Consumables Reduction in Cu CMP

Part 1: Comparison of Cu Disc and Cu Wafer Polishing Processes in Terms of their Kinetic, Tribological and Thermal Characteristics

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Motivation & Outline

- ## Driving force

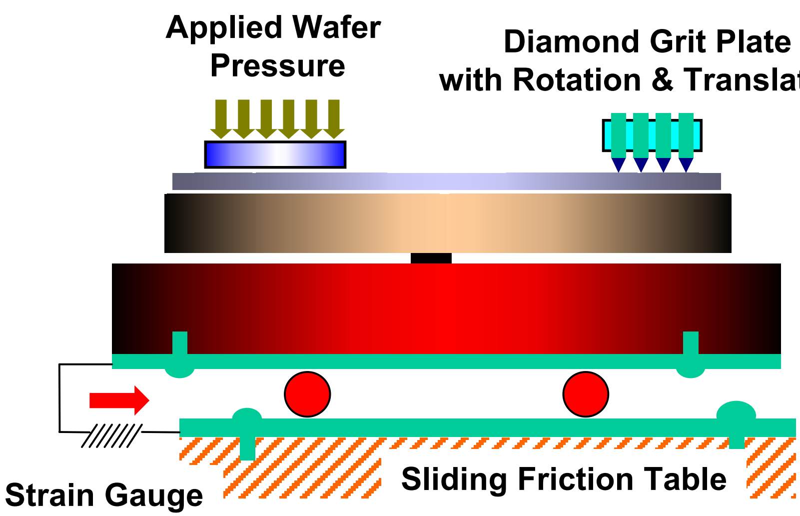
  A serious cost and EHS concern … Numerous blanket copper deposited silicon wafers are needed to perform reliable 'screening' of copper removal rate & frictional characteristics a particular slurry or pad

- ## Goal

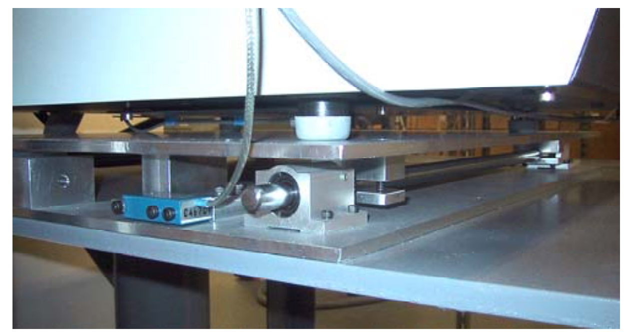
  Determine if blanket copper discs are viable replacements for copper deposited wafers by performing a comparative analysis in terms of :
  - COF
  - Lubrication mechanism
  - Material removal
  - Temperature

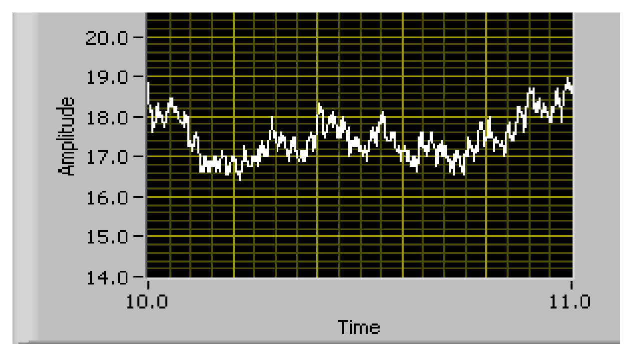
Apparatus

Parameter	Scaling Factor	Speedfam-IPEC 472	Scaled Polisher
Down Pressure	1	4 PSI	4 PSI
Platen Speed	Reynolds Number	Relative pad-wafer velocity of 0.5 m per second (30 RPM)	Relative pad-wafer velocity of 0.5 m per second (55 RPM)
Platen Diameter / Wafer Diameter	D_{platen} / D_{wafer}	51 cm / 20 cm	31 cm / ~ 10 cm
Slurry Flow Rate	Platen Surface Area	220 cc per minute	80 cc per minute



