Characteristics of Spatial Endpoint Uniformity of CMP for Reduced Consumables and Improved Yield

May 31, 2001

Task A4- 2:
Sensors and Control for CMP Waste Reduction

MIT Microsystems Technology Laboratories

Student
David White
(dwhite@mtl.mit.edu)

Faculty
Duane S. Boning
(boning@mtl.mit.edu)

Impact of Sensors and Controls for CMP

Manufacturing Metrics:

❑ Single CMP tools now run around 63% of capacity (40 wafers/hour) where 2-3 hours of an 8 hour shift are spent performing metrology to achieve better endpoint and uniformity.

✓ Availability of in-situ sensors and controls may: increase production by 40-60%, eliminate 1-2 test wafers per hour (5-6K wafers per year, per machine), eliminate 3-4 reworked wafers per hour (9K per year),

❑ Single CMP tool may consume $275,000 of slurry per year [1] and produce 27,500 gallons of waste slurry that requires treatment & resources.

❑ CMP tools now account for 30% to 40% of total water consumed by fabs [2].

✓ reduce processing times and effectively reduce slurry and water by at least 10-15%.

ESH Metrics:

	Usage Reduction			**Emission Reduction**			
Goals / Possibilities	**Energy**	**Water**	**Chemicals**	**PFCs**	**VOCs**	**HAPs**	**Other Hazardous Wastes**
In-situ sensors and controls for CMP	10 -15%	10 - 15%	> 15% reduction in slurry	N/A	N/A	N/A	> 15% reduction in pads

[1] T. Bibby and K. Holland, Chemical Mechanical Polishing in Silicon Processing, series Semiconductors and Semimetals, vol. 63, Academic Press, 2000.
[2] G. Corlett, "Can CMP Waste Treatment Ever Be Environmentally Friendly?", J. Adv. Appl. Contamin. Control, December 1998.

Example: CMP Sequence Capture with IR Camera

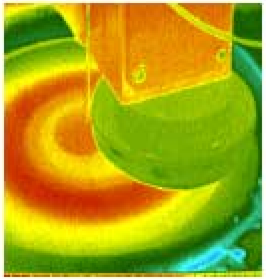
- Examining Factors in Wafer-level Uniformity
- Developing In-situ Spatial Endpoint Detection
- Results:
  - Gathered data from Cu polish experimental designs
  - Correlated radial dependence of oxide removal rate with IR images
  - IR thermography not suitable in-situ, spatial endpoint detection
  - IR thermography does provide visibility into CMP and is suitable for developing thermal models.
  - Examined new in-situ reflectance based sensor that measures spatial endpoint

***Acknowledgements:* Kai Yang and Darrel Erb at AMD Submicron Development Center and Jian-Yu Lai, Jason Melvin and Prof. Chun at MIT**

(a.) Carrier retrieves a wafer while the polishing pad achieves desired speed.

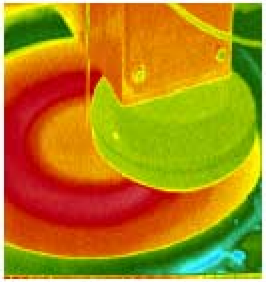
(b.) Carrier begins lowering the wafer onto the polishing pad for planarization.

(c.) The wafer makes contact with the polishing pad indicated by the heating of pad underneath.



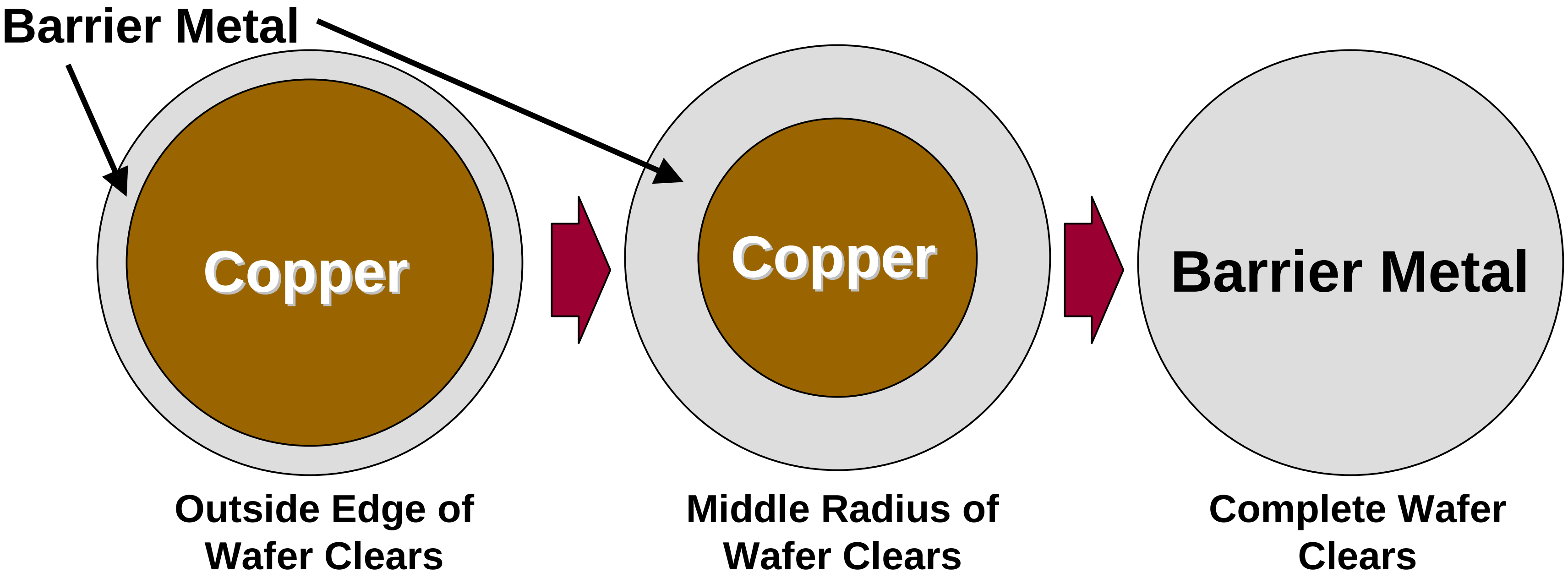
(d.) The pad continues to heat up. Note the degree of heating corresponds to the arc lengths where the wafer meets the pad.

(e.) The pad heats up during planarization and approaches the steady-state heating profile across the polishing pad.



(f.) The pad achieves the steady-state heating profile across the polishing pad. The heating profile retains this profile until near endpoint.

Spatial Variation in Wafer Level Removal Rate and Endpoint Non-Uniformity



Barrier Metal

Copper

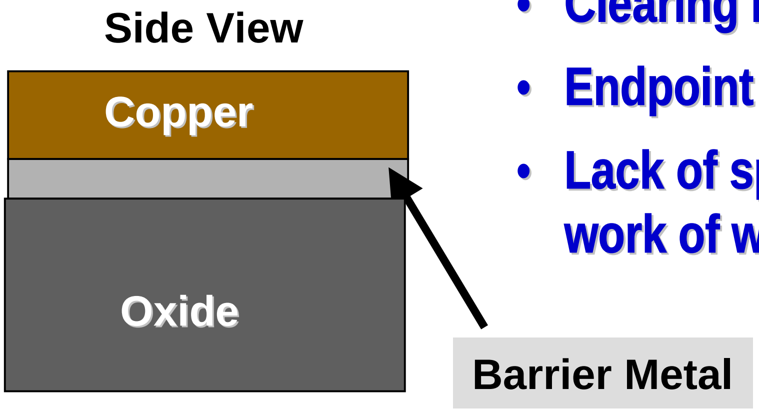
Copper

Barrier Metal

Outside Edge of Wafer Clears

Middle Radius of Wafer Clears

Complete Wafer Clears



Side View

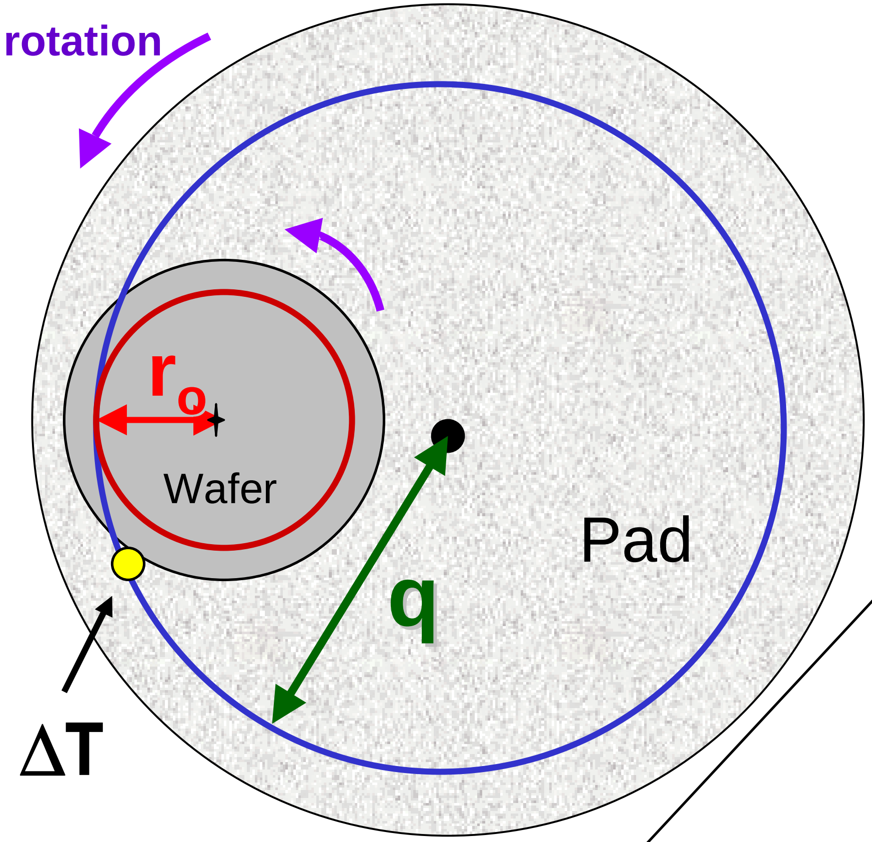
Copper

Oxide

Barrier Metal

- **Clearing may occur from outside to inside**
- **Endpoint non-uniformity increases dishing and erosion**
- **Lack of spatial endpoint information often results in the re-work of wafers to remove remaining material**

Why Does Material Removal Vary with Radial Position?



Temperature along (q) and removal rate at (r) are related spatially through the relative velocities and force between the pad & wafer.

