Characterization and Modeling of CMP Pad Asperity Properties

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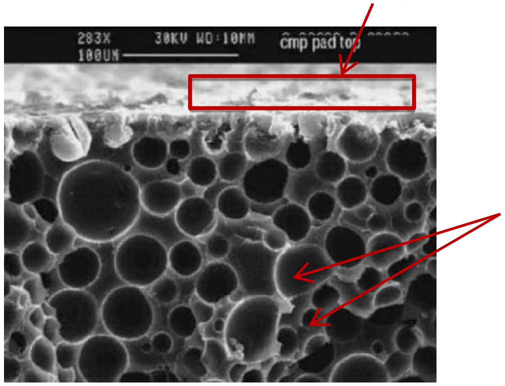
CMP System and Consumables

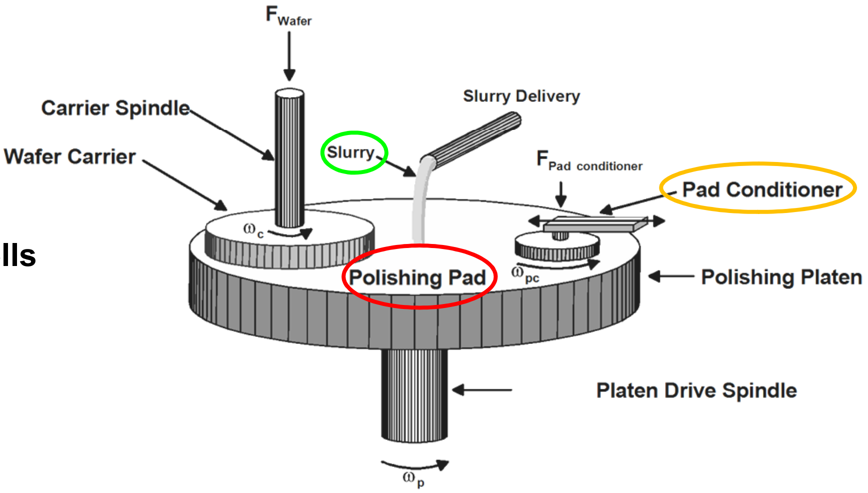
IC1000 pad grooves

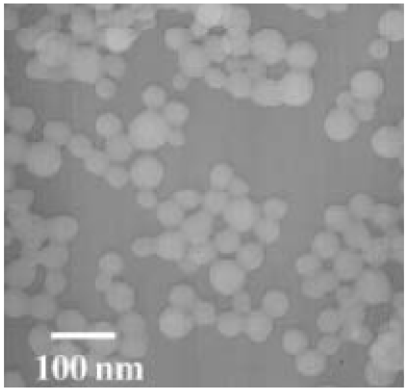


Surface Asperities

Cells

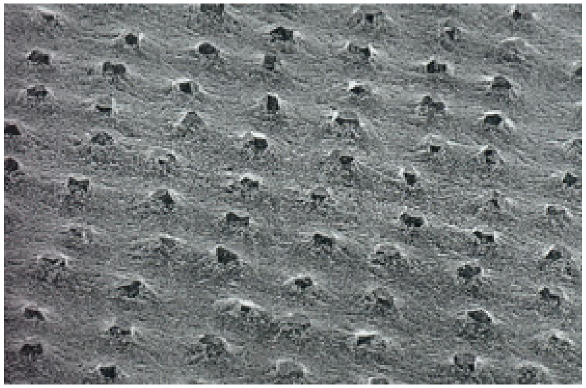
IC1000 pad micro structure





Abrasive particles in slurry

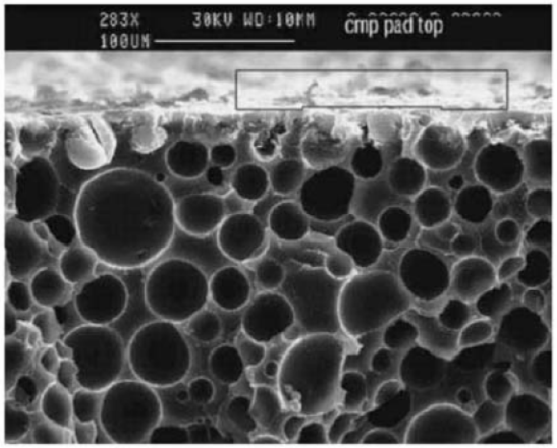
Conditioning disk



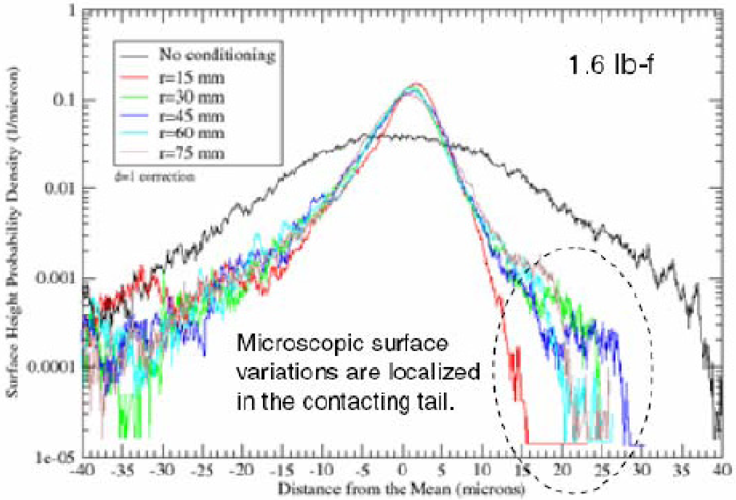
Diamonds on conditioning disk

Polishing Pad Properties

- Polishing pad is typically made of polyurethane
- Pad is designed to
  - Provide elastic response
  - Transport slurries
- Pad surface
  - Consists of asperities with range of sizes around 50μm
  - Tail of the pad surface height is ≈ exponentially distributed



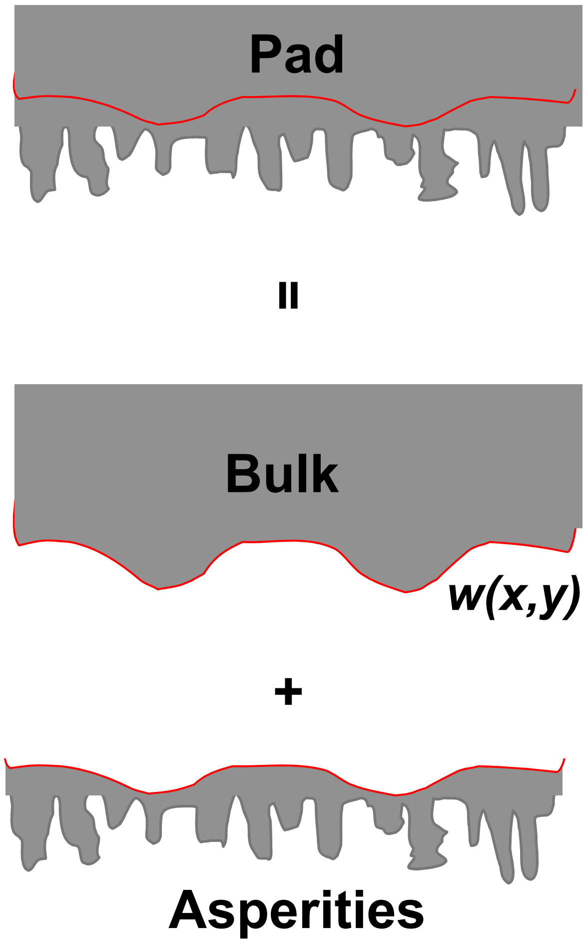
SEM of conditioned pad
L. Borucki, 2004



Surface Height Distribution
L. Borucki, 2006, ICPT

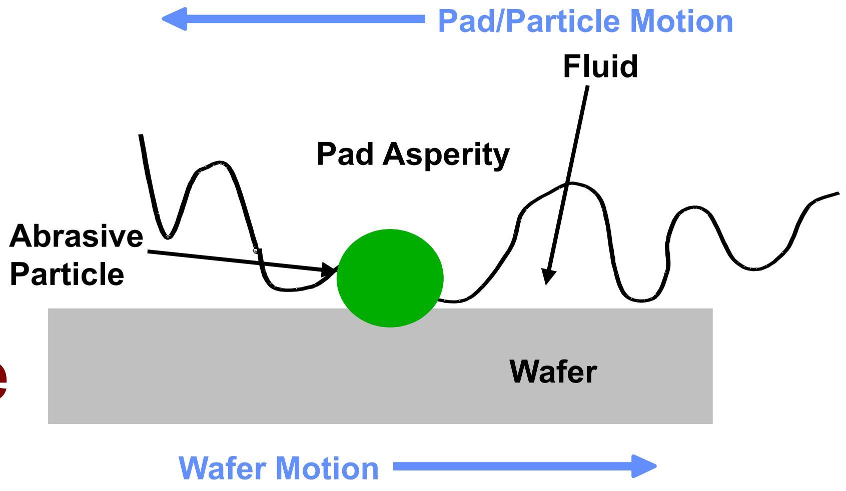
Pad Response Model: Bulk and Surface

- Pad is assumed to consist of a bulk material and asperities
- Bulk material is assumed to be elastic
  - Model with effective pattern density
- Asperities are assumed to
  - Observe Hook’s law, i.e., the force asperity exerts is proportional to its compression
  - Have a statistical distribution of asperity heights



Pad-Wafer Interaction: Contact-Based Removal Mechanisms

- Material removal is believed to be due primarily to 3-body contact
- Surface modification by the slurry is necessary
- Different nanoscale removal mechanisms have been proposed
  - Indentation models
  - Chemical tooth models
  - Pressure-driven dissolution models

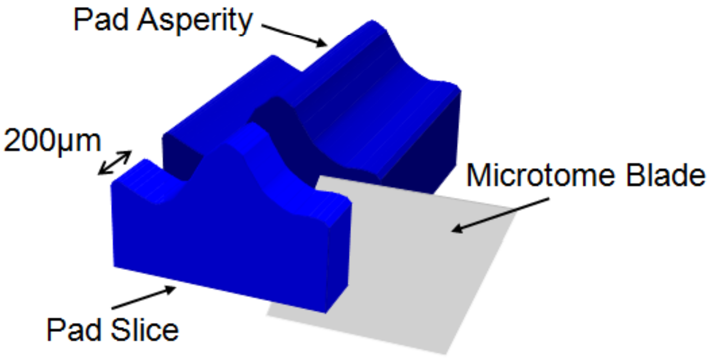


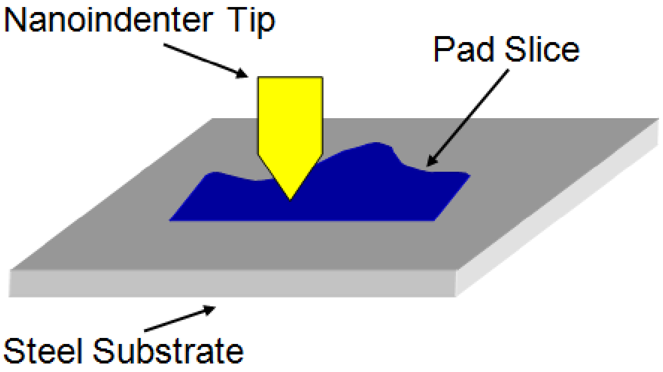
Outline

- Physical measurements of CMP pad properties
  - Pad modulus
  - Asperity height distribution
- Pad aging experiment and property tests
  - Cu wafer polishing and pad sample collection
  - Time dependence of pad properties
  - Spatial variation in pad properties
- Model for pad-wafer contact
  - Based on mechanical response of pad asperity
  - Assumptions and mathematical derivation
  - Contact area and pressure predictions and trends
- Conclusions and future work

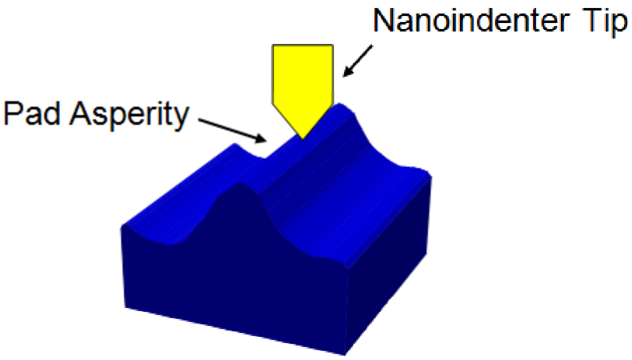
Pad Modulus Measurement: Nanoindentation

