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

(*Task 425.039)*

Subtask 1: Experimentation

PI:

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Other Researchers:

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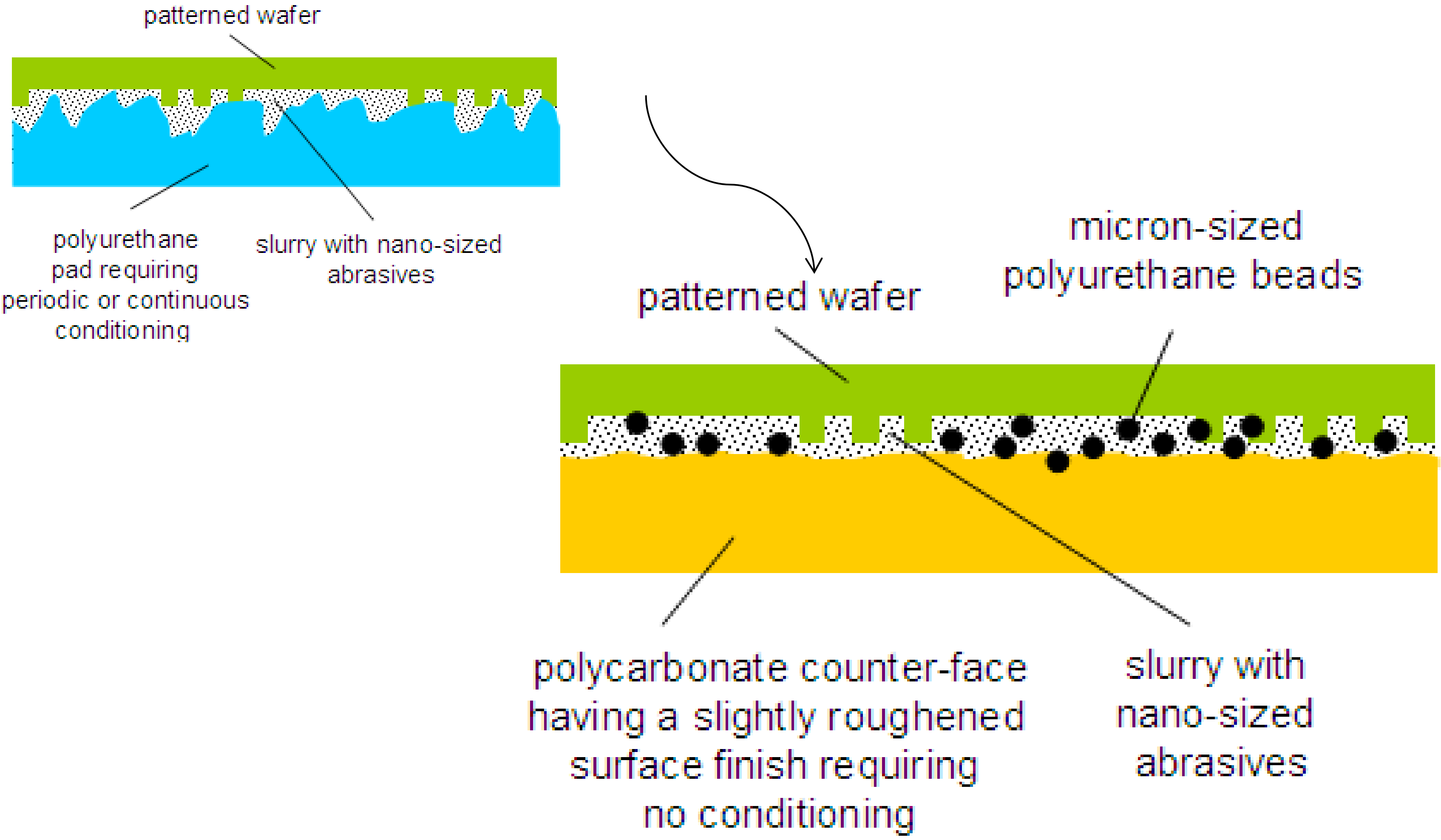
- Yasa Sampurno, Postdoctoral Fellow, Chemical and Environment Engineering, UA

Experimental Approach



Objectives and EHS Impacts

Objectives

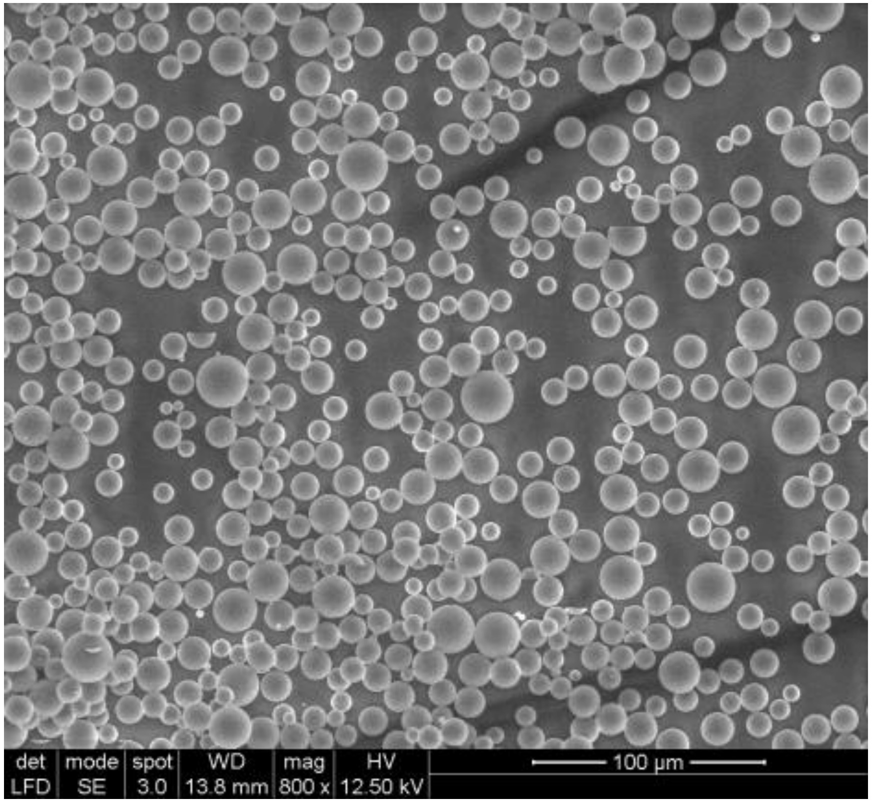
- Determine whether PU beads will function as a replacement for pad asperities for copper polishing
- Investigate the effect of additive (i.e. surfactant added to the slurry to disperse PU beads), polishing pressure as well as size and concentration of PU beads for copper polishing

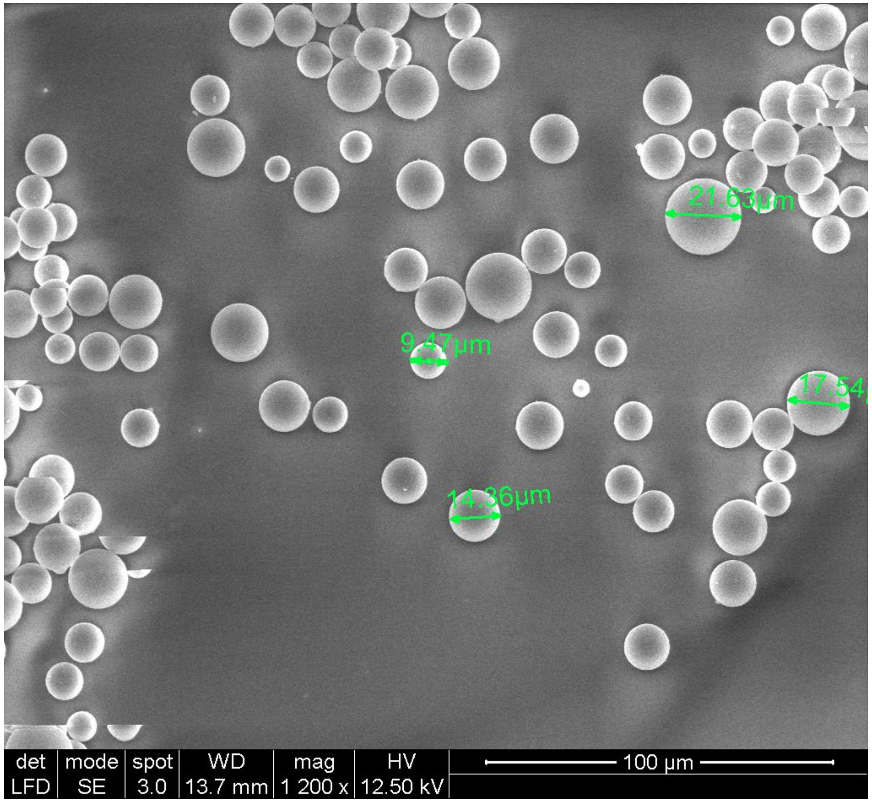
EHS Impacts

- Eliminating the use of pads for copper polishing (by 100%)
- Reduce the use of diamond disc conditioners (by 95%)

SEM Images of PU Beads

D_{50} = 15 µm

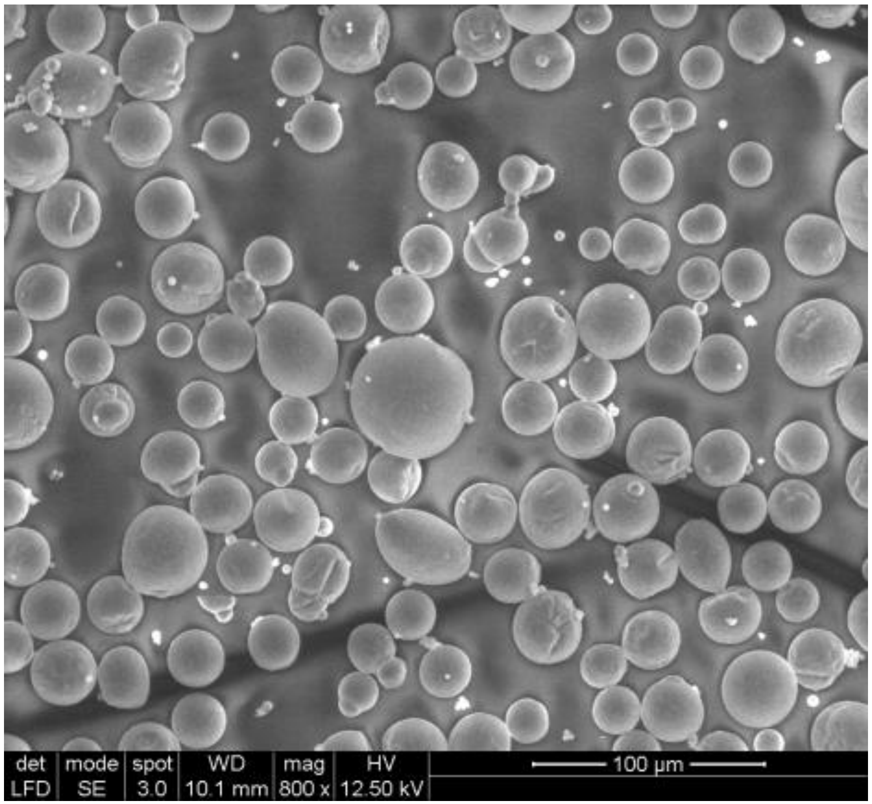


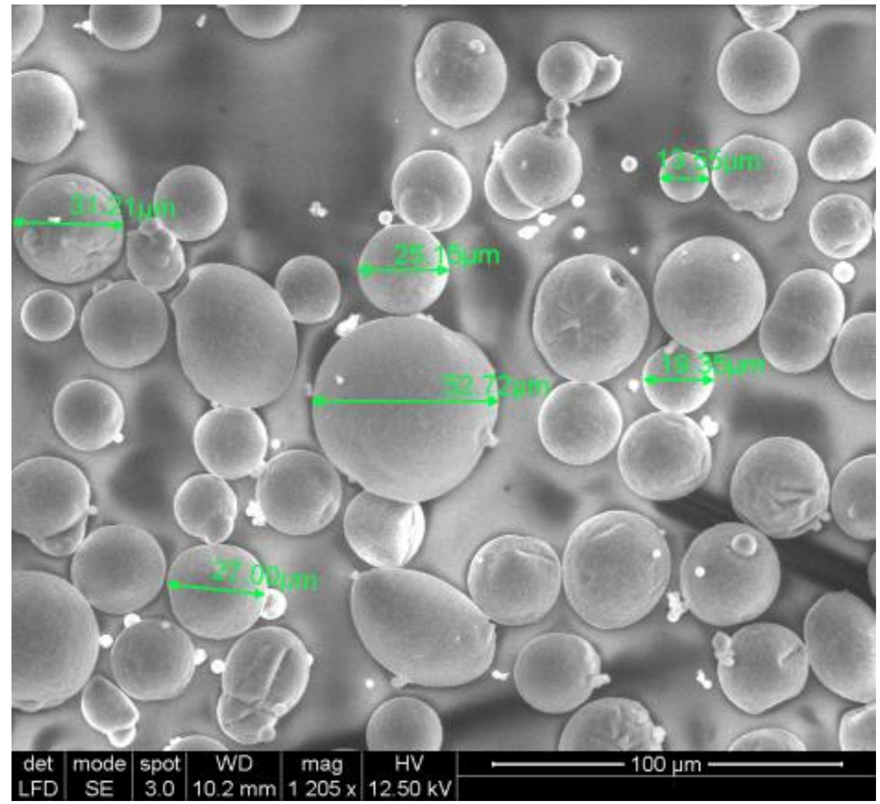


PU beads are in spherical shape and have a smooth surface.

SEM Images of PU Beads

D_{50} = 35 µm





PU beads have irregular round shapes and some beads have a rough surface.