$$COF_{avg} = \frac{\overline{F}_{Shear}}{F_{Normal}}$$

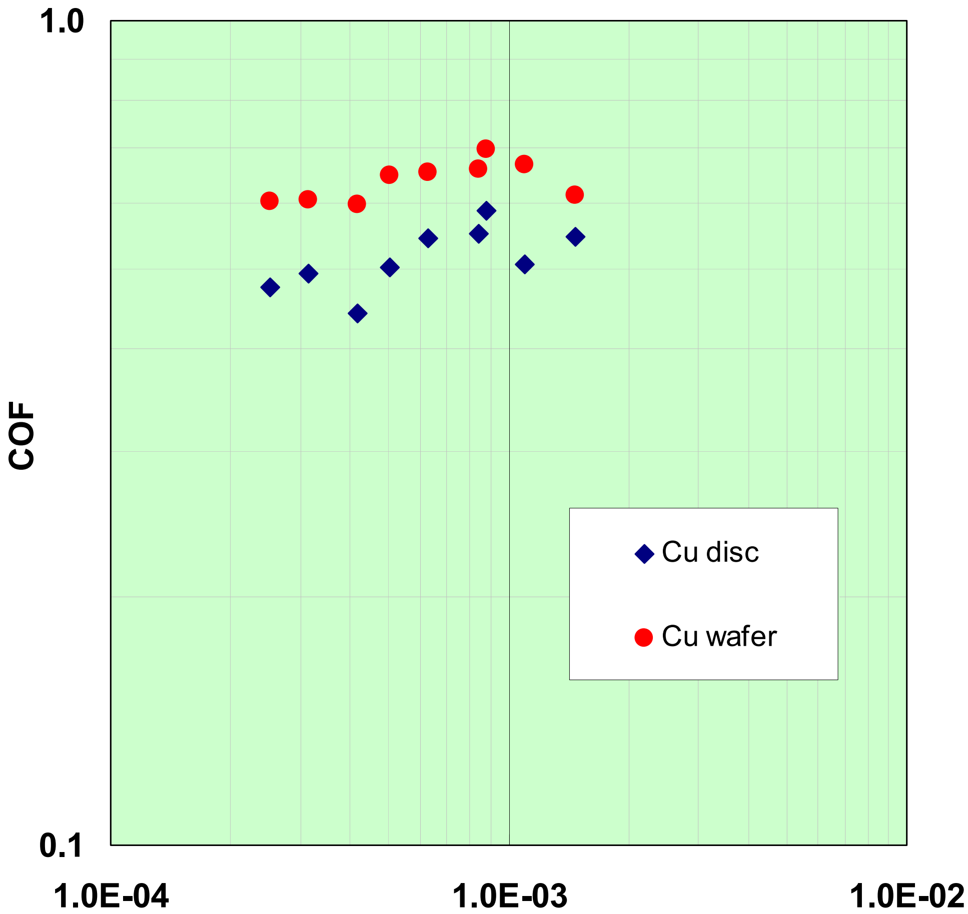




Experimental Conditions

- **Constants:**
  - Conditioning
    - 100 grit diamond disc
    - 30 min with UPW at 30 rpm disk speed and 20 per min sweep frequency
  - Break-in
    - 100 grit diamond disc
    - In-situ with Fujimi PL-7102 at 30 rpm disk speed and 20 per min sweep frequency
  - Wafers
    - Cu disc (purity of 99.99%)
    - Cu wafer
      - 2000 nm PVD Cu on 100 nm Ta on 100 nm silicon dioxide on Si)
  - Pad type
    - Rodel IC-1000 k-groove
  - Slurry
    - Fujimi PL-7102
    - 80 cc per minute
- **Variables:**
  - Relative pad-wafer velocity (m/s)
    - 0.31
    - 0.62
    - 1.09
  - Wafer pressure
    - 1.5 PSI (~ 10 kPa)
    - 2.0 PSI (~ 14 kPa)
    - 2.5 PSI (~ 17 kPa)

