In Situ Characterization of the Mechanical Aspects of CMP

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Objectives

Multi-scale, multi-dimensional *in situ* CMP characterization

Obtain in-situ images of the slurry layer thickness during CMP and quantify wafer-pad contact during polishing – Caprice Gray, PhD (May 2008)

DELIF: Contact/Film thickness

Mechanical: Global forces, motion, MRR

Concurrent measurement of spatially averaged force (3-axis, COF, moments), force spectra, wafer attitude, and material removal rate under a variety of polishing conditions – James Vlahakis, PhD (August 2008)

Measure local (100 μm scale), high sample rate (0.1 ms) asperity scale forces at the pad-wafer interface during CMP – Andrew Mueller, MS (May 2007) & Douglas Gauthier (MS Candidate, November 2008)

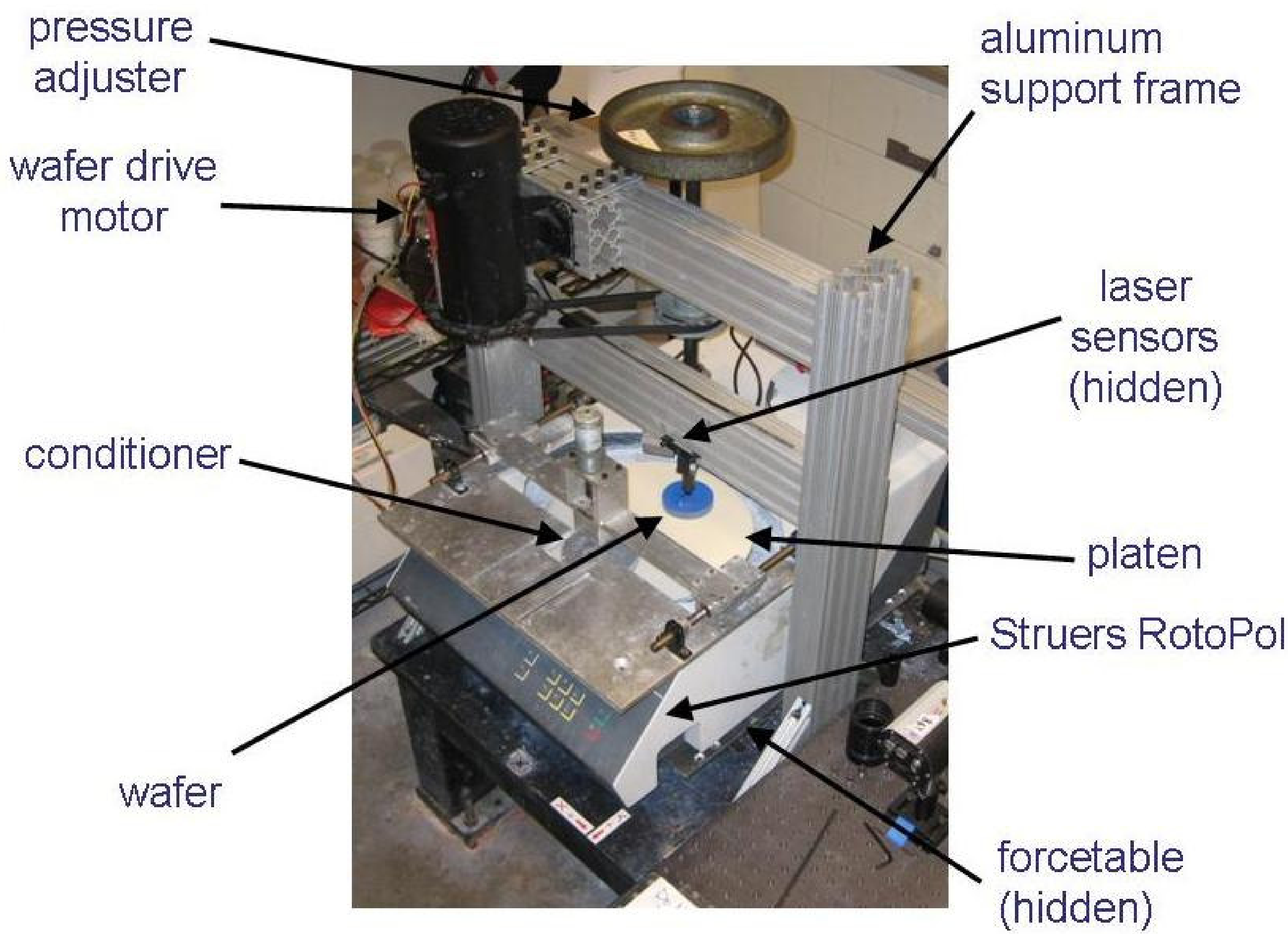
MEMS: Microscale force sensors

PIV/Flow Vis: Visualizing full-pad flows

(Feasibility study) Investigate the feasibility of using particle image velocimetry (PIV) to quantitatively measure particle-slurry flow in-situ. – Nicole Braun, MS (May 2008)

Laboratory Scale Polisher

- Struers RotoPol-31 benchtop polisher.
- 3” and 4” BK7 glass wafers and a 12” pad.
- Fumed silica slurry.
- Conditioner is present during processing.
- 6 DoF force table.
- High speed microscopy setup integrated (10,000 fps, 1.7 μm/pixel)
- DELIF for film thickness/pad-wafer contact.
- Laser sensors for wafer pitch & roll.

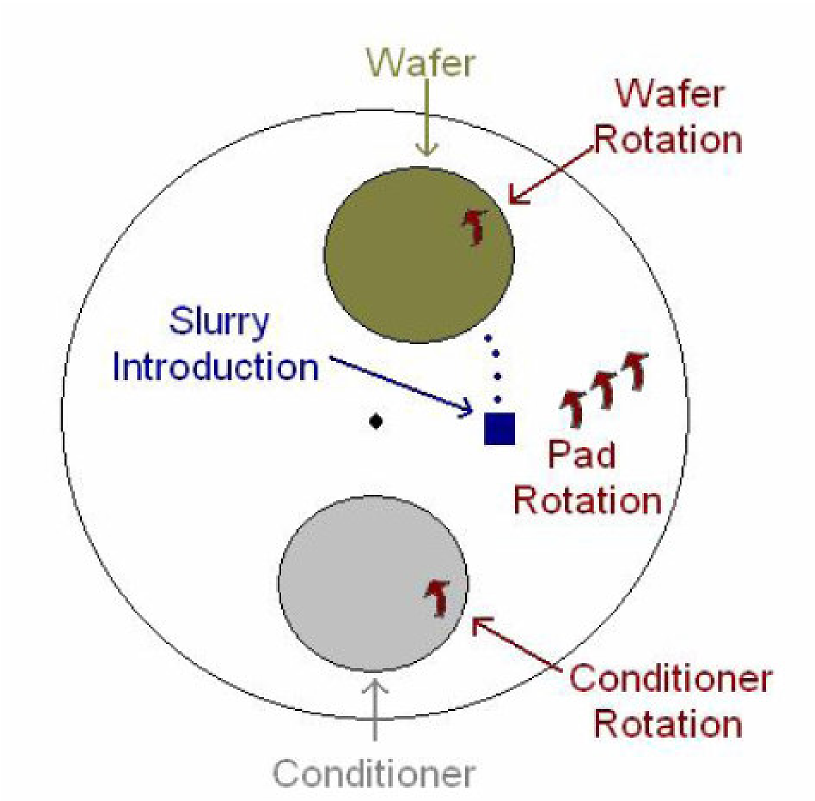


Laboratory Scale Polisher

-Wafer and pad co-rotate.

-Wafer rotation rate is maintained at 10% above the platen rotation rate.

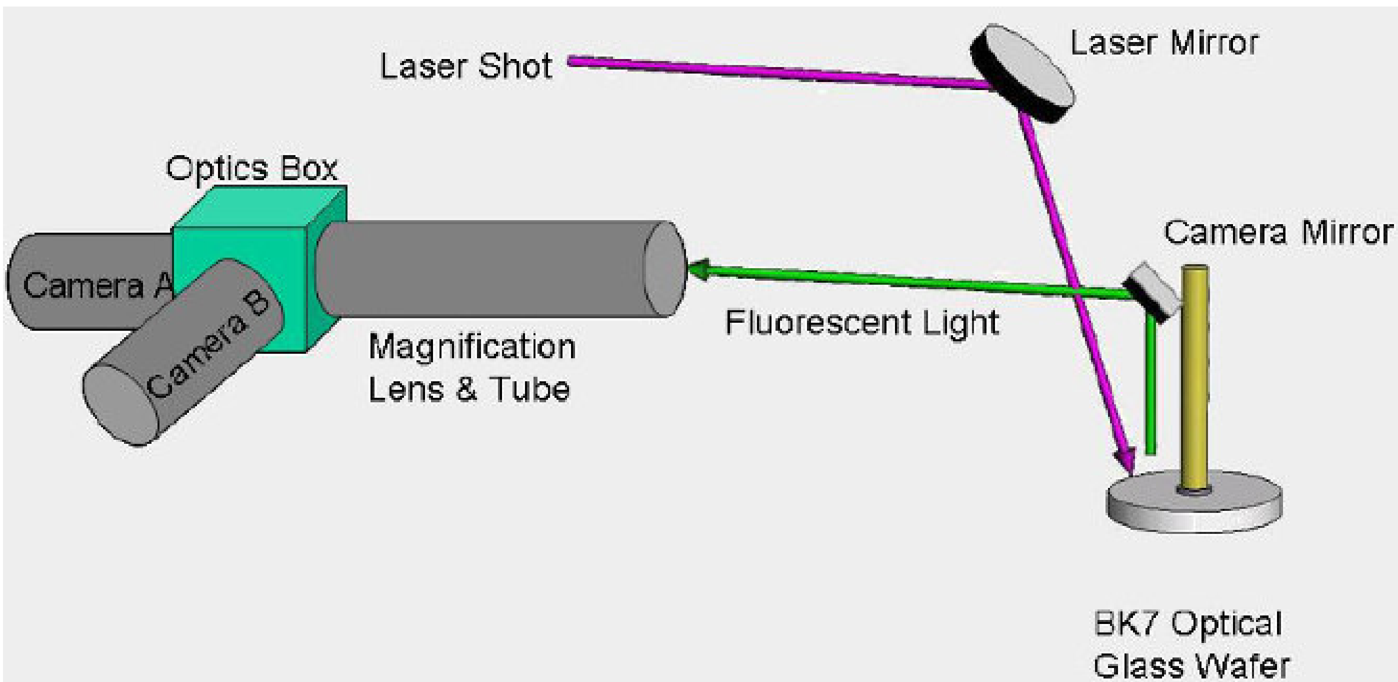
-Slurry injection point, platen rotation rate, downforce, and slurry dilution are varied.



Dual Emission Laser Induced Fluorescence

Dual Emission Laser Induced Fluorescence (DELIF)

- In-situ contact images
- 6 ns time integration, 2 images/sec (nanosecond laser pulse)
- ~3 micron/pixel to resolve asperity sized features
- Pads (all polyurethane based): CMC D100, CMC D200, Fruedenburg FX9, IC1000



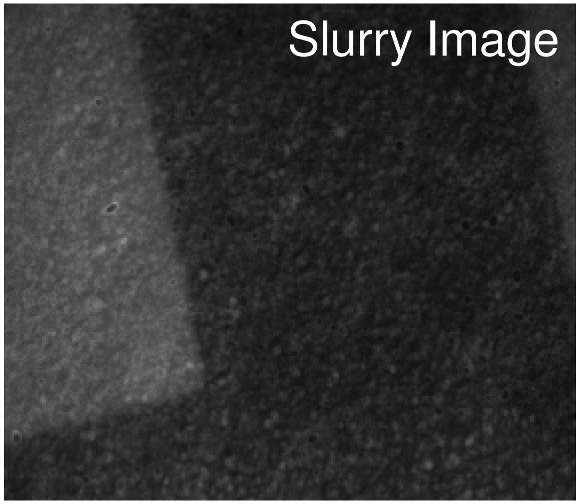
DELIF: Film Thickness

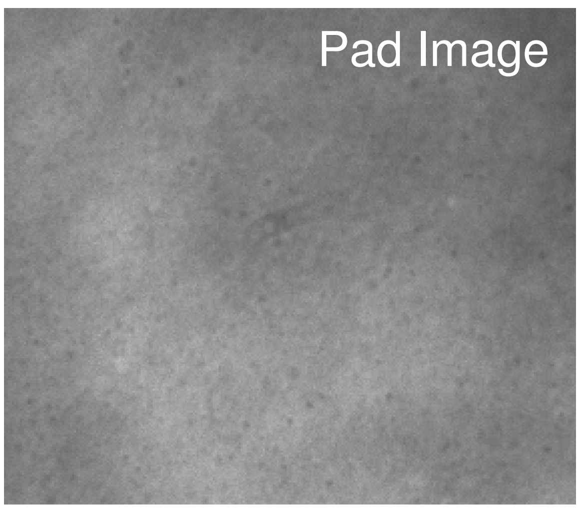
Two cameras:

(1) wavelength of slurry dye

(2) wavelength of pad fluorescence

Image ratio cancels source intensity variation





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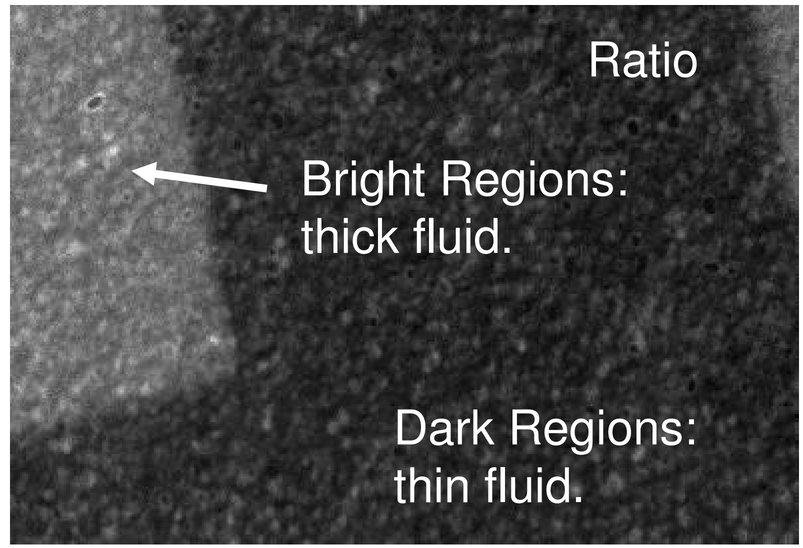
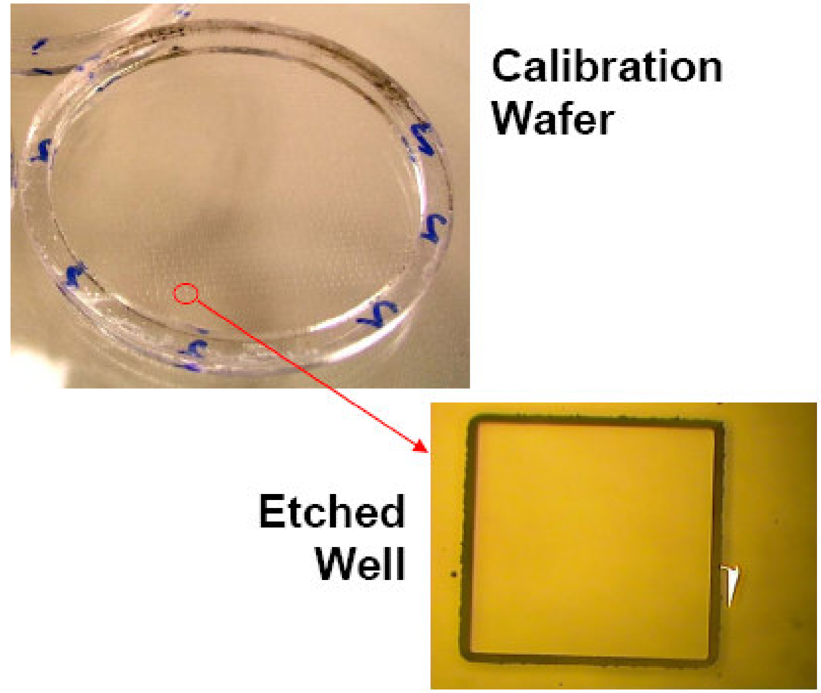
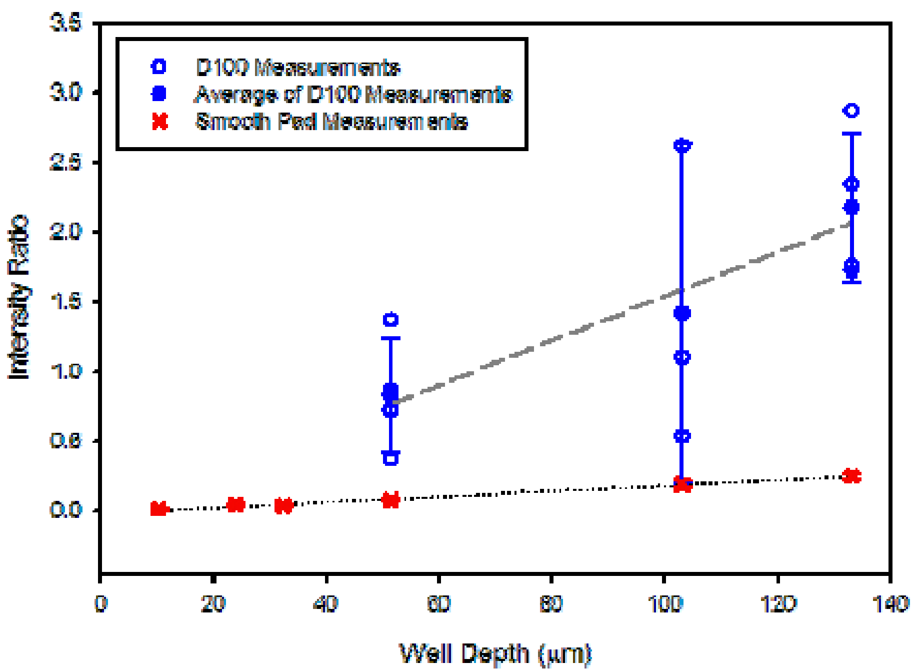


Brighter regions are thicker fluid layers.