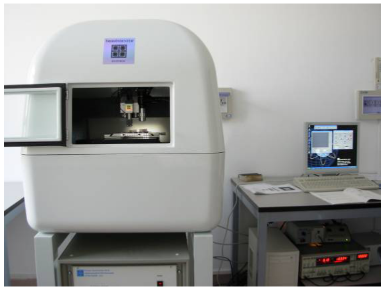
- **Pad slice nanoindentation:**





- **Pad asperity nanoindentation:**





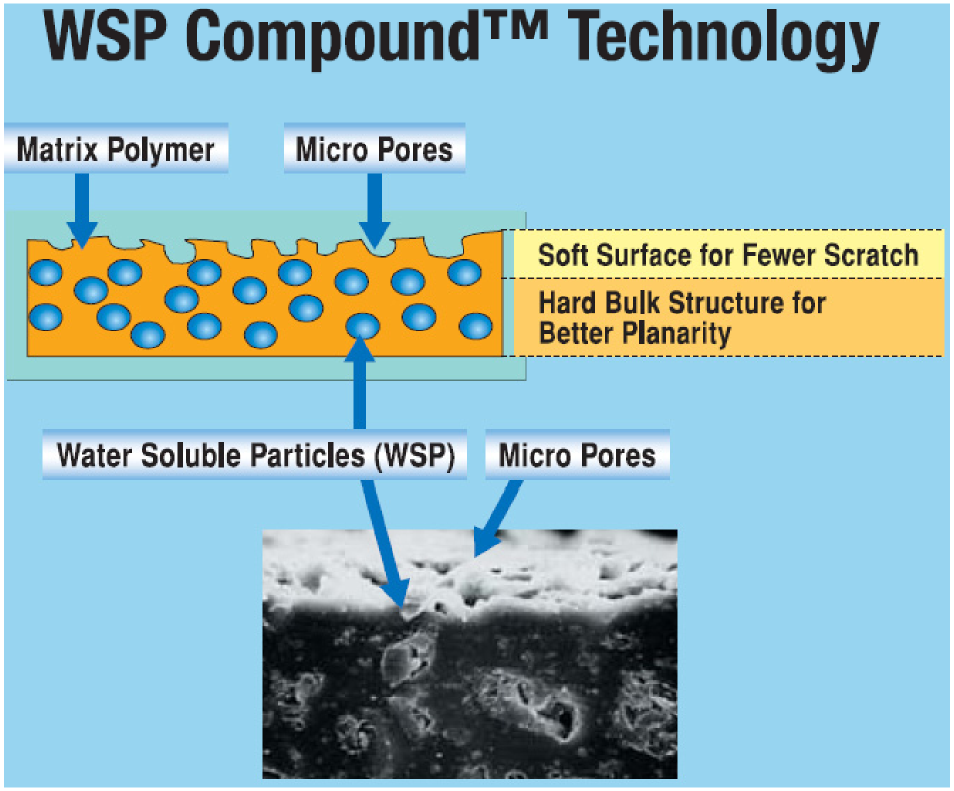
Hysitron TriboIndenter

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 Sample

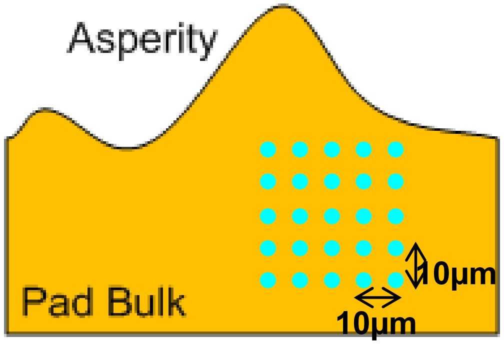
- JSR water soluble particle (WSP) pad
  - Soft surface for less scratch
  - Hard bulk consist of soft matrix and WSP for better planarization
  - Surface porosity controlled by WSP size



http://www.jsr.co.jp/jsr_e/pd/images/pad.pdf

Pad Slice: Contour Plot of Reduced Modulus

Test Pattern: slice, multiple points



Pad Sample

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

1st test

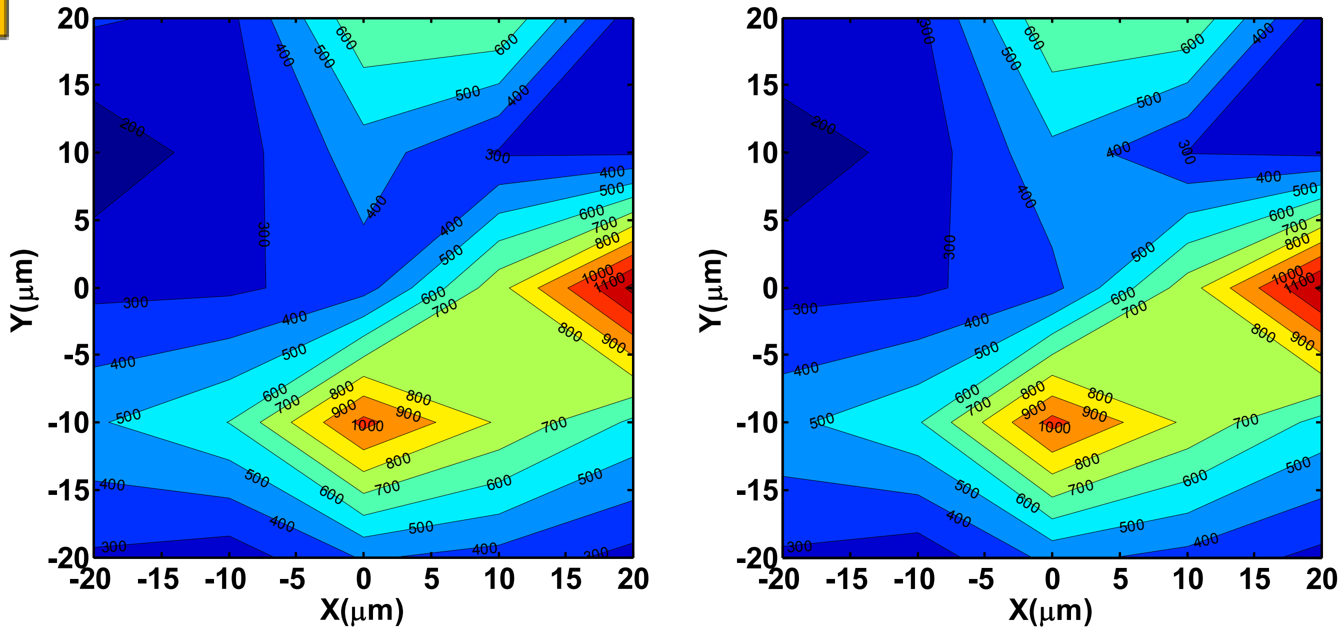
Mean: 462.69MPa

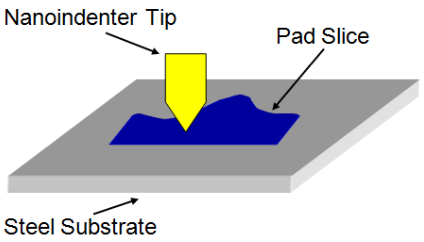
Standard Deviation: 272.44MPa

2nd test (same position on the sample)

Mean: 460.93MPa

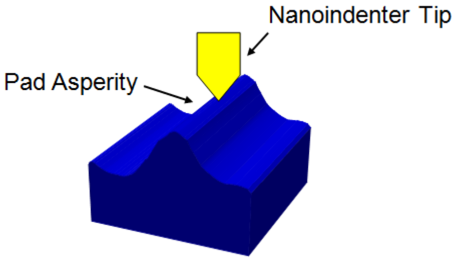
Standard Deviation: 270.58MPa

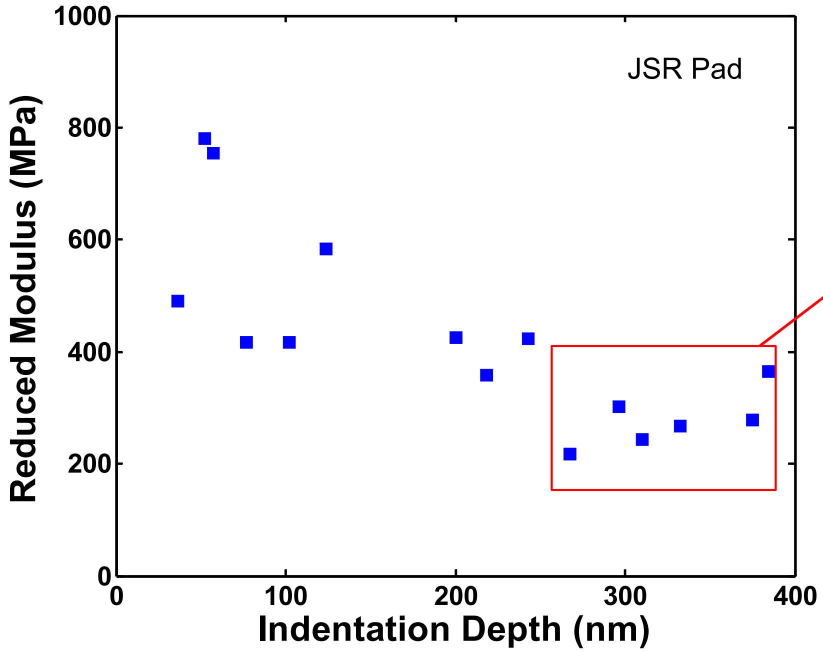


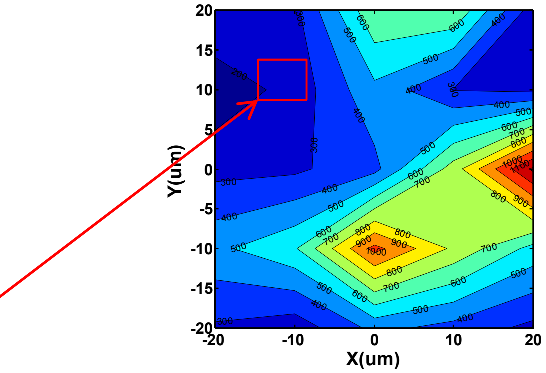


- There is spatial variation in pad mechanical properties

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)

Apparent Stiffness of Polymer Surfaces under Contact (Tweedie et al.)

