Planarization Long Range Plan

Last Updated in November 2010

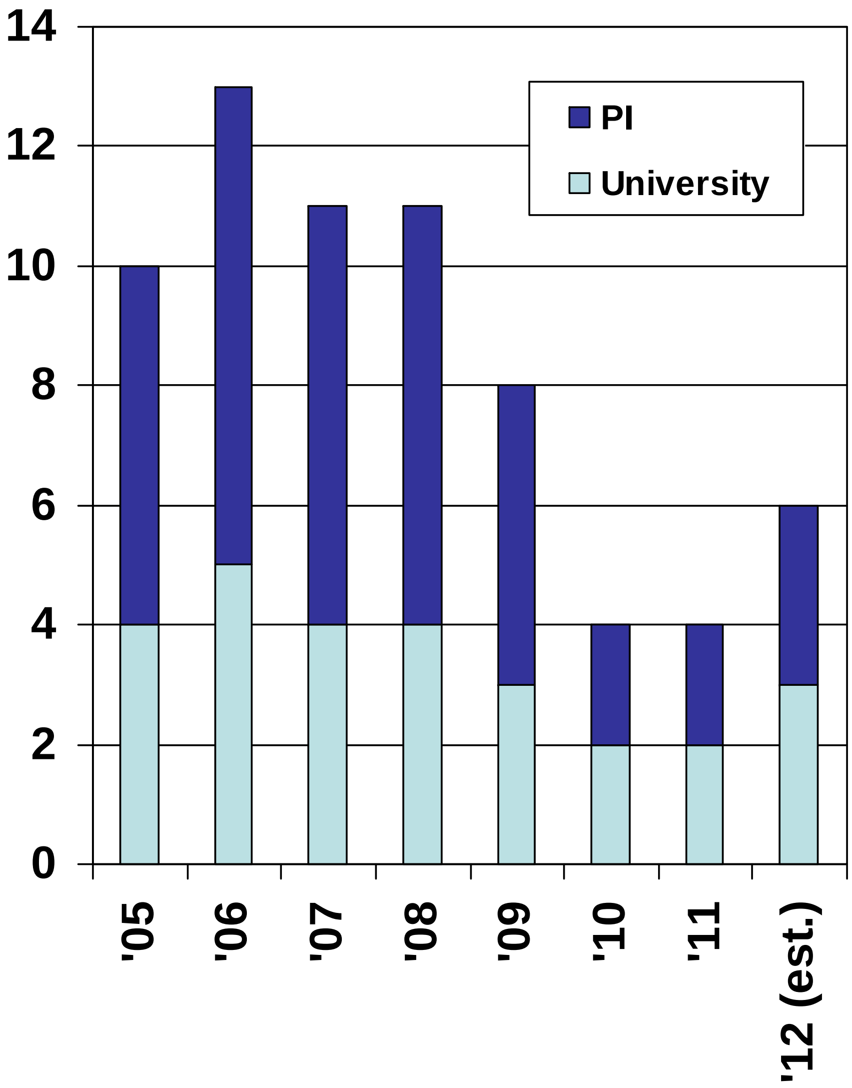
SIGILLVM VNIVERSITATIS ARIZONENSIS 1885

MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1861

IBM Cabot Microelectronics intel Leap ahead GLOBALFOUNDRIES

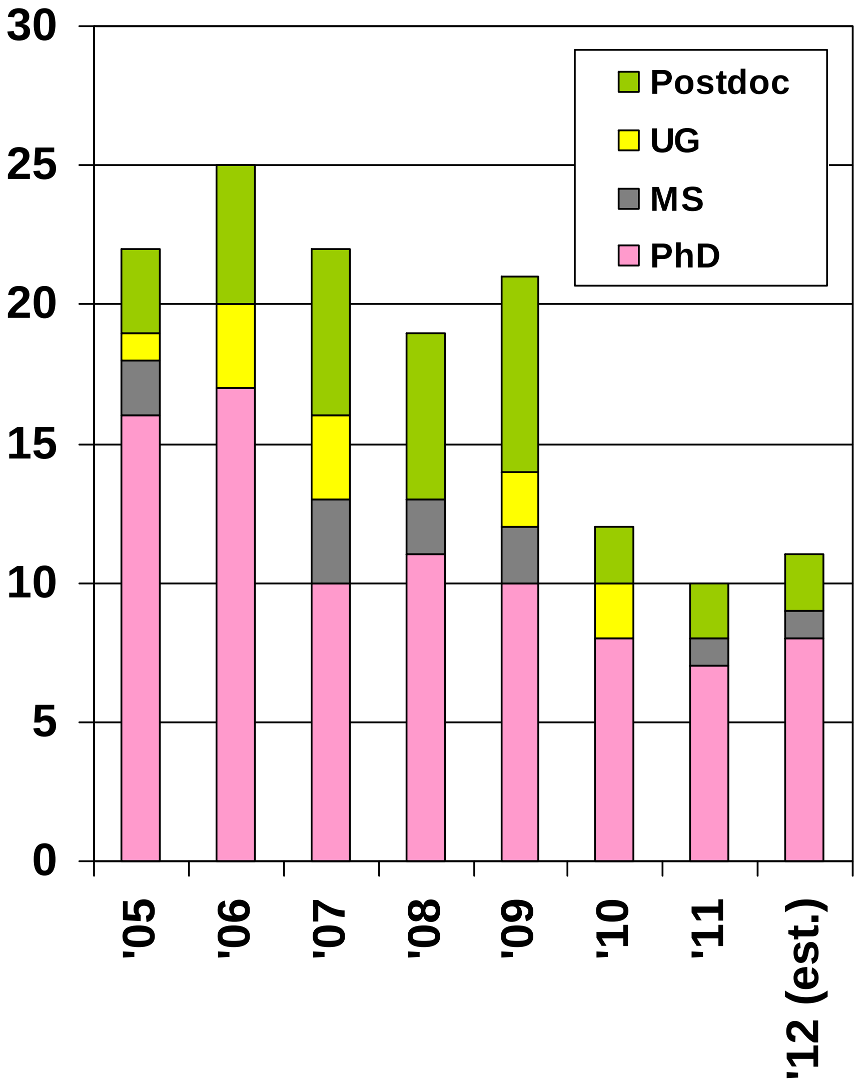
SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

Trends in the Planarization Thrust Team



- Reduction in the number of PIs and universities due to certain research themes no longer being in synch with industry and ITRS needs (i.e. E-CMP and pad-level embedded force sensors).
- Currently exploring the possibility of adding a new PI with core expertise in surface chemistry.
- Also looking to add a CMP Advisory Committee member from Micron
- For the next 3 years, we have funding in place from our affiliate members (CMC, Ehwa, Entegris and Morgan Cermics) with matching funds from Sematech/SRC.
- We plan is to submit 3 proposals to Sematech/SRC this year for projects starting in 2012.

Trends in the Planarization Thrust Team



- **Reduction in the number of students and post-docs; consistent with the drop in the number of PIs**
- **In 2012, we are looking to add one new PhD candidate once we have secured a new PI to spearhead our chemistry-related programs**
- **Except for one, all MS and PhD graduates are employed in industry and government:**
  - **Intel**
  - **Draper Labs**
  - **Novellus**
  - **CMC**
  - **Micron**
  - **NexPlanar**
  - **Cadence**
  - **Araca**
  - **McKinzie**
  - **Goldman Sachs**
  - **DC Energy**
  - **CIA**

Landscape for the Next Five Years

Research, fundamental yet industrially relevant, addressing the technological, economic and environmental challenges of planarization technologies

! ··· YIELD CANNOT BE COMPROMISED ··· !

A process change motivated by EHS, that results in lower yields, WILL NOT BE ADOPTED since economic losses resulting from lower yields dominate any gains realized through consumables reduction.

Sustainable HVM can only be realized through yield improvement AND consumables reduction

Advanced Processes and Consumables for Planarization

- **Objectives and Approaches**
  - Wear phenomena and their effects on process performance
    - Investigate the effect of pad conditioning (both conventional and CVD) on pad surface micro-texture, frictional force, removal rate and wafer topography (dishing/erosion)
    - Investigate frictional force, removal rate, pad surface micro-texture evolution during pad and conditioner wear tests
    - Understand the fundamentals of in-situ vs. ex-situ conditioning of soft pads (NEW)
  - Effect of retaining ring on pad micro-texture and slurry flow
    - Investigate the effect of retaining ring material and geometry on pad surface micro-texture
    - Investigate the effect of retaining ring geometry on slurry flow at bow wave and within pad-wafer interface

Advanced Processes and Consumables for Planarization

- **Objectives and Approaches (continued)**
  - **Effect of film morphology on process performance (NEW)**
    - **Investigate the effect of tungsten and copper film morphology (modulated through various deposition and anneal processes as well as through aging) on thermal, tribological and kinetic attributes of CMP**
  - **Wafer-level and die-level CMP modeling**
    - **Develop new models of pad macro-texture, micro-texture and slurry flow to study interactions between wafer-level effects, retaining ring design and chip-scale planarization performance**
    - **Extend die-level models to include key pad micro-texture dependencies to better predict dishing and erosion**
    - **Integrate die-level and wafer-level models to enable overall uniformity and performance optimization**

Advanced Processes and Consumables for Planarization

- Objectives and Approaches (continued)
  - Novel metrology developments
    - Use laser confocal microscopy to measure pad surface micro-texture, including contact area, near-contact area, pad surface abruptness, and summit curvature
    - Use UV-enhanced fluorescence technique to visualize slurry flow and measure slurry film thickness at retaining ring bow wave and within pad-wafer interface
    - Measure pad asperity modulus through nano-indentation
    - Develop new (or modify existing) methods to study abrasive nano-particle, wafer and pad surface reactivities (other than zeta potential and Si-OH density measurements) to gain a better understanding of the CMP process (NEW)
  - 450 mm pathfinding via equipment- and wafer-level modeling (NEW)

Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

(*Task 425.032) – March 2011*

Subtask 1: Effect of Retaining Ring Geometry on Slurry Flow and Pad Micro-Texture

PI:

- **Ara Philipossian, Chemical and Environment Engineering, UA**

Graduate Students:

- **Xiaoyan Liao, PhD candidate, Chemical and Environmental Engineering, UA**
- **Xiaomin Wei, PhD candidate, Chemical and Environment Engineering, UA**
- **Anand Meled , PhD candidate, Chemical and Environment Engineering, UA**

Undergraduate Student:

- **Adam Rice, Chemical and Environment Engineering, UA**

Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

(Task 425.032) – March 2011

Subtask 1: Effect of Retaining Ring Geometry on Slurry Flow and Pad Micro-Texture

Other Researchers:

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

Cost Share (other than core ERC funding):

- **In-kind donation (pads) from Cabot Microelectronics Corporation**
- **In-kind donation (retaining rings) from Entegris, Inc.**

Primary Anticipated Results

- **Understand how pad micro-texture and slurry availability are fundamentally affected by:**
  - **Pad type (i.e. porous vs. non-porous, and various degrees of hardness)**
  - **Diamond disc type (i.e. grain size, and morphology)**
  - **Retaining ring slot designs**
  - **Slurry flow rate and injection schemes**

- **Via die-scale and wafer-scale empirical, theoretical and numerical methods, gain a deeper understanding of how the above:**
  - **Interact with one another**
  - **Affect polishing outcomes (on 300 mm rotary platforms)**
  - **May be extendible to 450 mm rotary processes (theoretically)**

- **Ultimately, our goal is for this work to lead to new designs of polishing protocols and consumables with superior performance (i.e. wafer-level topography, uniformity, consumable durability, throughput …) and more environmentally benign consequences.**

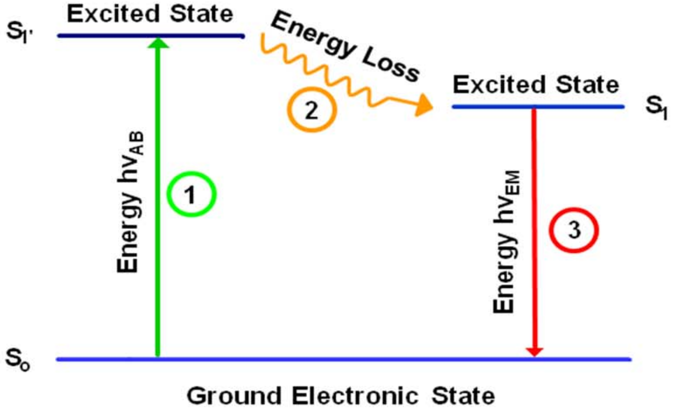
Specific Objectives and EHS Impact

- **Develop a UV enhanced fluorescence system and quantify the extent of fluorescent light emitted by the slurry**
- **Employ the fluorescent light data to rapidly assess slurry flow patterns as a function of retaining ring designs, slurry flow rates, pad groove designs, and tool kinematics**
- **Investigate the effect of retaining ring slot design and polishing conditions including pad/retaining ring sliding velocity, retaining ring pressure and slurry flow rate on fluid dynamics at the bow wave**

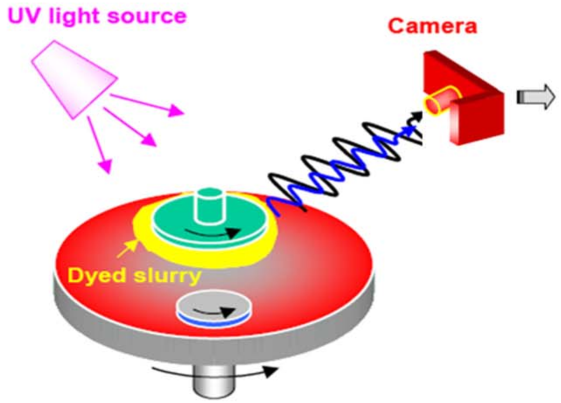
Reduce slurry consumption by 40 percent

General Approach

- Tag slurry with a special set of fluorescent dyes
- Use UV – LED as light sources to excite the dyes in the slurry causing them to emit fluorescent light
- Employ a high resolution CCD camera to record the emission of fluorescent light
- Develop software and quantitatively assess the flow pattern using the movie from CCD camera



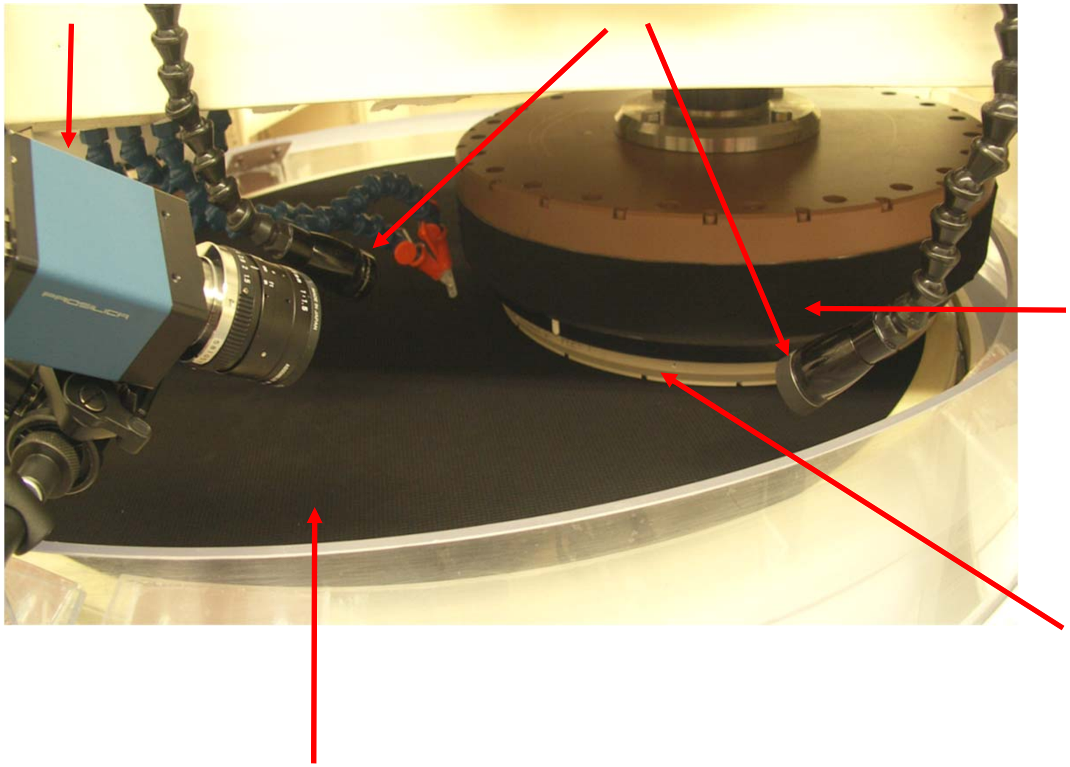
Jablonski Energy Level Diagram



UV Fluorescence Technique

Experimental Setup

Polisher : Araca APD – 800
Camera shutter : 0.02 sec
Frequency : 5 Hz
Frames per run : 50 frames

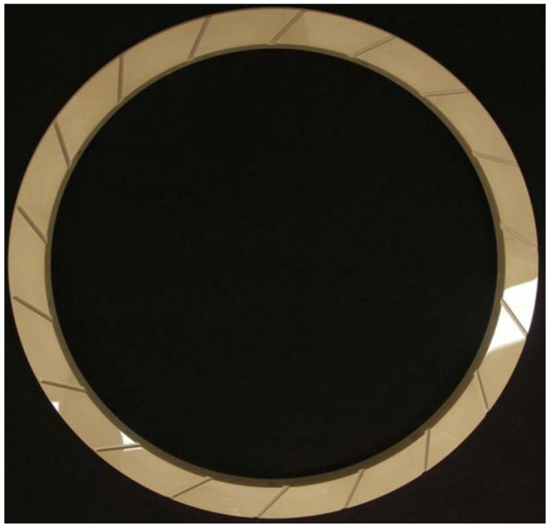


HD CCD Camera

UV Lights

Carrier Head

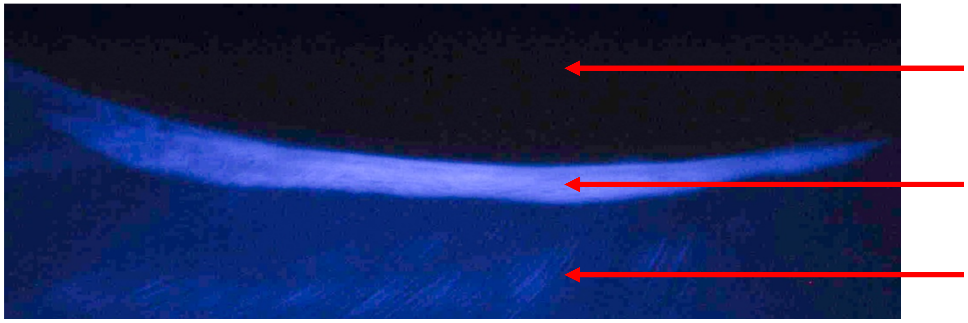
Politex Pad



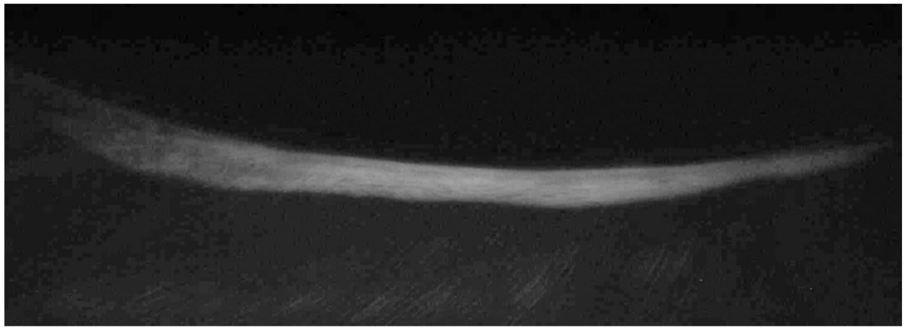
Retaining Ring

Image Analysis Procedure

Raw Image



Grey Scale Image



Cropped Image

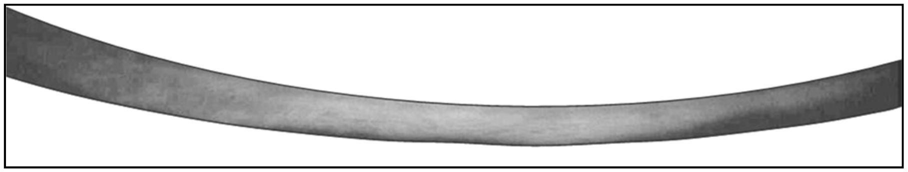
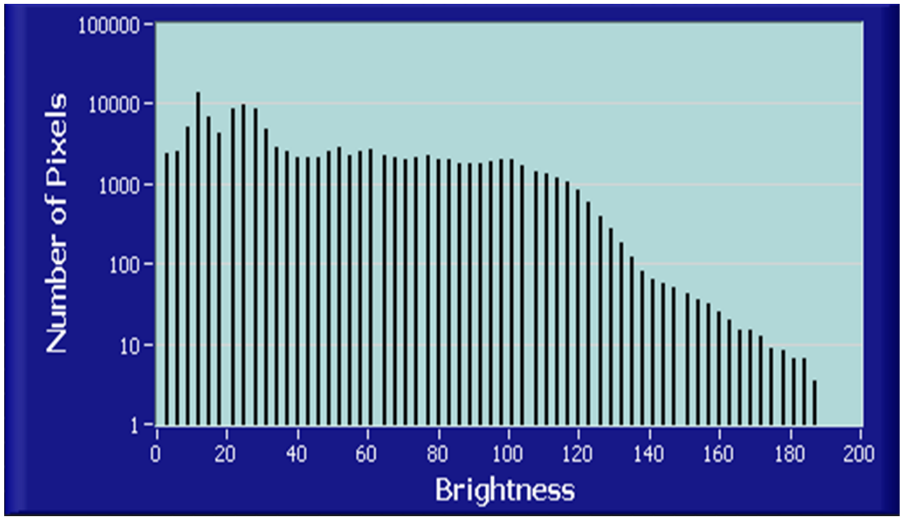
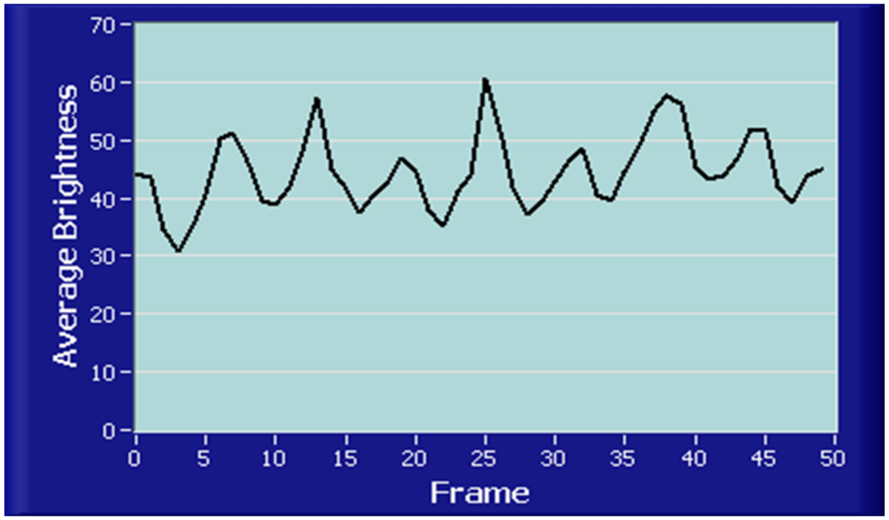