Relationship can be observed in comparing Preston's removal rate *R(r)* equation with that for the change in temp. due to polish (at bottom).

$$R(r) = -k_p \cdot (F_N(r)/A) \cdot V(r)$$

Changes in temperature ΔT measured spatially across the pad are effected by:

Differences in Force Across Wafer

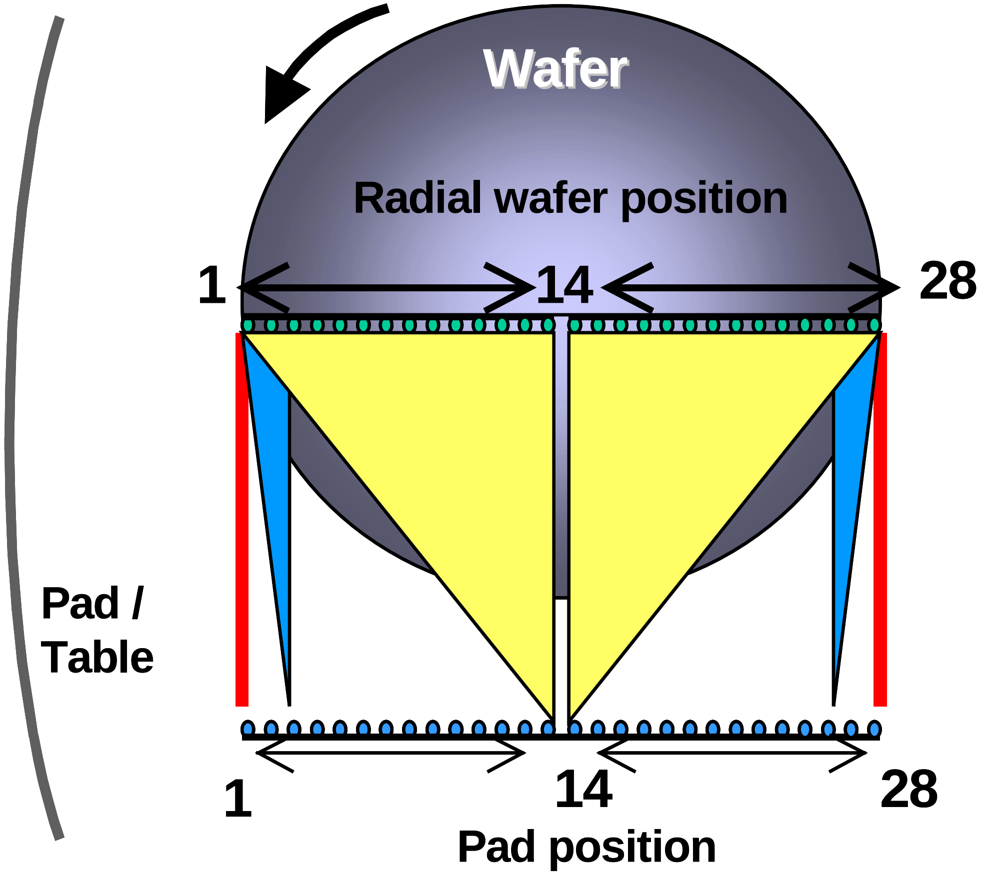
Differences in Relative Velocities

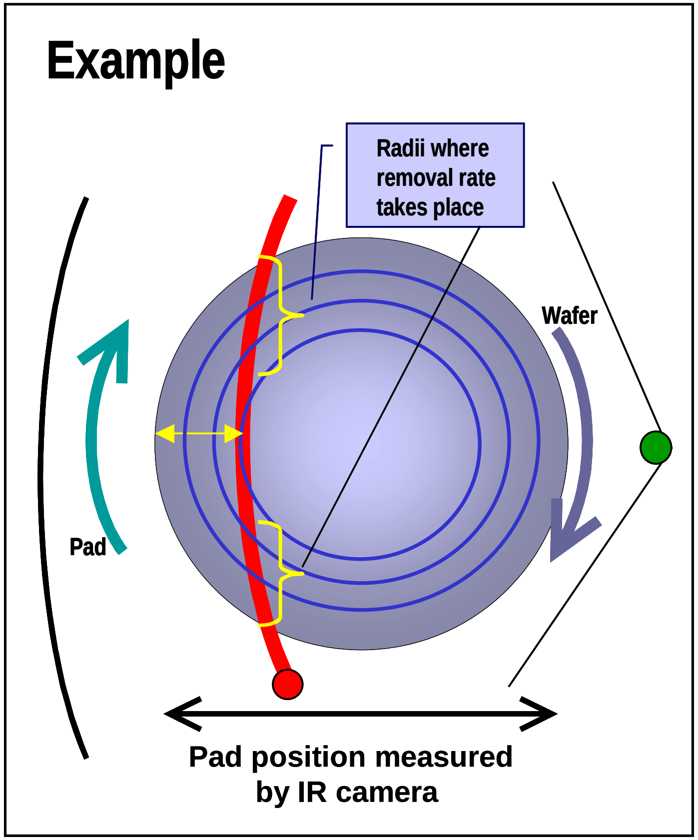
Changes in the coefficient of friction when transitioning from one material to another (at endpoint).

$$\Delta T(q)\,\alpha\,(\Delta E = P(r,q)\cdot \Delta t = \overbrace{c_f}\cdot \overbrace{(F_N(r))}\cdot \overbrace{V(r,q)}\cdot \Delta t)$$

Spatial Mapping Between Pad and Wafer Positions

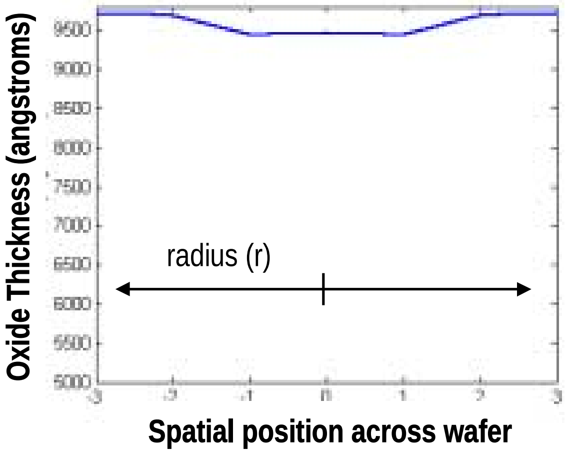
- Measured pad positions map to sets of intersecting wafer radii
- Contributions of each wafer radius to measure pad position depend upon spatial uniformity (e.g. relative velocities or force)



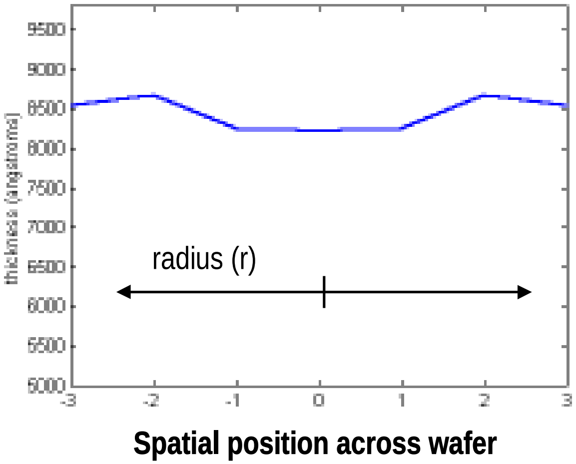


Goal of Sensor Development: Controlling Uniformity

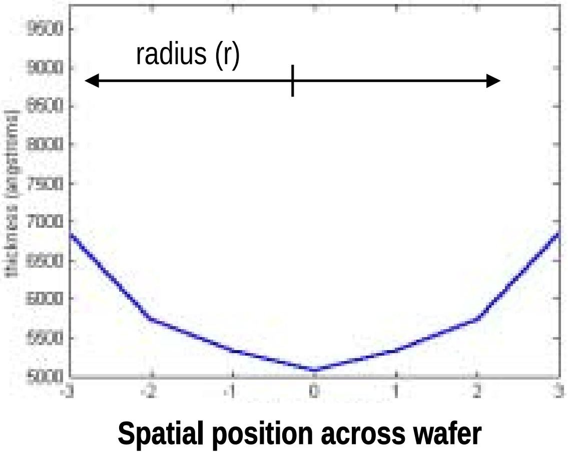
Polish time: 20 sec.



Polish time: 60 sec.

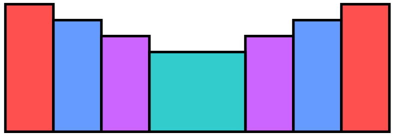


Polish time: 180 sec.

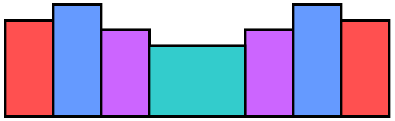


Spatial removal rate sensors enable controls

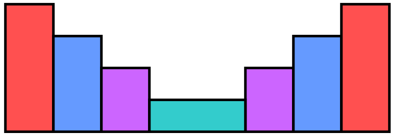
Side view



Corresponding Head Correction

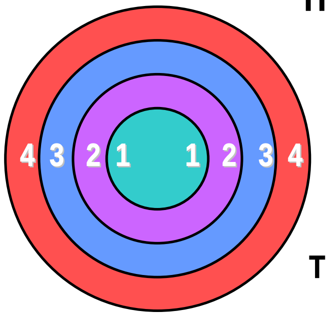


Corresponding Head Correction



Corresponding Head Correction

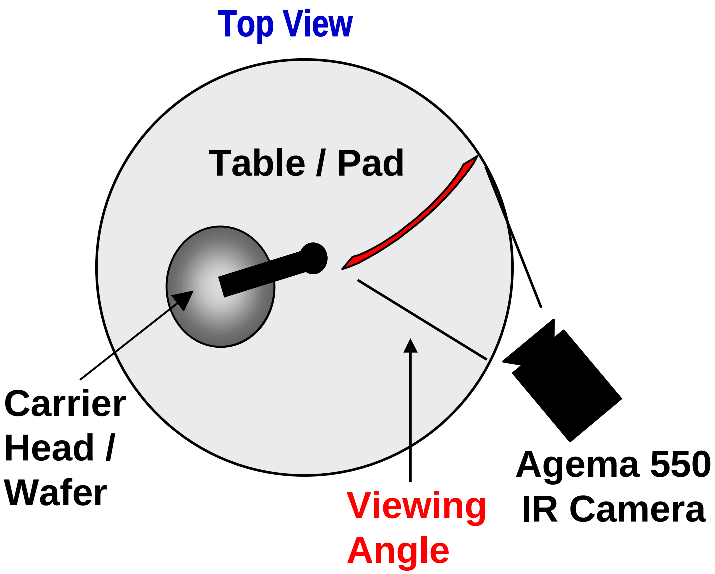
Carrier head allows for differential pressures in four zones to improve uniformity



Top view

Two Approaches to Measure Spatial Endpoint and Removal Rate

IR Thermography



Pros:

Not dependent upon material properties

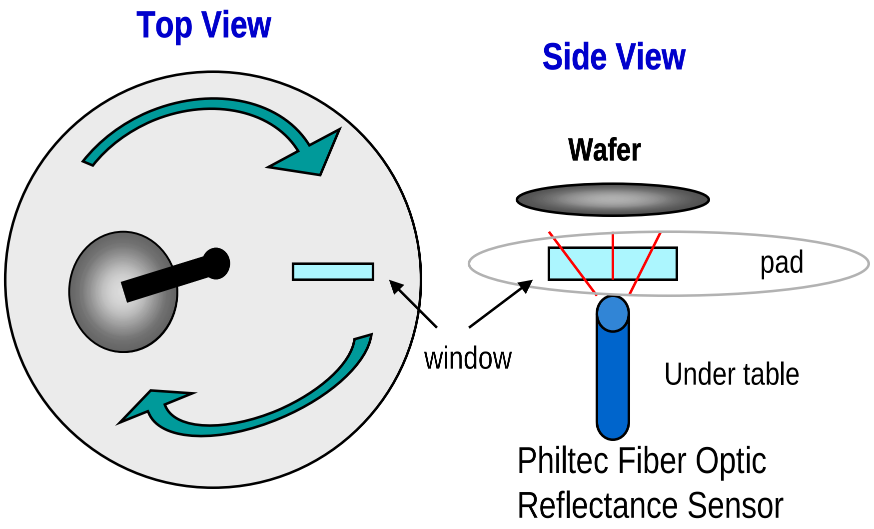
Can be used with almost any CMP machine

Cons:

Signal to noise highly dependent upon slurry transport and available viewing position on pad

Cost of sensor high but steadily decreasing

Fiber Optic Reflectance



Pros:

Spatial resolution, signal-to-noise is fantastic

Low cost sensor

Cons:

Limited to copper wafers

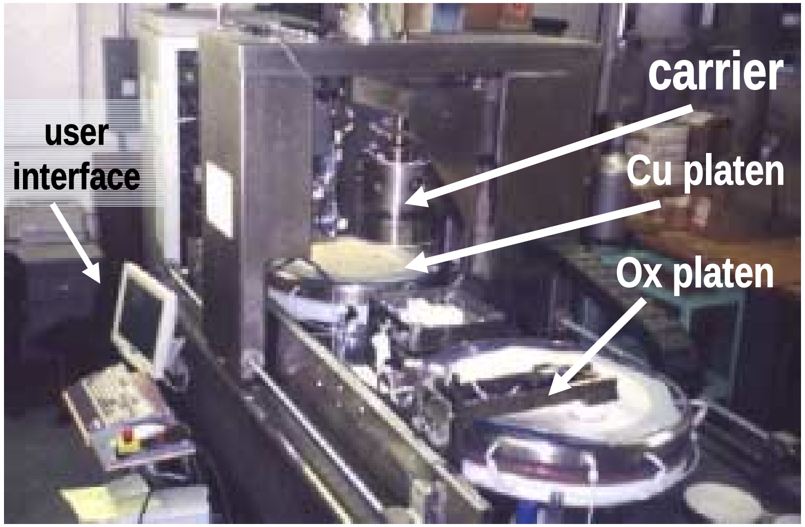
Installation may be limited to particular equipment

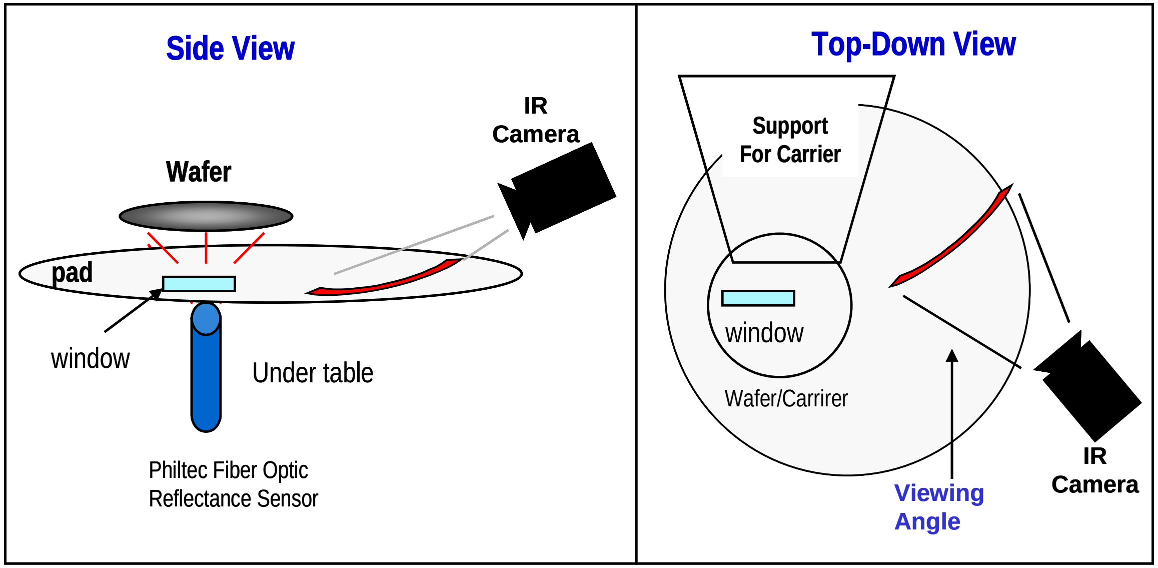
Special pads with fitted windows are used

8-inch Copper CMP Experiments at MIT

- **MIT dual platen CMP tool (right)**
- **Illustrations of how optical reflectance and IR thermography are used during copper polish (below)**

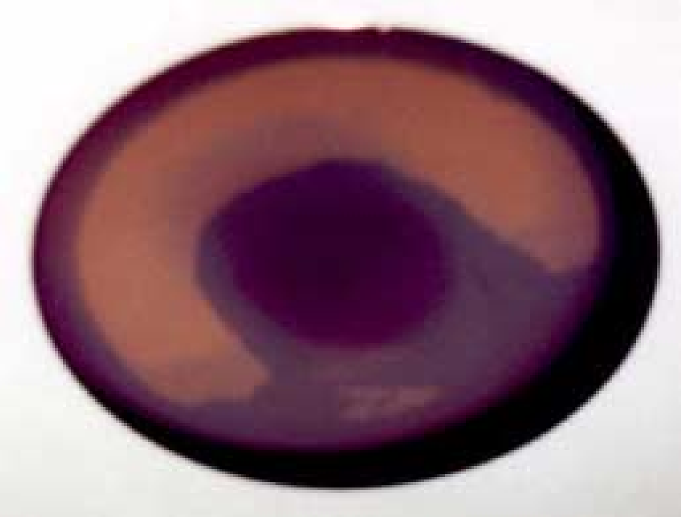
Acknowledgements: Prof. Jung-Hoon Chun and Jason Melvin in MIT Mechanical Engineering Dept.





MIT 8-inch Copper Experiments:
Partial Clearing Case

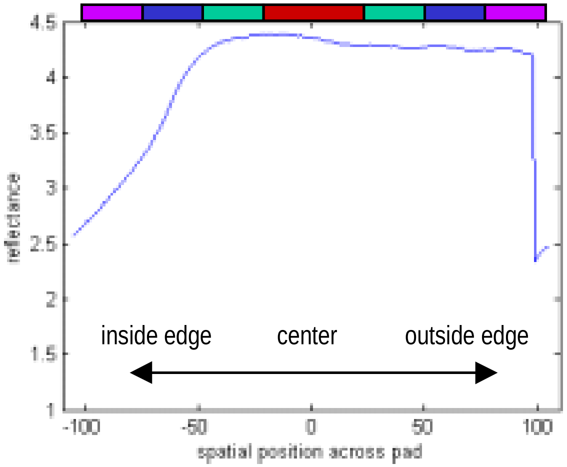
- Experimental Conditions for 8-inch Copper Polish:
  - Matched table and carrier velocities: 60 rpm
  - Pressure: 6 psi
  - Slurry flow rate: 250 ml/min
  - Duration: 250s
- Resulting in a partially cleared wafer:



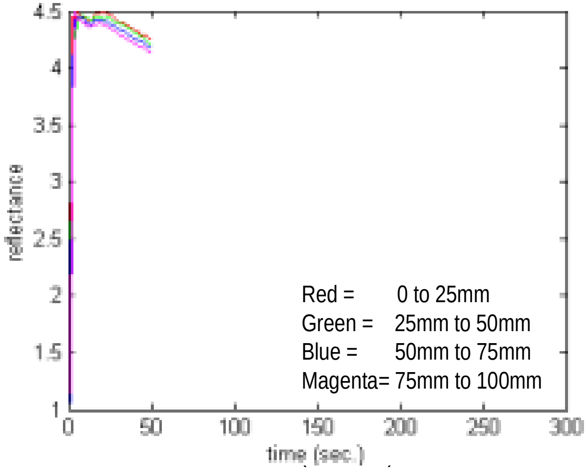
In-situ Reflectance Sensor for Copper

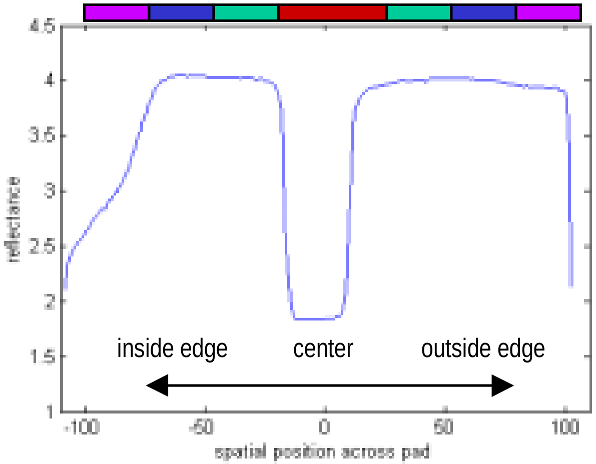
Measures spatial thickness of copper on wafer through a window in pad

Acknowledgements: Prof. Jung-Hoon Chun and Jason Melvin in MIT Mechanical Engineering Dept.

