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

(*Task 425.032)*

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

PI:

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

Graduate Student:

- **Xiaomin Wei, PhD candidate, Chemical and Environment Engineering, UA**

Undergraduate Student:

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

Other Researcher:

- **Yasa Sampurno, 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.**

Objectives

- **Develop 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**

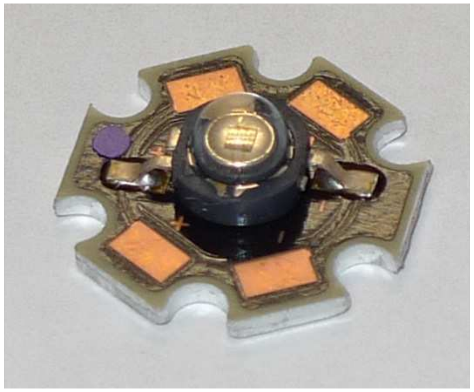
ESH Metrics and Impact

Goal: reduce slurry consumption by 40 %

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**

UV – LED and CCD Camera

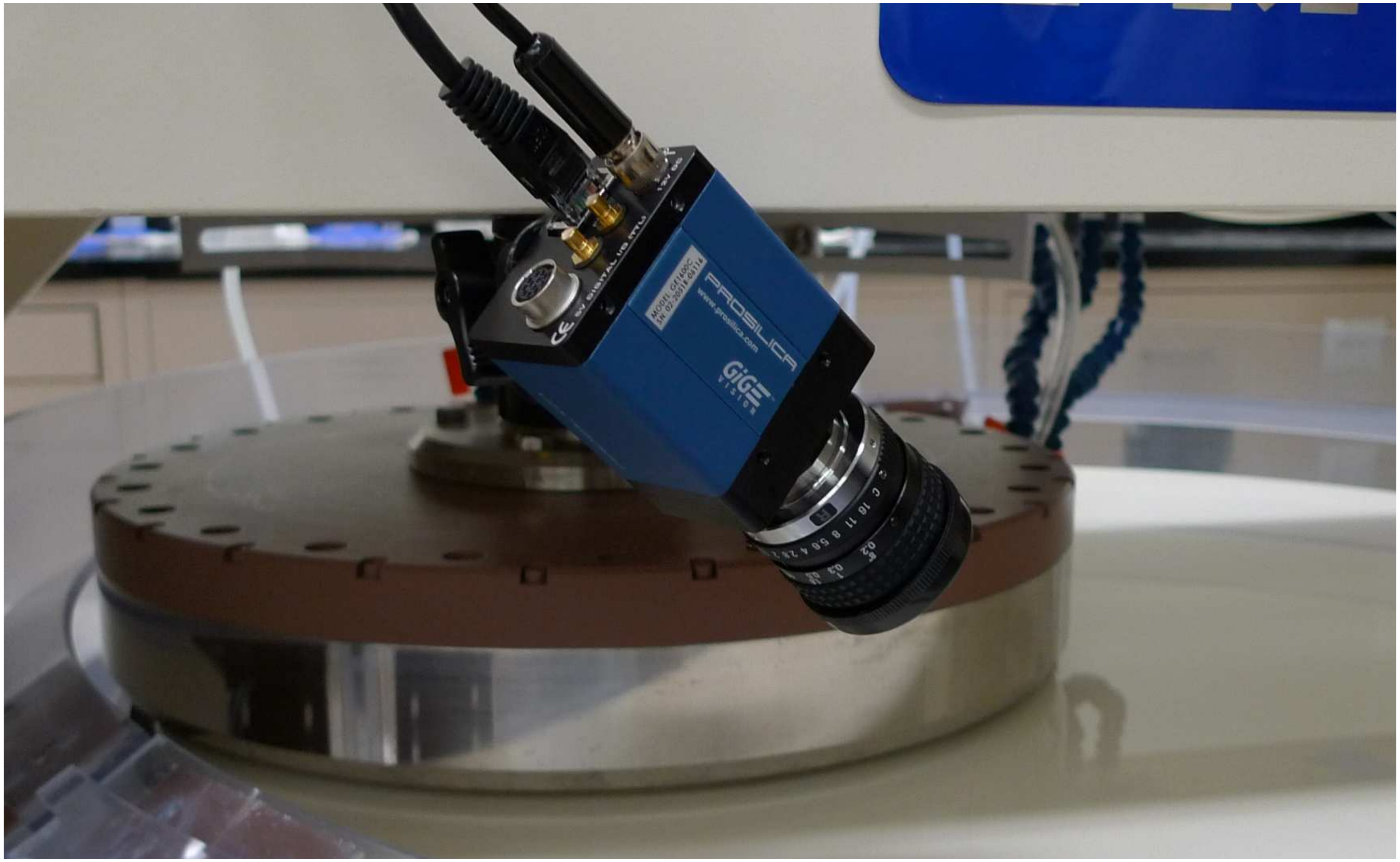


UV – LED

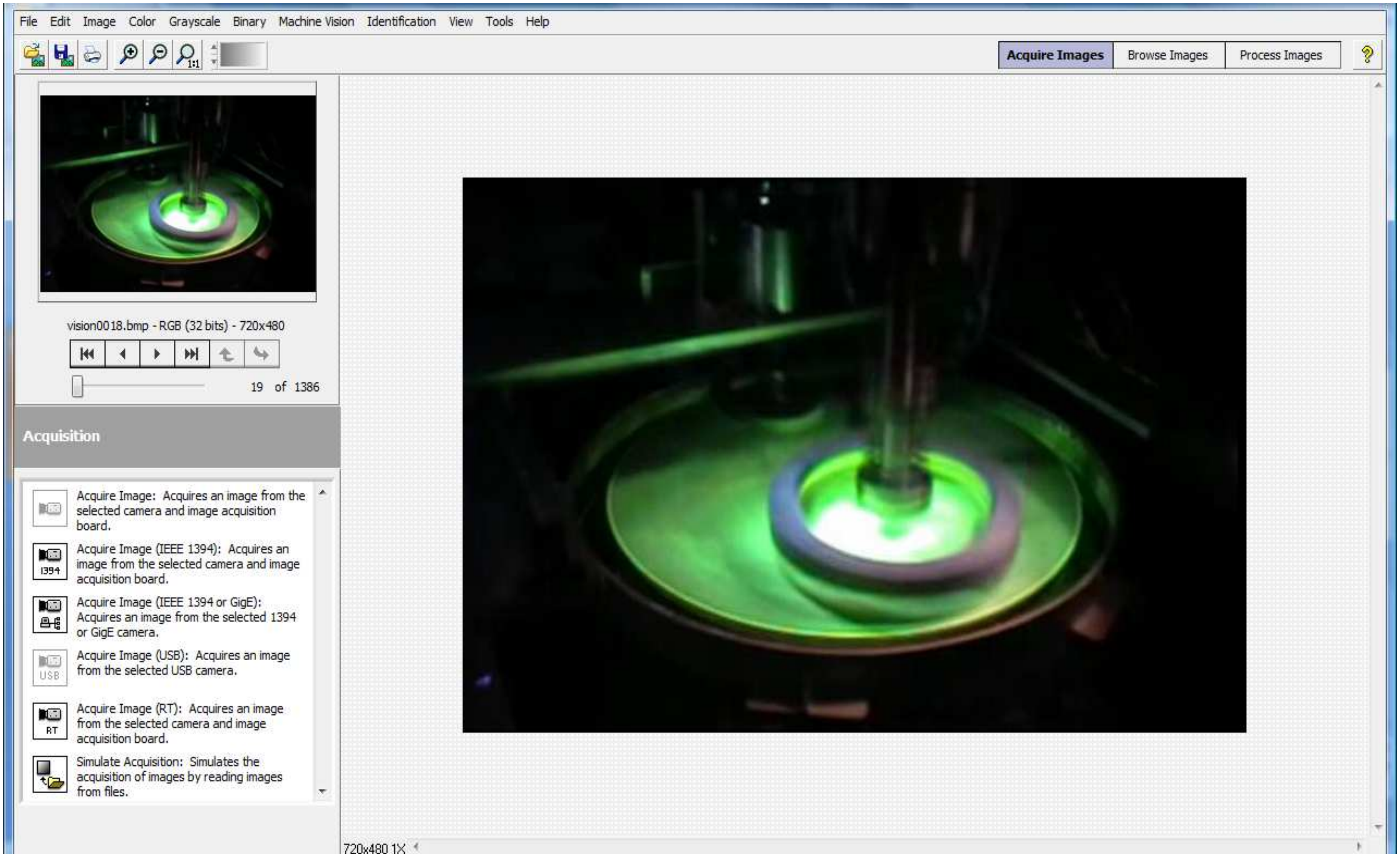
UV – LED Cover

High Resolution CCD Camera

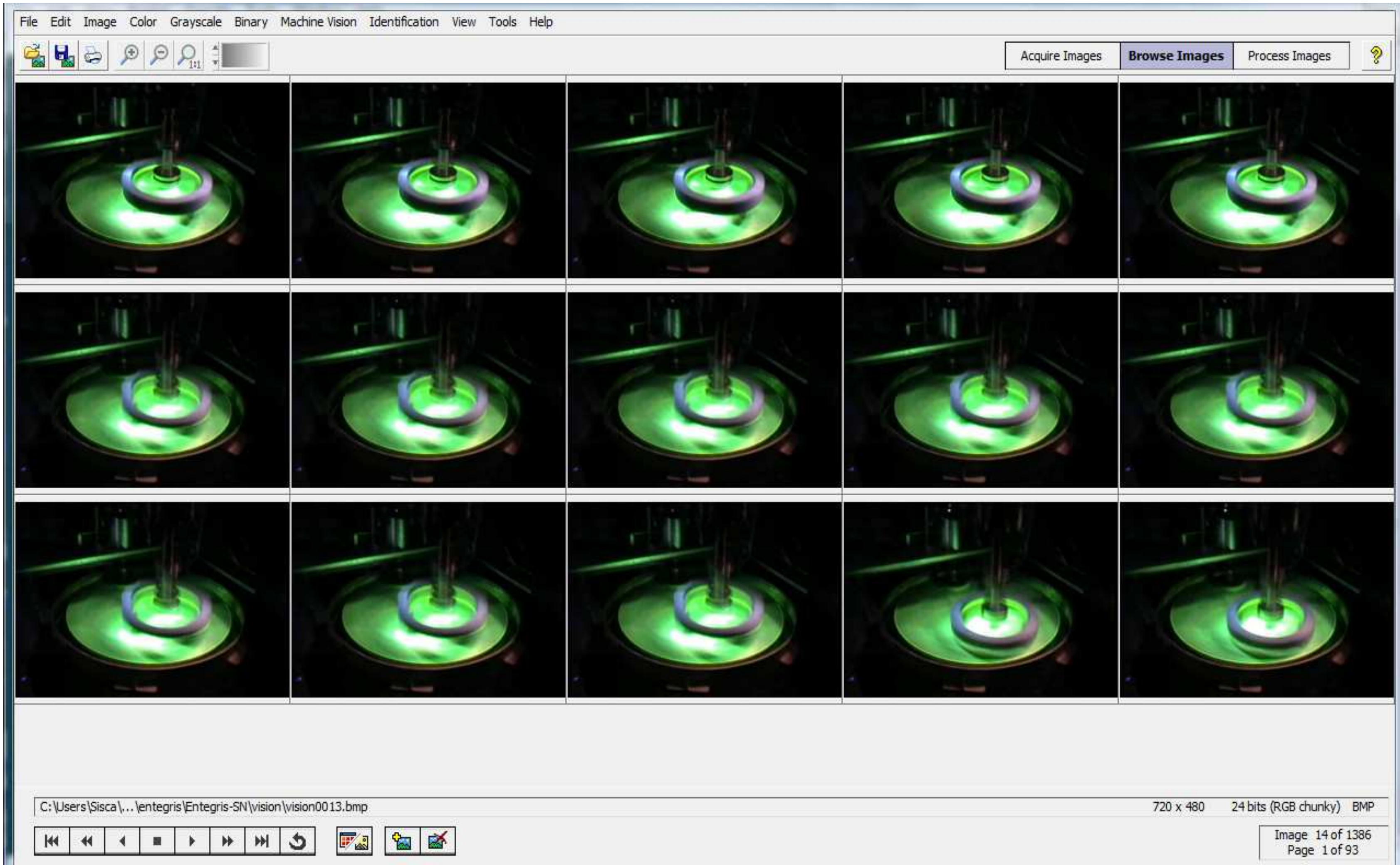
CCD Camera Setup with 300-mm Polisher



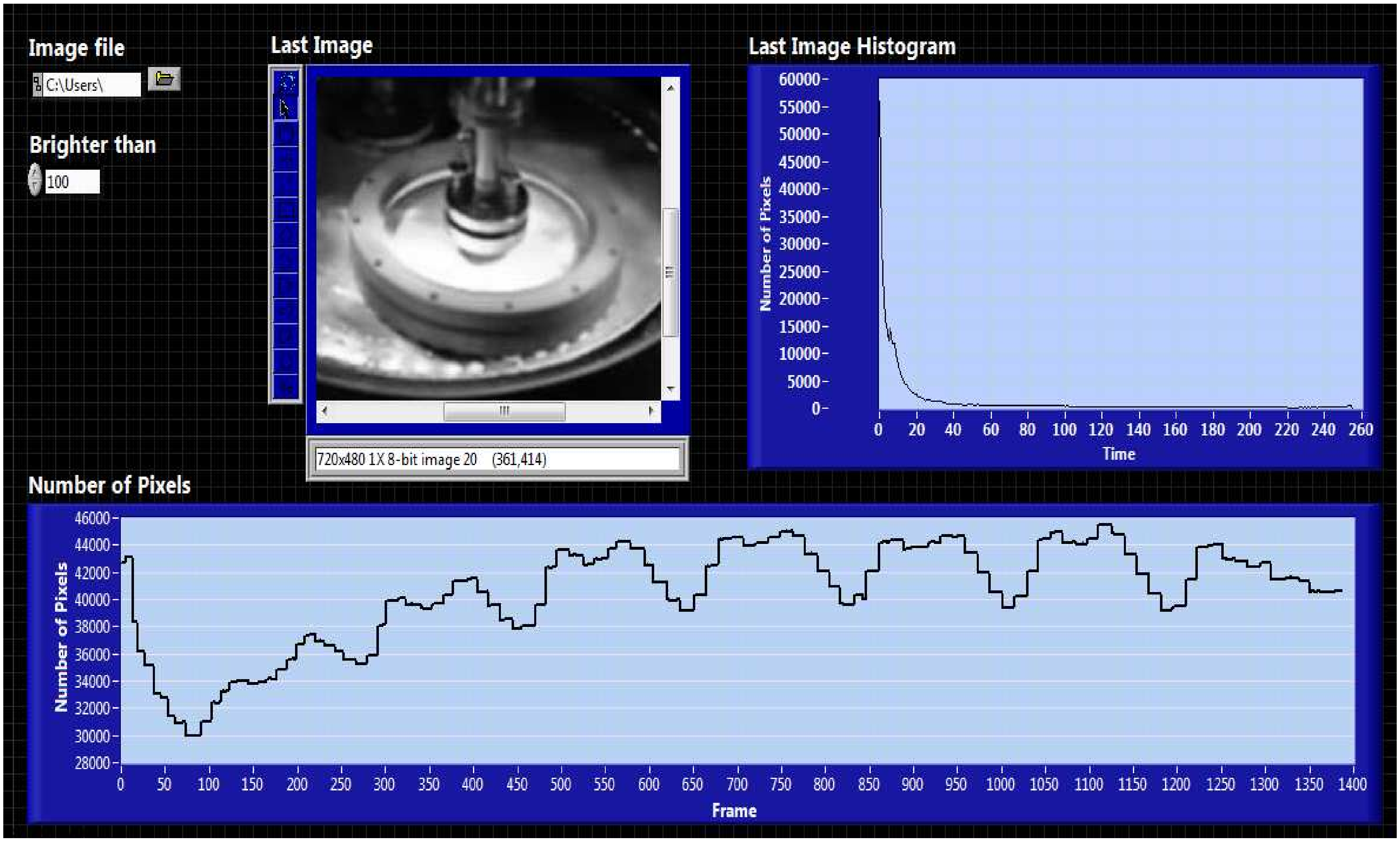
Software Interface for Image Acquisition



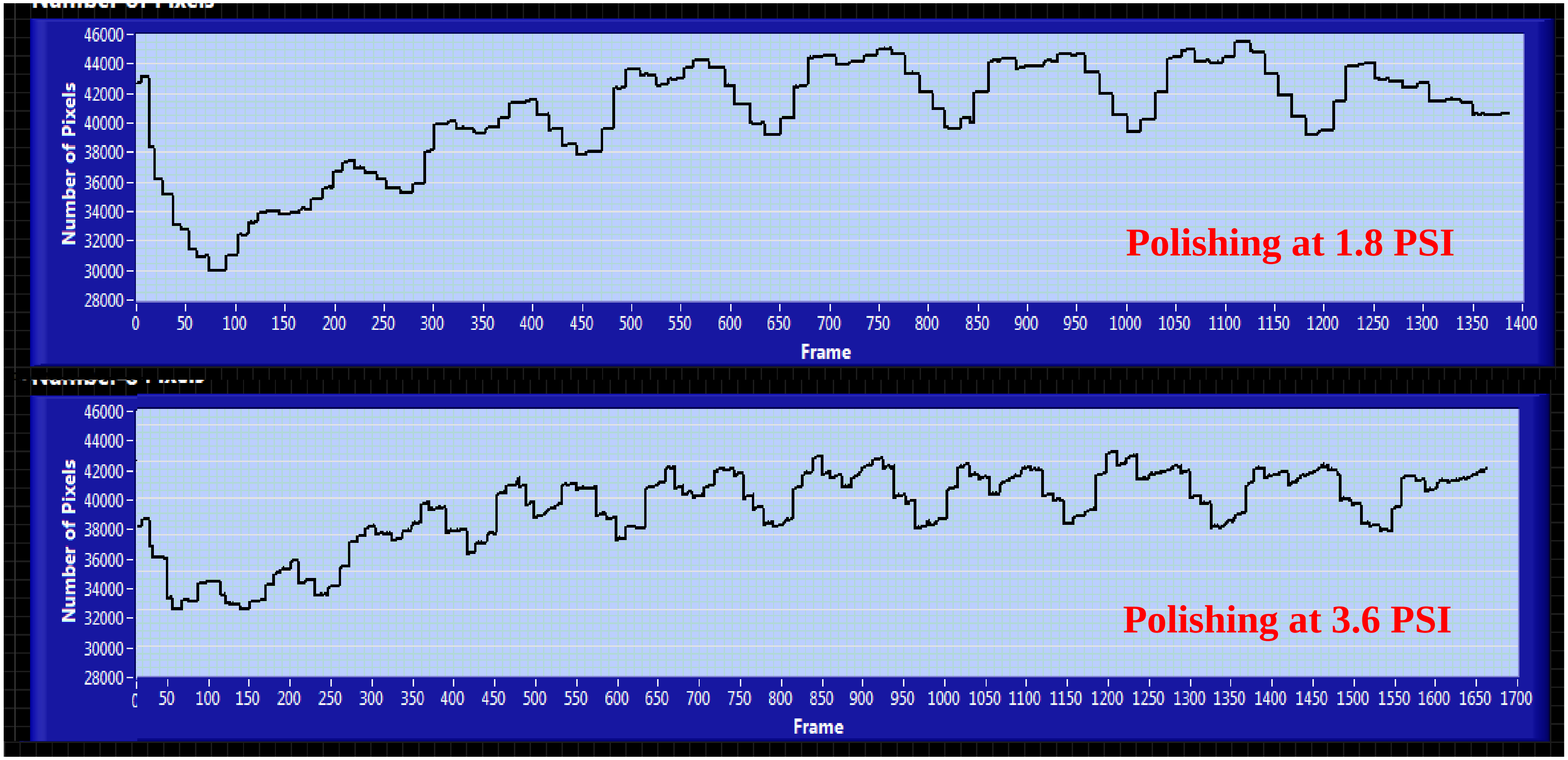
Software Interface for Image Browsing



Software Interface for Image Analysis



Effect of Polishing Pressure



The UV enhanced fluorescence system can be used to assess differences in slurry flow characteristics at two different polishing pressures.

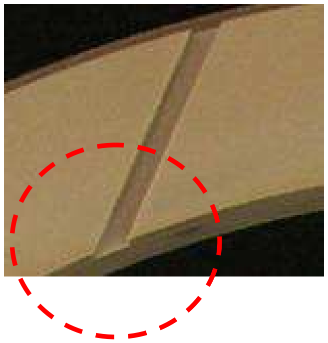
Industrial Interactions and Technology Transfer

Industrial mentors and contacts:

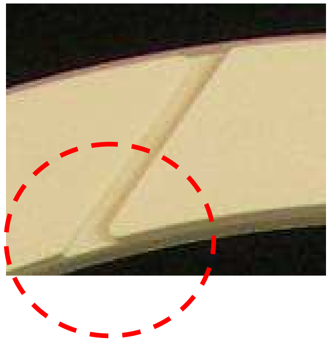
- **Christopher Wargo (Entegris)**
- **Cliff Spiro (Cabot Microelectronics)**