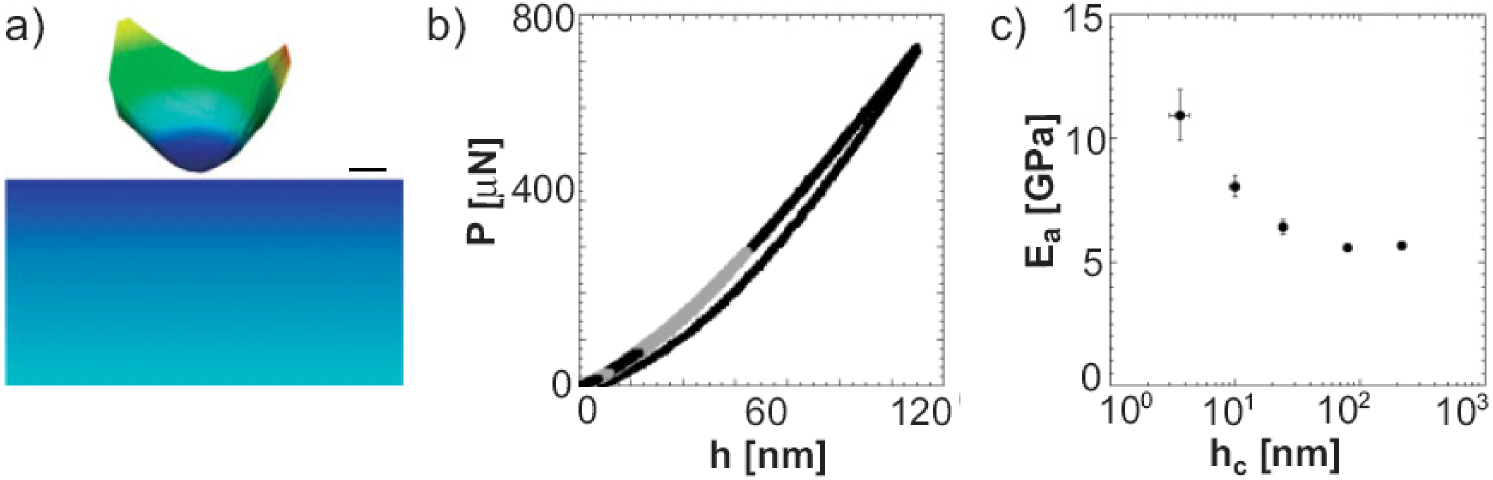
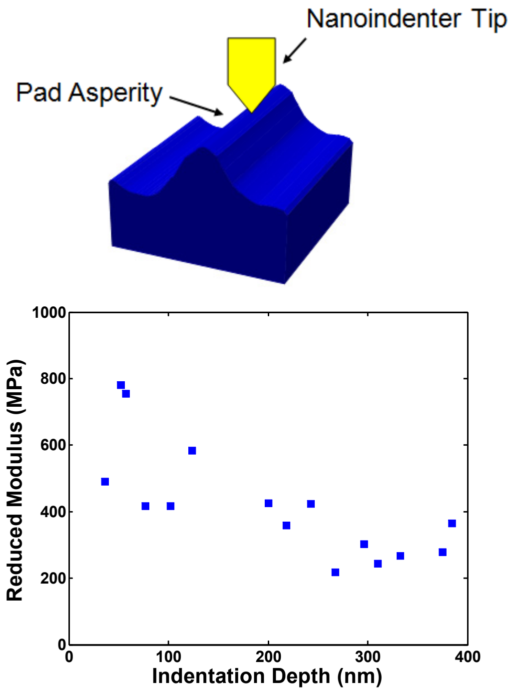


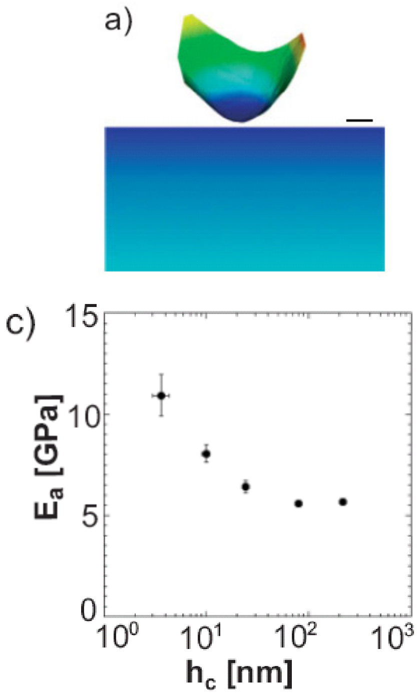
Figure 1. Apparent stiffness of polymer surfaces under contact. a) Schematic of a nanoindentation probe (image reconstructed from atomic force microscopy, scalebar = 500 nm) approaching an amorphous polymer surface with higher molecular mobility over the first ~40 nm from the surface. b) Representative indentation load-displacement curves to five maximum loads P corresponding to a range of indentation depths h are displayed alternately in black and grey. c) The indentation elastic modulus E increases with decreasing indentation depth h_c in compression molded polystyrene, molecular weight M_w = 12 kg/mol. Error bars represent one standard deviation and may be smaller than the symbol.

C. Tweedie et al., Adv. Mat., 19, 2540-2546, 2007.

Depth Dependence of Asperity Modulus



Boning and Fan, MRS Spring Meeting, April 2010.

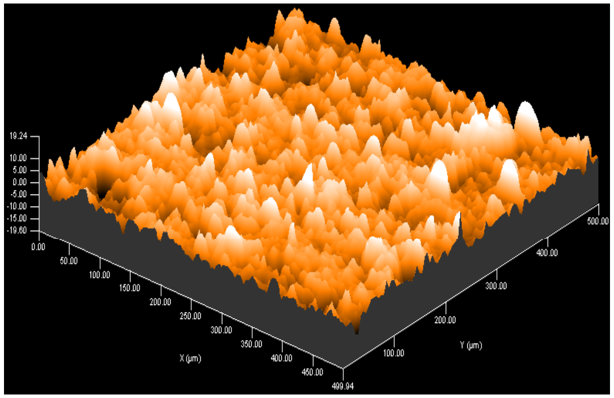


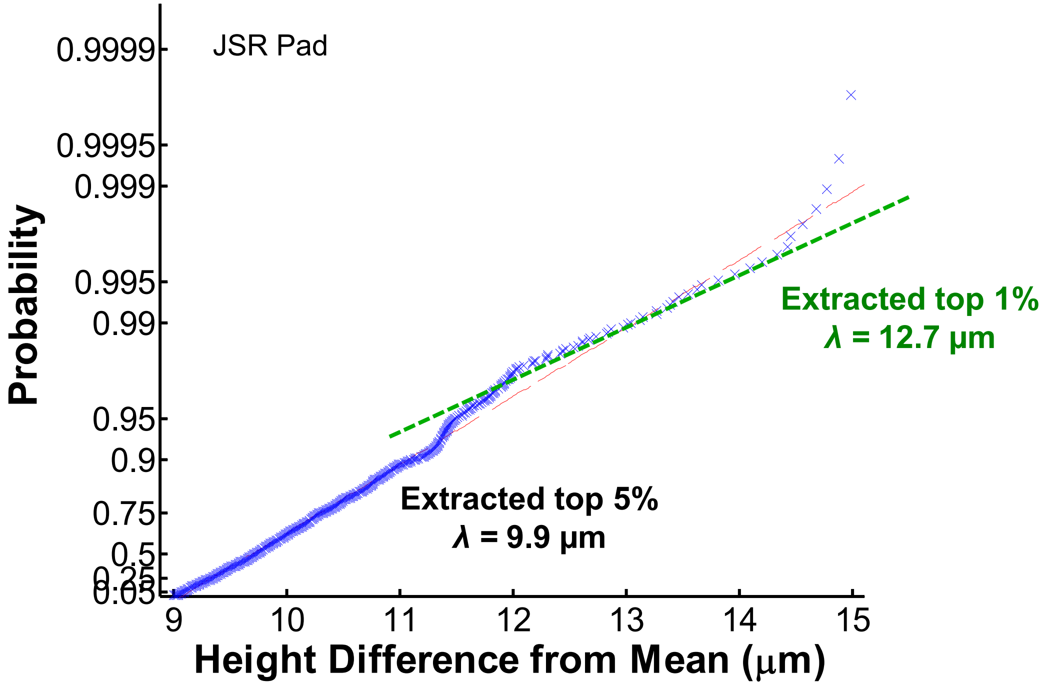
C. Tweedie et al., Adv. Mat., 19, 2540-2546, 2007.

- Surface structure effect or material property
  - Needs to be verified by experiments: e.g., flat pad sample test

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 0.02%). We ignore these.
  - Possibility of a **bimodal** (exponential) distribution; useful to extract both.

Outline

- Physical measurements of CMP pad properties
  - Pad modulus
  - Asperity height distribution
- ➡ Pad aging experiment and property tests
  - Cu wafer polishing and pad sample collection
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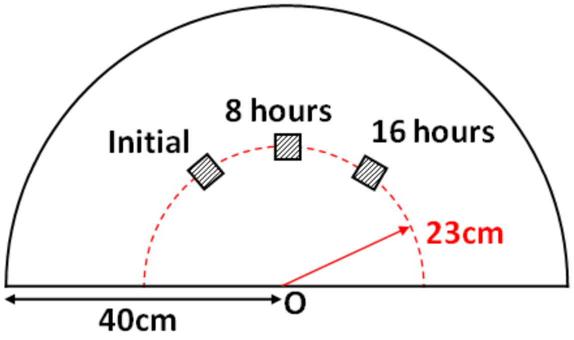
Pad Aging Study

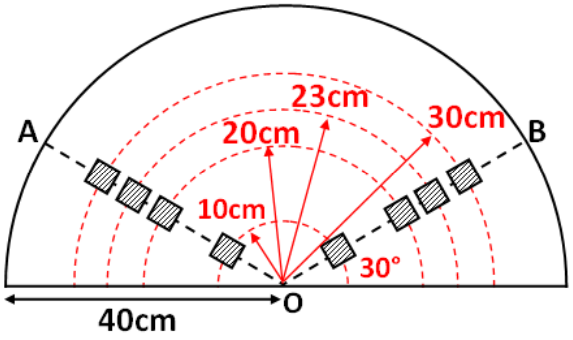
- Motivations
  - Understand how pad properties change during CMP process
  - Evaluate pad conditioning effect
- Physical measurements of pad properties
  - Asperity reduced modulus: nanoindenter
  - Asperity height distribution: micro profilometer
  - Pad groove depth: microscope and positioning system on nanoindenter

Pad Aging Experiment

- Cu wafer polishing with JSR WSP pad
  - Polisher: Araca APD-800
  - Polishing head speed: 25 rpm
  - Reference pressure: 1.5 psi
  - Condition head speed: 95 rpm
  - Conditioner down force: 8 lbF
- Pad sample collection
  - **Aging samples:**
  - **Spatial samples after 16 hours:**



