protective film on copper during CMP in acidic slurries containing BTA

•A portion of the protective material is removed by the action of asperities/abrasives



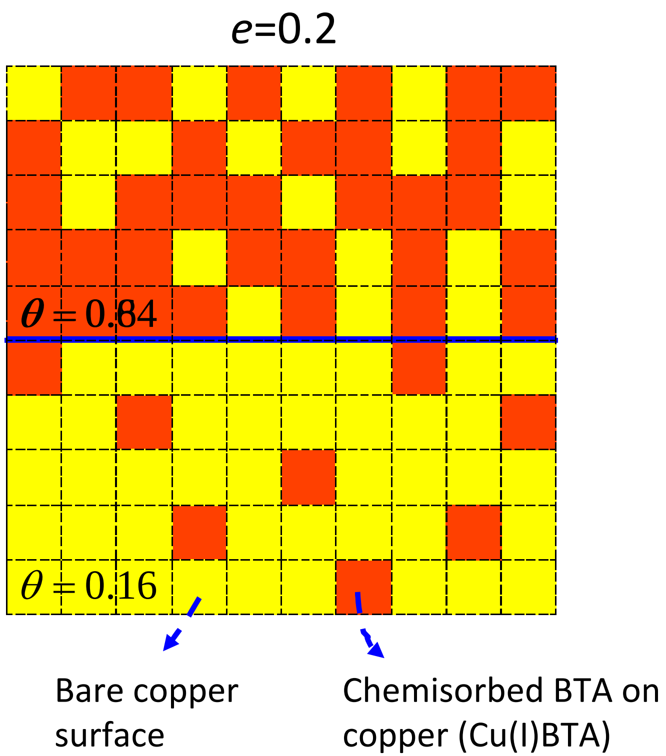
[Tripathi, 2008]

Removal of Protective Film During CMP

- The coverage ratio, Θ is reduced by asperities/abrasives-copper interactions (equivalent to the film thickness reduction where thicker film is formed)
- Removal efficiency:

$$e = 1 - \frac{\theta_{after\ removal}}{\theta_{before\ removal}}$$

- Determined by duration of contact between the material being removed and asperity/abrasives and the material properties of pad, abrasives and the material being removed



Implications for Design of Consumables

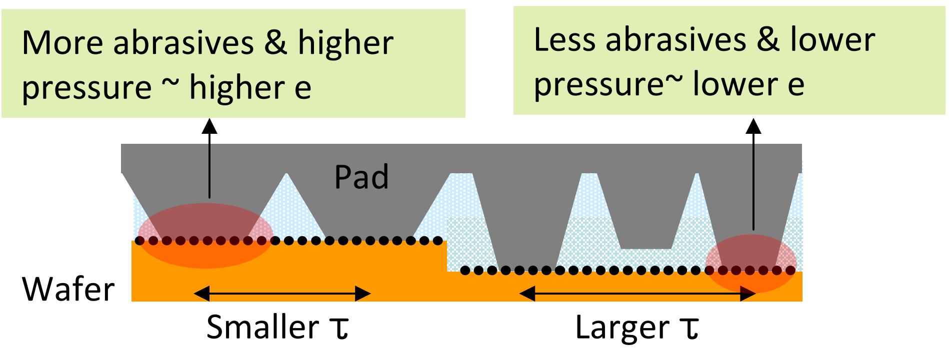
- Draw principal consumables design parameters from the model

Principal design parameters	Interval between consecutive copper-asperity contacts (τ)	Removal efficiency, e	Passivation kinetics
Pad Design	Adjusting distance between asperities and pad compliance*	Adjusting pad compliance and material properties	-
Abrasive Design	-	Varying abrasive concentrations, size or materials	-
Slurry Design	-	-	Varying slurry chemistry

* same effect can be obtained by adjusting processing parameters such as applied pressure and rotational speeds

Implications on Pattern Dependence of Copper CMP

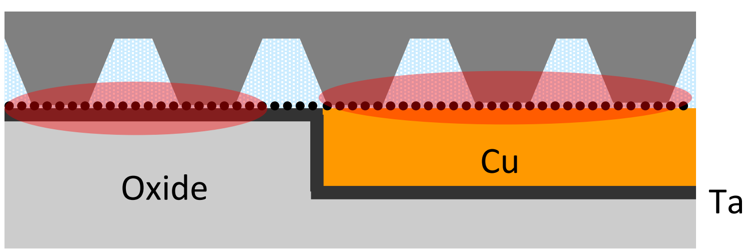
- MRR discrepancy by step height



✓Different removal efficiency, e

✓Different interaction interval, τ

- MRR discrepancy by different materials being removed



✓Different removal efficiency, e

✓Different passivation kinetics

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Summary and Future Work

Summary

- Copper CMP model developed here recognizes principal consumables design parameters, namely passivation kinetics, removal efficiency, e and asperity-copper interaction interval τ
- Pattern related defects can be accounted for and potentially be addressed by these design parameters

Future Work

- To identify factors that affect removal efficiency for Cu in various slurry chemistries
- To develop pattern dependence model by incorporating developed material removal model

Acknowledgement

- Part 1: Interfacial Phenomena

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- Part 2: Modeling
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the UC Discovery Grant

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