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

(*Task 425.039*)

Subtask 1: Experimentation

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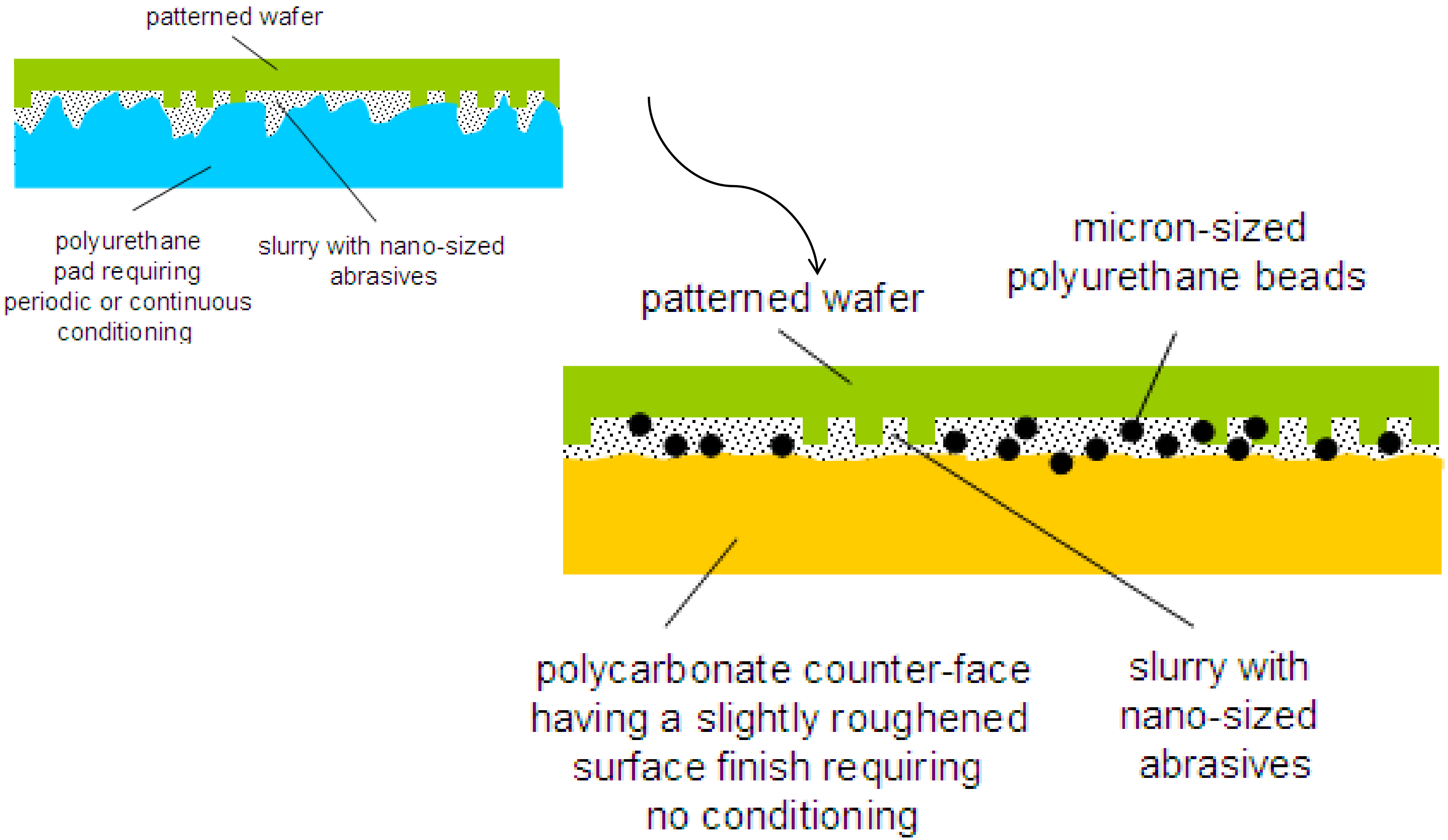
Pad-in-a-Bottle Concept



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

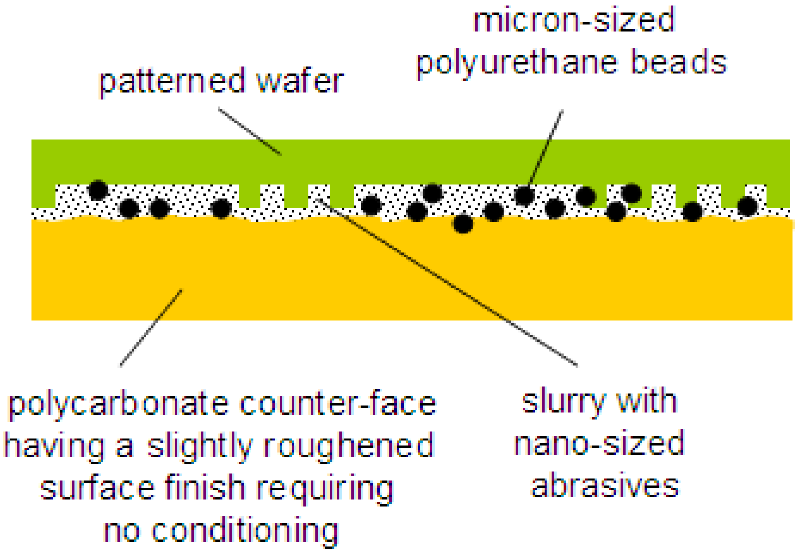
slurry with nano-sized abrasives

EHS Benefits and Tradeoffs of PIB Process

ESH Benefits

- Elimination of the need for CMP pads (100% reduction)
- At least 20X reduction in pad conditioner consumption (95% reduction)
- Combined yield and efficiency improvement possible with PIB could reduce film deposition and over-polish time by 25%
- Reduction in health risks associated with counter-face change (counter-face material has significantly longer life than polyurethane pads and requires less frequent changes)

Pad in a Bottle (PIB)



ESH Tradeoffs

- Use of counter-face material
- Comparable amounts of worn polyurethane material in waste stream as in conventional CMP

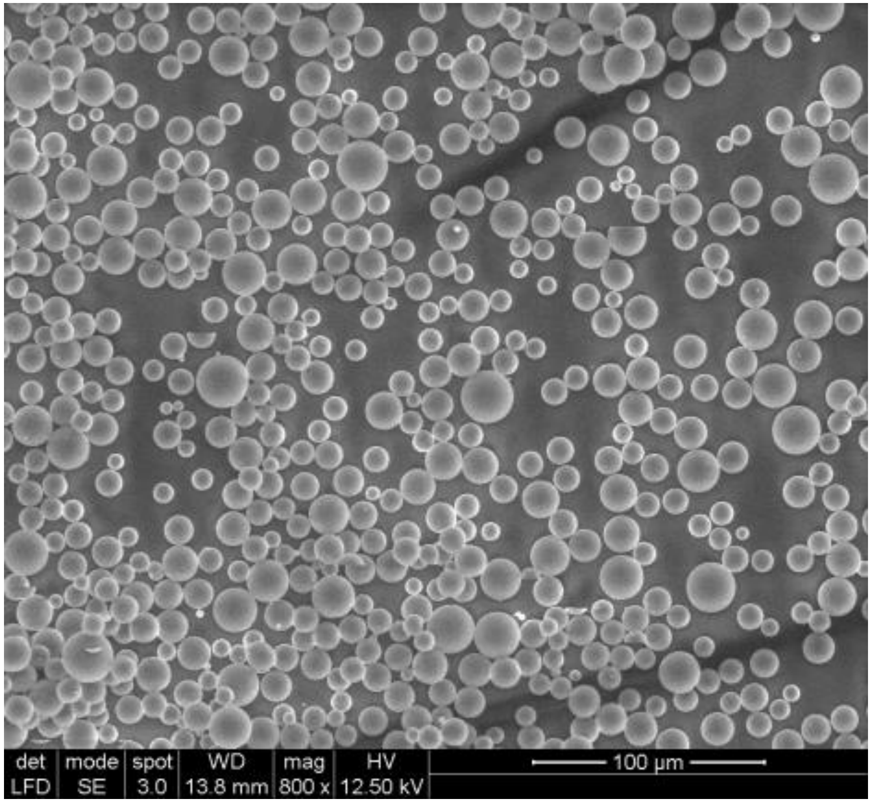
Objectives

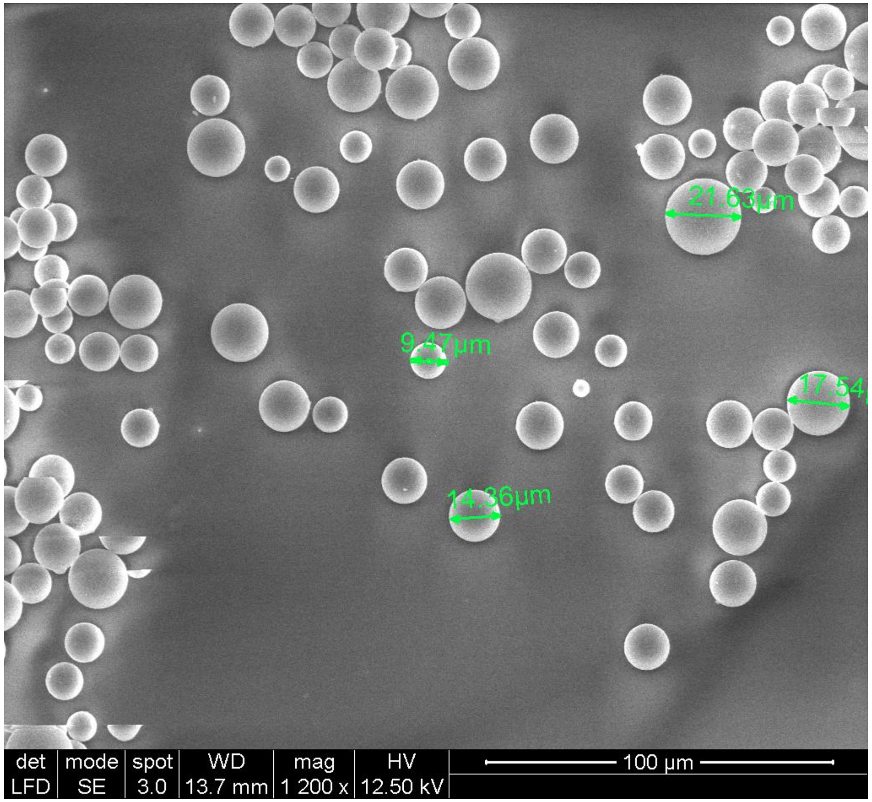
Objectives

- **Determine whether PU beads will function as a replacement for pad asperities**
- **Investigate the effect of PU bead size and polishing pressure on oxide removal rate and dishing/erosion**