Experimental Conditions

– **Sliding Velocity**
  • **0.6 m/s**

– **Polishing Pressures**
  • **1.5 and 2.5 PSI**

– **Slurry**
  • **CMC iCue EP-C600Y-75**

– **Surfactant and Concentrations**
  • **Fluorosil**
  • **0.7 and 7 g/L**

– **Slurry Flow Rate**
  • **200 ml/min**

– **Polishing Time**
  • **60 seconds**

– **Counter-face**
  • **Polycarbonate with circular grooves**

– **Counter-face Break-in**
  • **MMC 325-grit at 6 lb_f for 15 minutes**

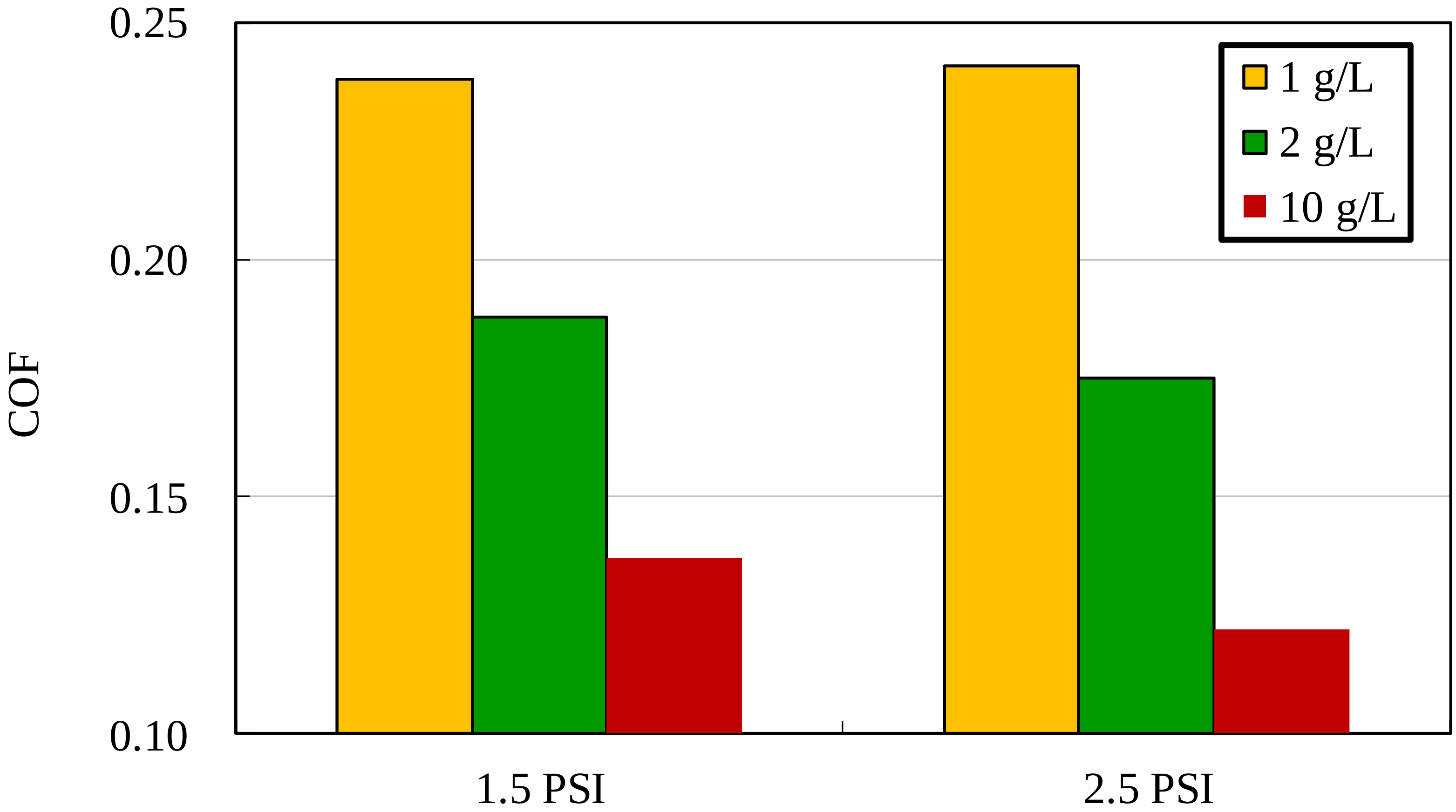
– **Counter-face Cleaning**
  • **3M PB32A brush at 3 lb_f for 30 s between polishes**

– **PU Beads and Concentrations**
  • **D_{50} of 15 and 35 microns**
  • **1, 2 and 10 g/L**

– **Polisher**
  • **APD-500 polisher and tribometer**

Effect of PU Bead Concentration

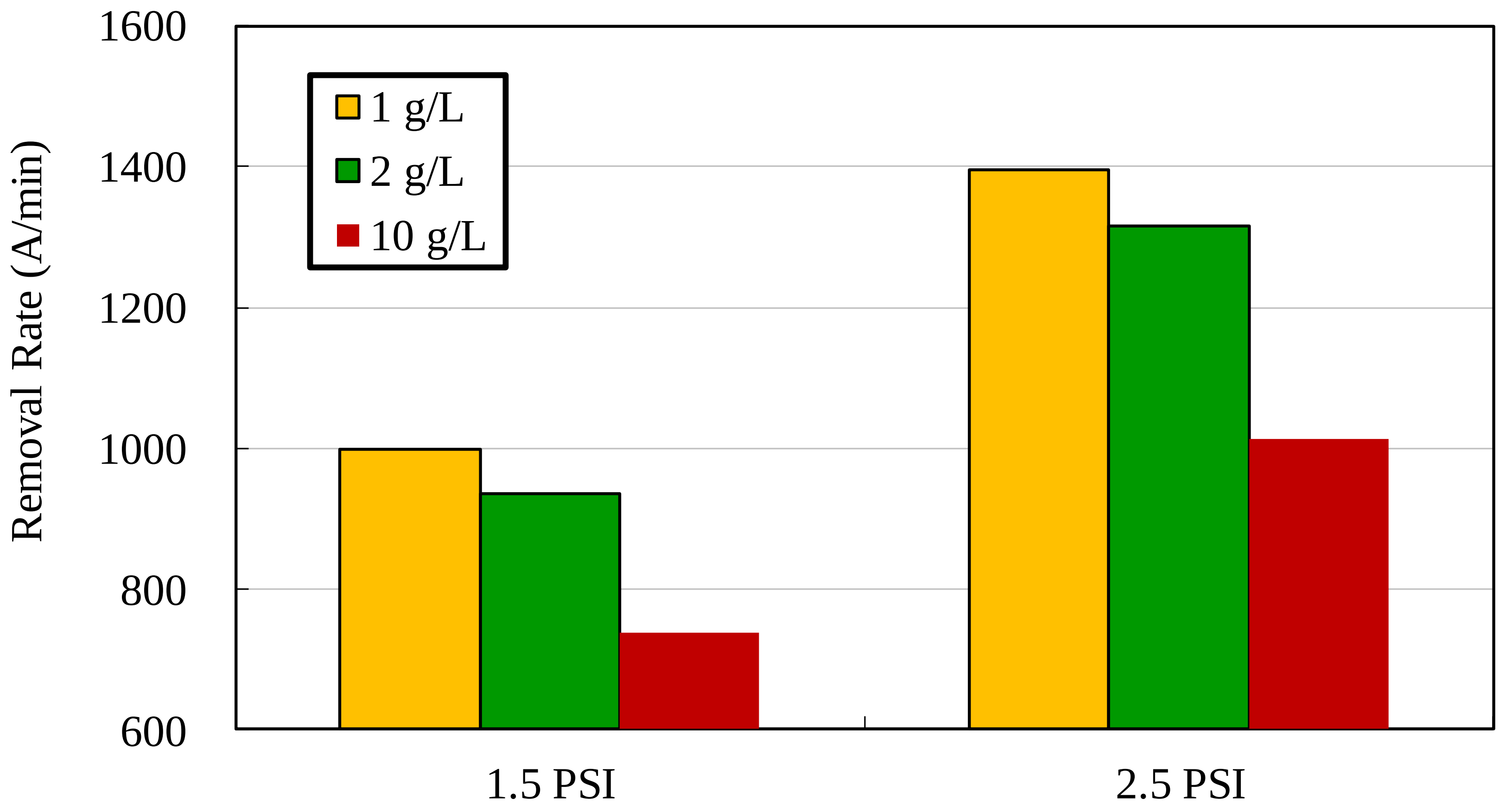
D_{50} = 15 μm, $C_{Fluorosil}$ = 7 g/L



COF decreases with an increase of PU bead concentration.

Effect of PU Bead Concentration

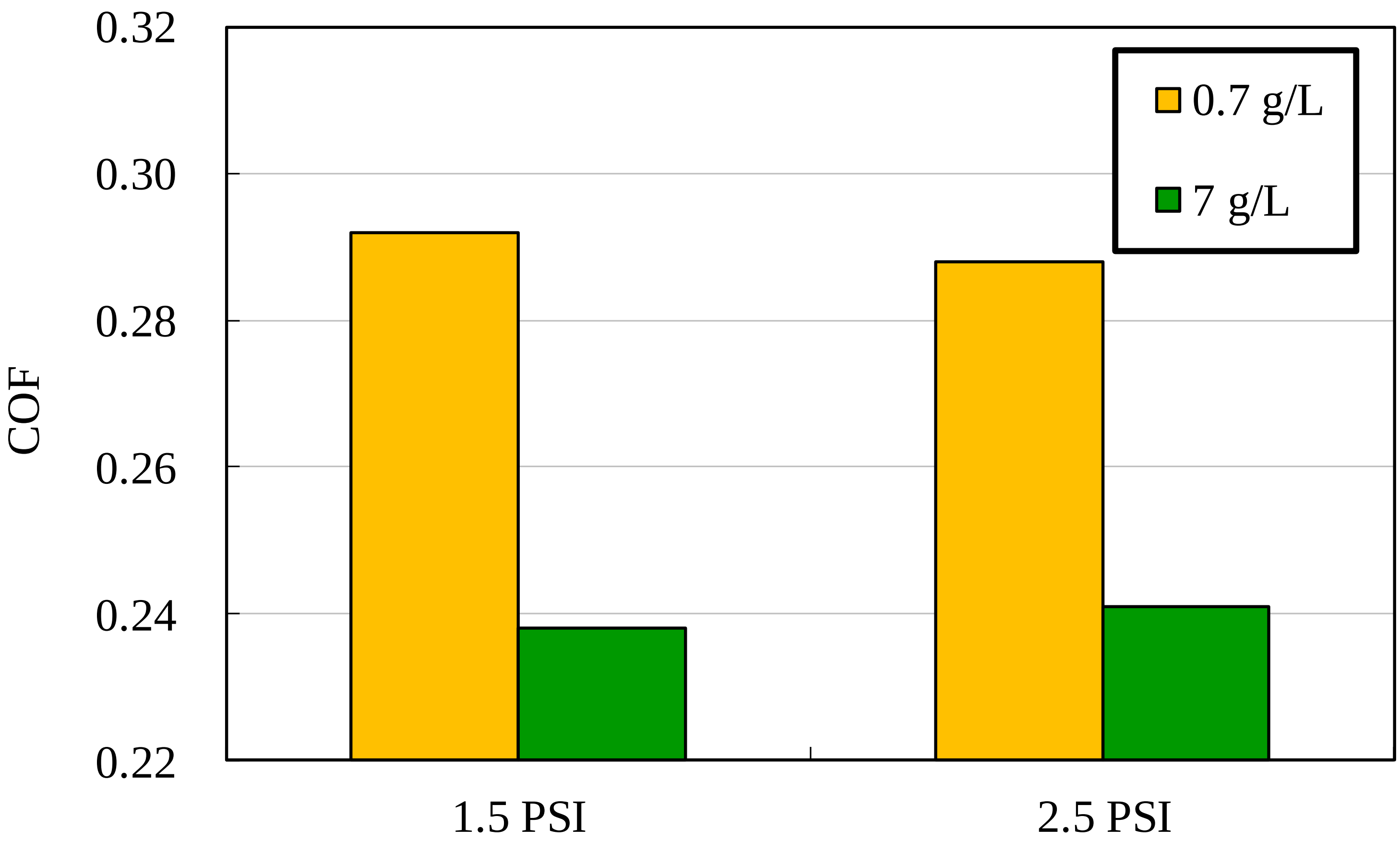
D_{50} = 15 μm, $C_{Fluorosil}$ = 7 g/L



Removal rate decreases with an increase of PU bead concentration.

Effect of Fluorosil Concentration

D_{50} = 15 µm, $C_{PU\ Bead}$ = 1 g/L



COF decreases with an increase of Fluorosil concentration.

Effect of Fluorosil Concentration

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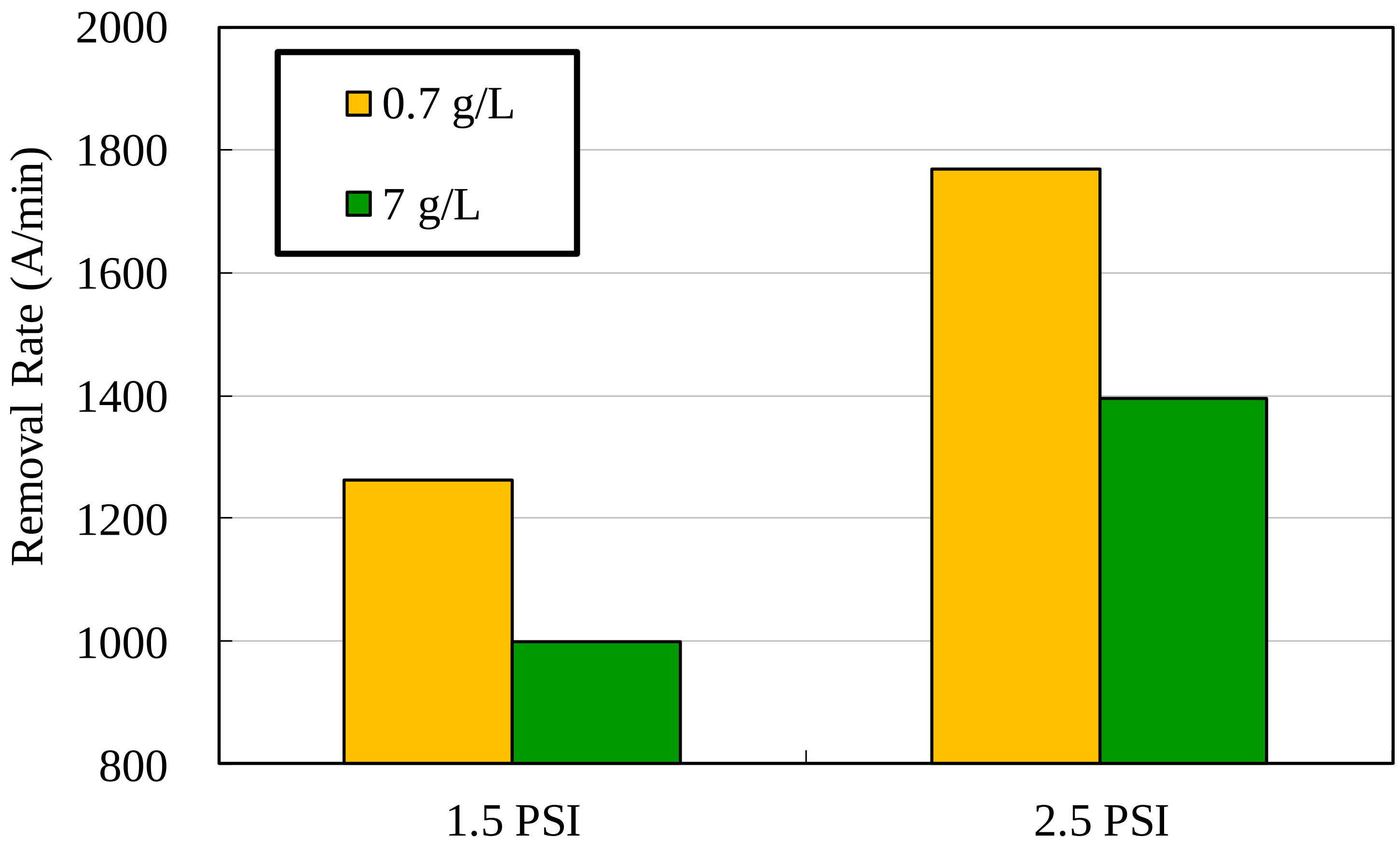
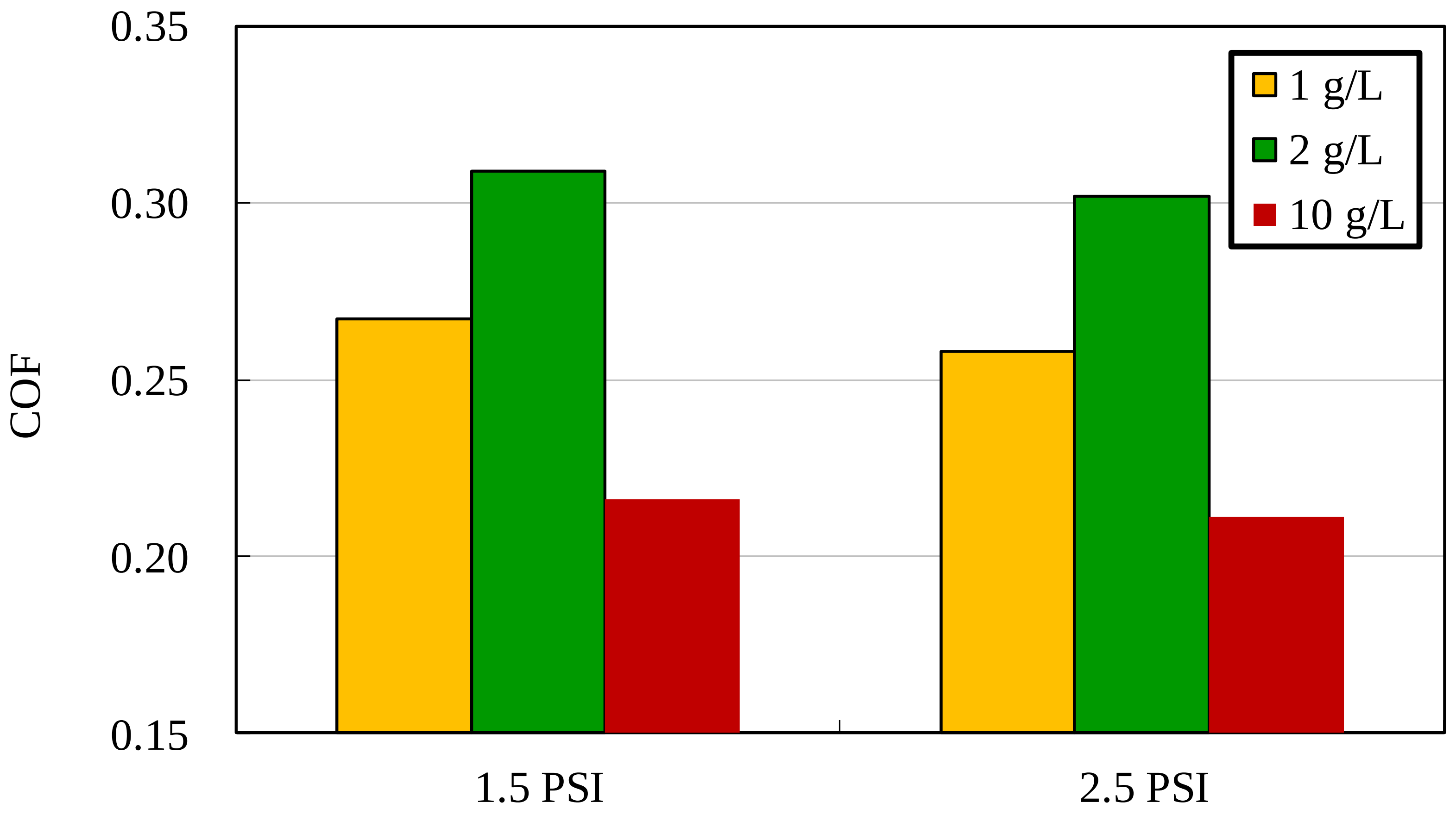