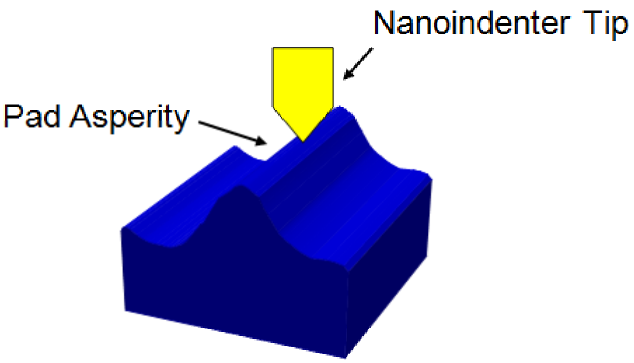
Sample size: 2.5cm×2.5cm

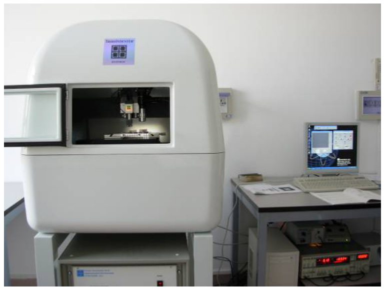


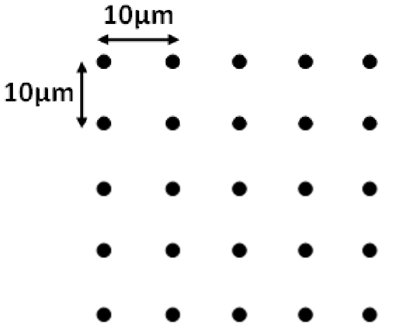
Sample size: 1.5cm×1.5cm

Pad Properties:
Pad Asperity Indentation

- **Pad asperity nanoindentation:**



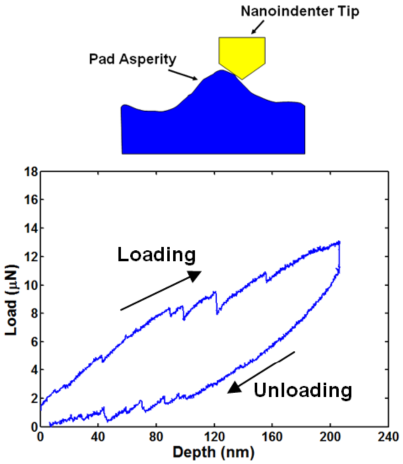

Hysitron TriboIndenter



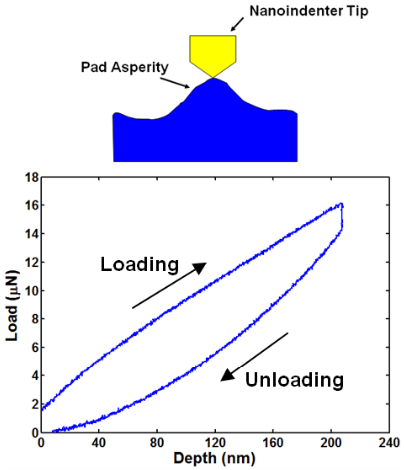
Test Pattern Applied

- **Indentation curves:**

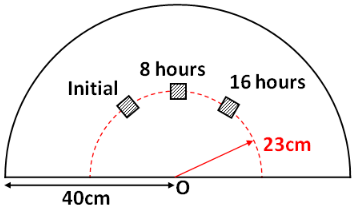
Failed test: indenter tip sliding

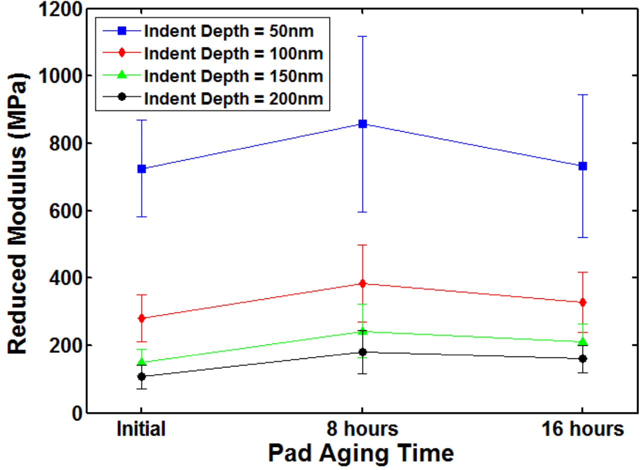


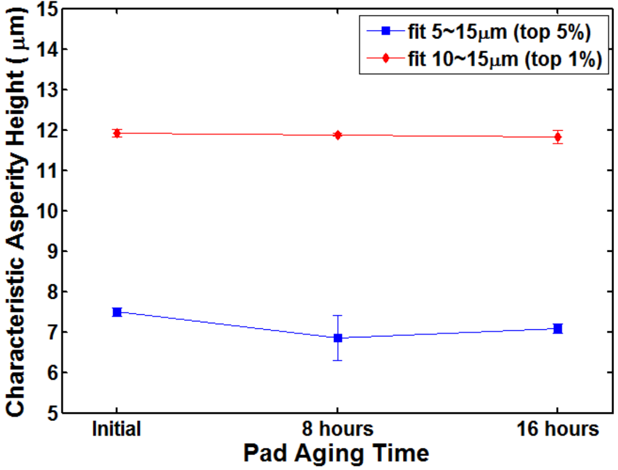
Successful test: solid contact

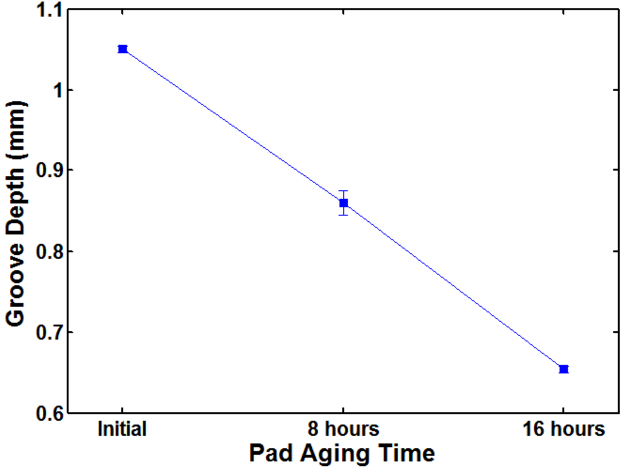


Pad Aging Results



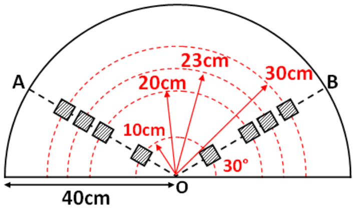

Asperity Modulus


Asperity Height

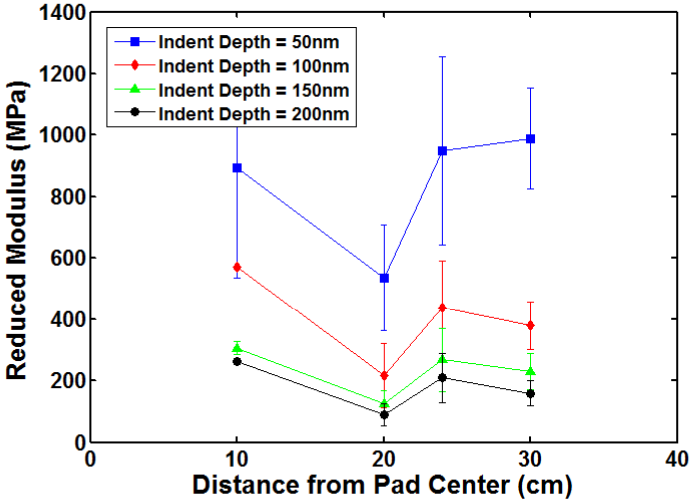

Groove Depth

- **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**

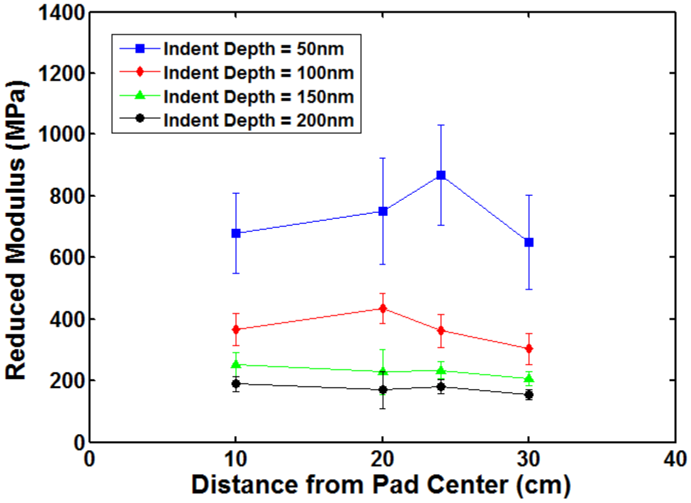
Spatial Results: Asperity Modulus



OA direction:

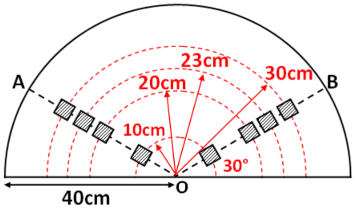


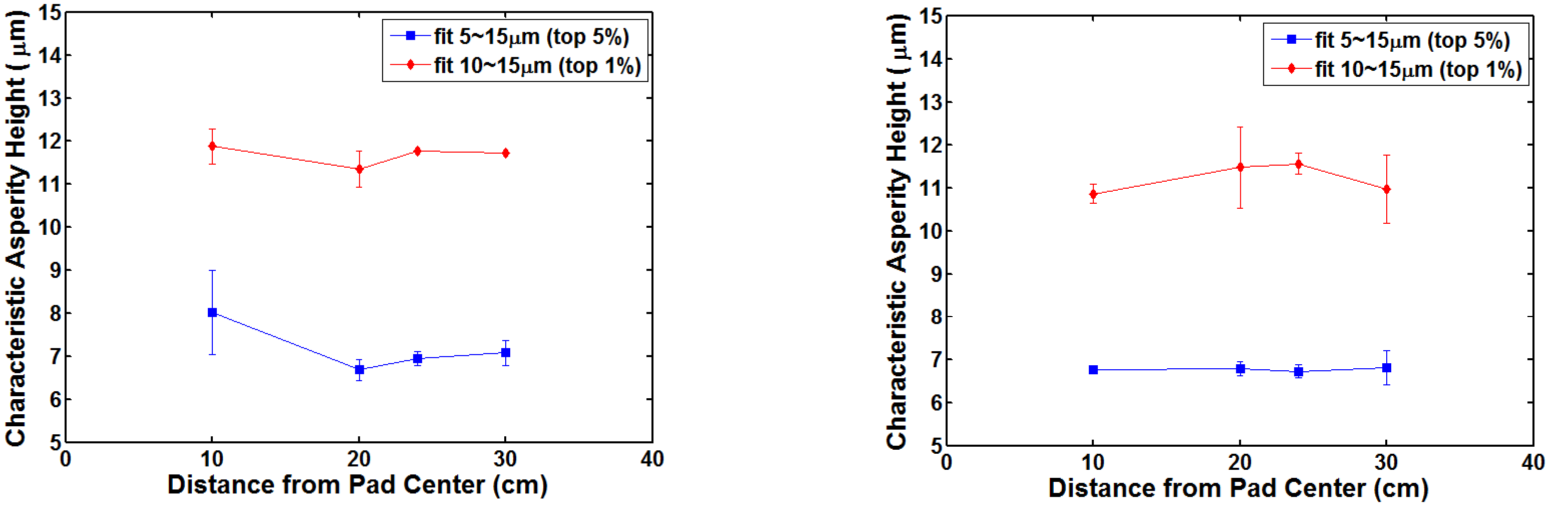
OB direction:



- **No clear 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





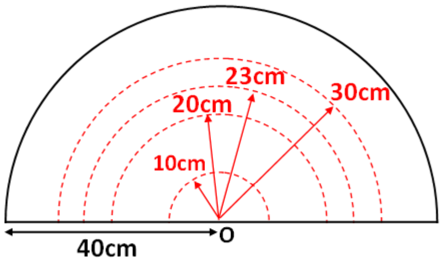
OA direction:

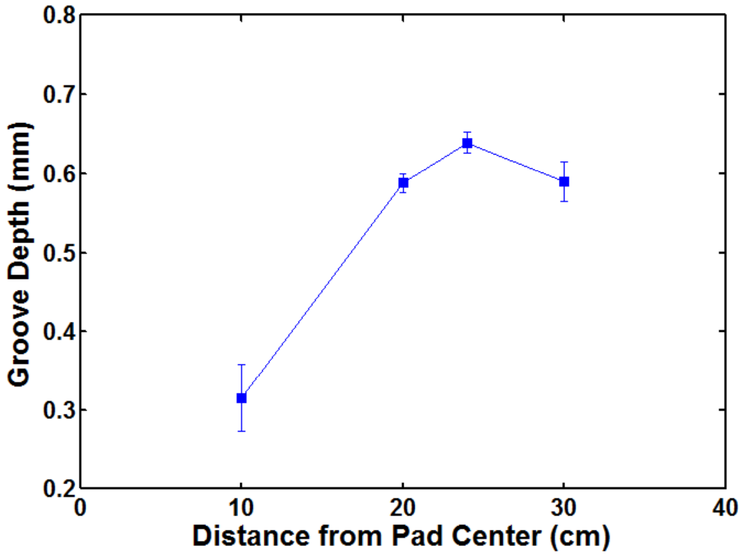
OB direction:

After 16 hours polishing (with conditioning)

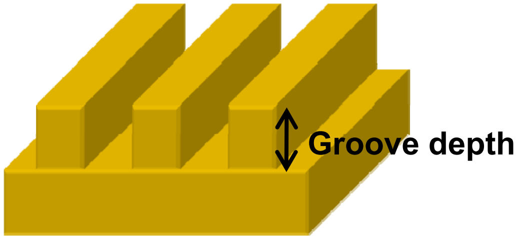
- No strong radial dependence of asperity height distribution: good spatial uniformity of asperity heights with conditioning

Spatial Results: Groove Depth





After 16 hours polishing (with conditioning)



Pad sample

- Groove depth has a strong radial dependence: more pad wear near the center (non-optimized pad conditioning in this case)

Summary of Pad Aging Results

- Depth dependence of asperity modulus
- Pad conditioning keeps asperity properties consistent during CMP process
  - Asperity modulus and asperity height distribution are both consistent across polishing/conditioning times
  - No strong radial dependence of asperity modulus of asperity height
- Pad wears linearly with polish time (as measured by groove depth)
- Pad wear and thickness does not strongly affect asperity properties: conditioning effective in maintaining pad asperity structure