SEM Images of PU Beads

D_{50} = 15 µm

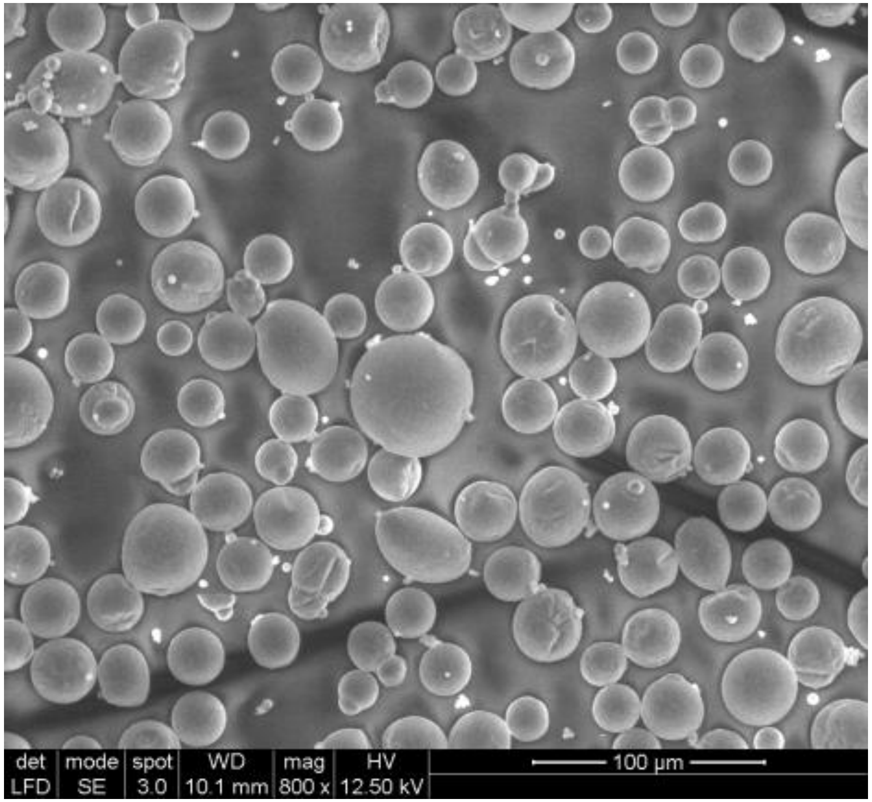


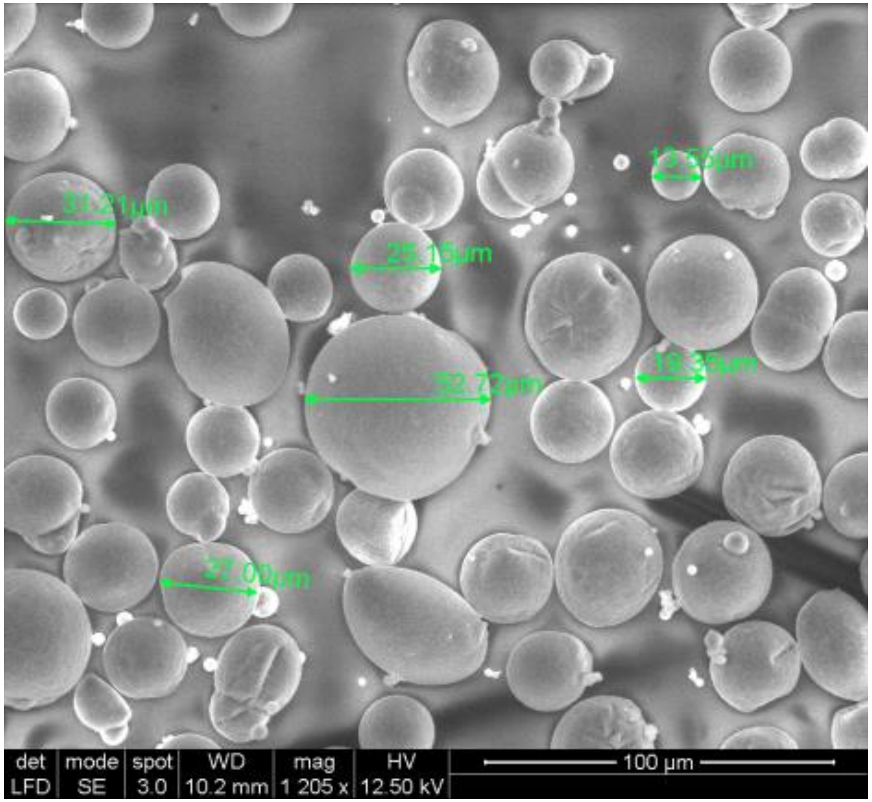


PU beads are in spherical shape and have a smooth surface.

SEM Images of PU Beads

$D_{50} = 35\ \mu m$





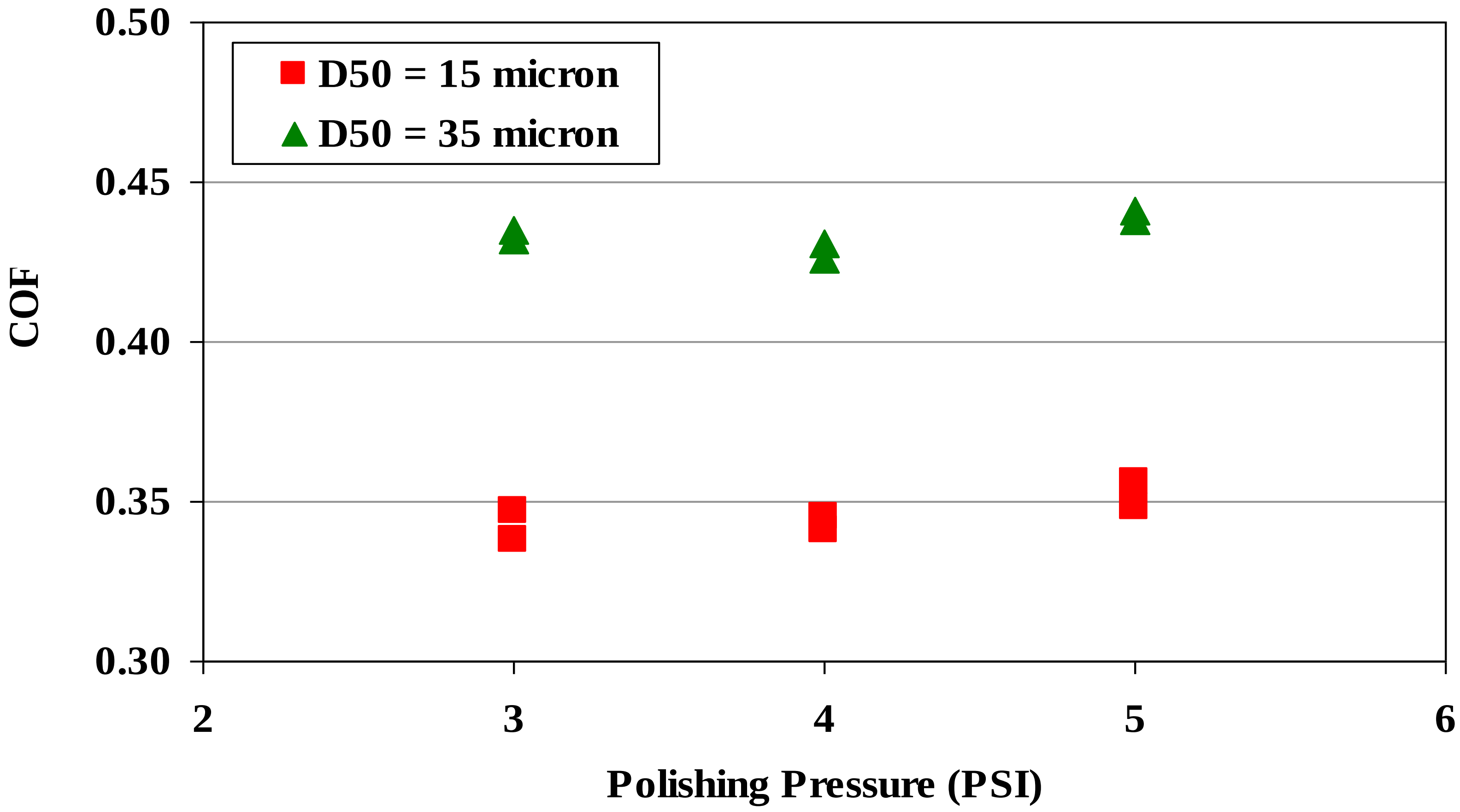
PU beads have irregular round shapes and some beads have a rough surface.