COF and Lubrication Mechanism



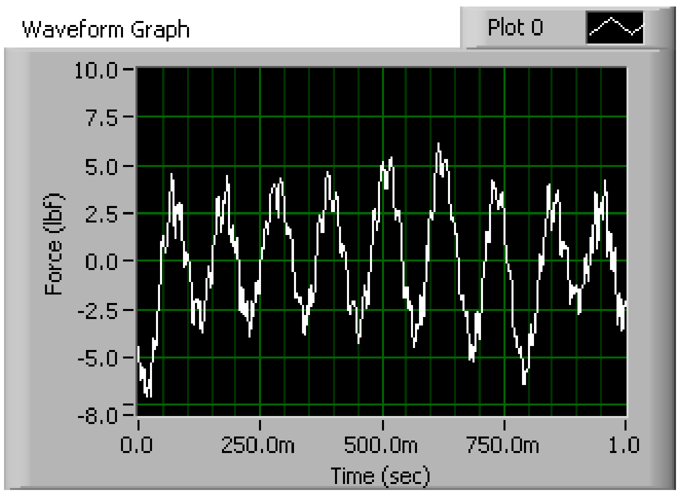
$$So = \frac{(u)\times(\mu)}{(P_{act})\times(\delta_{eff})}$$

- Lubrication mechanism = <u>'Boundary Lubrication'</u>
- COF of wafer > COF of disc:
  - 0.637 vs. 0.517
  - Stribeck curves for both types of substrate track one another very well

Analyzing Raw Frictional Data

- **Typical Polish Run:**
  - 75-seconds
  - 1000 frictional force measurements per second
  - 75,000 data points per run

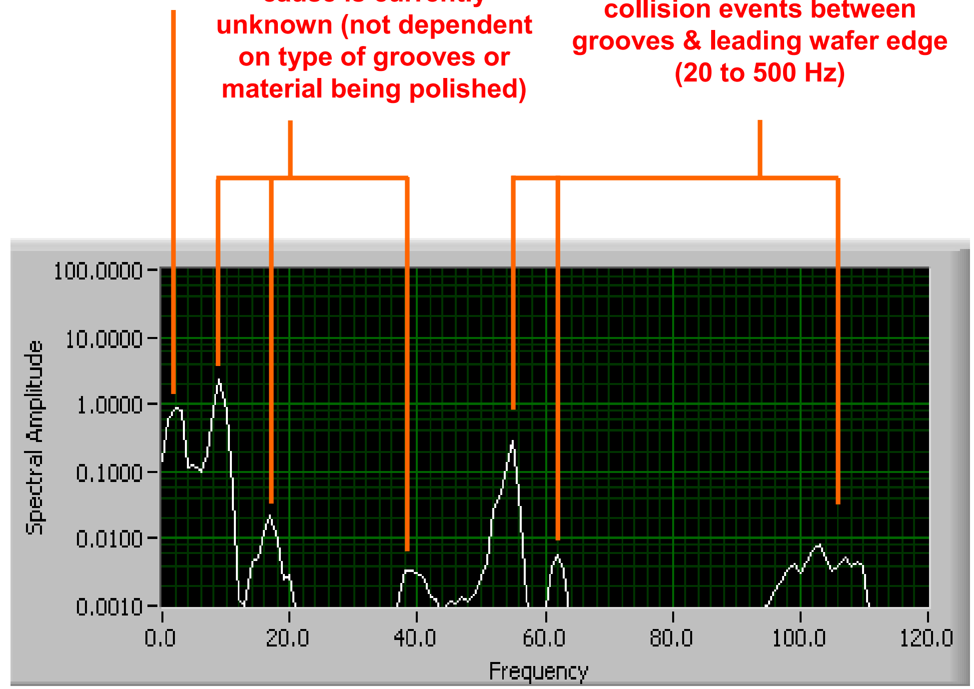
γ = Interfacial Interaction Index
γ = Area under the curve
γ = Total amount of mechanical energy caused by stick-slip
γ = 7.51



tool kinematics (0.5 to 2.4 Hz)

cause is currently unknown (not dependent on type of grooves or material being polished)

unique to k-groove pads related to distribution of collision events between grooves & leading wafer edge (20 to 500 Hz)