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- ➡ Model for pad-wafer contact
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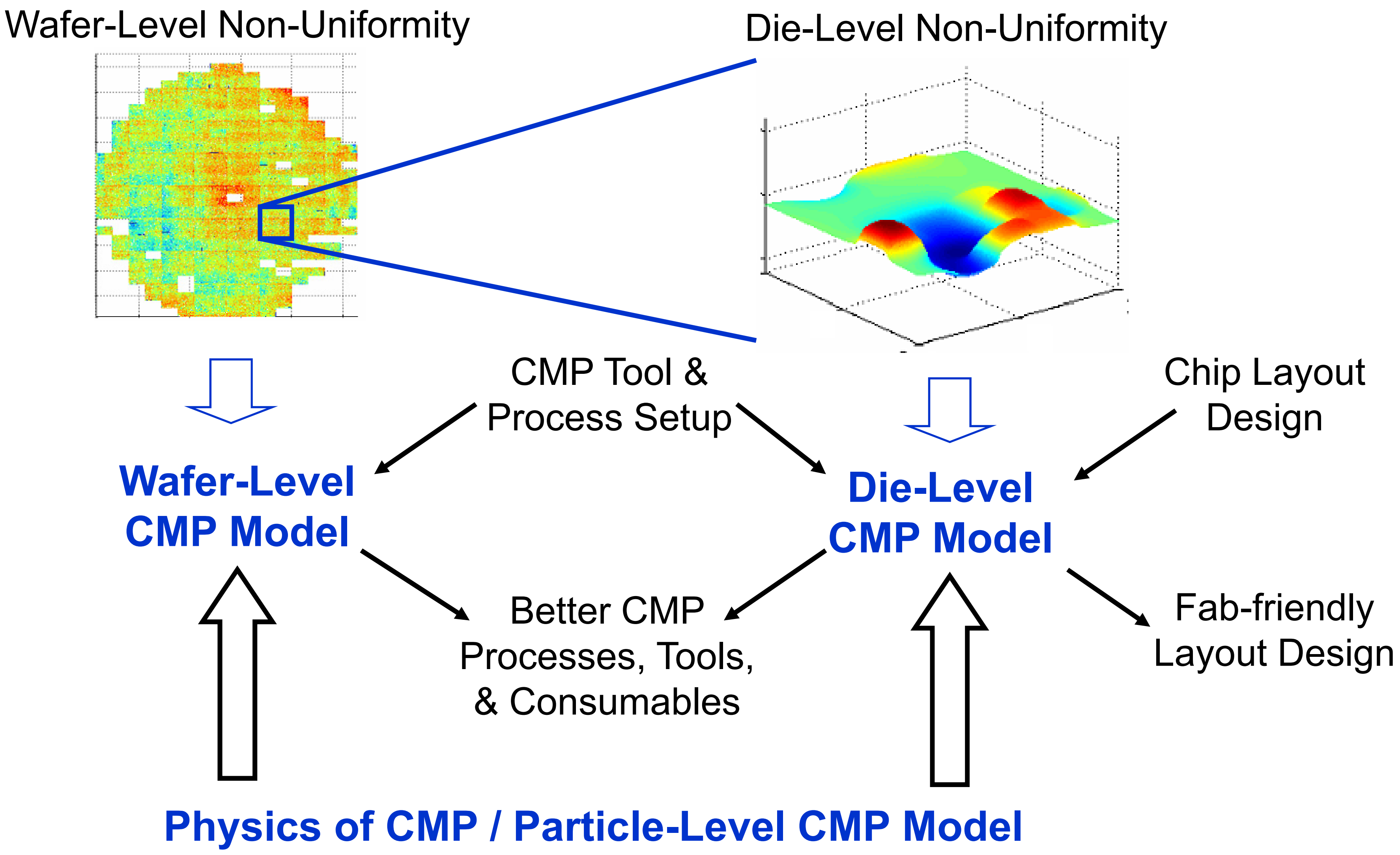
Motivation: CMP Models



Wafer-Level Non-Uniformity

Die-Level Non-Uniformity

CMP Tool & Process Setup

Chip Layout Design

Wafer-Level CMP Model

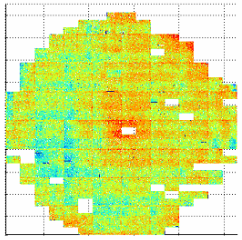
Die-Level CMP Model

Better CMP Processes, Tools, & Consumables

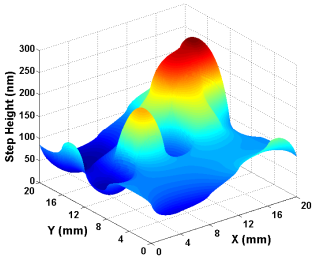
Fab-friendly Layout Design

Physics of CMP / Particle-Level CMP Model

State of Modeling in CMP

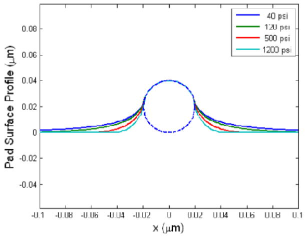


- Wafer-level modeling
  - Velocity, wafer edge pressure distributions
- Die-level modeling
  - Pattern density
  - Step height
  - Pad bulk vs. asperities: height and diameter distributions



- Particle-level modeling: basic mechanisms
  - What part of pad participates in polishing?
  - What is nature of pad/particle/wafer interaction?

Focus



- Challenges for the CMP community
  - **Have: effective chip-scale models for a *fixed* process – useful in chip design and optimization**
  - **Need: fundamental mechanisms and models for *varying* process, pad, slurry, tool, and wafer materials and patterns – useful in process design and optimization, and in tool/consumable design and optimization**

Particle-Level CMP Model

Input variables of CMP

- Applied pressure
- Relative velocity
- Abrasive size
- etc

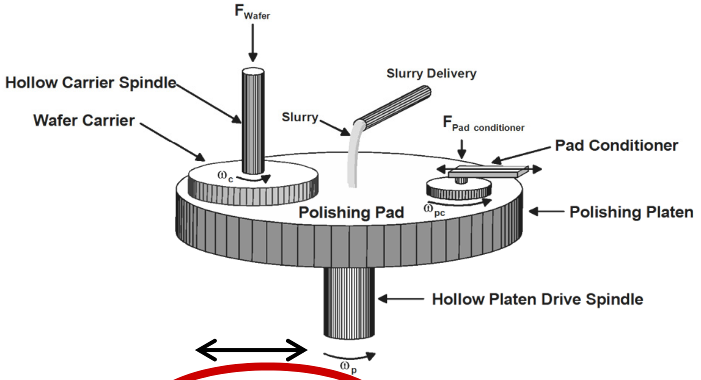
Particle-Level CMP Model

Output variables of CMP

- Blanket removal rate
- Surface quality
- etc

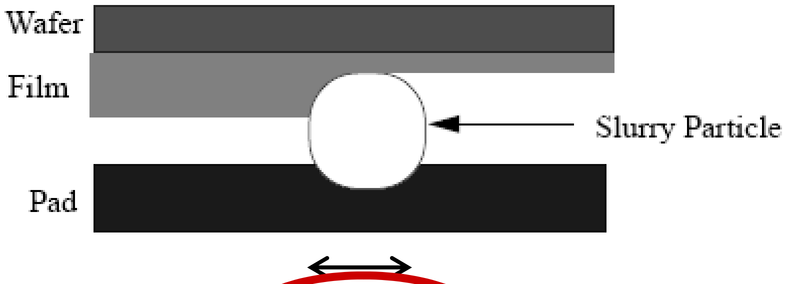
Physics of CMP

Macroscopic Phenomenon



300 mm

Microscopic Mechanism

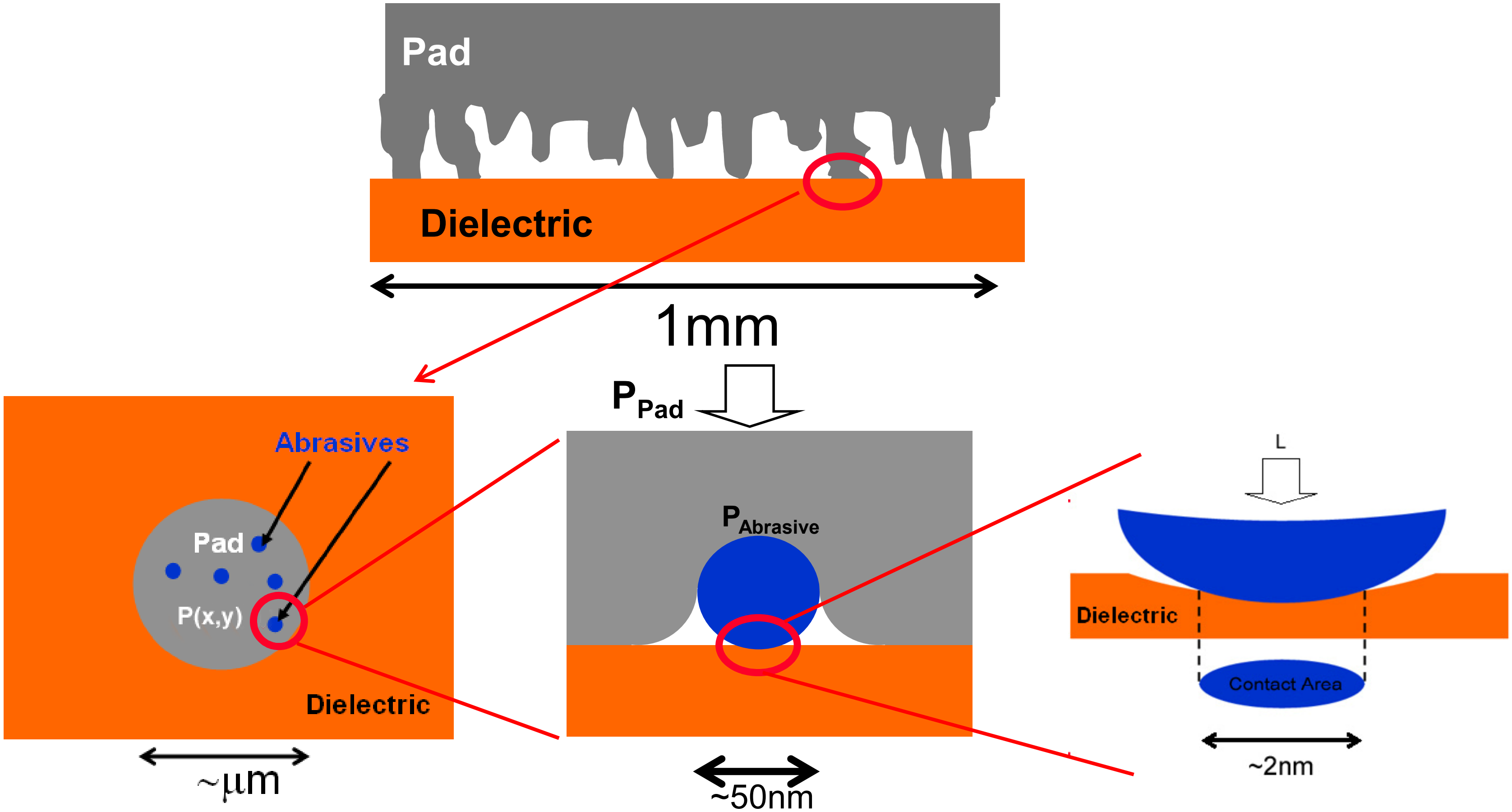


50 nm

~10^7 difference in scale

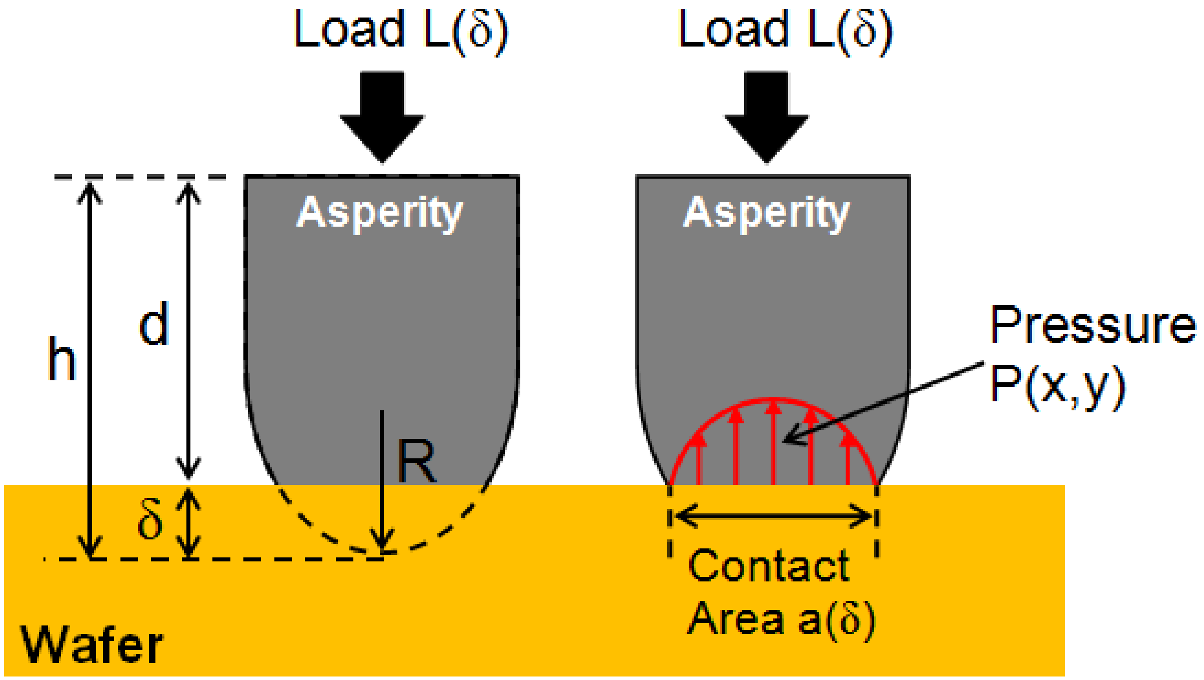
Overall Physical Modeling Approach

- Pad-wafer interaction
- Pad-abrasive interaction
- Abrasive-wafer interaction



Pad-Wafer Interaction

- Assume “fully supported” asperities
- Asperity compression and asperity contact
- Can predict local asperity contact pressure