Removal rate decreases with an increase of PU bead concentration.

Effect of PU Bead Concentration

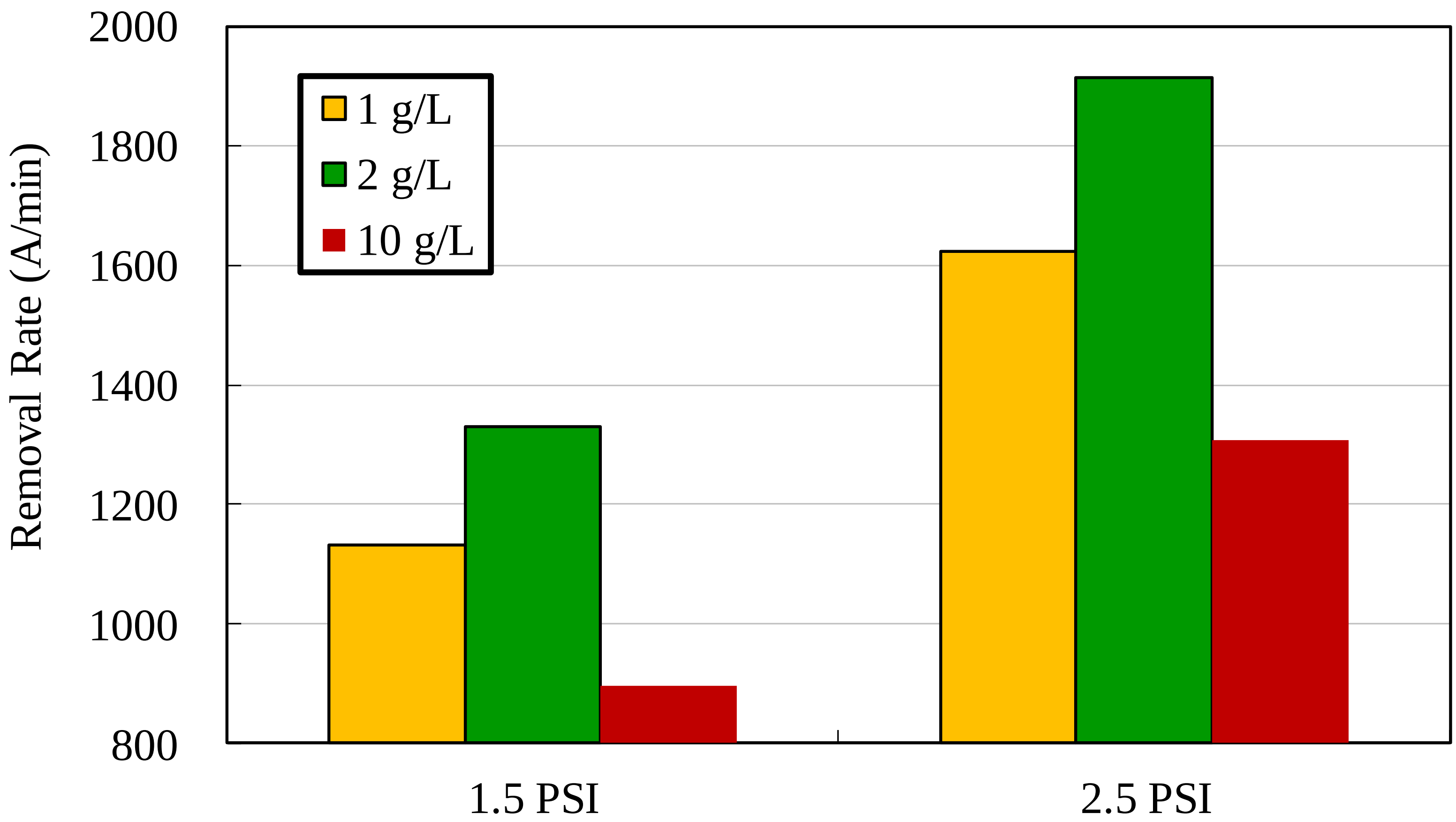
D_{50} = 35 µm, $C_{Fluorosil}$ = 7 g/L



COF first increases when PU bead concentration increases from 1 to 2 g/L and then decreases when PU bead concentration increases further to 10 g/L.

Effect of PU Bead Concentration

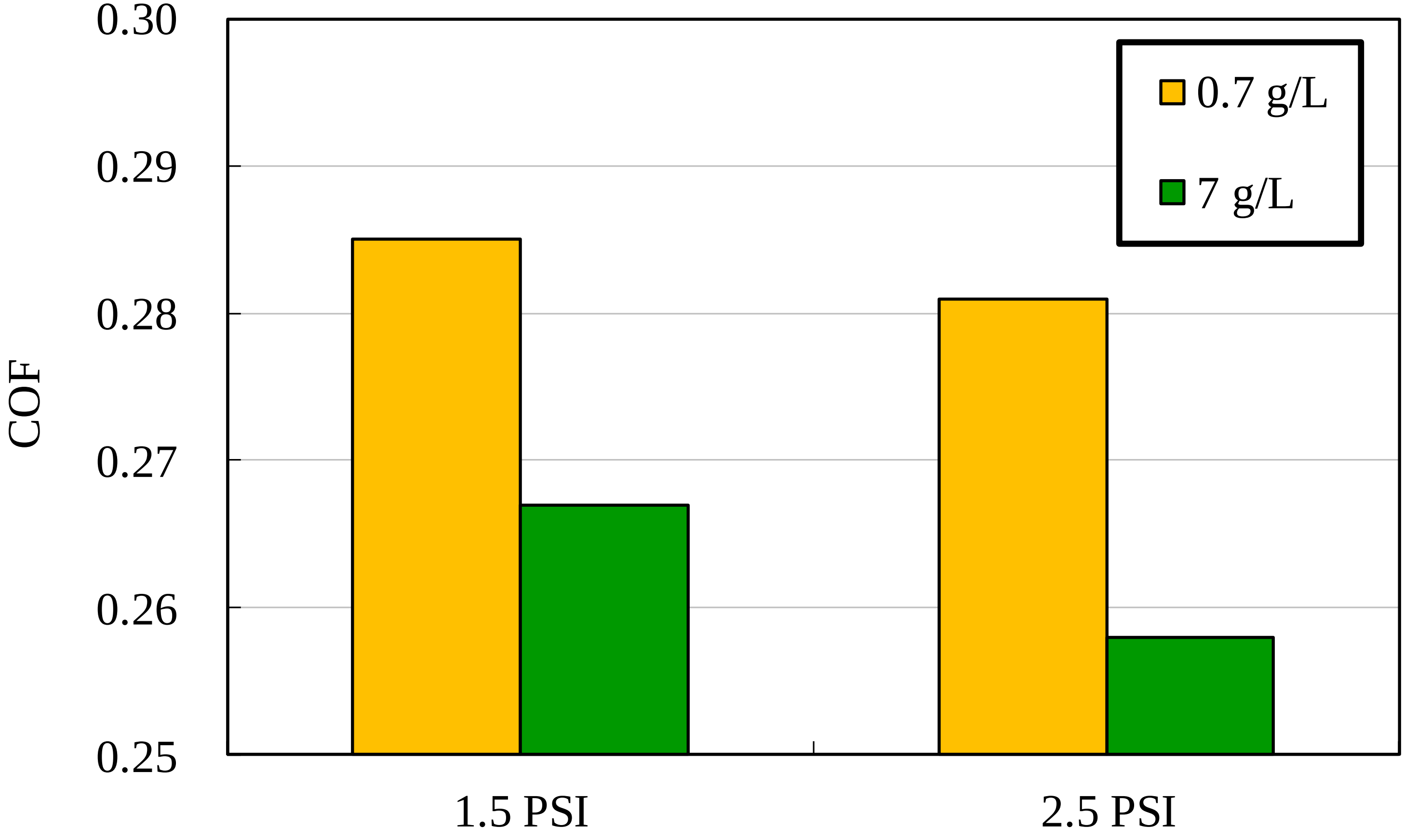
D_{50} = 35 μm, $C_{Fluorosil}$ = 7 g/L



Removal rate first increases when PU bead concentration increases from 1 to 2 g/L and then decreases when PU bead concentration increases further to 10 g/L.

Effect of Fluorosil Concentration

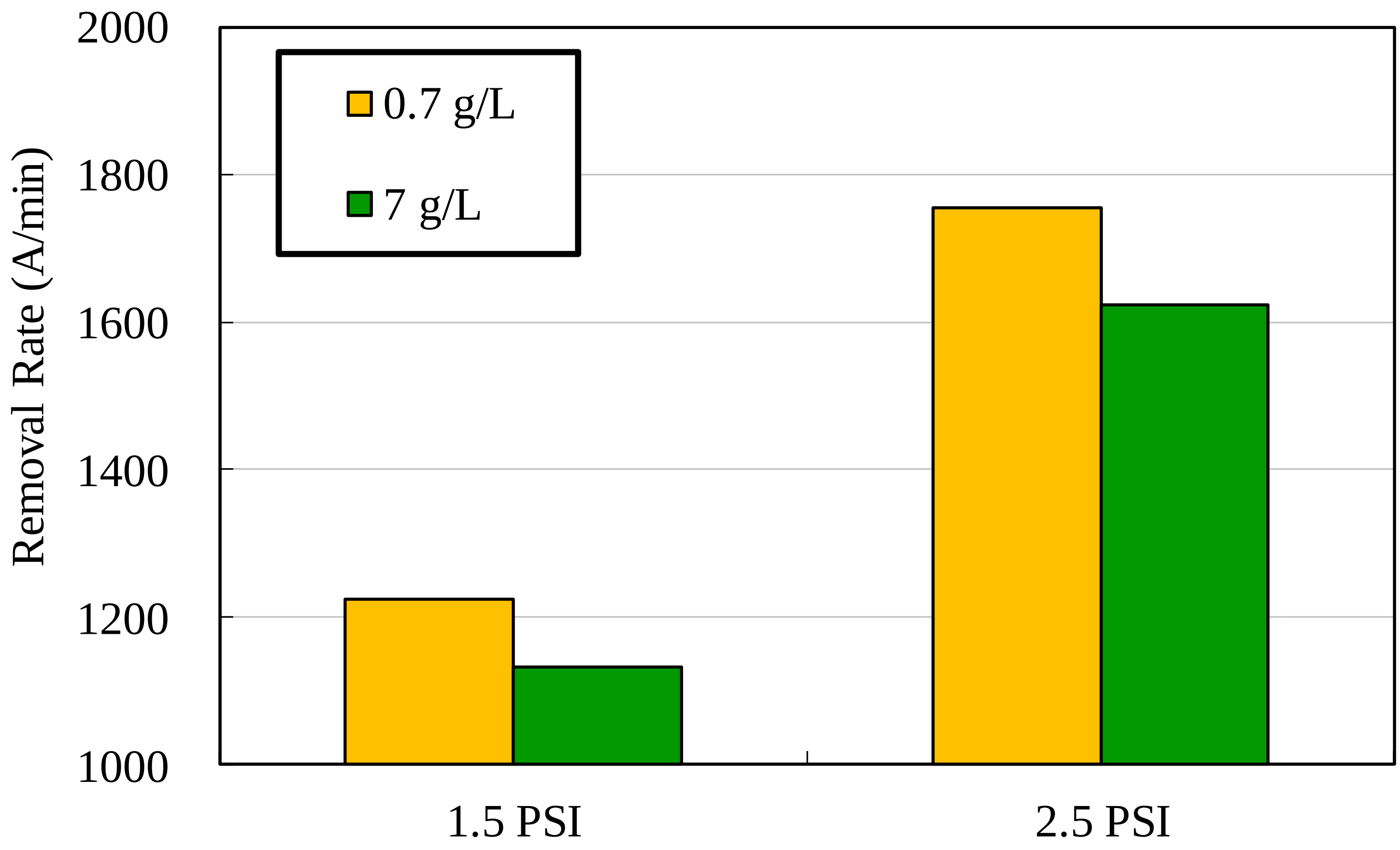
D_{50} = 35 μm, $C_{PU\ Bead}$ = 1 g/L



COF decreases with an increase of Fluorosil concentration.