DELIF Depth Calibration

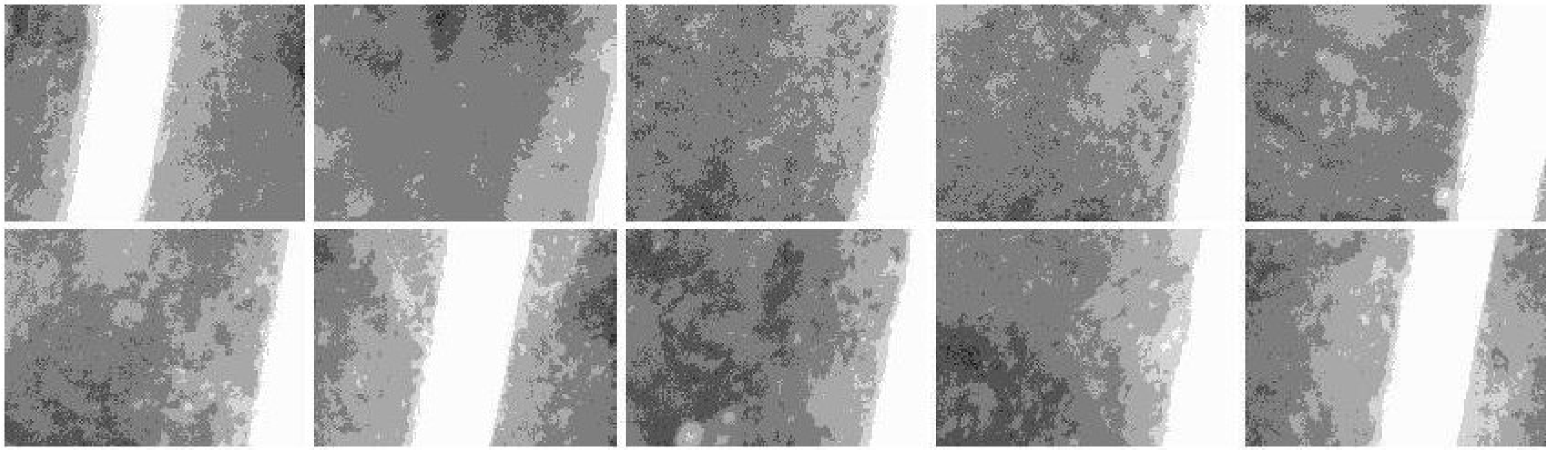
Square wells of known depth are etched into BK7 glass wafers, and the resulting DELIF intensity in the wells is measured under normal polishing conditions.

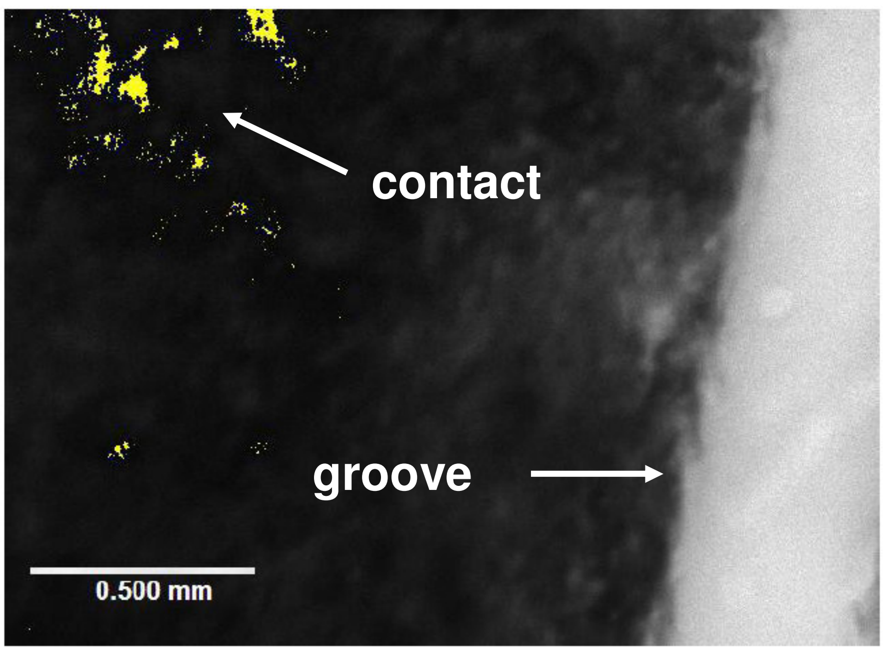


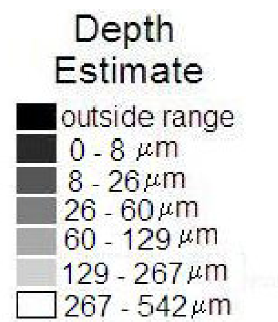


Calibration on a smooth (Cabot non-production, Ra=0.2 µm, polyurethane) pad is low-noise and linear. On a rough pad (Cabot D100, Ra=8 µm), the pad roughness is on the same order as well depth, so data scatter is much greater. Slope also changes due to changes to the optical properties of the pad.

DELIF Example Results



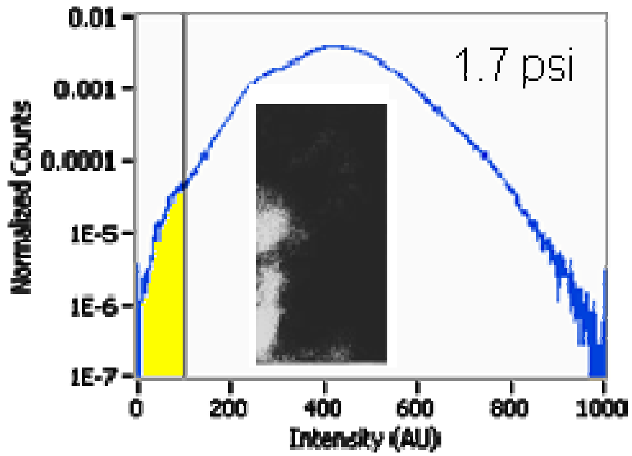


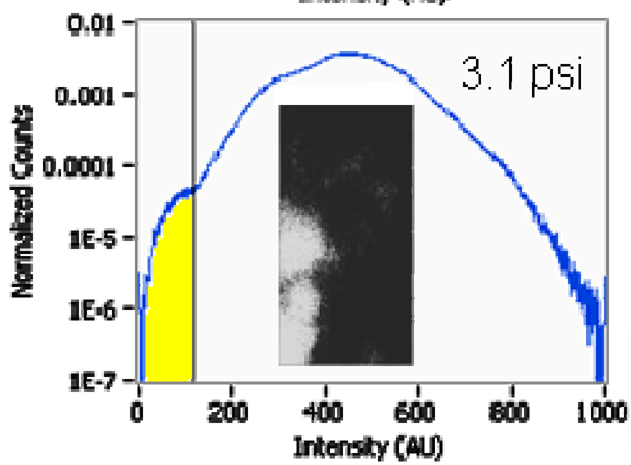


-Images above show slurry depths between grooves varying from 100 μm down to zero.

-Image to the left is an example contact image. We may miss contact close to groove edges due to optical bleeding.

DELIF: Static Contact



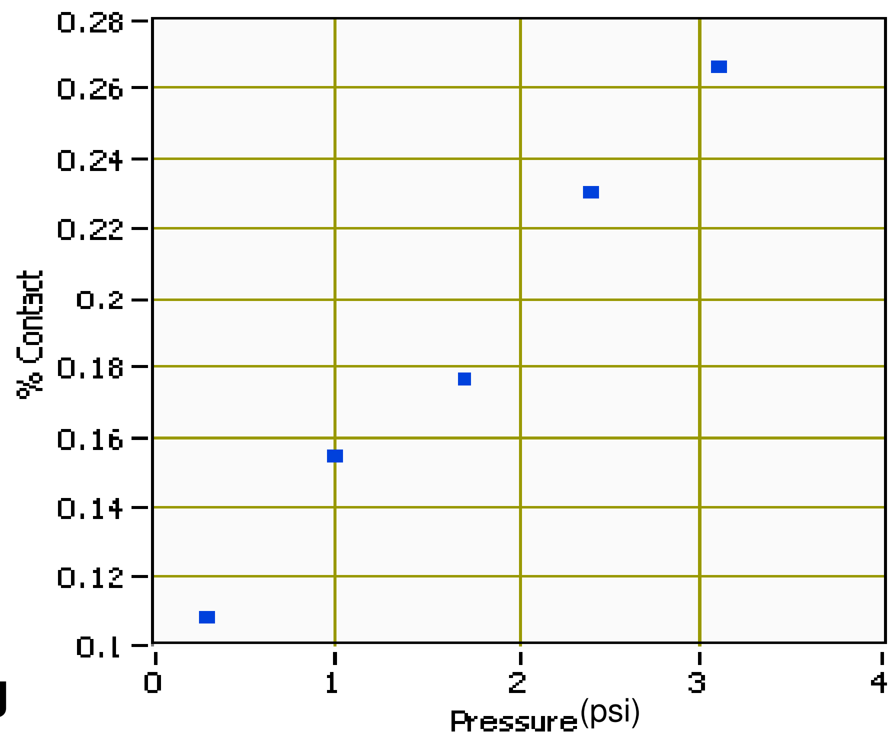


Histogram of height with thresholding gives contact percentage.

Static (no rotation) contact area on <u>ungrooved pads</u> is linearly pressure dependent

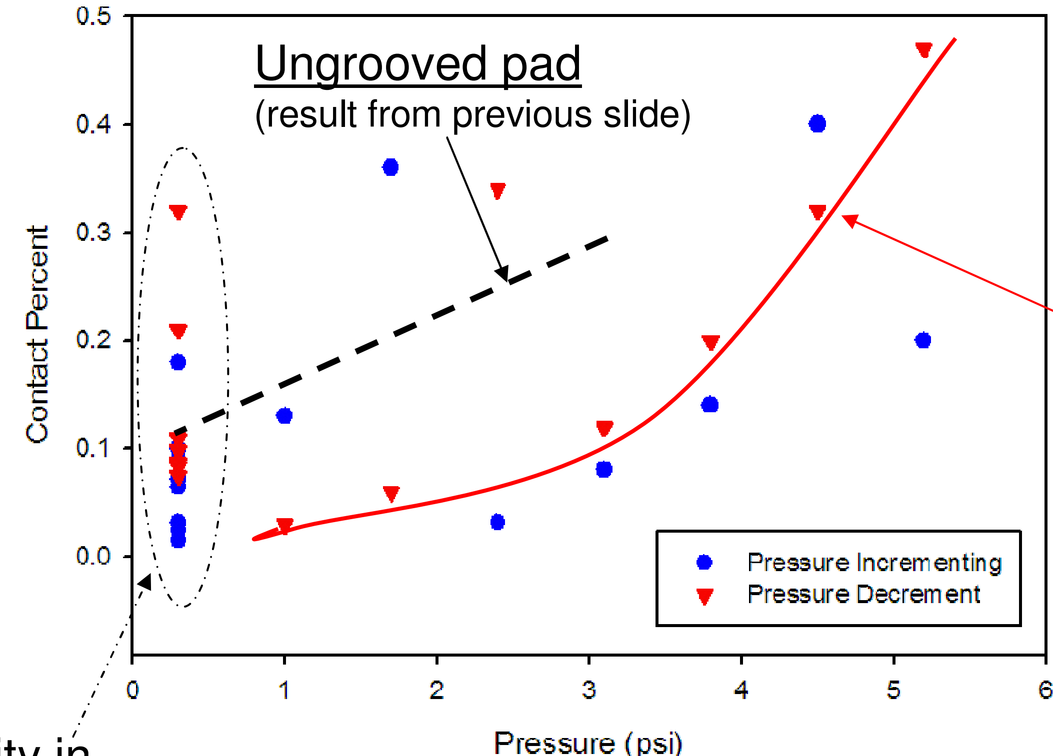
CMC D100 un-grooved pad, BK7 glass wafer

9:1 Cab-o-sperse SC1 slurry (fumed silica, 3 wt% at this dilution)



DELIF: Static Contact

Measured static contact area on grooved pads at low downforce shows more variability; this appears to be a limitation of the optical technique at groove edges.



Grooved pad: shows increasing contact with pressure, but less contact than ungrooved case. This may be due to missed contact at the groove edges.

Variability in measurement for low down-force. Contact is undetectable (?).

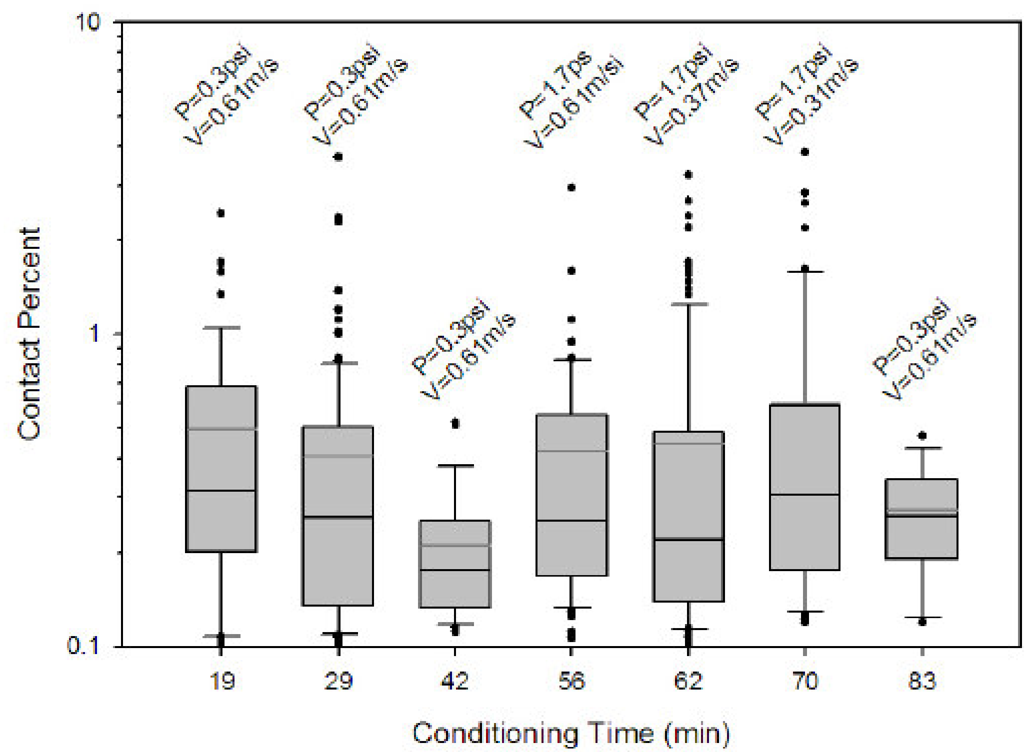
CMC D100 AC grooved pad, 3:2 Cab-o-sperse SC1 slurry (fumed silica, 12 wt% at this dilution)

DELIF: Dynamic Contact

Condition Time (min)	Pad V (RPM)	Wafer V (RPM)	Relative V (m/s)	Load (psi)
19	60	66	0.61	0.3
29	60	66	0.61	0.3
42	60	66	0.61	0.3
56	60	66	0.61	1.7
62	30	63	0.37	1.7
70	30	33	0.31	1.7
83	60	66	0.61	0.3

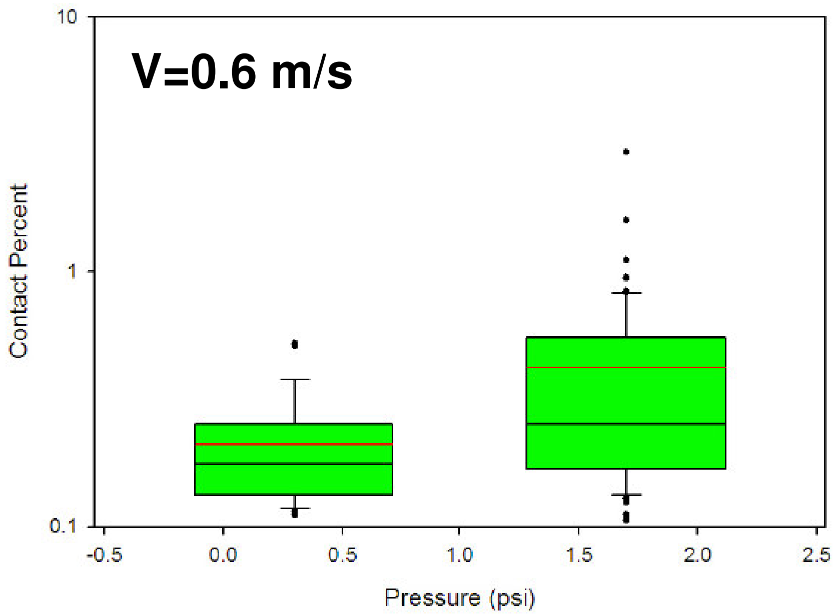
Box Plot
Box Bounds – 25% to 75%
Black Line = Median
Gray Line = Mean
Error Bars – 10% & 90%
Points – outlying data

- AC Grooved CMC D100 Pad (Cabot Microelectronics)
- 12% wt. fumed silica slurry (Cab-o-sperse SC1, Cabot Microelectronics)
- Contact percentage is between 0.1-1% across all images. Median is 0.2-0.3%.
- This is the same as was measured statically, suggesting that static measurements are relevant.