Experimental Conditions

Blanket Wafer Polishing

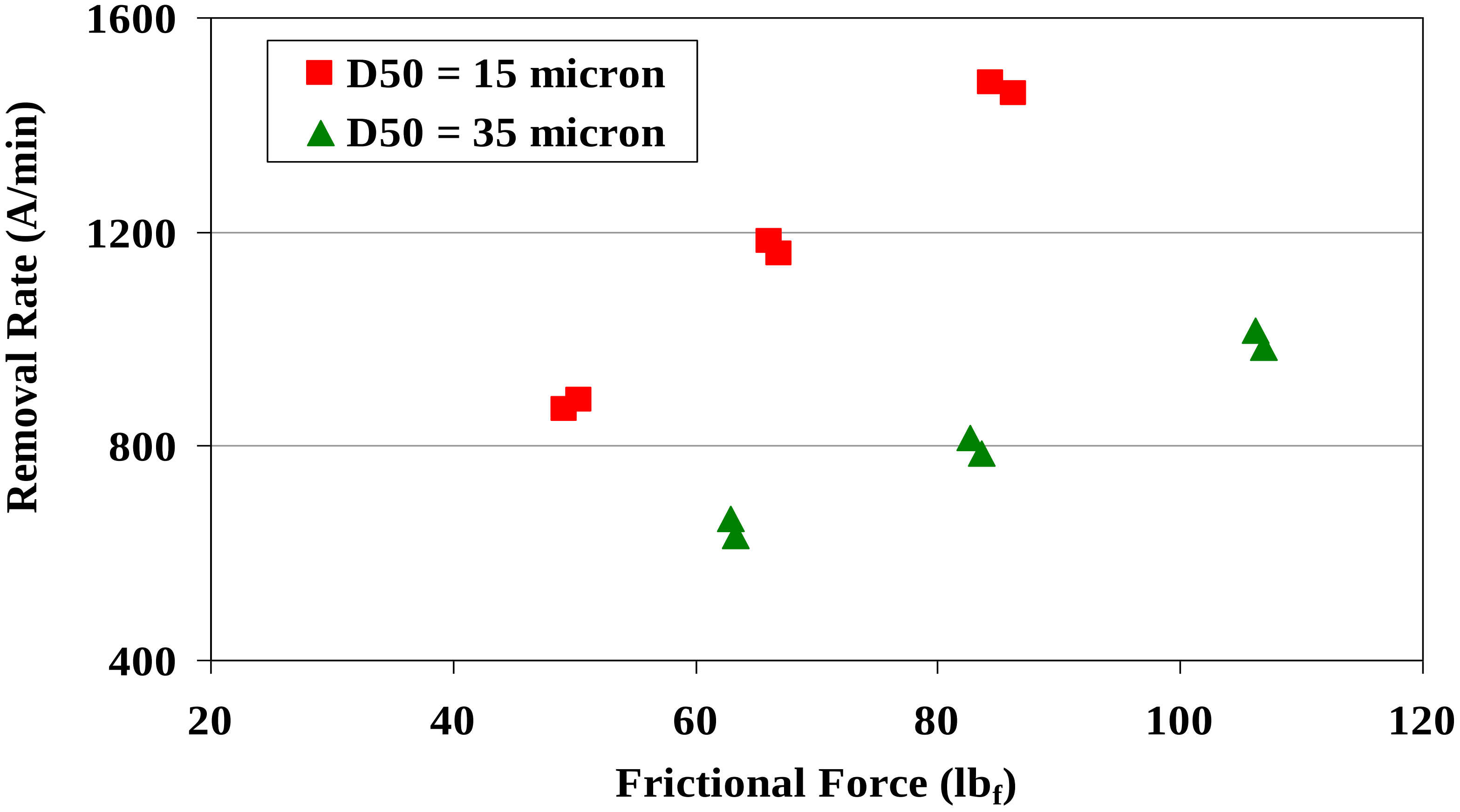
- **APD-500 Polisher and Tribometer**
- **Sliding Velocity**
  - **1.2 m/s**
- **Polishing Pressures**
  - **3, 4 and 5 PSI**
- **Slurry**
  - **Cabot Microelectronics Corporation SS25**
- **Additive (i.e. surfactant)**
  - **Silsurf at 0.7 g/L**
- **Slurry Flow Rate**
  - **200 ml/min**
- **Wafer**
  - **200-mm blanket TEOS wafers**
- **Counter-face**
  - **Polycarbonate with concentric groove design**
- **Counter-face Break-in**
  - **MMC 325-grit at 6 $\mathrm{lb_f}$ for 15 minutes**
- **Counter-face Cleaning**
  - **3M PB32A brush at 3 $\mathrm{lb_f}$ for 30 s between polishes**
- **PU Beads**
  - **15 and 35 micron**
  - **2 g/L**
- **Polishing Time and Repeat**
  - **60 seconds**
  - **Repeat once for each condition**

Effect of PU Beads on COF



COF remains stable at different polishing pressures for both PU beads.
PU beads with D_{50} of 35 µm provide higher COF than PU beads with D_{50} of 15 µm.

Removal Rate vs. Frictional Force



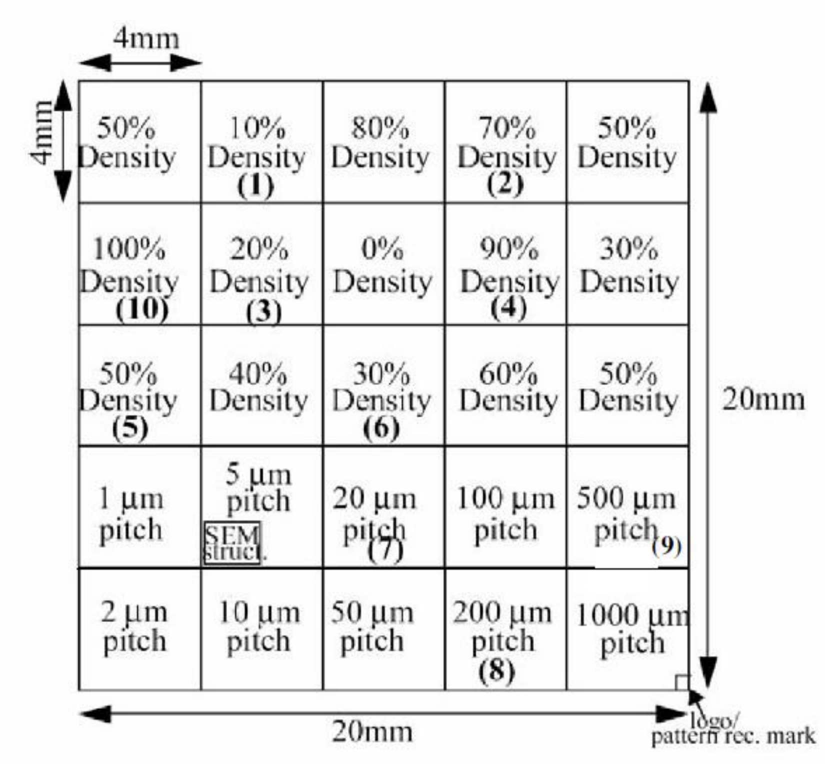
Removal rate shows a linear trend with frictional force for both PU beads.
PU beads with D_{50} of 15 µm provide higher removal rates than PU beads with D_{50} of 35 µm.

Experimental Conditions

Patterned Wafer Polishing

- **APD-500 Polisher and Tribometer**
- **Sliding Velocities**
  - **1.2 m/s**
- **Polishing Pressure**
  - **5 PSI**
- **Slurry**
  - **Cabot Microelectronics Corporation SS25**
- **Additive (i.e. surfactant)**
  - **Silsurf at 0.7 g/L**
- **Slurry Flow Rate**
  - **200 ml/min**
- **Wafer**
  - **200-mm SKW3-2 patterned wafers**
- **Counter-face**
  - **Polycarbonate with concentric groove design**
- **Counter-face Break-in**
  - **MMC 325-grit at 6 $\mathrm{lb_f}$ for 15 minutes**
- **Counter-face Cleaning**
  - **3M PB32A brush at 3 $\mathrm{lb_f}$ for 30 s between polishes**
- **PU Beads**
  - **15 and 35 micron**
  - **2 g/L**
- **Polishing Time and Repeat**
  - **7 minutes for D_{50} of 15 micron**
  - **10 minutes for D_{50} of 35 micron**
  - **Repeat once for each condition**

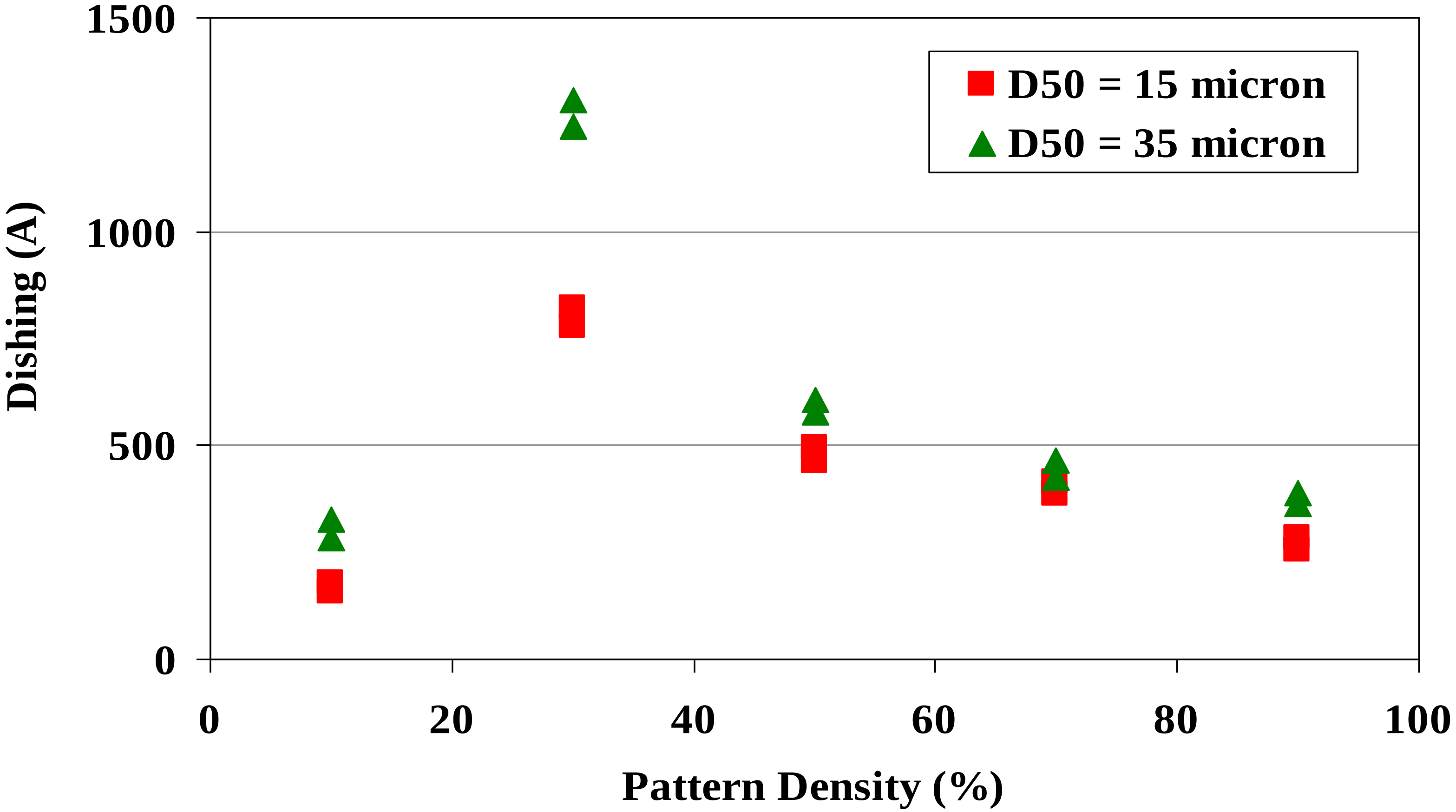
SKW3-2 Patterned Wafer



50% Density	10% Density (1)	80% Density	70% Density (2)	50% Density
100% Density (10)	20% Density (3)	0% Density	90% Density (4)	30% Density
50% Density (5)	40% Density	30% Density (6)	60% Density	50% Density
1 µm pitch	5 µm pitch SEM struct.	20 µm pitch (7)	100 µm pitch	500 µm pitch (9)
2 µm pitch	10 µm pitch	50 µm pitch	200 µm pitch (8)	1000 µm pitch