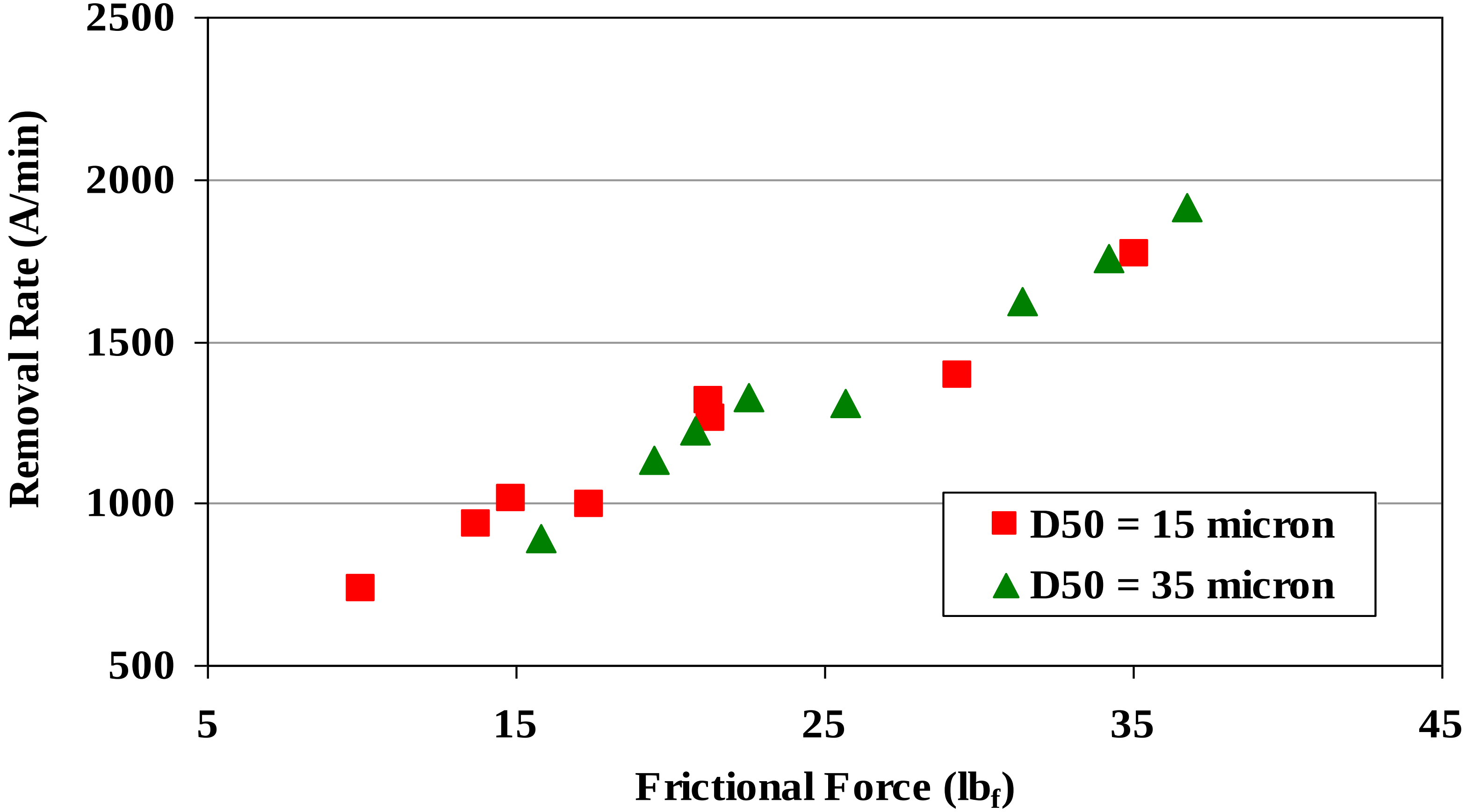
Effect of Fluorosil Concentration

D_{50} = 35 µm, $C_{PU\ Bead}$ = 1 g/L



Removal rate decreases with an increase of Fluorosil concentration.

Removal Rate vs. Frictional Force



In general, removal rate increases with measured frictional force.

With the same weight concentration, PU beads with D_{50} of 35 µm provide higher frictional force and removal rate than PU beads with D_{50} of 15 µm.

Summary

- **PU beads are successfully suspended in the CMC iCue EP-C600Y-75 slurry with surfactant Fluorosil.**

- **PU beads with D_{50} of 15 µm are in spherical shape and have a smooth surface. In comparison, PU beads with D_{50} of 35 µm have irregular round shapes and some beads have a rough surface.**

- **For PU beads with D_{50} of 15 µm, COF and removal rate decrease with an increase of PU bead concentration and Fluorosil concentration.**

- **For PU beads with D_{50} of 35 µm, COF and removal rate first increase when PU bead concentration increases from 1 to 2 g/L and then decrease when PU bead concentration increases further to 10 g/L. COF and removal rate decrease with an increase of Fluorosil concentration.**

- **With the same weight concentration, PU beads with D_{50} of 35 µm provide higher frictional force and removal rate than PU beads with D_{50} of 15 µm.**

Future Plans

- **Year 3 plan: polish patterned wafers using commercial slurry containing PU beads and study the effect of PU bead size and concentration**

- **Long-term plan: develop fundamental understanding of the tribological, thermal and kinetic 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**

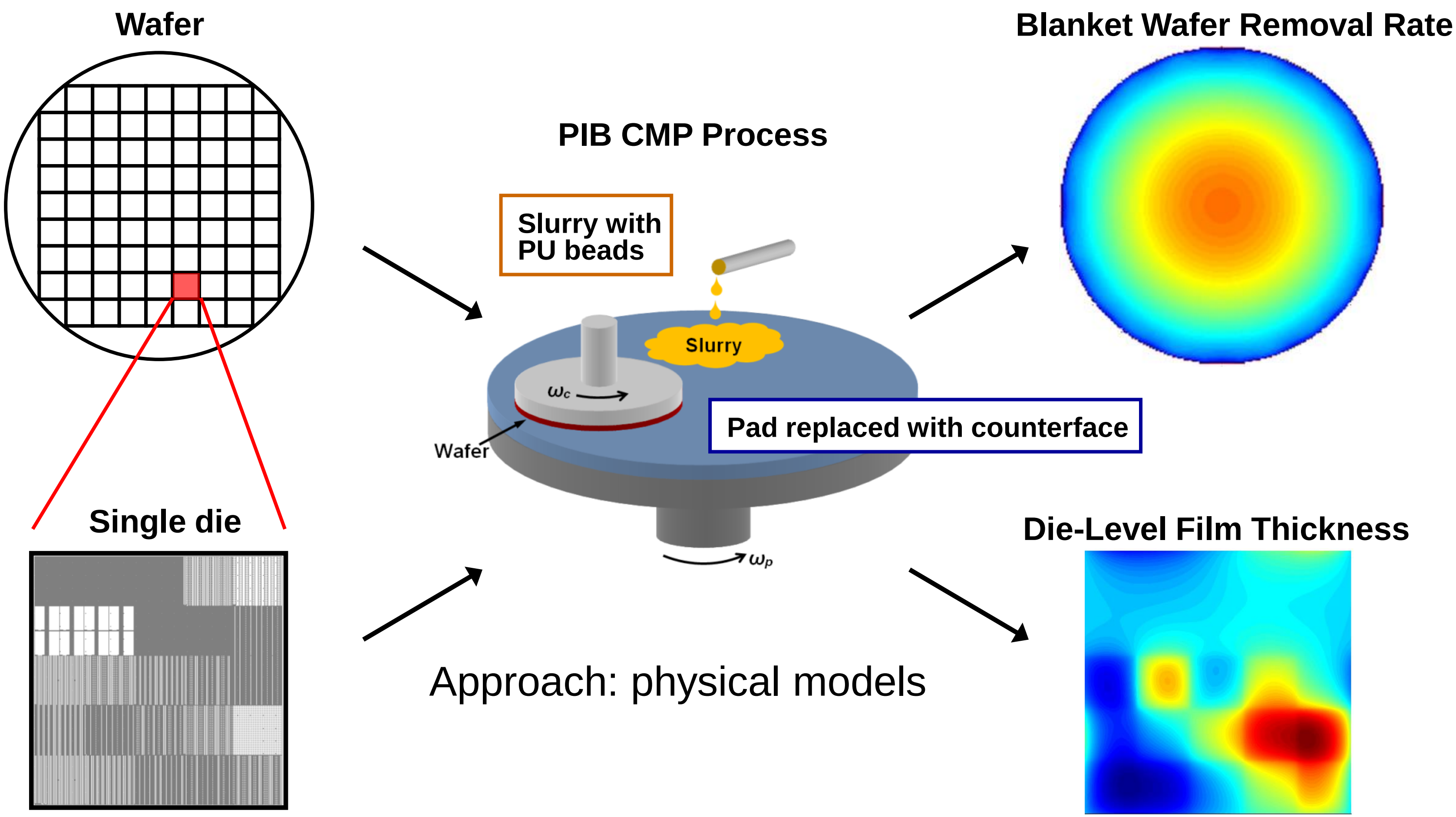
Graduate Students:

- **Joy Johnson, Ph.D. candidate, EECS, MIT**

Collaborators:

- **Dr. Wei Fan, Cabot Microelectronics**

Overview – PIB Modeling



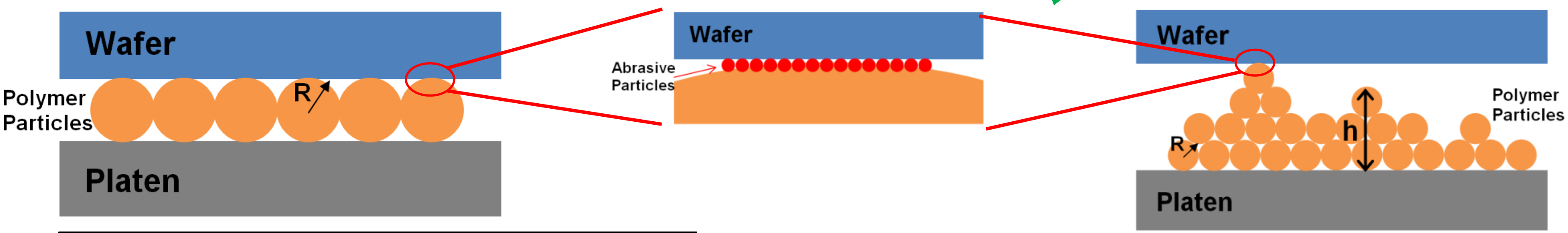
Approach: physical models

Year 2 and Year 3 Plans

- **Subtask 2 – Simulations under Prof. Boning**
  - **In Year 2, models to predict chip-scale planarization performance using the new consumables will be developed.**
  - **Die-level models will be extended, enabling prediction of chip topography evolution including dishing and erosion effects.**
  - **In Year 3, comparisons to patterned wafer experiments will be used to guide required improvements in the model.**
  - **Optimization studies will be conducted using the models to identify process consumable minimization, dishing and erosion limits, alternative design rule formulations, and dummy fill strategies.**

Previous: Blanket Model for Pad-in-a-Bottle

Case 1: bead packing | **Case 2: height distribution**

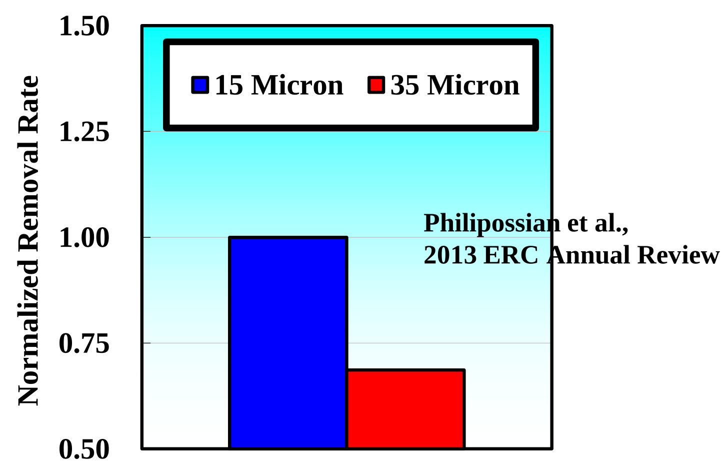


$$RR = \frac{1}{\pi R^2}\left(\frac{E_p}{3}\right)^{\frac{2}{3}} K'V\left(P_0^{\frac{1}{3}} - P_{th}^{\frac{1}{3}}\right)$$

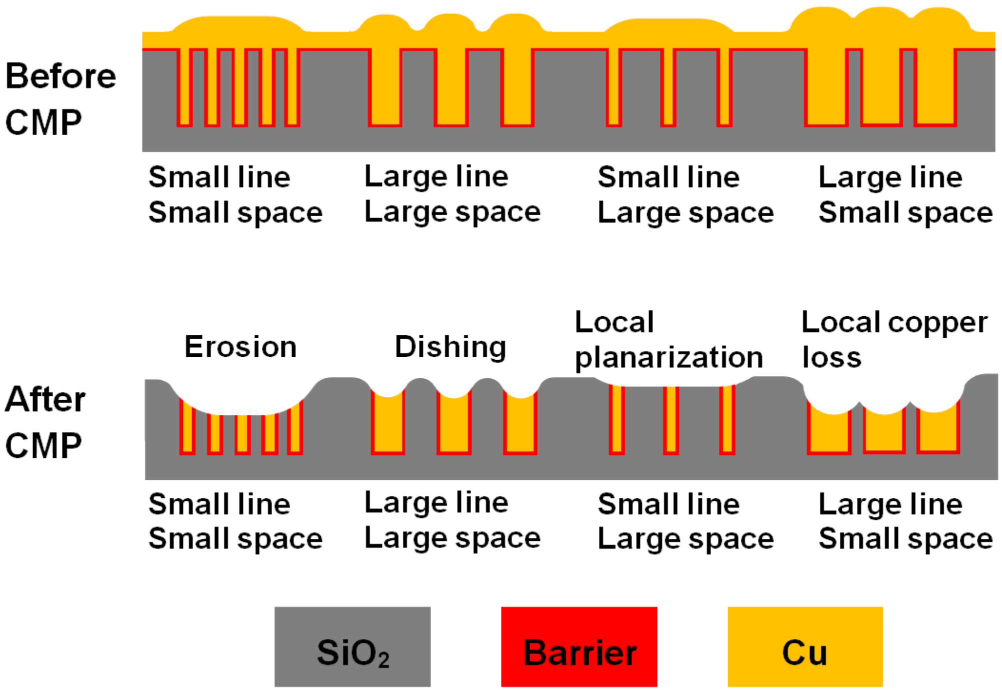
$$RR = \overline{RR}_p \frac{N}{A_0} = \frac{1}{\pi R \lambda} K'VP_0$$

Conclusion – need height distribution:

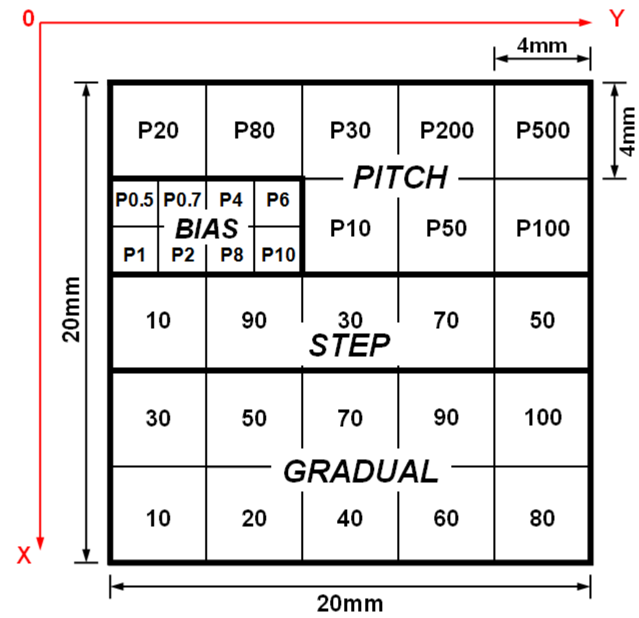
- **Bead packing model suggests negligible removal (insufficient point pressures) in the pure packing case)**
- **Experimental results (at right) suggest 1/R rather than $1/R^2$ bead radius impact on removal rate, consistent with bead stacking or other bead height distribution model**