Future Plans

- **Next year plan: investigate the effect of retaining ring geometry and material (PPS vs. PEEK) on slurry flow and pad micro-texture**



Slot Design #1



Slot Design #2

- **Long-term plan: develop fundamental understanding of retaining ring's effects on slurry flow and polishing performance to overcome difficult challenges in environmental and manufacturing efficiency.**

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

(*Task 425.032)*

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:

- **Ting Sun, Chemical and Environmental Engineering, UA, graduated with Ph. D. degree in May 2009**
- **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**
- **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)*

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

Other Researchers:

- **Yun Zhuang, Postdoctoral Fellow, Chemical and Environment Engineering, UA**
- **Yasa Sampurno, Postdoctoral Fellow, Chemical and Environment Engineering, UA**
- **Jiang Cheng, Visiting Scholar, Chemical and Environment Engineering, UA**

Cost Share (other than core ERC funding):

- **In-kind donation (slurry) from Hitachi Chemical**
- **In-kind support from Araca, Inc.**

Objectives

- **Investigate the effect of pad conditioning on pad surface micro-texture, as well as frictional force, removal rate, and wafer topography (dishing/erosion) during ILD/STI CMP processes**
- **Investigate the origin of pad surface contact in CMP processes**
- **Characterize pad asperity height using stylus micro profilometry**