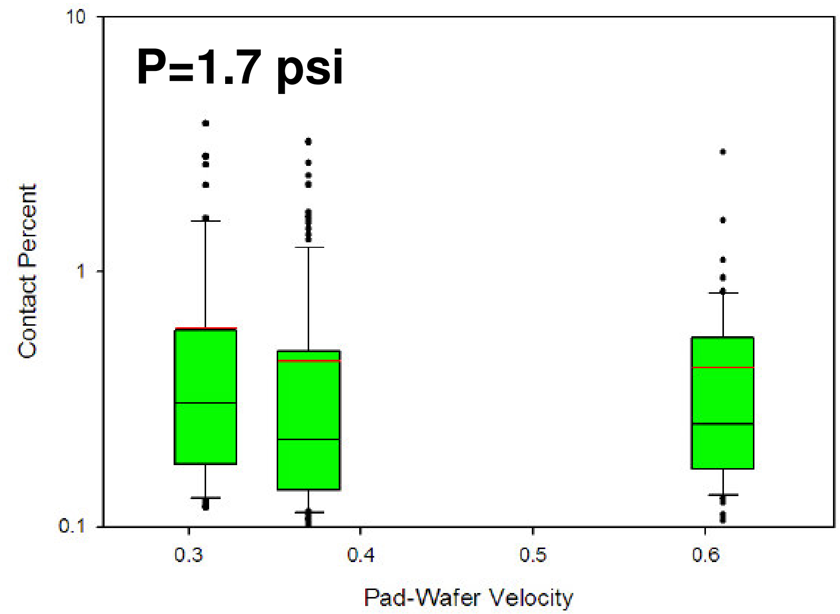


DELIF: Dynamic Contact

Contact increases with increasing pressure (0.2% to 0.3% as we go from 0.3 psi to 1.7 psi)



Contact does not change much as velocity changes. This is consistent with the static/dynamic observation.



Box Plot

Box Bounds – 25% to 75%

Black Line = Median

Red Line = Mean

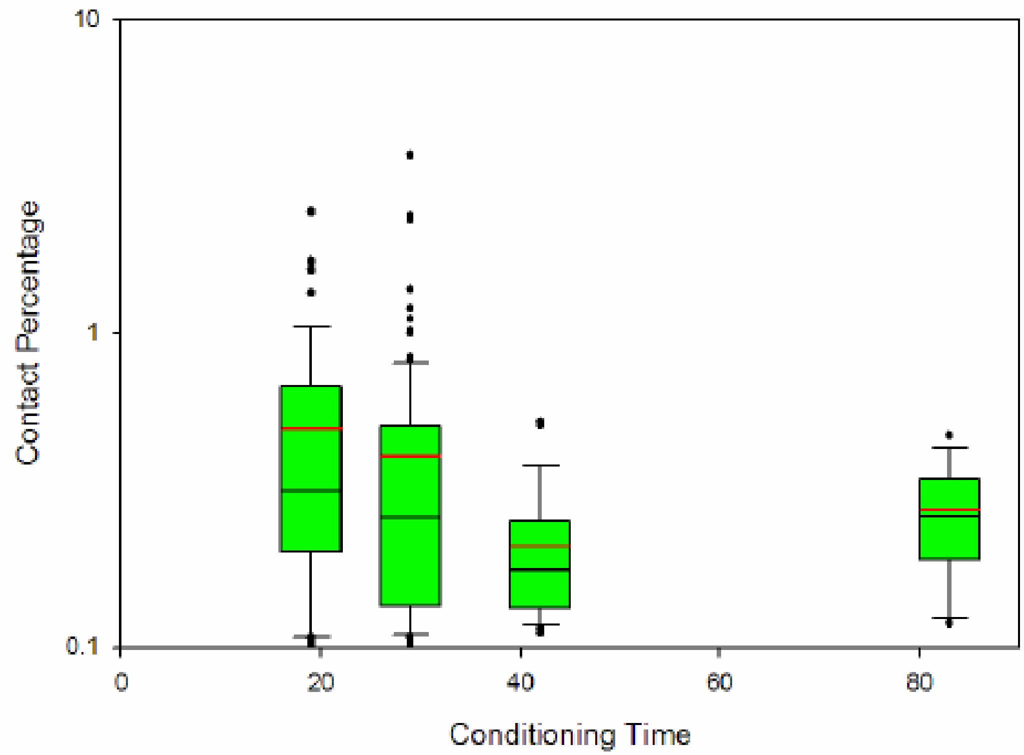
Error Bars – 10% & 90%

Points – outlying data

CMC D100 pad, AC grooves, 3:2 Cab-o-sperse SC1 (12 wt%, fumed silica)

DELIF: Dynamic Contact

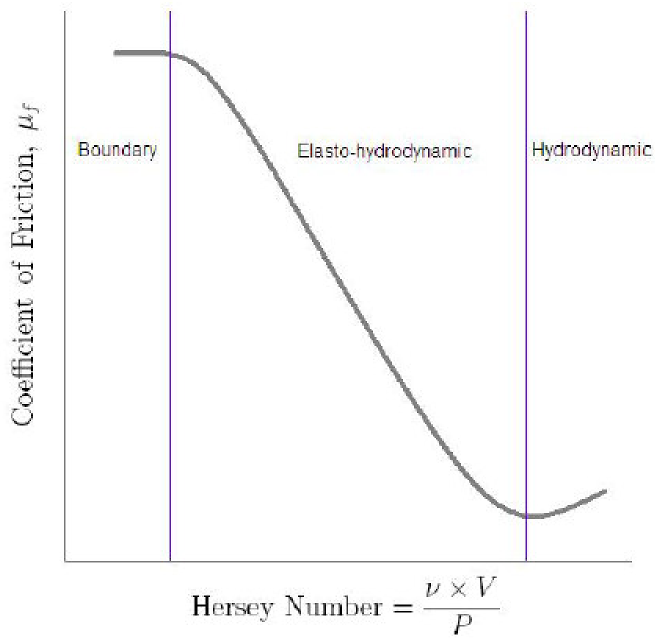
- Contact *decreases with conditioning time* for the first 40 minutes of conditioning and break in.
- *Other studies*: Agrees with Borucki, *et al,* Lake Placid, 2007. Opposite trend from Elmufdi and Muldowney, MRS, 2007.
- It is possible that the regions of contact are becoming smaller with conditioning, and we are losing the ability to detect with DELIF due to spatial resolution limitations of the method.

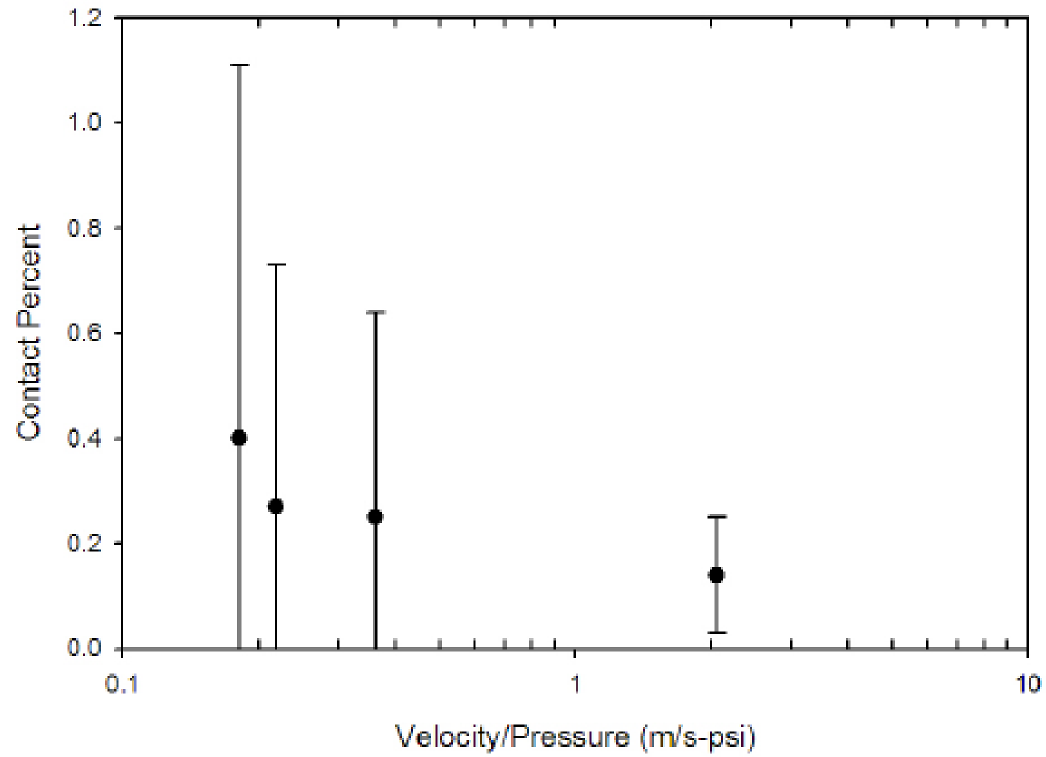


CMC D100 pad, AC grooves, 3:2 Cab-o-sperse SC1 (12 wt%, fumed silica)

DELIF: Dynamic Contact

On a Stribeck curve (plotted vs. pseudo-Sommerfeld number… viscosity is constant here), contact percentage decreases slightly with V/P, weakly suggesting an elasto-hydrodynamic regime, although the scatter is considerable.

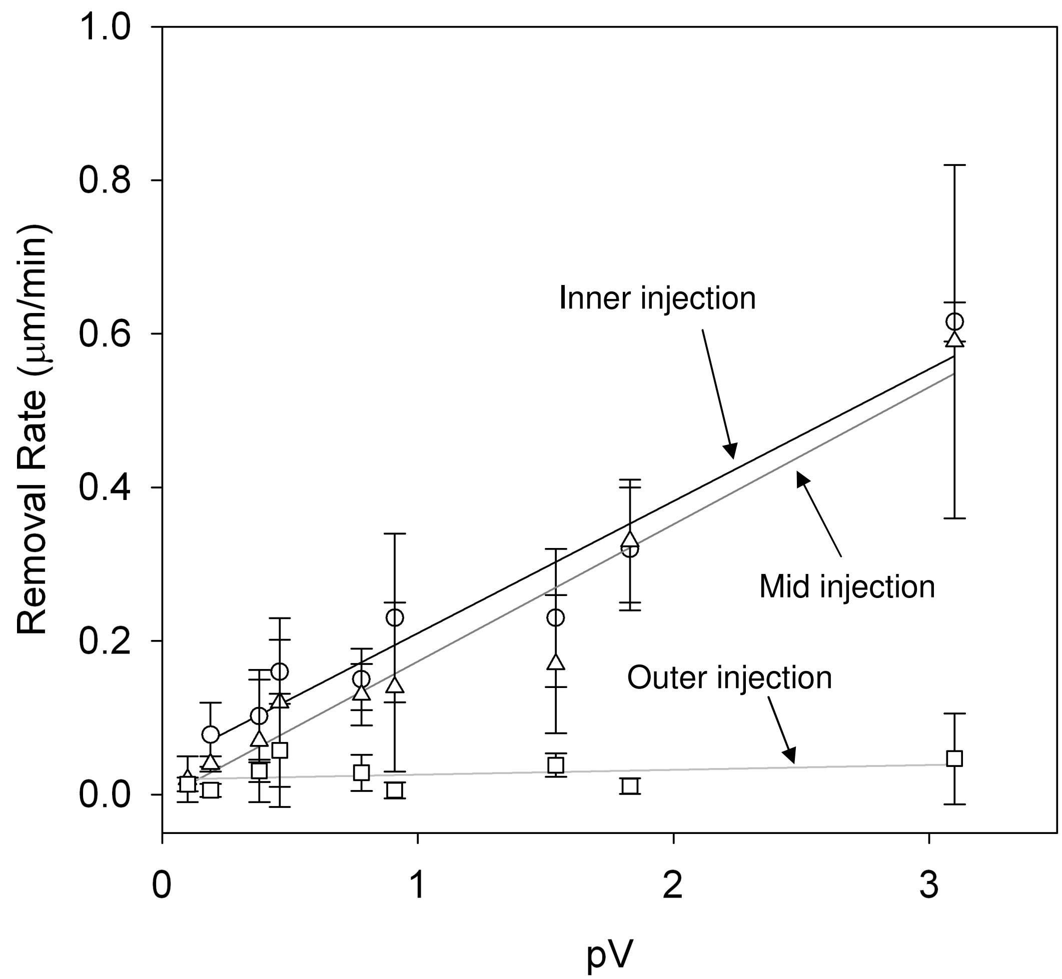




CMC D100 pad, AC grooves, 3:2 Cab-o-sperse SC1 (12 wt%, fumed silica)

Material Removal Rate

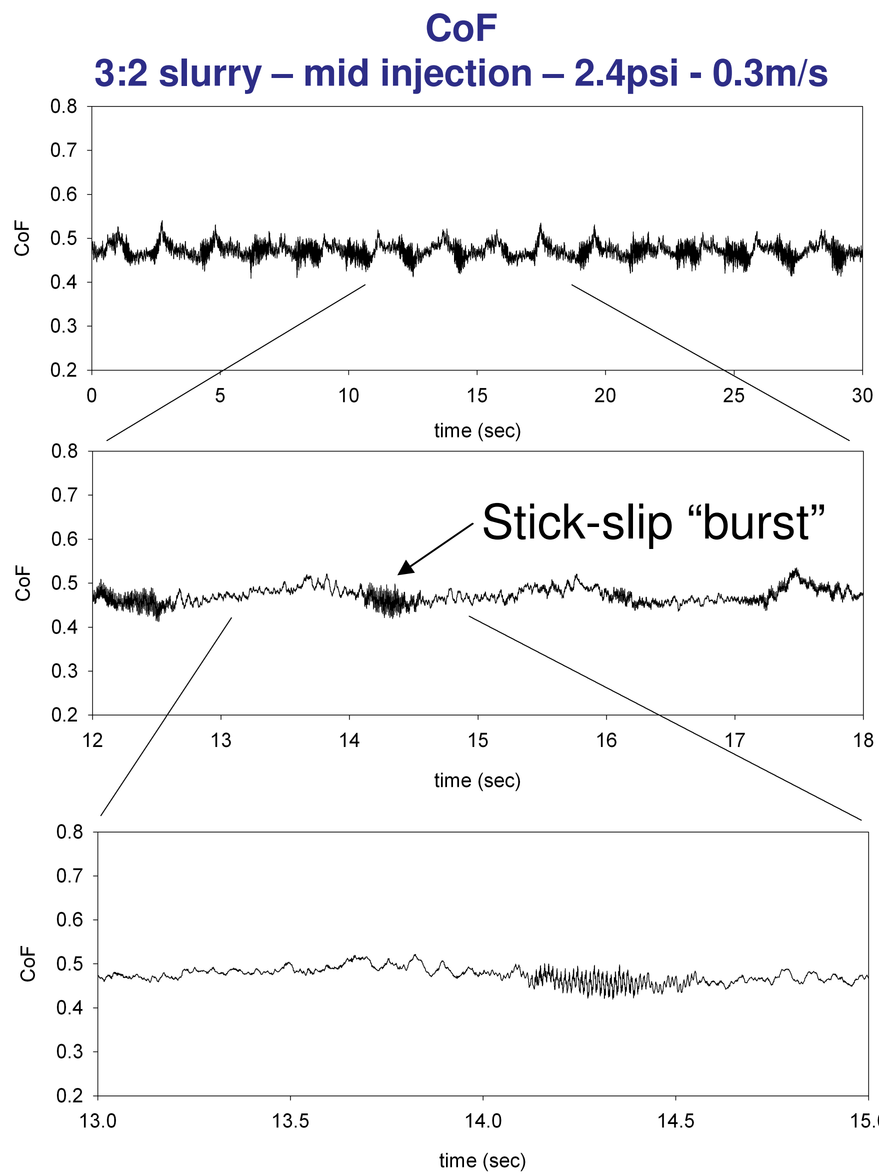
- Material removal rate (MRR) is Prestonian.
- MRR is 50-600 nm/min over the 0.1 to 3.1 psi-m/s range.
- MRR can vary dramatically with injection point in some cases – here, we see MRR drops nearly to 0 with outer injection.