Image Analysis – Effect of Pressure



Brightness Data of One Image

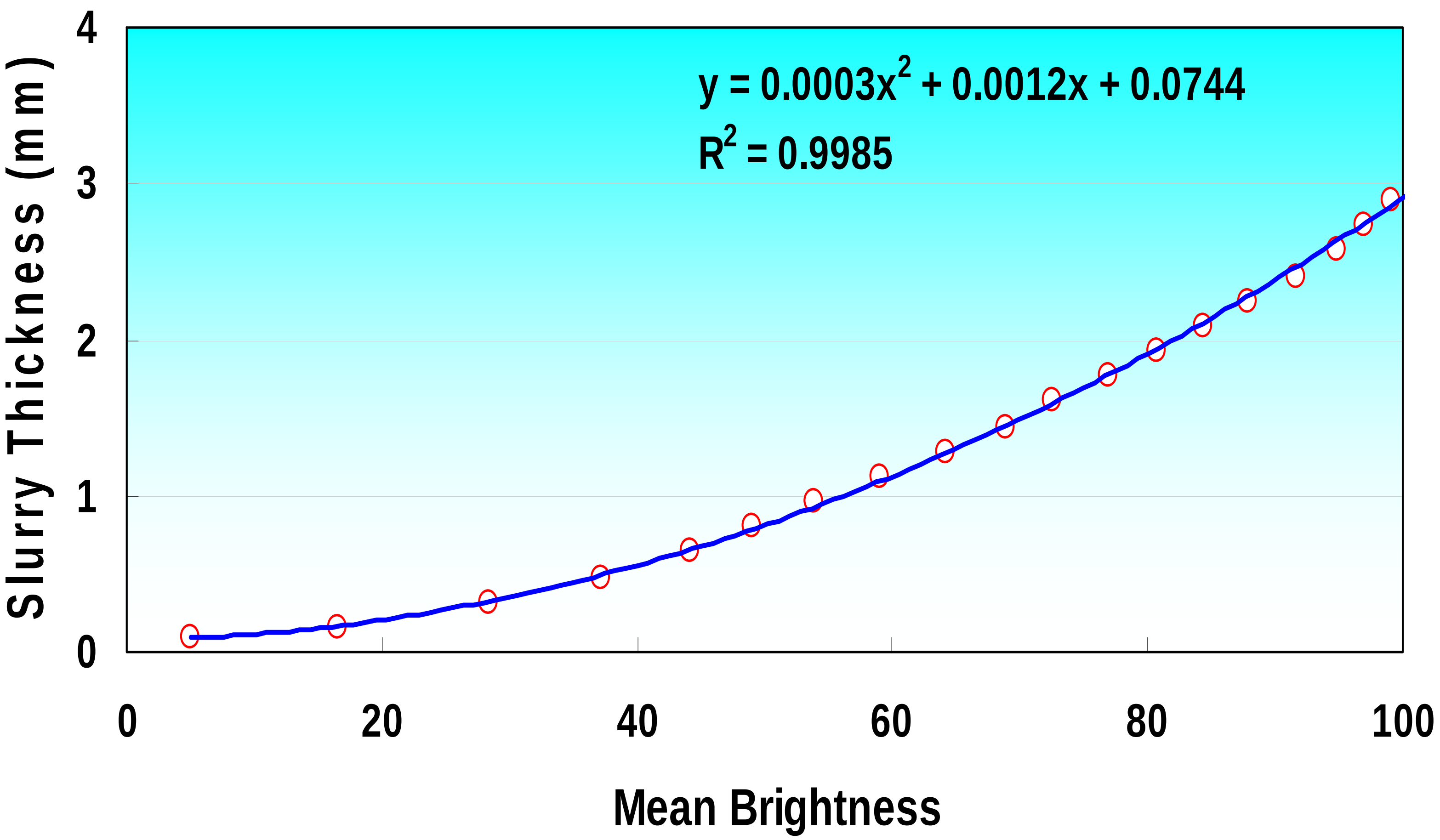


Average Brightness Calculation

Mean brightness: 44.5

Standard deviation: 6.4

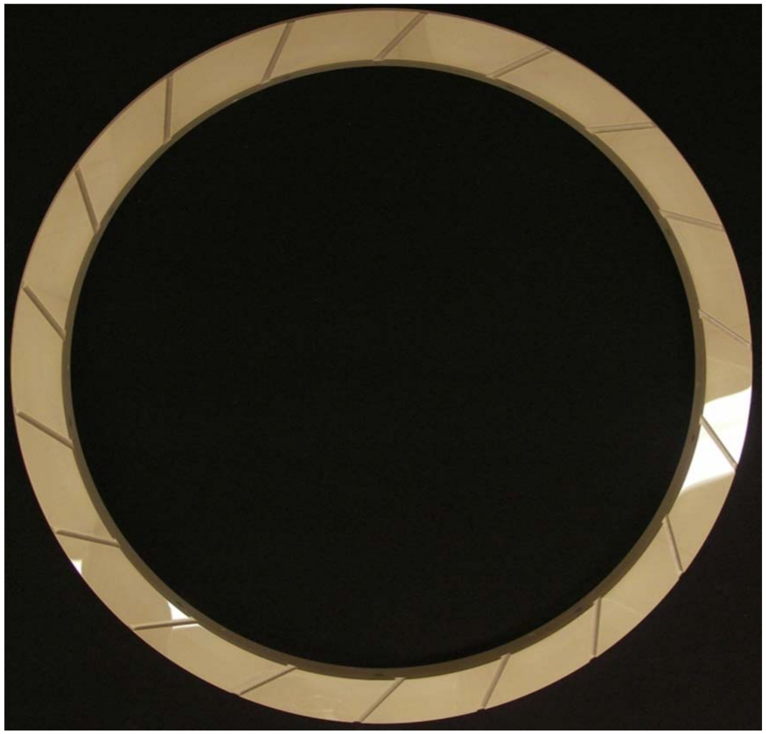
Slurry Film Thickness Calibration Curve



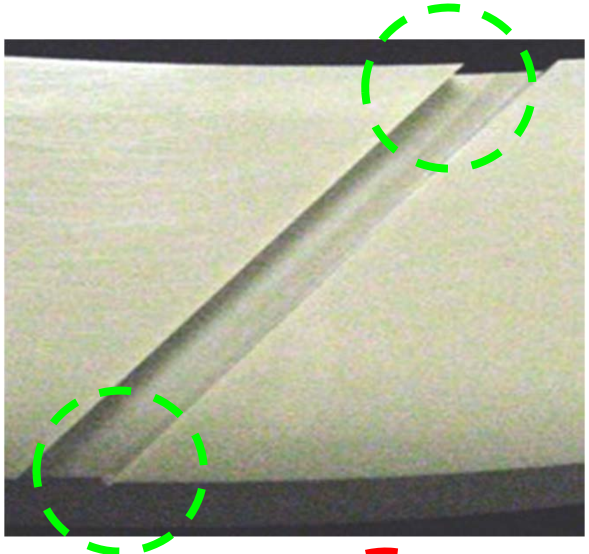
Experimental Conditions

- Retaining Ring Designs
  - PEEK-1 and PEEK-2
- Sliding Velocities
  - 0.6 and 1.2 m/s
- Ring Pressures
  - 1.4 and 2.8 PSI
- Slurry Flow Rates
  - 150 and 300 ml/min
- Pad
  - Dow Electronic Materials Politex REG
- Pad Conditioning
  - In-situ conditioning at 3 lb_f by 3M PB32A brush
- Slurry
  - 1 part of Fujimi PL-7103 slurry + 4 parts of DI H_2O + 0.5 g/L Coumarin (4-Methyl-umbelliferone)
- Polishing Time
  - 20 seconds

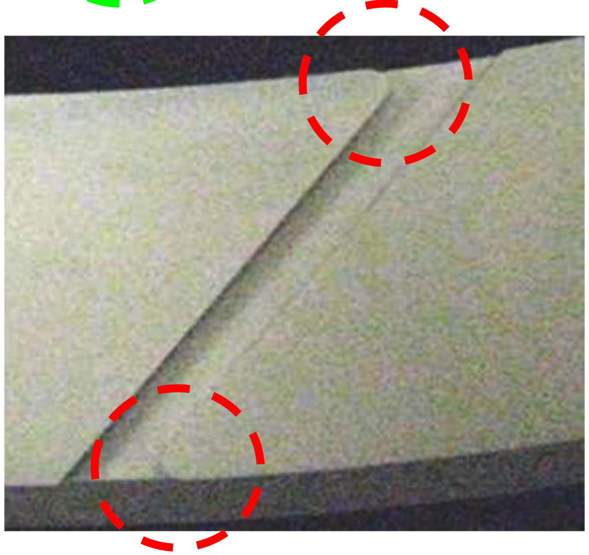
Retaining Ring Slot Designs



Retaining Ring for 300-mm Wafer Process



PEEK-1



PEEK-2

Example – Effect of Retaining Ring Designs

0.6 m/s, 2.8 PSI, 300 ml/min

PEEK-1

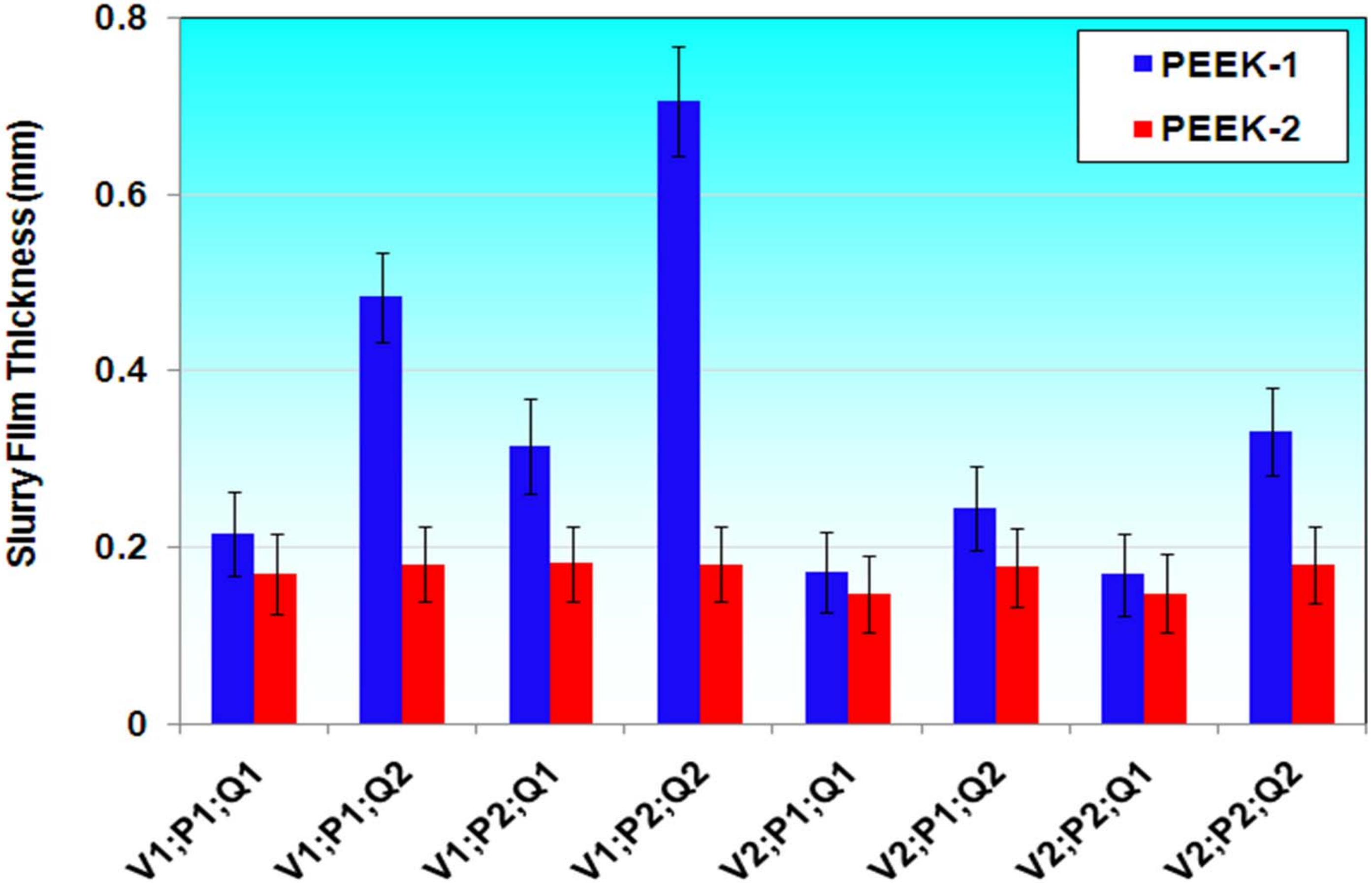
Mean slurry film thickness: 0.71 mm

PEEK-2

Mean slurry film thickness: 0.18 mm

Bow Wave Slurry Film Thickness

Effect of Retaining Ring Design

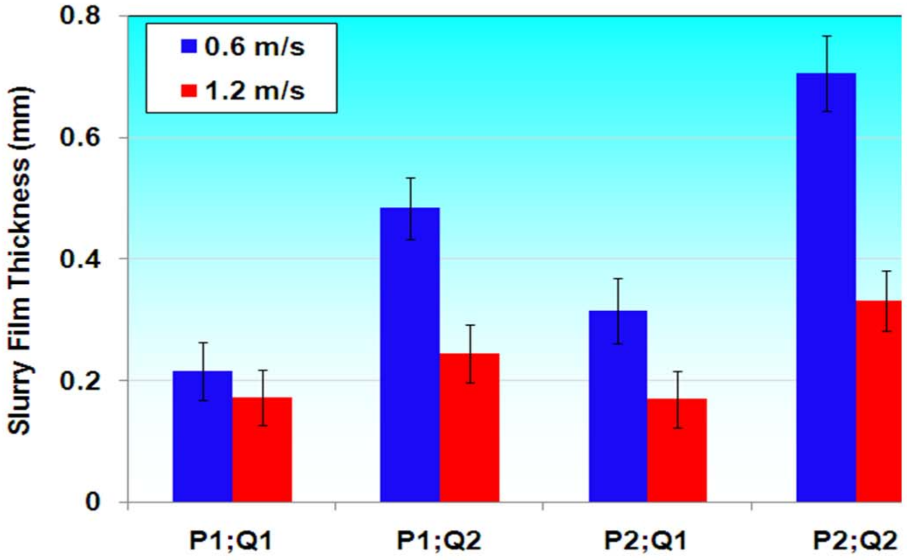


V1 = 0.6 m/s, V2 = 1.2 m/s, P1 = 1.4 PSI, P2 = 2.8 PSI, Q1 = 150 ml/min, Q2 = 300 ml/min

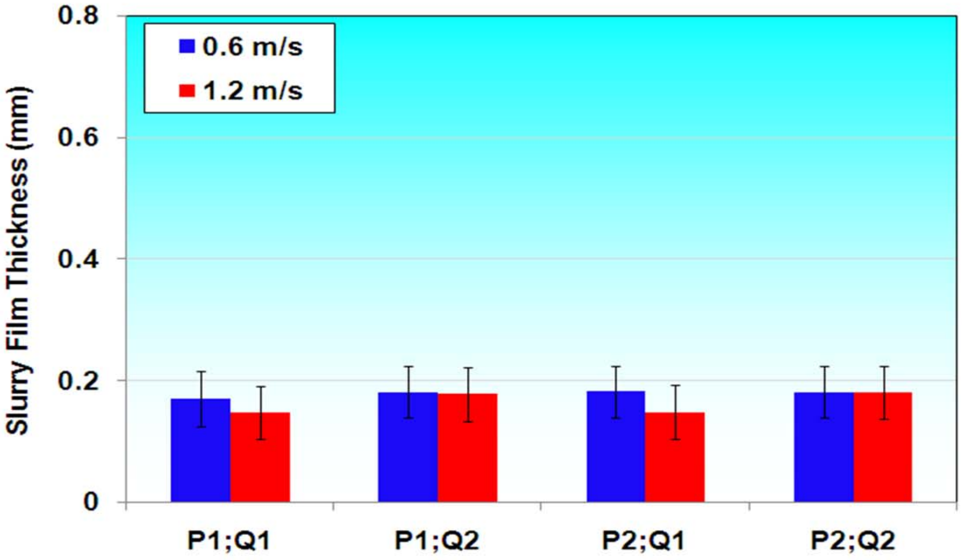
Bow Wave Slurry Film Thickness

Effect of Sliding Velocity

PEEK-1



PEEK-2

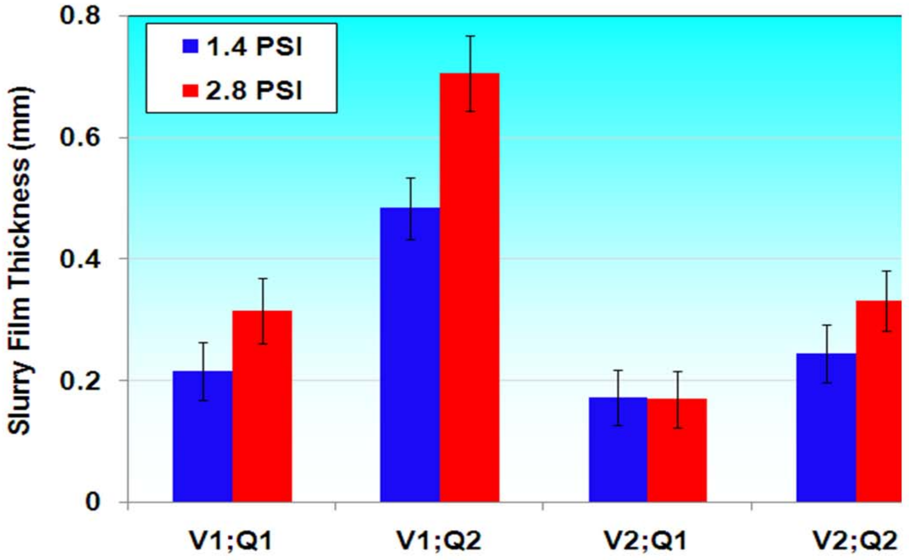


P1 = 1.4 PSI, P2 = 2.8 PSI, Q1 = 150 ml/min, Q2 = 300 ml/min

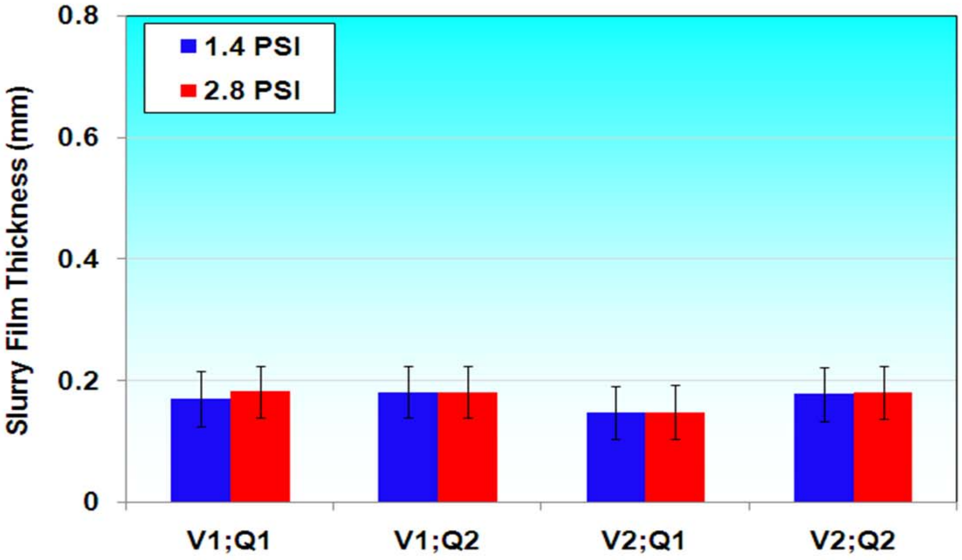
Bow Wave Slurry Film Thickness

Effect of Retaining Ring Pressure

PEEK-1



PEEK-2

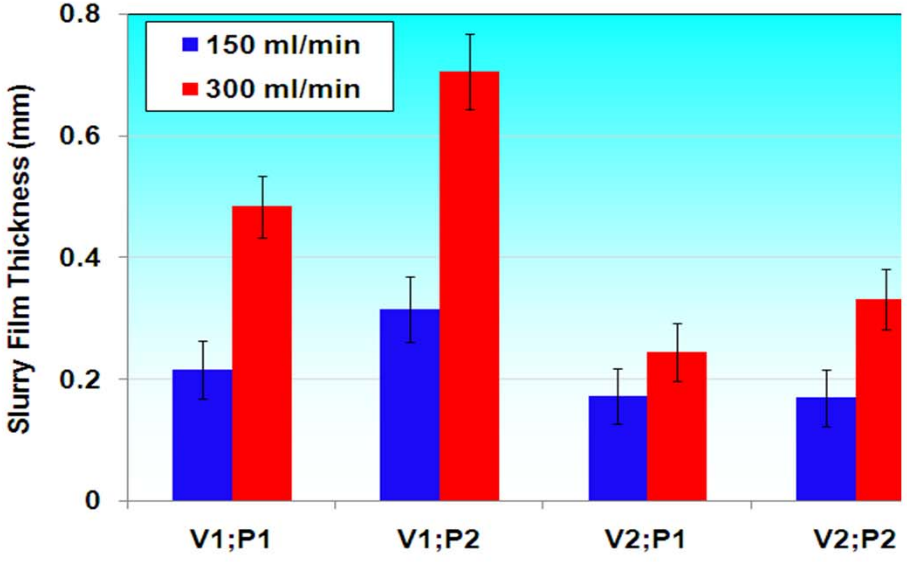


V1 = 0.6 m/s, V2 = 1.2 m/s, Q1 = 150 ml/min, Q2 = 300 ml/min

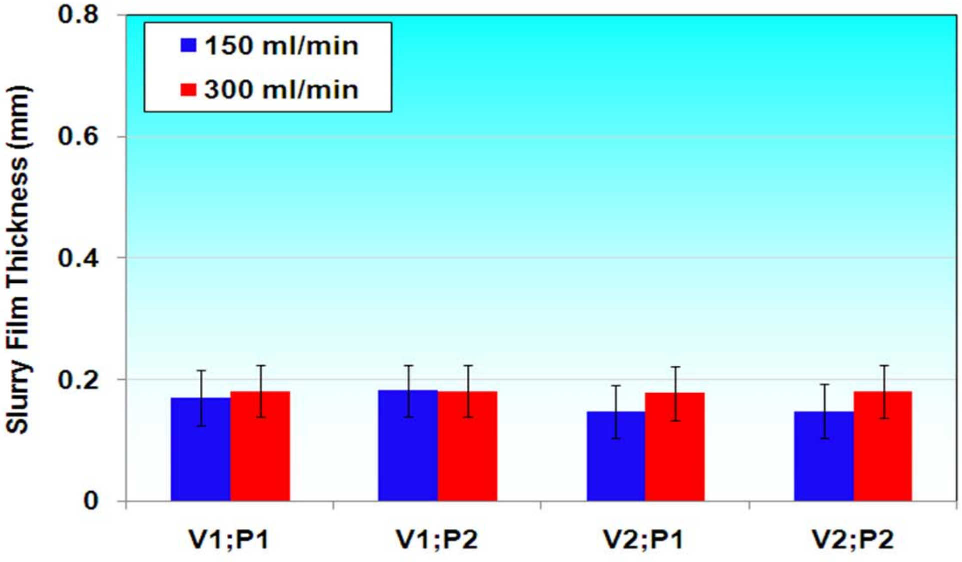
Bow Wave Slurry Film Thickness

Effect of Slurry Flow Rate

PEEK-1



PEEK-2



V1 = 0.6 m/s, V2 = 1.2 m/s, P1 = 1.4 PSI, P2 = 2.8 PSI

Summary

- Slurry film thickness at the bow wave was successfully measured by the UVIZ - 100® system using UV fluorescence methods.

- Results indicated that the retaining ring with the sharp angle slot design (PEEK-1) generated significantly thicker slurry film at the bow wave than its counterpart with the round angle slot design (PEEK-2), as such, we believe PEEK-2 is more efficient in slurry transport.

- For PEEK-1, slurry film thickness at the bow wave increased with increasing flow rate and ring pressure while it decreased with increasing pad/retaining ring sliding velocity.

- For PEEK-2, slurry film thickness at the bow wave did not change significantly under different polishing conditions indicating an apparent robustness of the PEEK-2 design to various operating conditions.

Future Plans

- Next year plan: investigate the effect of slurry injection scheme on bow wave characteristics, slurry availability and pad micro-texture

- Long-term plan: develop fundamental understanding of the effect of retaining ring and injection scheme on slurry flow and polishing performance to overcome difficult challenges in environmental and manufacturing efficiency.

