"Pad-in-a-Bottle": Planarization with Slurries Containing Suspended Polyurethane Beads

(*Task 425.039*)

Subtask 1: Experimentation

PI:

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Graduate Students:

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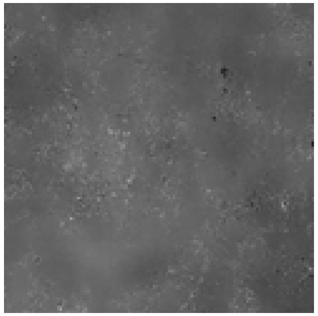
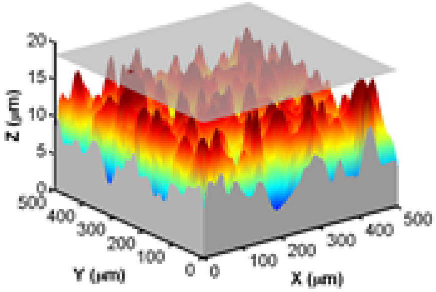
Other Researchers:

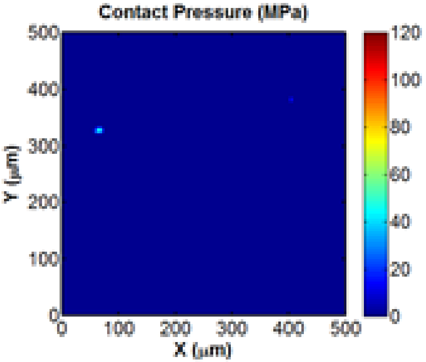
- **Yun Zhuang, Postdoctoral Fellow, Chemical and Environment Engineering, UA**
- **Yasa Sampurno, Postdoctoral Fellow, Chemical and Environment Engineering, UA**

Random Particle – Wafer Contact Events

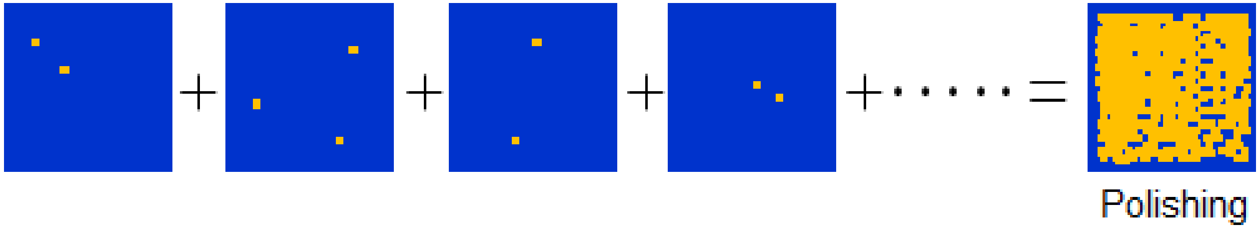
- **Current understanding of conventional CMP:**
  - ✓ **Contact area between pad and wafer is extremely small (0.01%).**
  - ✓ **Polishing is driven by random microscopic contact events.**
  - ✓ **Polishing is achieved by accumulation of single removal events with random pad asperity heights, and random asperity contacts.**