Current: Within-Die Non-uniformity



Test Chip: Feature Pitch/Size and Pattern Density



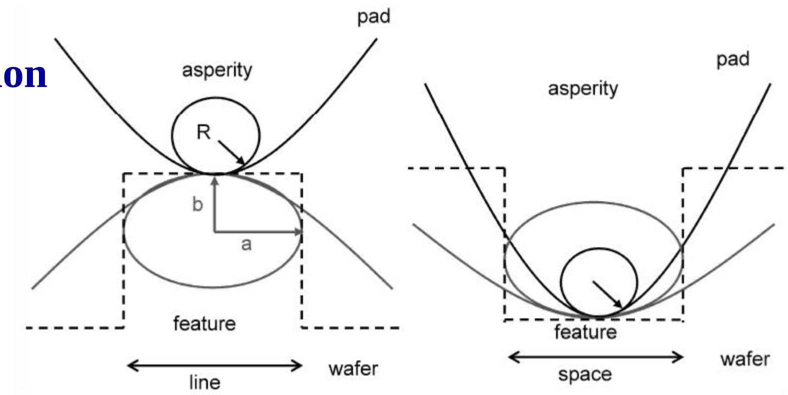
- Feature size effects: dishing (down area polish) and erosion (up area loss)
- Chip scale effects: mm-scale interaction between pattern density regions

PIB Die-Level Model: Key Parameters

- **Bead size**
  - **Bead radius *R* affects down-area removal (dishing)**
  - **Impact and benefits:**
    - Bead size larger than conventional polishing pad asperities, potentially decreasing dishing
- **Bead height distribution**
  - **Assume exponential distribution (with parameter λ) in the height of bead stacks**
  - **Impact and benefits:**
    - Tighter height distribution can potentially reduce within-die variation
- **Use of counterface pad**
  - **Counterface pad can be stiffer than conventional polishing pad**
  - **Impact and benefits:**
    - Potential for reduced dependence on neighboring pattern densities within the chip, and improved die-level uniformity

Model – Bead Radius and Height Distribution

- **Greenwood Williamson approach**
  - **Beads have idealized spherical surfaces with given radius (similar to previous approximation of pad asperity tip)**
  - **Elastic Hertzian contact**
- **Geometry of Hertzian contact**
  - **Describe bead and wafer surfaces with radius of curvature κ_U and κD, and with bead height distribution λ**
  - **Solve for local up and down pressures:**



Vasilev, IEEE Trans. on Semiconductor Manufacturing 2011

$$\begin{cases} w(x,y) = F(x,y) \otimes P(x,y) + w_0 \\ P_U(x,y) = \dfrac{e^{\frac{h}{\lambda}} \kappa_U \sqrt{\kappa_D}}{\kappa_{asp}\left(\sqrt{\kappa_U}(1-\rho) + e^{\frac{h}{\lambda}}\sqrt{\kappa_D}\,\rho\right)} P(x,y) \\ P_D(x,y) = \dfrac{\kappa_D \sqrt{\kappa_U}}{\kappa_{asp}\left(\sqrt{\kappa_U}(1-\rho) + e^{\frac{h}{\lambda}}\sqrt{\kappa_D}\,\rho\right)} P(x,y) \end{cases}$$

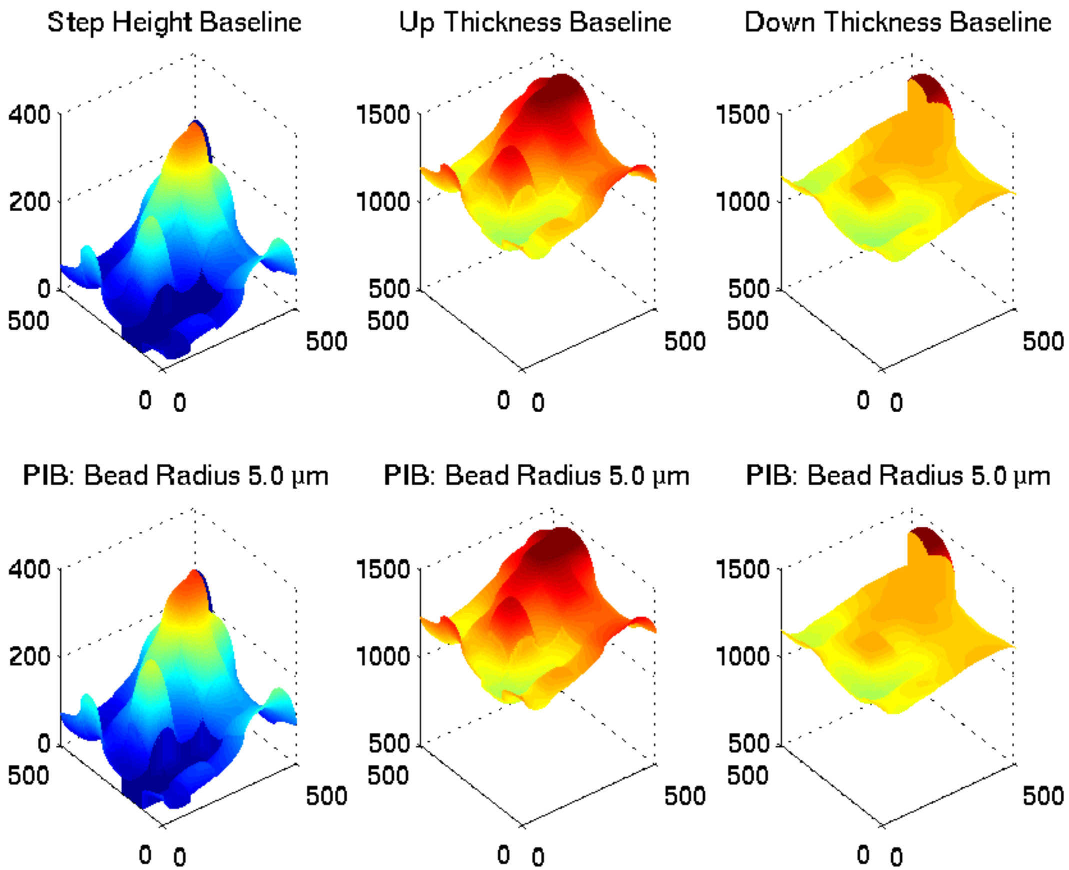
$$\kappa^{U,D} = \frac{1}{R_{asperity}} \pm \frac{1}{R_{feature}} = \kappa_{asperity} \pm \kappa_{feature}$$

$$\kappa_{feature} = \kappa_{ellipse} = \frac{b}{a^2}$$

$$\kappa^U = \kappa_{asperity} + \frac{4\alpha h}{line^2}$$

$$\kappa^D = \kappa_{asperity} - \frac{4\alpha h}{space^2}$$

Bead Size Impact (1)

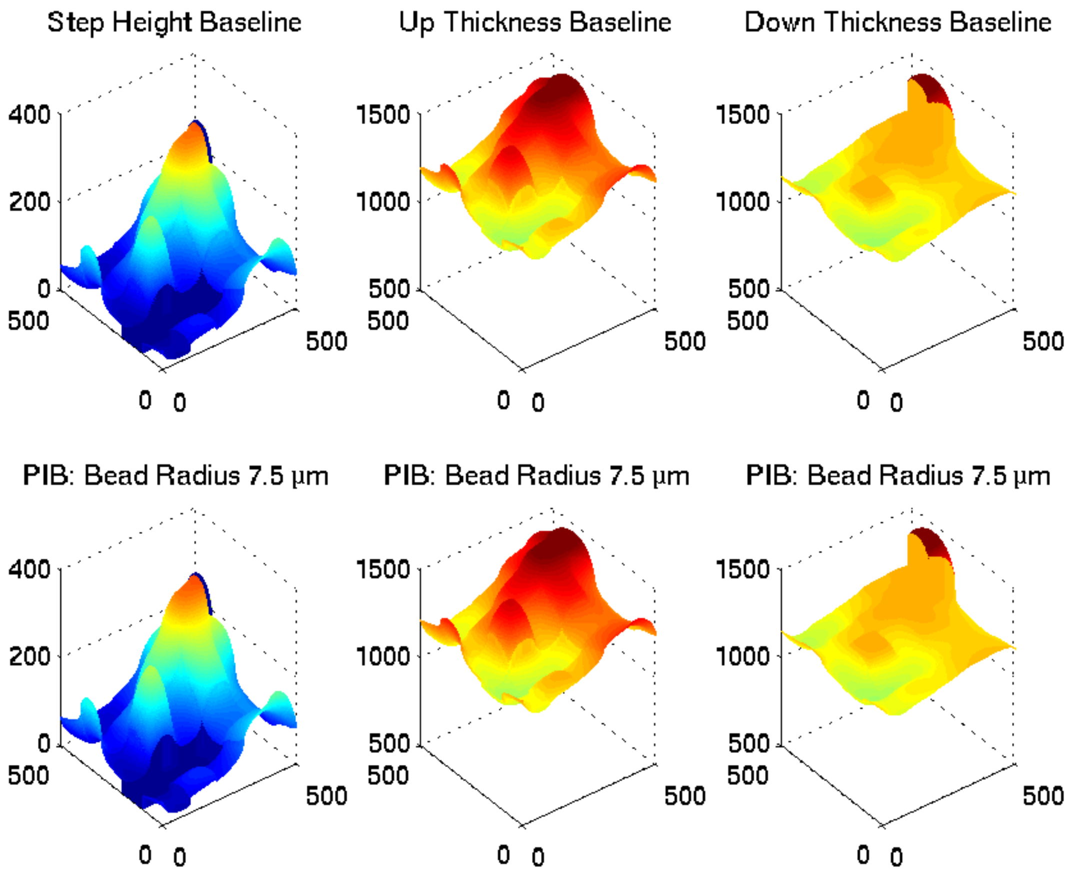


$R_{asp} = 10\ \mu m$

$R_{bead} = 5\ \mu m$

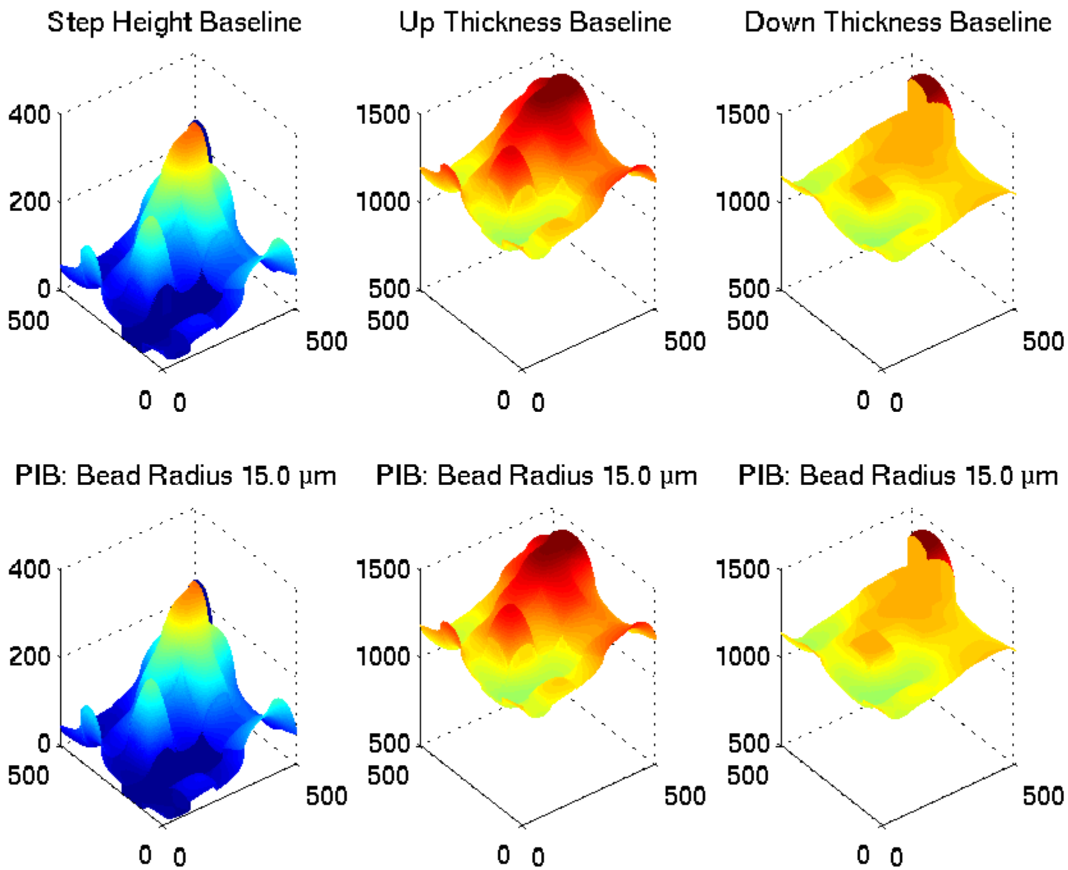
- **Top: baseline CMP case; final heights (nm) on chip, 100 s polish**
- **Bottom: PIB bead radius**

Bead Size Impact (2)



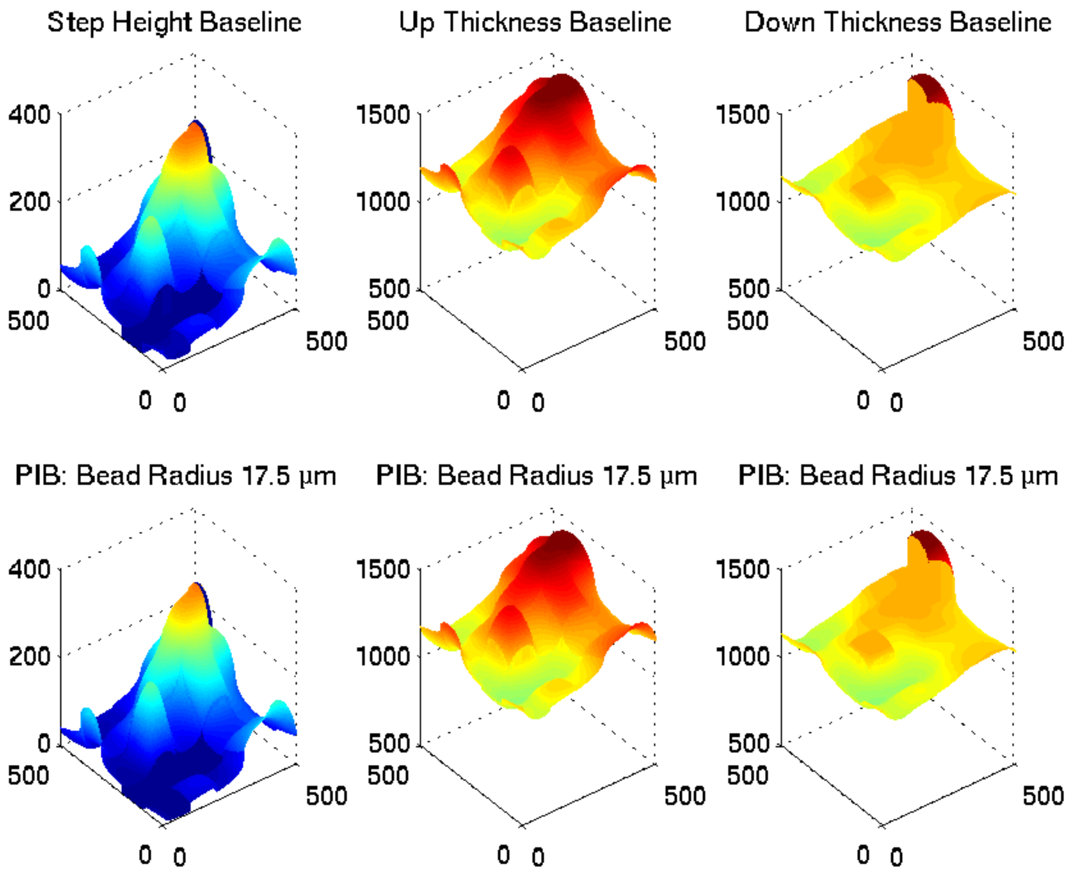
R = 7.5 µm

Bead Size Impact (3)