Industrial Interactions and Technology Transfer

Industrial mentors and contacts:

- **Christopher Wargo and Joseph Smith (Entegris)**
- **Cliff Spiro (Cabot Microelectronics)**
- **Peter Ojerholm (Ehwa)**

Publications and Presentations

- Effect of Retaining Ring Slot Design on Slurry Film Thickness during CMP. X. Wei, Y. Sampurno, Y. Zhuang, R. Dittler, A. Meled, J. Cheng, C. Wargo, R. Stankowski and A. Philipossian. Electrochemical and Solid-State Letters, 13(4), H119-H121 (2010).
- Tribological, Thermal and Wear Characteristics of Polyphenylen Sulfied and Polyetheretherketone Retaining Rings in Inter-Layer Dielectric CMP. X. Wei, Y. Zhuang, Y. Sampurno, F. Sudargho, C. Wargo, L. Borucki and A. Philipossian. Electrochemical and Solid-State Letters, 13(11), H391-H395 (2010).
- Effect of Retaining Ring Slot Design and Polishing Conditions on Slurry Flow Dynamics at Bow Wave. X. Liao, Y. Sampurno, A. Rice, Y. Zhuang and A. Philipossian. 2010 International Conference on Planarization/CMP Technology Proceedings, 31-35 (2010).
- Effect of Retaining Ring Slot Design and Polishing Conditions on Slurry Flow Dynamics at Bow Wave. X. Liao, Y. Sampurno, A. Rice, Y. Zhuang and A. Philipossian. 2010 International Conference on Planarization/CMP Technology, Phoenix, Arizona, November 14-17 (2010).

Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

(*Task 425.032) – March 2011*

Subtask 2: Effect of Pad Conditioning on Pad Micro-Texture and Polishing Performance

PI:

- **Ara Philipossian, Chemical and Environment Engineering, UA**
- **Duane Boning, Electrical Engineering and Computer Science, MIT**

Graduate Students:

- **Xiaoyan Liao, Ph. D. candidate, Chemical and Environment Engineering, UA**
- **Yubo Jiao, Ph. D. candidate, Chemical and Environment Engineering, UA**
- **Zhenxing Han, Ph. D. candidate, Chemical and Environment Engineering, UA**
- **Anand Meled, Ph. D. candidate, Chemical and Environment Engineering, UA**
- **Changhong Wu, Ph. D. candidate, Chemical and Environment Engineering, UA**
- **Wei Fan, Ph. D. candidate, Electrical Engineering and Computer Science, MIT**

Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

(*Task 425.032) – March 2011*

Subtask 2: Effect of Pad Conditioning on Pad Micro-Texture and Polishing Performance

Other Researchers:

- Yun Zhuang, Post-doctoral Fellow, Chemical and Environment Engineering, UA
- Yasa Sampurno, Post-doctoral Fellow, Chemical and Environment Engineering, UA

Cost Share (other than core ERC funding):

- In-kind donation (slurry) from Hitachi Chemical
- In-kind donation (diamond discs) from 3M Corporate
- In-kind donation (diamond discs) from Mitsubishi Materials Corporation
- In-kind support (confocal microscopy) from Araca, Inc.

Specific Objectives and EHS Impact

- Investigate the effect of pad conditioning on pad surface micro-texture, as well as frictional force, removal rate, and wafer topography (dishing) during copper CMP process
- Characterize pad asperity modulus using nano-indentation
- Characterize pad asperity height using micro profilometry
- Understand how pad properties change during CMP process

Reduce CMP consumable consumption (pad, slurry, UPW, chemicals, pad conditioner, and retaining ring) by increasing yield through 1 – 3X reduction in dishing and erosion

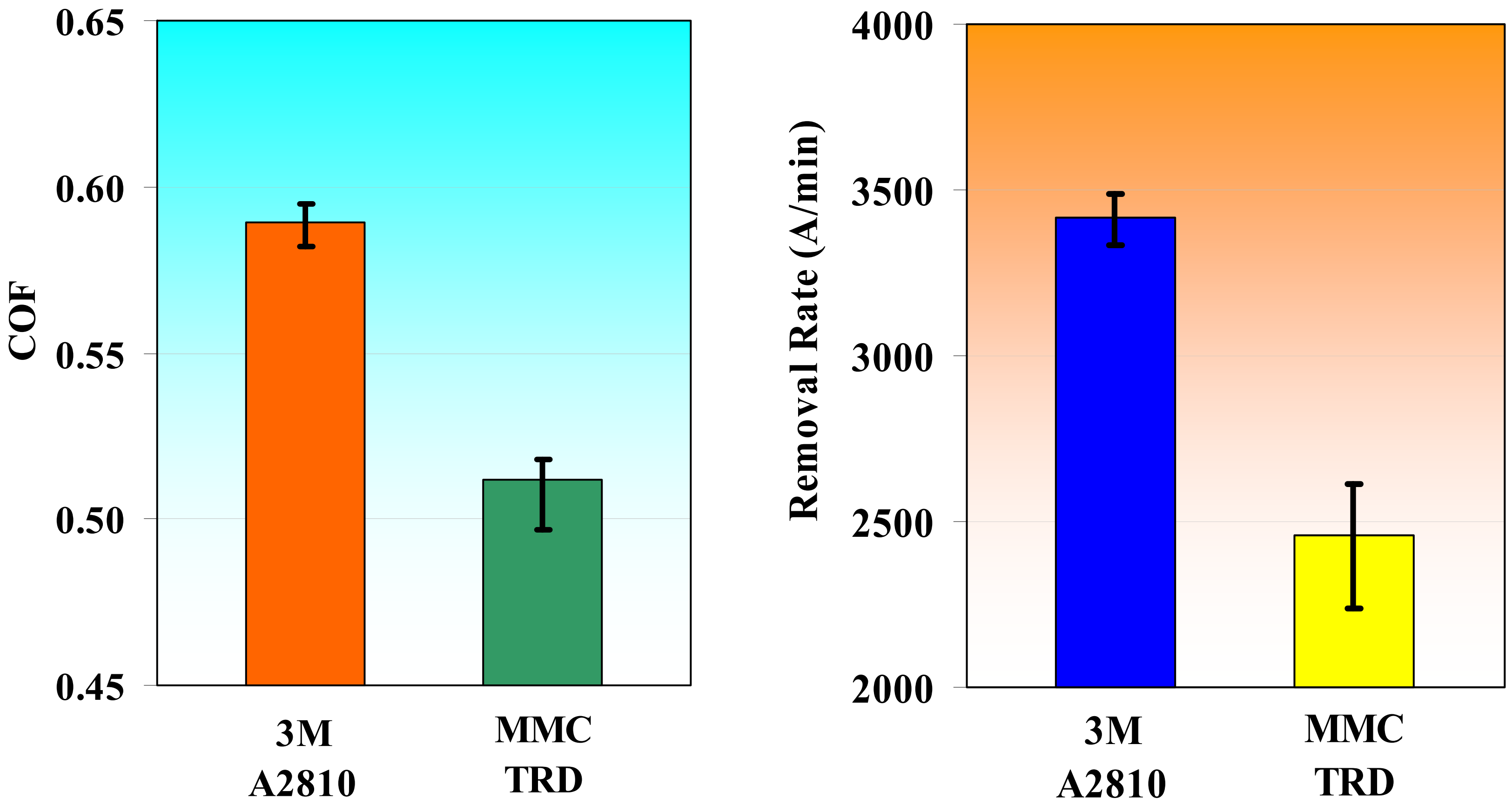
General Approach

Polish 200-mm blanket copper and patterned SEMATECH 854 wafers with a 3M A2810 disc and a Mitsubishi Materials Corporation 100-grit TRD disc, and analyze pad micro-texture through laser confocal microscopy:

- **Blanket wafer polishing: frictional force and removal rate**
- **Patterned wafer polishing: dishing**
- **Pad micro-texture analyses: contact area, near contact area, and summit curvature**

COF and Removal Rate Comparison

Blanket Wafer Polishing

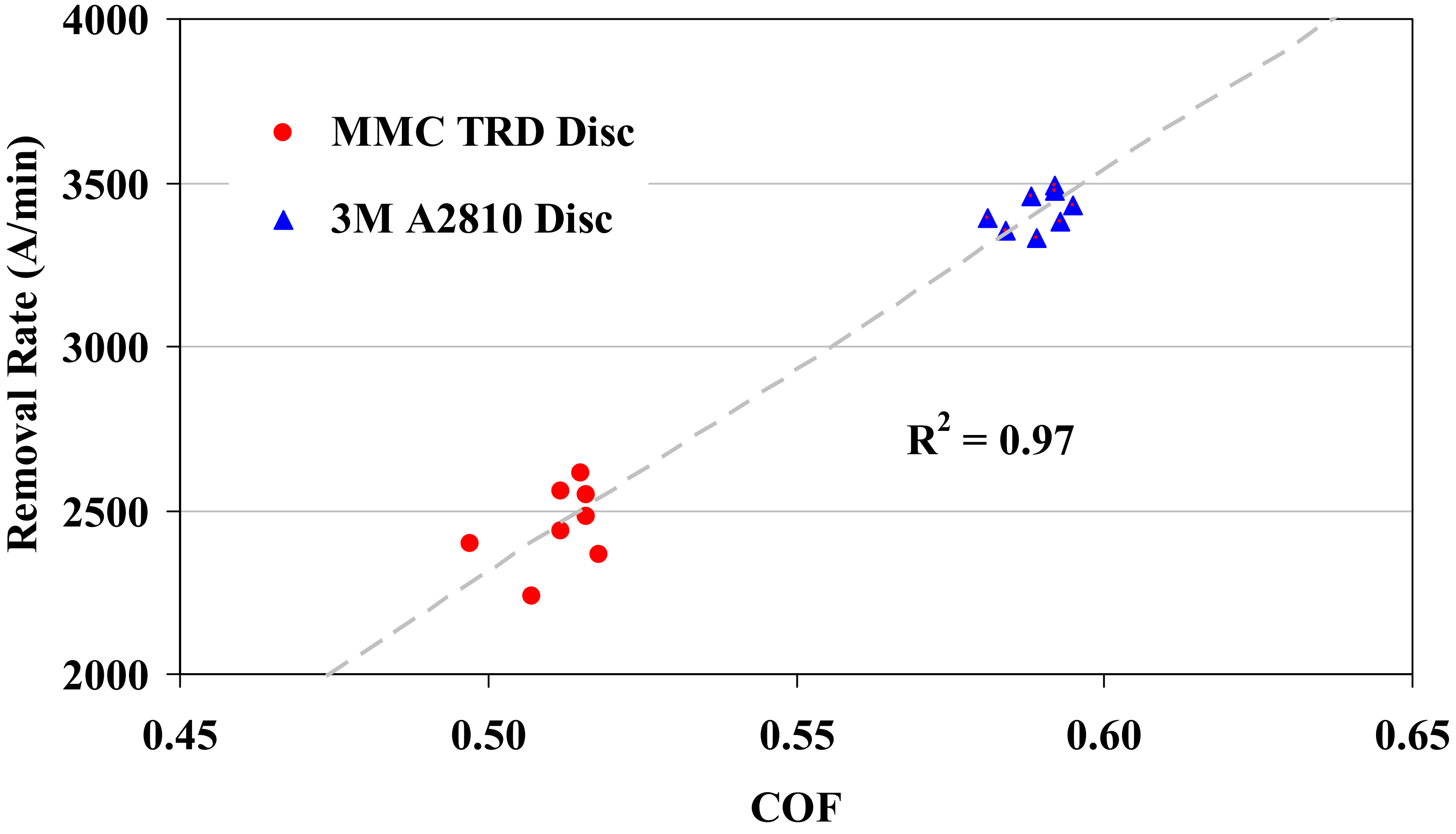


$\text{COF}_{\text{3M A2810}} > \text{COF}_{\text{MMC TRD}}$

$\text{RR}_{\text{3M A2810}} > \text{RR}_{\text{MMC TRD}}$

Removal Rate vs. COF

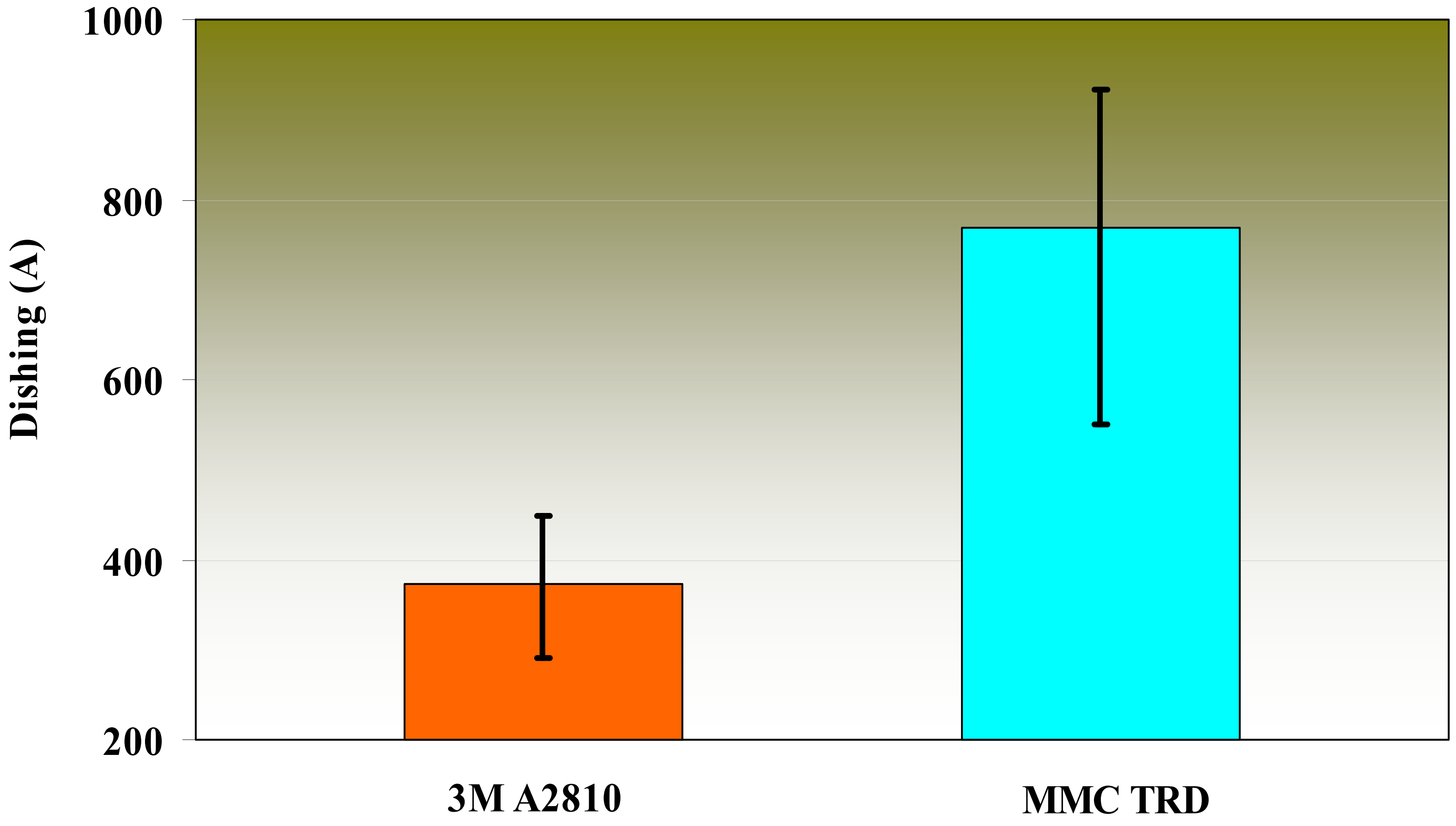
Blanket Wafer Polishing



As expected, removal rate increased with COF.

Dishing Comparison

Patterned Wafer Polishing, Center Die, 100/100 Micron Feature



$\text{Dishing}_{\text{3M A2810}} < \text{Dishing}_{\text{MMC TRD}}$

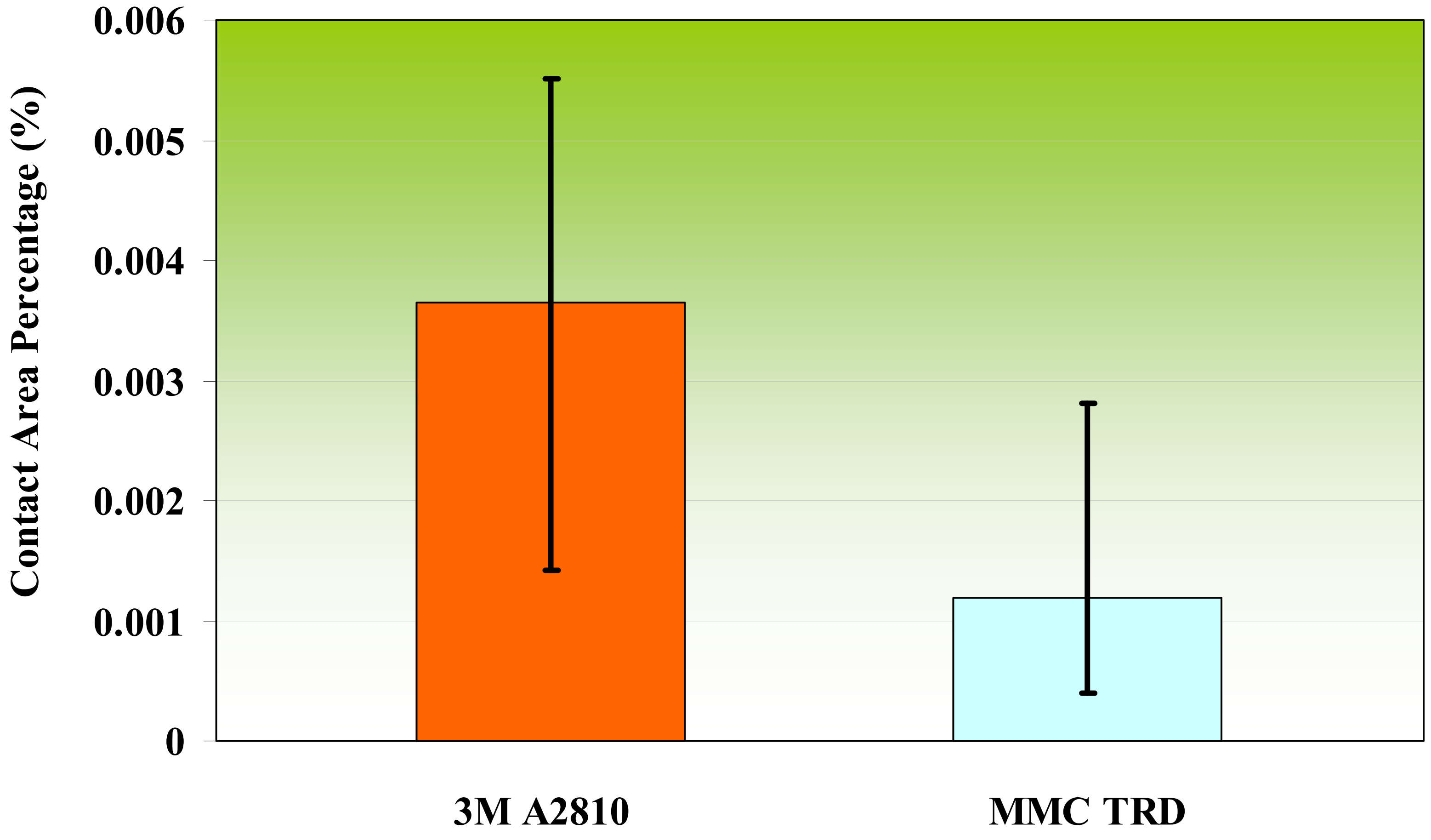
Laser Confocal Microscopy

Zeiss LSM 510 Meta NLO

Pad surface contact area and topography analyses were performed through laser confocal microscopy.

Pad Surface Contact Area Comparison

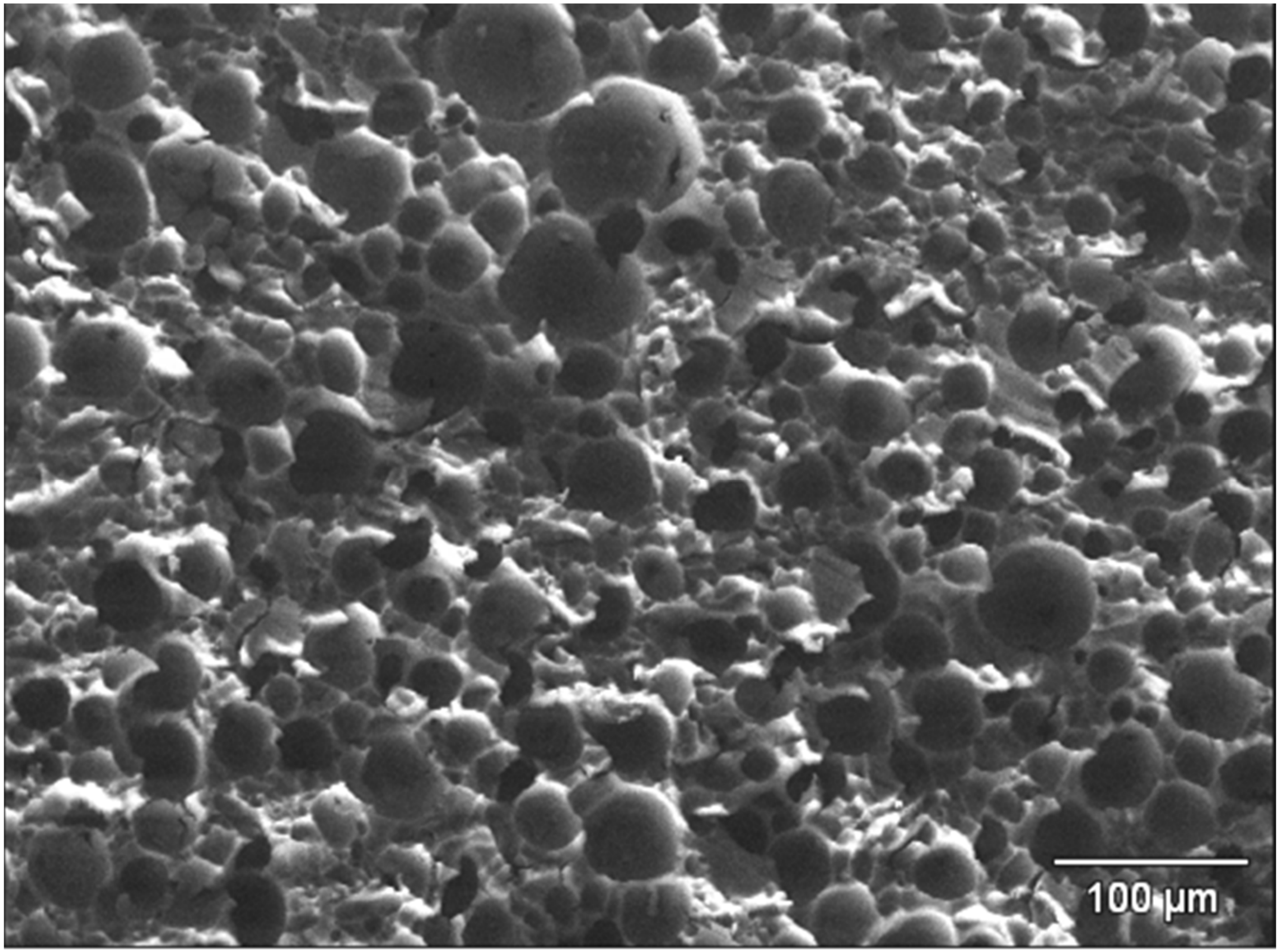
Blanket Wafer Polishing



Contact Area Percentage $_{\text{3M A2810}}$ > Contact Area Percentage $_{\text{MMC TRD}}$