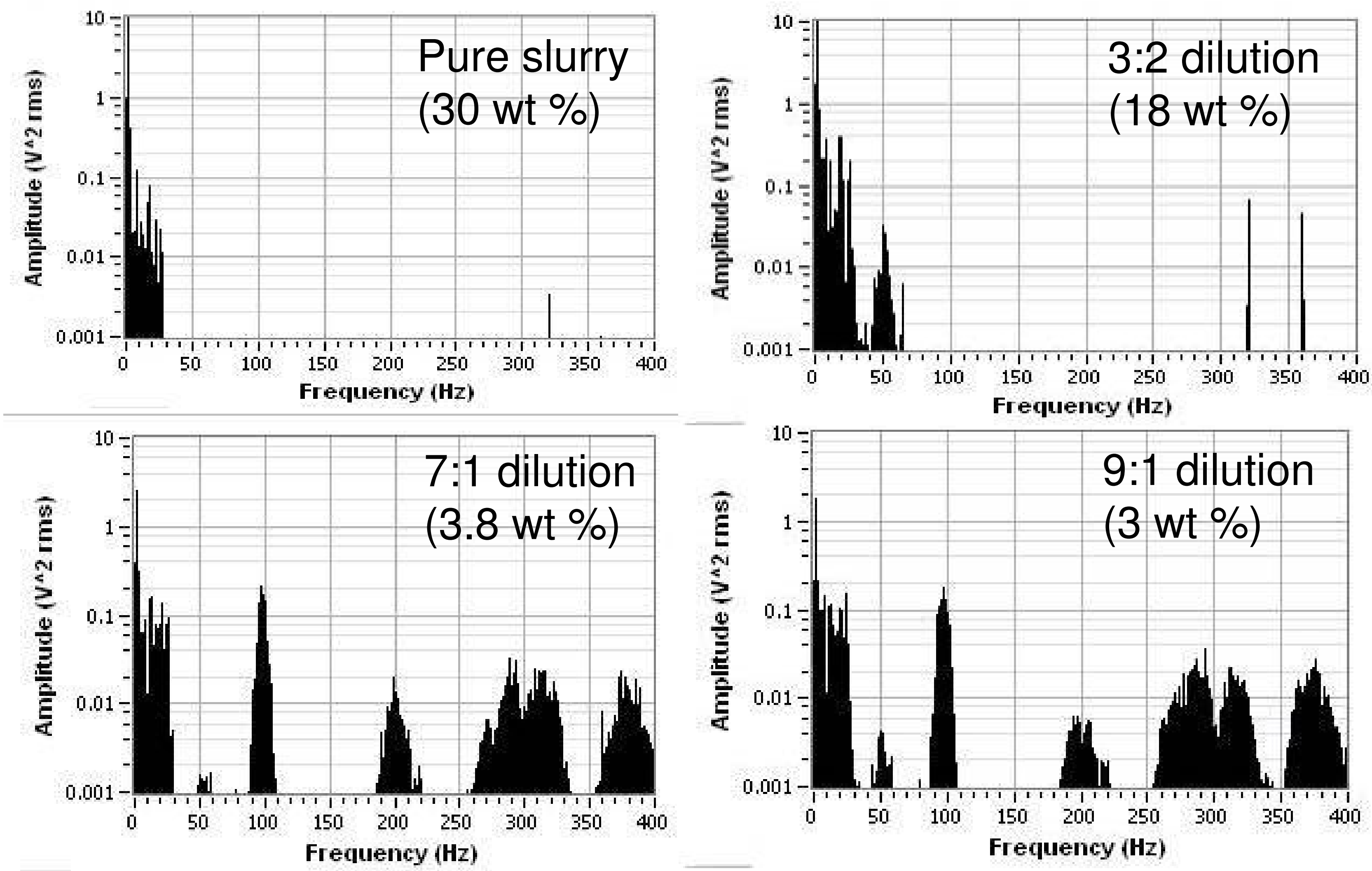
AC grooved CMC D100 pad, 12% by wt fumed silica slurry.

Global Forces – Time Domain

- CoF exhibits a harmonic component at platen rotational rate.
- Occasional bursts of stick-slip are seen in time domain data.
- Stick-slip more prevalent at lower velocities-higher pressures combinations



Global Force Measurement

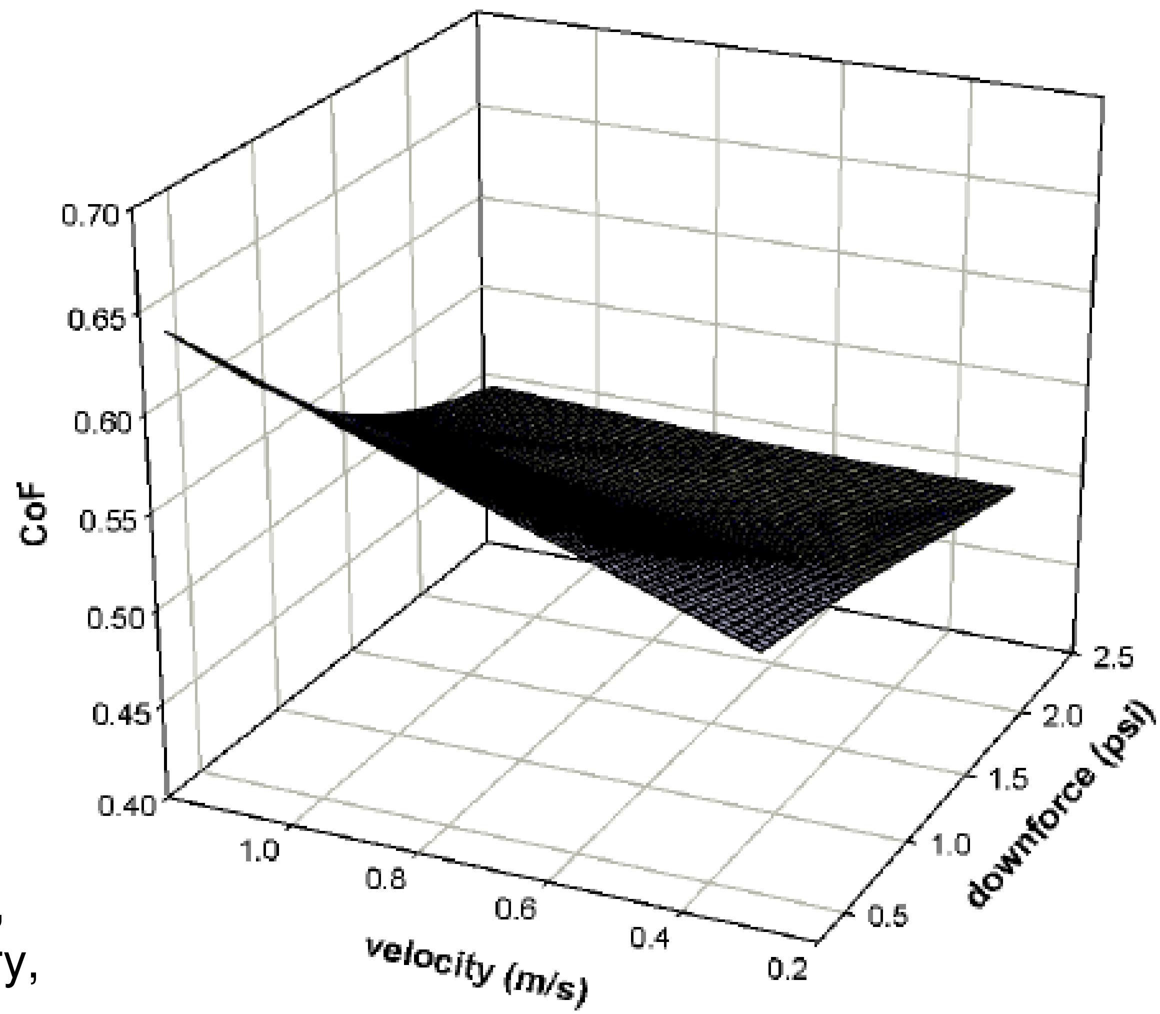


Spectra vary with slurry dilution. High frequencies are indicative of stick-slip.

Coefficient of Friction

- CoF is usually between 0.5-0.55, except in one extreme case (high velocity, low downforce).

- MRR varies considerably over this range; hence CoF and MRR are not directly related.

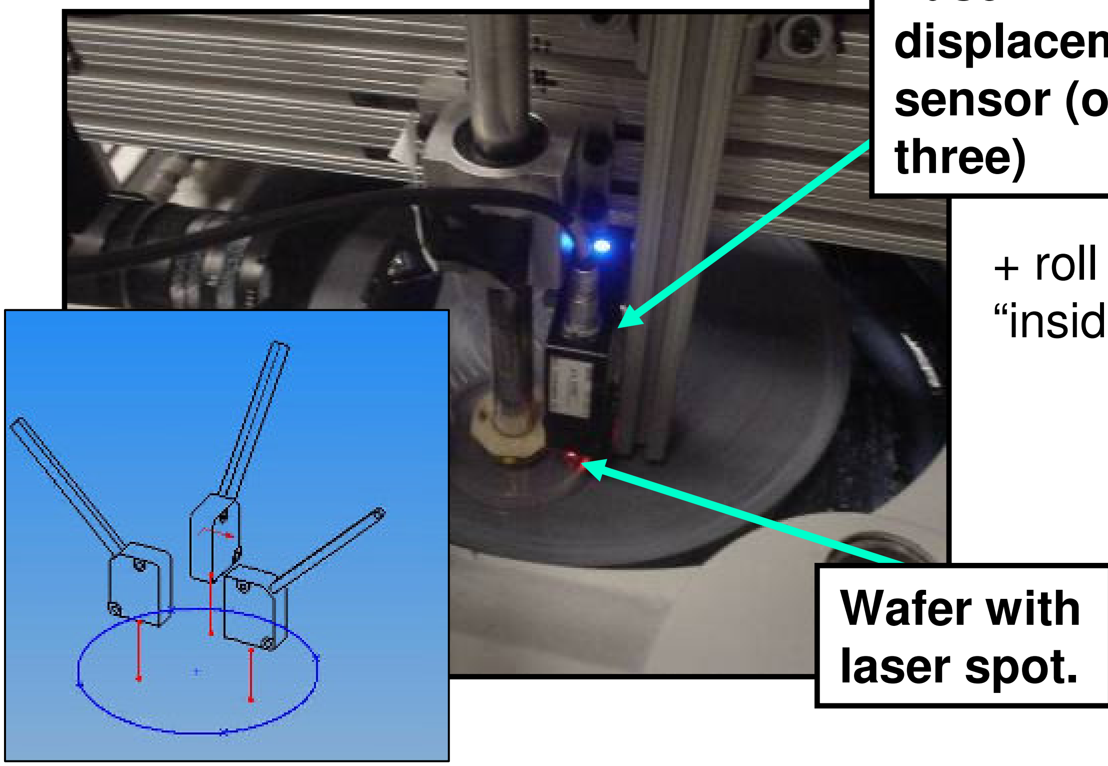


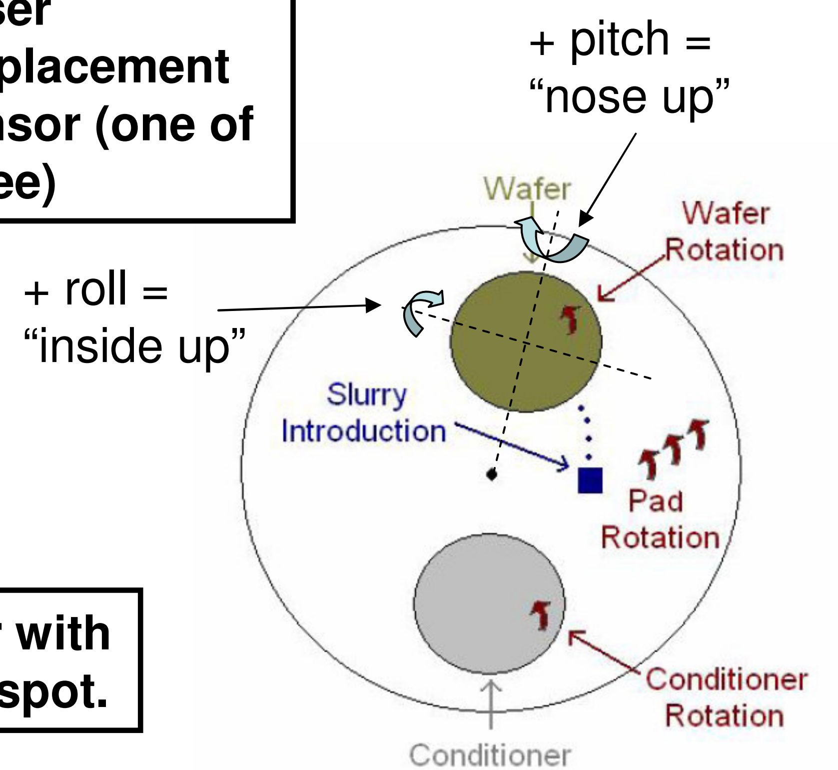
AC grooved CMC D100 pad, 12% by wt. fumed silica slurry, center injection point.

Wafer Attitude

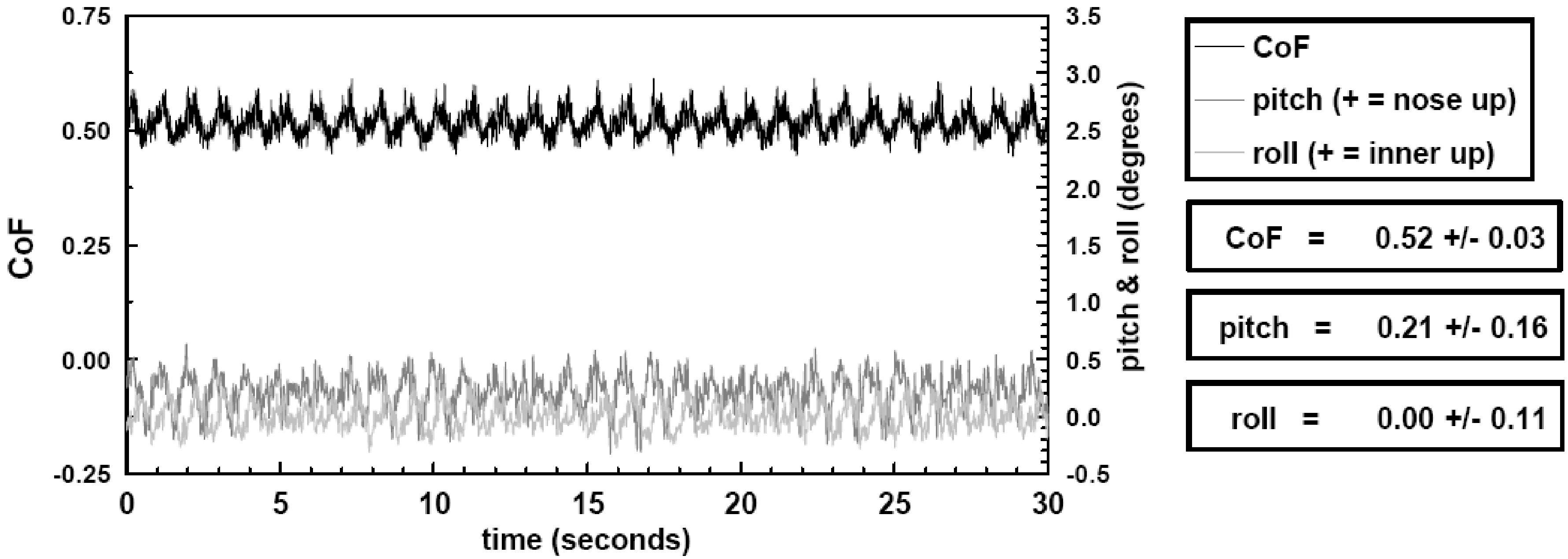
• Three laser displacement sensors are mounted in the rig to measure the wafer pitch and roll during polishing.

• Wafer displacement is correlated to pad angular position (measured with an encoder).





Time Domain Data



- Pitch and roll also exhibit oscillations with a period equal to the pad rotation rate (1 second in this case).

-**Wafer is always nose up at approximately 0.2-0.3 degrees.**

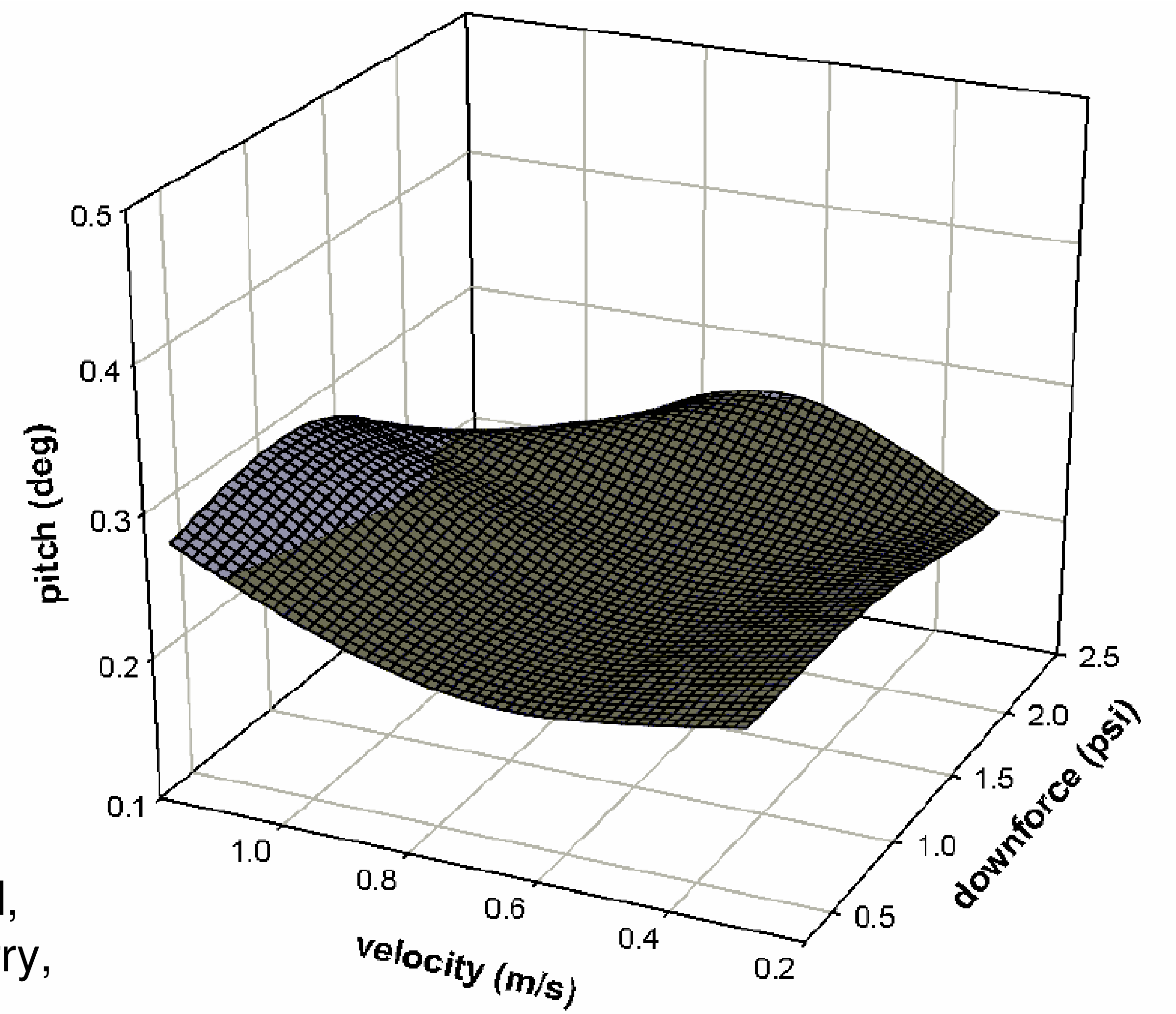
-**Roll and pitch variation are 0.1-0.2 degrees peak-to-peak.**

AC grooved CMC D100 pad, 12% by wt. fumed silica slurry, center injection point, 1.4 psi, 0.6 m/s (60 rpm).