ESH Metrics and Impact

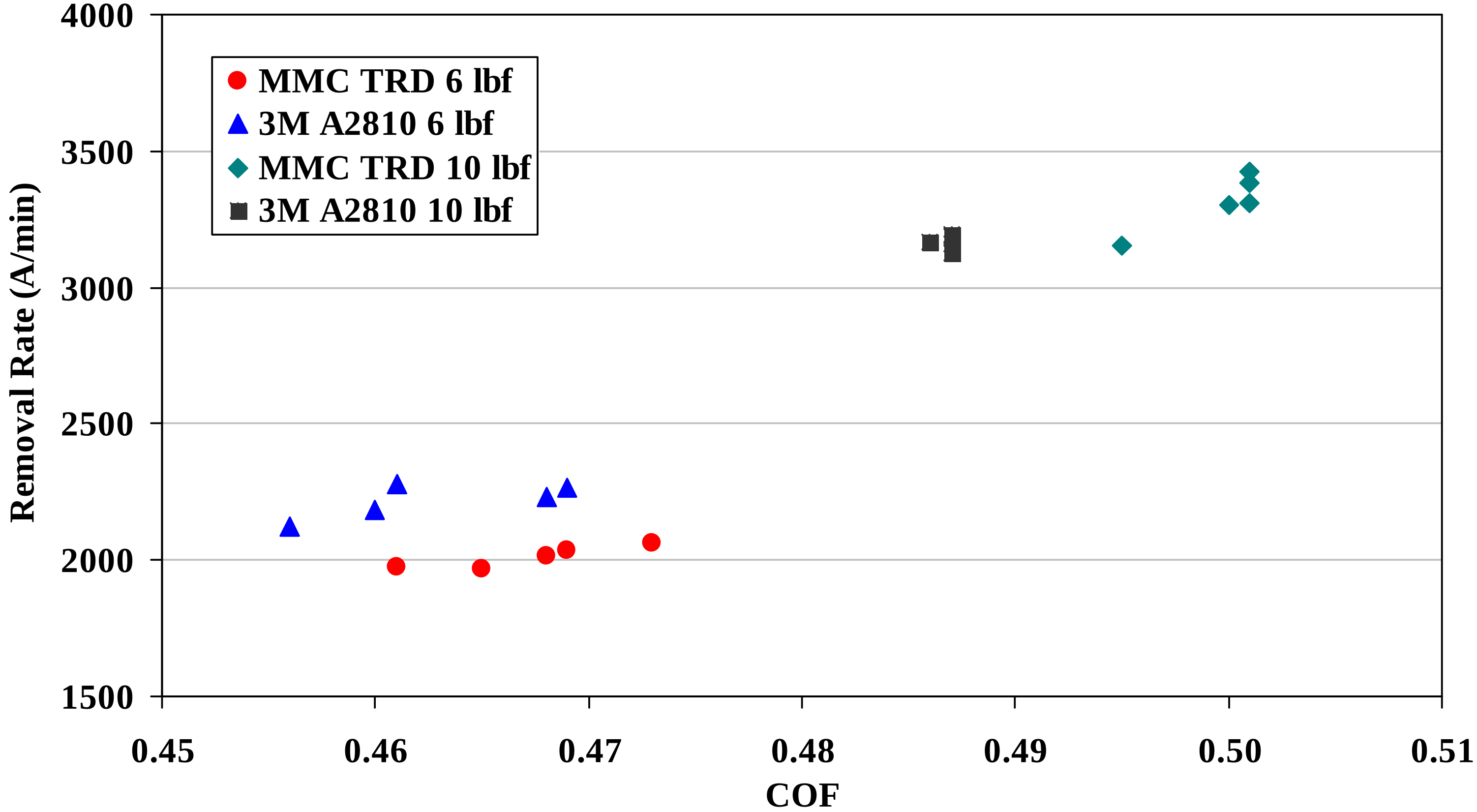
1. *Reduce CMP consumable consumption (pad, slurry, UPW, chemicals, pad conditioner, and retaining ring) by increasing yield through 1-3X dishing and erosion reduction*

General Approach

Polish 200-mm blanket TEOS and SKW3-2 STI wafers under 6 and 10 lb conditioning forces 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 and erosion**
- **Pad micro-texture analyses: contact area, surface abruptness, and summit curvature**

Removal Rate vs. COF



The removal rate increased much more significantly with the conditioning force (65% for the MMC TRD disc and 43% for the 3M A2810 disc) than the COF (7% for the MMC TRD disc and 5% for the 3M A2810 disc).

Dishing and Erosion Analysis

Center Die, 100 Micron Pitch

Conditioning Force (lb)	Diamond Disc	Dishing (A)					Erosion (A)				
		Pattern Density					Pattern Density				
		10%	30%	50%	70%	90%	10%	30%	50%	70%	90%
6	3M A2810	125	1200	300	300	275	110	134	125	113	117
	MMC TRD	325	2800	500	500	325	330	215	406	129	172
10	3M A2810	275	600	200	125	175	34	22	49	11	4
	MMC TRD	750	1400	300	225	275	103	23	86	24	18

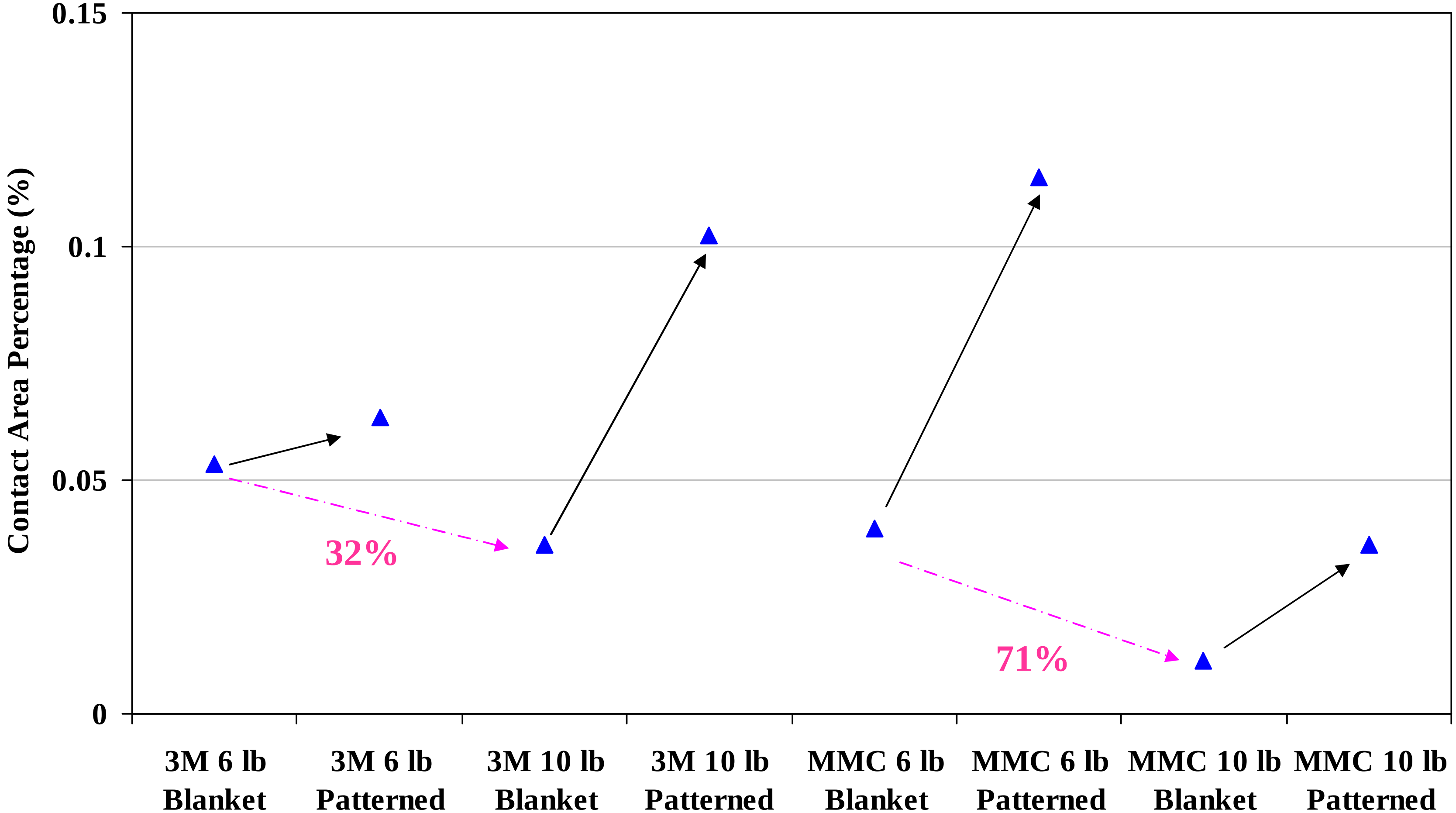
At both conditioning forces, Dishing/Erosion$_{\text{3M A2810 disc}}$ < Dishing/Erosion$_{\text{MMC TRD disc}}$.

Laser Confocal Microscopy

Zeiss LSM 510 Meta NLO

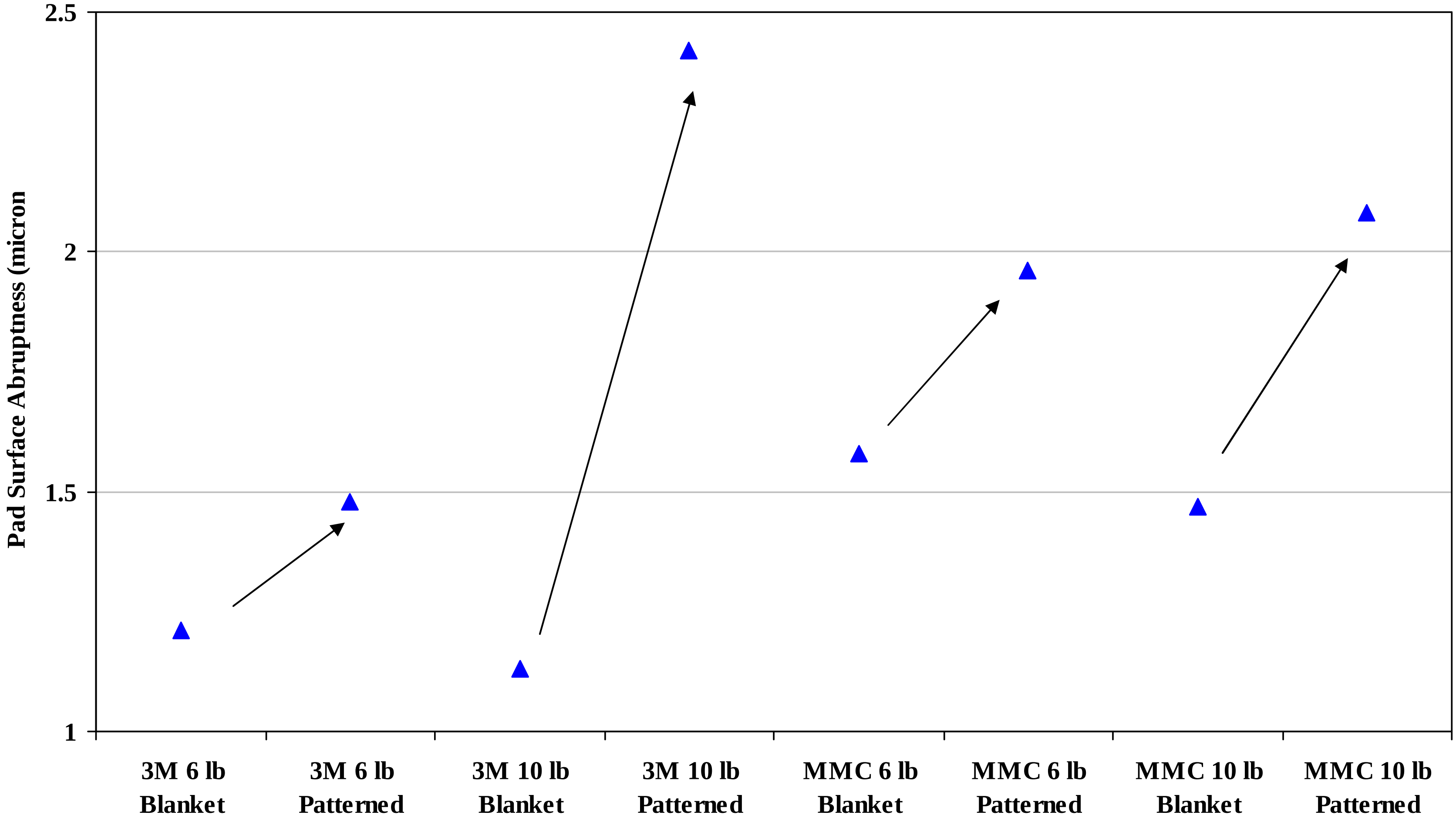
Pad surface contact area and topography analyses were performed through laser confocal microscopy.