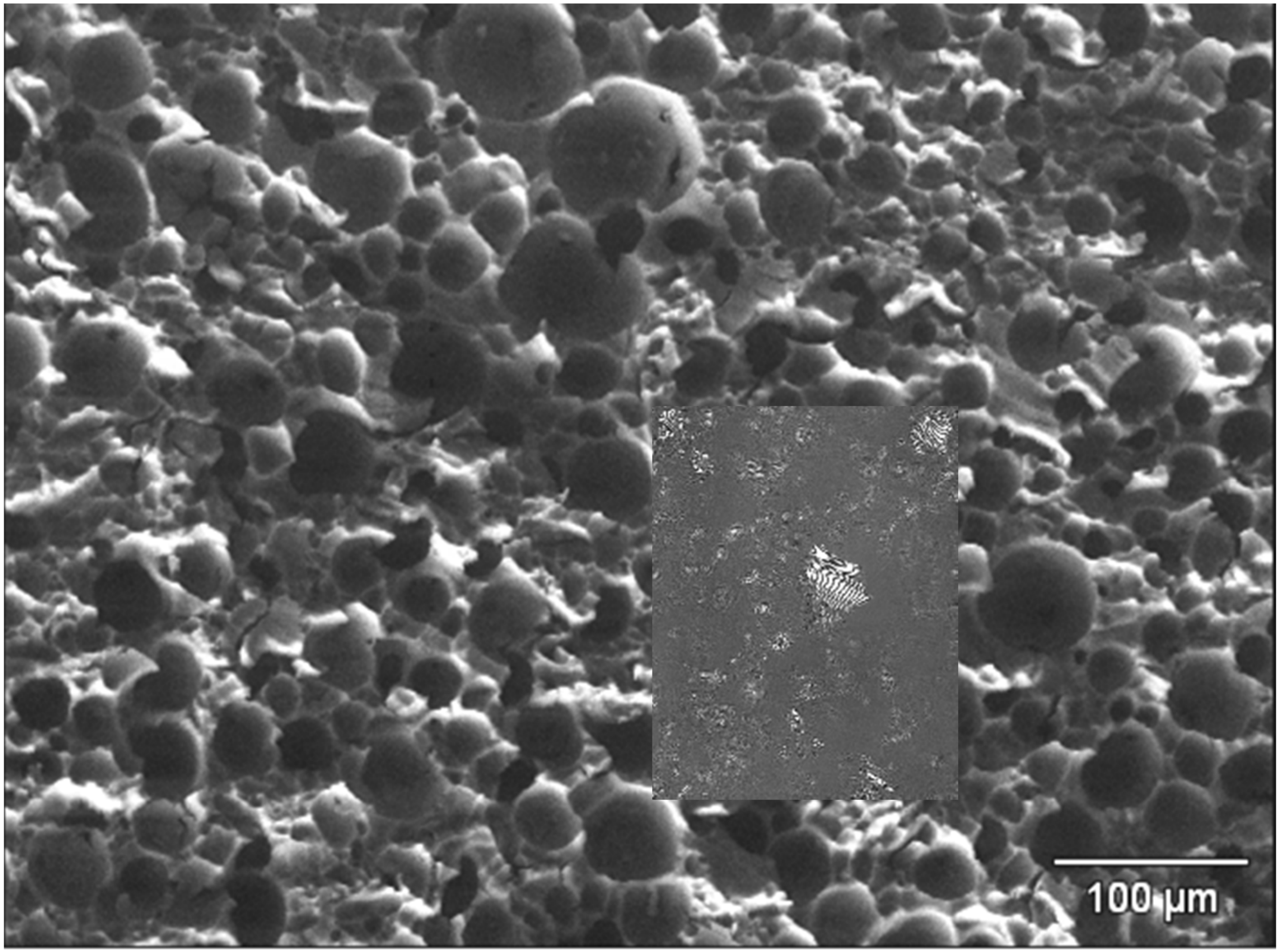
Pad Surface SEM Image

Blanket Wafer Polishing, MMC TRD Disc



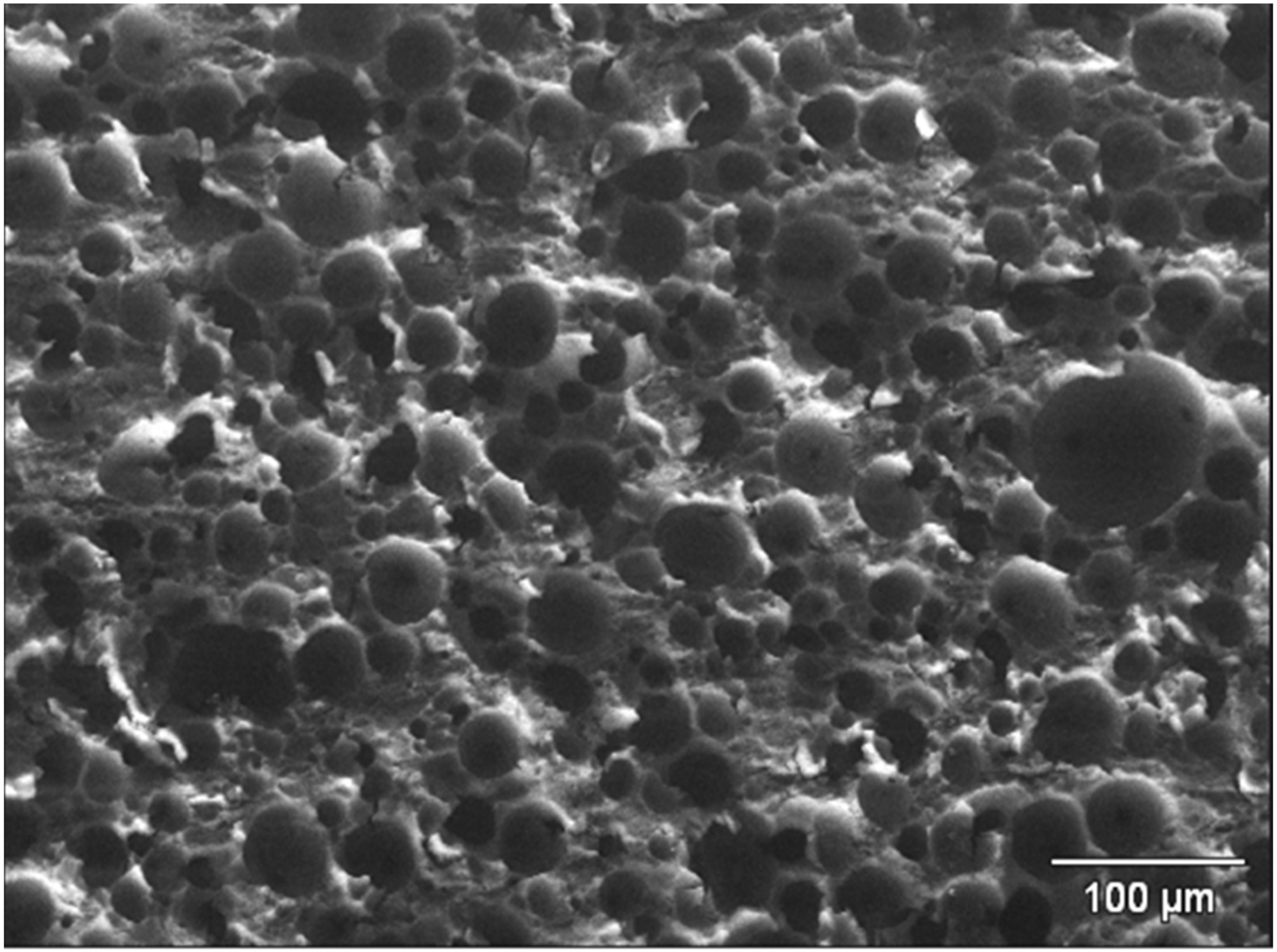
Pad Surface SEM and Contact Images

Blanket Wafer Polishing, MMC TRD Disc



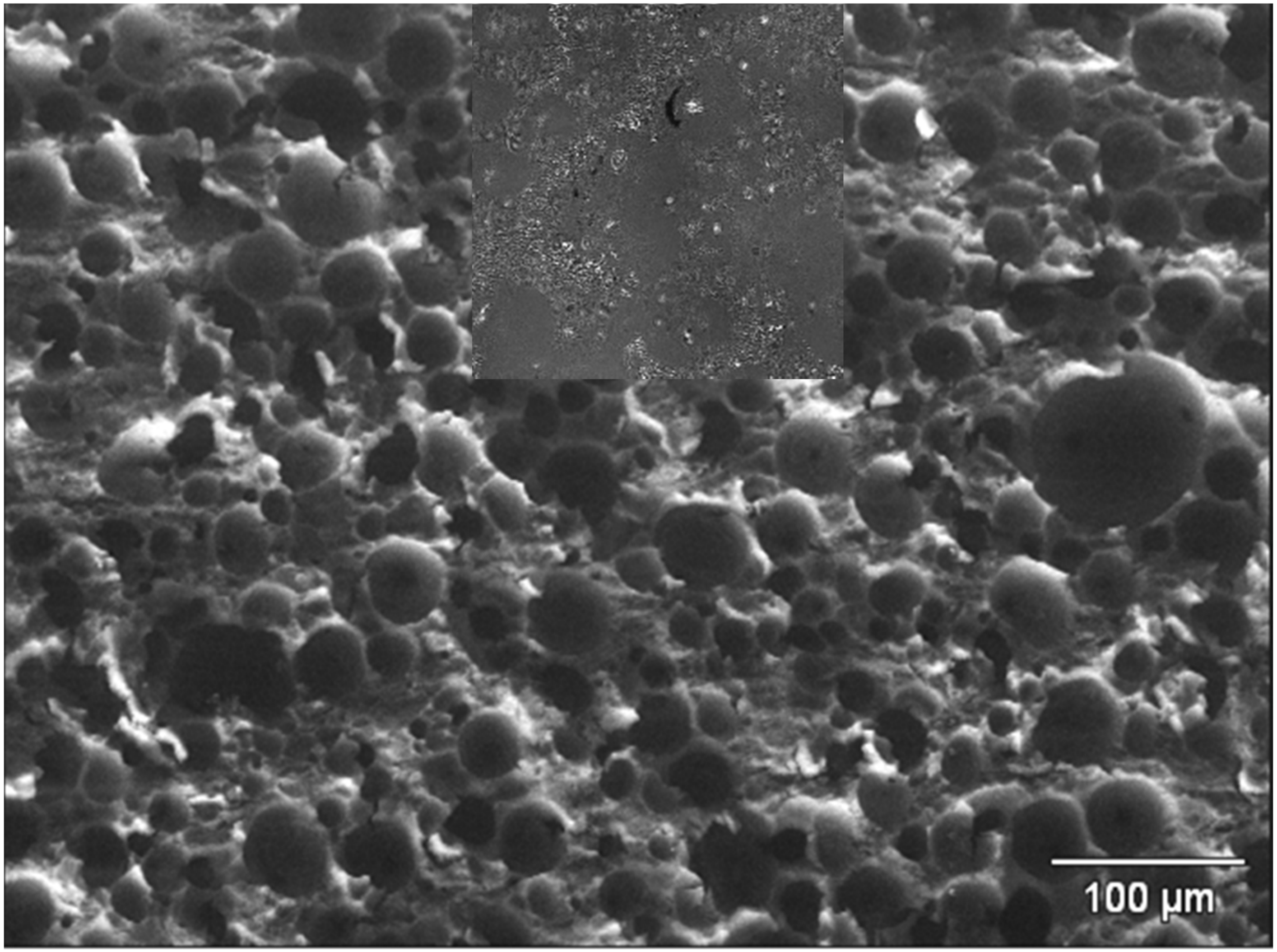
Pad Surface SEM Image

Blanket Wafer Polishing, 3M A2810 Disc



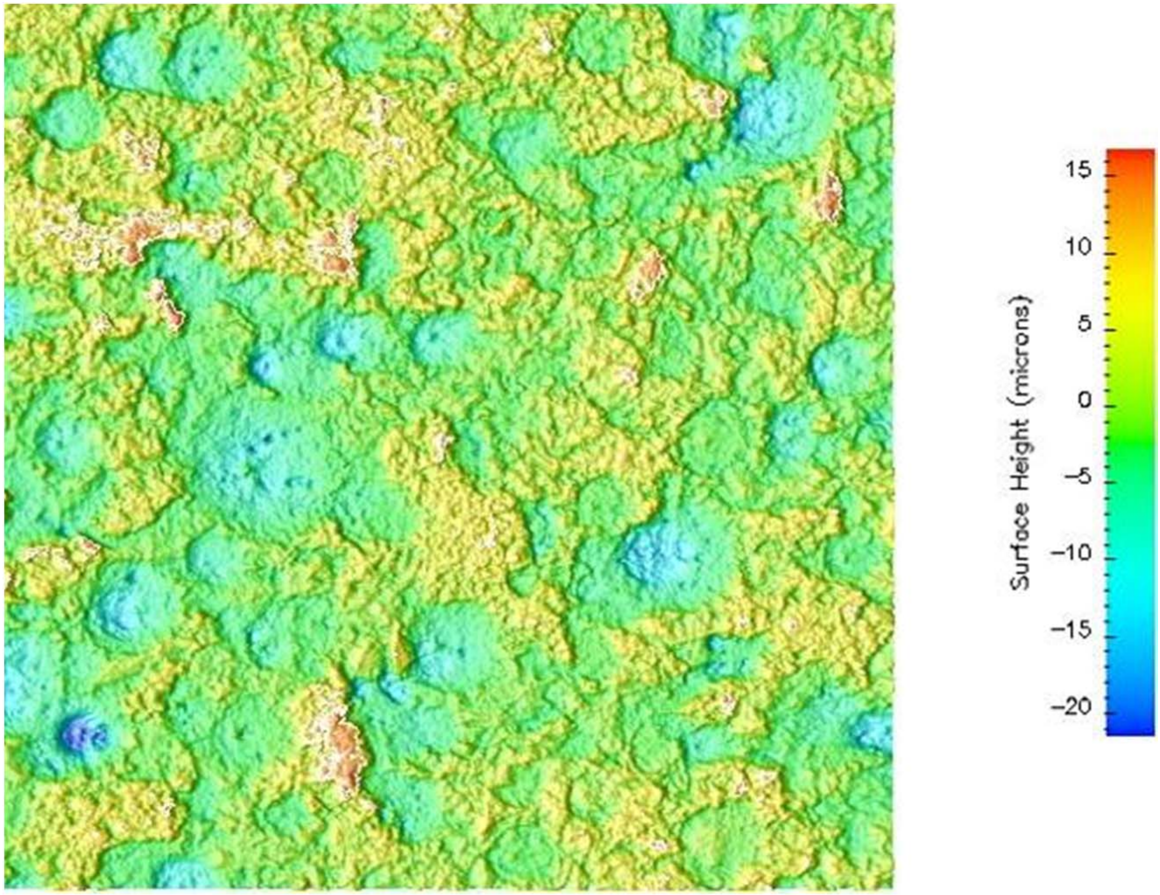
Pad Surface SEM and Contact Images

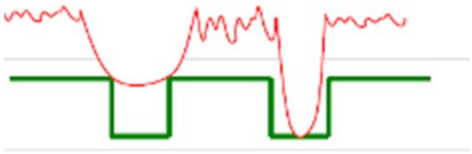
Blanket Wafer Polishing, 3M A2810 Disc



Pad Surface Summit Curvature Comparison

Patterned Wafer Polishing





Disc	K_s (micron^{-1})
3M A2810	**1.80**
MMC TRD	**2.13**

Higher summit curvatures correspond to sharper pad asperities.

Summary

During blanket copper wafer polishing, MMC TRD disc generated fewer pad surface contact areas than 3M A2810 disc.

In addition, MMC TRD disc generated much larger flat near contact areas corresponding to conditioning debris and pore walls that had been fractured and collapsed.

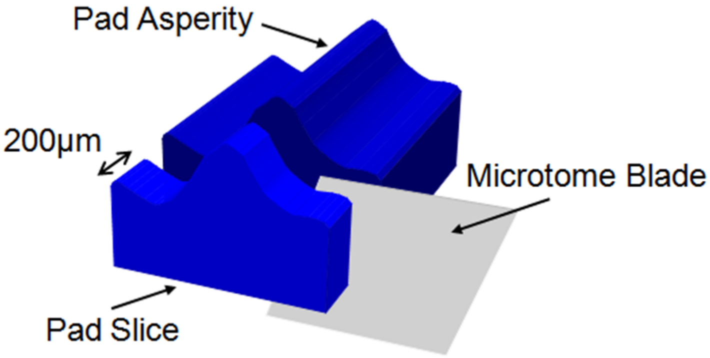
The conditioning debris and fractured/collapsed pore walls partly covered the adjacent pores, making the pad surface more lubricated and rendering a lower COF and removal rate compared with the 3M A2810 disc.

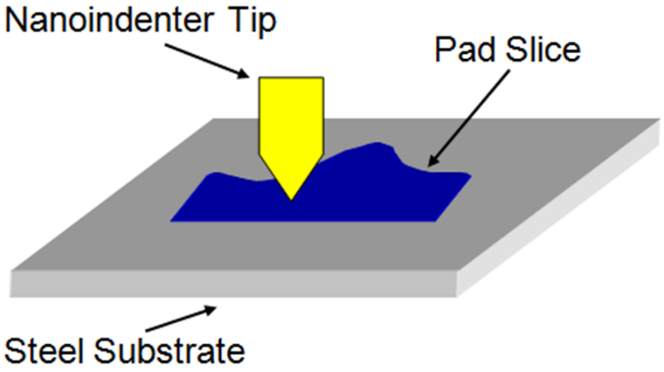
During patterned copper wafer polishing, MMC TRD disc generated a higher mean summit curvature than 3M A2810 disc.

Sharper pad summits contributed to higher dishing for MMC TRD disc.

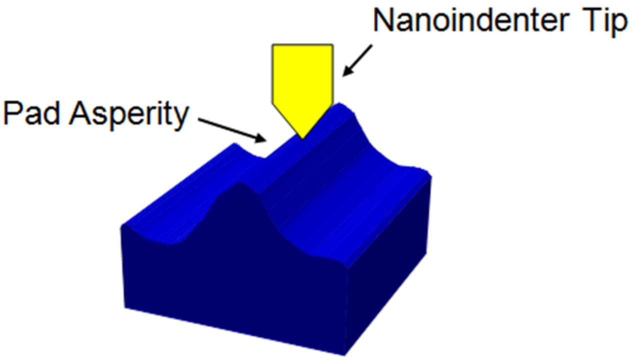
Pad Modulus Measurement: Nanoindentation

- **Pad slice nanoindentation:**





- **Pad asperity nanoindentation:**



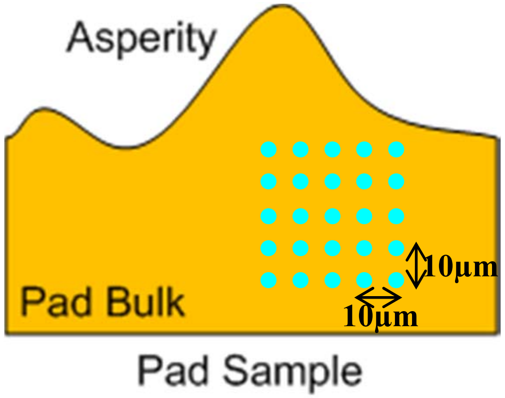
Hysitron TriboIndenter

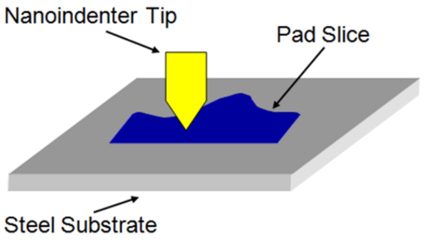
Indent Working Mode

Max Force	10 mN
Force Resolution	2 nN
Min Contact Force	<100 nN
Force Load Rate	>50 mN/s
Max Displacement	5 µm
Displacement Resolution	0.04 nm

Pad Slice: Contour Plot of Reduced Modulus

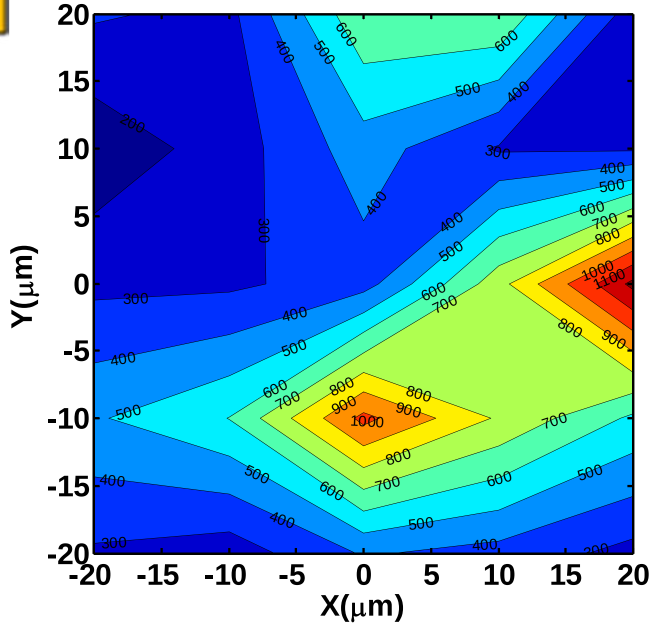
Test Pattern: slice, multiple points



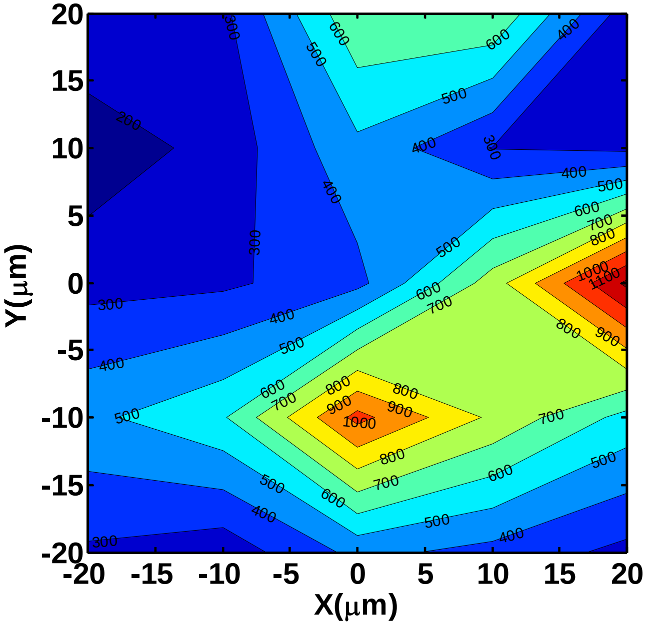


Example: JSR pad slice, same test area, repeat twice

1st test
Mean: 462.69MPa
Standard Deviation: 272.44MPa

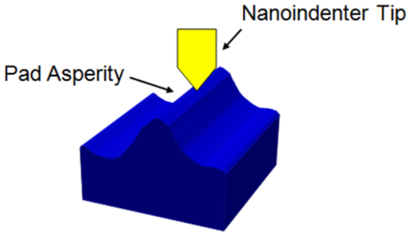


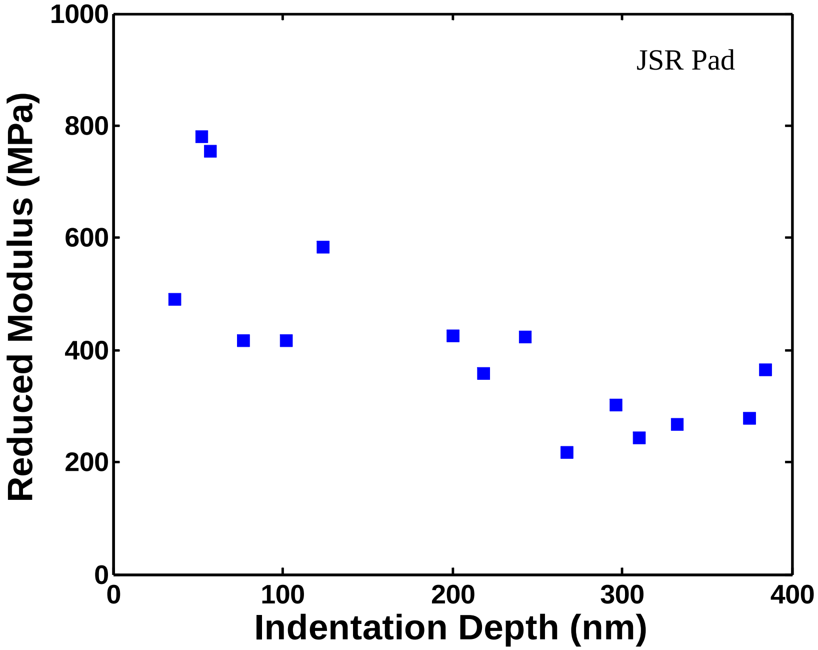
2nd test (same position on the sample)
Mean: 460.93MPa
Standard Deviation: 270.58MPa



- **There is spatial variation in pad mechanical properties**

Pad Asperity: Depth Dependence of Reduced Modulus



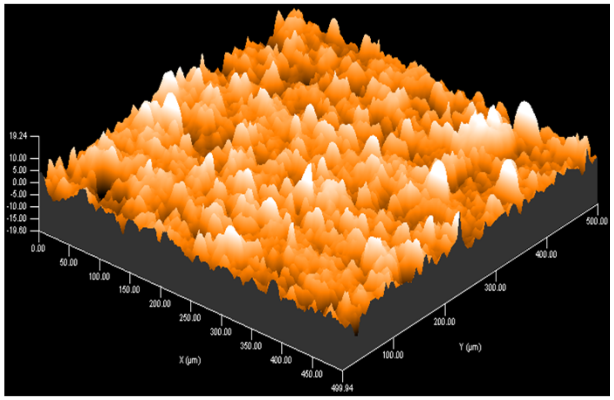


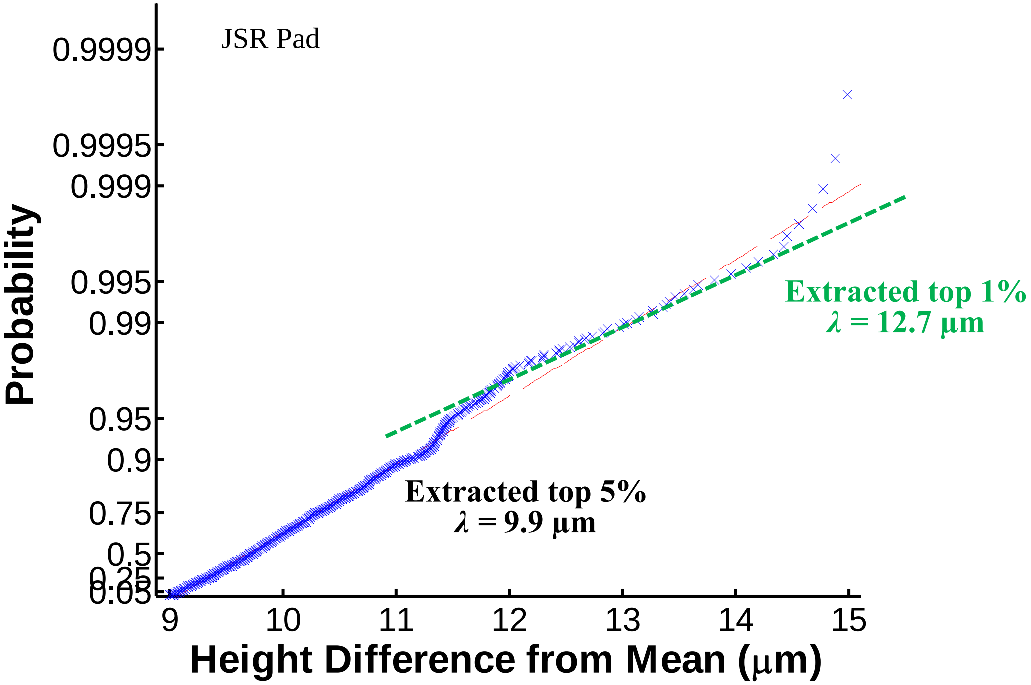
Boning and Fan, MRS Spring Meeting, April 2010.