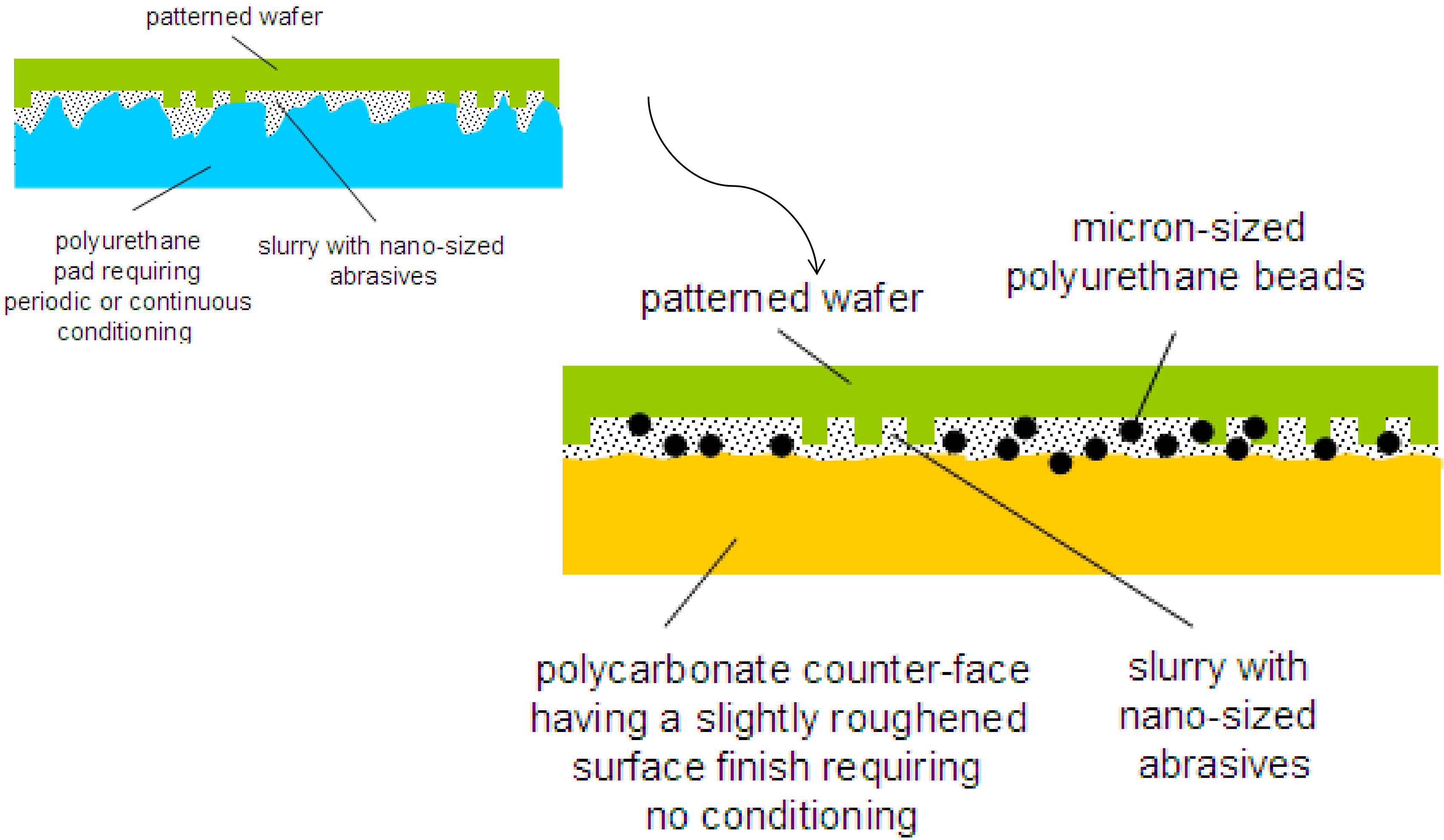




P_0 = 5 PSI (35,000 Pa)



Experimental Approach



patterned wafer

polyurethane pad requiring periodic or continuous conditioning

slurry with nano-sized abrasives

patterned wafer

micron-sized polyurethane beads

polycarbonate counter-face having a slightly roughened surface finish requiring no conditioning

slurry with nano-sized abrasives

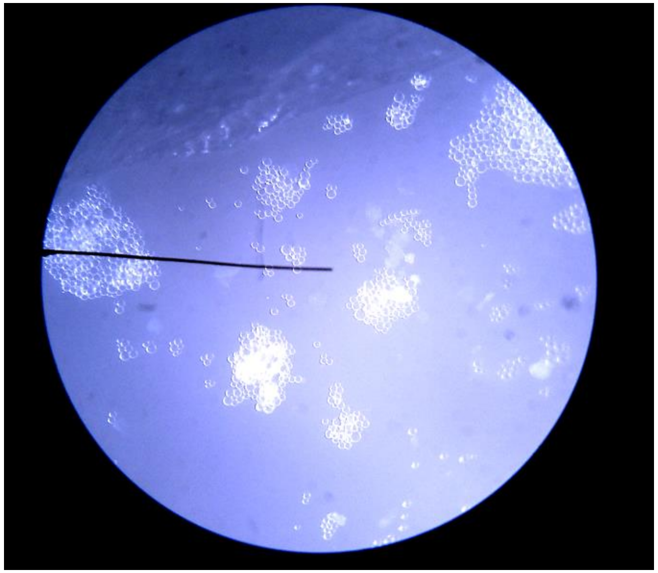
Objectives and EHS Impact

- **Gain fundamental understanding of polishing using polyurethane (PU) beads suspended in slurries**
- **Determine whether PU beads will function as a replacement for pad asperities**
- **Investigate the effect of additive (i.e. surfactant added to the slurry), polishing conditions (i.e. polishing pressure and sliding velocity) as well as size and concentration of PU beads**

EHS Impact – Eliminating the use of pads and diamond disc conditioners by the use of PU beads in slurries