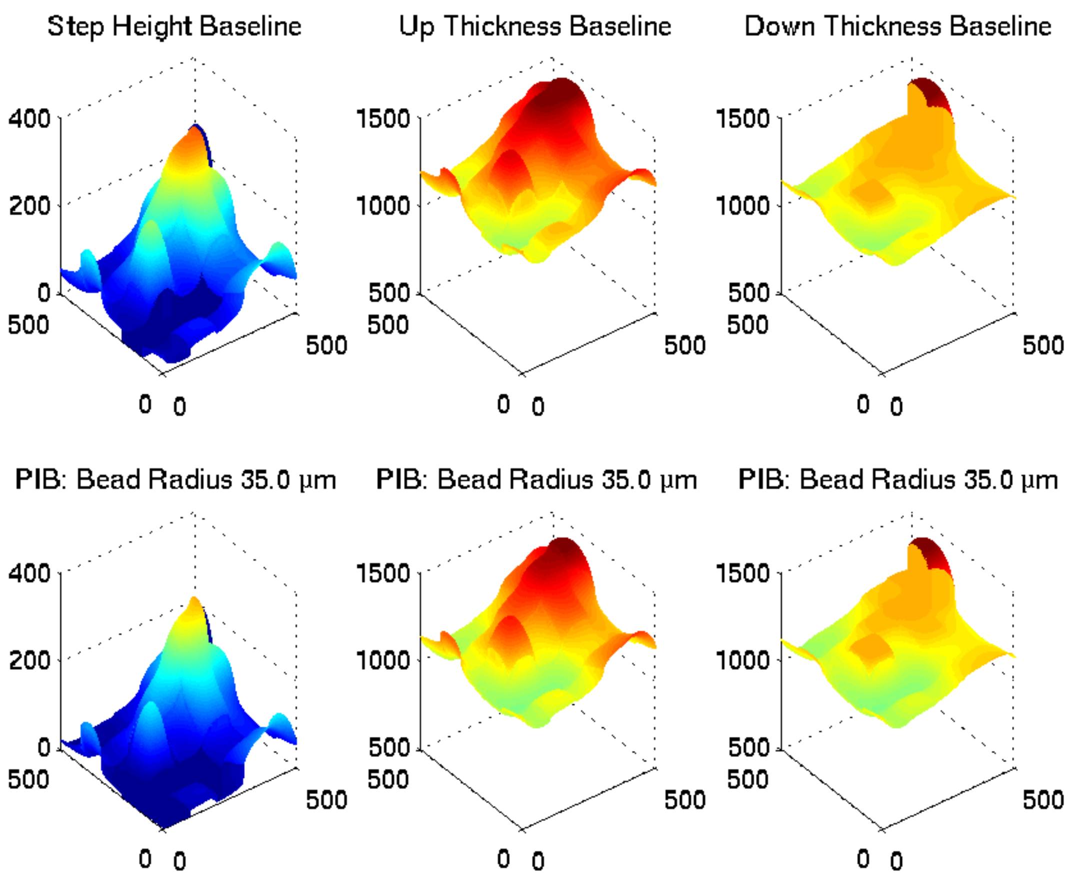
R = 15 μm

Bead Size Impact (4)



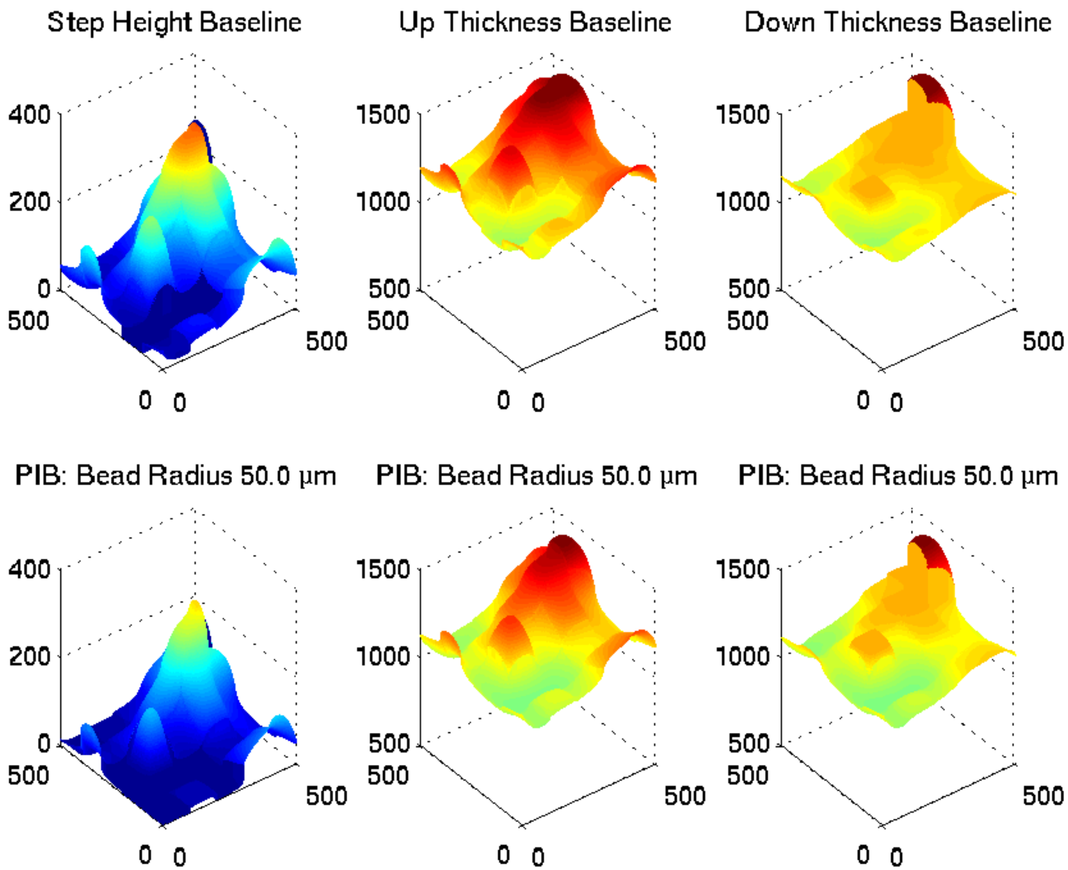
R = 17.5 µm

Bead Size Impact (5)



R = 35 μm

Bead Size Impact (6)

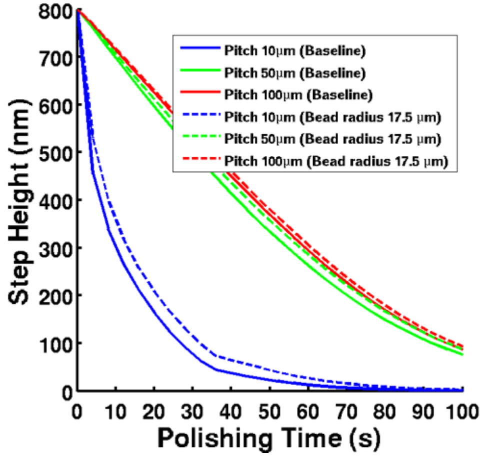


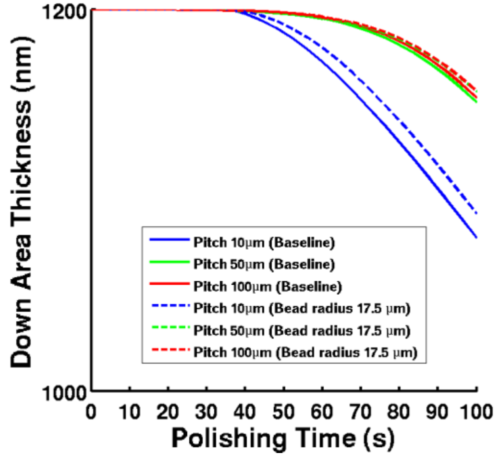
R = 50 µm

- **Conclusion: Some improvement in step height reduction, dishing, and erosion/pattern density effect, as the bead radius R increases**

Bead Size Impact

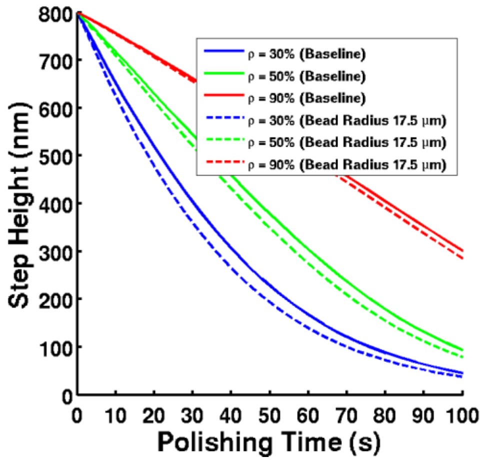
R = 17.5 μm

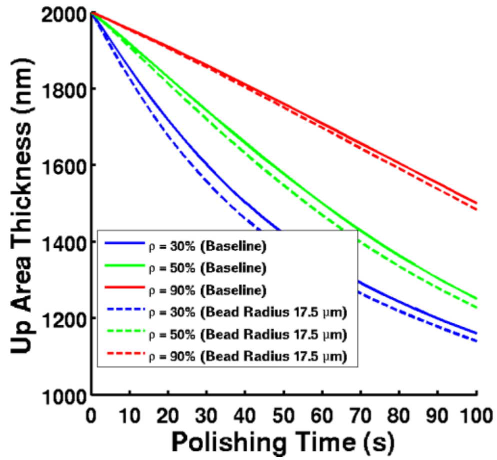




For feature size, at 50% density

Slightly reduced dishing for very large features



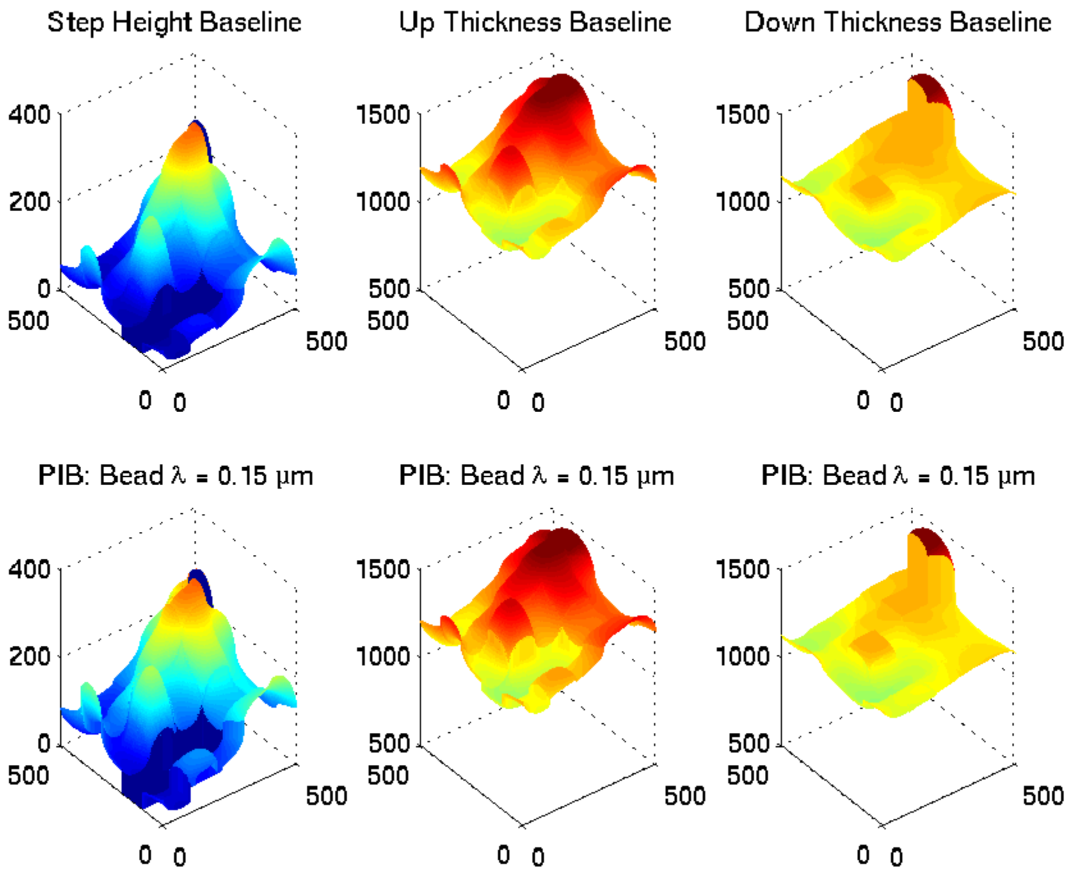


For pattern density, at constant pitch

PIB Die-Level Model: Key Parameters

- **Bead size**
  - **Bead radius *R* affects down-area removal (dishing)**
  - **Impact and benefits:**
    - Bead size larger than conventional polishing pad asperities, potentially decreasing dishing
- **Bead height distribution**
  - **Assume exponential distribution (with parameter λ) in the height of bead stacks**
  - **Impact and benefits:**
    - Tighter height distribution can potentially reduce within-die variation
- **Use of counterface pad**
  - **Counterface pad can be stiffer than conventional polishing pad**
  - **Impact and benefits:**
    - Potential for reduced dependence on neighboring pattern densities within the chip, and improved die-level uniformity

Bead Height Distribution Impact (1)