Wafer Attitude

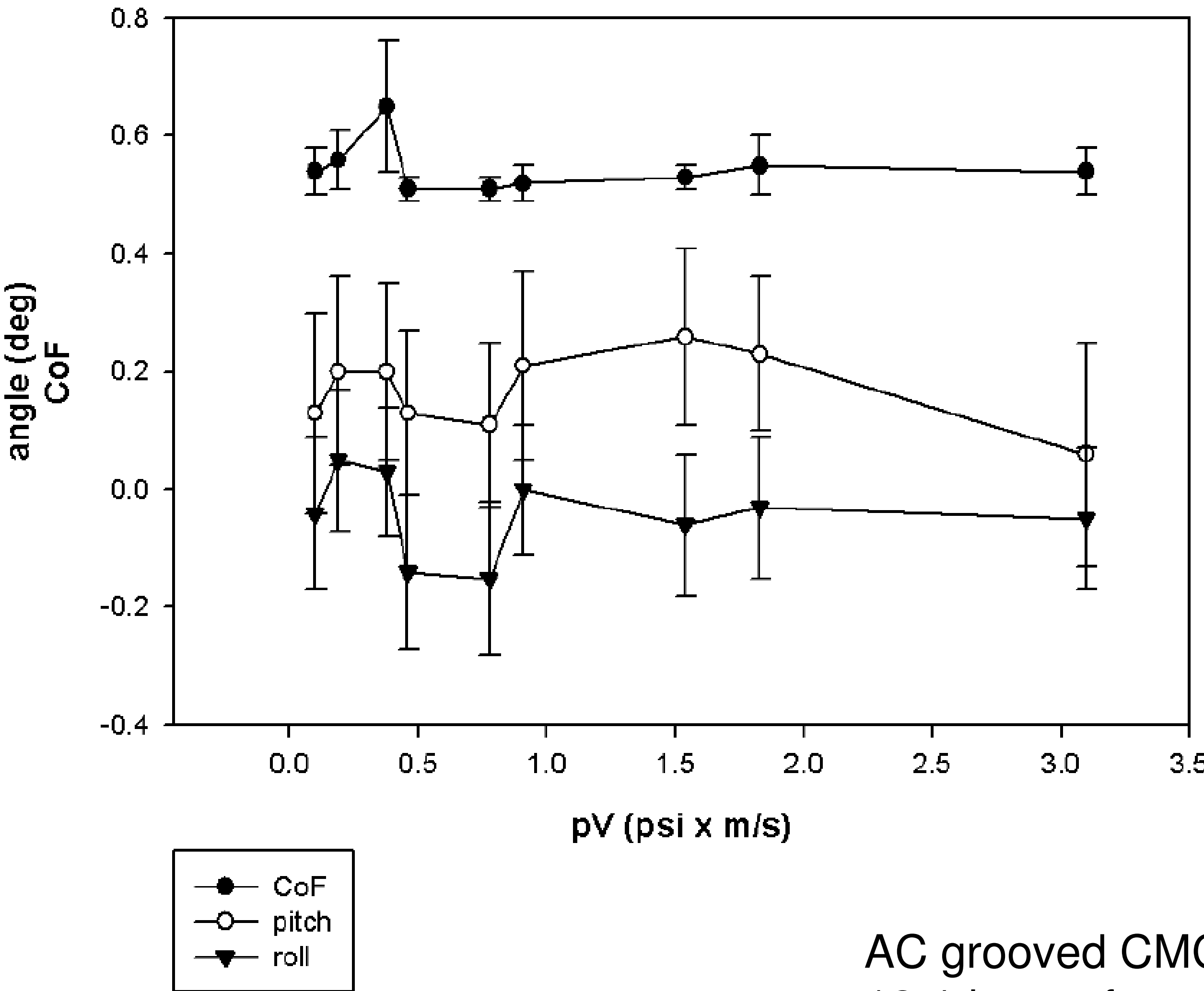
Wafer is consistently pitched "nose-up" (leading edge up) by 0.2-0.3 degrees with little variation across speed and pressure.

Average roll is less than 0.1 degrees in all cases.



AC grooved CMC D100 pad, 12% by wt. fumed silica slurry, center injection point.

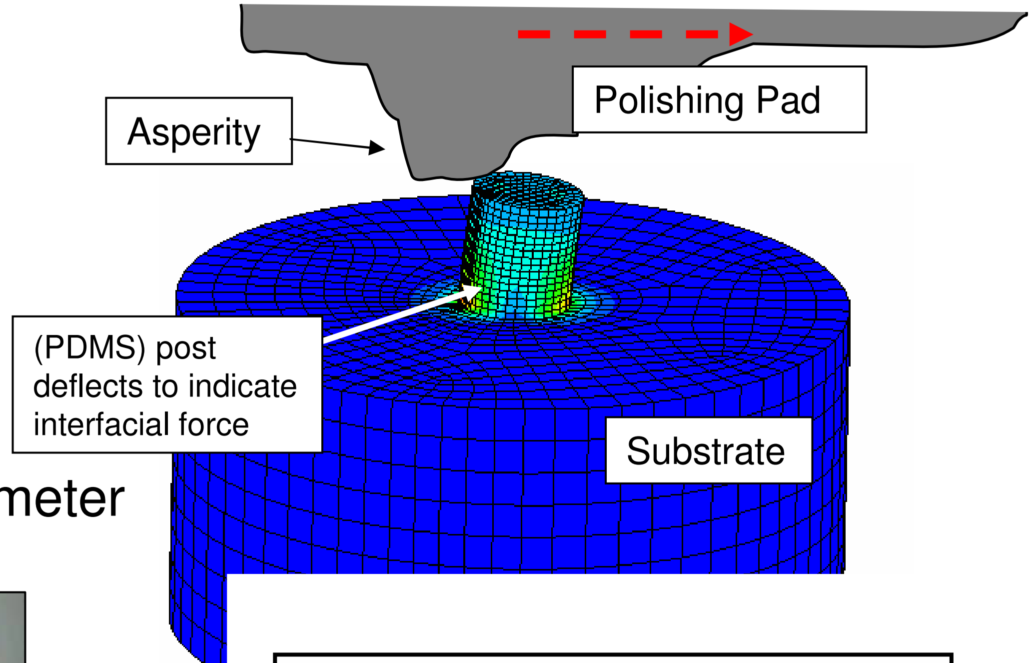
Wafer Attitude and CoF

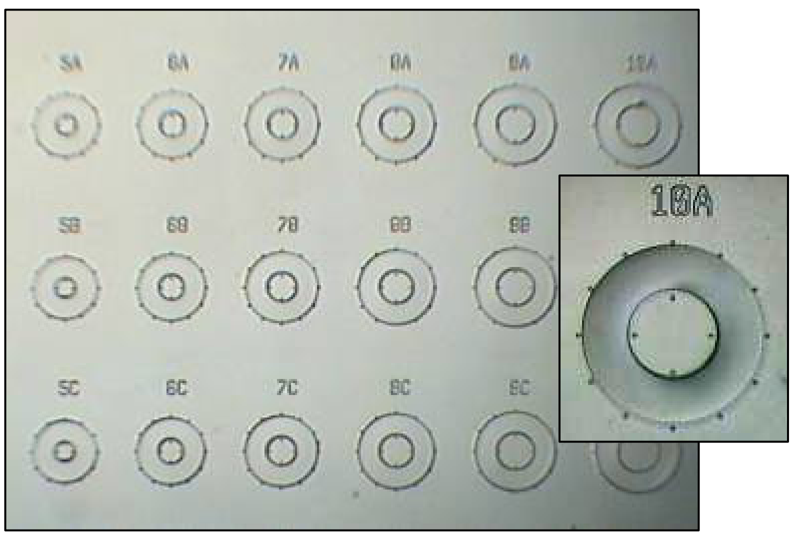


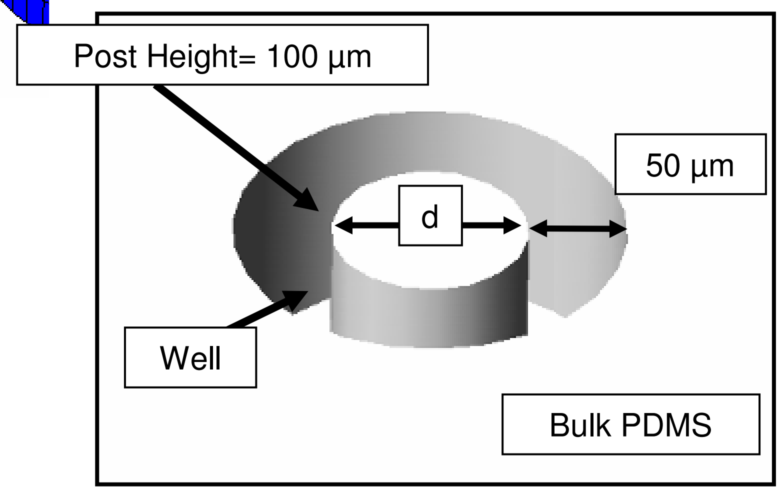
AC grooved CMC D100 pad,
12% by wt. fumed silica slurry,
center injection point.

MEMS Force Sensors

- Cylindrical PDMS posts:
  - 100 µm tall, 30-100 µm diameter.
  - Deflect due to shear force.
  - Recessed in wells.
- Calibrated sensitivity is linear:
  - 200 nm/µN for 100 µm diameter

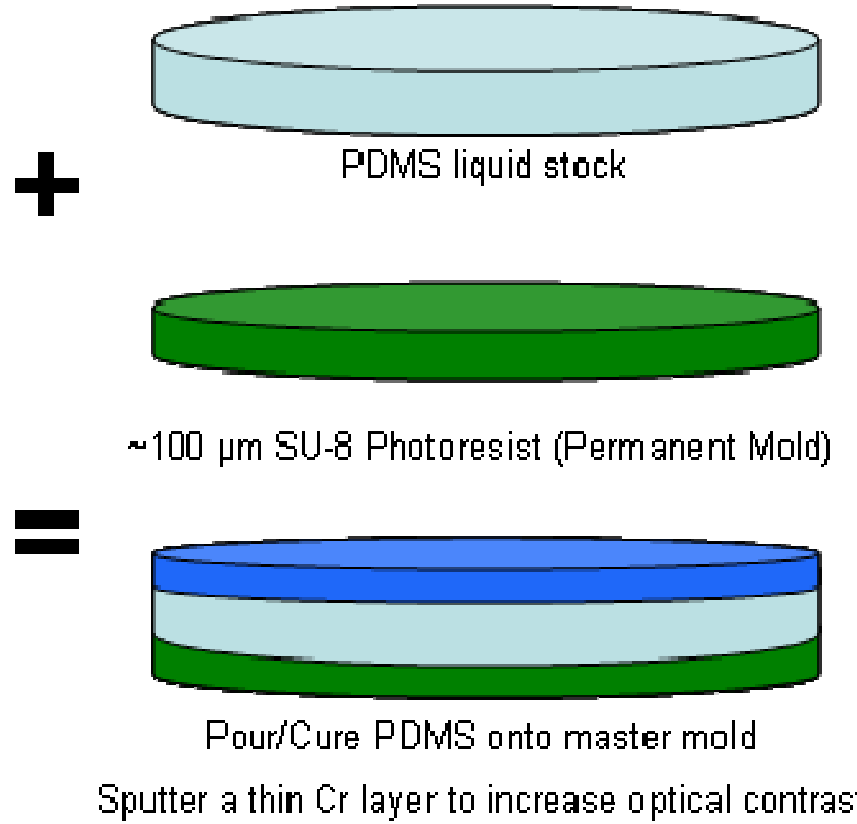


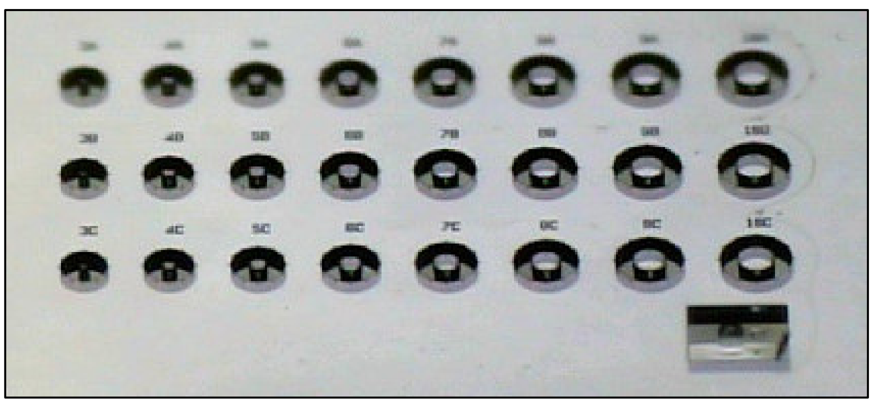




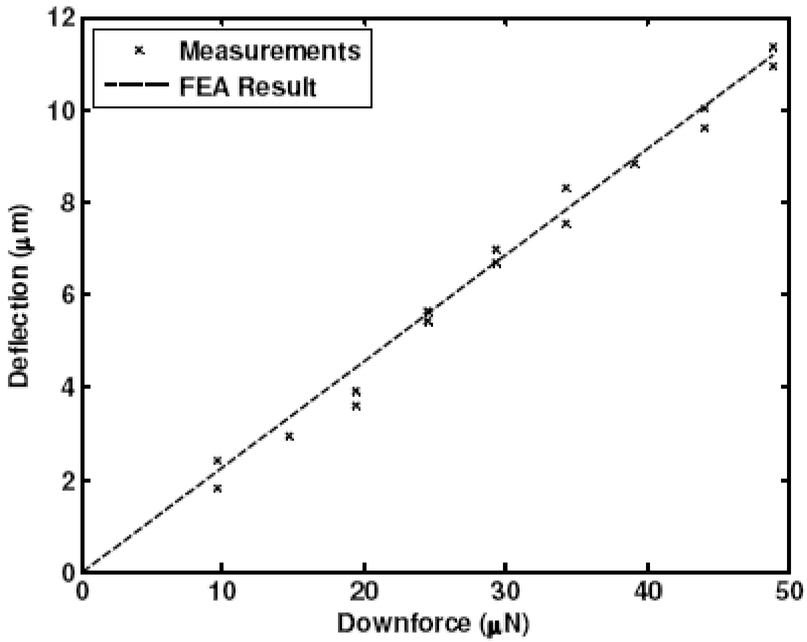
MEMS Force Sensor Fabrication

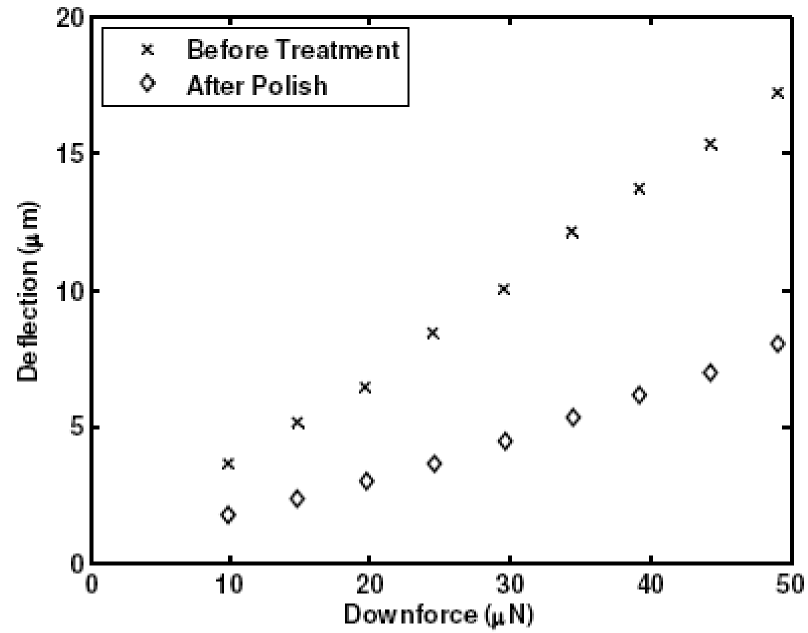
- PDMS is cast over an SU-8 mold
- PDMS structure is de-molded and bonded to a glass wafer with sensors exposed
- A thin metal film (Chromium) is applied to the top surface to increase contrast during observation