Direct Assembly of PU Beads on Polycarbonate

In Ultra Pure Water

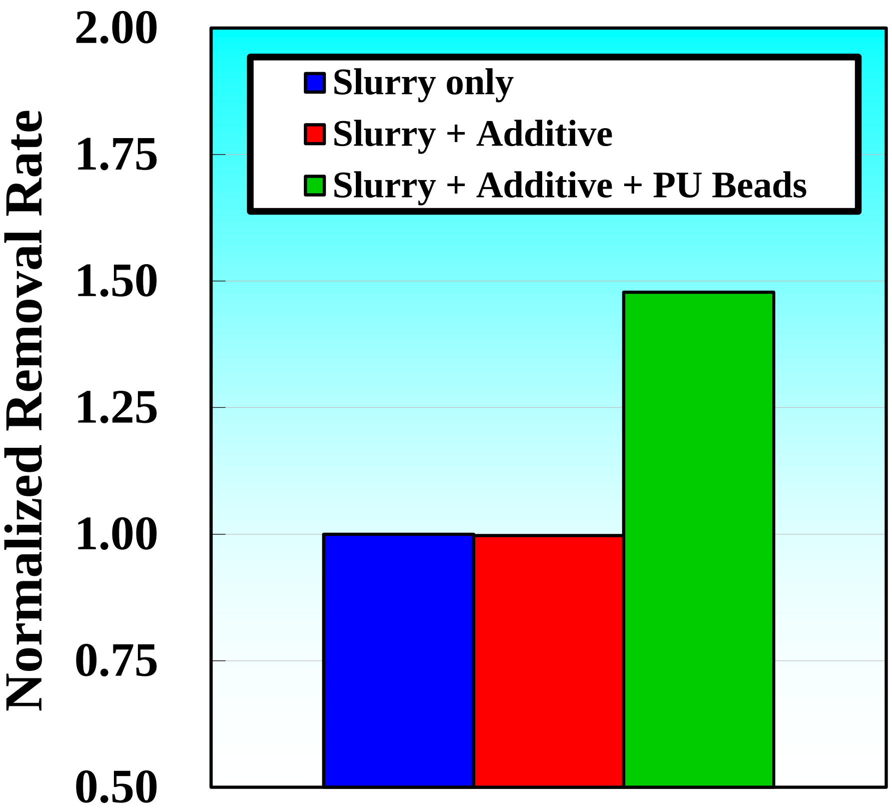


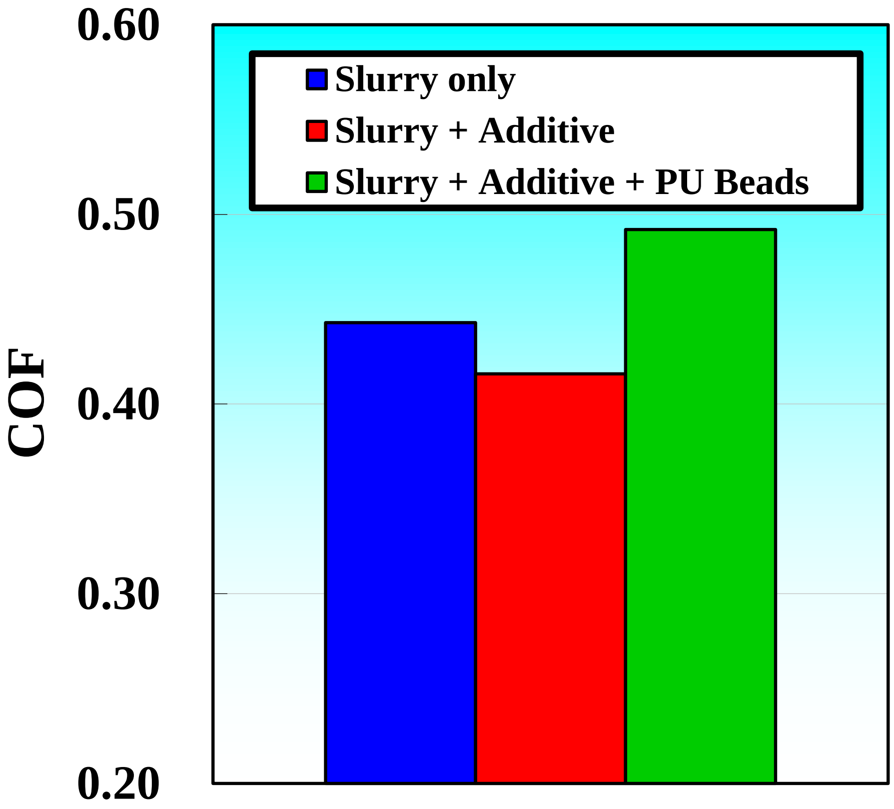
In CMC SS25 slurry (pH 12)