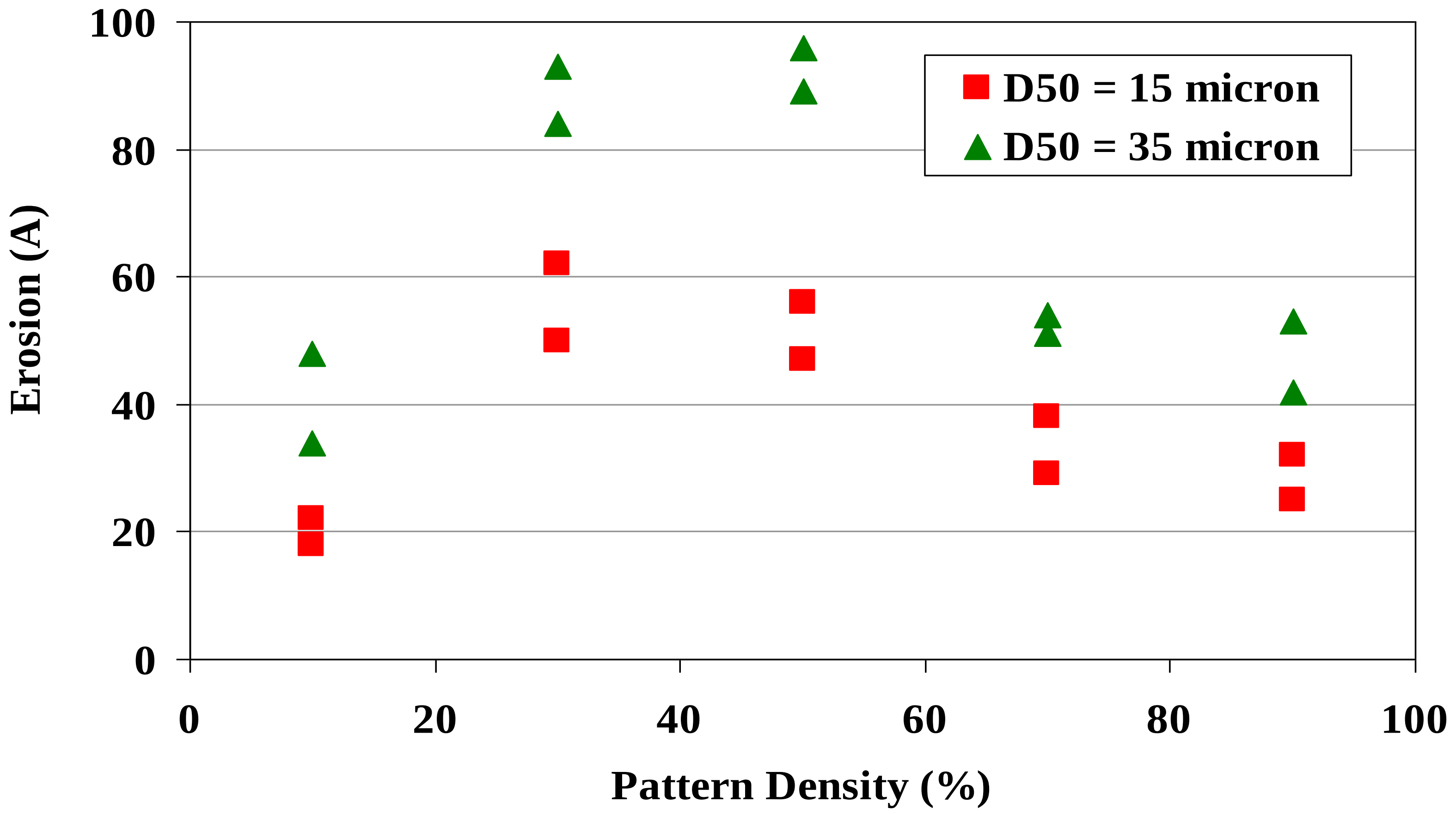
A surface profiler was used to scan the wafer center die with 100-micron pitch and extract dishing and erosion for areas with different pattern densities.

Effect of PU Beads on Dishing



PU beads with D_{50} of 15 µm provide lower dishing than PU beads with D_{50} of 35 µm.

Effect of PU Beads on Erosion



PU beads with D_{50} of 15 µm provide lower erosion than PU beads with D_{50} of 35 µm.

Summary

- For both PU beads, COF remained stable at different polishing pressures. PU beads with D_{50} of 35 µm provided higher COF than PU beads with D_{50} of 15 µm.

- For both PU beads, the oxide removal rate increased linearly with polishing pressure. This indicated that the PU beads were not monosizely packed between the wafer and polycarbonate counter-face.

- PU beads with D_{50} of 15 µm provided higher oxide removal rates than PU beads with D_{50} of 35 µm.

- PU beads with D_{50} of 15 µm provided lower dishing and erosion than PU beads with D_{50} of 35 µm.

“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**

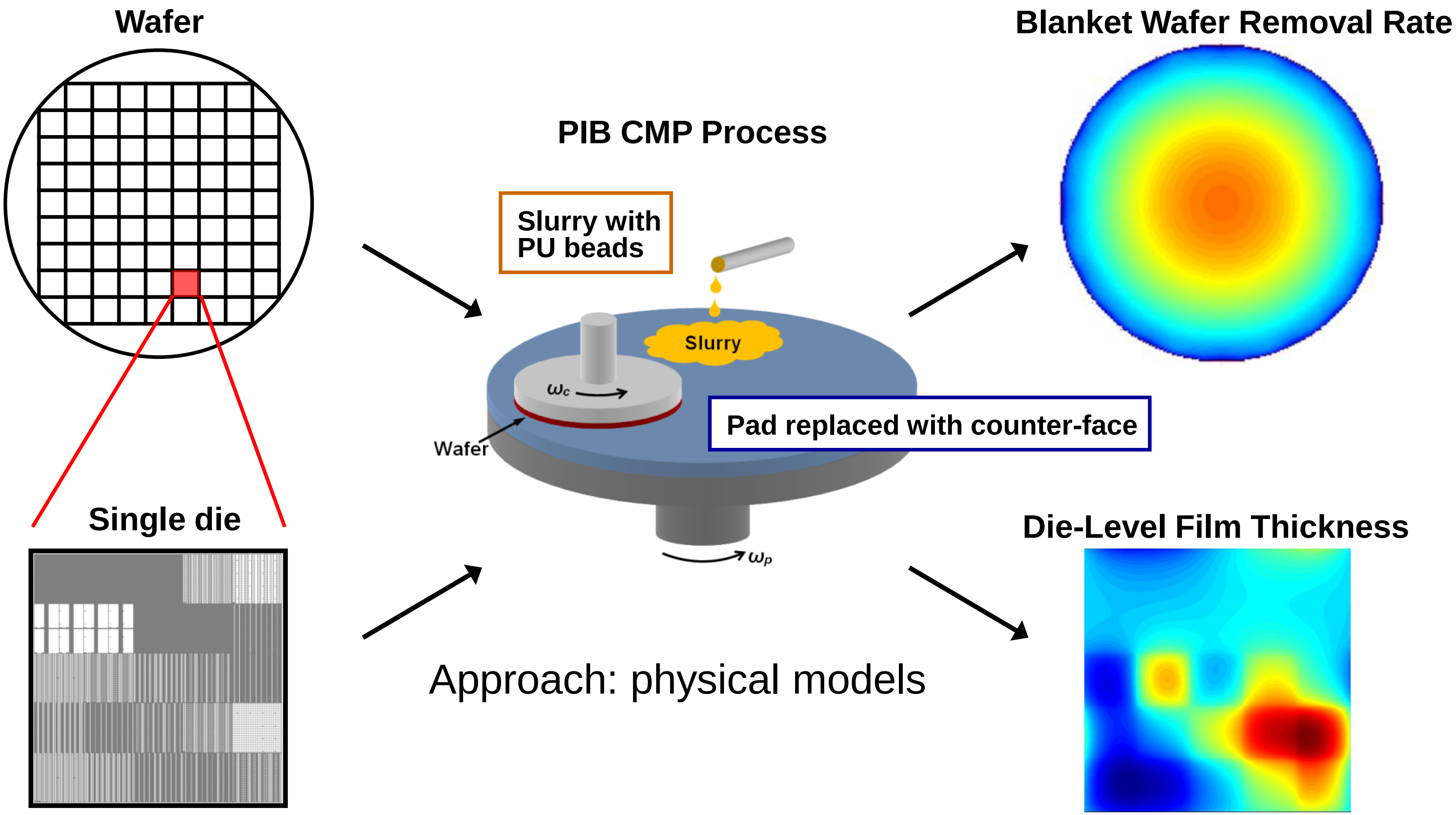
Graduate Student:

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

Collaborator:

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

Overview – PIB Modeling



Wafer

Single die

PIB CMP Process

Slurry with PU beads

Pad replaced with counter-face

Blanket Wafer Removal Rate

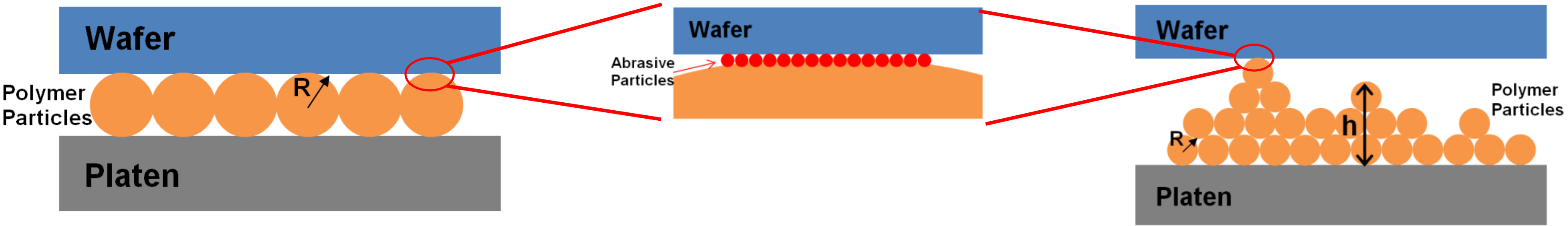
Die-Level Film Thickness

Approach: physical models

Year 1: Blanket Model for Pad-in-a-Bottle

Case 1: bead packing

✓ **Case 2: height distribution**

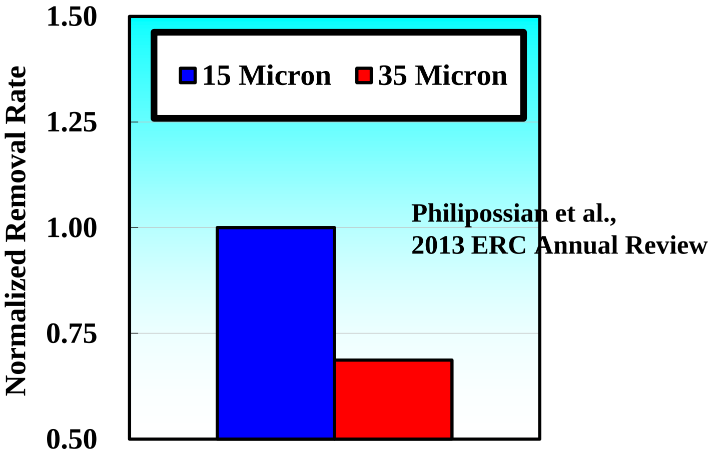


$$RR = \frac{1}{\pi R^{2}}\left(\frac{E_{p}}{3}\right)^{\frac{2}{3}} K'V\left(P_{0}^{\frac{1}{3}} - P_{th}^{\frac{1}{3}}\right)$$

$$RR = \overline{RR_{p}}\,\frac{N}{A_{0}} = \frac{1}{\pi R\lambda}K'VP_{0}$$

Conclusions – need height distribution:

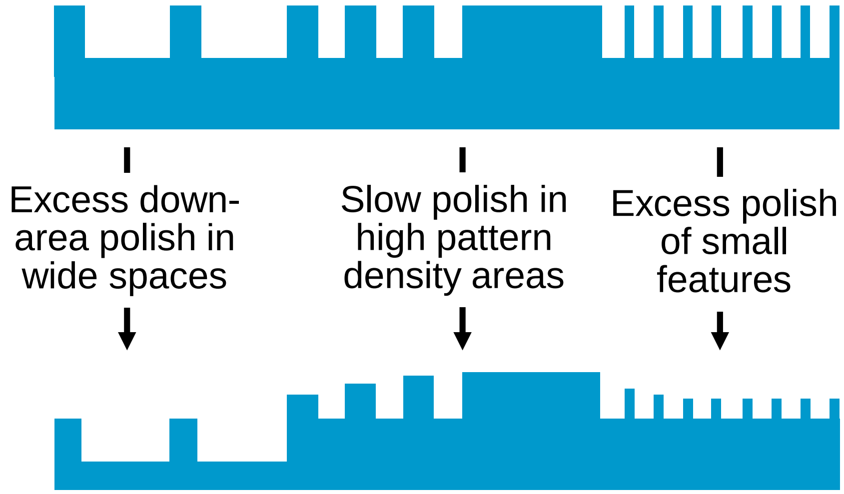
- Bead packing model suggests negligible removal (insufficient point pressures) in the pure packing case)
- Experimental results (at right) suggest 1/R rather than $1/R^2$ bead radius impact on removal rate, consistent with bead stacking or other bead height distribution model



Philipossian et al.,
2013 ERC Annual Review

Year 2: Single-Material PIB Die-Level Model Implementation and Simulation Studies

Goal: Understand chip-scale across-die non-uniformity

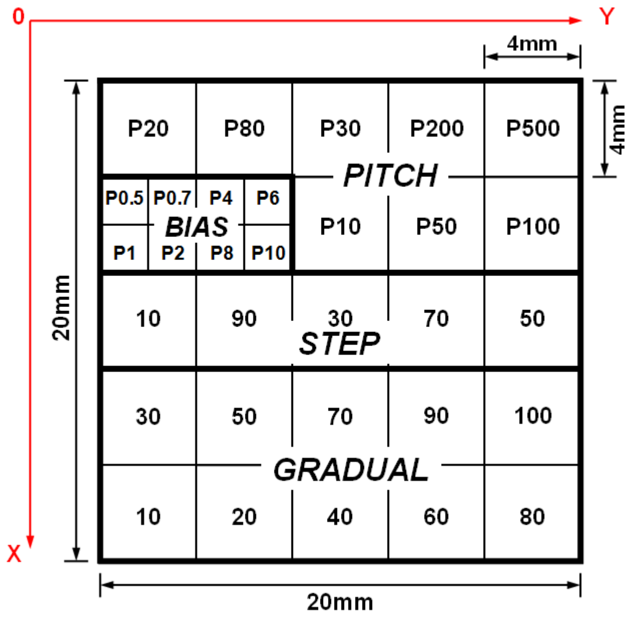


Excess down-area polish in wide spaces

Slow polish in high pattern density areas

Excess polish of small features

Test Chip: Feature Pitch/Size and Pattern Density in Oxide CMP Test Mast

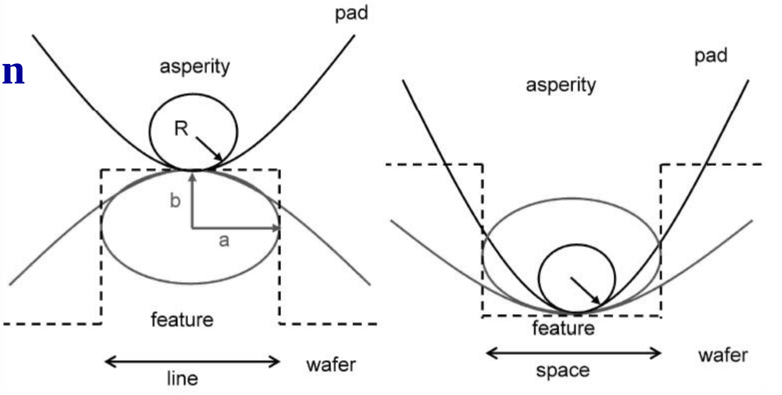


- **Feature size effects: up-area (raised) features and down-area (recessed spaces) polish at different rates, depending on up/down feature size**
- **Chip scale effects: mm-scale interaction between pattern density regions**

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:**

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



Vasilev, IEEE Trans. on Semiconductor Manufacturing 2011

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

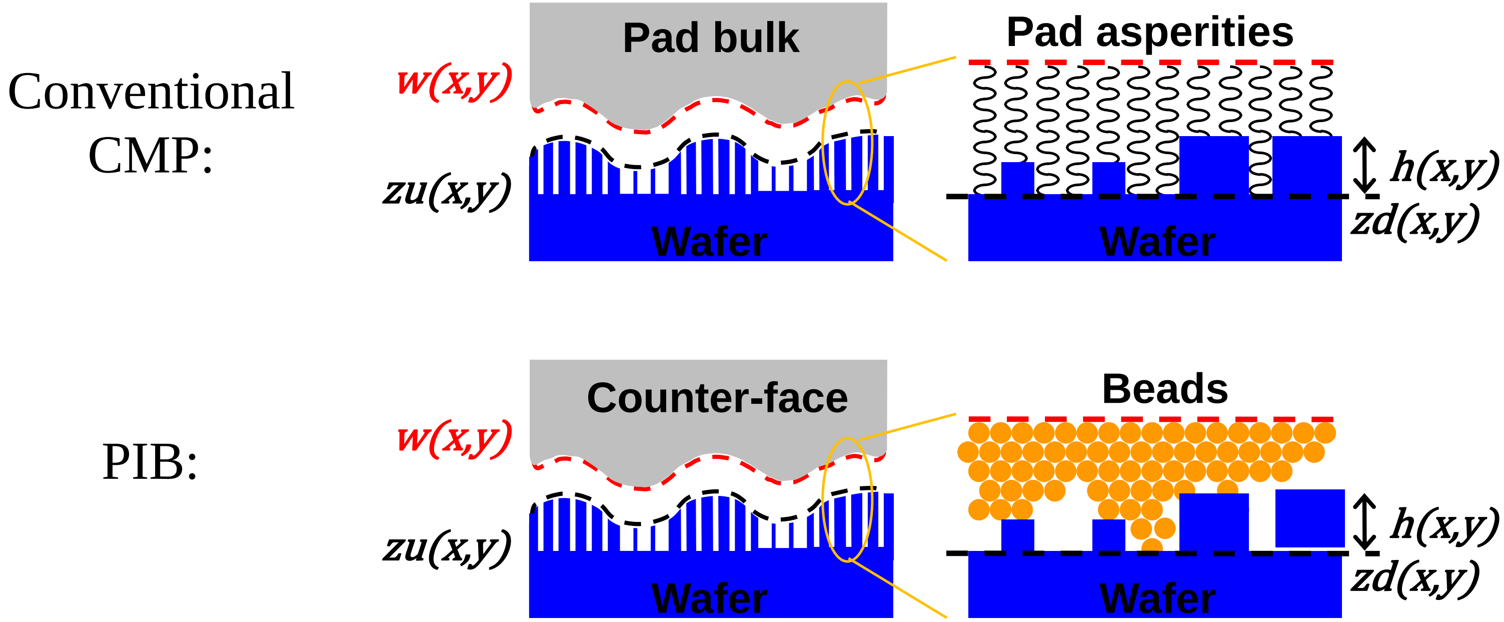
$$\kappa_{feature} = \kappa_{ellipse} = \frac{b}{a^2}$$

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

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

Model – Pad/Counter-face Modulus

- **Pressure application mechanism**
  - **Conventional CMP: pad (long-range) + asperities (short-range)**
  - **PIB CMP: counter-face (long-range) + beads (short-range)**
- **Long-range pad/counter-face bending**
  - **Causes localized pressure differentials across the chip**
  - **Lateral bending of the pad or counter-face depends on the Young's modulus, *E***



Year 2: Single-Material PIB Die-Level Simulation Study Conclusions

- **Bead size**
  - Larger *R* gives *slightly* better pattern performance
  - But larger *R* decreases removal rate

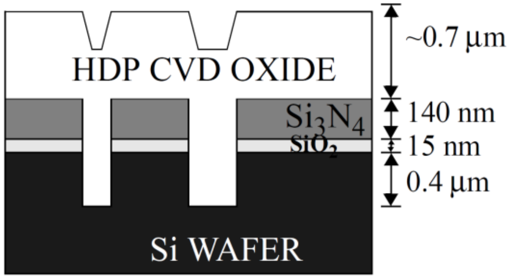
- **Bead stacking height distribution**
  - Smaller λ (tight control on bead stacking, or tight control on bead size distribution) gives slightly better pattern performance
  - Need some height distribution to achieve appreciable removal rate

- **Use of counter-face pad**
  - **Using a stiffer counter-face pad and polyurethane beads, vs. conventional pad, is the dominant source of potential patterned wafer die-level performance improvement**
  - Roughening of counter-face could generate or increase λ height distribution, but that negative λ effect is small compared to major improvements coming from stiff counter-face