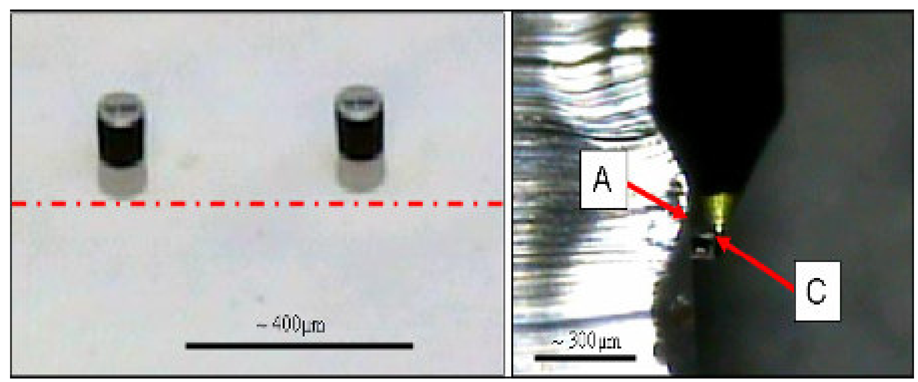
MEMS Sensor Calibration





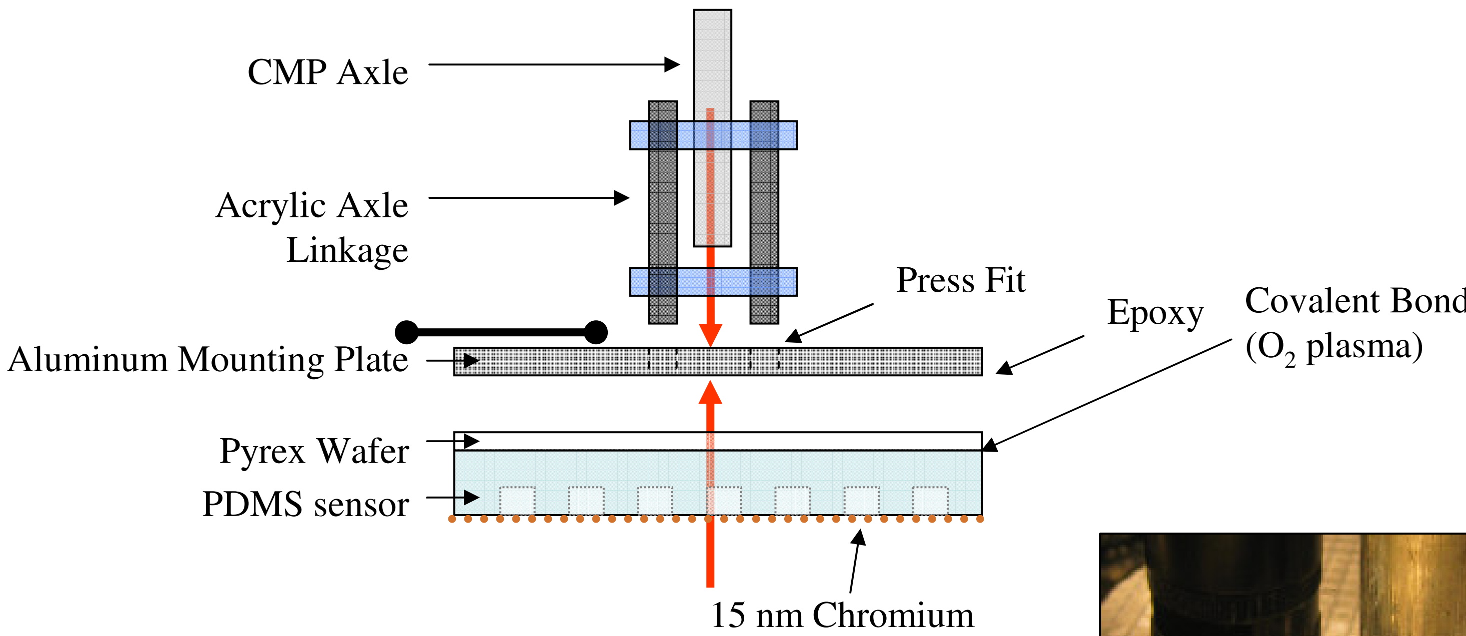
Calibration is linear elastic and agrees very well with FEA simulation of post deflection using standard modulus values for PDMS (750 kPa, ν=0.5).

O_2 plasma treatment results in stiffening of the posts, so calibration is performed after polishing as well as before.

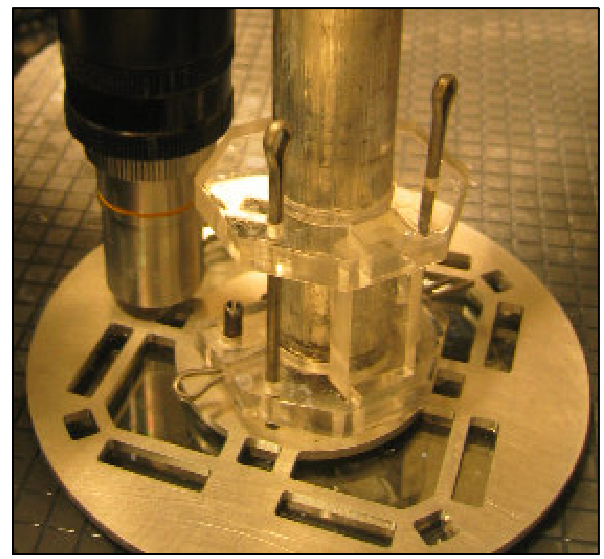


Note: Technique adapted from M. Hopcroft, et al, Fatigue and Fracture of Engineering Materials and Structures. 28(8), (2005).

MEMS Sensor Integration

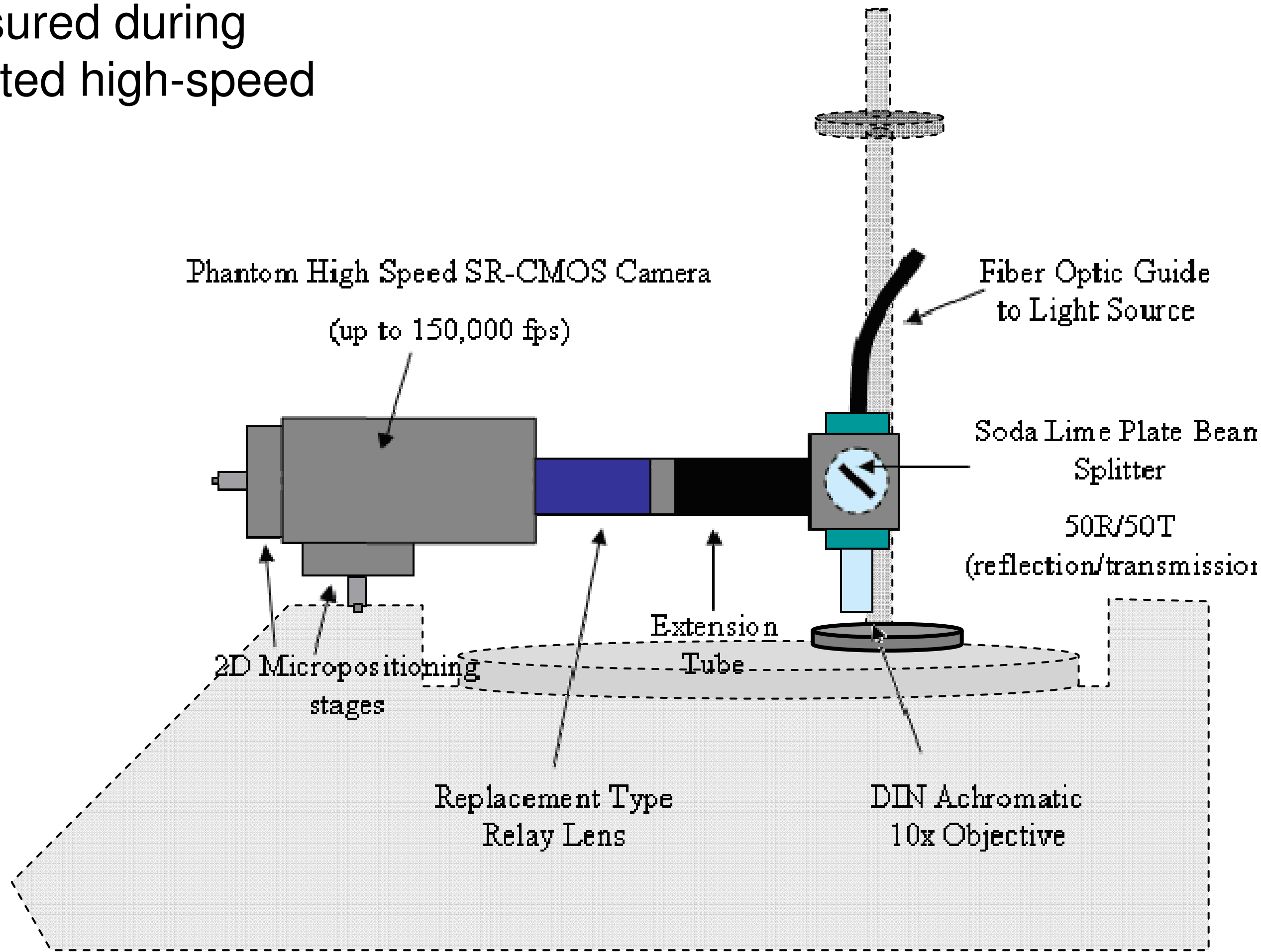


- Bond to Pyrex wafer
  - O_2 plasma – 200 mT, 25W, 30s
- Metallization
  - 15nm Chromium (sputter) – 3 mT, 300W, 35s
- Epoxy to aluminum mounting plate
- Pressed into acrylic CMP axle linkage



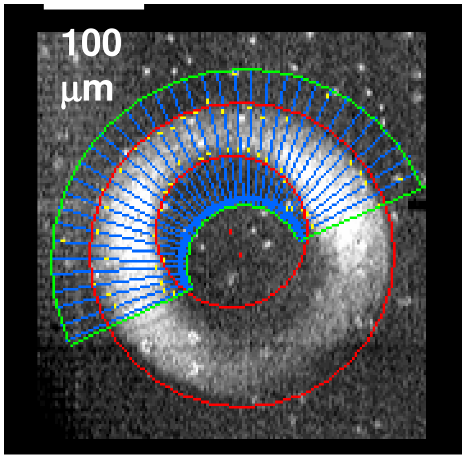
MEMS Sensor Integration

Sensor deflection is measured during polishing using an integrated high-speed microscopy setup.

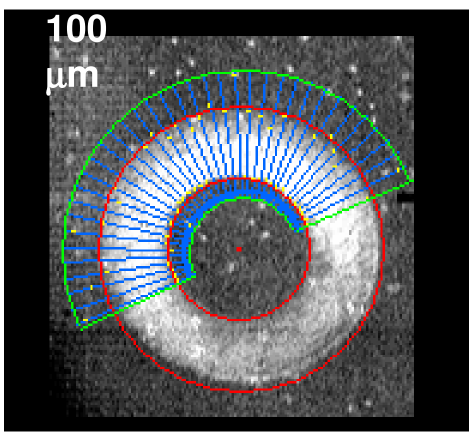


Asperity Level Forces

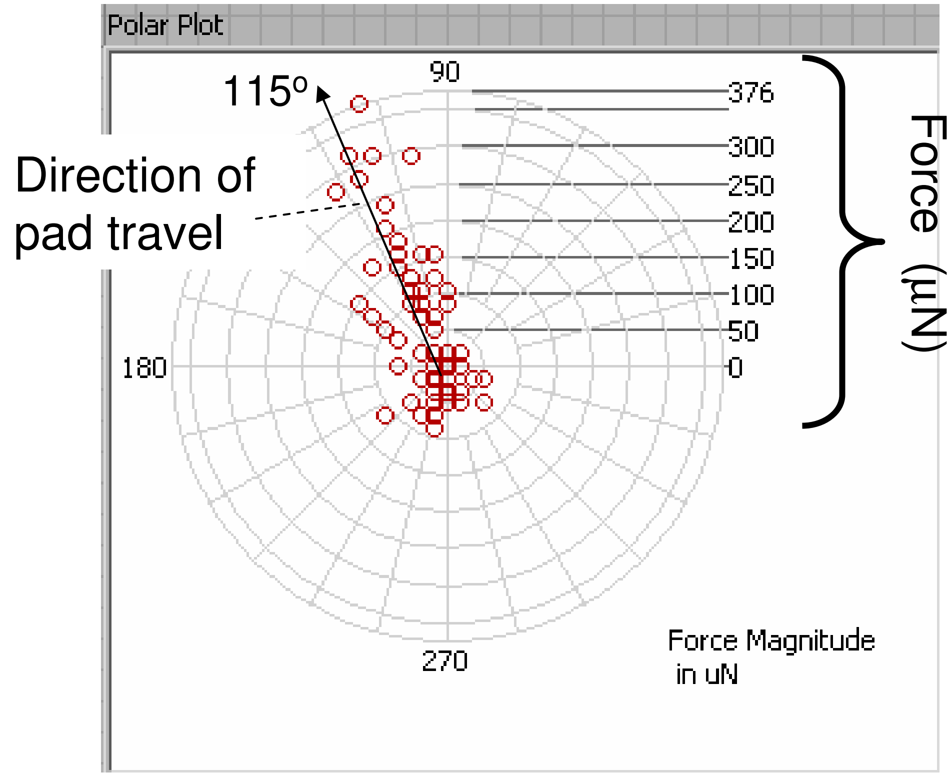
Image processing extracts motion of the post from high-speed (10,000 fps) video.



Deflected

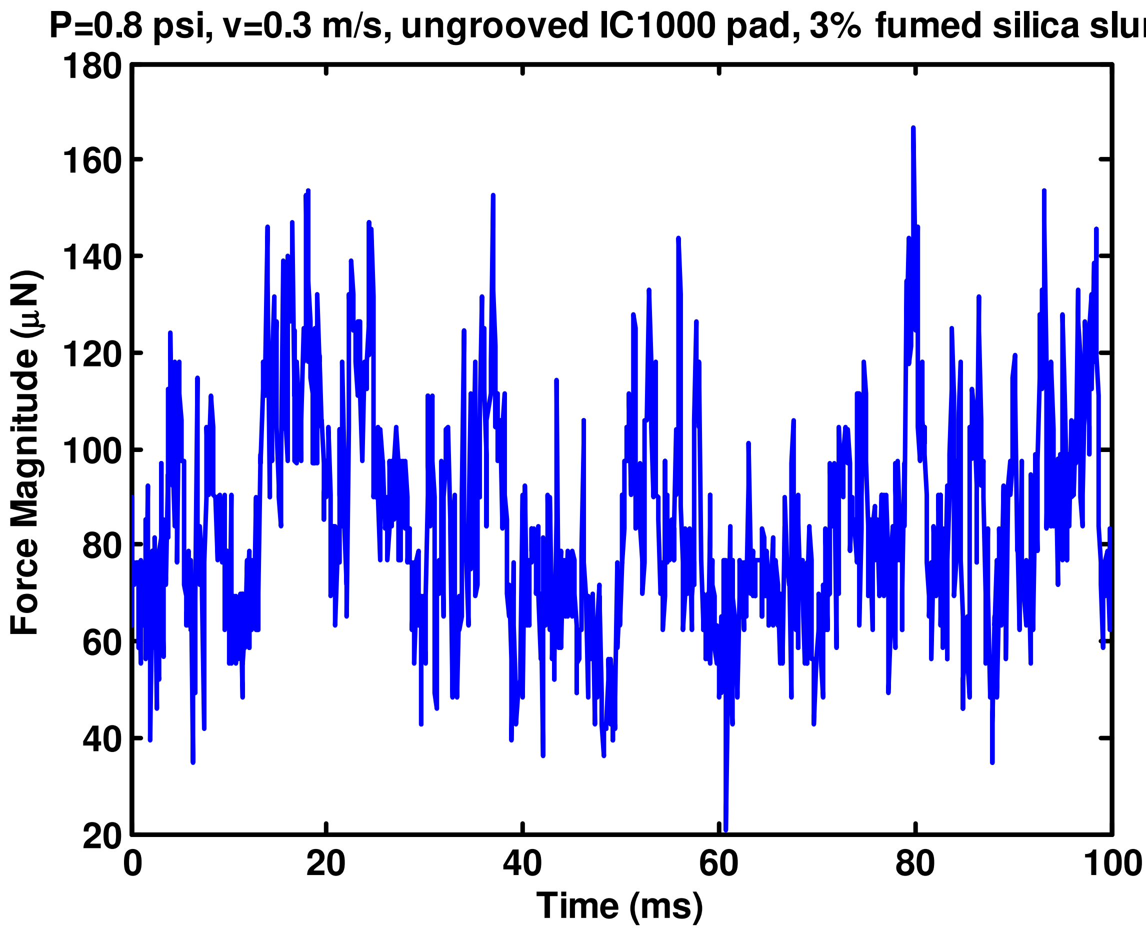


Not deflected



Each point corresponds to the force (direction and magnitude) measured at each 100 microsecond time step. The average force direction aligns with the direction of pad travel.