Experimental Conditions

- **APD-500 Polisher and Tribometer**
- **Sliding Velocities**
  - **0.3 and 0.6 m/s**
- **Polishing Pressure**
  - **4.4 PSI**
- **Slurry**
  - **CMC SS25**
- **Additive (i.e. surfactant)**
  - **Silsurf at 0.7 g/L**
- **Slurry Flow Rate**
  - **200 ml/min**
- **Counter-face**
  - **Polycarbonate (flat and circular groove)**
- **Counter-face Break-in**
  - **MMC 325-grit at 6 lb$_f$ for 15 minutes**
- **Counter-face Cleaning**
  - **3M PB32A brush at 3 lb$_f$ for 30 s between polishes**
- **PU Beads**
  - **15 and 35 micron**
  - **0.4 g/L and 2 g/L**
- **Polishing Time**
  - **60 seconds**

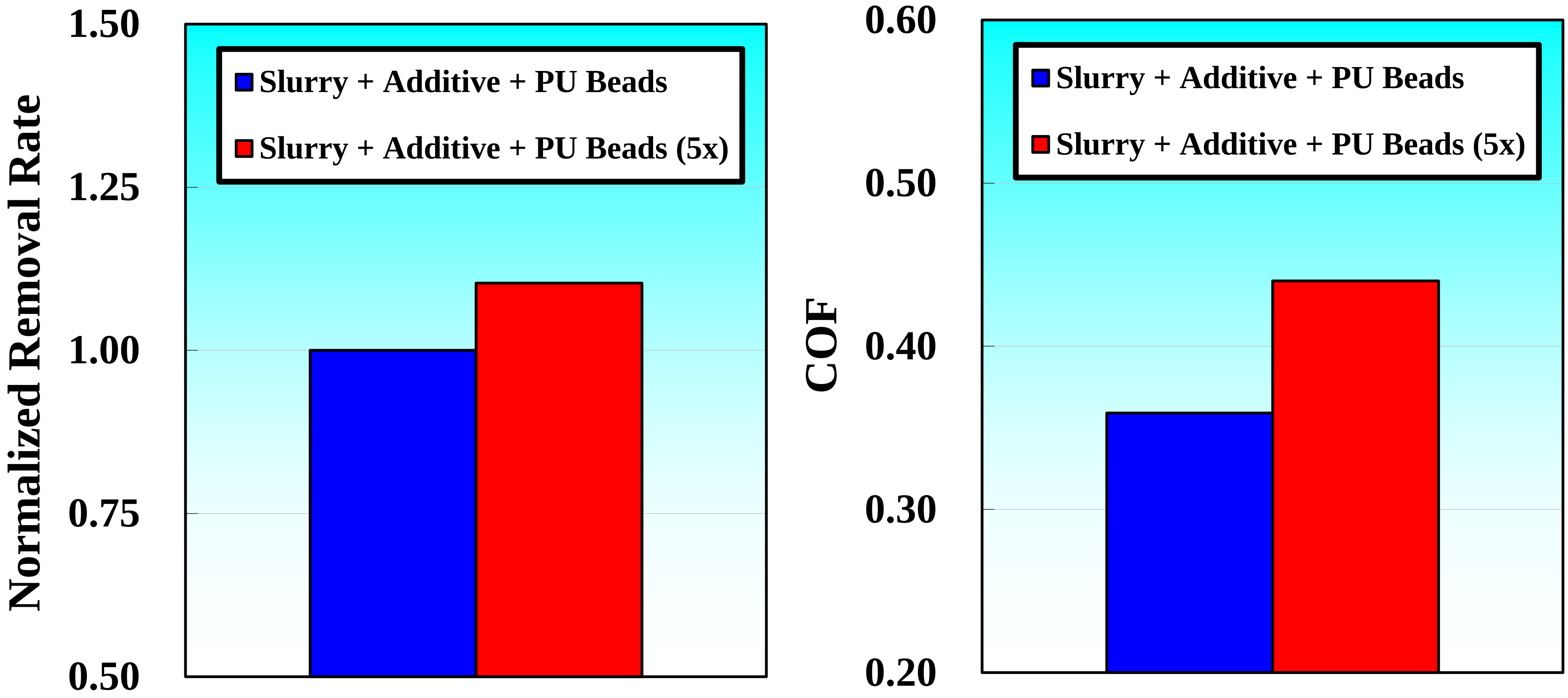
Effect of Additive and PU Beads





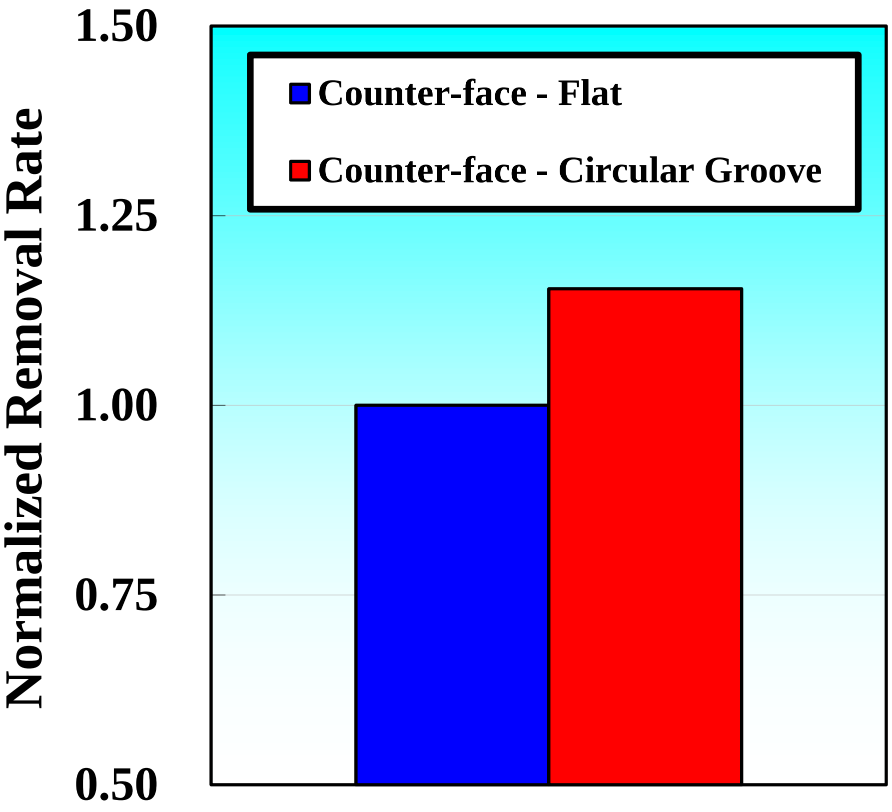
- **Additive does not affect removal rate**
- **The presence of PU beads increases removal rate by as much as 50 percent**