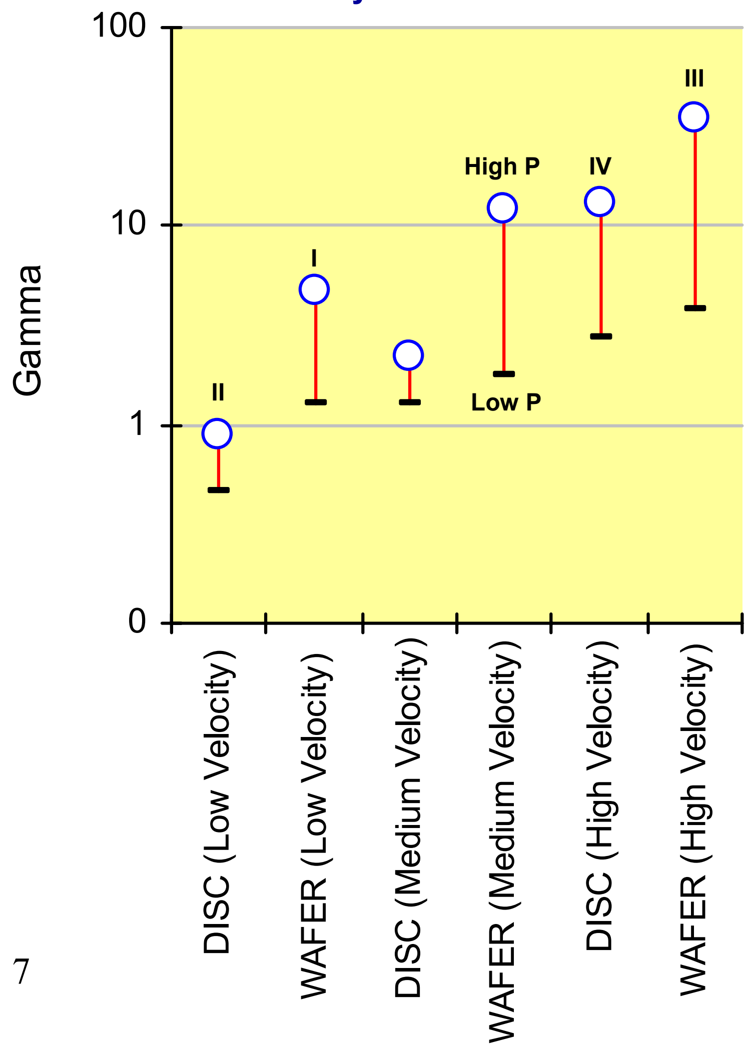
$$F_{shear}(t) = \boxed{\overline{F}_{shear}} + f(t)$$