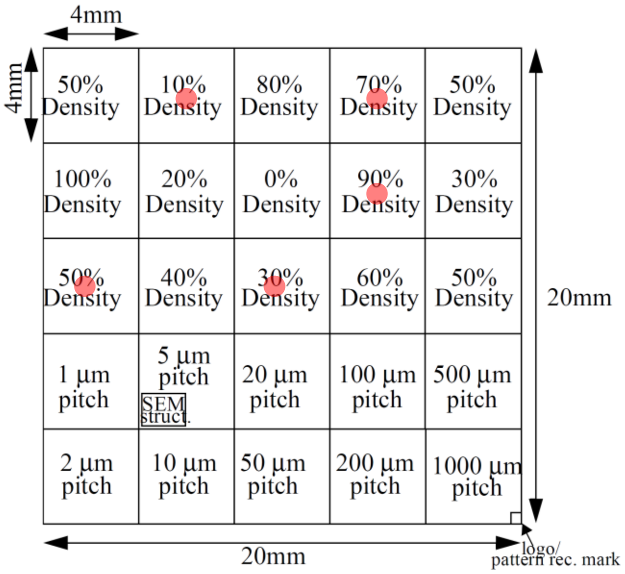
Year 3: Dual-Material PIB Die-Level Model Implemented for Dishing/Erosion Evaluation

- **Extended PIB die-level model to handle dual-material cases**
  - **STI: removal of excess oxide over nitride, while seeking to avoid eroding the nitride layer, or dishing into the oxide trench regions**
  - **Consider layer materials; selectivity in oxide-to-nitride removal rate**
- **Match to UA patterned wafer experiments: PIB model parameters**
- **Quantify potential dishing/erosion improvements PIB vs. conventional**

Test Chip: SKW3-2
STI Patterned CMP Wafers



Cross Sectional View



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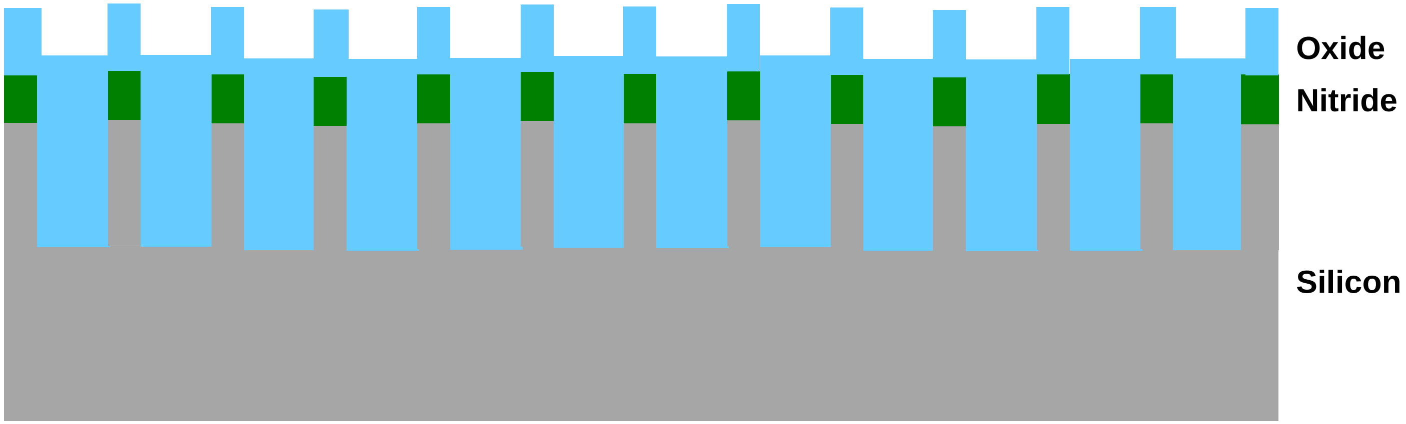
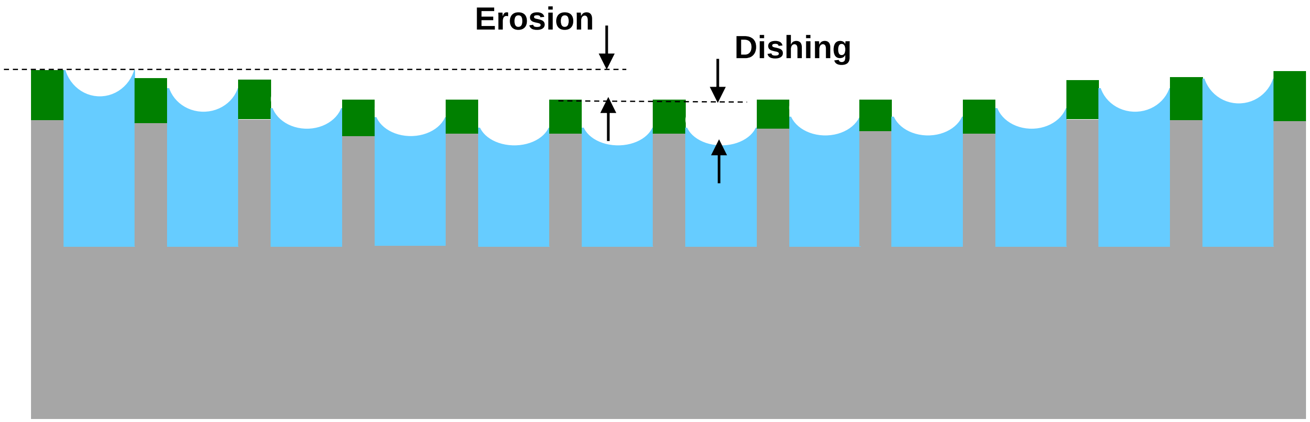
100% Density	20% Density	0% Density	90% Density	30% Density
50% Density	40% Density	30% Density	60% Density	50% Density
1 µm pitch	5 µm pitch	20 µm pitch	100 µm pitch	500 µm pitch
2 µm pitch	10 µm pitch	50 µm pitch	200 µm pitch	1000 µm pitch