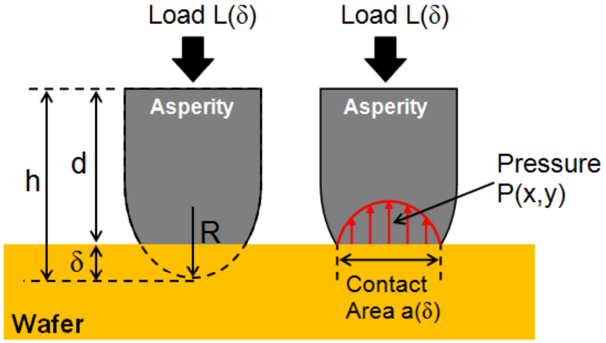
Have Physical Model… But Many Assumptions!

- Many of these assumptions have not been experimentally nailed down:
  - What part of pad participates in polish? Asperity height and size distributions? Mechanical properties of asperities?
  - What slurry particles participate? Large particles only? What particle/asperity loading occurs?
  - Effects of slurry chemistry, temperature, …
- Alternative physical assumptions and models are possible and have been proposed
- If we can find the correct physics, then model can be used to predict results for different pads, slurries (e.g. particle sizes), pressures, velocities, etc., …

Focus

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
- Result: Predict contact area fraction *f*

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

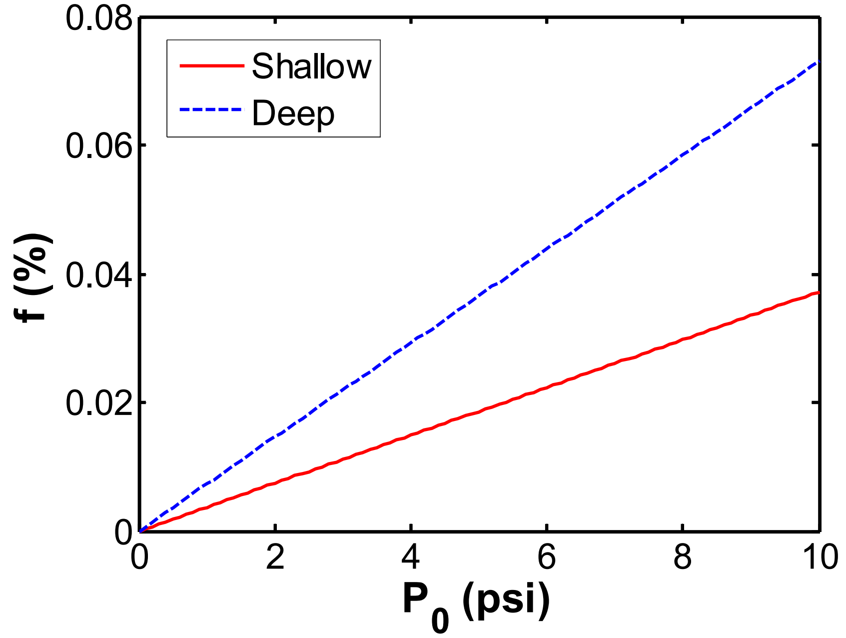
$$f(P_0) = \frac{P_0}{E}\sqrt{\frac{\pi R}{\lambda}}$$

E: asperity reduced modulus

P_0: reference pressure

Boning and Fan, MRS Spring Meeting, April 2010.