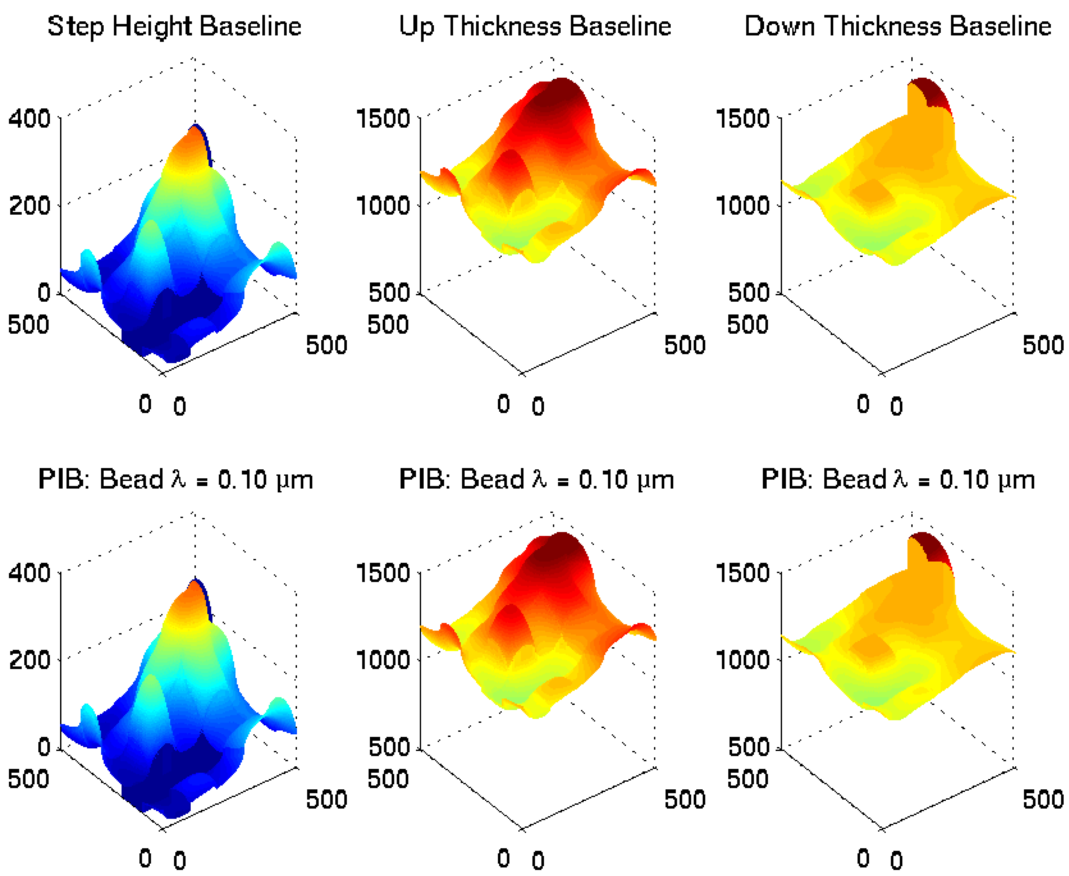


λ = 0.1 um

λ = 0.15 um

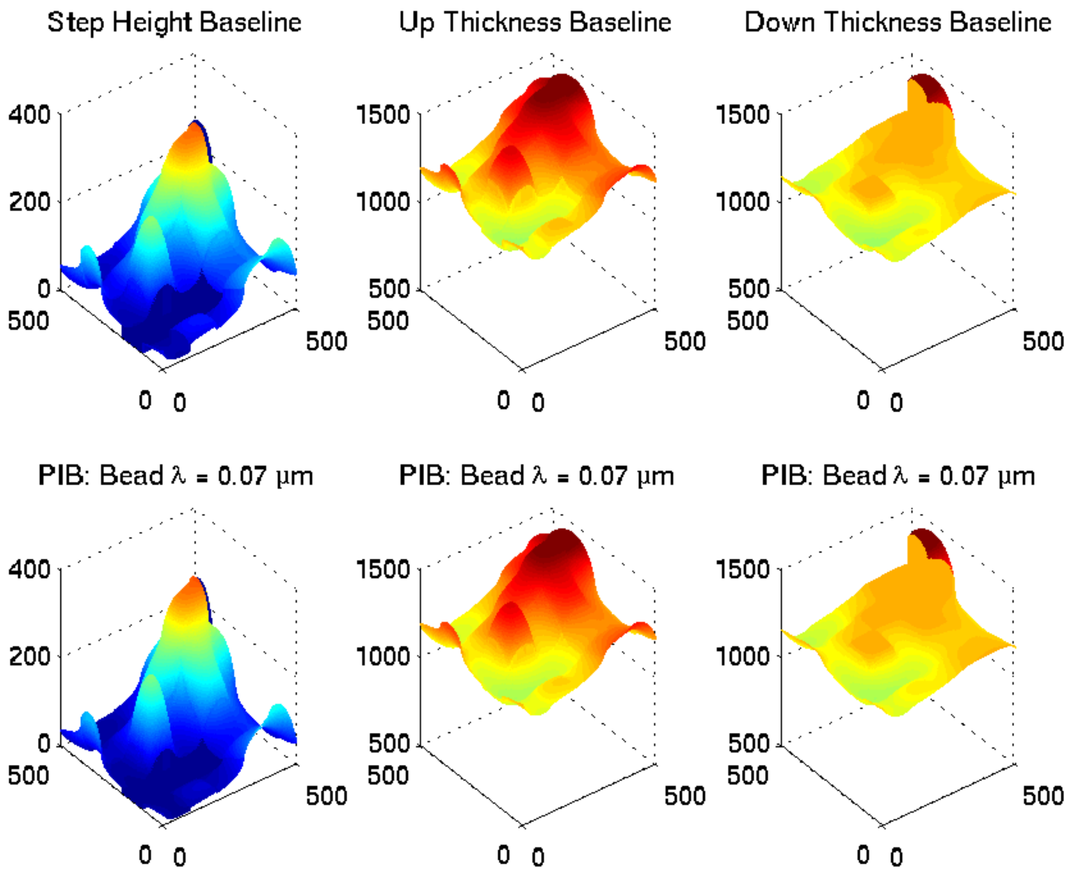
- **Top: baseline CMP case**
- **Bottom: PIB bead height distribution (small λ indicates tighter heights)**

Bead Height Distribution Impact (2)



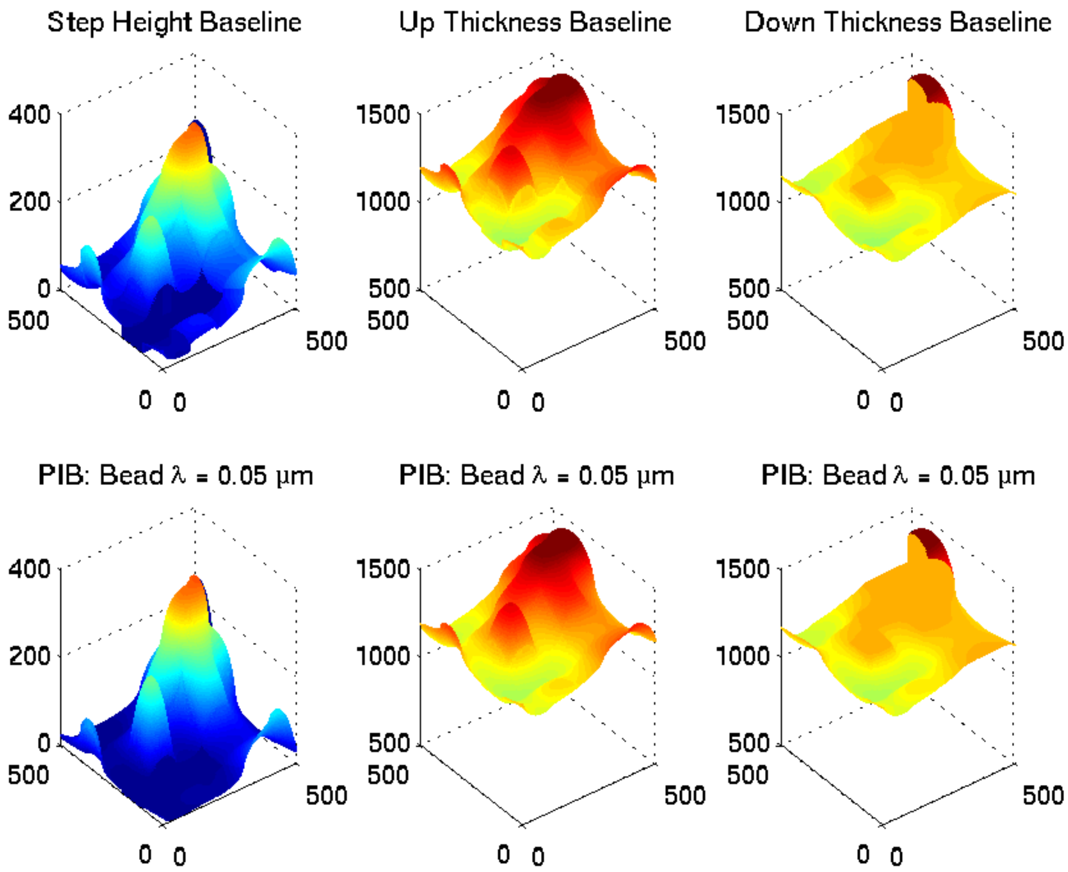
λ = 0.1 um

Bead Height Distribution Impact (3)



$\lambda = 0.07$ um

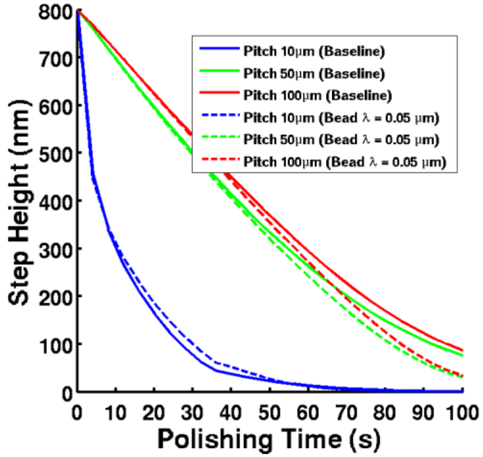
Bead Height Distribution Impact (4)

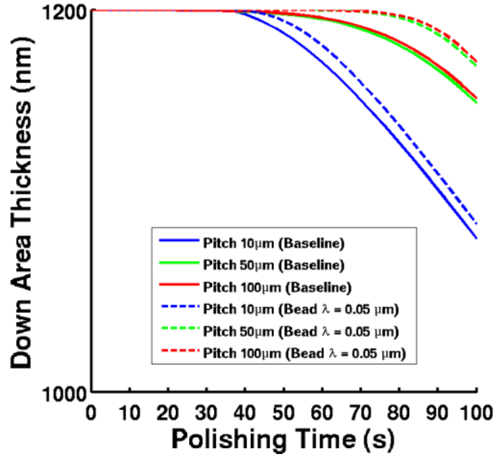


$\lambda = 0.05$ um

- **Conclusion: As λ decreases (bead height distribution becomes tighter), modest improvement in step height**

Bead Height Distribution Impact

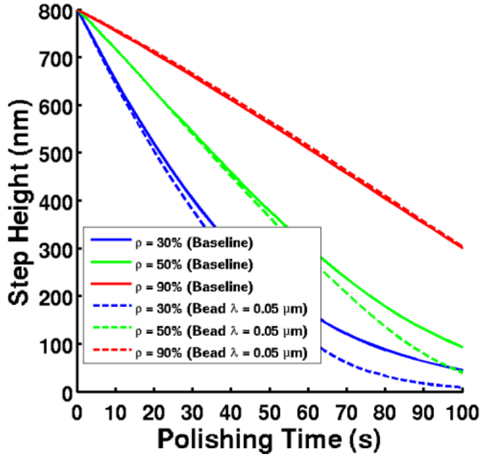


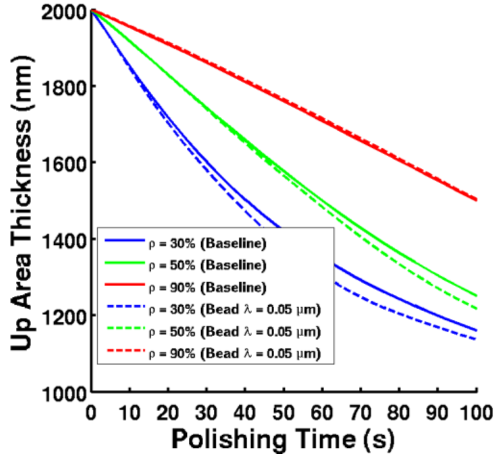


For feature size, at 50% density

Slightly reduced dishing for large features

λ = 0.05 um





For pattern density, at constant pitch

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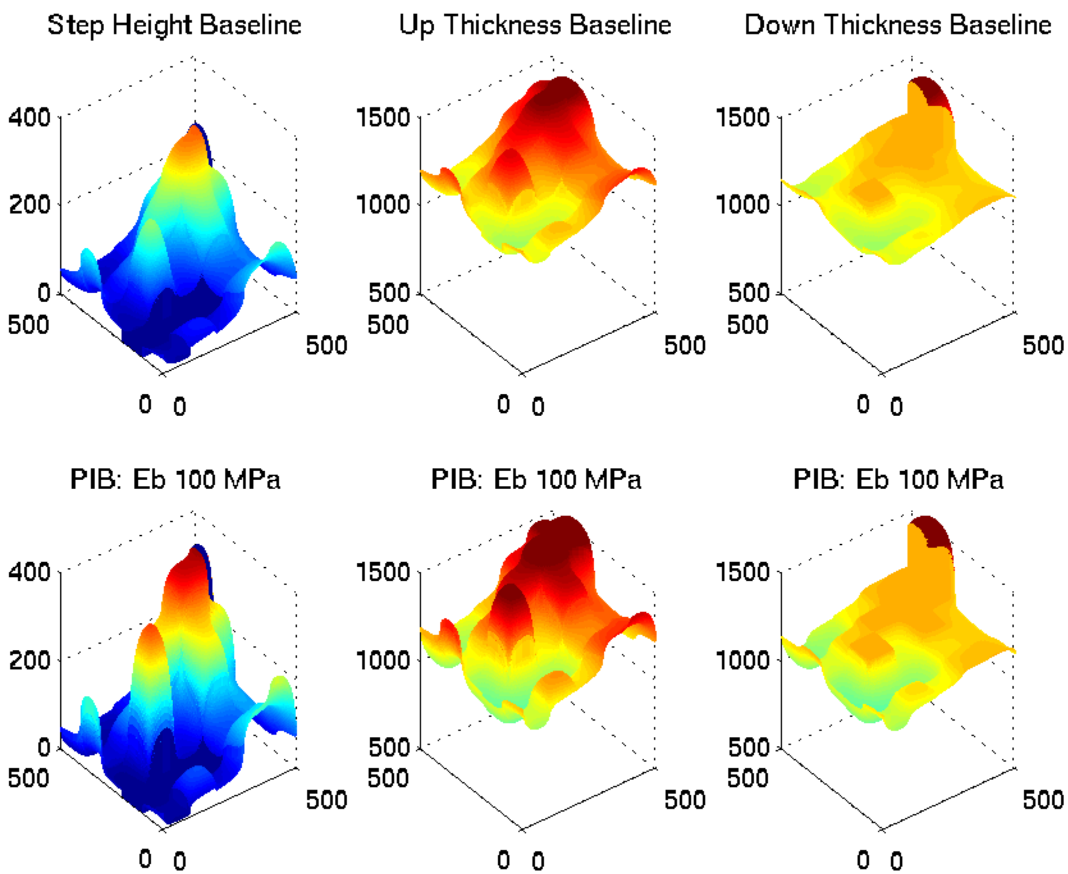
Pad/Counterface Impact (1)