Definitions: Dishing & Erosion

Before Planarization

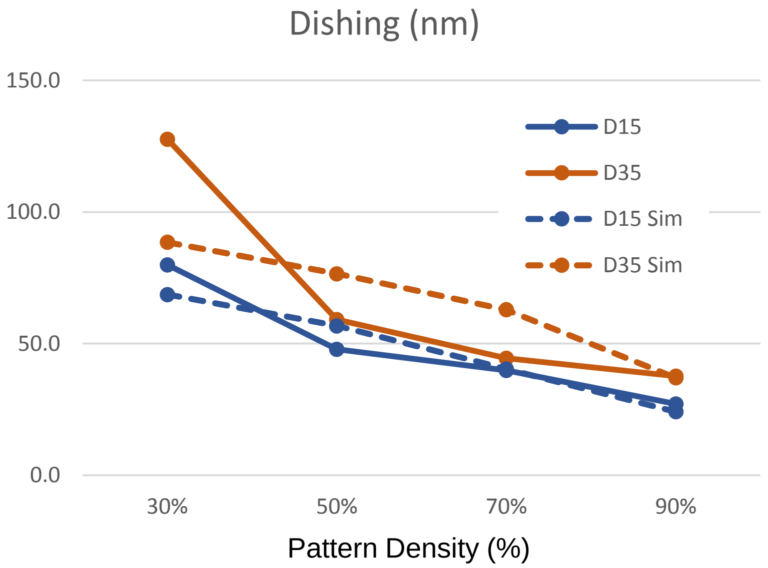


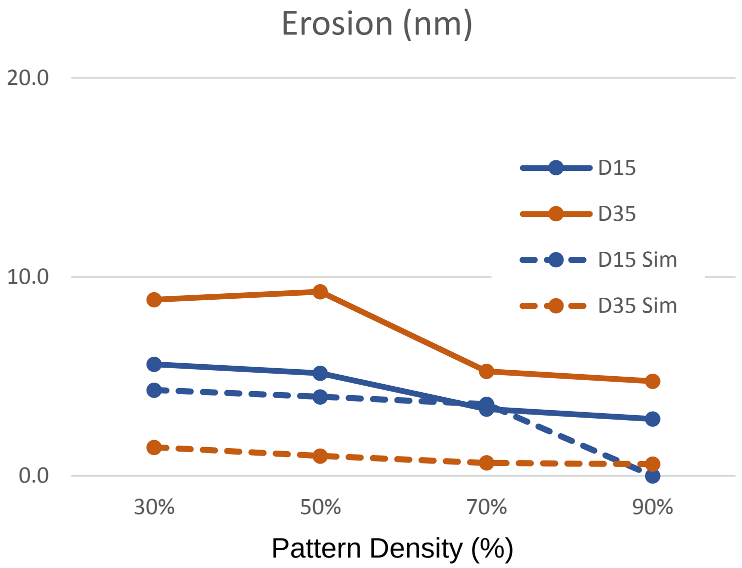
After Planarization



PIB Model Extractions from UA Experiments

- **Best fit to UA experimental data (final polish dishing/erosion data)**





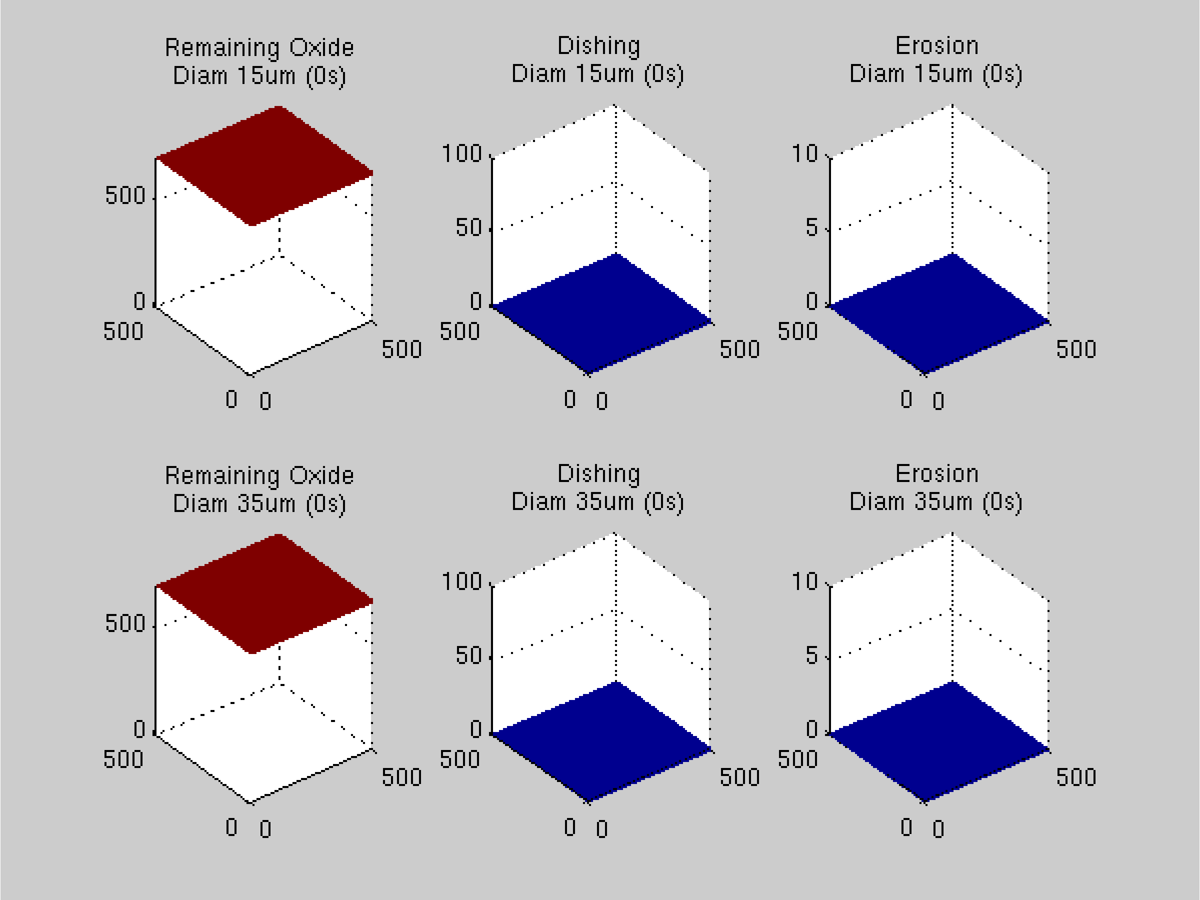
Bead Diameter: 15 um
- **Counter-face modulus (E): 1700 MPa**
- **Bead height (λ): 0.14 um**
- **Stacking (α): 11**
- **Oxide rate (K_0): 62 nm/min**
- **Nitride rate (K_1): 1.03 nm/min (selectivity = 60)**

RMS data to simulation: 5.32 nm

Bead Diameter: 35 um
- **Counter-face modulus (E): 1700 MPa**
- **Bead height (λ): 0.14 um**
- **Stacking (α): 11**
- **Oxide rate (K_0): 45nm/min**
- **Nitride rate (K_1): 0.75 nm/min (selectivity = 60)**

RMS data to simulation: 17.2 nm

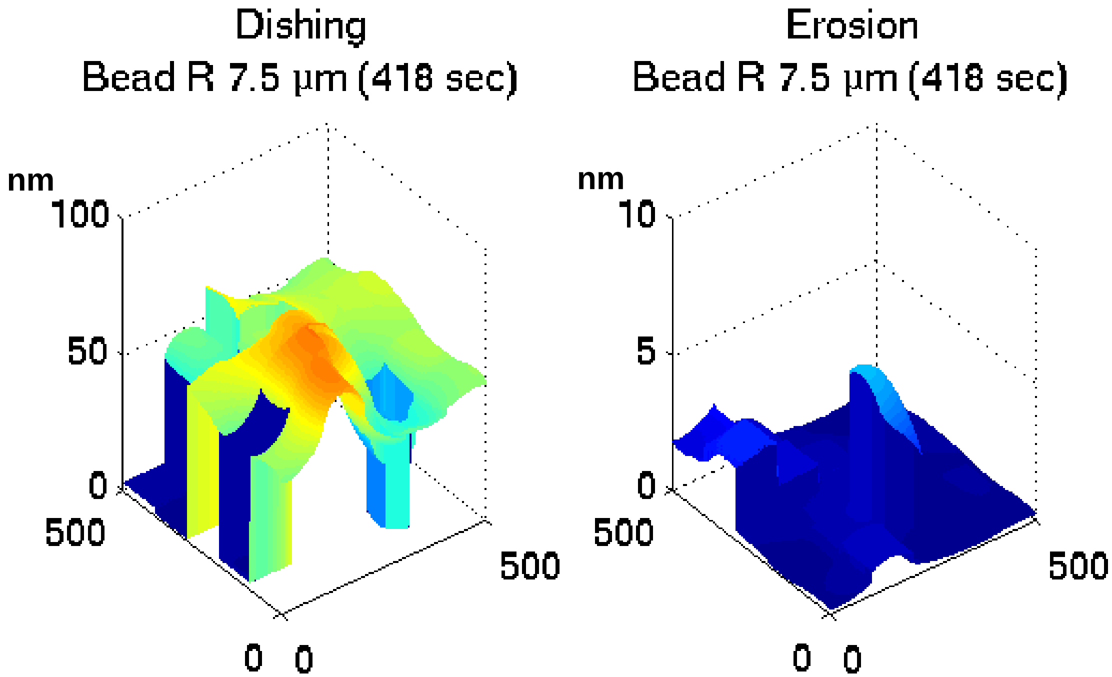
Full Chip Simulation for 15 um and 35 um Bead Diameter Experiments



Simulation Animation

SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

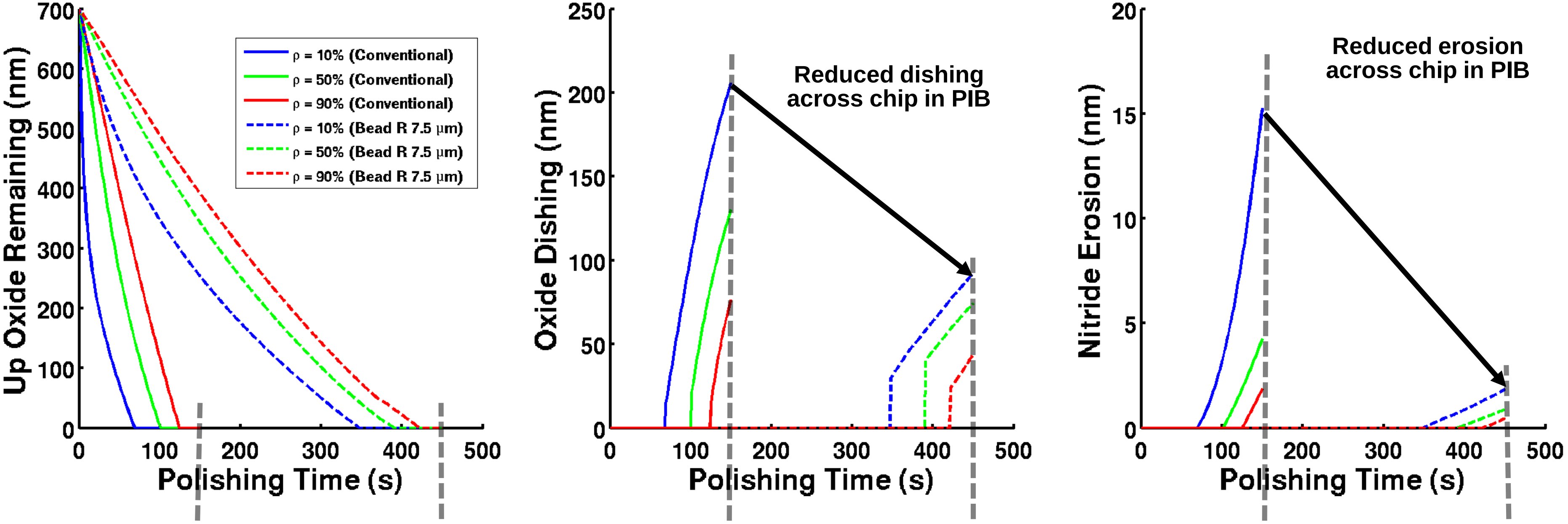
Full Chip Simulation for 15 um Bead Diameter Experiment



Chip
20 mm X 20 mm

- **Across-chip metrics:**
  - **Dishing: max = 75.5 nm; rms = 51.0 nm**
  - **Erosion: max = 4.91 nm; rms = 2.35 nm**

Comparison: PIB vs. Conventional



nitride clear compete (conventional)

nitride clear compete (PIB)

nitride clear compete (conventional)

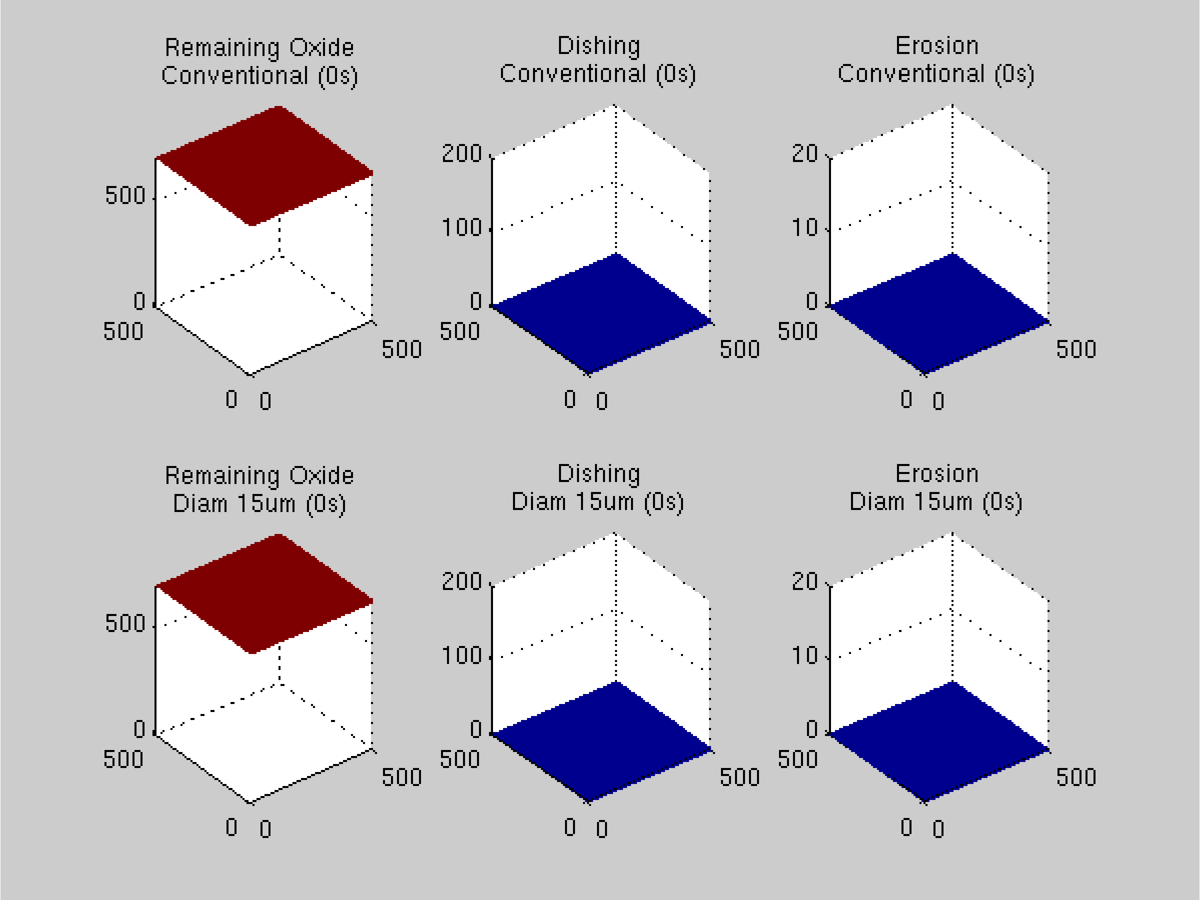
nitride clear compete (PIB)

nitride clear compete (conventional)

nitride clear compete (PIB)