- **Deep indentation (> 300 nm):**
  - Asperity modulus approaches bulk modulus
  - Bulk estimate = 291 MPa (depth > 300 nm)
- **Shallow indentation (< 100 nm):**
  - Substantially higher modulus, ~2x or greater the bulk value
  - Surface estimate = 572 MPa (depth < 100nm)

Pad Asperity Height Distribution

Pad Surface Profilometry



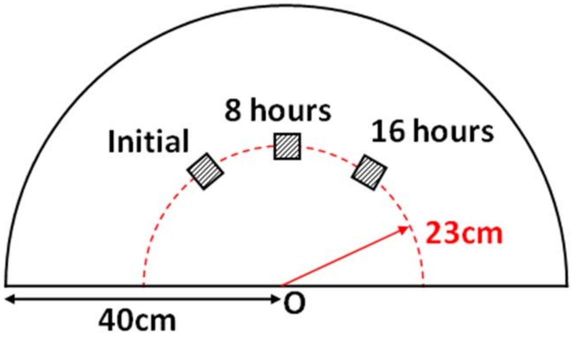


- **Consistent with an exponential height distribution**
  - Exponential in the tail of the distribution, i.e., for heights substantially greater than the mean height
  - A very small number of very tall asperities (i.e. fewer than 0.05%). We ignore these.
  - Possibility of a **bimodal** (exponential) distribution; useful to extract both.

Pad Aging Experiment

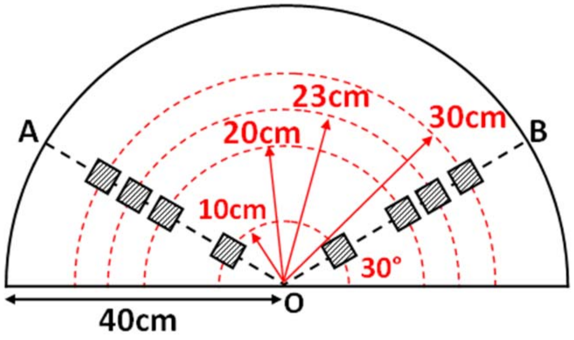
- Cu wafer polishing with JSR WSP pad
  - Polisher: Araca APD-800
  - Polishing head speed: 25 rpm
  - Polishing pressure: 1.5 psi
  - Condition head speed: 95 rpm
  - Conditioner down force: 8 lbF
- Pad sample collection

Aging samples:



Sample size: 2.5cm × 2.5cm

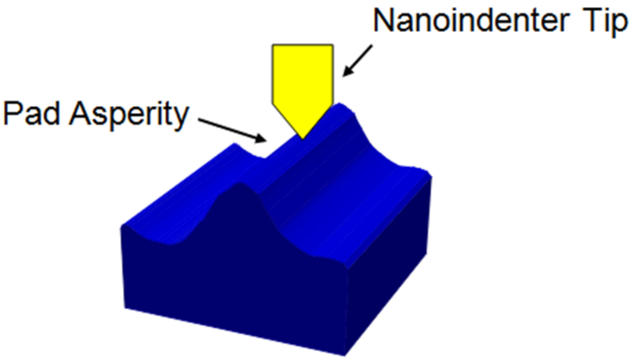
Spatial samples after 16 hours:

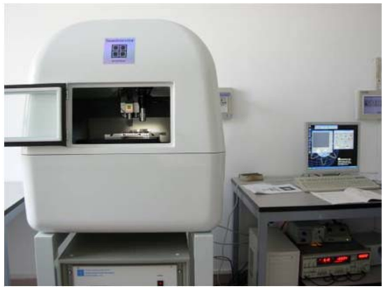


Sample size: 1.5cm × 1.5cm

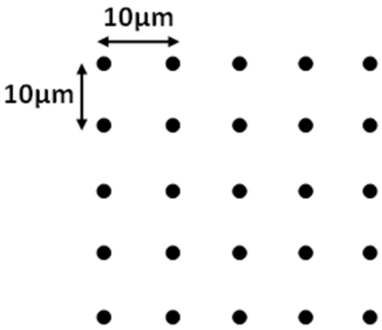
Pad Properties: Pad Asperity Indentation

- **Pad asperity nanoindentation:**





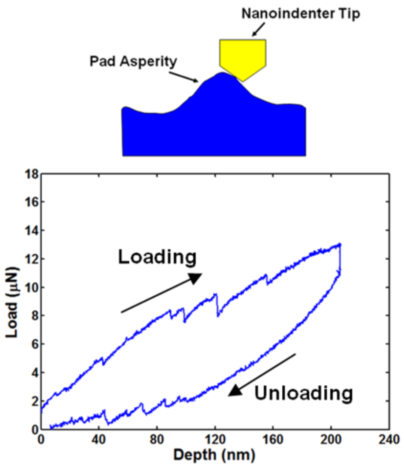
Hysitron TriboIndenter



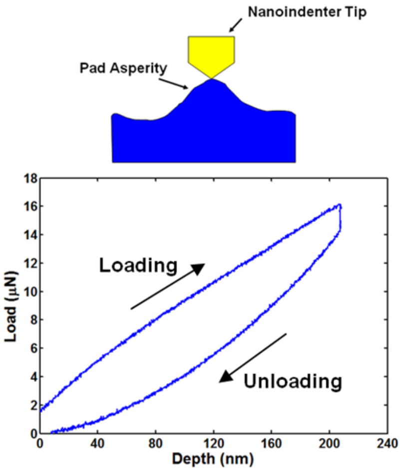
Test Pattern Applied

- **Indentation curves:**

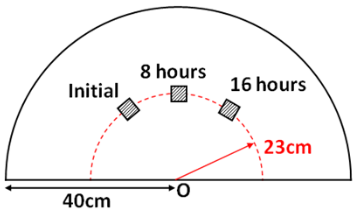
Failed test: indenter tip sliding



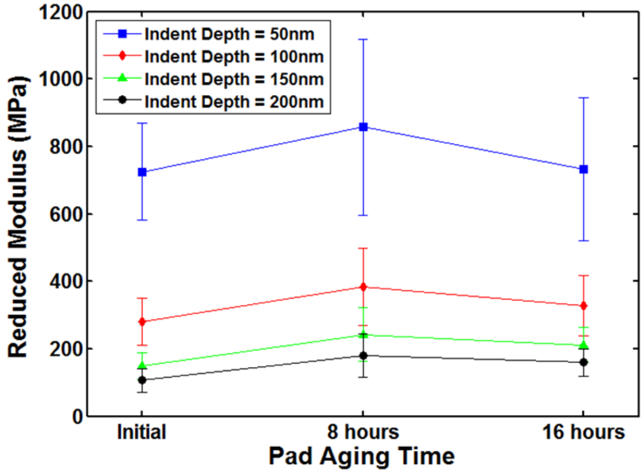
Successful test: solid contact



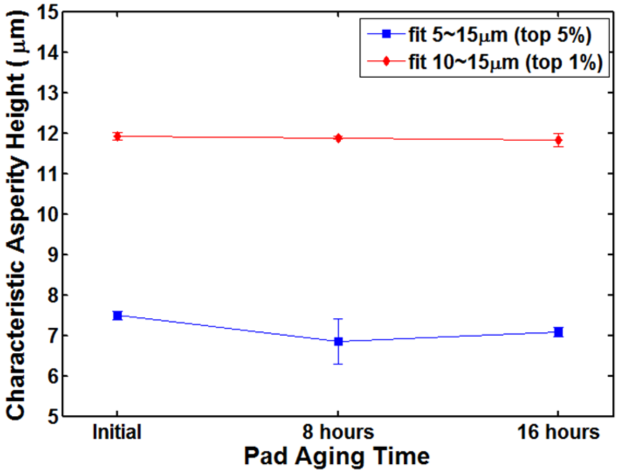
Pad Aging Results



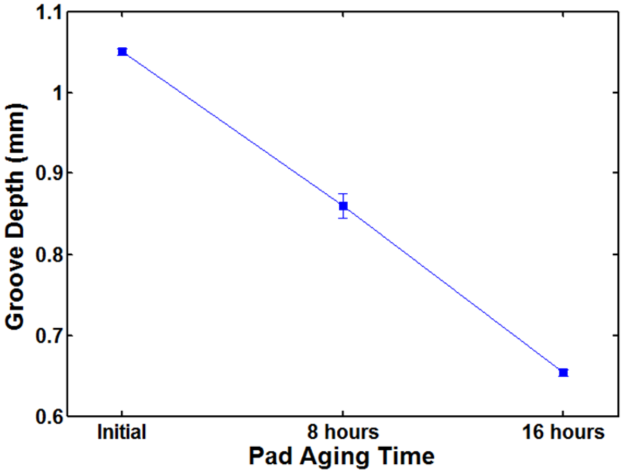
Asperity Modulus



Asperity Height

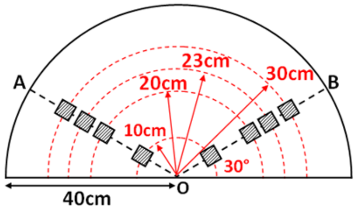


Groove Depth

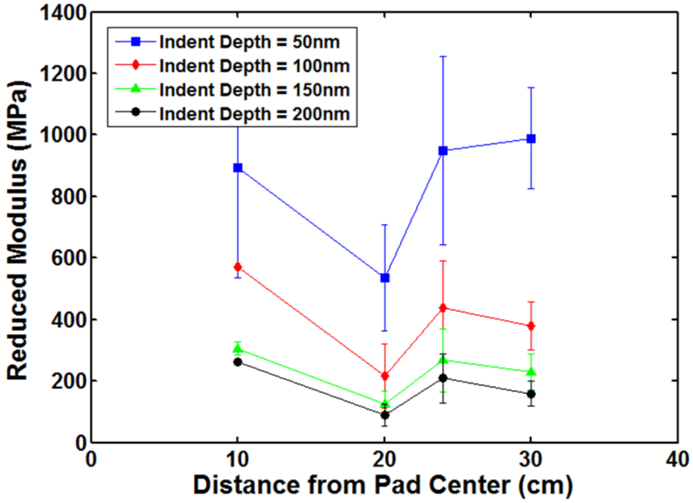


- **Asperity modulus and asperity height distribution are both consistent across polishing/conditioning times**
- **Depth dependence of modulus**
  - Deep indentation: asperity modulus approaches bulk modulus (<200 MPa)
  - Shallow indentation: substantially higher modulus, ~2x or greater the bulk value
- **Substantial pad wear during CMP process: groove depth decreases linearly with polish time**

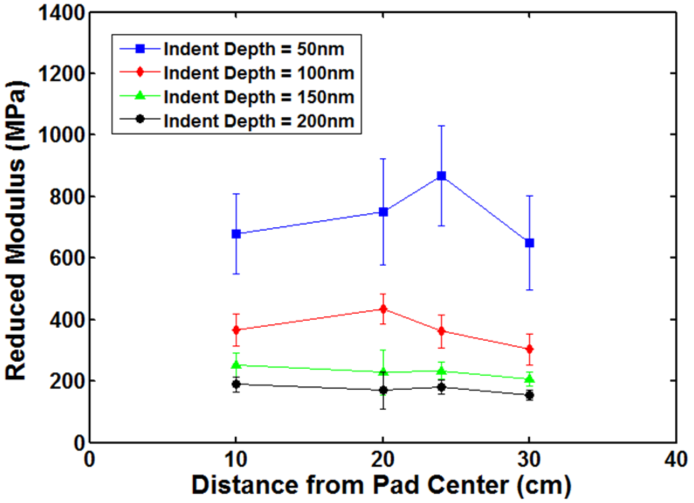
Spatial Results: Asperity Modulus



OA direction:

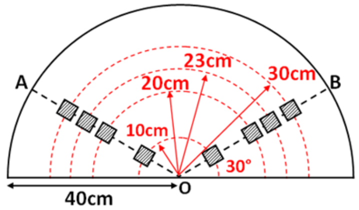


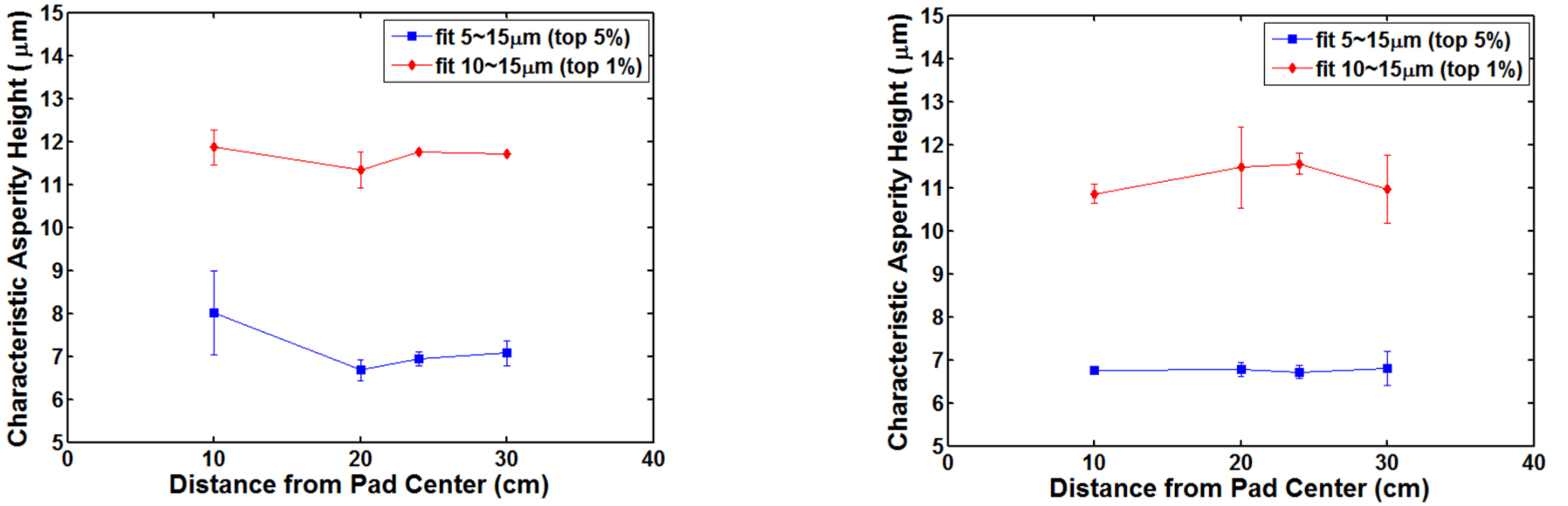
OB direction:



- **No strong radial dependence of asperity reduced modulus**
- **Depth dependence of modulus**
  - Deep indentation: asperity modulus approaches bulk modulus (<200 MPa)
  - Shallow indentation: substantially higher modulus, ~2x or greater the bulk value

Spatial Results: Asperity Height



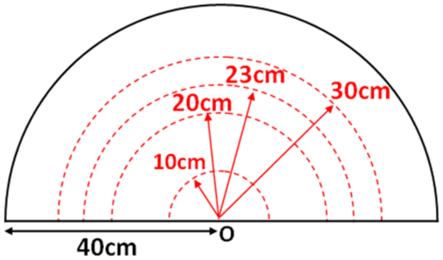

OA direction:

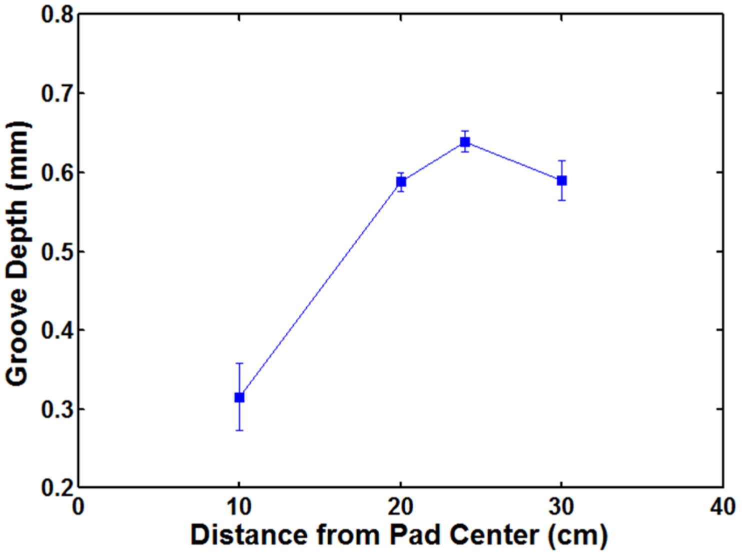
OB direction:

After 16 hours polishing (with conditioning)

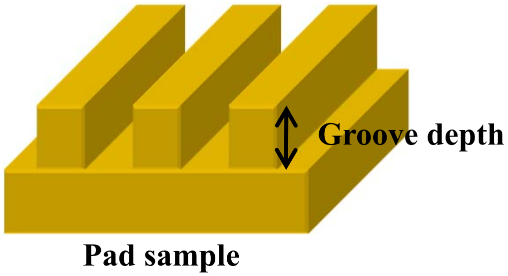
- **No strong radial dependence of asperity height distribution: good spatial uniformity of asperity heights with conditioning**

Spatial Results: Groove Depth





After 16 hours polishing (with conditioning)



- **Groove depth has a strong radial dependence: more pad wear near the center (in this non-optimized process)**
- **Despite large and non-uniform pad wear, pad surface properties are maintained**

Industrial Interactions and Technology Transfer

Industrial mentors and contacts:

- **Lenoard Borucki (Araca)**
- **Toranosuke Ashizawa (Hitachi Chemical)**

Future Plans

- **Next year plan: continue to investigate the effect of pad conditioning on pad surface micro-texture, as well as frictional force, removal rate, and wafer topography (dishing/erosion) during copper and oxide/STI CMP processes.**

- **Long-term plan: develop fundamental understanding of the effect of pad conditioning and pad-wafer contact in CMP processes.**

Publications

- **Investigating the effect of diamond size and conditioning force on chemical mechanical planarization pad topography. T. Sun, L. Borucki, Y. Zhuang and A. Philipossian. Microelectronic Engineering, 87, 553-559 (2010).**

- **Investigating the Effect of Conditioner Aggressiveness on Removal Rate during Inter-Layer Dielectric CMP through Confocal Microscopy and Dual Emission UV Enhanced Fluorescence Imaging. T. Sun, L. Borucki, Y. Zhuang, Y. Sampurno, F. Sudargho, X. Wei, S. Anjur and A. Philipossian. Japanese Journal of Applied Physics, 49(2), 026501 (2010).**

- **Slurry Induced Pad Wear Rate in Chemical Mechanical Planarization. A. Meled, Y. Sampurno, Y. Zhuang and A. Philipossian. Electrochemical and Solid-State Letters, 13(3), H52-H54 (2010).**

- **Analyses of Diamond Disc Substrate Wear and Diamond Micro-Wear in Copper Chemical Mechanical Planarization Process. A. Meled, Y. Zhuang, X. Wei, J. Cheng, Y. Sampurno, L. Borucki, M. Moinpour, D. Hooper and A. Philipossian. Journal of The Electrochemical Society, 157(3), H250-H255 (2010).**

- **Studying the Effect of Temperature on the Copper Oxidation Process Using Hydrogen Peroxide for Use in Multi-Step CMP Models. D. DeNardis, D. Rosales-Yeomans, L. Borucki and A. Philipossian. Thin Solid Films, 518, 3903-3909 (2010).**

Publications

- A Three-Step Copper CMP Model Including the Dissolution Effects of a Commercial Slurry Dissolution. D. DeNardis, D. Rosales-Yeomans, L. Borucki and A. Philipossian. Thin Solid Films, 518, 3910-3916 (2010).

- Optical and Mechanical Characterization of Chemical Mechanical Planarization of Pad Surfaces. T. Sun, Y. Zhuang, L. Borucki and A. Philipossian. Japanese Journal of Applied Physics, 49(4), 046501 (2010).

- End-Point Detection of Ta/TaN Chemical Mechanical Planarization via Forces Analysis. Y. Sampurno, X. Gu, T. Nemoto, Y. Zhuang, A. Teramoto, A. Philipossian and T. Ohmi. Japanese Journal of Applied Physics, 05FC01 (2010).

- Characterization of Pad-Wafer Contact in CMP Using Confocal Microscopy. T. Sun, Y. Zhuang, L. Borucki and A. Philipossian. Japanese Journal of Applied Physics, 49(6), 066501 (2010).

- Novel Diamond Disc Diagnostic Method Based on 'Dry' Coefficient of Friction Measurements. A. Meled, Y. Sampurno, F. Sudargho, Y. Zhuang and A. Philipossian. Electrochemical and Solid-State Letters, 13(12), H457-H459 (2010).

Presentations

- The Nature of Large Contact Areas in Chemical-Mechanical Planarization. L. Borucki, Y. Zhuang, Y. Sampurno and A. Philipossian. The International Semiconductor Technology Conference / China Semiconductor Technology International Conference (ISTC/CSTIC 2010), Pudong, Shanghai, China, March 18-19 (2010).