Model Trend: Contact Area vs. Reference Pressure



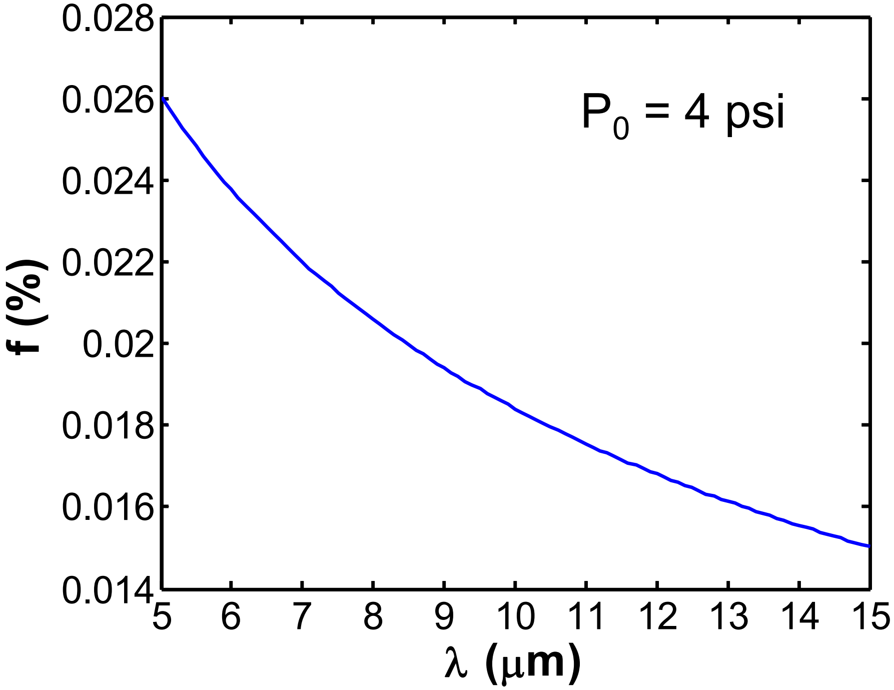
E = 291 MPa

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

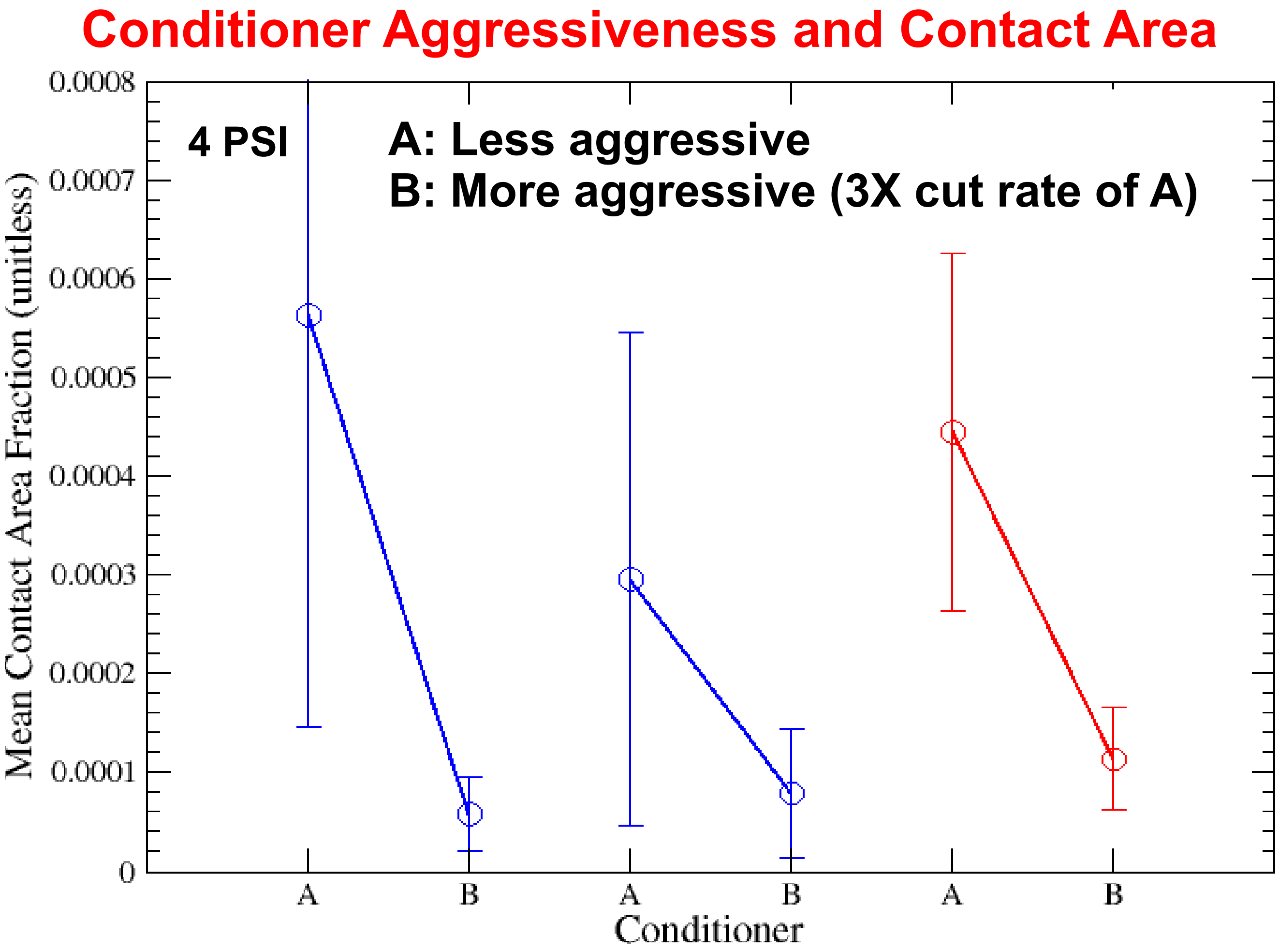


$$f(P_0) = \frac{P_0}{E}\sqrt{\frac{\pi R}{\lambda}}$$

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

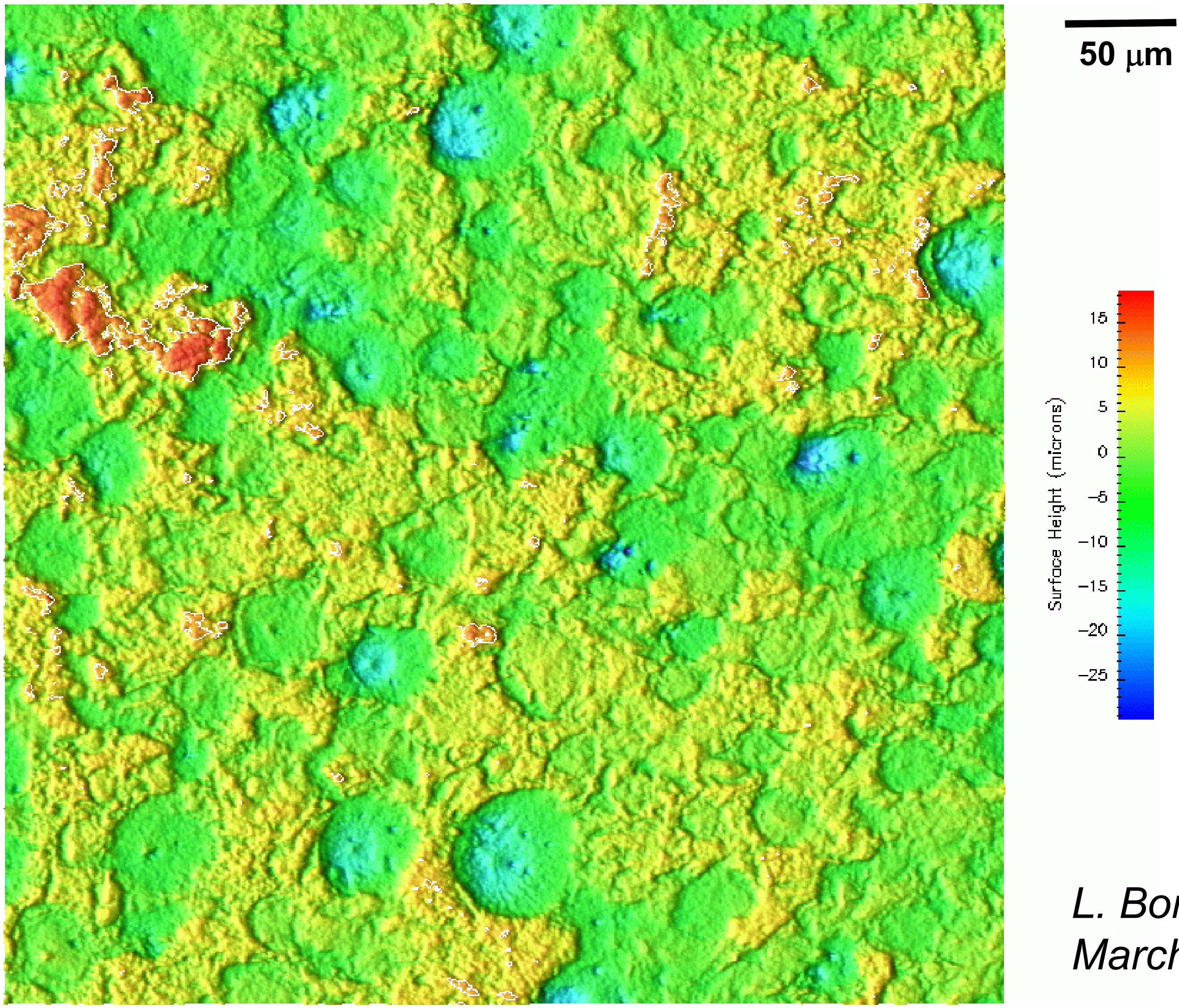
- Contact area decreases with larger *λ*
  - Larger *λ* implies wider distribution (more taller asperities)
  - For wider distribution, a smaller number of tall asperities bear the load, reducing the contact area percent

Consistent with Conditioning/Contact Area Data



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

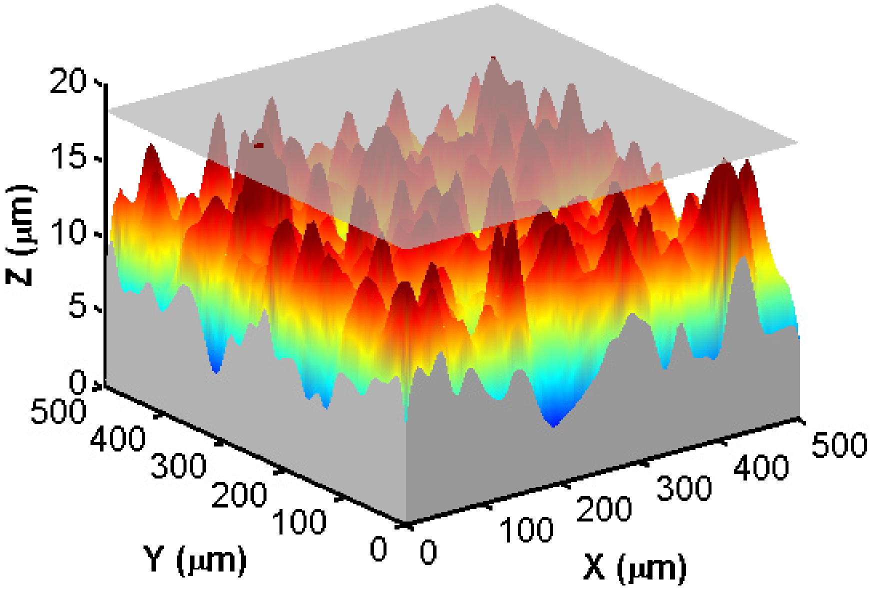
Example Polishing Pad Topography

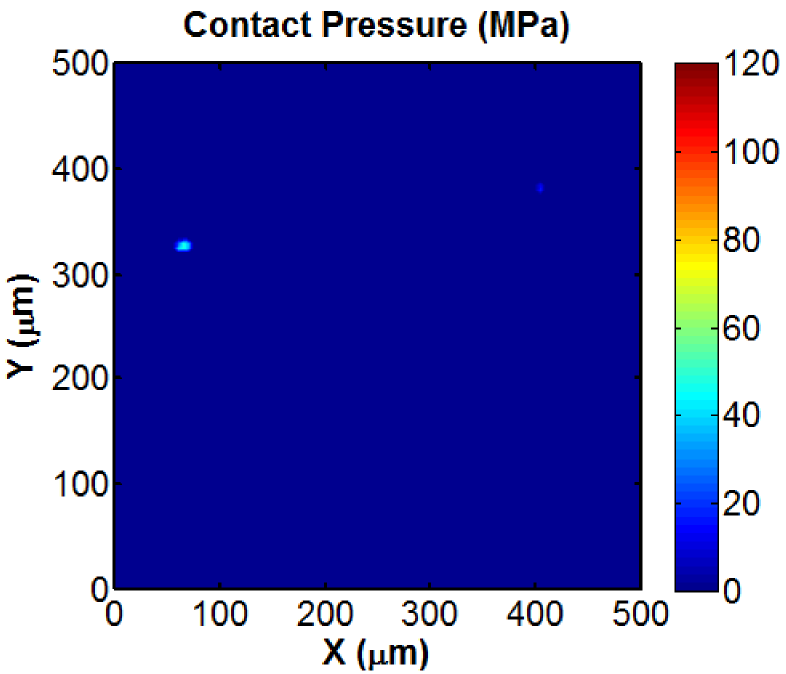


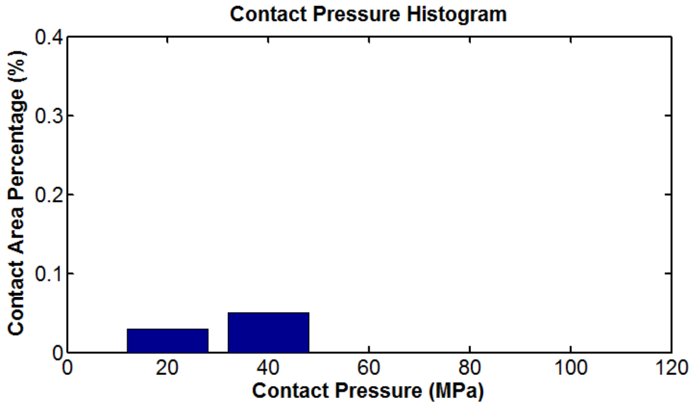
L. Borucki et al., CSITC, March 2010.