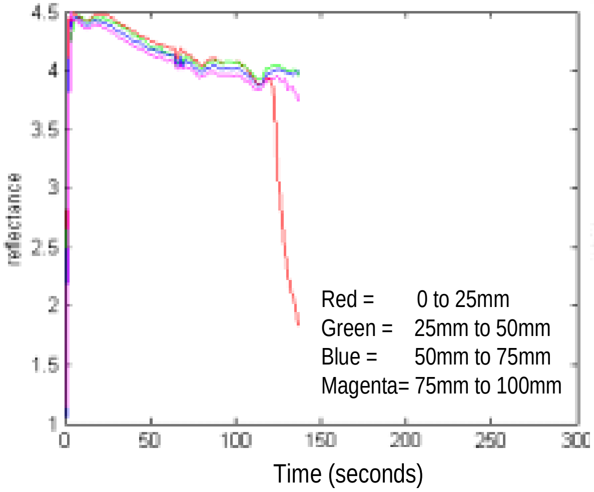


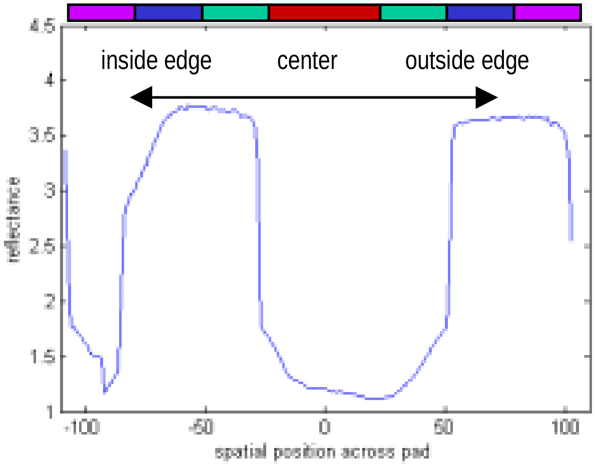
Polish time: 50 sec.



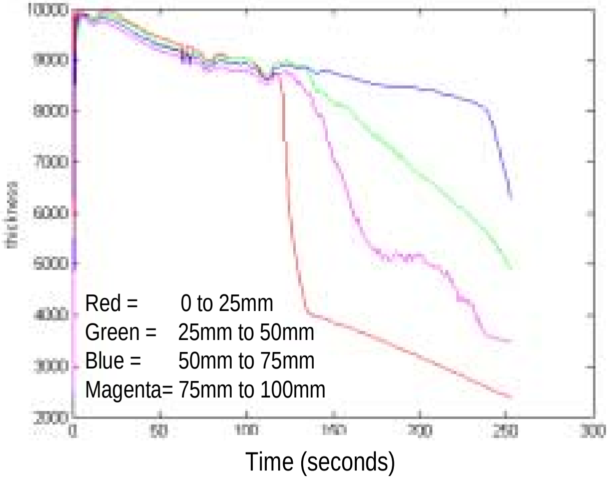


Polish time: 138 sec.





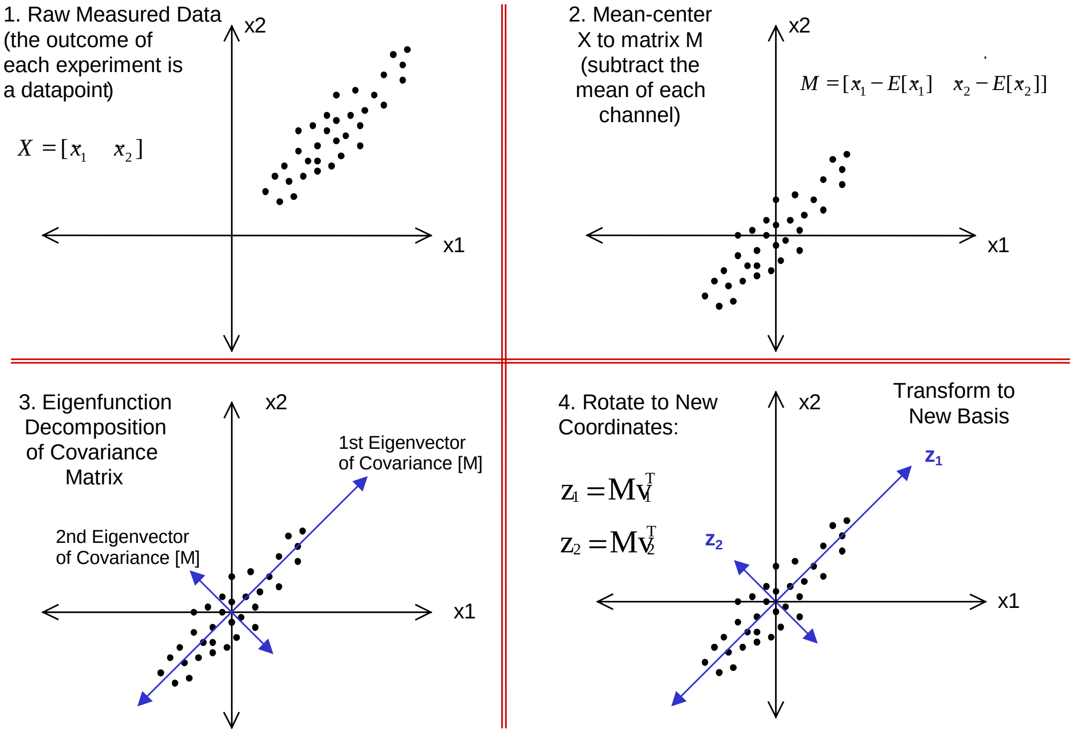
Polish time: 250 sec.



Principal component analysis (PCA):

How does it work?

- PCA uses eigenfunction decomposition to maximize the information content of a given data set
- Correlations captured by PCA may not necessarily be the desired correlations – resulting in much cause-effect related analysis



1. Raw Measured Data (the outcome of each experiment is a datapoint)

$X = [x_1 \quad x_2]$

2. Mean-center X to matrix M (subtract the mean of each channel)

$M = [x_1 - E[x_1] \quad x_2 - E[x_2]]$

3. Eigenfunction Decomposition of Covariance Matrix

4. Rotate to New Coordinates:

$z_1 = M v_1^T$

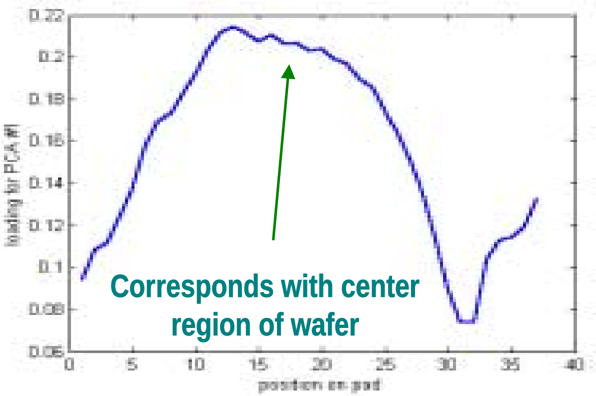
$z_2 = M v_2^T$

PCA Based IR Thermography Measurements and Comparison with Reflectance Sensor

IR Thermography Results:

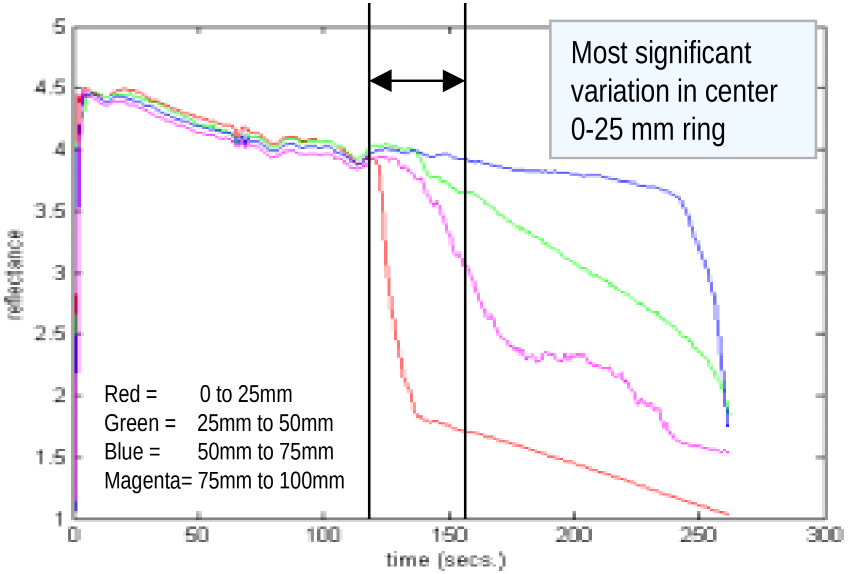
- Most significant variation occurs in center of wafer occurs from 125 to 177 sec.
- Coincidence or correlation with pad variation?
- Resembles score for PCA #3, both seeing global endpoint?
- Results inconclusive, until better S/N can be achieved

IR Camera Measurements (PCA #1)



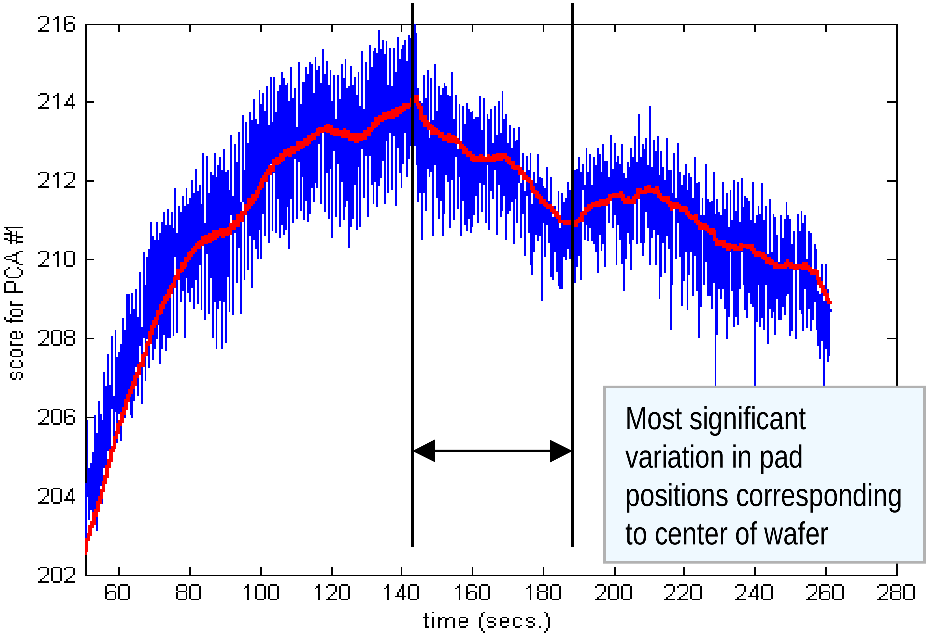
Corresponds with center region of wafer

Reflectance Measurements



Most significant variation in center 0-25 mm ring

Red = 0 to 25mm
Green = 25mm to 50mm
Blue = 50mm to 75mm
Magenta= 75mm to 100mm



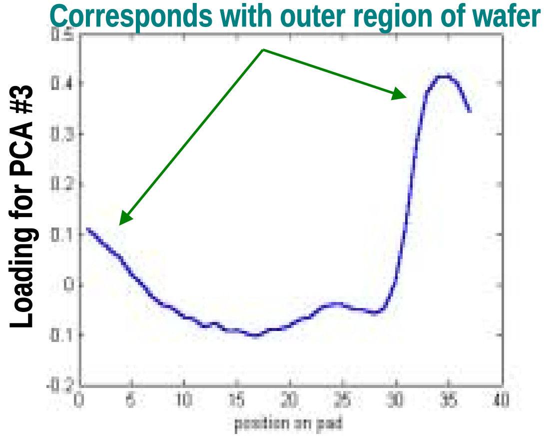
Most significant variation in pad positions corresponding to center of wafer