Contact Area Percentage



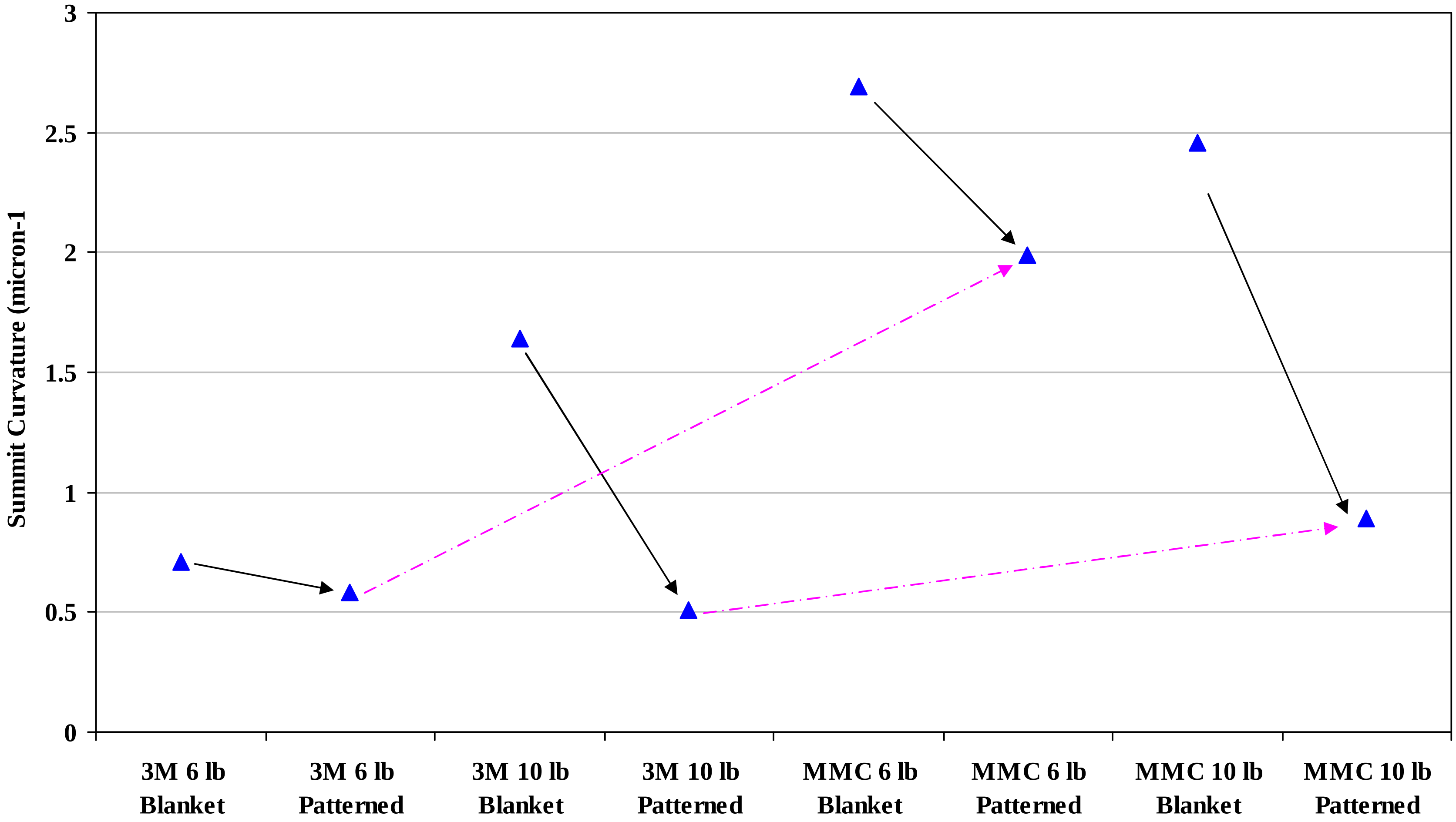
Contact area percentage decreased significantly when the conditioning force increased from 6 to 10 lb for both diamond discs during blanket wafer polishing, resulting in significantly smaller contact area, larger mean contact pressure, and higher removal rate.

Pad Surface Abruptness



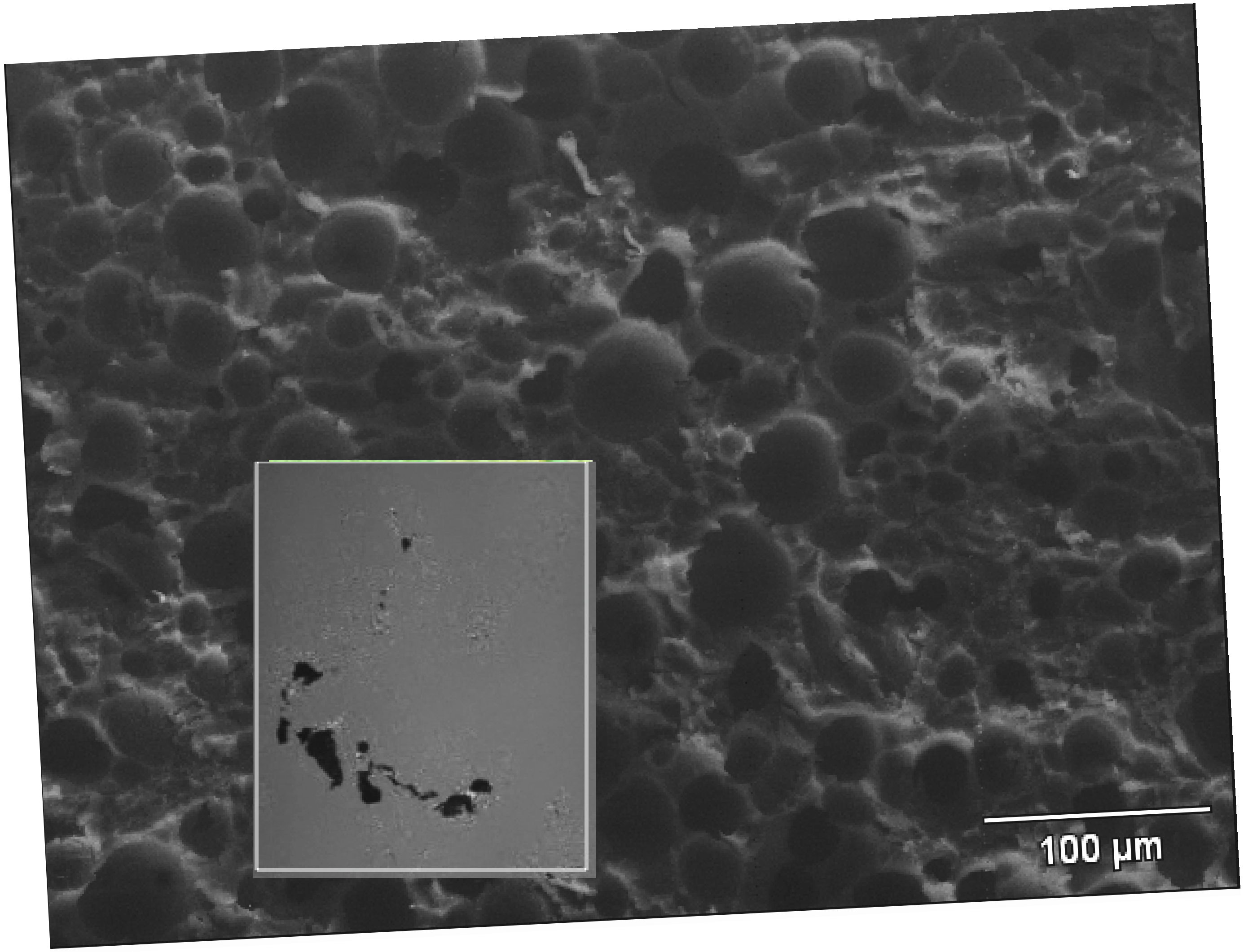
The topography on the patterned wafer surface created extra collisions with pad summits, resulting in less abrupt pad surface compared with blanket wafer polishing.

Mean Summit Curvature

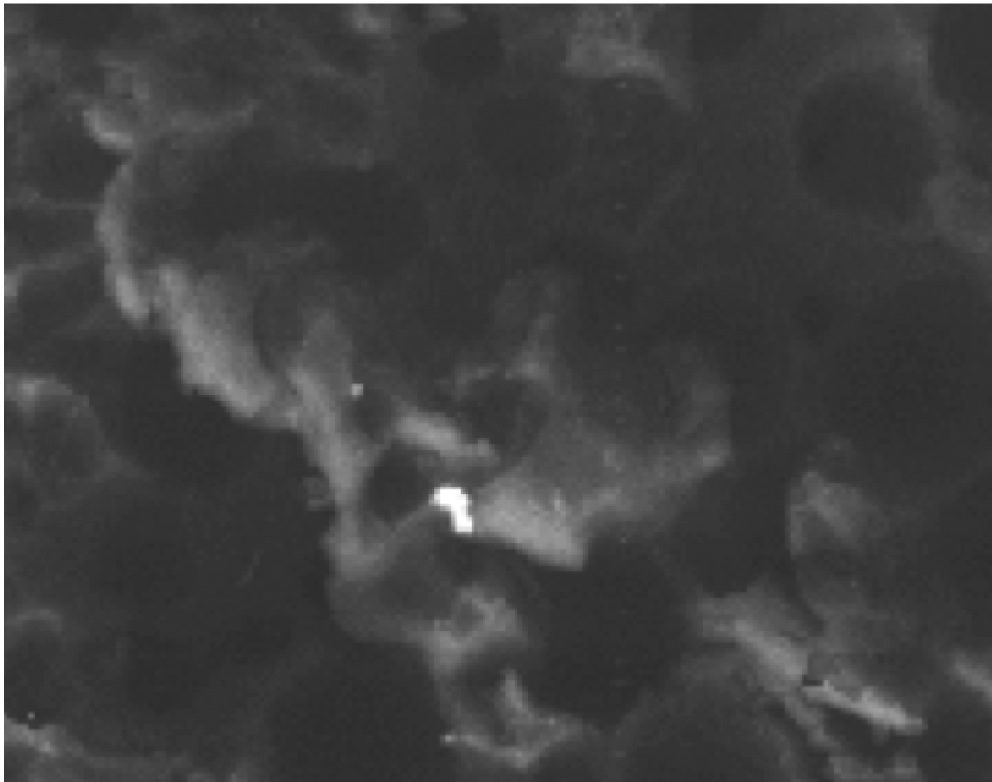


Sharper pad summits (larger summit curvature) contributed to higher dishing and erosion.