- Tribological and Kinetic Characterization of 300-mm Copper Chemical Mechanical Planarization Process. Z. Han, Y. Zhuang, Y. Sampurno, A. Meled, Y. Jiao, X. Wei, J. Cheng, M. Moinpour, D. Hooper and A. Philipossian. The International Semiconductor Technology Conference / China Semiconductor Technology International Conference (ISTC/CSTIC 2010), Pudong, Shanghai, China, March 18-19 (2010).

- Effect of Pad Micro-Texture on Frictional Force, Removal Rate, and Wafer Topography during Copper CMP Process. Y. Zhuang, X. Liao, L. Borucki, S. Theng, X. Wei, T. Ashizawa and A. Philipossian. The International Semiconductor Technology Conference / China Semiconductor Technology International Conference (ISTC/CSTIC 2010), Pudong, Shanghai, China, March 18-19 (2010).

- Novel Diamond Disc Diagnostic Method Based on 'Dry' Coefficient of Friction Measurements. Y. Sampurno, F. Sudargho, A. Meled, Y. Zhuang and A. Philipossian. The International Semiconductor Technology Conference / China Semiconductor Technology International Conference (ISTC/CSTIC 2010), Pudong, Shanghai, China, March 18-19 (2010).

Presentations

- Method for Ultra-rapid Determination of the Lubrication Mechanism of CMP Processes. Y. Sampurno, S. Theng, F. Sudargho, Y. Zhuang and A. Philipossian. 2010 Materials Research Society Spring Meeting, San Francisco, California, April 5-7 (2010).

- Tribological and Kinetic Characterization of 300-mm Copper Chemical Mechanical Planarization Process. Y. Jiao, A. Meled, X. Wei, Z. Han, J. Cheng, Y. Sampurno, Y. Zhuang, M. Moinpour, D. Hooper and A. Philipossian. 2010 Materials Research Society Spring Meeting, San Francisco, California, April 5-7 (2010).

- Overcoming Some of the Challenges Associated with Slurry Injection in CMP. A Philipossian, L. Borucki, Y. Zhuang and Y. Sampurno. 2010 Materials Research Society Spring Meeting, San Francisco, California, April 5-7 (2010).

- Characterization and Modeling of Pad Asperity Response in CMP. D. Boning and W. Fan. 2010 Materials Research Society Spring Meeting, San Francisco, California, April 5-7 (2010).

- Tribological, Thermal, and Kinetic Characterization of 300-mm Copper CMP Process. Y. Zhuang, Z. Han, Y. Sampurno, A. Meled, Y. Jiao, X. Wei, J. Cheng, M. Moinpour, D. Hooper and A. Philipossian. The fifteenth International Symposium on Chemical-mechanical Planarization, Lake Placid, New York, August 8-11 (2010).

Presentations

- **Characterization of CMP Pad Surface Properties. W. Fan, D. Boning, Y. Zhuang, Y. Sampurno, A. Philipossian, D. Hooper and M. Moinpour. The fifteenth International Symposium on Chemical-mechanical Planarization, Lake Placid, New York, August 8-11 (2010).**

- **Tribological, Thermal and Kinetic Studies of Ti and TiN CMP. R. Duyos-Mateo, X. Gu, T. Nemoto, S. Sugawa, T. Ohmi, Z. Han, Y. Zhuang, Y. Sampurno and A. Philipossian. 2010 International Conference on Planarization/CMP Technology, Phoenix, Arizona, November 14-17 (2010).**

Fundamentals of Advanced Planarization: Pad Micro-Texture, Pad Conditioning, Slurry Flow, and Retaining Ring Geometry

(Task 425.032) – March 2011

Subtask 3: Implementation of an Extended Die-Level and Wafer-Level CMP Model

PI:

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

Graduate Students:

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

Cost Share (other than core ERC funding):

- **Experimental support, Intel**

Objectives

Goal: Improve fundamental understanding of CMP thru modeling and experimentation of CMP consumables to:

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

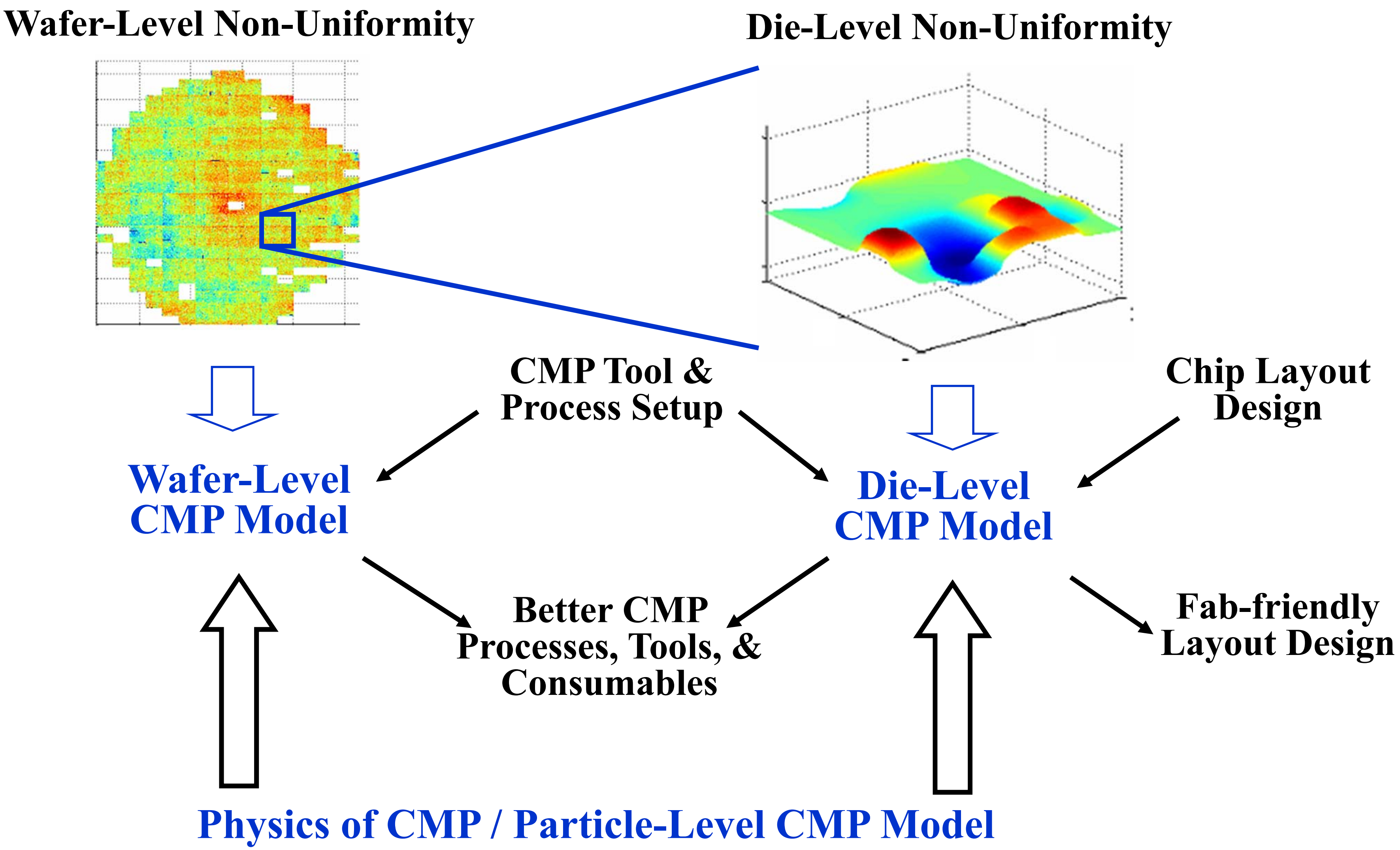
1. **Nano-scale model for pad-wafer contact:**
   - Analyze mechanical response of pad asperities
   - Understand pad-wafer interaction
2. **Slurry agglomeration/wafer-level CMP modeling:**
   - Understand how slurry abrasive particles, pad debris, and wafer debris affect agglomeration
   - Understand how agglomeration relates to process efficiency, planarization capability, and defectivity

ESH Metrics and Impact

Driving principle and goals: Joint improvement in CMP performance and ESH performance

1. *Reduction in the use or replacement of ESH-problematic materials*
2. *Reduction in emission of ESH-problematic material to environment*
   - Reduce slurry particle use and Cu solid waste by 20-50%
3. *Reduction in the use of natural resources (water and energy)*
   - Shorten CMP polish times (copper, barrier) by 20-50%
   - Improve yield (multiplication over all inputs/outputs) by 1-2%
4. *Reduction in the use of chemicals*
   - Reduce slurry usage by 20%
   - Improve pad lifetime by 20-50%

Motivation: CMP Models



Wafer-Level Non-Uniformity

Die-Level Non-Uniformity

CMP Tool & Process Setup

Chip Layout Design

Wafer-Level CMP Model

Die-Level CMP Model

Better CMP Processes, Tools, & Consumables

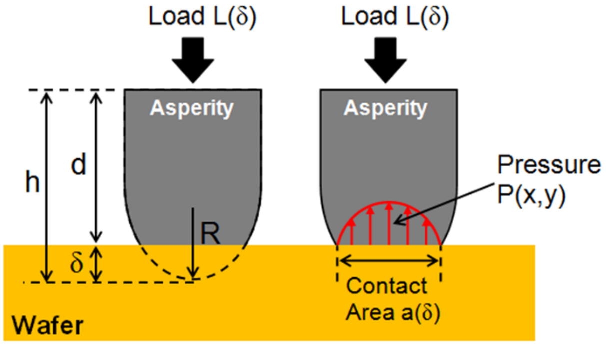
Fab-friendly Layout Design

Physics of CMP / Particle-Level CMP Model

1. Summary of Pad-Wafer Interaction Model

- **Greenwood Williamson approach**
  - **Asperities have spherical surfaces with same radius**
  - **Elastic Hertzian contact**

- **Single asperity compression**



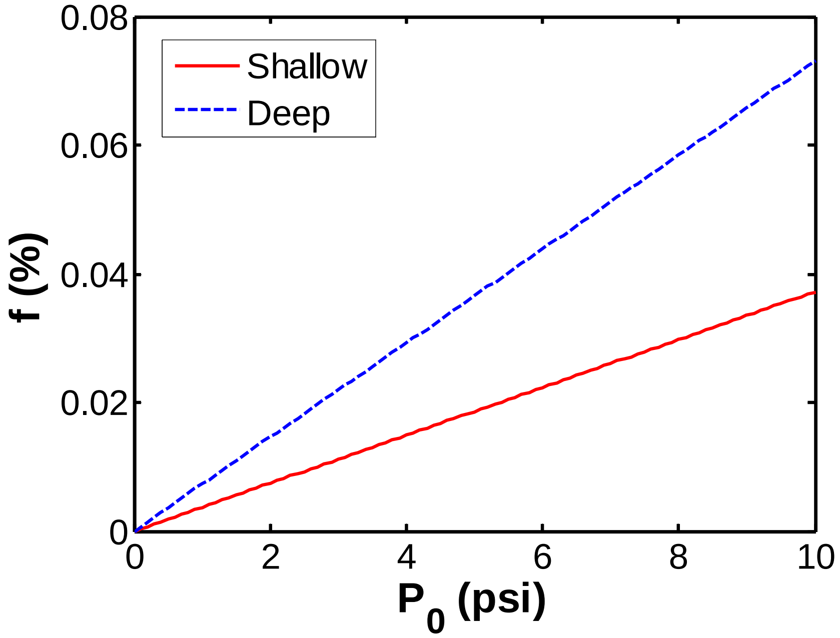
- **Exponential asperity height distribution** $\xi(h) = \frac{1}{\lambda} e^{-\frac{h}{\lambda}}$

- **Result: Predict contact area fraction *f***

$$f(P_0) = \frac{P_0}{E}\sqrt{\frac{\pi R}{\lambda}}$$

E: asperity reduced modulus
P_0: reference pressure

Model Trend: Contact Area vs. Reference Pressure



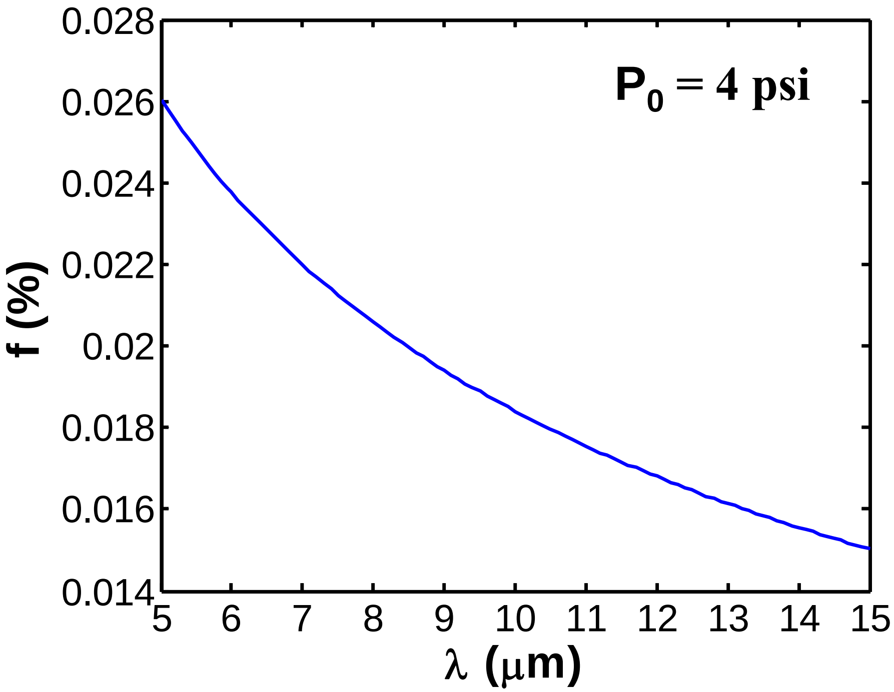
E = 291 MPa

E = 572 MPa

$$f(P_0) = \frac{P_0}{E}\sqrt{\frac{\pi R}{\lambda}}$$

- **Contact area increases linearly with P_0**
  - Depends on reduced pad modulus
  - Using shallow modulus average (stiffer asperities): smaller f% for same pressure
  - Using deep modulus average (asperities same as bulk): predicts larger f% for same pressure

Model Trend: Contact Area vs. Characteristic Asperity Height

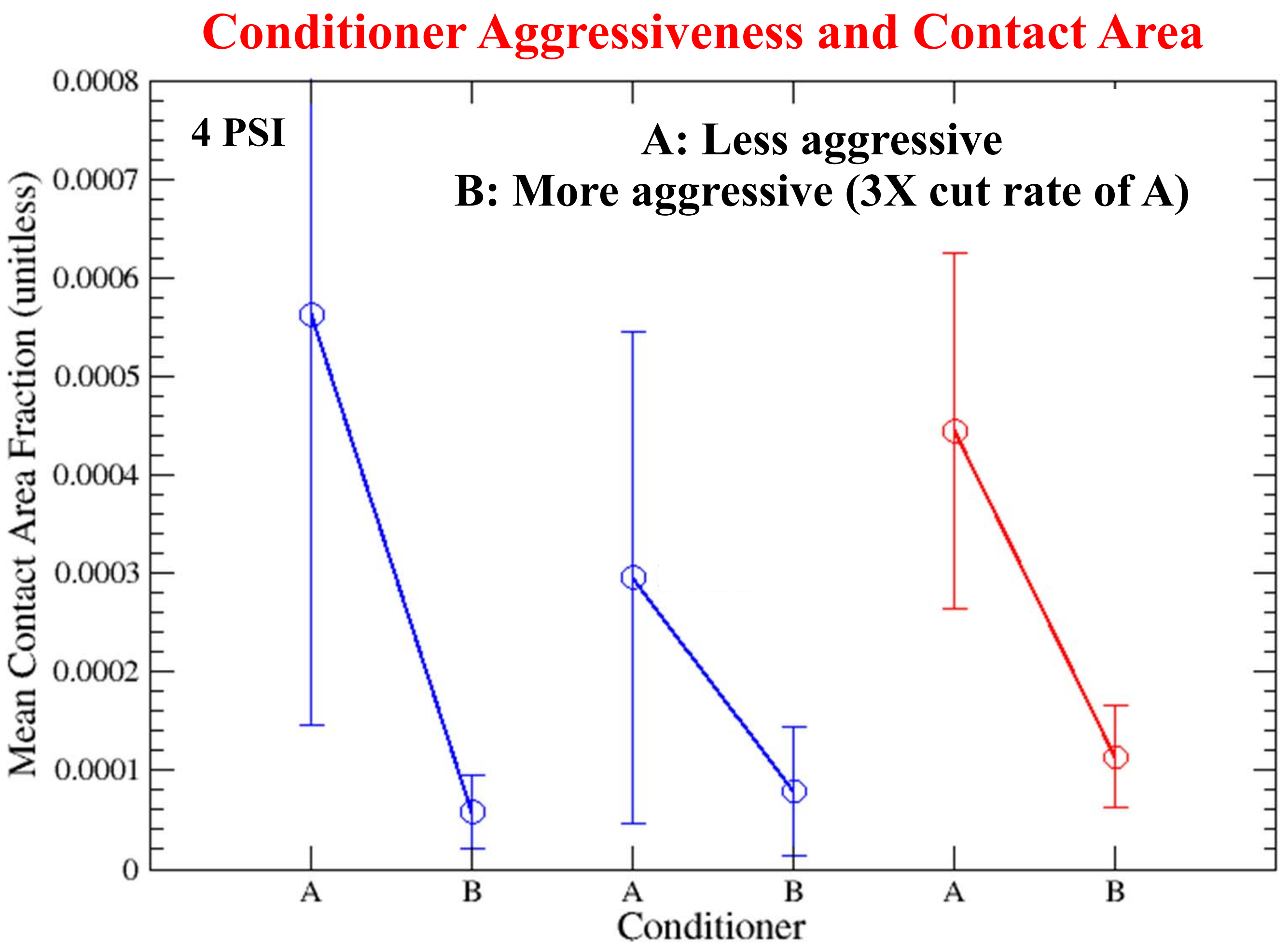


$$f(P_0) = \frac{P_0}{E}\sqrt{\frac{\pi R}{\lambda}}$$

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

- **Contact area decreases with larger *λ***
  - Larger *λ* implies wider distribution (more taller asperities)
  - For wider distribution, a smaller number of tall asperities bear the load, reducing the contact area percent

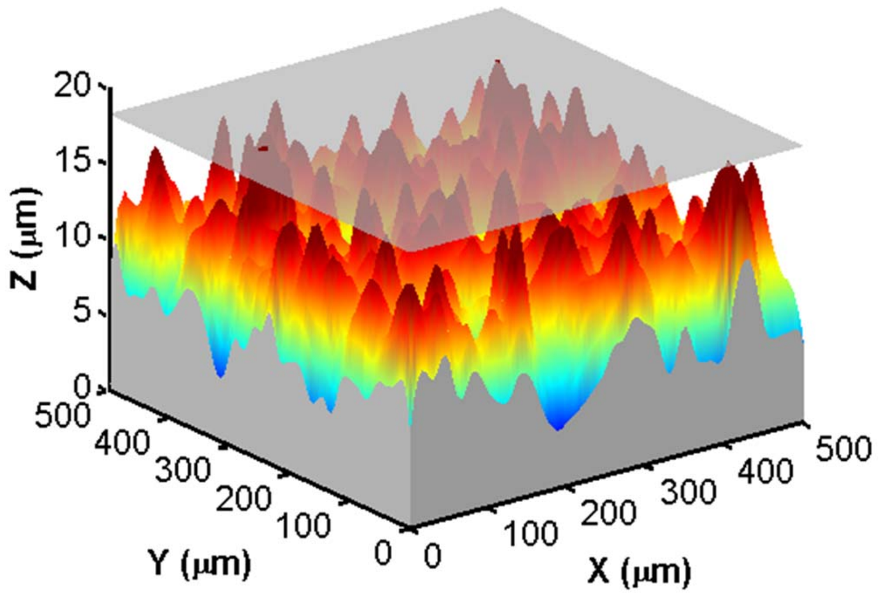
Consistent with Conditioning/Contact Area Data

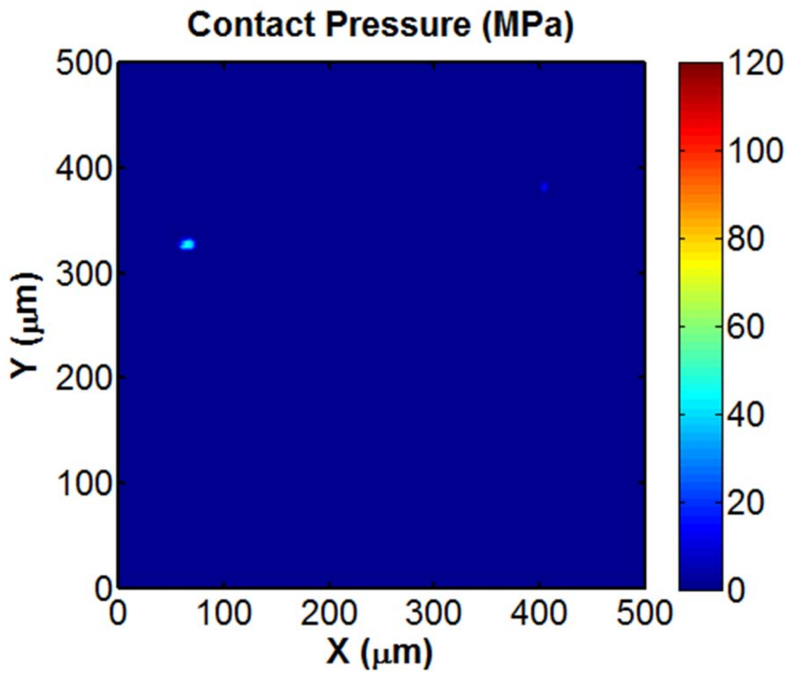


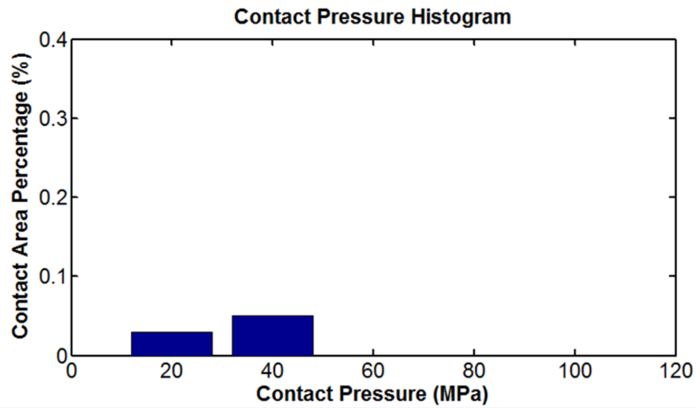
L. Borucki et al., CSITC, March 2010.