Simulated Pad-Wafer Interaction

P_0 = 5 psi





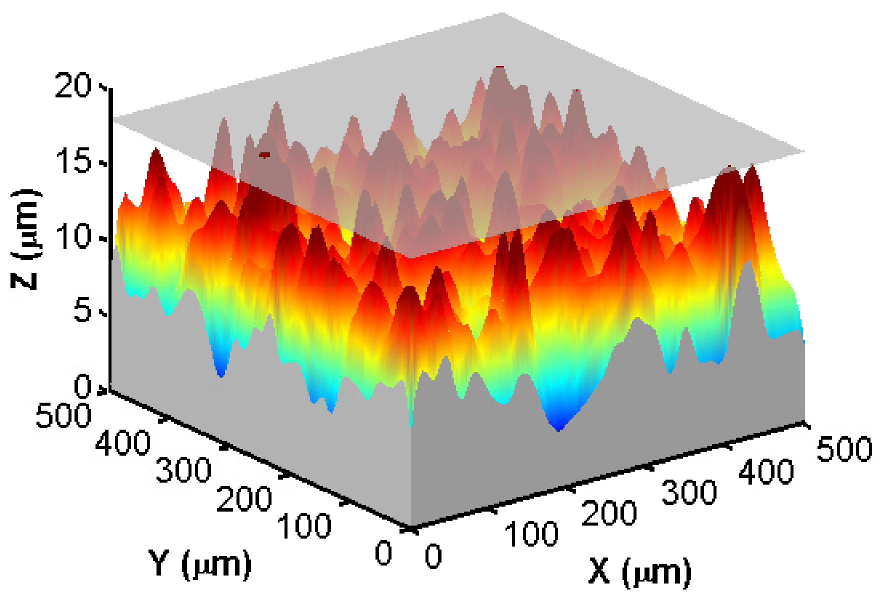


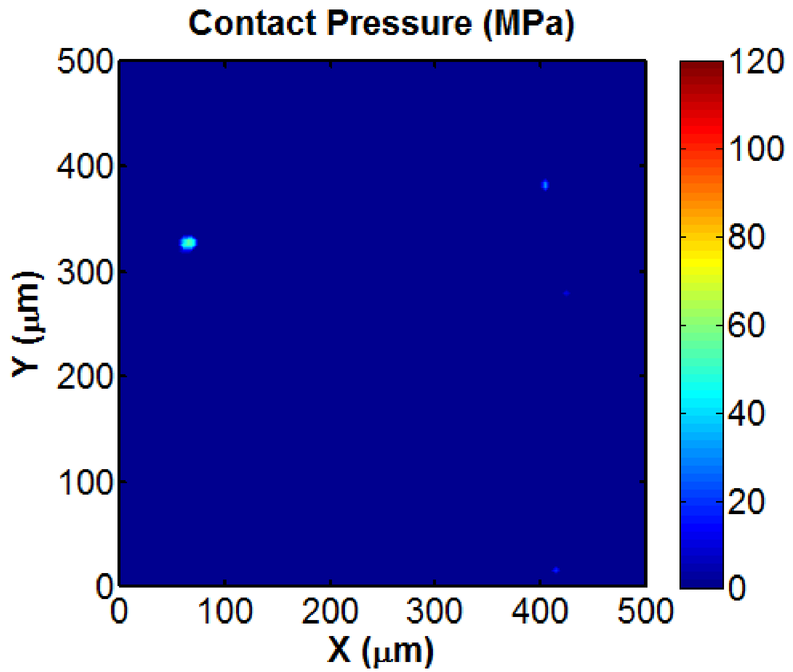
λ = 11.8 μm

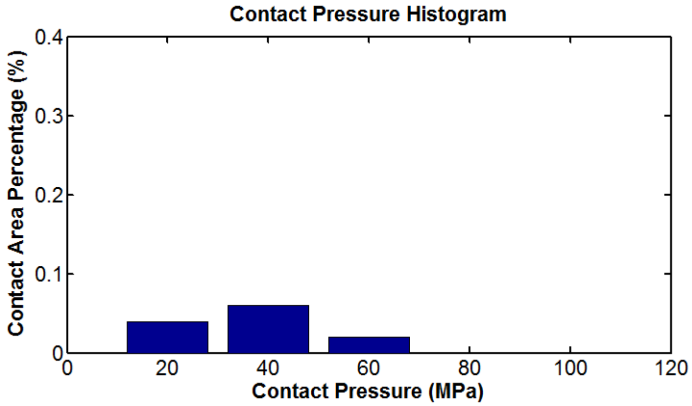
E = 460 MPa

Simulated Pad-Wafer Interaction

P_0 = 10 psi





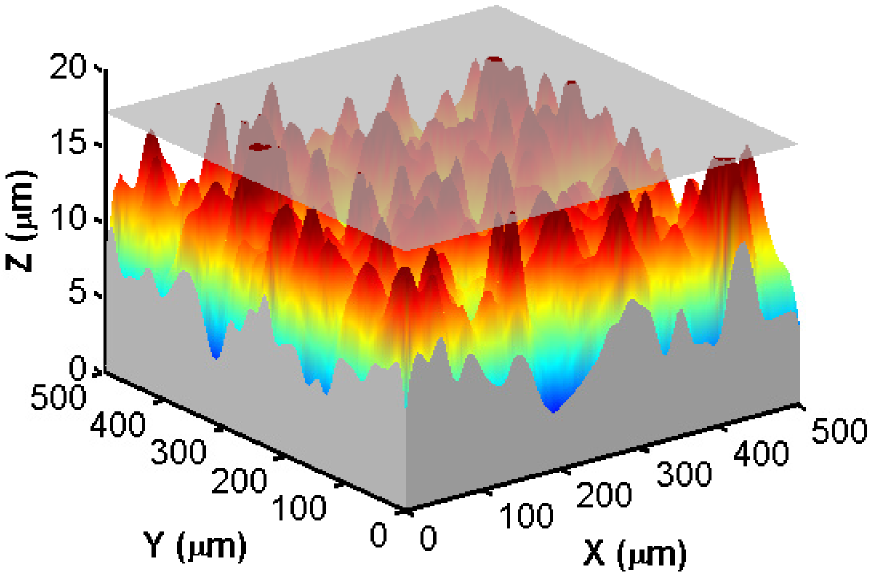


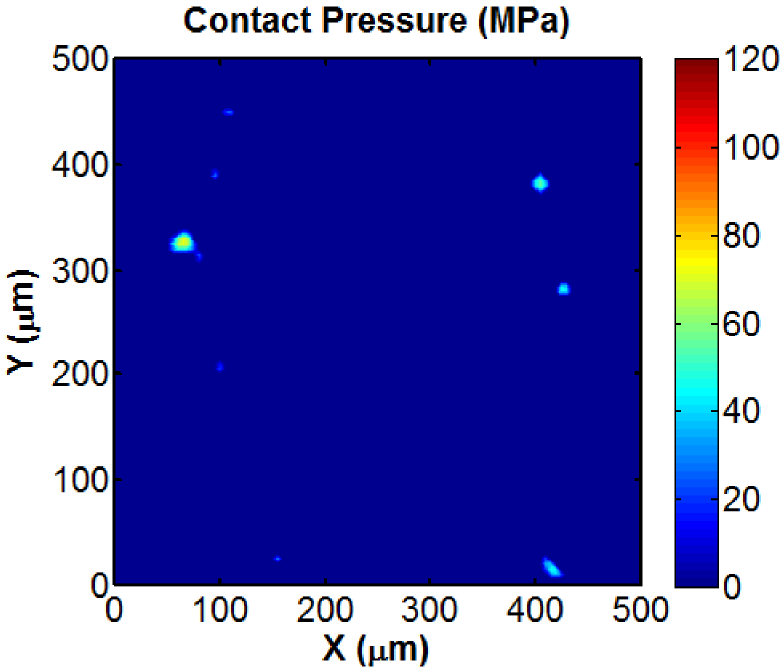
λ = 11.8 µm

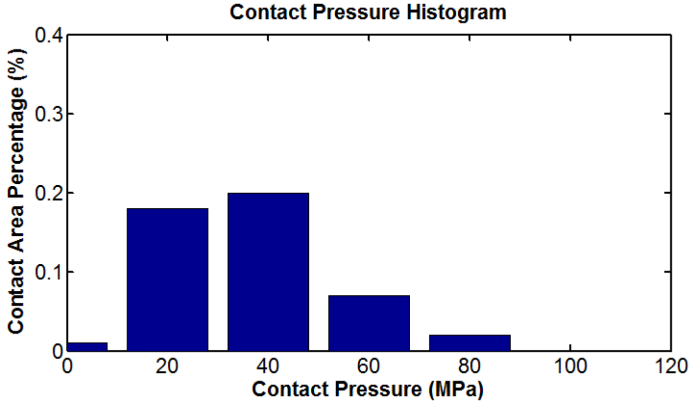
E = 460 MPa

Simulated Pad-Wafer Interaction

P_0 = 50 psi





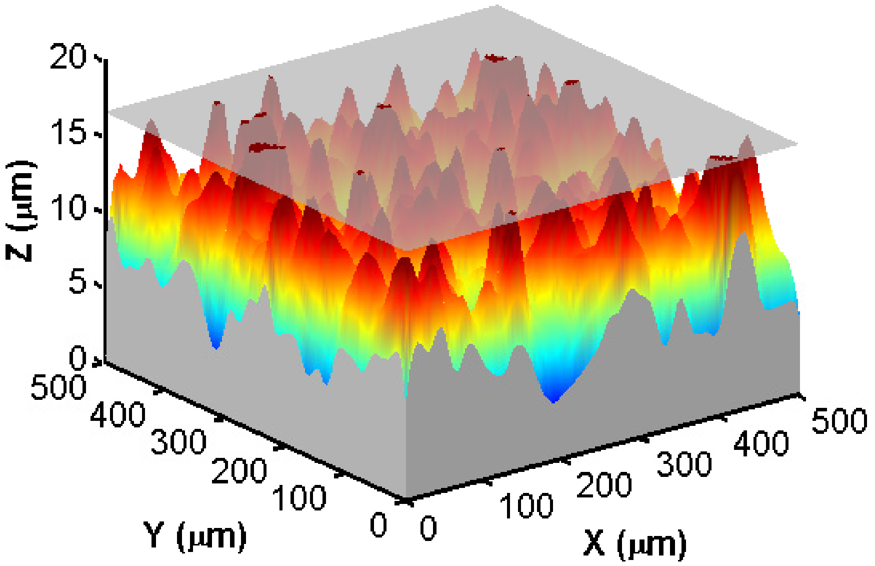


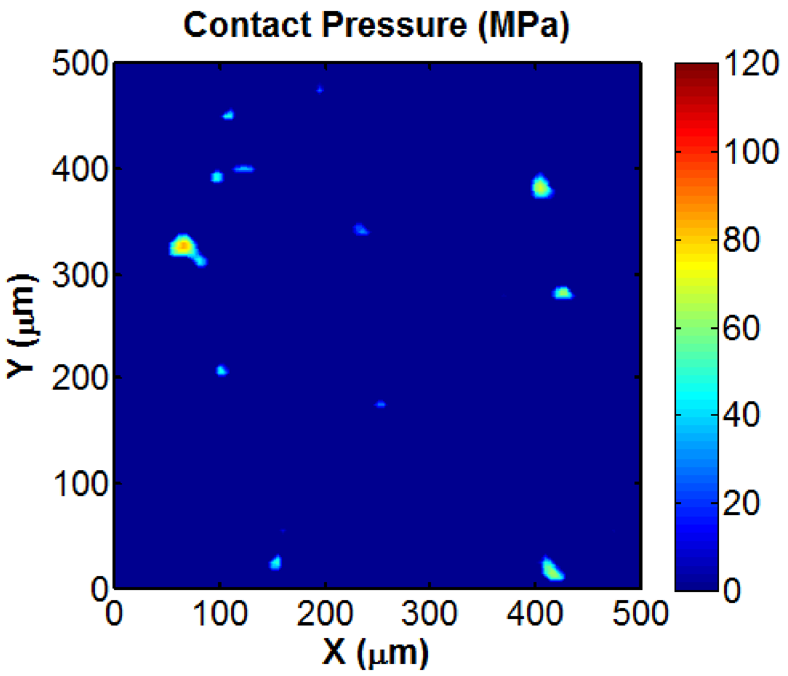
λ = 11.8 μm

E = 460 MPa

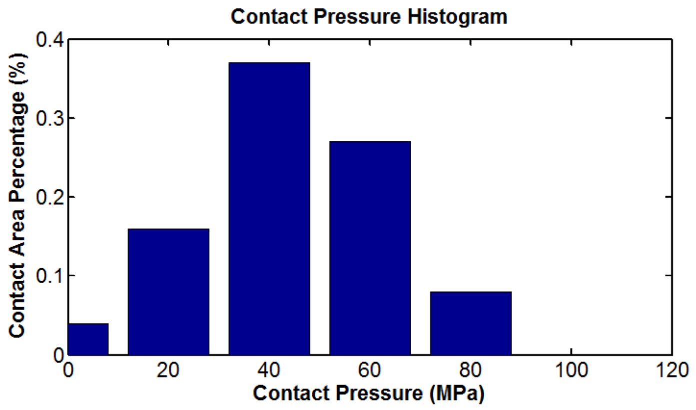
Simulated Pad-Wafer Interaction

P_0 = 150 psi





- Contact area changes with overall applied pressure
- There is also a ***distribution*** of asperity contact pressures: has implications for modeling



λ = 11.8 μm

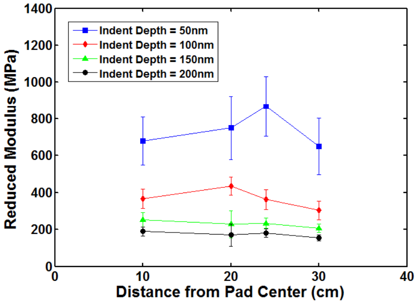
E = 460 MPa

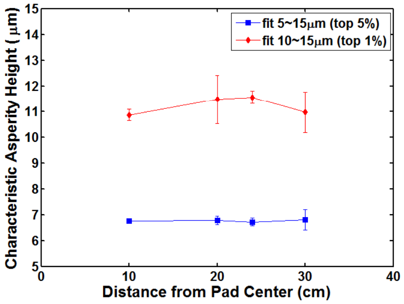
Model Parameters and Measured Results

- Model parameters
  - *E* and *λ* are single fixed values

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

- Physical measurements
  - Depth dependence of *E*
  - Height range of extracted *λ*





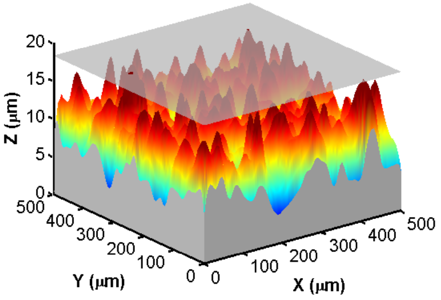
- How to utilize the measure results in the model
  - Modify the model to include nonlinear effect?
  - Take the mean value of measured result in a certain range?

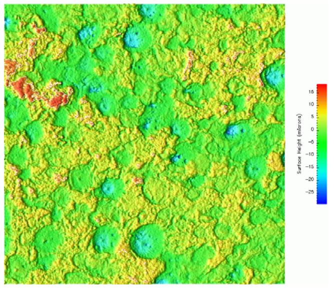
Conclusions

- Measurement approaches developed:
  - Pad slice indentation test
  - Asperity reduced modulus
  - Asperity height distribution
- Measurement observations:
  - See strong depth dependence of pad asperity modulus
  - Pad aging evaluation: surface properties remain consistent with conditioning
- Model for pad-wafer contact
  - Based on mechanical response of pad asperities
  - Contact area predictions and trends

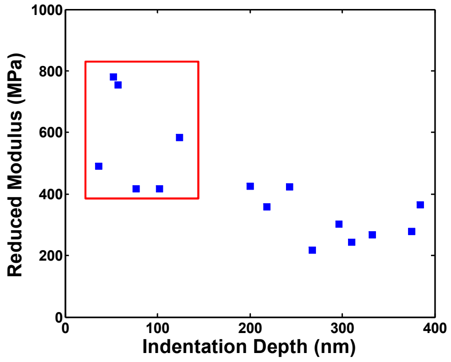
Future Work

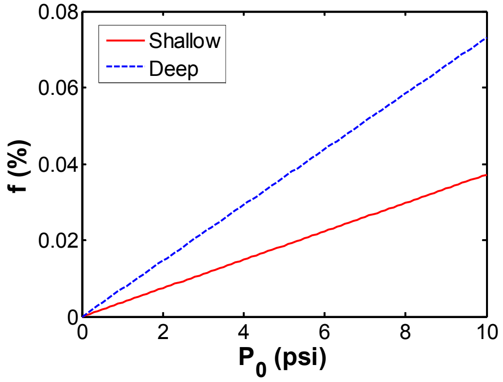
- Compare predicted and measured contact fractions





- Understand *distribution* of asperity size, heights, *and* mechanical properties
- Consider implications of shallow indentation modulus





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