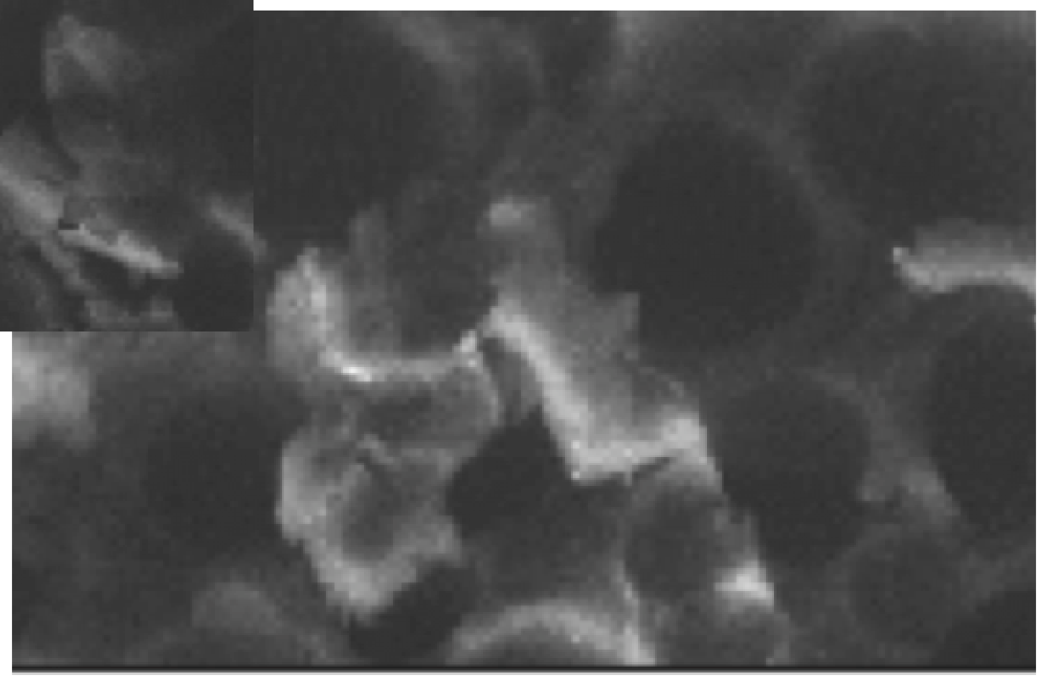
SEM, Topography and Contact Image



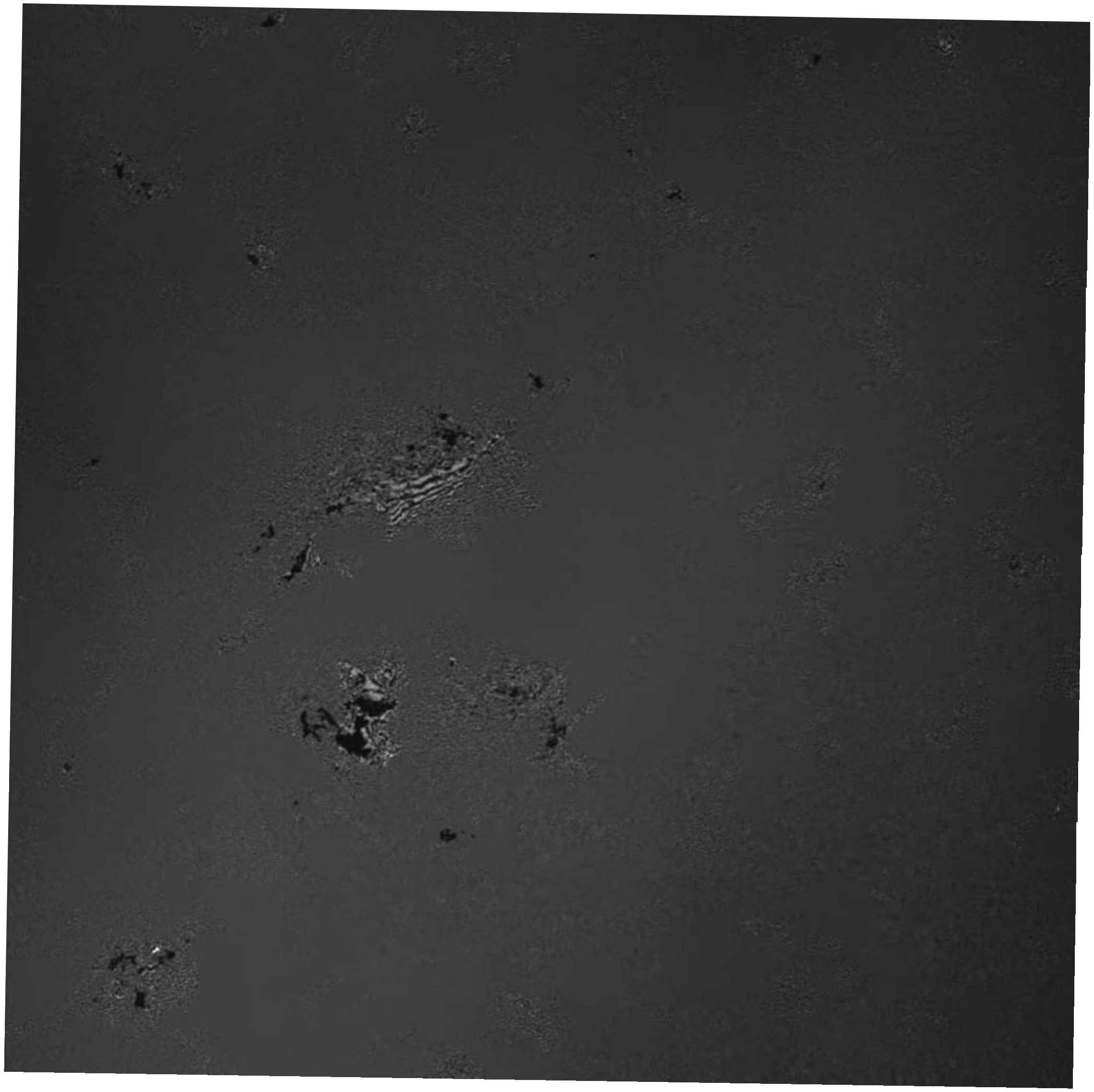
More Examples of Contact



Contacting material appears to consist of fractured and collapsed pore walls.