Simulated Pad-Wafer Interaction

P_0 = 5 psi



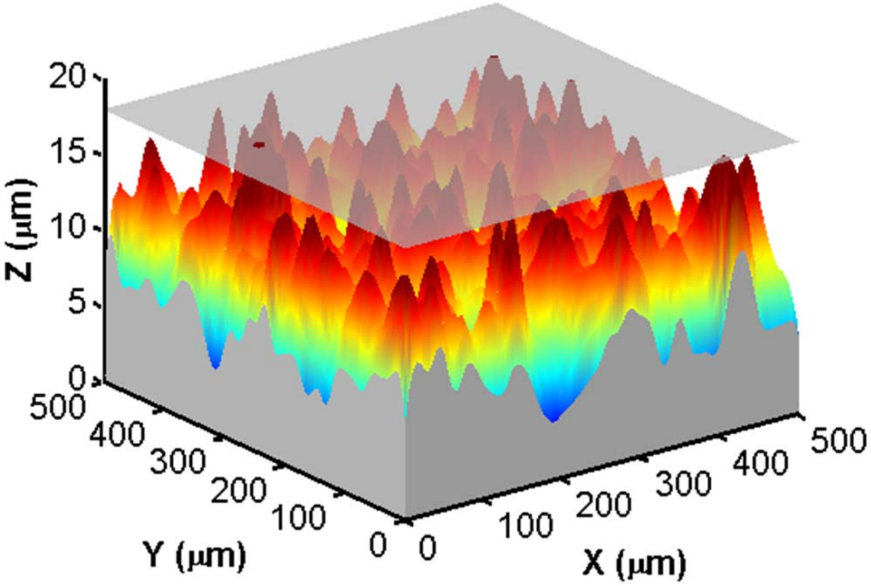


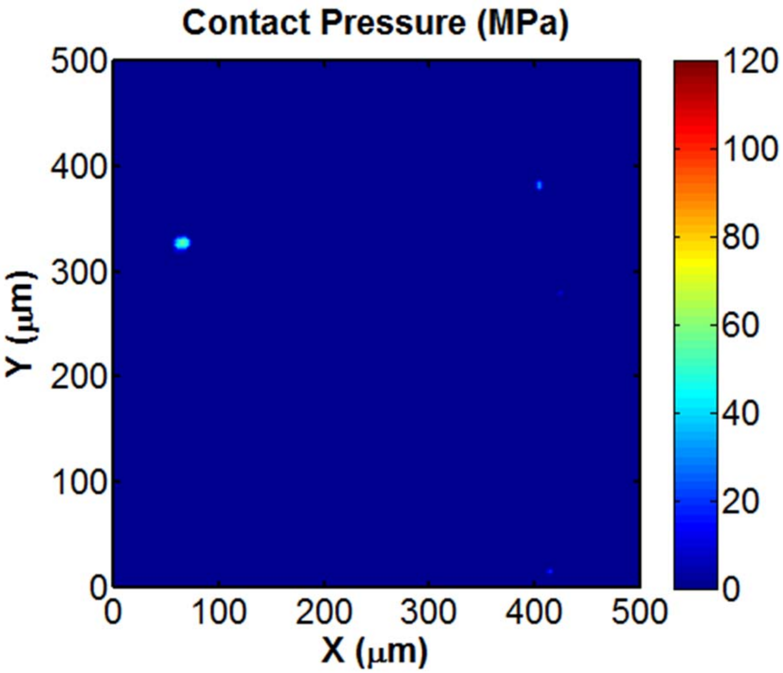


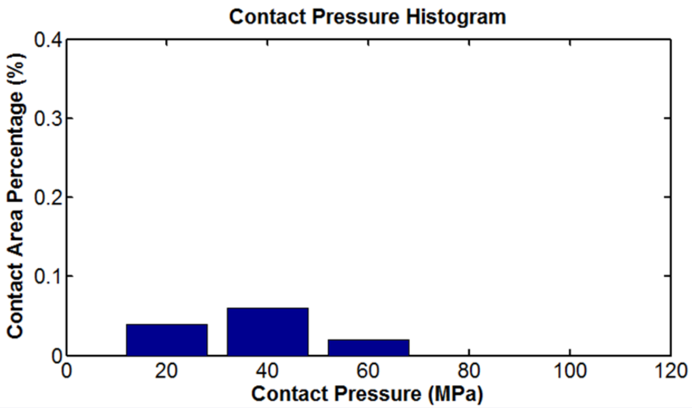
λ = 11.8 µm
E = 460 MPa

Simulated Pad-Wafer Interaction

P_0 = 10 psi



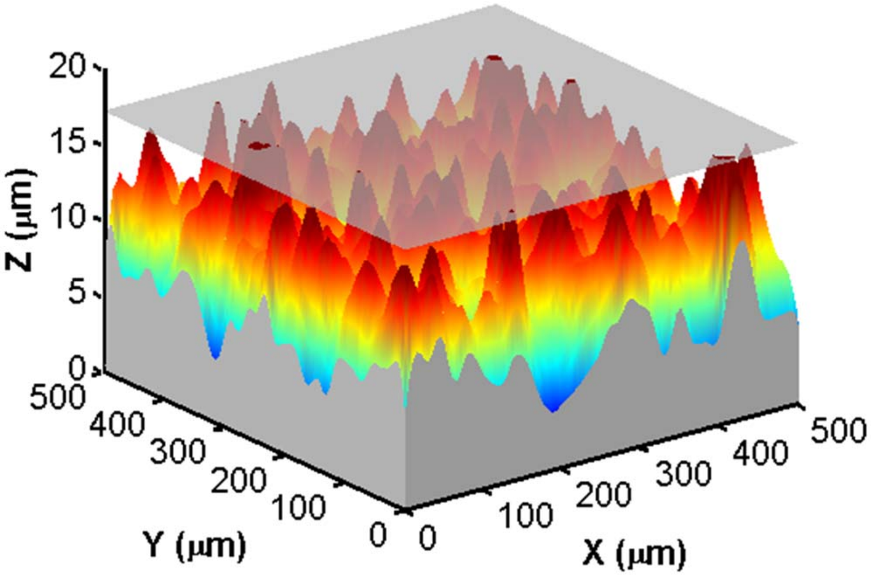


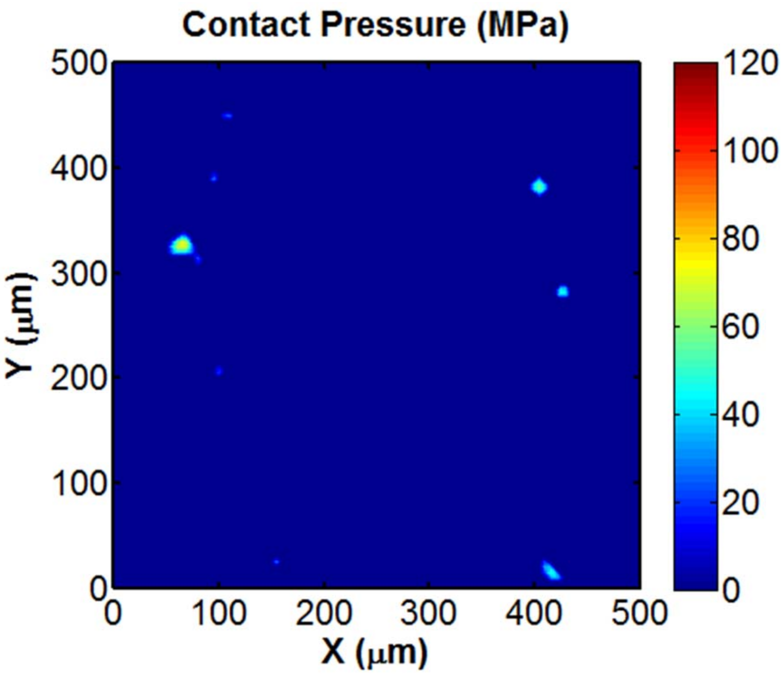


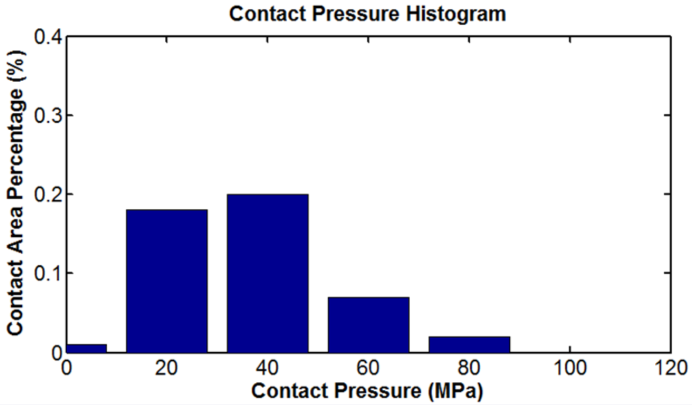
λ = 11.8 μm
E = 460 MPa

Simulated Pad-Wafer Interaction

P_0 = 50 psi



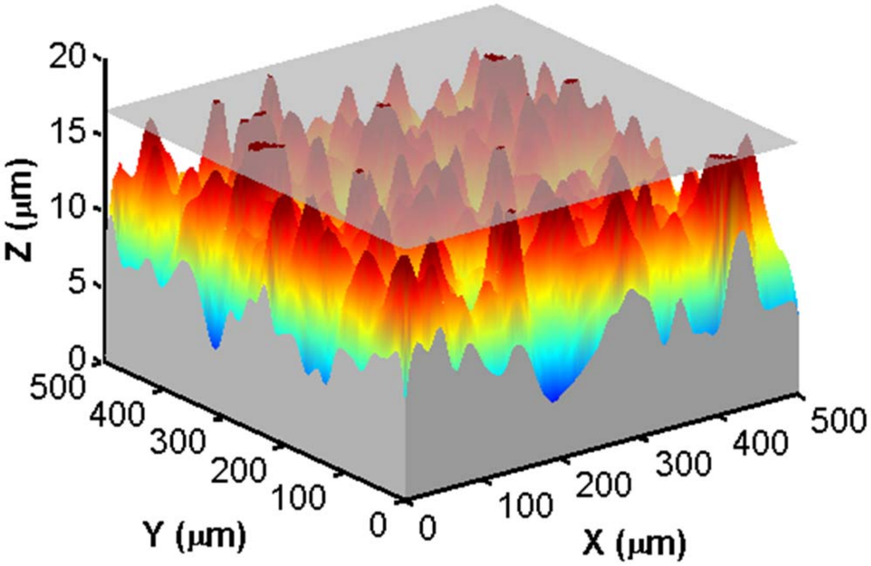


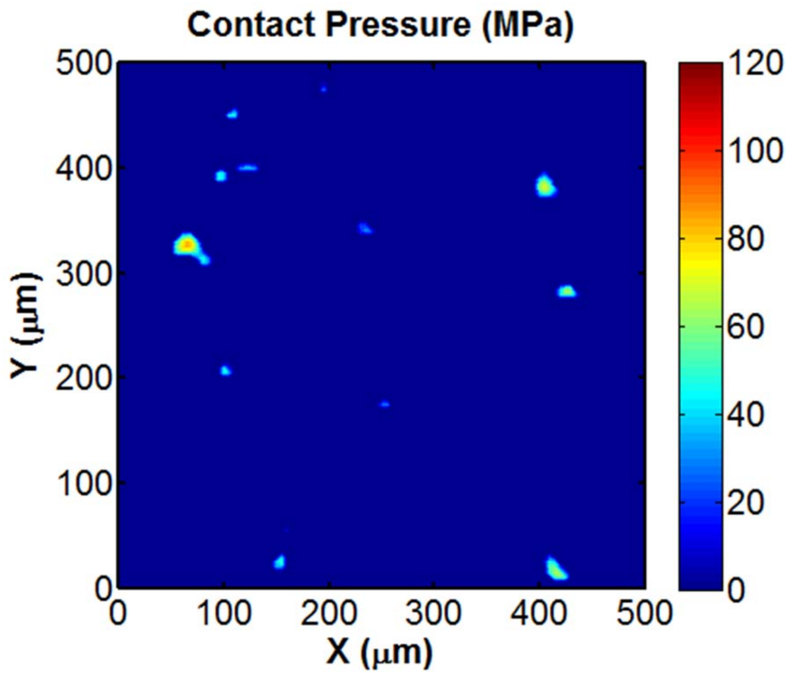


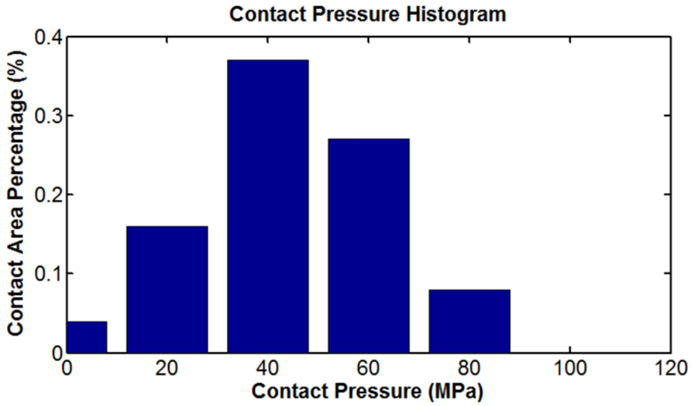
λ = 11.8 µm
E = 460 MPa

Simulated Pad-Wafer Interaction

P_0 = 150 psi







- **Contact area changes with overall applied pressure**
- **There is also a distribution of asperity contact pressures**

λ = 11.8 μm
E = 460 MPa

Next Steps

- Extended die-level CMP model including detailed properties
  - Integrate physical die-level CMP model with nano-scale pad-wafer contact model
  - Consider implications of shallow indentation modulus
  - Understand material removal mechanism using 3-body contact model
- Extended wafer-level CMP model including polishing tool effects
  - Retaining ring slot design: effects on wafer/ring edge pressure distributions
  - Pad thickness changes: examine pattern wafer effects due to finite (and changing) pad thickness

2. Slurry Agglomeration/Wafer-Level CMP Modeling:

Issue: Slurry chemistry, process conditions, and tool design affect slurry particle size and agglomeration

- **Model how/when slurry abrasive particles form agglomerates**
- **Understand how agglomeration relates to process efficiency, planarization capability, and defectivity**
  - **agglomerate (particle) size distribution, slurry stability**
  - **dependency of wafer-scale uniformity (pattern density)**
- **Integrate with *wafer- and die-scale* models:**
  - **Pressure/velocity (shear) impact on slurry**
  - **Pad microstructure and slurry interactions**

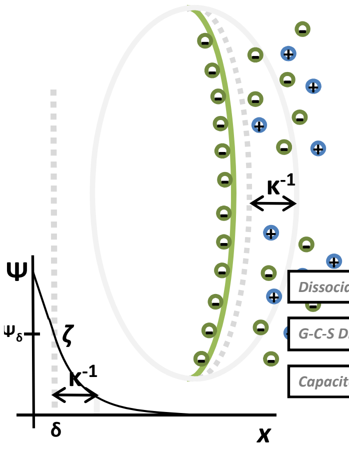
Accomplishments and Current Work: Slurry Agglomeration Model

- **Agglomeration model development:**
  - **Account for slurry particles, and wafer debris in the creation of agglomerates (respective of size and composition)**
  - **Account for slurry stability based on agglomerates, chemical composition, and shear forces during CMP**
  - **Calculate probability of agglomerate size distribution and corresponding stability**
- **CMP model/experimental preliminary investigations:**
  - **Slurry particle size distribution and stability**
- **CMP wafer-scale model application**
  - **Studies of planarization and defectivity as a function of slurry agglomerates**
  - **Possible integration of agglomeration model metrics in planarization model on wafer scale**

Agglomeration Model Validation

theory

Surface Chemistry

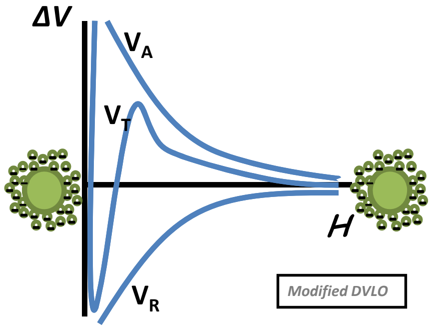


Dissociation Model

G-C-S DL Model

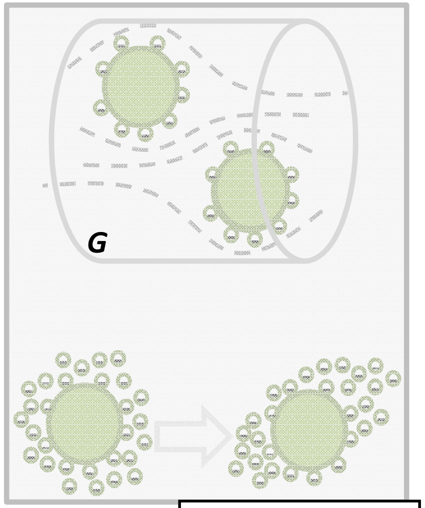
Capacitor Model

Inter-Particle Interactions



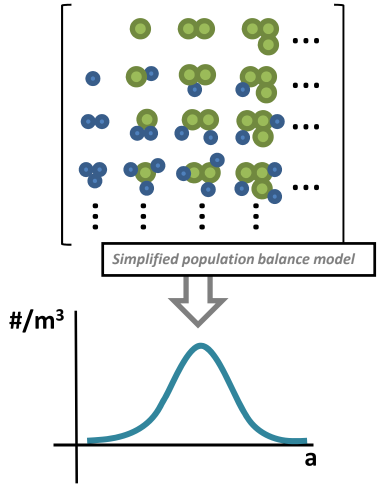
Modified DVLO

Kinetics



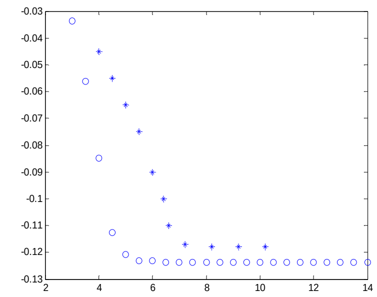
Orthokinetic aggregation model

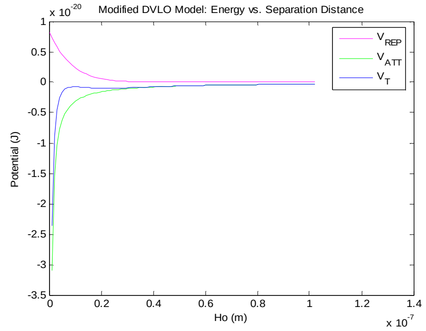
Population Balance

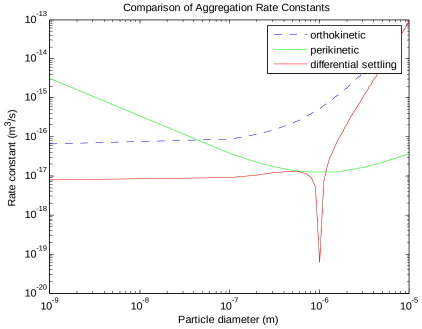


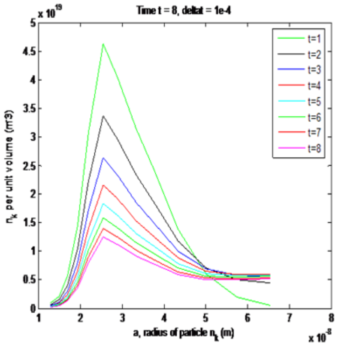
Simplified population balance model

model

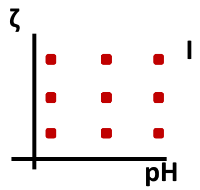


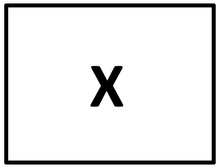


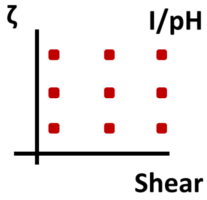


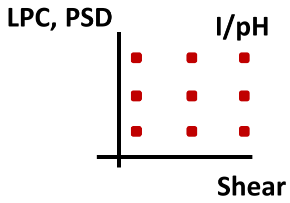


experiments

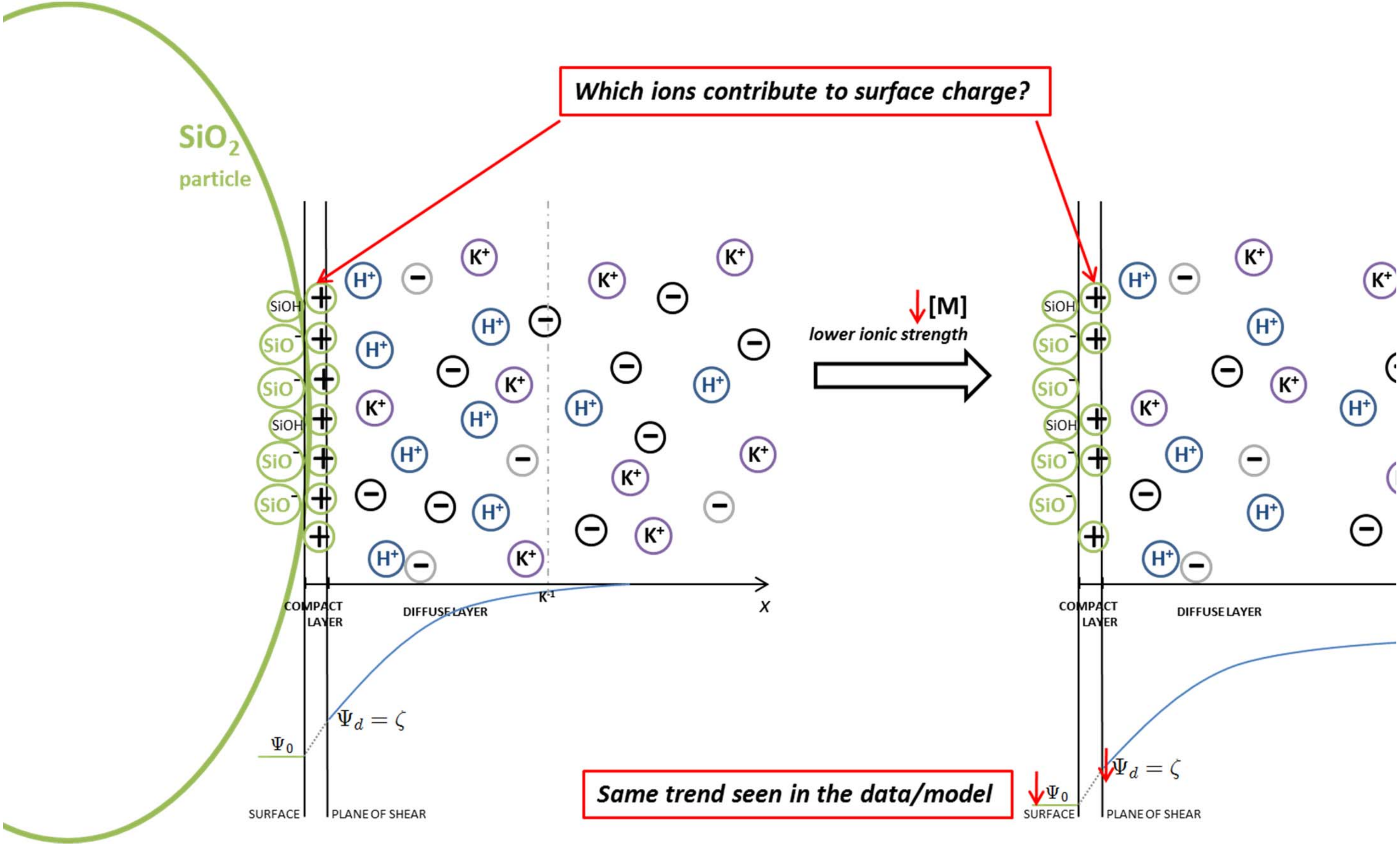








Surface Chemistry

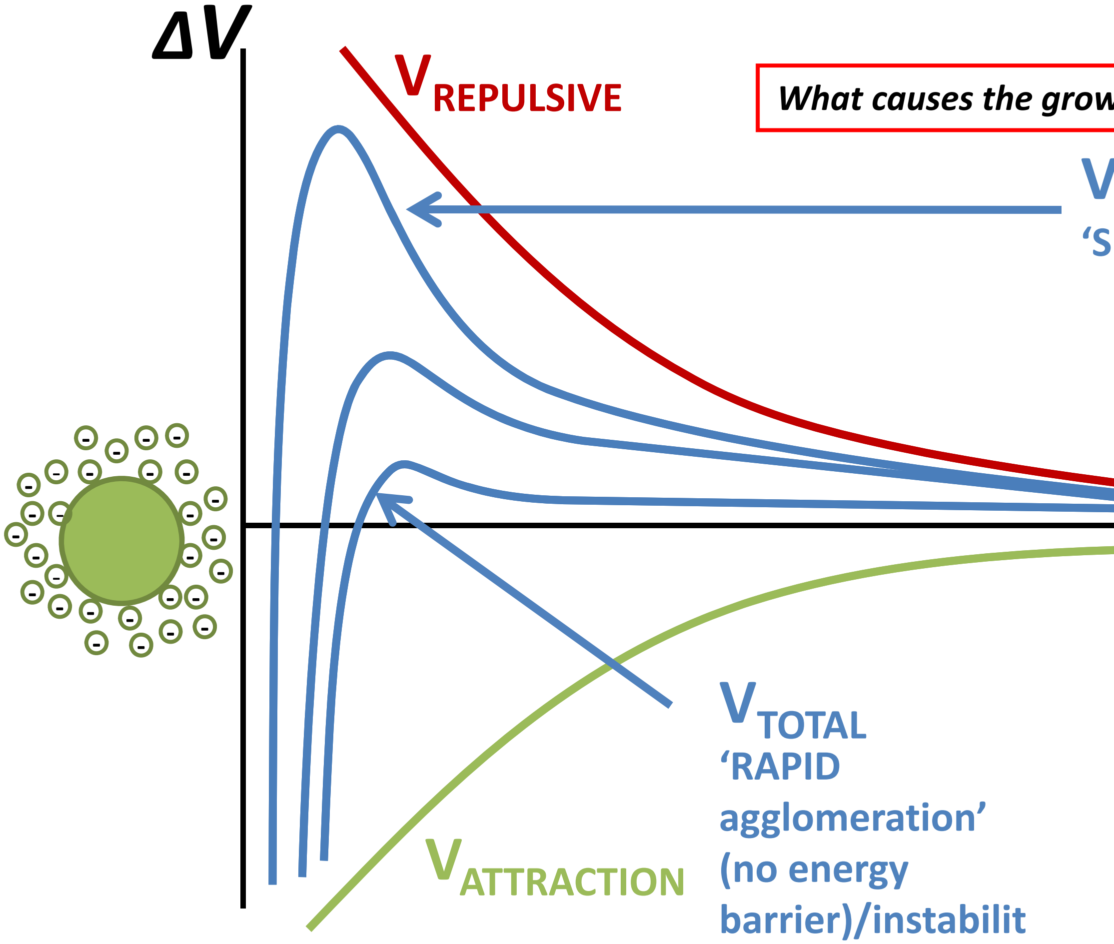


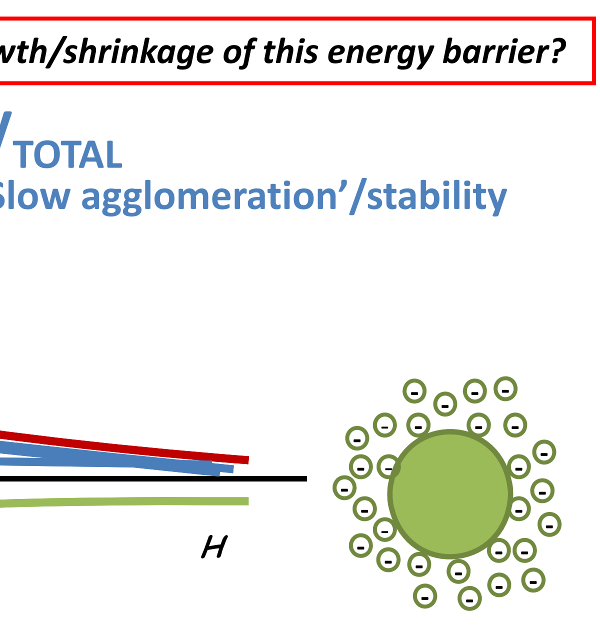
Which ions contribute to surface charge?