PCA Based IR Camera Measurements and Comparison with Reflectance Sensor

IR Thermography Results:

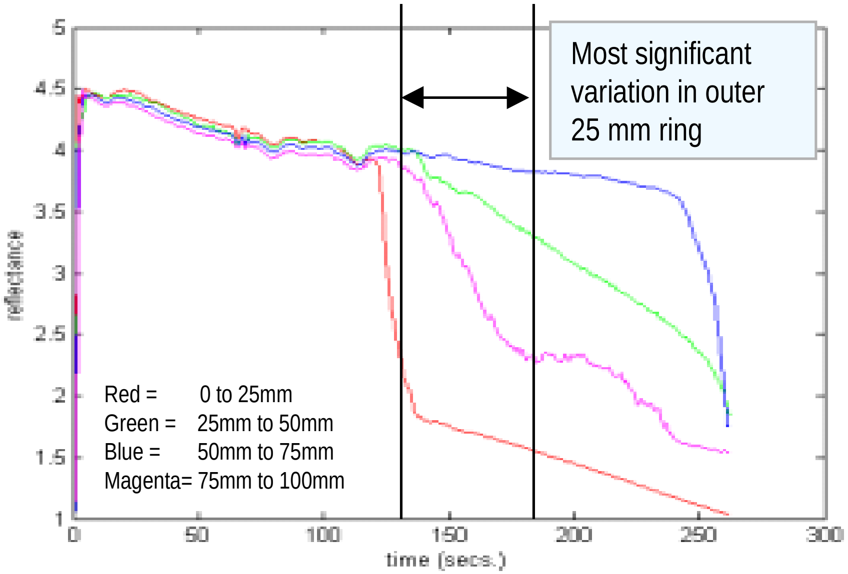
- Most significant variation occurs in center of wafer occurs from 140 to 180 sec.
- Coincidence or correlation with pad variation?
- Resembles score for PCA #1, both seeing global endpoint?
- Results inconclusive, until better S/N can be achieved

IR Camera Measurements (PCA #3)

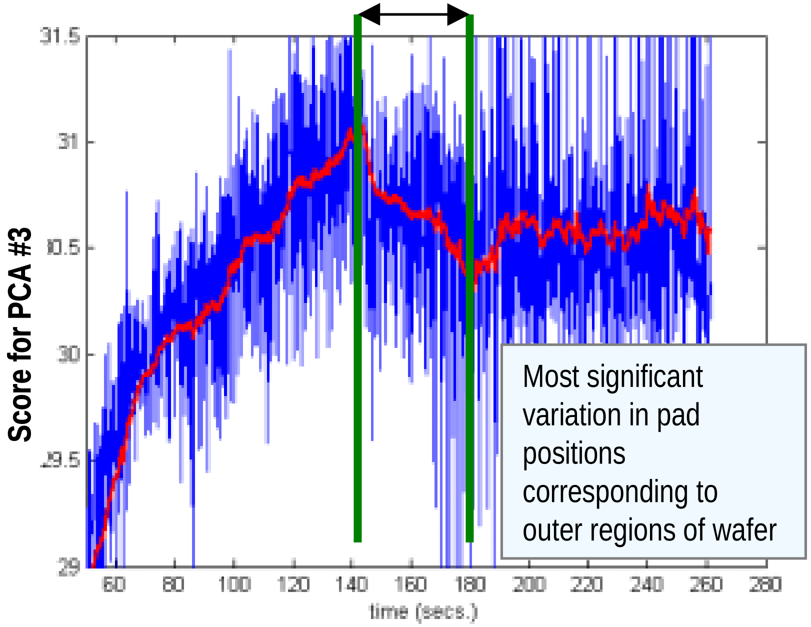


Corresponds with outer region of wafer

Reflectance Measurements



Most significant variation in outer 25 mm ring

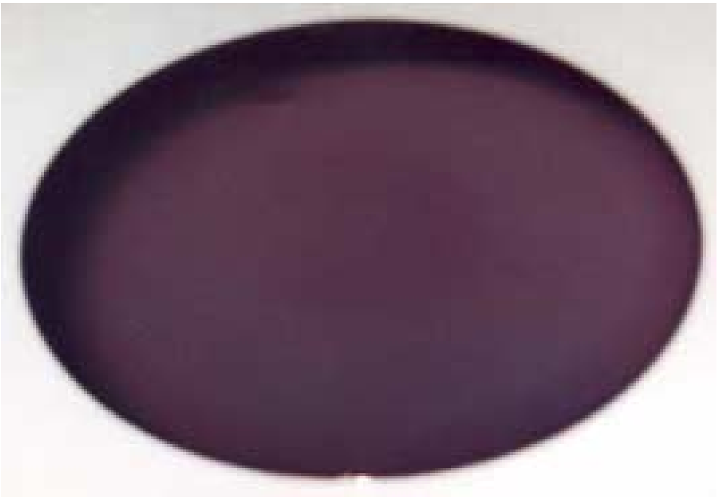


Most significant variation in pad positions corresponding to outer regions of wafer

MIT 8-inch Copper Experiments:
Complete Clearing Case

- Experimental Conditions for 8-inch Copper Polish:
  - Matched table and carrier velocities: 60 rpm
  - Pressure: 6 psi
  - Slurry flow rate: 250 ml/min
  - Duration: 350s

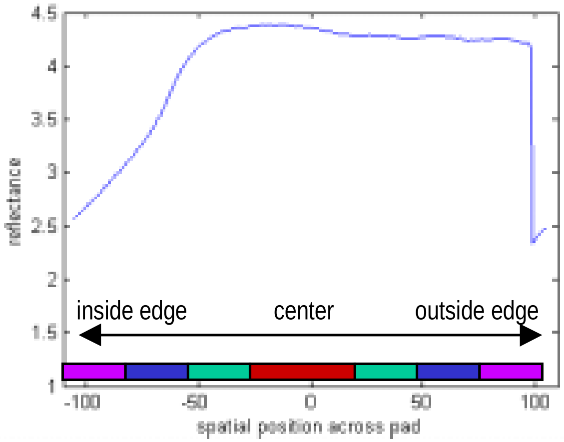
- Resulting in a fully cleared wafer:



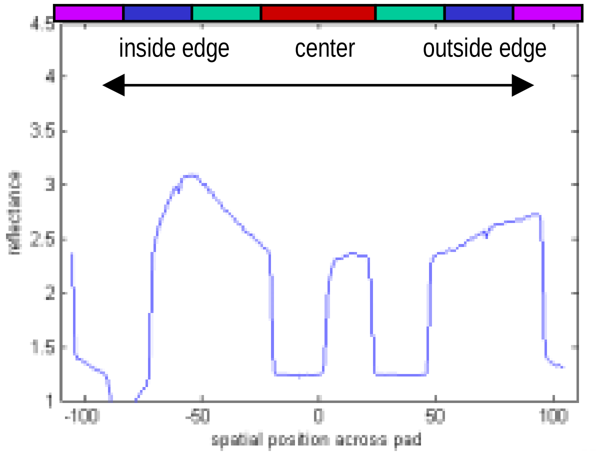
In-situ Reflectance Sensor for Copper

Measures spatial thickness of copper on wafer through a window in pad

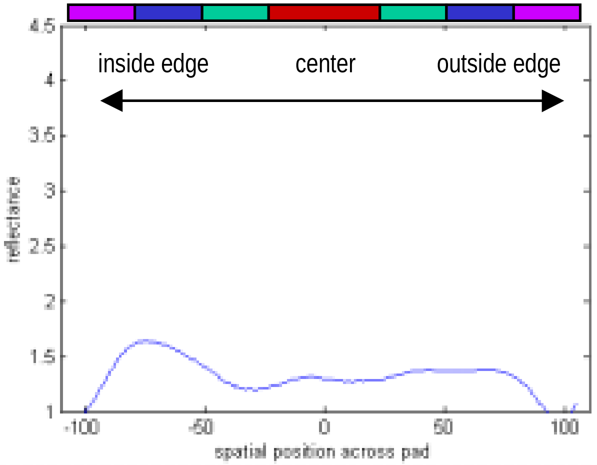
Acknowledgements: Prof. Jung-Hoon Chun and Jason Melvin in MIT Mechanical Engineering Dept.



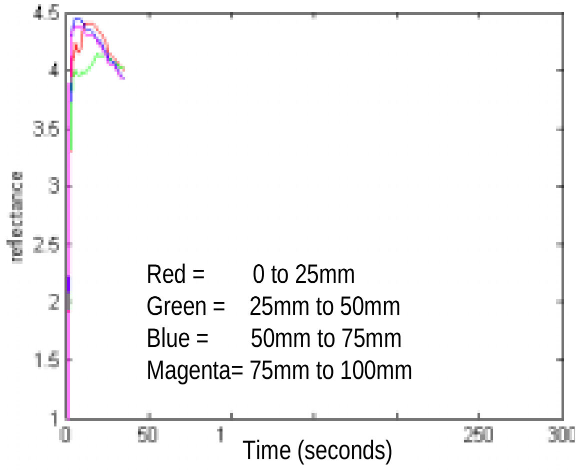
Polish time: 35 sec.

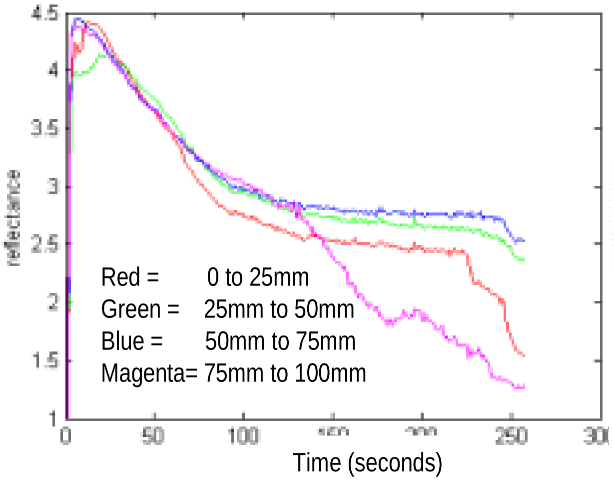


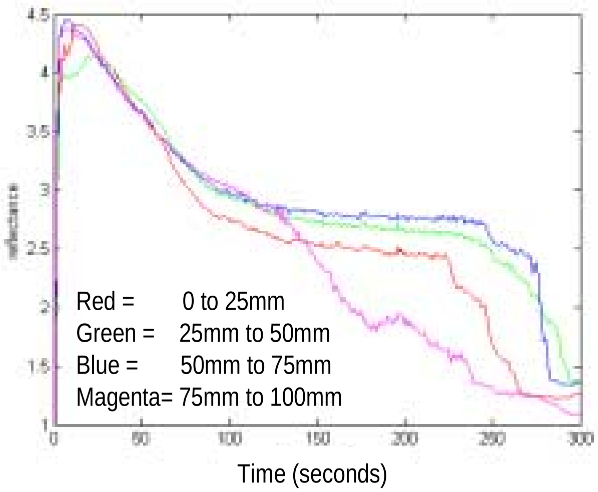
Polish time: 258 sec.