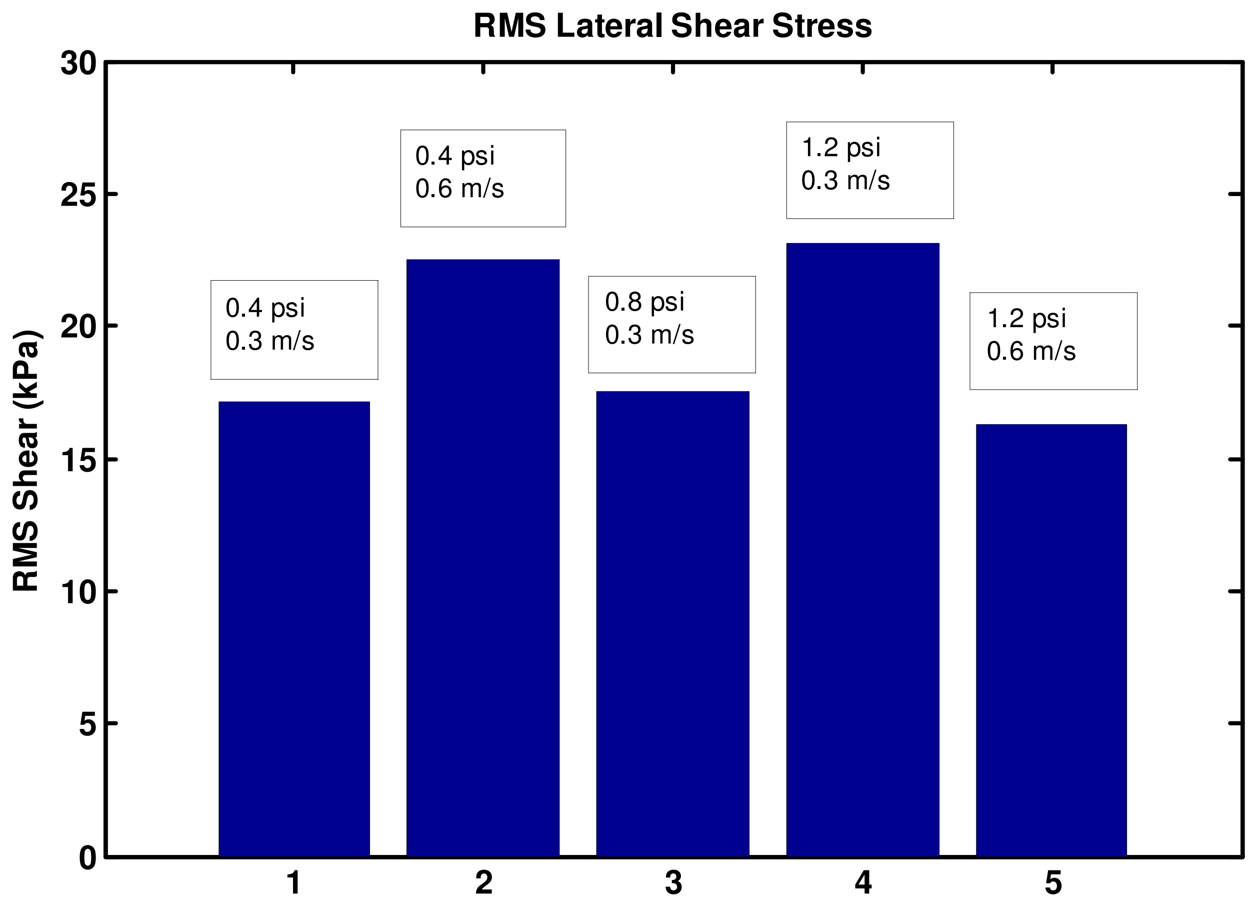
Asperity Level Forces



- Example force trace for ***PDMS polishing*** with ***no wafer rotation*** and ***no conditioning***.
- ***Force is highly variable in time.*** *Large force events have durations on the order of 0.1-1 ms, which is the time for a point on the pad to pass a post.*

Lateral force vs. time on a 80 μm post. 30 rpm (0.3 m/s), 0.8 psi, 9:1 slurry (3% by wt fumed silica slurry), ungrooved IC1000 pad.

Asperity Level Forces: Trends



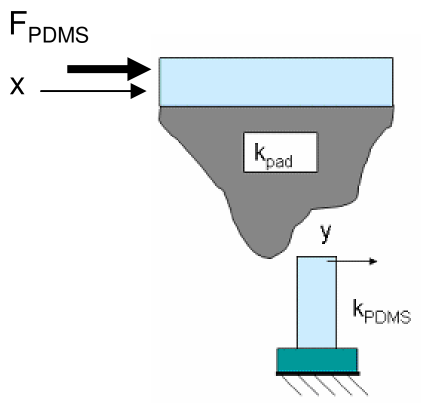
0.4 psi = 2.8 kPa

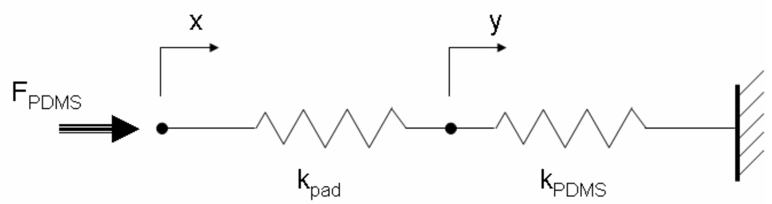
Since CoF is on the order of 0.5 globally, this suggests that approximately

1-5% of the structures are bearing the majority of the load (note this is an unconditioned pad).

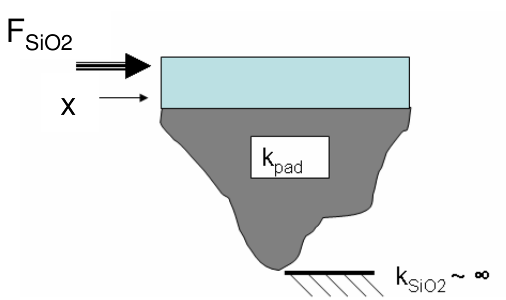
RMS lateral force for 80 and 90 μm diameter PDMS posts, 3% fumed silica slurry, ungrooved IC1000 pad, no conditioning, no wafer rotation.

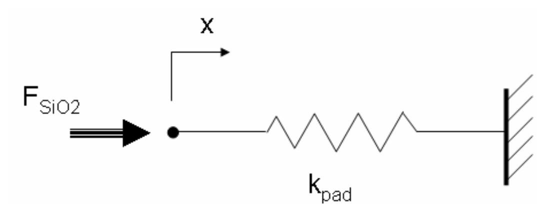
Force Interpretation





$$F_{PDMS} = x \cdot k_{eq} = \frac{x}{\frac{1}{k_{pad}} + \frac{1}{k_{PDMS}}}$$





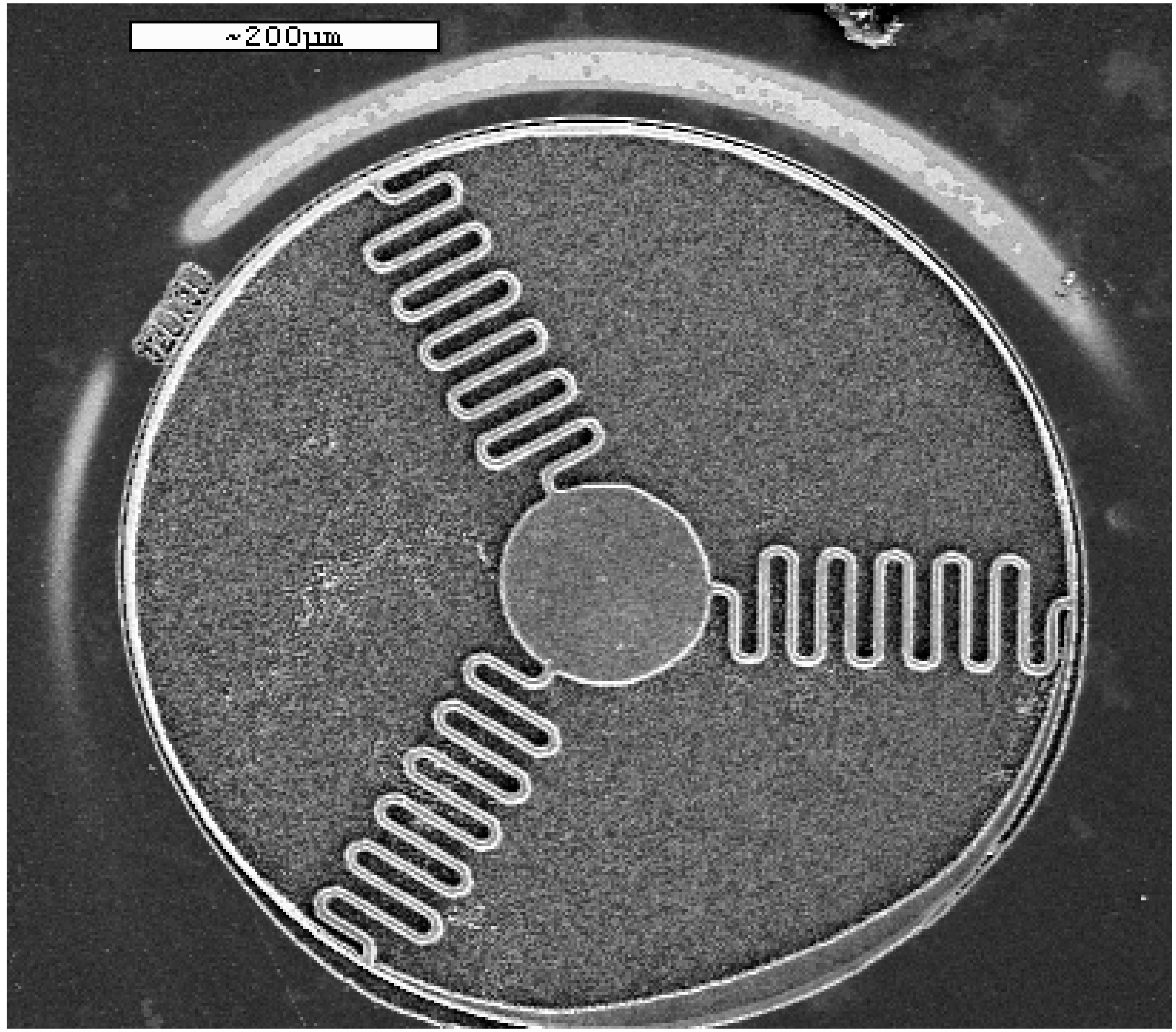
$$F_{SiO_2} = x \cdot k_{pad}$$

When moving from the PDMS posts to a stiffer substrate, a first order estimate of the ratio of the local polishing forces can be easily obtained:

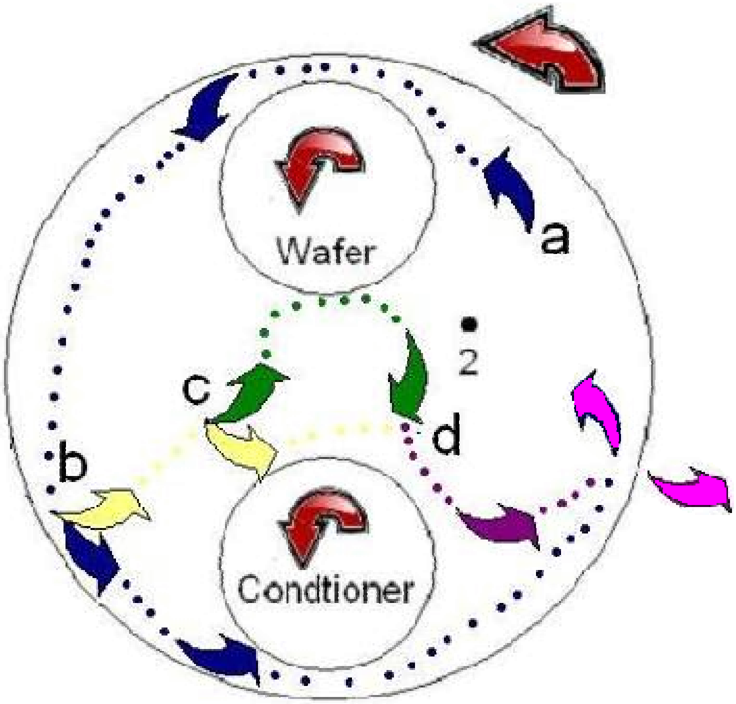
$$\frac{F_{SiO_2}}{F_{PDMS}} = 1 + \frac{k_{pad}}{k_{PDMS}}$$

Silicon Force Sensors

Silicon sensors are under development to span the same force range, but allow us to polish a hard, less tacky material so we can condition.

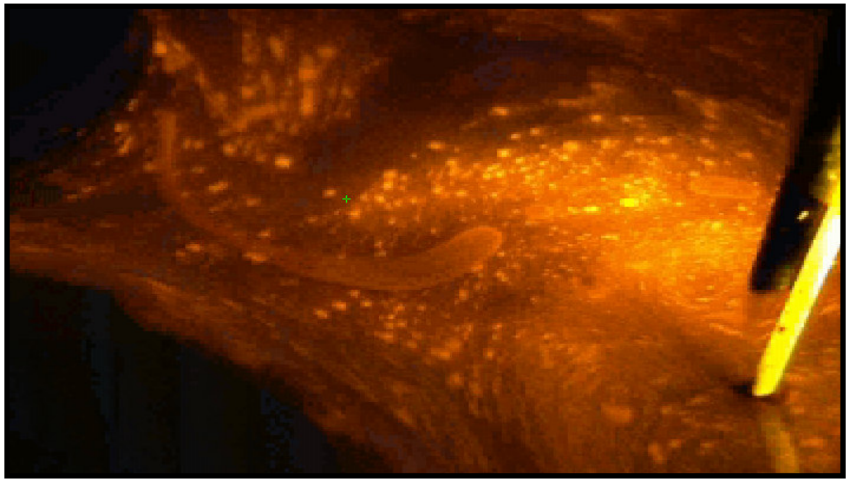


Flow Visualization



Flow visualization using oil drop tracers allows determination of:

1. Slurry path.
2. Slurry residence.
3. Presence of vorticity.
4. Presence of bow waves.



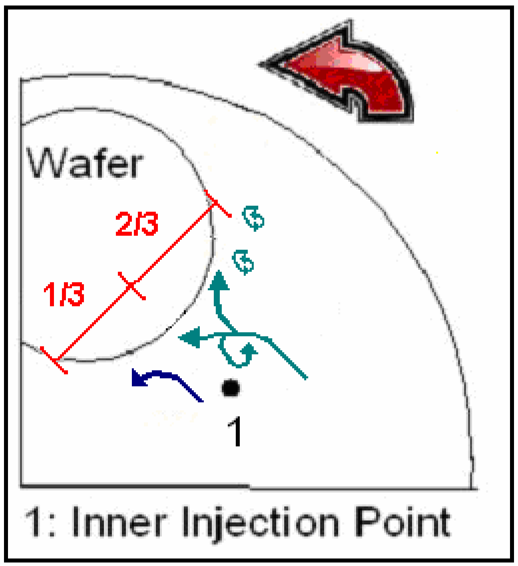
Variables of interest:

1. **Slurry injection point.**
2. **Pad grooving.**
3. **Wafer speed.**
4. **Downforce.**

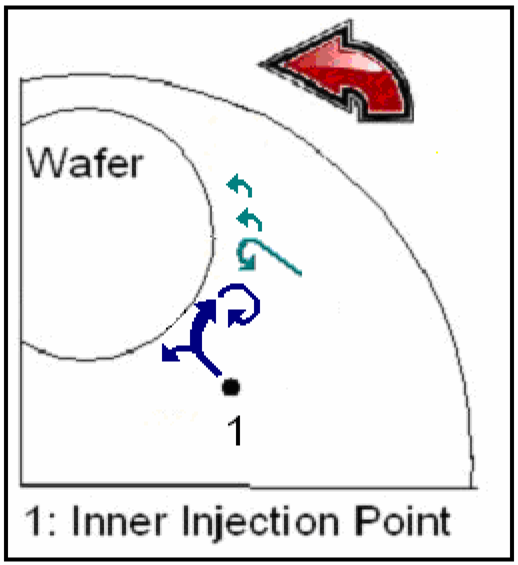
Data is available at:
http://docs.google.com/Doc?id=dc9dhhdb_13fphfz7dp

Example of Flow Visualization

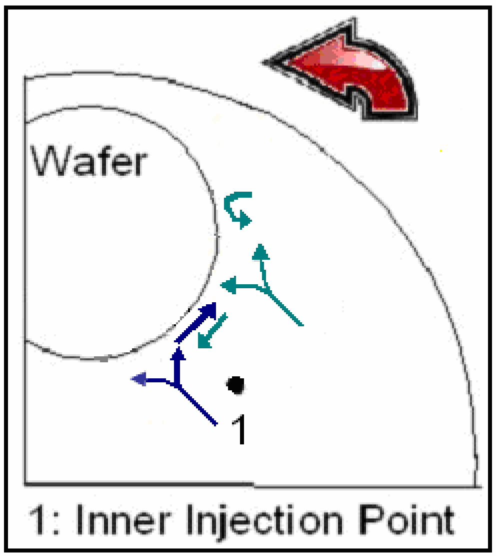
Pad grooving is observed to have a major impact on slurry flow patterns around the wafer.



Ungrooved FX9 pad:
Old slurry dominates wafer bow wave.



XY Grooved FX9 Pad:
New slurry dominates wafer bow wave.

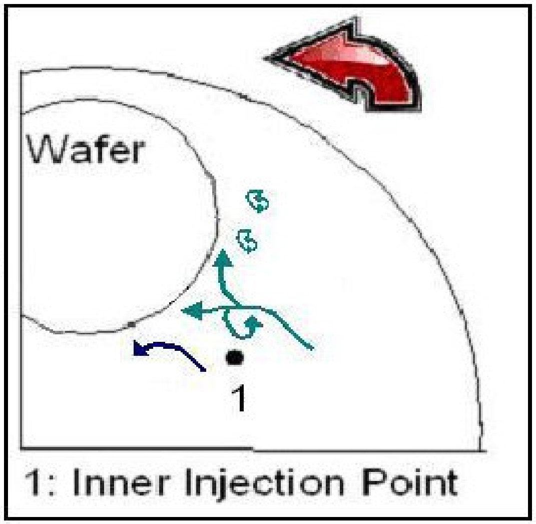


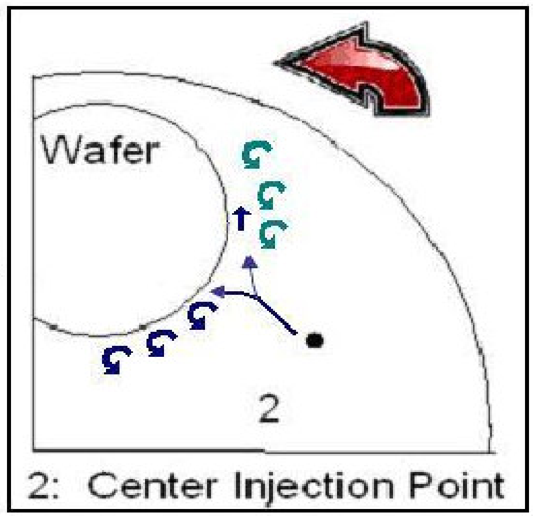
AC Grooved D100 Pad:
Shearing of old and new slurry, mixing at bow wave.