Same trend seen in the data/model

The Surface Chemistry Model provides a calculation of <u>surface charge density</u> and <u>zeta potential</u>.

Inter-Particle Interactions

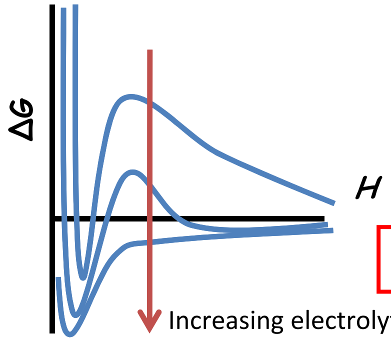




What causes the growth/shrinkage of this energy barrier?

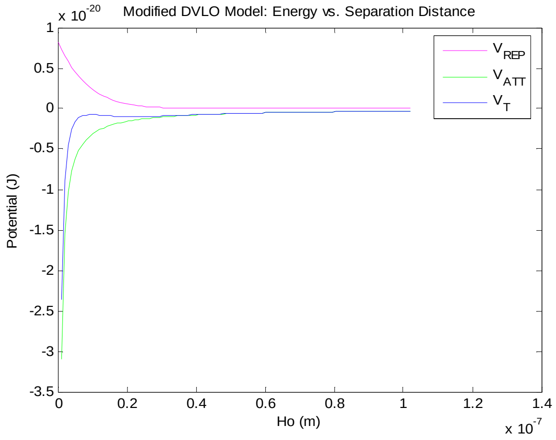
V_{TOTAL}
'Slow agglomeration'/stability

V_{TOTAL}
'RAPID agglomeration' (no energy barrier)/instabilit
y



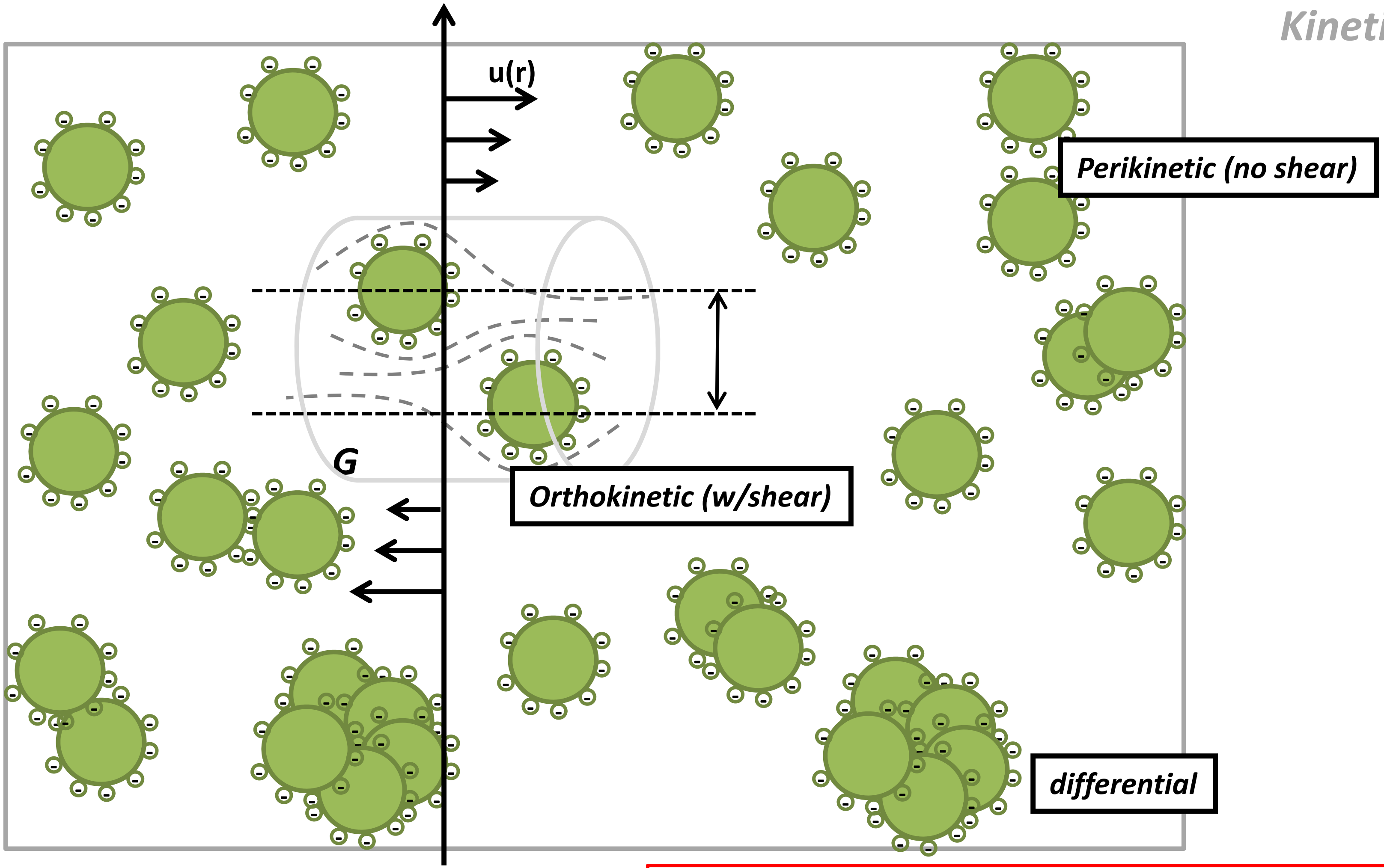
Increasing electrolyte concentration

Same trend seen in the model



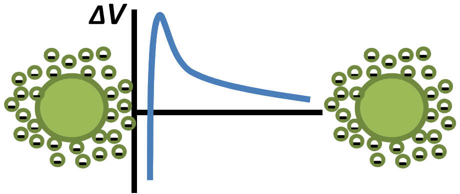
The modified DVLO Model provides a calculation of <u>interaction energy</u> as it relates to the surface chemistry.

Kinetics

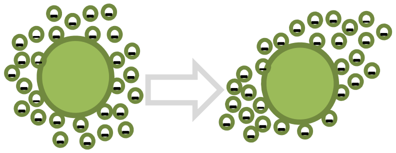


Additional Variables:

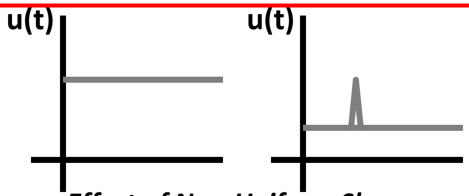
The Orthokinetic Aggregation Model provides a calculation of __agglomeration rate__ as a function of shear



Effect of Repulsive Forces



~~*Shear effect on zeta potential*~~



Effect of Non-Uniform Shear

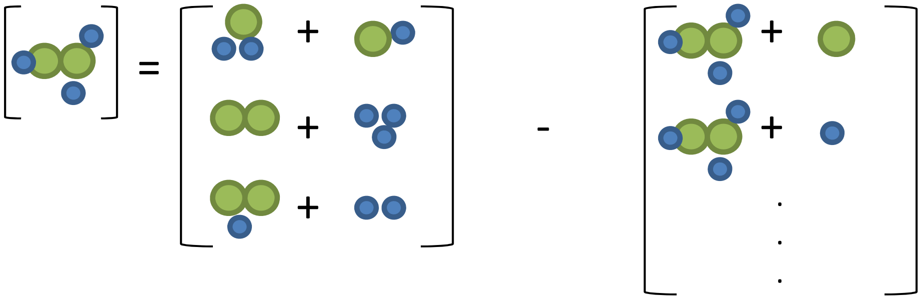
How do these variables reduce/increase the shear effects on agglomeration?

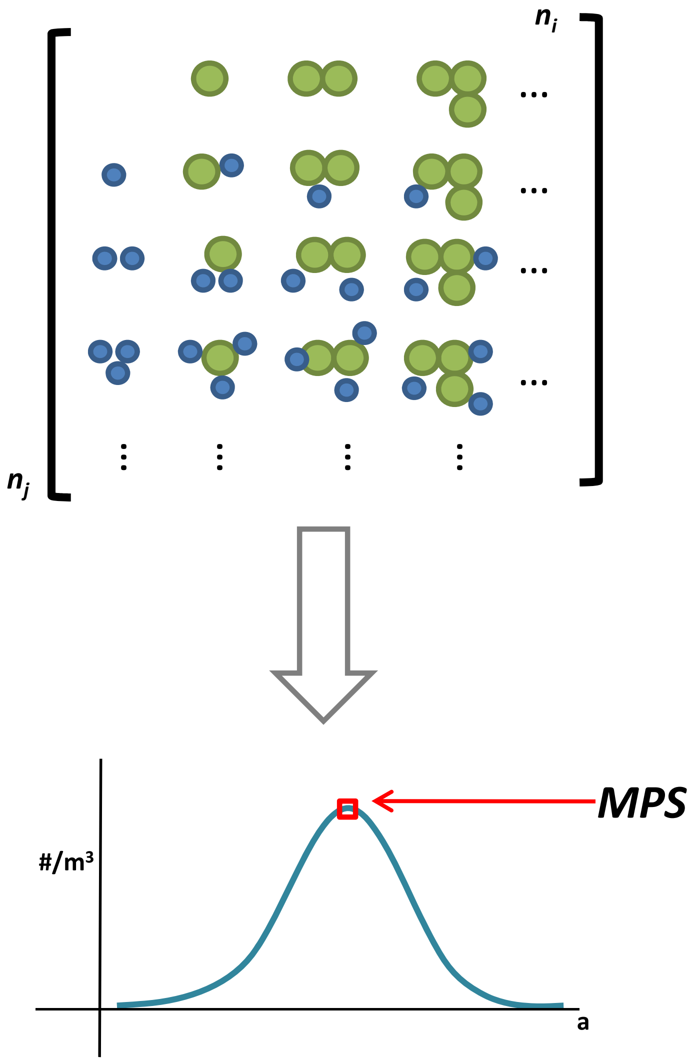
Standard Case

Simplified Population Balance Model **of the Orthokinetic Agglomeration rate**

Birth rate of n_k ***Death rate of n_k***

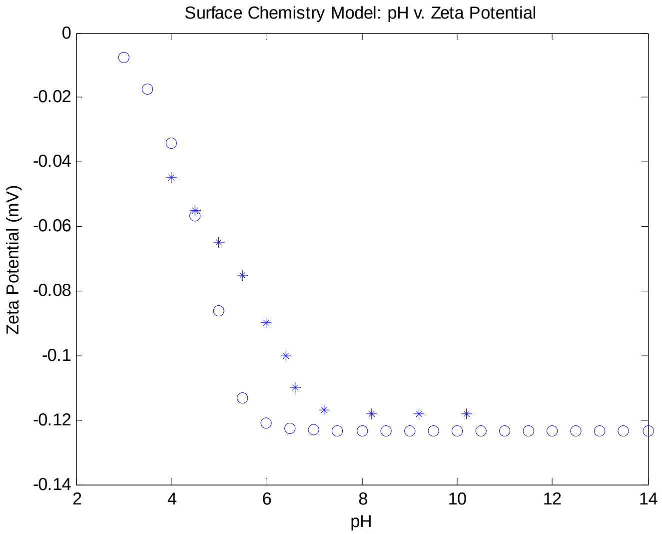
$$\frac{dn_k}{dt} = \frac{1}{2}\sum_{i+j=k}^{i=k-1} k_{ij}\, n_i n_j - n_k \sum_{k=1}^{\infty} k_{ik}\, n_i$$

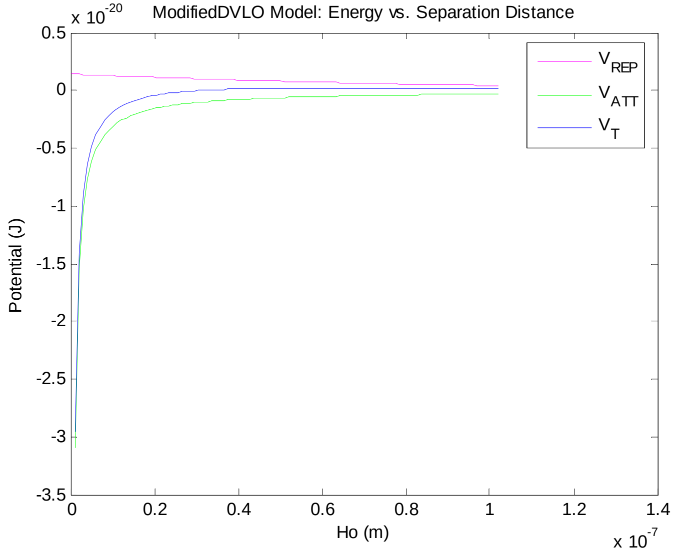




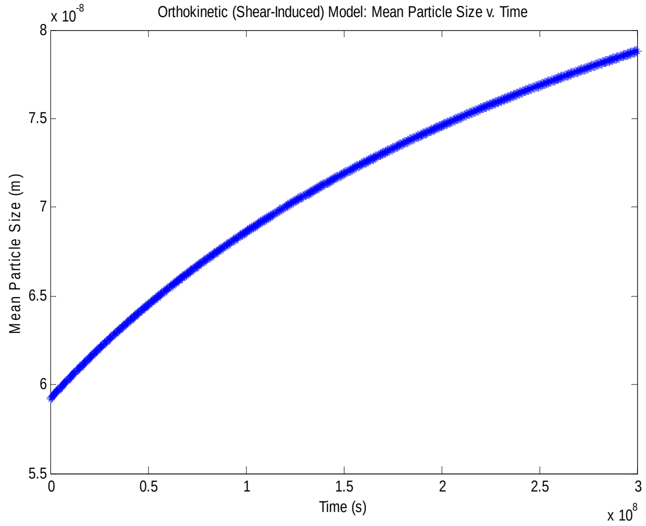
The Population Balance Model provides a calculation of <u>rate for each particle combinative pair</u> .

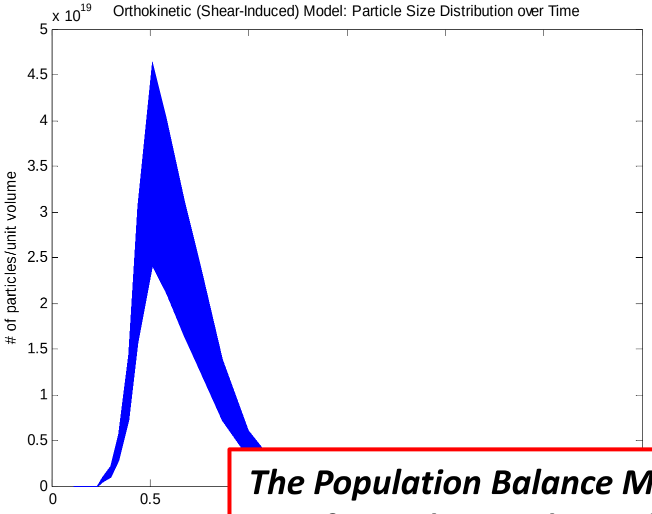
Standard Case





- ***Input Params:***
  - ***I = 0.001M***
  - ***pH = 4***
  - ***particletype = 'silica'***
  - ***MPS = .051μm***
  - ***PSD (initial measured PSD)***





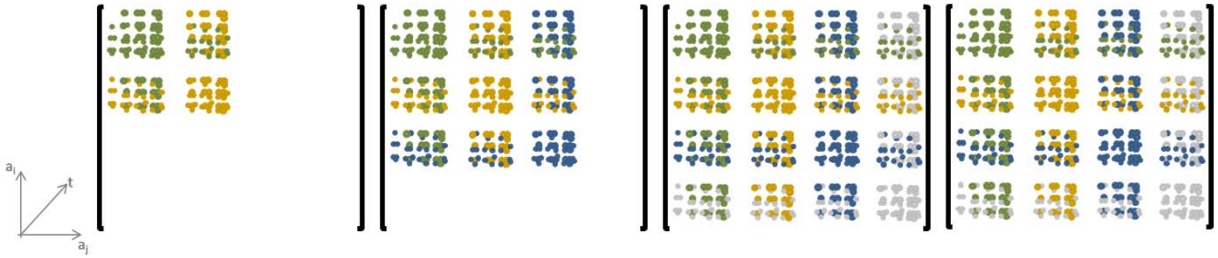
The Population Balance Model provides a calculation of <u>rate for each particle combinative pair</u> .

Future Plans

Next Year Plans

- Complete agglomeration experiments (in collaboration with Intel)

- Explore model paths for multi-particle systems in both conventional CMP and alternative pad particle-based processes



- Explore alternative pad-particle CMP, in comparison to conventional CMP

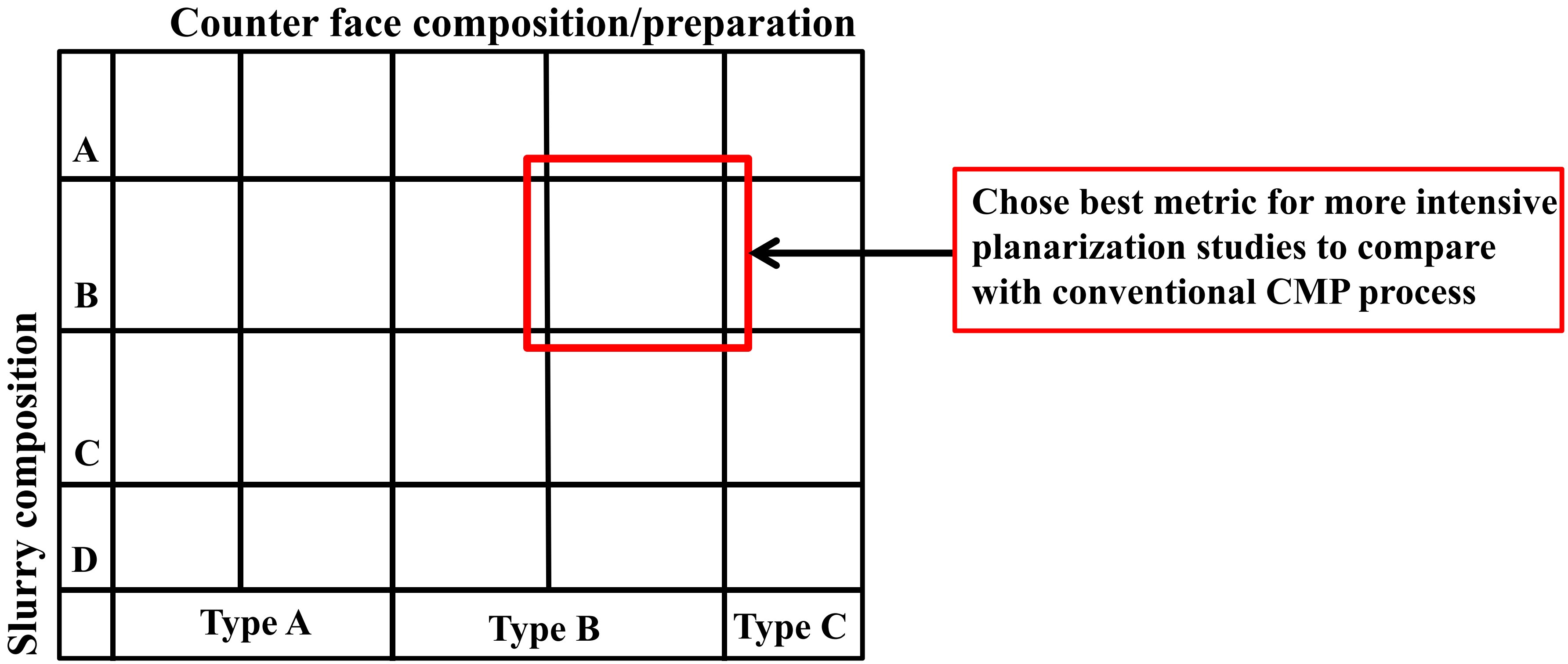
Pad/Slurry Alternative: Controlled Pad Particles vs. Pad Surface Asperities

Opportunity: Explore a recently proposed approach that uses pad "particles" or beads suspended in a slurry to replace CMP pad asperities

- **Gain fundamental physical understanding of key planarizing mechanisms, e.g. random pad asperities vs. controlled size of pad particles**
- **Understand environmental, cost, performance benefits, as well as viability of new approach**
- **Integrate with slurry particle agglomeration models to predict effects of new particles in the slurry**

Initial Experimentation:

- **Explore *proof of principle* baseline experiments on a bench top polisher**
- **Experiment with appropriate:**
  - **slurry composition: bead type, wt %, size distribution, surfactant**
  - **counter face: composition type and/or preparation (grooved/flat)**



Chose best metric for more intensive planarization studies to compare with conventional CMP process

Industrial Interactions and Technology Transfer

- **Intel**
  - **Conducting experiments for agglomeration model metrics and verification.**

Publications and Presentations

1. D. Boning and J. Johnson, "Slurry Particle Agglomeration Model for Chemical Mechanical Planarization (CMP)," CMP Symposium, MRS Spring Meeting, April 2010.
2. W. Fan, J. Johnson, and D. Boning, "Wafer-level Modeling of Electrochemical-Mechanical Planarization (ECMP)," International Conference on Planarization Technology (ICPT), Phoenix, AZ, Oct. 2010.
3. D. Boning, "CMP Mechanisms and Models: Progress and Challenges," Keynote, Symposium V: CMP and Post-CMP Cleaning, China Semiconductor Technology International Conference (CSTIC), Shanghai, China, March 18-19, 2010.