Polish time: 300 sec.





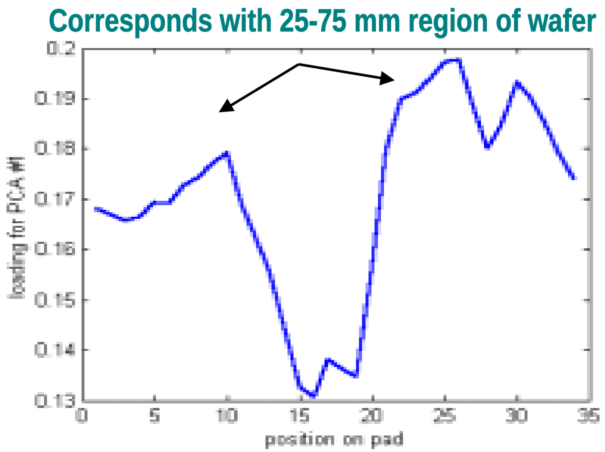


PCA Based IR Thermography Measurements and Comparison with Reflectance Sensor

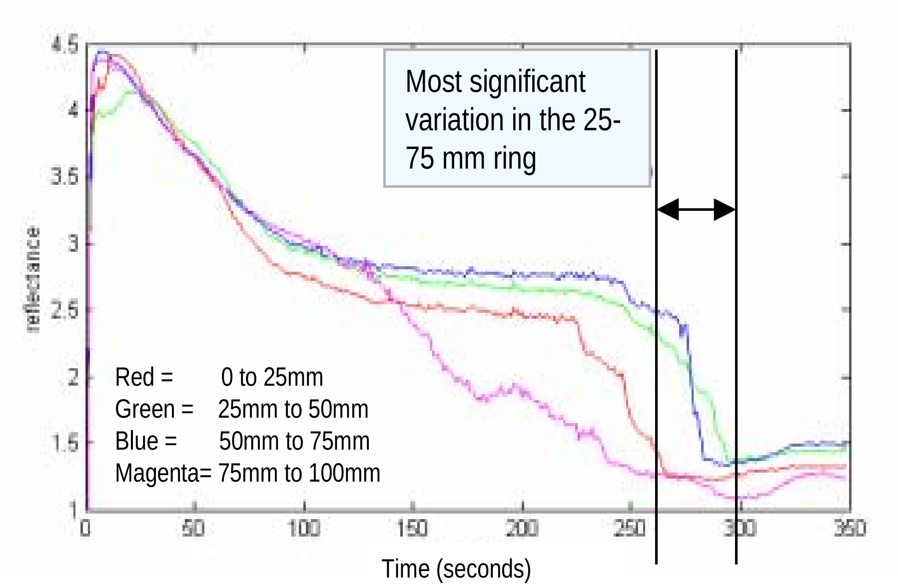
IR Thermography Results:

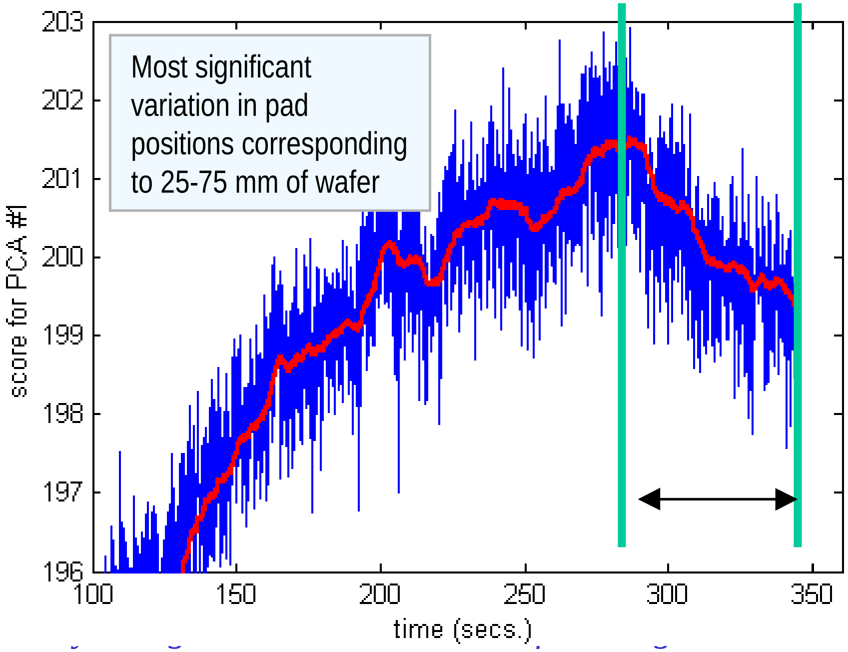
- Most significant variation in 25-75mm region occurs from 260 to 300 secs.
- Coincidence or correlation with pad score variation?
- Resembles score for PCA #3, both seeing global endpoint?
- Results inconclusive, until better S/N can be achieved

IR Camera Measurements (PCA #1)


Corresponds with 25-75 mm region of wafer

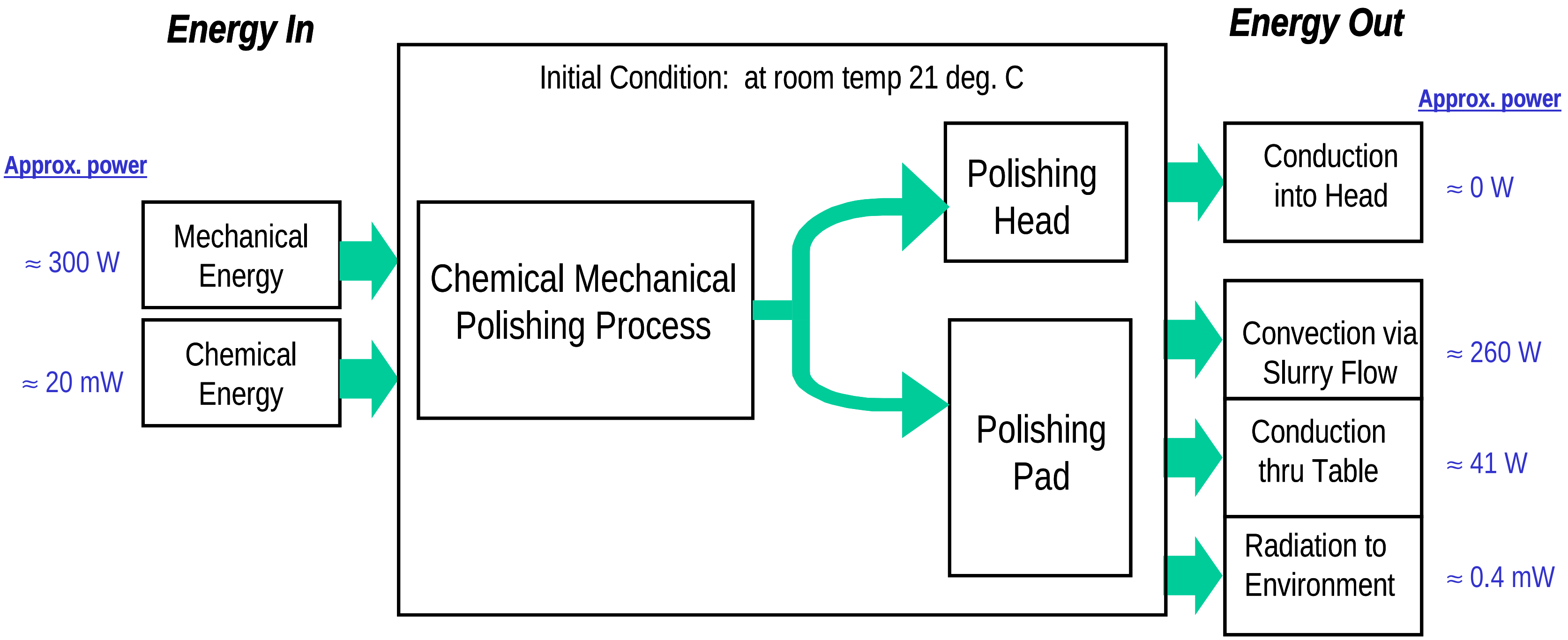
Reflectance Measurements


Most significant variation in the 25-75 mm ring


Most significant variation in pad positions corresponding to 25-75 mm of wafer

Thermal Modeling of CMP

- **Hypothesis:** **Most the thermal energy associated with polish is transferred via heat through pad and slurry**
- **Approach:**
  - **Energy balance formulation**
  - **Experimental verification**
  - **Model of thermal dynamic behavior**