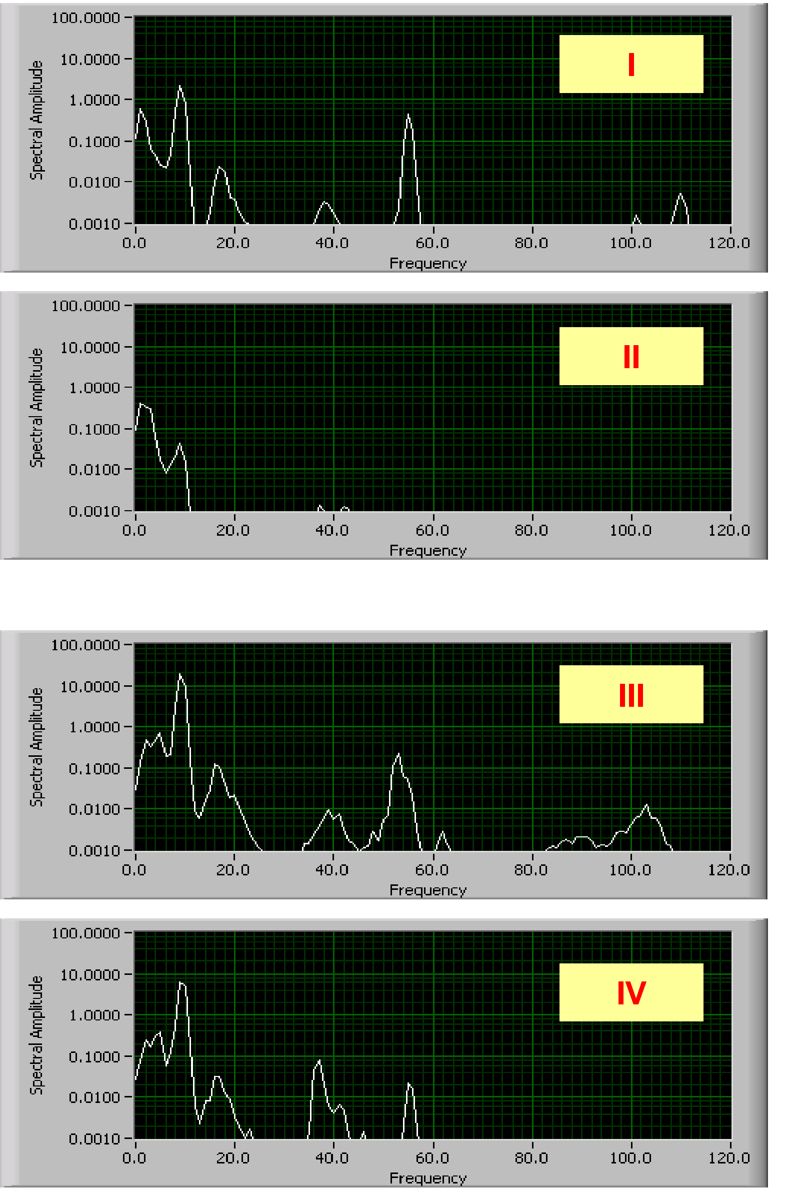
$$COF_{avg} = \frac{\overline{F}_{Shear}}{F_{Normal}}$$

Fast Fourier Transform

Trends in the Interfacial Interaction Index

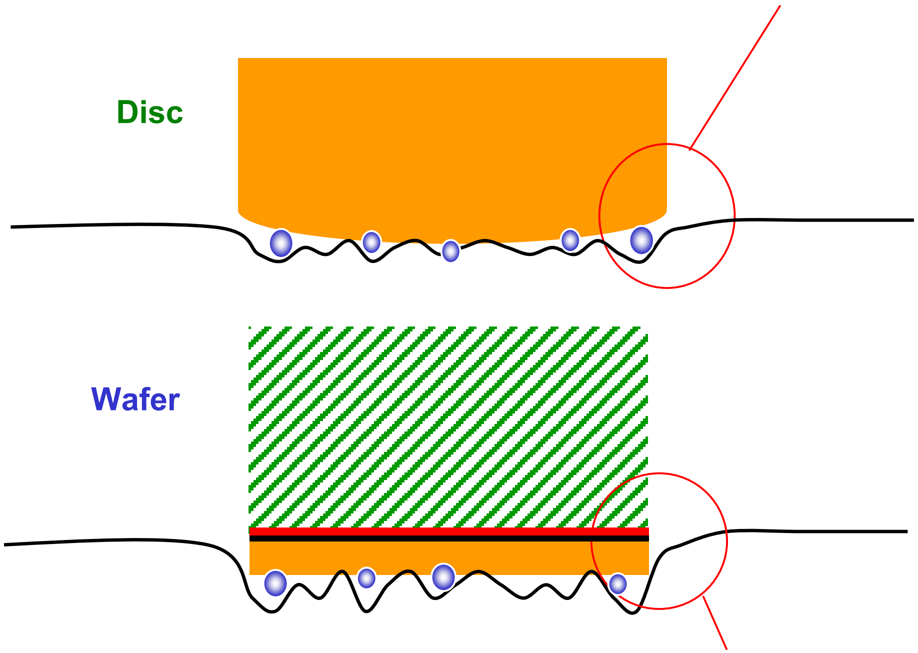
- **Gamma of wafer > Gamma of disc:**
  - **(1.2 – 34.7) vs. (0.5 – 13.0)**
  - **Trends in overall values of Gamma as a function of pad-wafer velocity and wafer pressure for both substrates track one another very well**