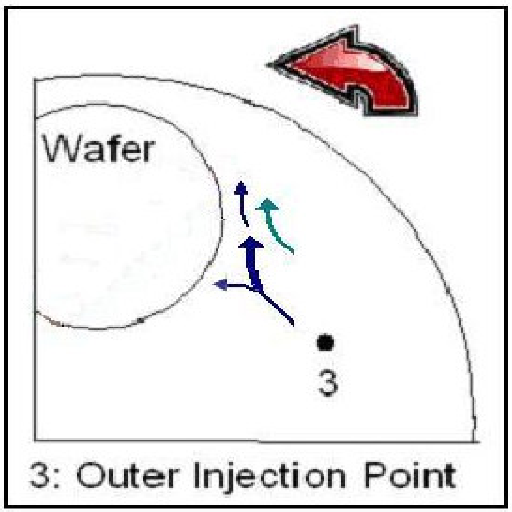
For inner injection point, 35 rpm, conditioning, 12% wt fumed silica slurry.

Example of Flow Visualization

Injection point also has an impact, this is most pronounced with flat (ungrooved) pads.







Inner Injection: Old slurry dominates wafer bow wave, considerable mixing.

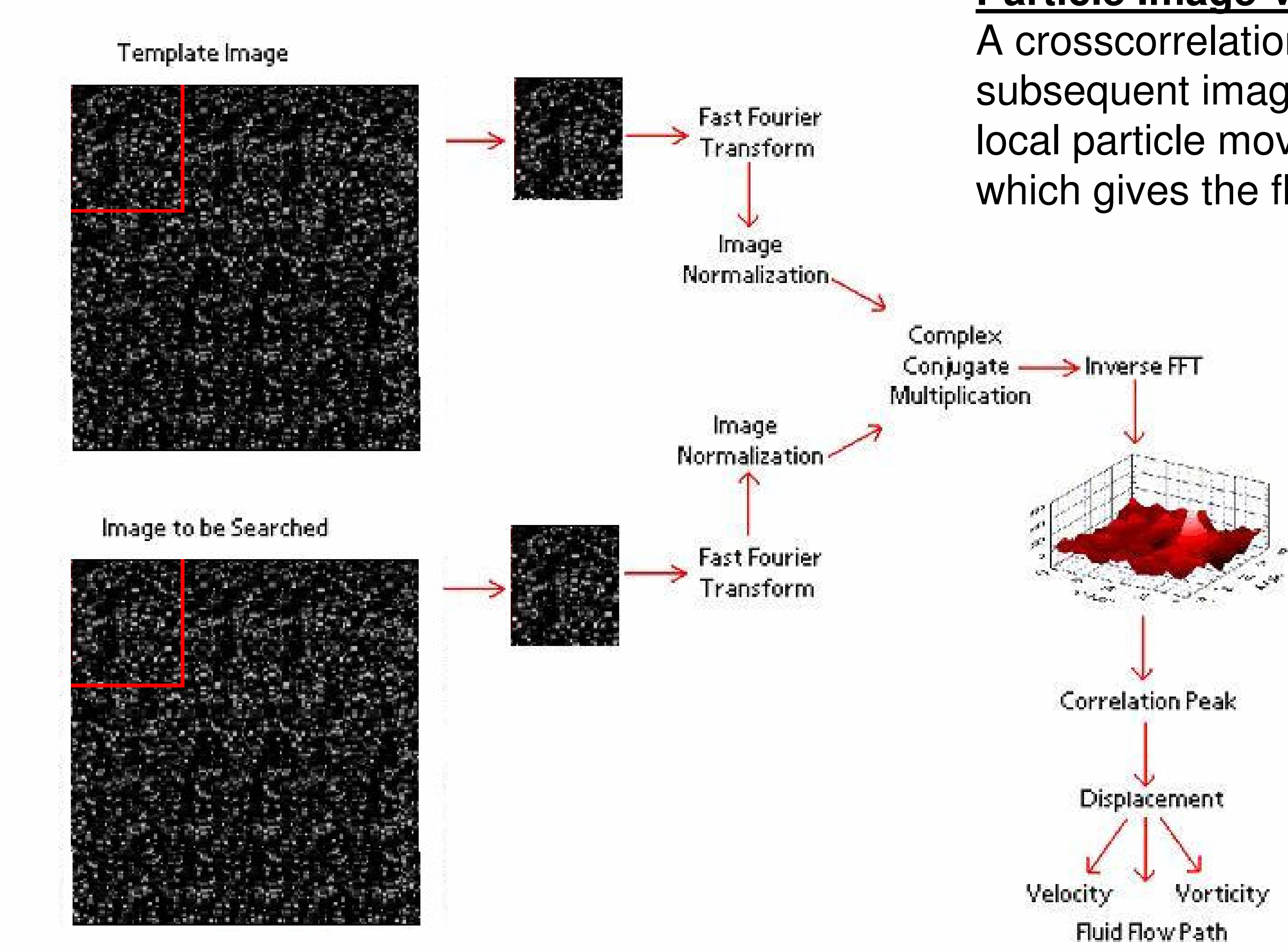
Mid Injection: New slurry dominates wafer bow wave, considerable mixing.

Outer Injection: New slurry dominates the box wave, very little mixing.

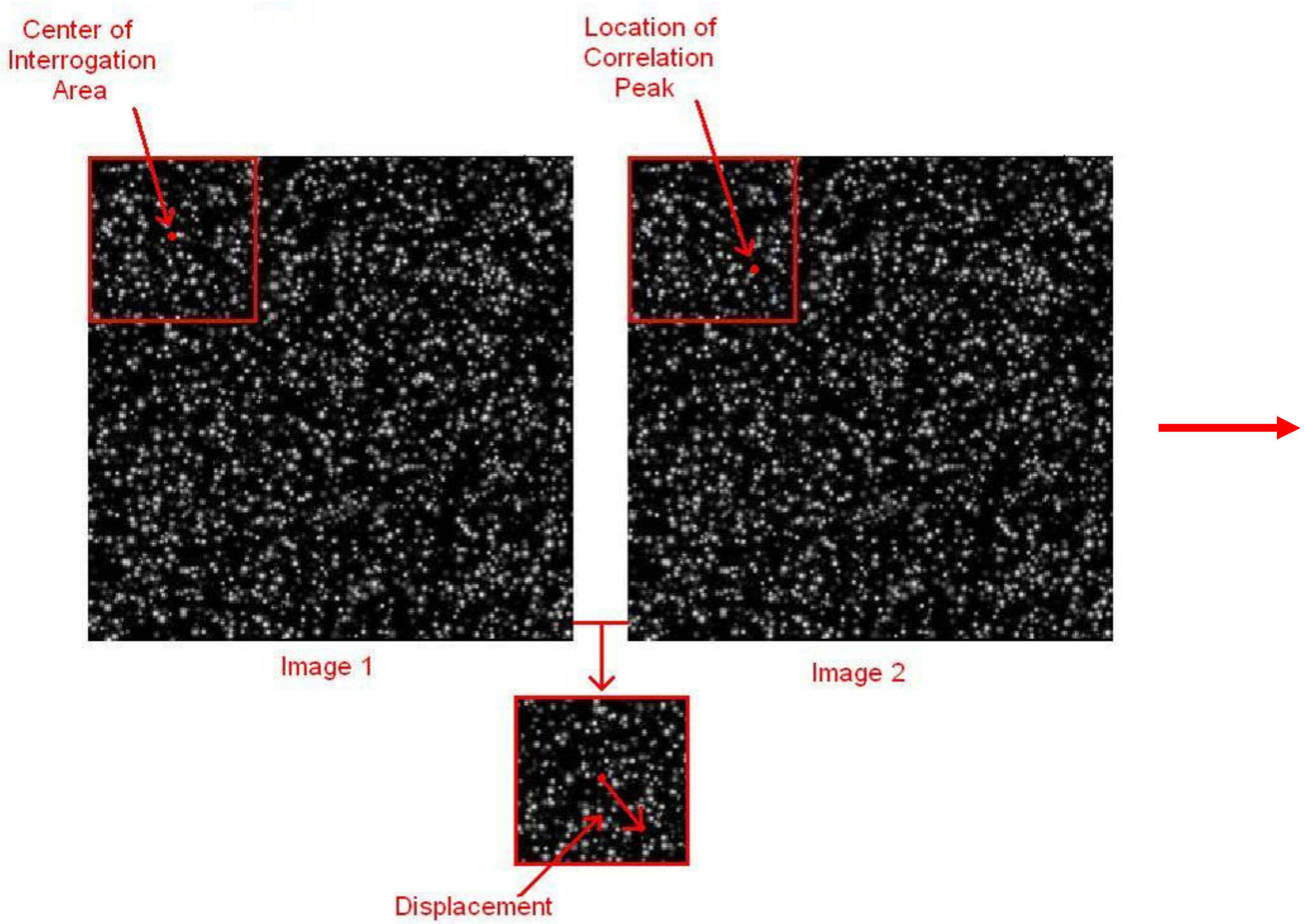
For ungrooved pad, 35 rpm, conditioning, 12% wt fumed silica slurry.

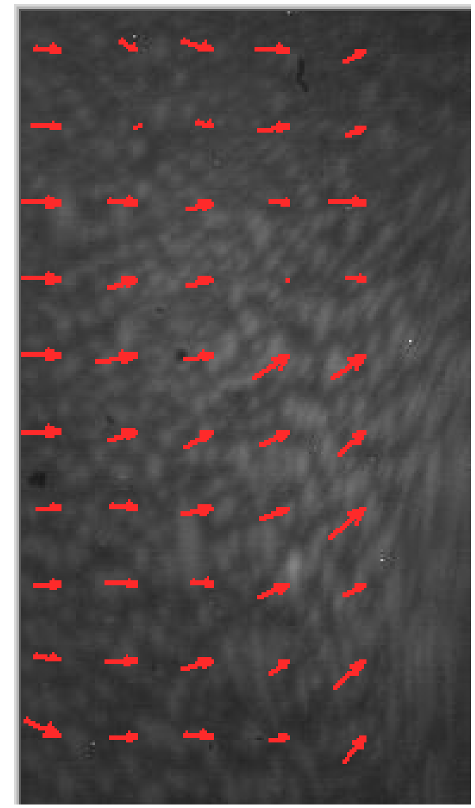
Quantitative Flow - PIV

Particle Image Velocimetry.
A crosscorrelation between subsequent images finds local particle movement, which gives the flow field.



Vector Field Assembly





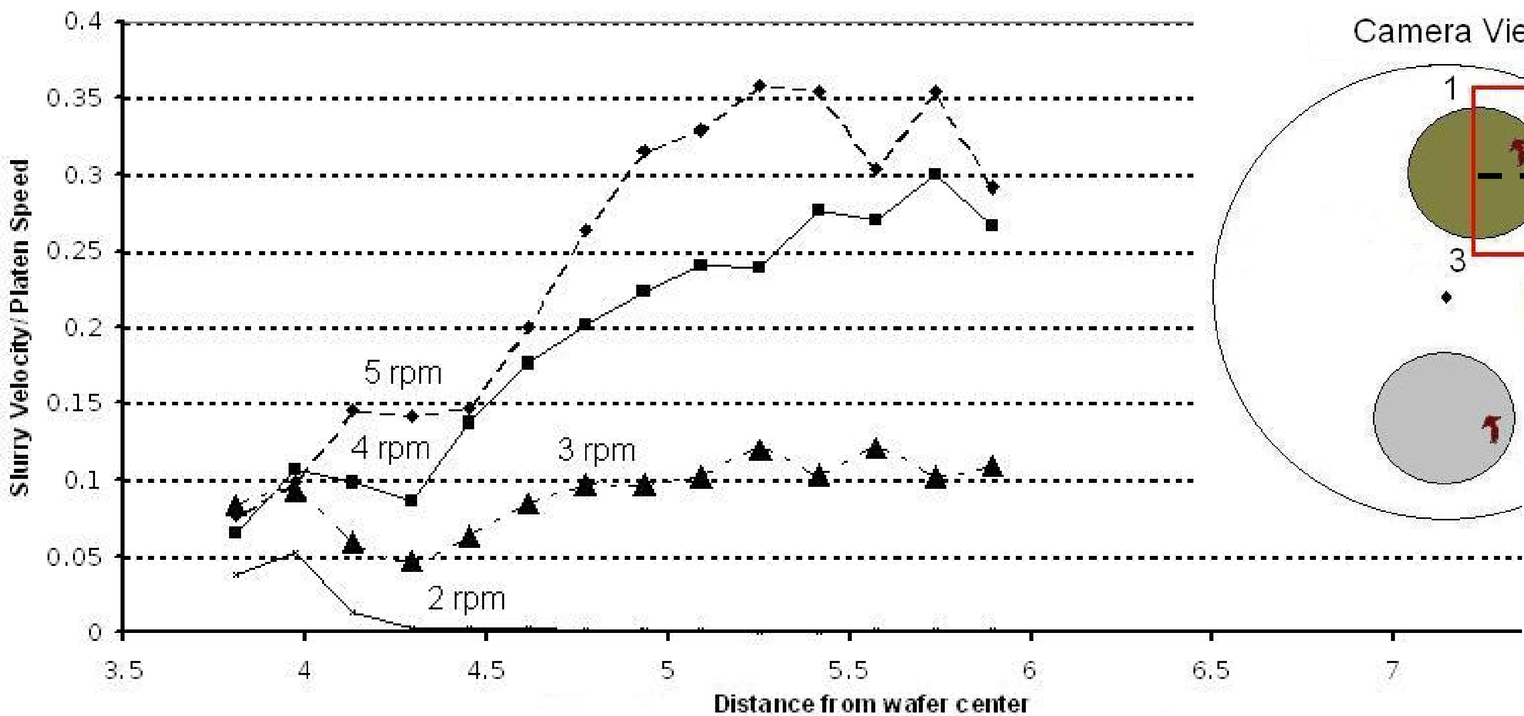
PIV results in a full vector flow field, as long as the contrast is good and frame rate is high enough.

In-Situ PIV: Slurry Velocity

• Initial measurements were carried out at slow speeds (2-5 rpm) which give relative pad wafer velocities of 0.02 – 0.05 m/s.

• We find slurry velocity increasing as we move away from the wafer.

• Slurry speed appears to reach a maximum of 10-30 % of the platen speed, implying through thickness shear at all locations.



Flow velocity as a function of distance from the wafer center.

Conclusions

DELIF: Contact/Film thickness

- Dynamic contact percentage is between 0.1-1% for a D100 pad across all images. Median is 0.2-0.3%. This is similar to static results, suggesting that static measurements are relevant.
- Slurry film thickness is < 100 μm everywhere outside the grooves.

Mechanical: Global forces, motion, MRR

- MRR is Prestonian. CoF is 0.5-0.55 for all but extreme cases.
- Mean nose up pitch of 0.3 deg. Mean roll is zero. Both exhibit 0.1 degrees peak-to-peak at the pad rotation frequency.

MEMS: Microscale force sensors

-80-90 μm diameter PDMS structures experience surface shear on the order of 20 kPa, with peak-to-peak variation of 20 kPa.
-Surface shear varies somewhat with velocity and downforce, but does not appear to be a direct indicator of MRR.

-*The combination of these results suggests that increasing downforce spreads the load over more contact areas, increasing global MRR but not changing local MRR.*

PIV/Flow Vis: Visualizing full-pad flows

-Pad scale slurry flow patterns (outside the wafer) are strongly influenced by pad grooving and slurry injection point. They are not strongly influenced by rotation rate or downforce. Full PIV is feasible and shows slurry slowing near the wafer.

Publications 2007-2008

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D. Gauthier, A. Mueller, R. D. White, V. Manno, C. Rogers, D. Hooper, S. Anjur, M. Moinpour, "*Micromachined Lateral Force Sensors for Characterization of Microscale Surface Forces During Chemical Mechanical Polishing",* in the **Proceedings of the Materials Research Society**, MRS Spring Meeting, March 24-28, 2008.

D. Gauthier, A. Mueller, R. D. White, V. Manno, C. Rogers, S. Anjur, M. Moinpour, "*Micromachined Lateral Force Sensors for Characterization of Microscale Surface Forces During Chemical Mechanical Polishing",* in **Proceedings of Nanotech 2008**, Boston, MA, June 1-6, 2008.

N. Braun, C. Gray, A. Mueller, J. Vlahakis, D. Gauthier, V. P. Manno, C. Rogers, R. White, S. Anjur, M. Moinpour. "*In-Situ Investigation of Wafer-Slurry-Pad Interactions during CMP*" in the **Proceedings of the International Conference on Planarization/CMP Technology,** Dresden, Germany, October 25-27, 2007.

Gray, C., Rogers, C. Manno, V., White, R., Moinpour, M., Anjur S.."*Determining Pad-Wafer Contact using Dual Emission Laser Induced Fluorescence*", in the **Proceedings of the Material Research Society**, Vol. 991, Symposium C, Advances and Challenges in Chemical Mechanical Planarization, 2007.

Mueller, A. White, R. D., Manno, V., Rogers, C., Barns, C. E., Anjur, S., and Moinpour, M. "*Micromachined Shear Stress Sensors for Characterization of Surface Forces During Chemical Mechanical Polishing*" in the **Proceedings of the Material Research Society**, Vol. 991, Symposium C, Advances and Challenges in Chemical Mechanical Planarization, 2007.