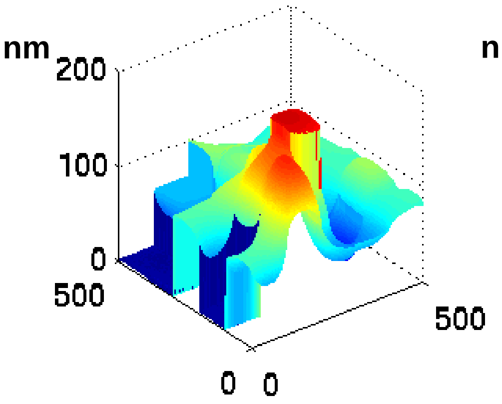
- **First stage: removal of oxide over nitride**
- **Second stage: dishing and erosion occurs in regions that have cleared, while waiting for rest of chip to clear**

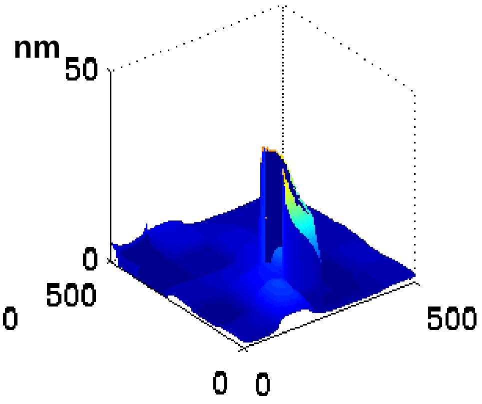
Comparison: PIB vs. Conventional



Simulation Animation

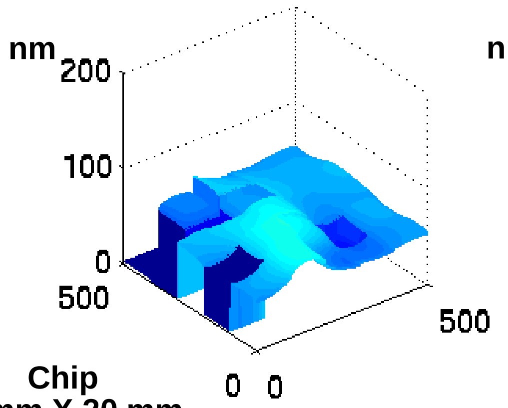
Comparison: PIB vs. Conventional

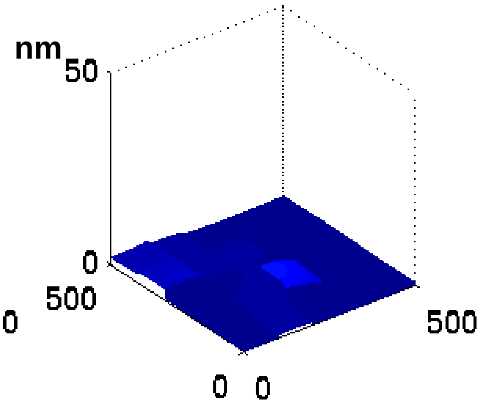

Dishing
Conventional (Clear 127 s)


Erosion
Conventional (Clear 127 s)

Conventional CMP

- Asperity diameter: 20 um
- Pad modulus (E): 300 MPa
- Bead height (λ): 0.1 um
- Stacking (α): 10
- Oxide rate (K_0): 240 nm/min
- Nitride rate (K_1): 4 nm/min
(selectivity = 60)


Dishing
Bead R 7.5 µm (Clear 423 s)


Erosion
Bead R 7.5 µm (Clear 423 s)

Chip
20 mm X 20 mm

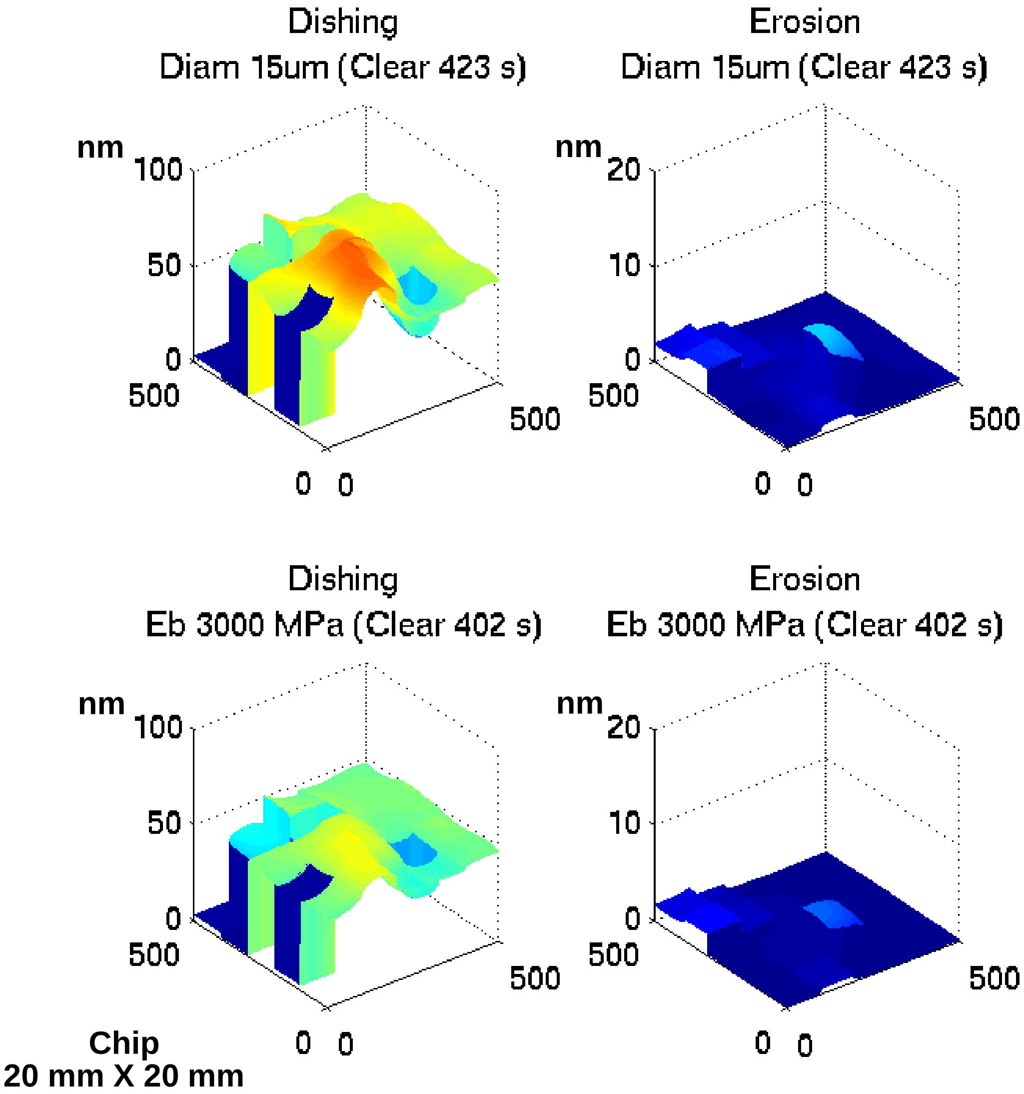
PIB CMP

- As fit to UA experiments

At best stopping time
(when nitride clears
across entire chip)

PIB Die-Level Optimization Results

- Impact of Stiff Counter-face
  - Nearly all of the improved die-uniformity, reduced dishing, and reduced erosion comes from the use of the stiffer counter-face compared to conventional pad
- Further Improvement?
- 3000 MPa vs. 1700 MPa
  - Additional reduction possible by choosing a stiffer polycarbonate counter-face
- Reduce oxide deposition
  - Reduce time, material, environmental impact from deposition



PIB Die-Level Optimization Results

- **Current PIB decreases dishing 2.3X, but 3.3X slower**
- **Stiffer PIB counterface decreases dishing 2.9X, slightly faster (3.2X conventional)**
- **Current PIB could achieve same dishing, but with 29% less oxide deposition and CMP time 2.1X conventional**
- **Stiffer PIB could achieve same dishing, but with 36% less deposition and more comparable CMP time 1.7X vs. conventional**

Case	Dishing Max (nm)	Clear Time (s)
Conventional (700 nm oxide)	182	127
Current PIB (1.7 GPa; 700 nm oxide)	79	423
PIB (3.0 GPa; 700 nm oxide)	62	402
PIB (1.7 GPa; 500 nm oxide)	161	265
PIB (3.0 GPa; 450 nm oxide)	177	218

Conclusions and Prospects: Pad-in-a-Bottle

- **Substantial improvements in die-scale planarization are enabled by PIB**
  - **Demonstrated reduced dishing and erosion in STI experiments**
  - **Compared with chip-scale models**
  - **Primary improvement: stiff counter-face replaces polyurethane pads**
- **Removal rates**
  - **Blanket wafer rates (and effective blanket wafer rates on patterned wafers) are currently low – about 3x lower than conventional slurries**
  - **Future possibility: increase rate with rough 15um beads?**
- **Environmental impact**
  - **Can replace polish pad with polycarbonate counter-face**
  - **Materials (beads, slurries with surfactants) are compatible with existing CMP processes and effluents**
- **Outlook: PIB technology a viable option when/if the CMP industry is forced to move to pads/counter-faces with 5X stiffness to address future dishing/erosion and die uniformity requirements**