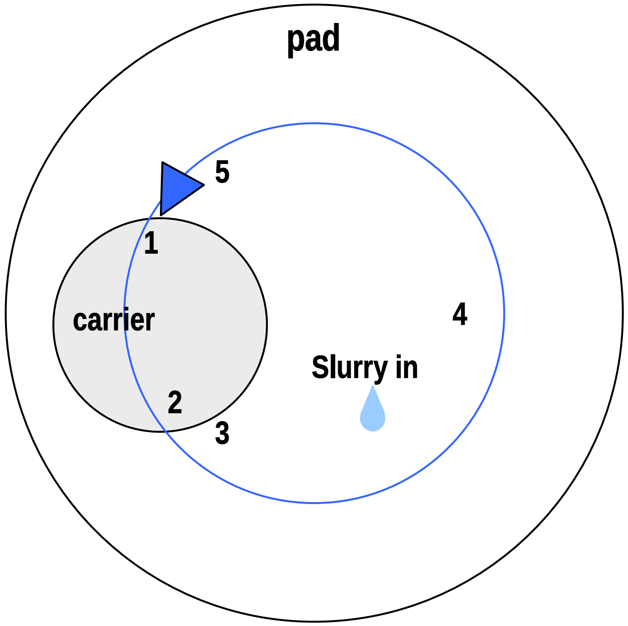
Pad Heating is a Dynamic Process

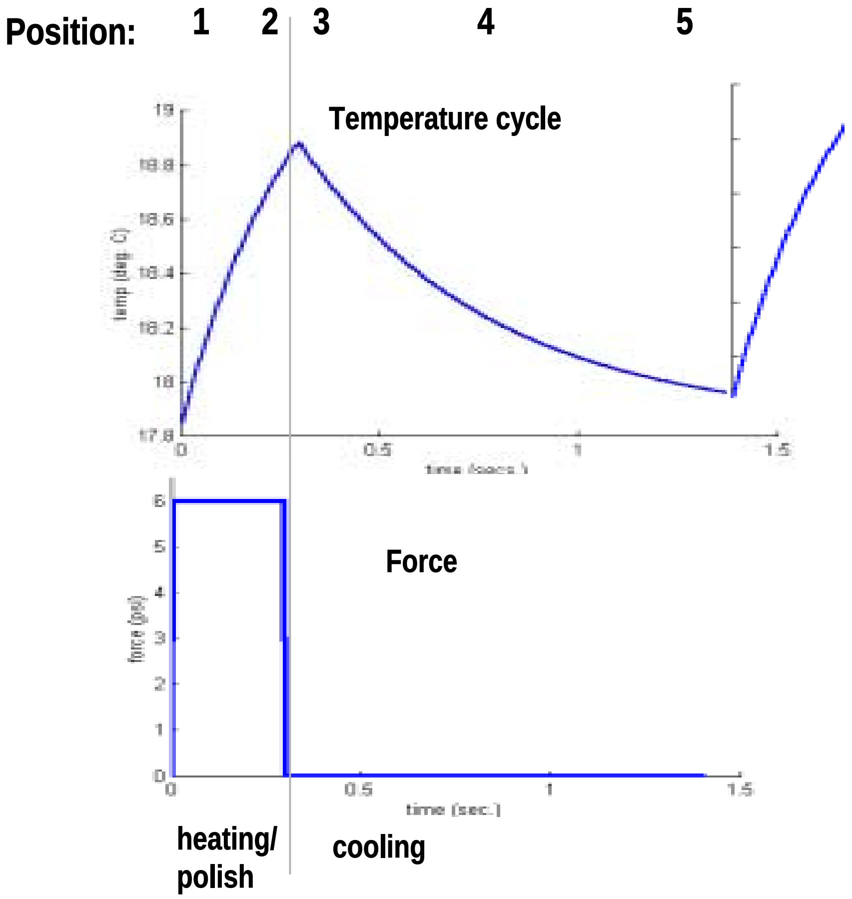
- Each pad position experiences heating and cooling cycle

Position:

- Pad begins polish against wafer
- Pad leaves contact with wafer
- Pad begins to cool under flow of slurry
- Pad continues to cool
- Pad concludes cooling cycle

Thermal Cycle for One Pad Revolution

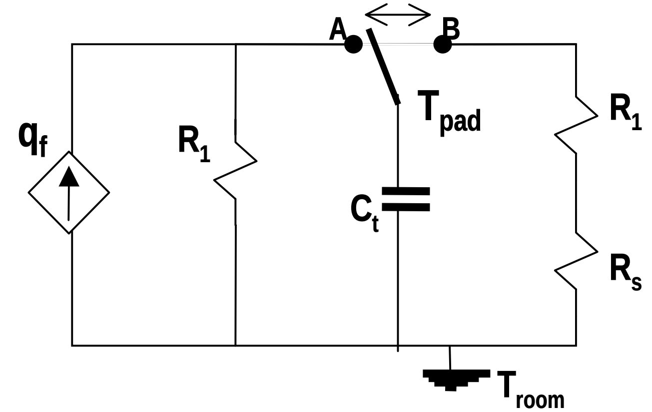


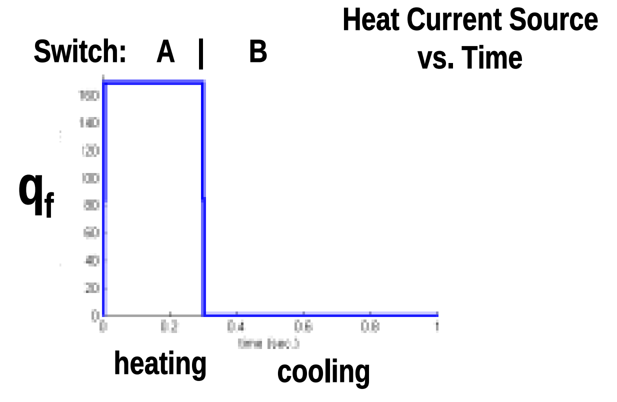


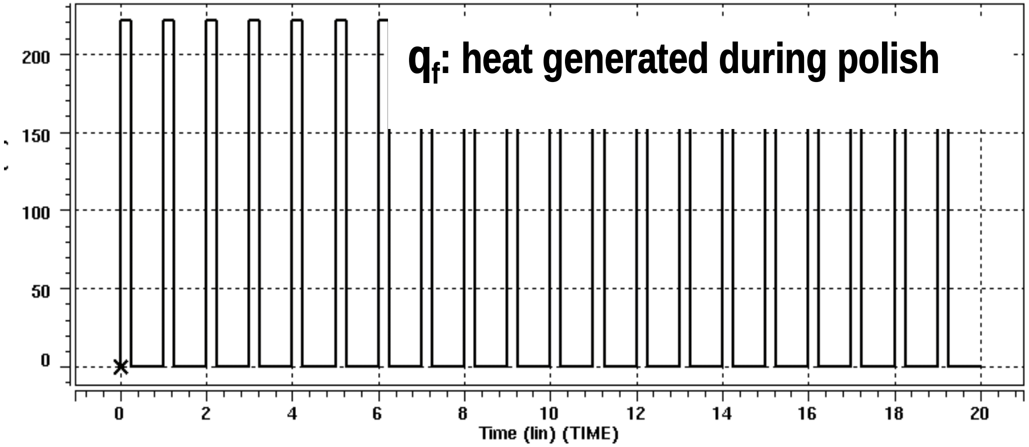
Pad Heat Dynamics: HSPICE Model and Simulation

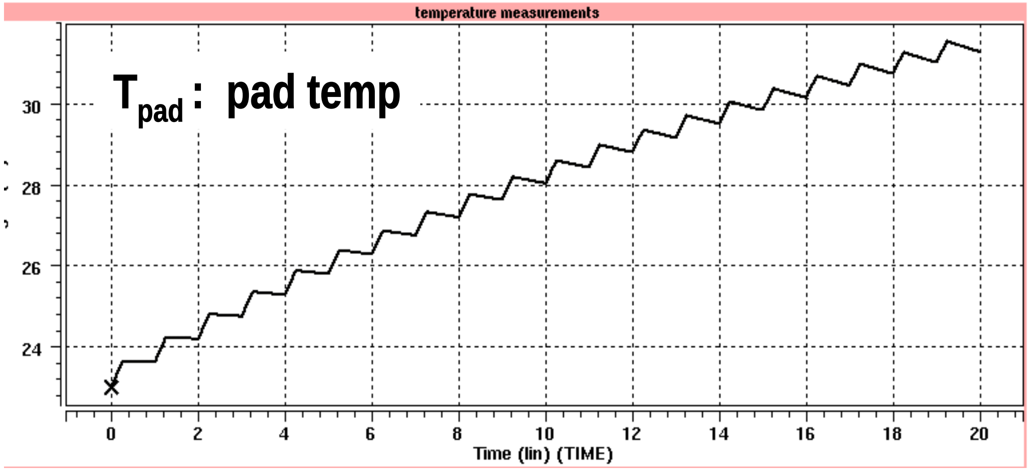
- Heat dynamics modeled and simulated using HSPICE
- q_f is the heat flow created during contact with wafer during polish
- R_1 is resistance presented by the pad (and some slurry contained in pores)
- R_s is resistance presented by slurry flowing over the pad
- C_t is thermal capacitance associated with energy stored within the pad

HSPICE Circuit Representation









HSPICE Simulation vs. Experimental Pad Temperatures

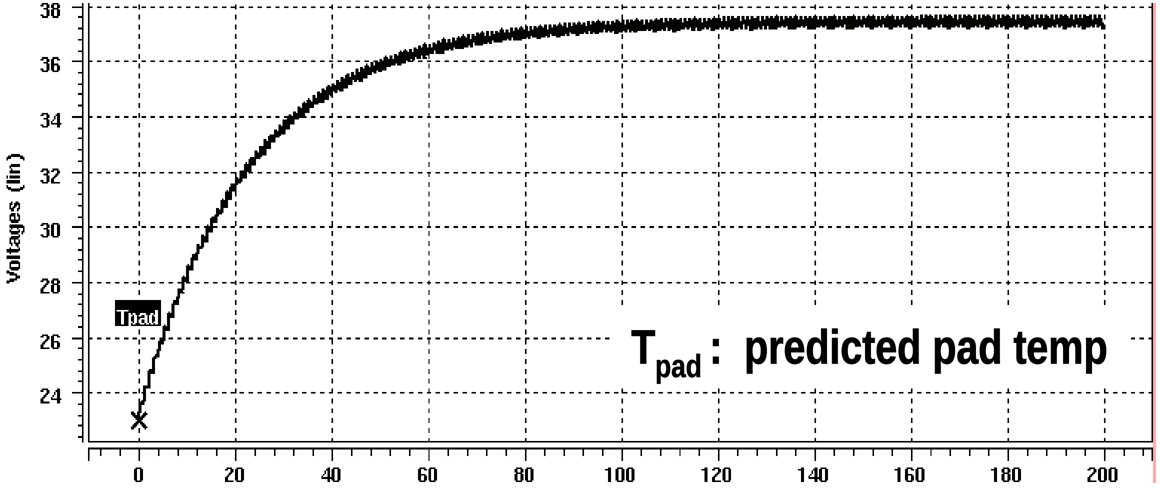
- Top plot:

  HSPICE simulation predicted pad temperature

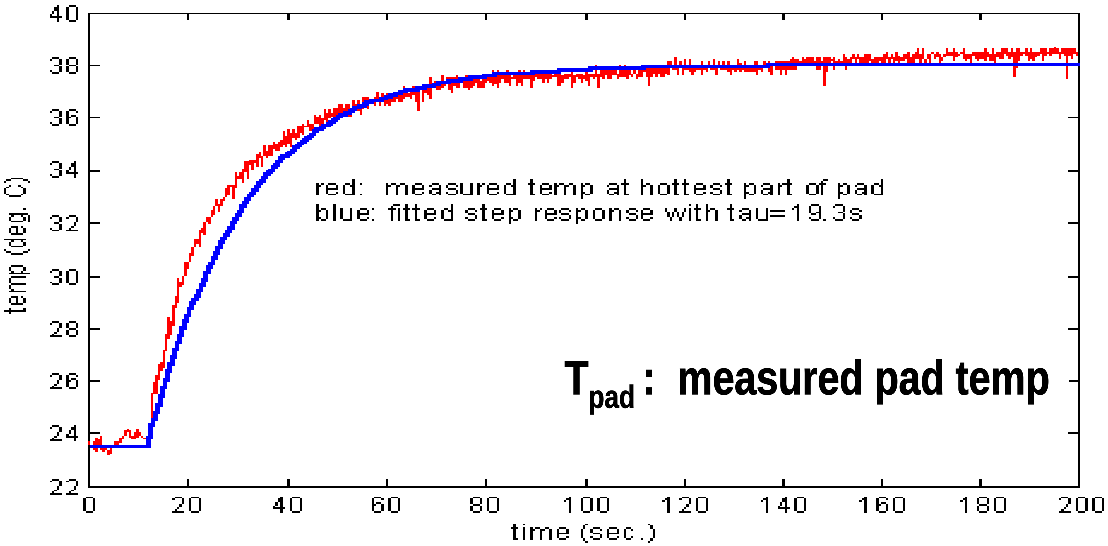
- Bottom plot:

  Experimentally measured temp (in red)

  Fitted step response with time constant, 19.3s (in blue)



T_{pad} : predicted pad temp



red: measured temp at hottest part of pad
blue: fitted step response with tau=19.3s

T_{pad} : measured pad temp

Conclusions

- Advances in in-situ sensors for CMP will have significant environmental and economic impact on processing
- Spatial endpoint is shown using optical reflectance sensor and will be used to demonstrate run-by-run uniformity control this summer
- Spatial endpoint is theoretically possible using IR thermography but requires improvement in signal-to-noise to be useful
- IR thermography may be useful for providing greater visibility into the CMP polishing fundamentals and pad conditioning effects
- Dynamic thermal model for CMP is simulated and validated against experimental data

Appendix – Extra slides for Q&A

- **What is the IR camera measuring?**
- **Results from prior AMD experiments (~1998)**

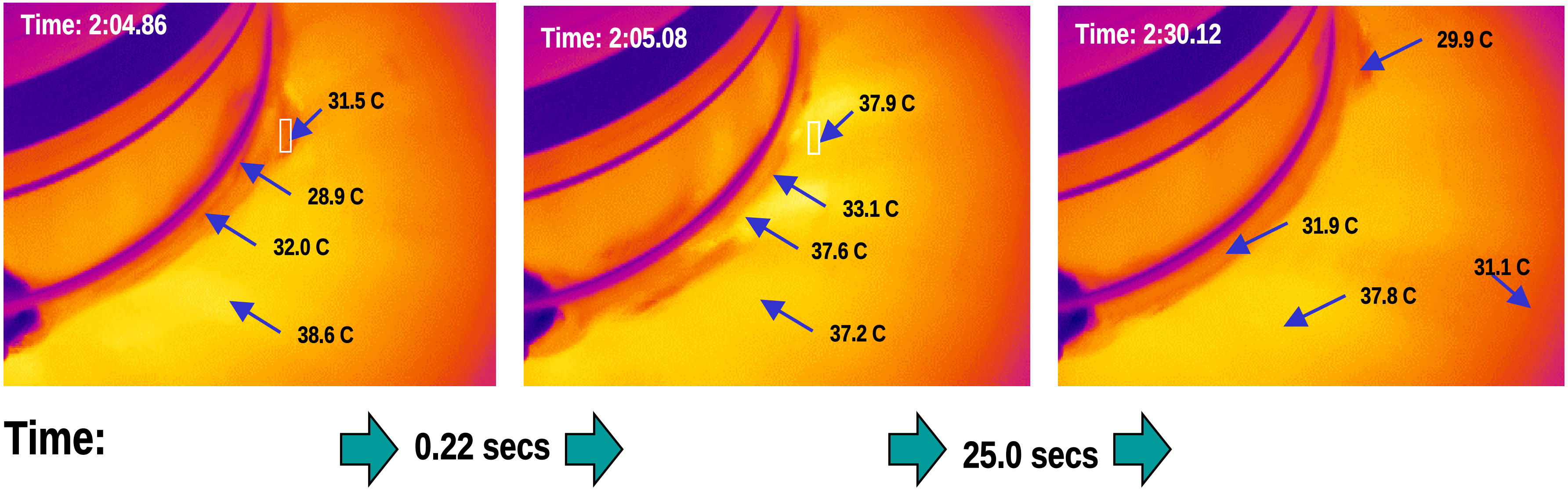
What is the IR Camera Measuring?

Question:

- Does the IR camera measure heat in the pad or from flow of slurry?

Experiments:

- Sequences indicate slurry under head heats to 32 ^{o}C and flows over the pad which is at 38 ^{o}C
- Changes in measured temp. on order of 0.1 seconds is due to slurry

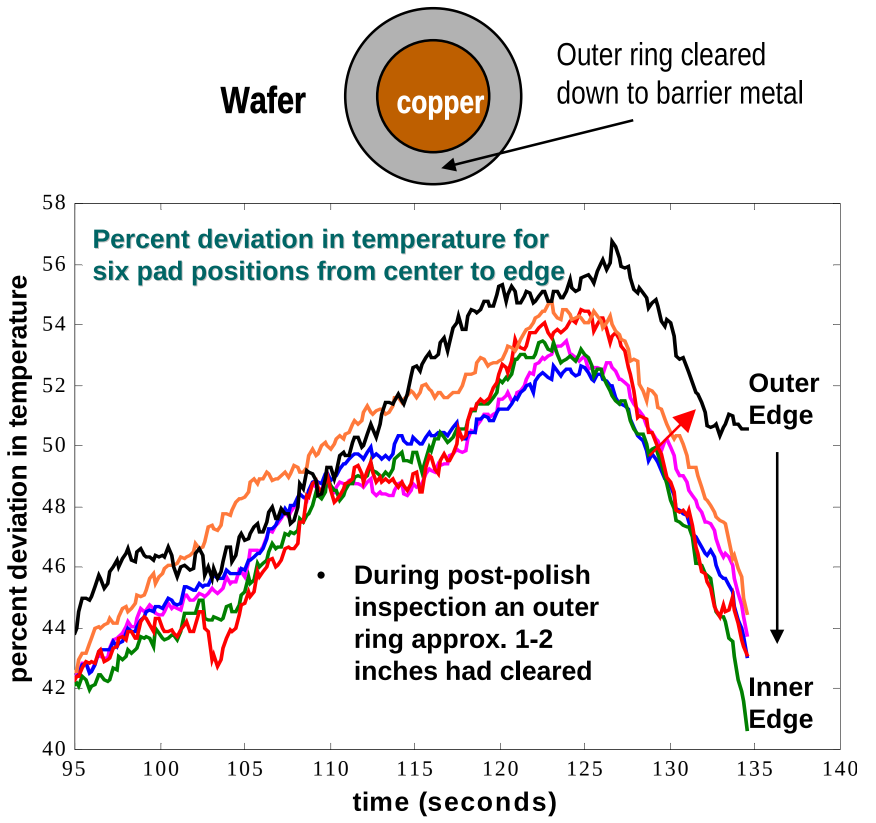


Time: 0.22 secs 25.0 secs

Results of IR Based Copper Endpoint at AMD

- **Experiments conducted with AMD to examine copper endpoint detection**
- **Endpoint detected spatially at various stages of clearing (shown below)**
- **T-squared endpoint signal shown to provide a global estimate of clearing**

Case 1: Polish stopped during clearing

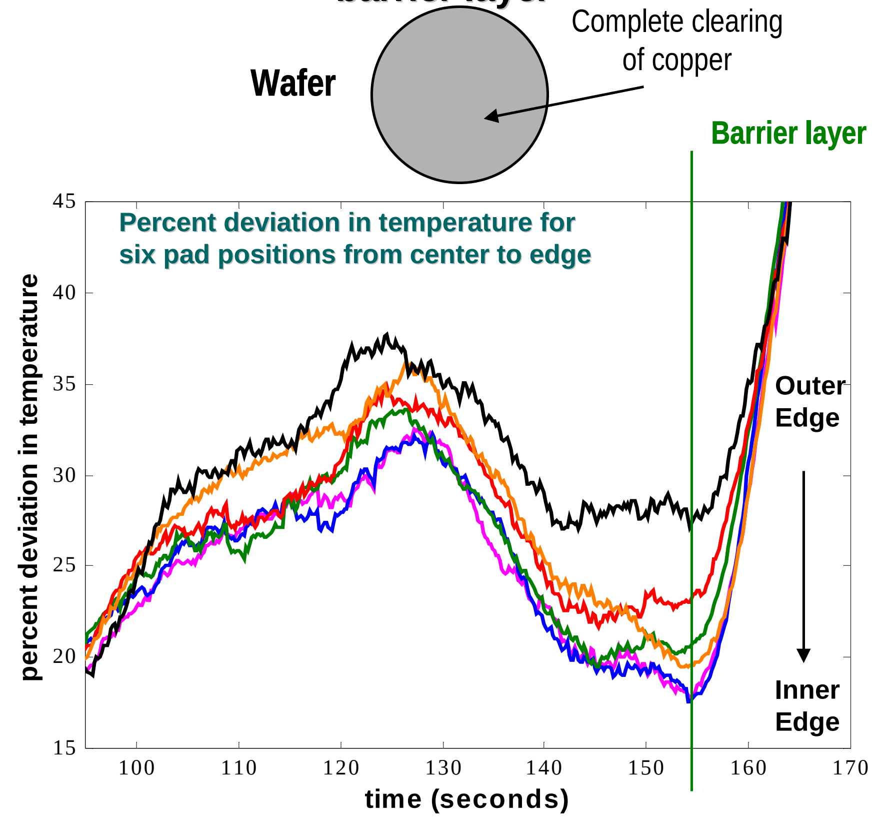


Outer ring cleared down to barrier metal

Percent deviation in temperature for six pad positions from center to edge

- During post-polish inspection an outer ring approx. 1-2 inches had cleared

Case 2: Polish through endpoint into the barrier layer



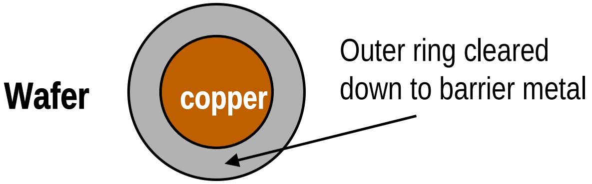
Complete clearing of copper

Percent deviation in temperature for six pad positions from center to edge

PCA Applied to AMD Thermal Measurements

- **Note that PCA seems to capture variation on areas of the pad associated with outer regions of the wafer during the partial clear**
- **Overall, the measured signals did not provide sufficient signal-to-noise and repeatability to be used as an in-situ spatial endpoint sensor**
- **Further analysis required**

Case 1: Polish stopped during clearing



Outer ring cleared down to barrier metal