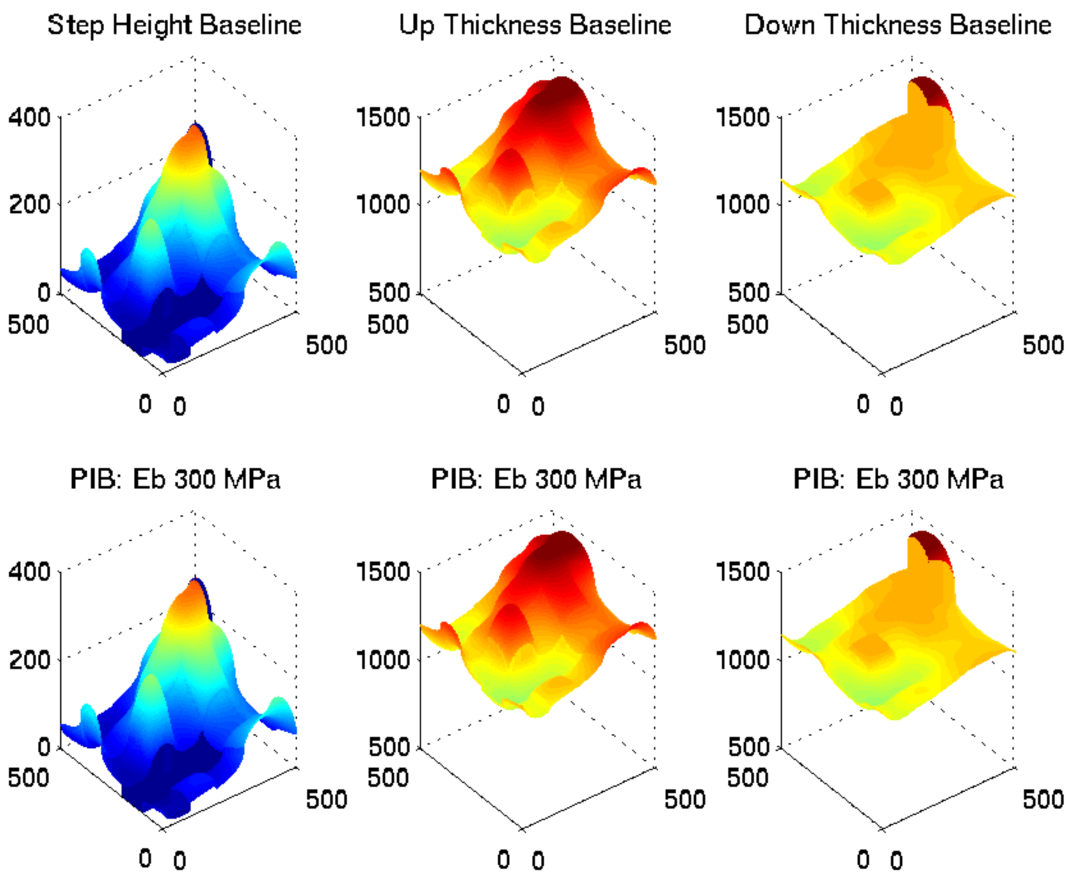


E_b = 300 MPa

E_b = 100 MPa

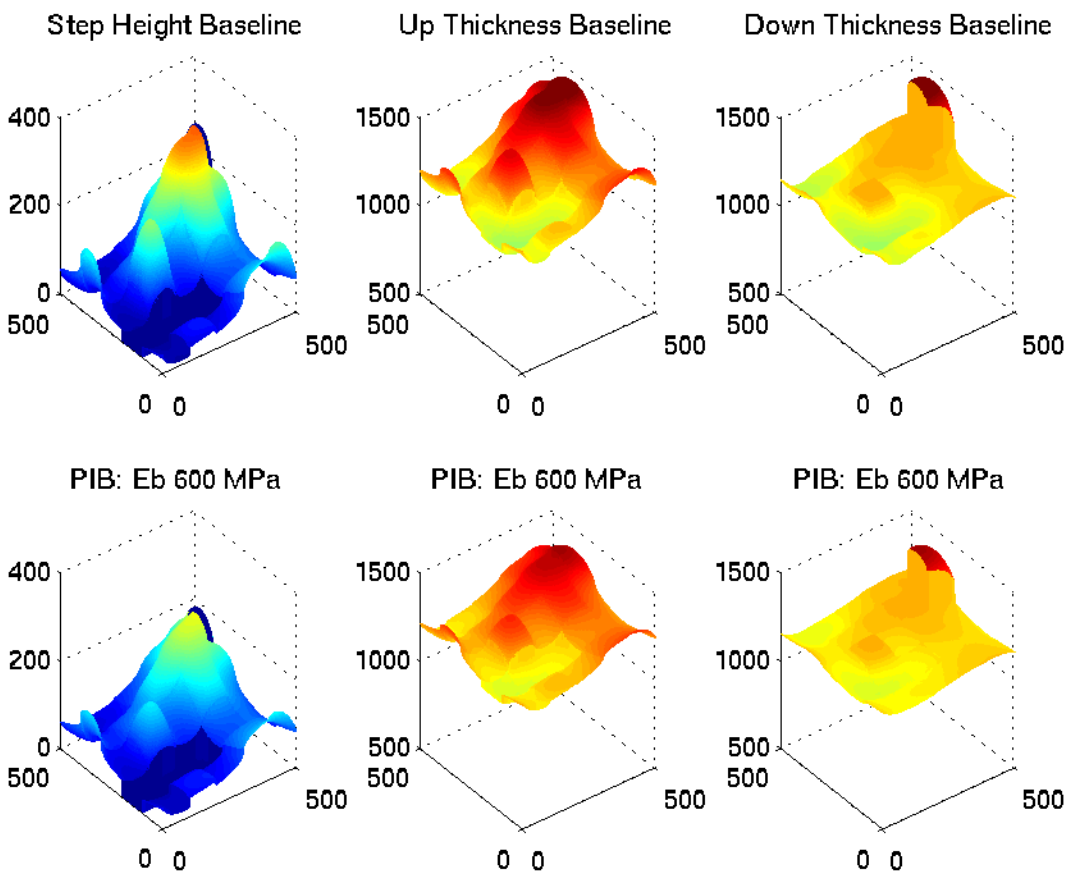
- **Top: baseline CMP case**
- **Bottom: Pad replaced with counterface with given E_b**

Pad/Counterface Impact (2)



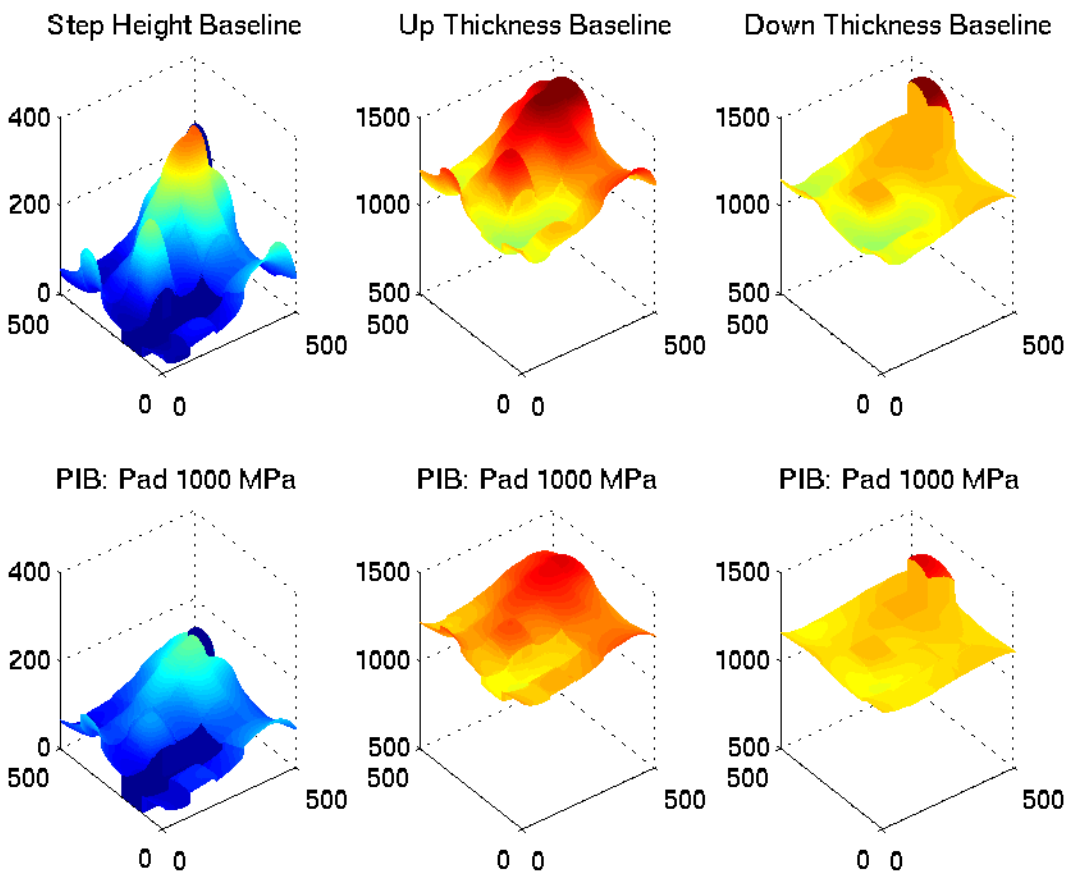
E_b = 300 MPa

Pad/Counterface Impact (3)



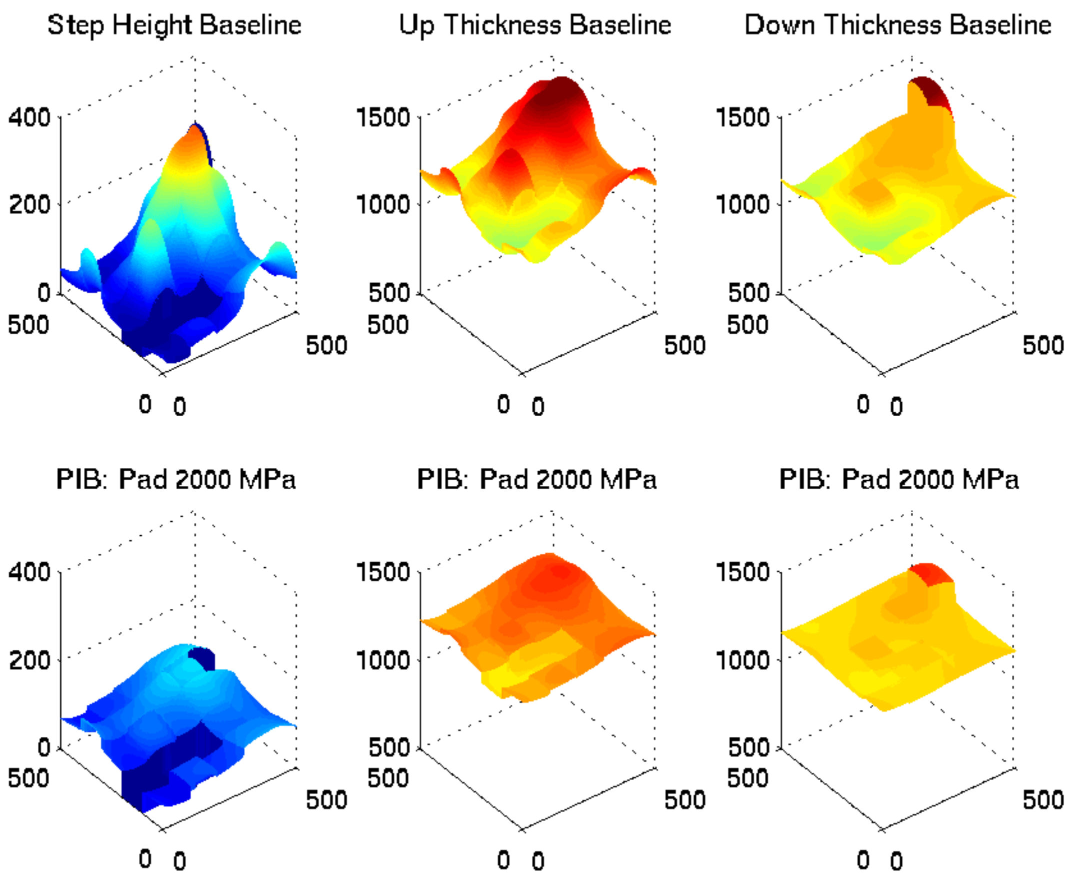
E_b = 600 MPa

Pad/Counterface Impact (4)



E_b = 1 GPa

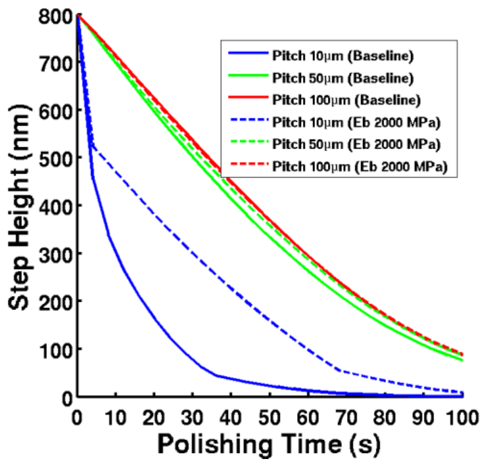
Pad/Counterface Impact (5)

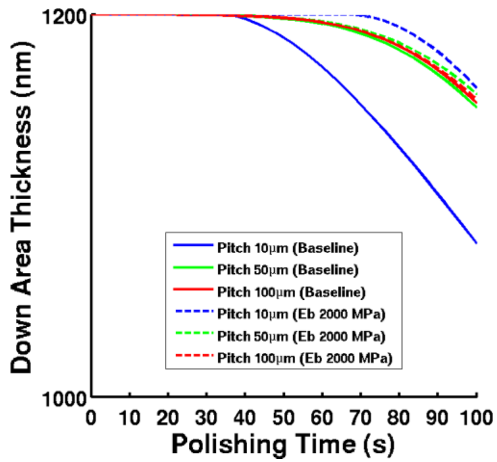


E_b = 2 GPa

- **Conclusion: Use of a harder counterface pad has *dramatic* improvement impact on within-die uniformity**

Pad/Counterface Impact

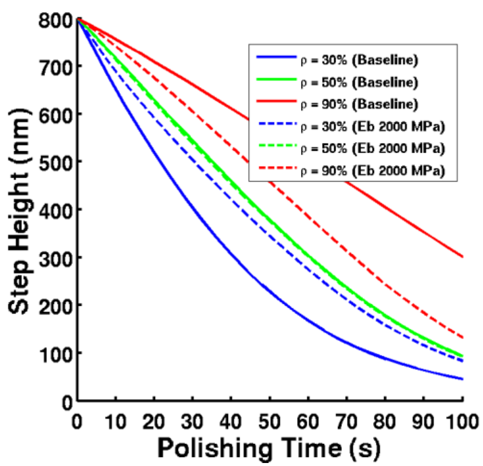


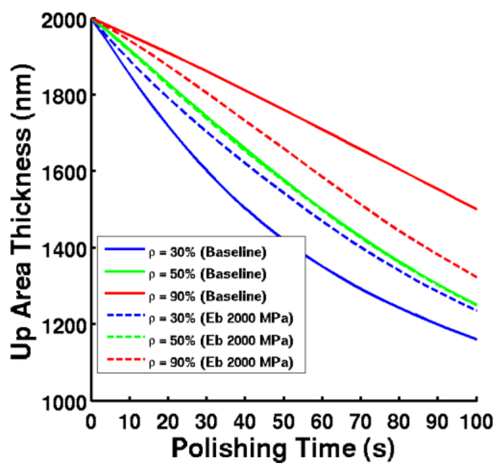


For feature size,
at 50% density

Reduced dishing for large features

$E_b = 2$ GPa





For pattern density,
at constant pitch

Large reduction of within-die variation

PIB Die-Level Model: Results

- **Bead size**
  - Larger *R* gives slightly better pattern performance
  - But larger *R* decreases removal rate
- **Bead stacking height distribution**
  - Smaller λ (tight control on bead stacking, or tight control on bead size distribution) gives slightly better pattern performance
  - Need some height distribution to achieve appreciable removal rate
- **Use of counterface pad**
  - **Using a stiffer counterface pad and polyurethane beads, vs. conventional pad, is the dominant source of potential patterned wafer die-level performance improvement**
  - Roughening of counterface could generate or increase λ height distribution, but that negative λ effect is small compared to major improvements coming from stiff counterface

Current/Year 3 Plans

- **Subtask 2 – Simulations under Prof. Boning**
  - **In Year 3, comparisons to patterned wafer experiments will be used to guide required improvements in the model.**
  - **Optimization studies will be conducted using the models to identify process consumable minimization, dishing and erosion limits, alternative design rule formulations, and dummy fill strategies.**

Publications and Presentations

- **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.**