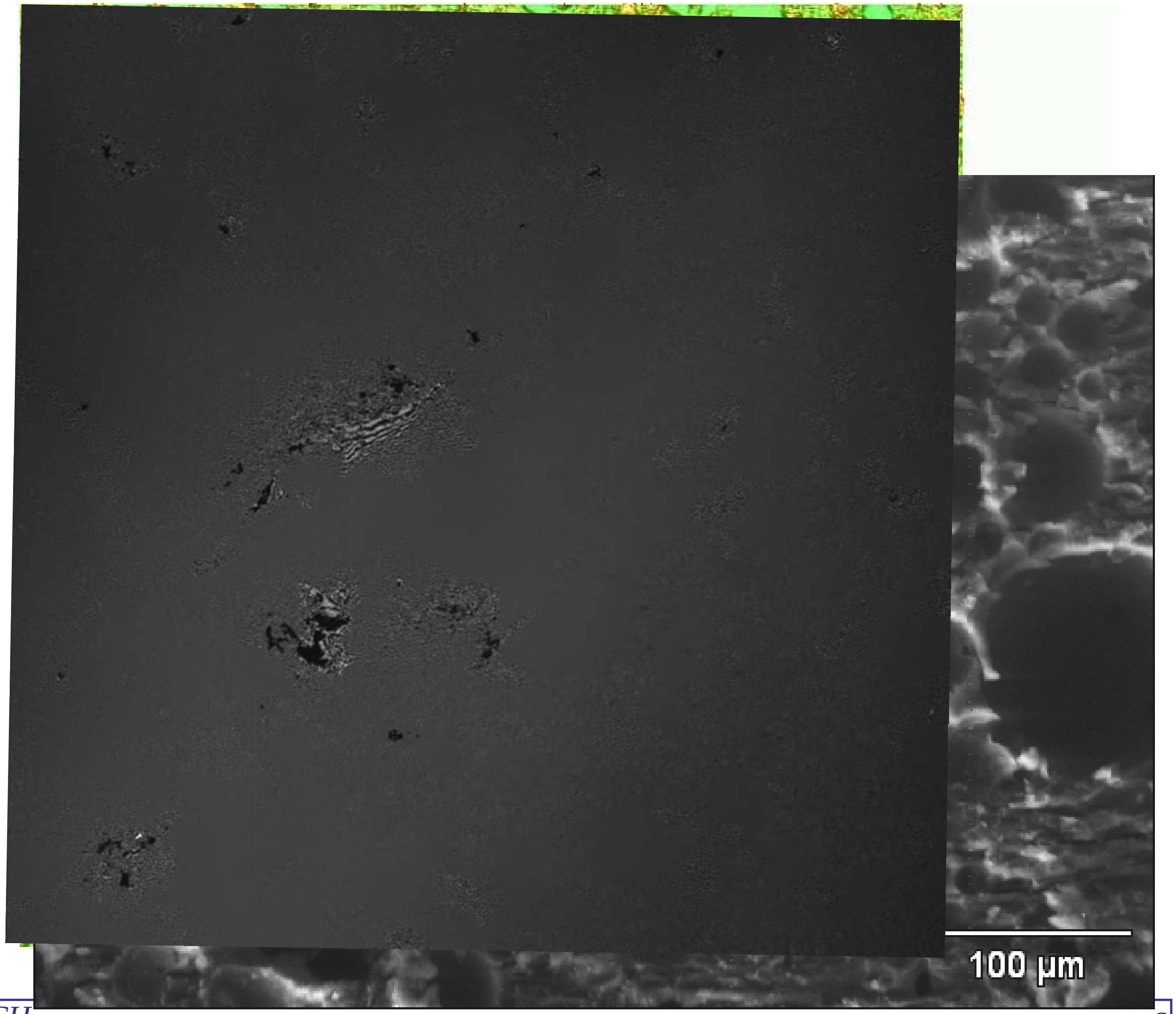


Large Contacts with Fringed Areas

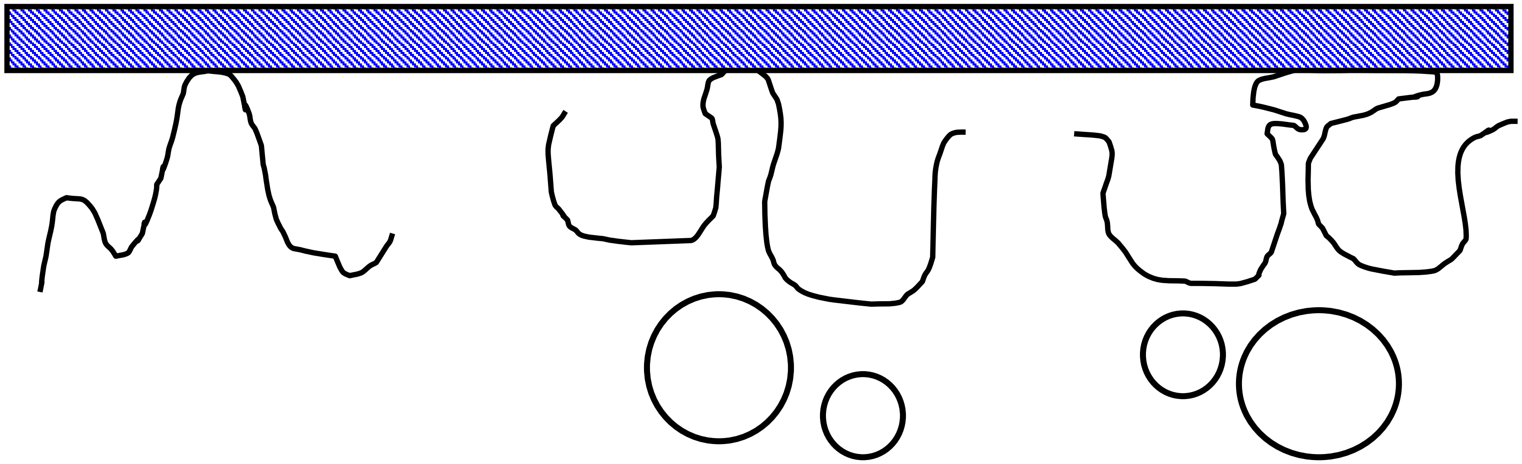


50 μm

Topography and SEM Comparison



Contacting Summit Types

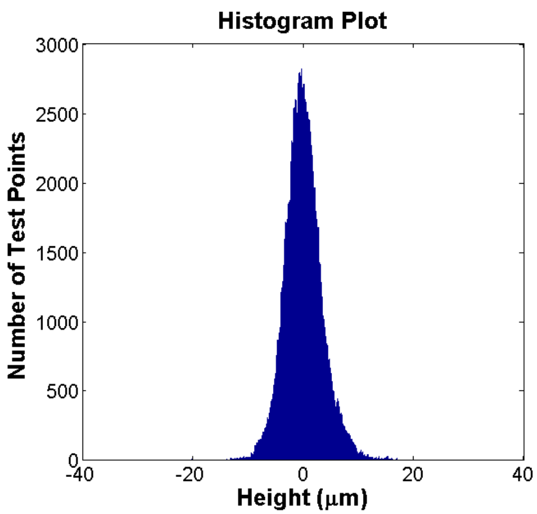


Fully supported contacting summit, solid underlying pad material.	Less well-supported contacting summit, pore-filled bulk.	Fractured, poorly supported contacting summit.
Applied force produces a small deflection and a small contact area.	Applied force produces a larger deflection but a small contact area.	Applied force produces a large, low pressure contact area.
Assumed in most rough surface contact theories.		Contact behaves like a compliant, flexible plate.
May be rare in CMP		**Very common in CMP**

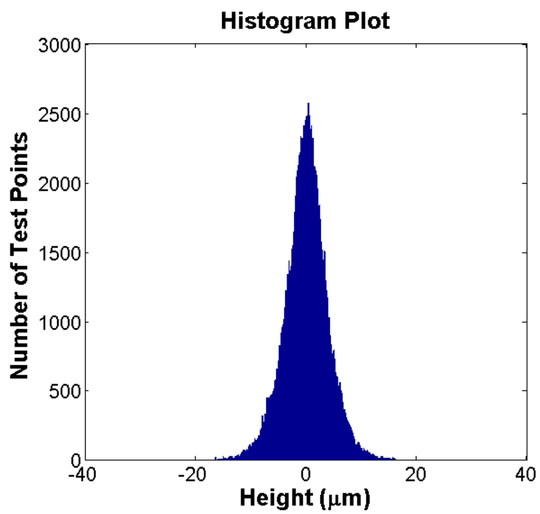
Pad Asperity Height Distribution

- Take pad samples during 16-hour polishing process
  - Initial, 8 hours and 16 hours
- Scan a 500µm by 500µm area on pad sample surface with a stylus micro profilometer

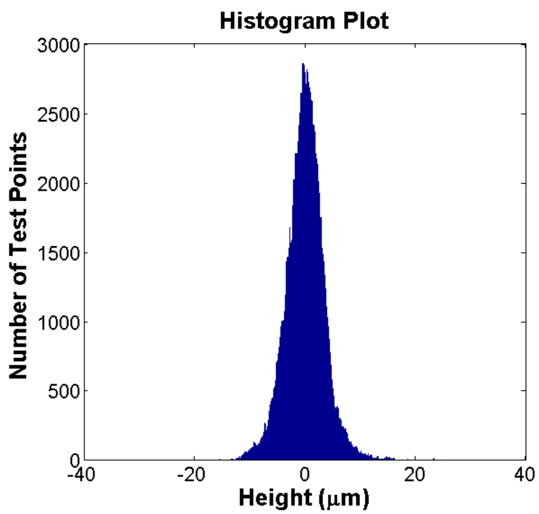
Initial



8 hours



16 hours



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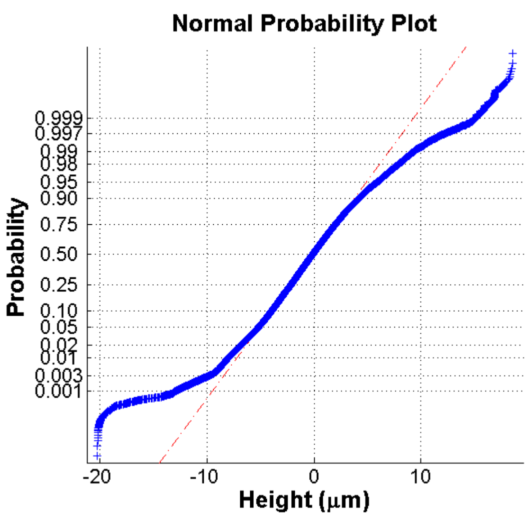
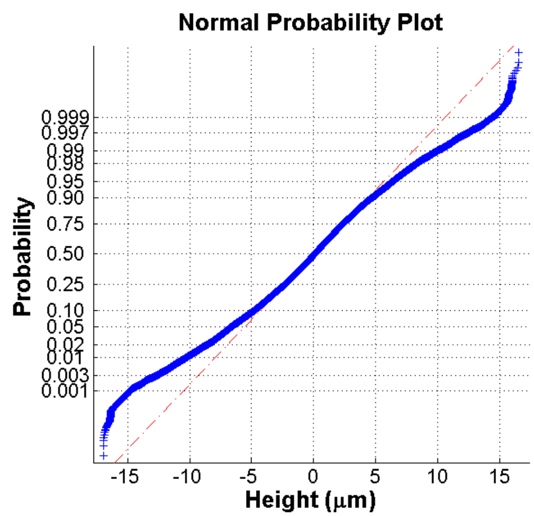
Pad Asperity Height Distribution

- **Pad asperity height range does not change significantly during 16-hour polishing**
- **Pad asperity height distribution changes during 16-hour polishing**
  - **The height distribution is symmetric on normal plot at 8 hours, but not at initial and 16 hours**
- **Asperity height distribution goes out of normal above 5 μm**

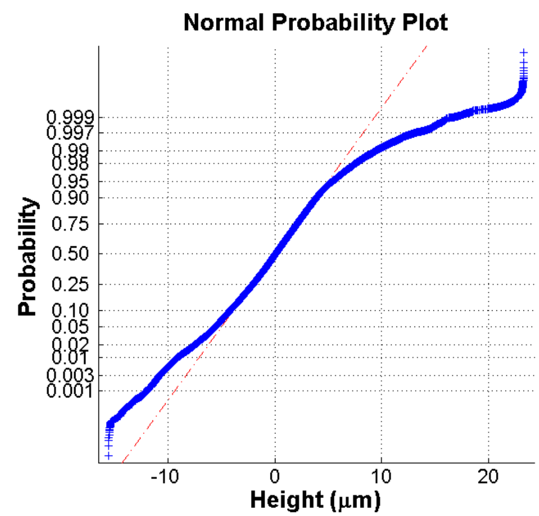
Initial



8 hours



16 hours



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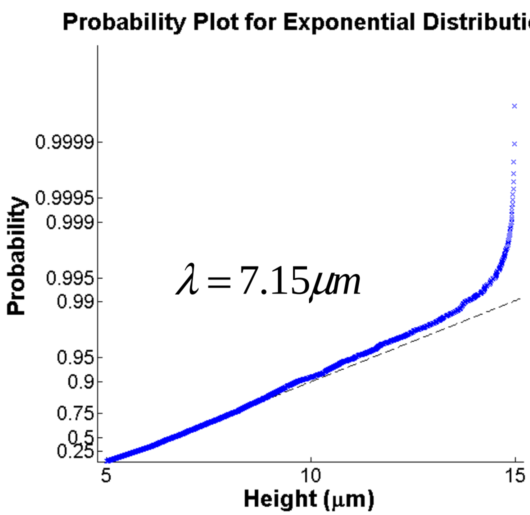
Pad Asperity Height Distribution

- **Exponential distribution fits medium high asperities (5~15μm) well**

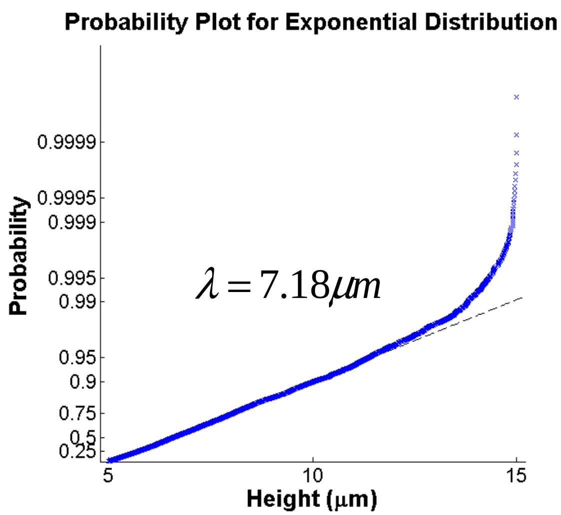
$$l(h) = \frac{1}{\lambda} e^{-\frac{h}{\lambda}} \qquad \lambda : \text{characteristic asperity height}$$

- **Characteristic asperity height does not change significantly in medium high region during 16-hour polishing**