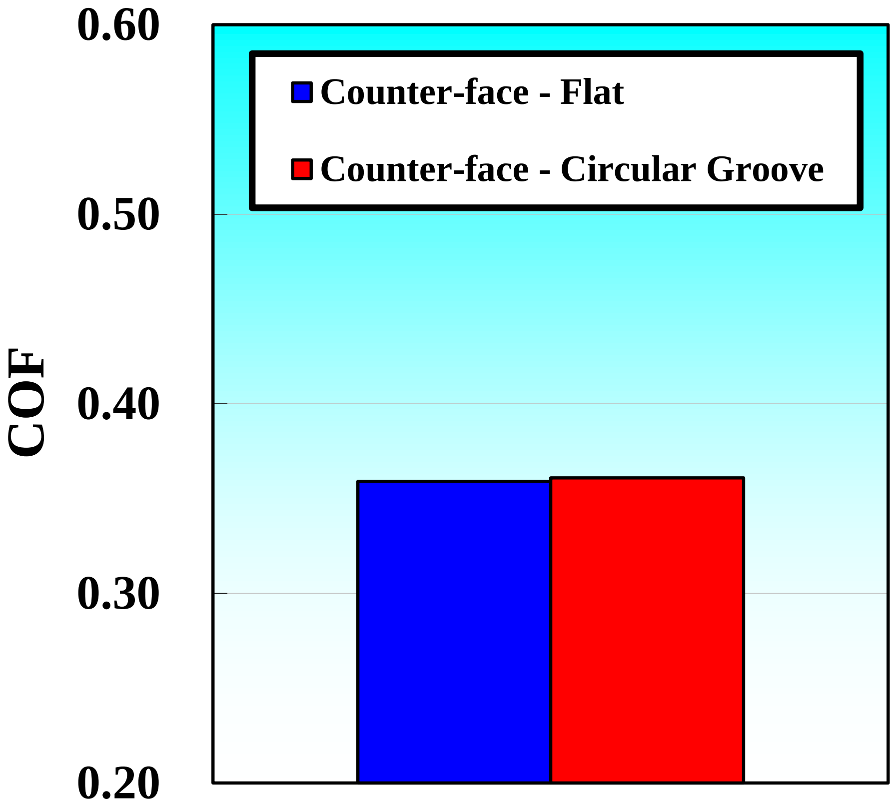
Effect of PU Bead Concentration



- **Removal rate increases with the concentration of PU beads**

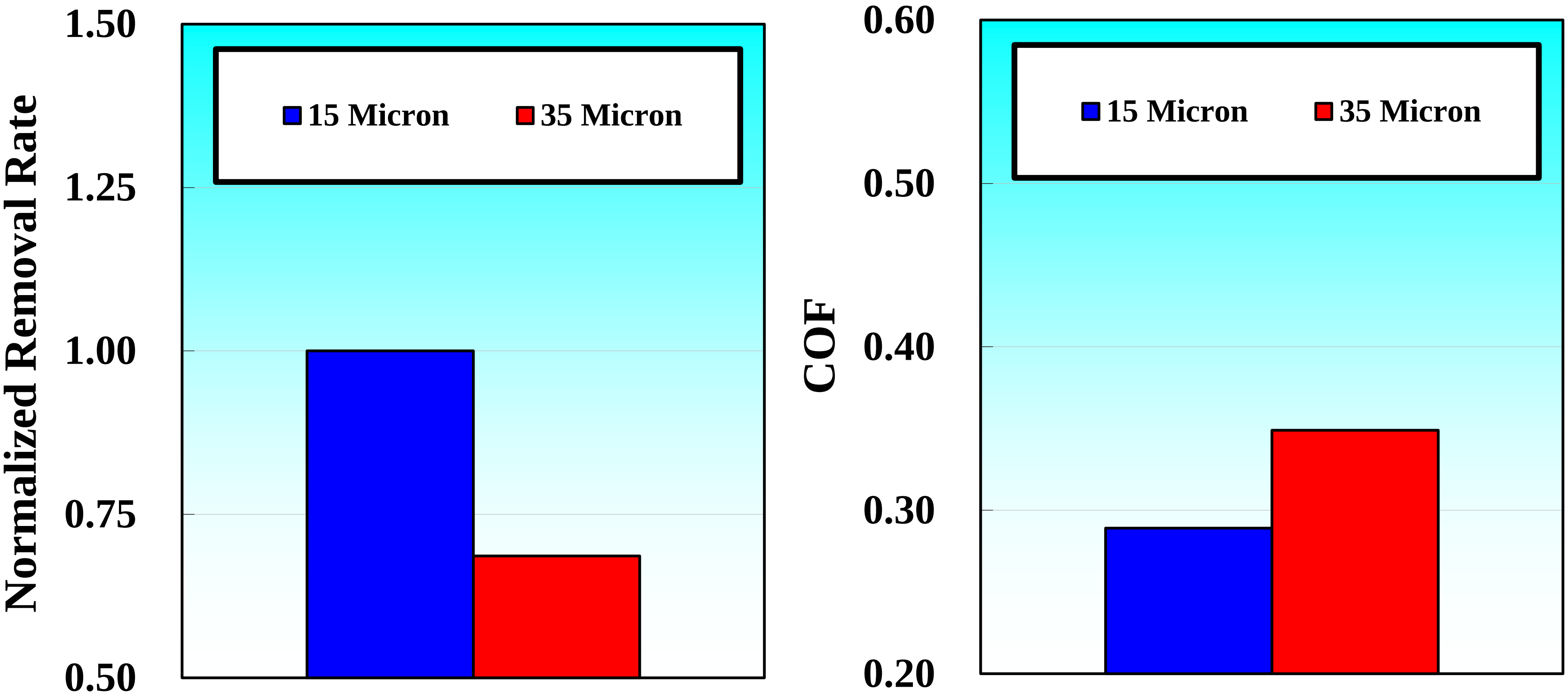
Effect of Grooving in Polycarbonate Counter-face





- **Circular groove in polycarbonate counter-face increases removal rate**

Effect of PU Bead Size



- **With the same weight percentage, PU beads with a larger size reduces removal rate**

Summary

- **Preliminary work of oxide CMP slurry containing suspended PU beads is encouraging.**

- **Additive (i.e. surfactant) is needed to disperse PU beads in the slurry.**

- **Circular grooving in the polycarbonate counter-face increases removal rate.**

- **PU beads modulate oxide removal rate:**
  - ✓ **The presence of PU beads increases oxide removal rate,**
  - ✓ **Higher PU beads concentration increases oxide removal rate,**
  - ✓ **With the same weight concentration, PU beads with a larger size provides a lower oxide removal rate.**

Future Plans

- **Next year plan: investigate different materials for the counter-face and bead**

- **Long-term plan: develop fundamental understanding of the tribological, thermal, kinetic and defect attributes of ‘Pad-in-a-Bottle’ CMP processes**

“Pad-in-a-Bottle”: Planarization with Slurries Containing Suspended Polyurethane Beads

(*Task 425.039)*

Subtask 2: Simulation

PI:

- **Duane Boning, Electrical Engineering and Computer Science, MIT**

Graduate Students:

- **Wei Fan, Ph.D. (completed), EECS, MIT**
- **Joy Johnson, Ph.D. candidate, EECS, MIT**

Objectives

Goal: Gain fundamental understanding of "Pad-in-a-Bottle" CMP thru modeling and experimentation to:

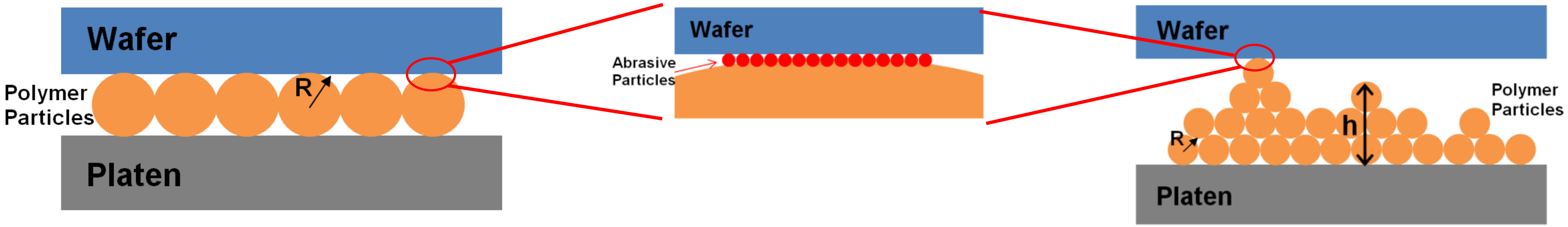
- **Reduce use of high-cost engineered consumables**
- **Reduce generation of by-product wastes**
- **Save processing times requiring significant energy**
- **Enable better process control**

Approach:

1. **Model of fundamental mechanism: (blanket wafer) removal rate modeling**

2. **Develop die-level (patterned wafer) PIB model**

Models for Pad-in-a-Bottle



Case 1: particle packing

Case 2: particle stacking

- Single size polymer particles
  - Polymer particles are much bigger than abrasive particles
- Pure translational motion
- Particles are densely packed
  - Multiple packing layers are possible
- Elastic Hertzian contact

- Single size polymer particles
  - Polymer particles are much bigger than abrasive particles
- Pure translational motion
- Particles are randomly stacked
  - Stacking height distribution can be found
- Elastic Hertzian contact

Case 1 & Case 2: Shared Modeling Assumptions and Approach

- **Single size polymer particles**
  - **Polymer particles with radius *R* are much bigger than abrasive particles**
- **Pure translational motion**
  - **Relative velocity *V***
- **Require a microscopic (local) pressure above a critical pressure *pc* in order for material removal to occur**

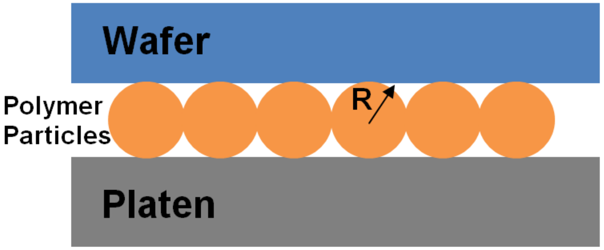
$$\overline{P} > p_c$$

- **Assume microscopic Preston's Law**

$$\overline{RR_p} = K'V(\overline{p} - p_c)$$

- **Under elastic Hertzian contact, can derive macroscopic removal rate relationship for our two cases**

Case 1: Particle Packing



- **Beads are densely packed**
  - **No gap between neighboring beads**
  - **All beads with radius *R* bear force from wafer, with compressed deflection δ**
  - **Express bead contact area *a*, single particle load *L*, and average pressure $\bar{p}(\delta)$ within contact:**

$$a(\delta) = \pi R \delta$$

$$L(\delta) = \frac{4}{3} E_p R^{\frac{1}{2}} \delta^{\frac{3}{2}}$$

$$\bar{p}(\delta) = \frac{L(\delta)}{a(\delta)} = \frac{4E_p}{3\pi} R^{-\frac{1}{2}} \delta^{\frac{1}{2}}$$

- **Require a microscopic (local) pressure above a critical pressure p_c in order for material removal to occur**
  - **Relate to macroscopic threshold pressure P_{th}:**

$$p_c = \frac{4}{\pi}\left(\frac{E_p}{3}\right)^{\frac{2}{3}} P_{th}^{\frac{1}{3}}$$

- **Relate average pressure within contact to the applied (wafer level) reference pressure P_0:**

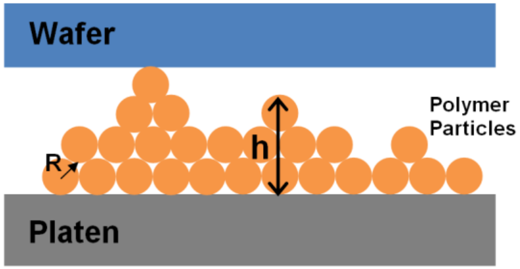
$$\bar{p}(P_0) = \frac{4}{\pi}\left(\frac{E_p}{3}\right)^{\frac{2}{3}} P_0^{\frac{1}{3}}$$