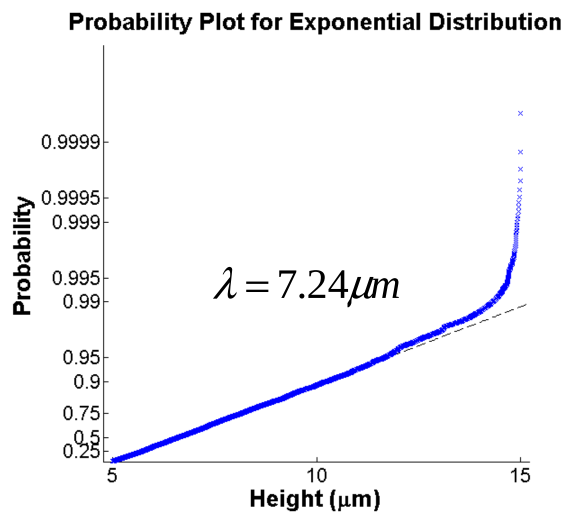
Initial



8 hours



16 hours



W. Fan (MIT)

Industrial Interactions and Technology Transfer

Industrial mentors and contacts:

- **Lenoard Borucki (Araca)**
- **Mansour Moinpour (Intel)**

Future Plans

- **Next year plan: 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 CMP processes.**

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

Publications

- **Theoretical and Experimental Investigation of Conditioner Design Factors on Tribology and Removal Rate in Copper Chemical Mechanical Planarization. L. Borucki, H. Lee, Y. Zhuang, N. Nikita, R. Kikuma and A. Philipossian. Japanese Journal of Applied Physics, 48(11), 115502 (2009).**

- **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, in press.**

- **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, in press.**

- **Effect of Pad Micro-Texture on Frictional Force, Removal Rate, and Wafer Topography during ILD/STI CMP Processes. Y. Zhuang, X. Liao, L. Borucki, J. Cheng, S. Theng, T. Ashizawa and A. Philipossian. International Conference on Planarization/CMP Technology Proceedings, 85-90 (2009).**

- **Pad Topography, Contact Area and Hydrodynamic Lubrication in Chemical-Mechanical Polishing. L. Borucki, T. Sun, Y. Zhuang, D. Slutz and A. Philipossian. Materials Research Society Symposium Proceedings, Vol. 1157, E01-02 (2009).**

Presentations

- **Effect of Pad Micro-Texture on Frictional Force, Removal Rate, and Wafer Topography during ILD/STI CMP Processes. Y. Zhuang, X. Liao, L. Borucki, J. Cheng, S. Theng, T. Ashizawa and A. Philipossian. International Conference on Planarization/CMP Technology, Fukuoka, Japan, November 19-21 (2009).**

- **The Origin and Mechanics of Large Pad-Wafer Contact Areas. L. Borucki, Y. Sampurno, Y. Zhuang and A. Philipossian. The Fourteenth International Symposium on Chemical-mechanical Planarization, Lake Placid, New York, August 9-12 (2009).**

- **Pad Topography, Contact Area and Hydrodynamic Lubrication in Chemical Mechanical Polishing. L. Borucki, T. Sun, Y. Zhuang, D. Slutz and A. Philipossian. Materials Research Society Spring Meeting, San Francisco, California, April 13-17 (2009).**

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

(*Task 425.032)*

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 data, Intel**
- **Experimental support, National Semiconductor Corporation**

Objectives

Goal: Improve fundamental understanding of CMP to

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

1. Retaining ring/wafer-level CMP modeling:

- **Evaluate within-wafer nonuniformity as function of process and tool design**
- **Retaining ring geometry: affect on edge polish uniformity**

2. Slurry agglomeration/wafer-level CMP modeling:

- **Understand how slurry abrasive particles, pad debris, and wafer debris affect agglomeration**
- **Understand how agglomeration relates to the *planarization* capability of CMP processes as well as defectivity**

ESH Metrics and Impact

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

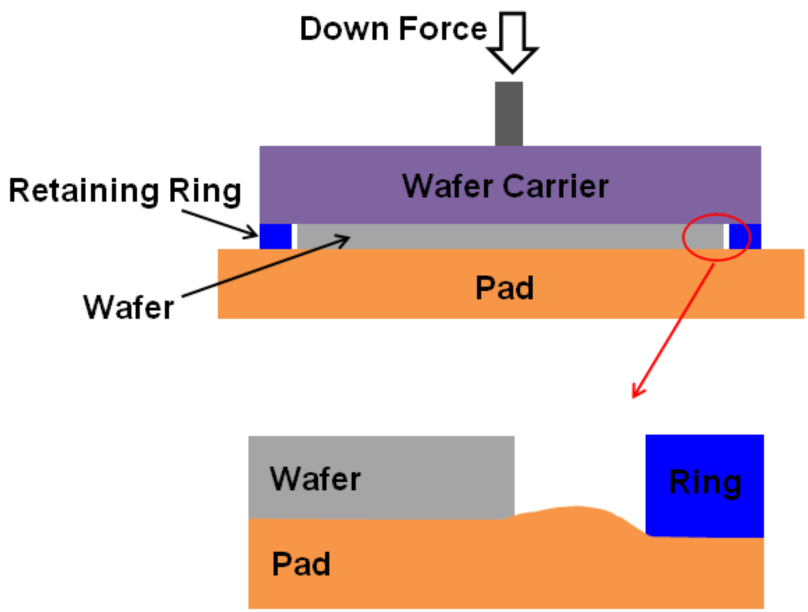
1. ***Reduction in the use or replacement of ESH-problematic materials***
2. ***Reduction in emission of ESH-problematic material to environment***
   - **Reduce slurry particle use and Cu solid waste by 20-50%**
3. ***Reduction in the use of natural resources (water and energy)***
   - **Shorten CMP 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%**

1. Retaining Ring/Wafer-Level CMP Model

- Evaluate Within-Wafer Polish Non-Uniformity
  - Pressure distribution is highly non-uniform near the wafer edge
  - The non-uniform removal rate causes a roll-off profile at wafer edge
- Investigate the Impact of CMP Tool System
  - Retaining ring geometry and design
  - Relative velocity affected by wafer speed, pad speed and polishing head position

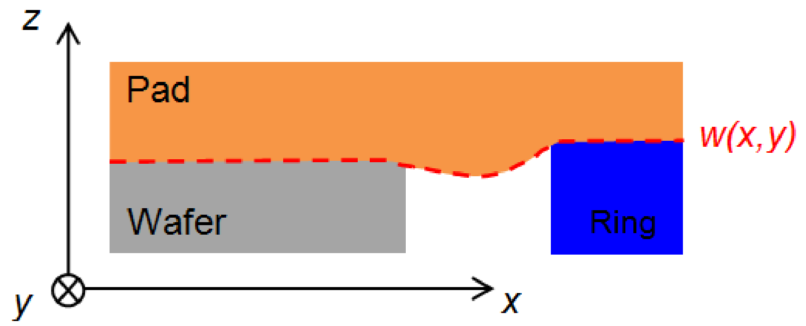
Modeling of Pressure Distribution

- Non-uniform pressure distribution results from the discontinuities of the process tool geometry at the wafer edge
- The retaining ring is usually under higher pressure to prevent the wafer from slipping out
- The pad bends around the wafer edge due to the existence of the gap and retaining ring
- Wafer edge pressure can be tuned by the ring pressure



Modeling of Pressure Distribution Cont'd

- **The pad can be treated as an elastic body**
- **Wafer and retaining are both rigid**
- **The relationship between pad deformation and wafer/ring surface topography can be calculated using a contact wear model**



Pad Surface Displacement

$$w(x,y) - w_0 = F(x,y) \otimes P(x,y)$$

Point Pressure Response

$$F(x,y) = \frac{1}{\pi E}\int d\xi \int d\eta \frac{1}{\sqrt{(x-\xi)^2 + (y-\eta)^2}}$$

E: pad effective modulus

Boundary Conditions

$$\begin{cases} P(x,y) \geq 0 \\ \frac{1}{S_0}\int_{wafer} P(x,y)\cdot dx \cdot dy = P_0 \\ \frac{1}{S_r}\int_{ring} P(x,y)\cdot dx \cdot dy = P_r \\ w(x,y) \geq z(x,y) \end{cases}$$

Pressure can not be negative

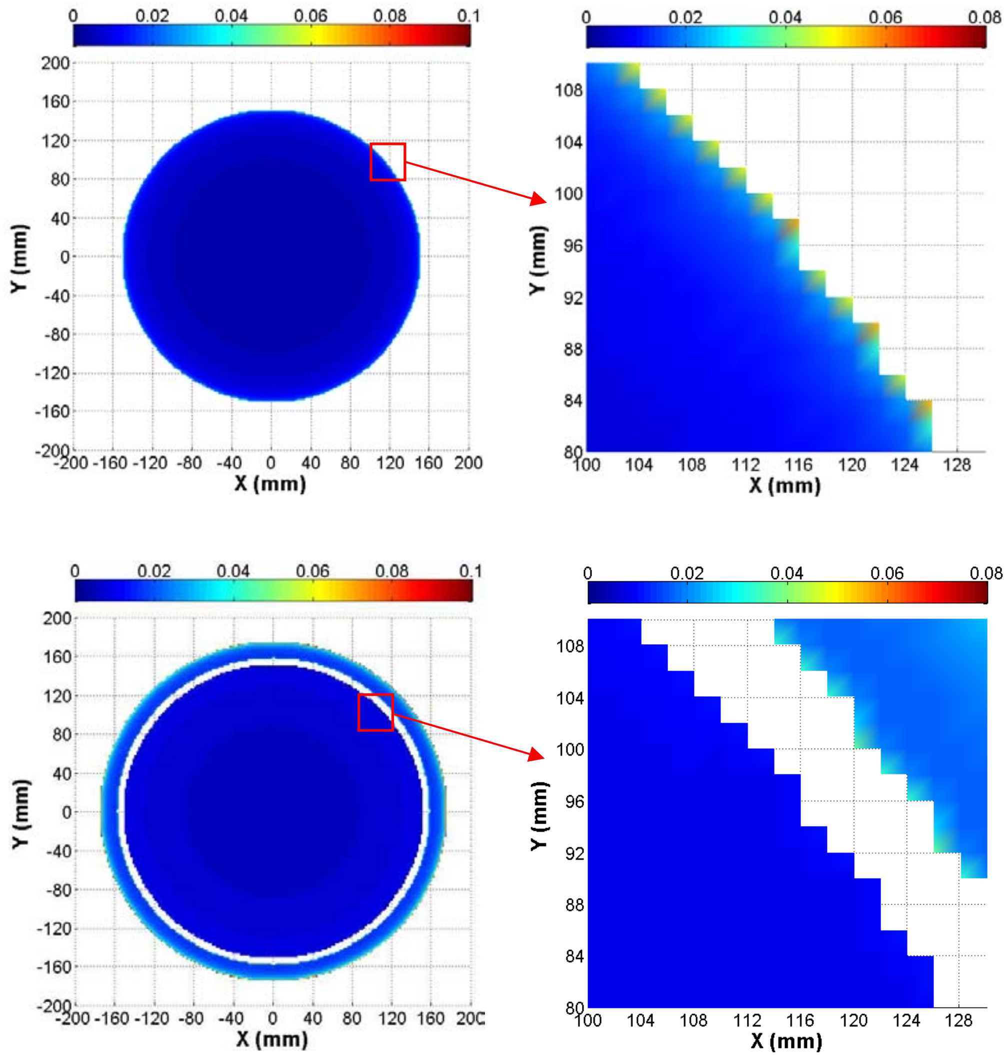
Average wafer pressure equals to wafer reference pressure

Average ring pressure equals to ring reference pressure

$z(x, y)$: surface of wafer and ring structure

Retaining Ring Effect on Wafer Edge Pressure

- **300mm flat wafer surface pressure (MPa) without and with retaining ring**
- **Assumptions of the simulation:**
  - **Pad effective modulus: 100MPa**
  - **Wafer reference pressure: 1psi**
  - **Ring reference pressure: 4psi**
  - **Ring width: 20mm**
  - **Gap between ring and water: 4mm**
- **Wafer edge pressure is tuned by the retaining ring**
  - **No pressure concentration at wafer edge when retaining ring is applied**



Modeling of Relative Velocity

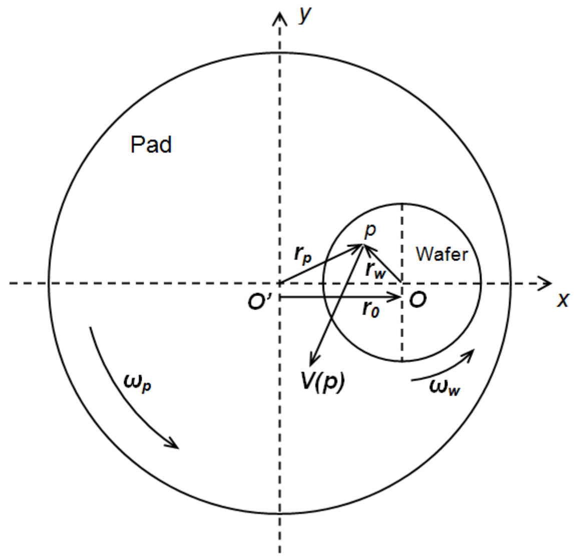
- **The instantaneous velocity distribution is a function of the configuration of the CMP machine**

$$\vec{V}(p) = -\omega_p(\vec{k}\times\vec{r}_0) + (\omega_w - \omega_p)(\vec{k}\times\vec{r}_w)$$

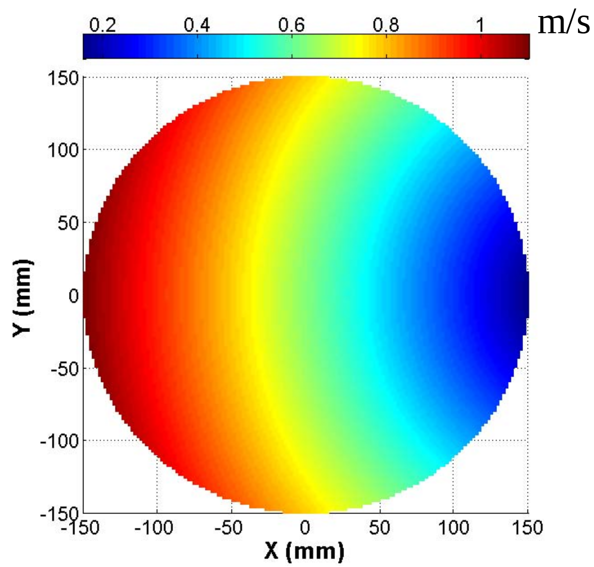
ω_w : wafer angular velocity

ω_p : pad angular velocity

$\vec{k}$: unit vector perpendicular to the rotation plane



- **Assumptions of the simulation:**
  - **300mm wafer**
  - **Pad rotation speed: 30rpm**
  - **Wafer rotation speed: 60rpm**
  - **Offset distance between pad and wafer centers: 200mm**



Next Steps – Wafer-level CMP Model

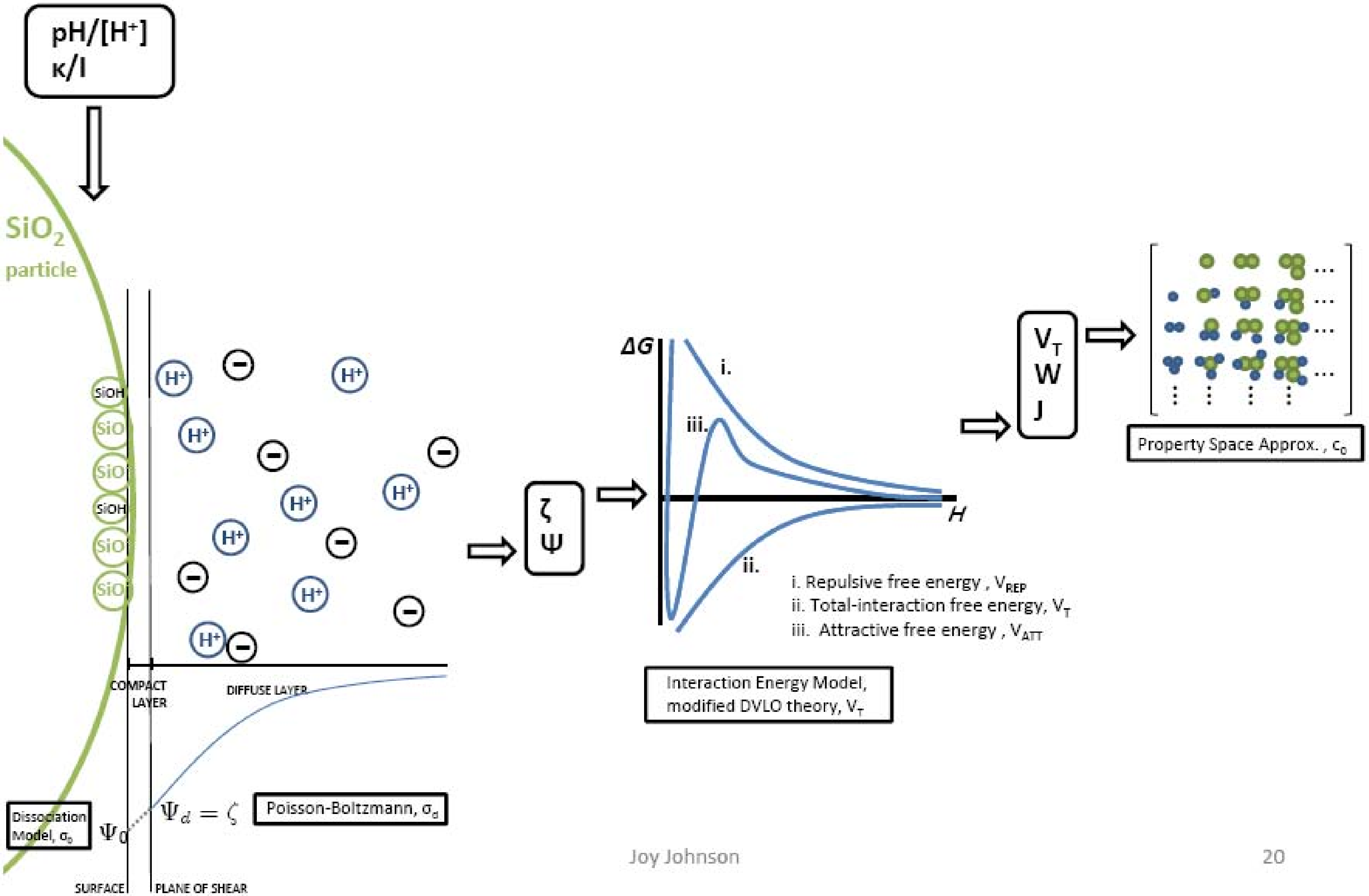
- **Integrate wafer-level model for conditioning**
  - **Geometric dependencies in pad surface microtexture generation/modification based on conditioning kinematics**
- **Model slurry dynamics**
  - **Based on wafer edge and across-wafer pressure profiles, relative velocity kinetics, and pad microtexture**
- **Integrate wafer-level with die-level CMP model**
  - **Understand and capture wafer level polish rate and slurry/pad-surface nonuniformity impacts on chip uniformity and feature planarization**
  - **Optimization studies: pad/process/tool to reduce consumables, time, cost and improve performance**

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 the *planarization* capability of CMP processes as well as 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**

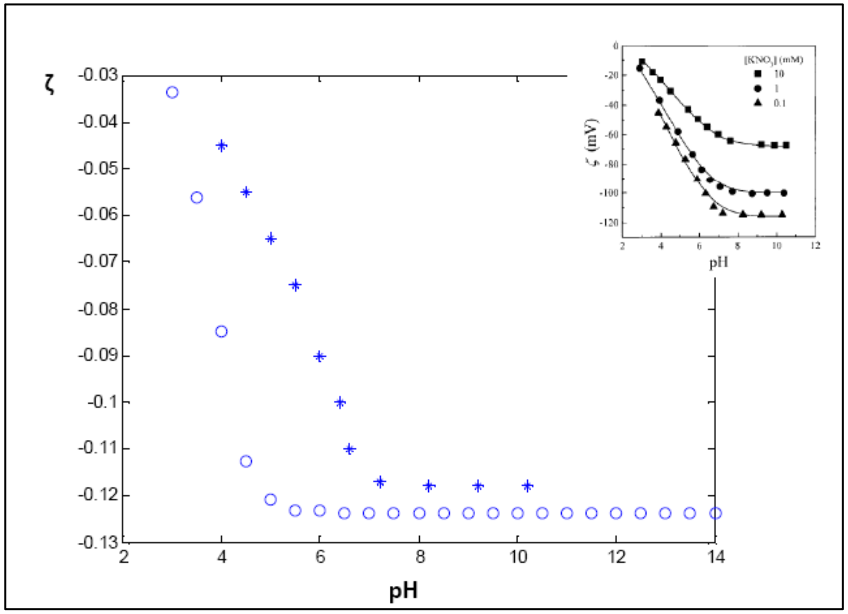
Initial Agglomeration Model



SRC/SEMATECH Engineering Research Center for Environmentally Benign Semiconductor Manufacturing

Initial Agglomeration Model

- Model to predict the zeta potential in order to correlate chemical parameters to slurry stability. (Comparison to published data shown at right.)



- Framework for calculating probable agglomerate size distribution and possible planarization efficiency:

pH
Ionic Strength
Particle
Size/Concentration

→ (1) Surface Charge, Ψ
Zeta Potential, ζ

→ (2) Total Interaction
Energy, V_T

→ (3) Stability Ratio
Of Agglomeration, W

→ (4) Agglomeration
Rate, J
*Particle Size/
Concentration

Next Steps – Slurry Agglomeration Model

- **Agglomeration model verification/improvement:**
  - Account for slurry particles, pad 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 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

Industrial Interactions and Technology Transfer

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

- **National Semiconductor**
  - **Experimental support for die-level CMP model improvements**

Publications, Presentations, and Recognitions/Awards

1. Fan, W., D. Boning, L. Charns, H. Miyauchi, H. Tano, and S. Tsuji, "Study on Hardness and Conditioning Effects of CMP Pad Based on Physical Die-level CMP Model," accepted in Journal of the Electrochemical Society, Dec. 2009.
2. D. Boning and J. Johnson, "Slurry Particle Agglomeration Model for Chemical Mechanical Planarization (CMP)," to be presented, CMP Symposium, MRS Spring Meeting, April 2010.

Students on Task 425.032

- **Graduated Students and Current Affiliation**

- **Current Students and Anticipated Grad Date**
  - Wei Fan (Ph.D.), June 2011
  - Joy Johnson (Ph.D.), June 2012

- **Internships**
  - Joy Johnson, summer 2009, Intel Corporation (Hillsboro, Oregon)