- **Gives a macroscopic removal rate with nonlinear dependence on pressure:**

$$\boxed{RR = \frac{1}{\pi R^2}\left(\frac{E_p}{3}\right)^{\frac{2}{3}} K'V\left(P_0^{\frac{1}{3}} - P_{th}^{\frac{1}{3}}\right)}$$

Result: Removal is applied pressure driven

Case 2: Particle Stacking



- **Assume random stacking height distribution with probability density ϕ(*h*). For wafer-platen distance *d*, number of peaks *n* in contact (*N* is total number of active peaks):**

$$n = N \int_d^\infty \phi(h)\, dh$$

- **For peaks with *h*>*d*, deformation is δ = *h*-*d* and total peak contact area *A* is:**

$$A = N \int^\infty a(h-d)\phi(h)\, dh$$

- **Applied force F_0 is:**

$$F_0 = N \int_d^\infty L(h-d)\phi(h)\, dh$$

- **Assume exponential height distribution:**

$$\phi(h) = \frac{1}{\lambda} e^{-\frac{h}{\lambda}}$$

- **Can solve for average pressure in contact:**

$$\bar{p} = \frac{F_0}{A} = \frac{E_p \sqrt{\lambda}}{\sqrt{\pi R}}$$

- **Gives macroscopic removal rate that is linearly dependent on applied pressure:**

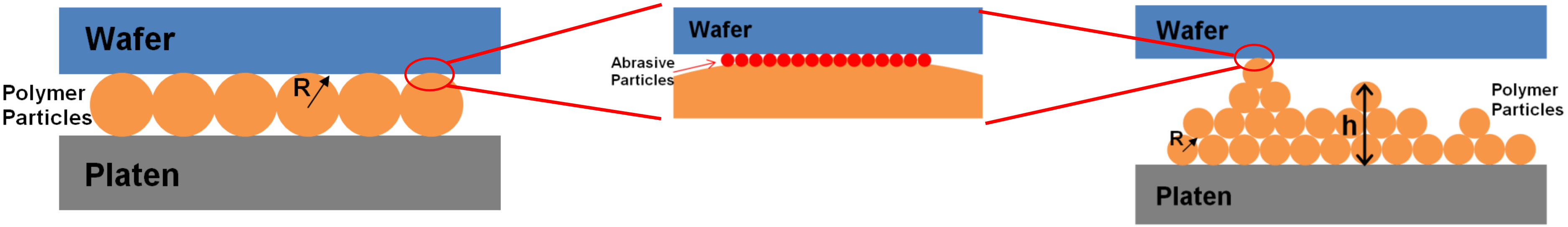
$$\boxed{RR = \overline{RR_p} \frac{N}{A_0} = \frac{1}{\pi R \lambda} K'VP_0}$$

Result: Removal is event (contacts) driven

Comparison: Models for Pad-in-a-Bottle

Case 1: particle packing

Case 2: particle stacking



$$RR = \frac{1}{\pi R^2}\left(\frac{E_p}{3}\right)^{\frac{2}{3}} K'V\left(P_0^{\frac{1}{3}} - P_{th}^{\frac{1}{3}}\right)$$

Applied pressure driven

$$RR = \overline{RR_p}\,\frac{N}{A_0} = \frac{1}{\pi R\lambda} K'VP_0$$

Event (contacts) driven

- **A high threshold pressure can be estimated, implying difficult or inefficient material removal:**

$$P_{th} = \frac{9}{64}\frac{\pi^3 p_c^{\;3}}{E_p^{\;2}} \sim 20\text{psi}$$

Summary

- **Developed modeling approach for PIB removal rate**
- **Consider two cases: dense-pack and stacked particles**
- **Model indicates that monosized, dense-pack PIB arrangement may not provide enough local contact pressure to enable efficient material removal/polishing**
- **Opportunity for experimental validation:**
  - **Different removal rate vs. pressure relationships**
  - **Different removal rate vs. bead size relationships**

Industrial Interactions

- **Cabot Microelectronics – Wei Fan, summer 2011 internship**

  Dr. Fan completed his MIT PhD in Fall 2012 and joined Cabot Microelectronics upon graduation.

Publications and Presentations

- J. M. Johnson, D. S. Boning, G.-S. Kim, P. Safier, K. Knutson, R. Mudhivarthi, and K. Pate, "Slurry Abrasive Particle Agglomeration Experimentation and Modeling for Chemical Mechanical Planarization (CMP)," International Conference on Planarization Technology (ICPT), Grenoble, France, Oct. 2012.

- W. Fan, J. Johnson, and D. Boning, "Modeling of 'Pad-in-a-Bottle': A Novel Planarization Process Using Suspended Polymer Beads," paper BB2.01, Symposium BB: Evolutions in Planarization – Equipment, Materials, Techniques, and Applications. Materials Research Society Spring Meeting, San Francisco, CA, April 2013.