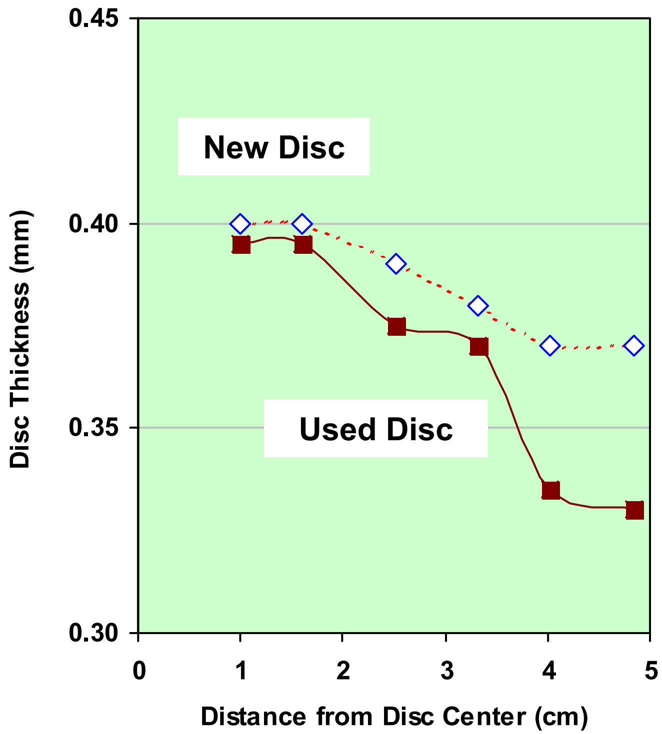


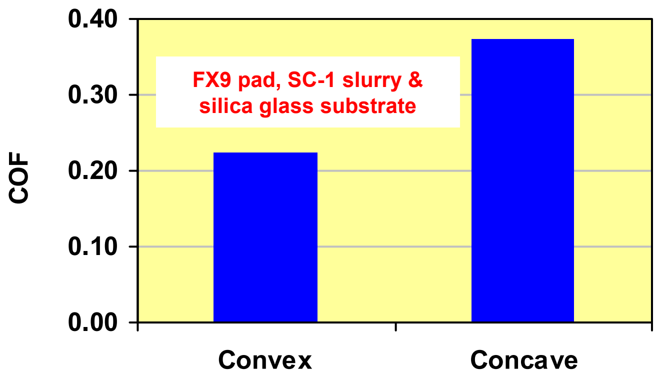
Likely Causes of Higher COF & Gamma for Wafers

<u>Rounded-off edge and increase in convexity with extended use</u> … sides are polished as well as the surface & process is intrinsically 'edge-fast'



<u>Sharp edge</u> … Since the silicon bulk prevents the wafer bevel to be polished by copper slurry & there is no extended use issue since wafer is used only once

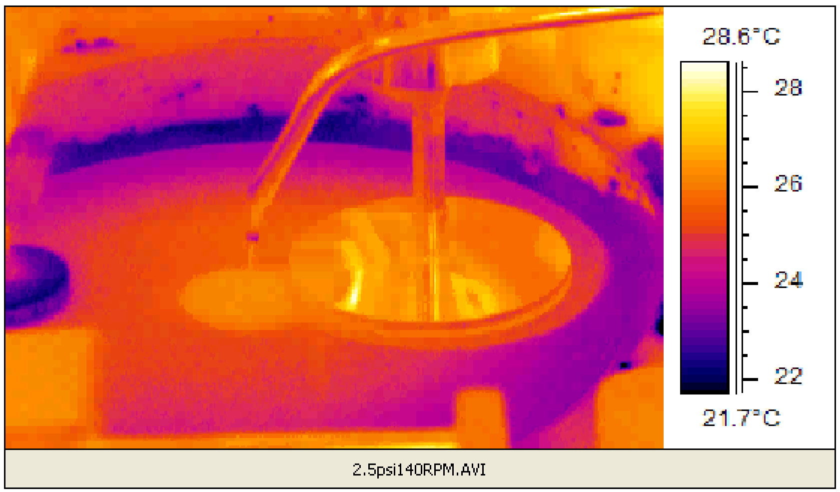


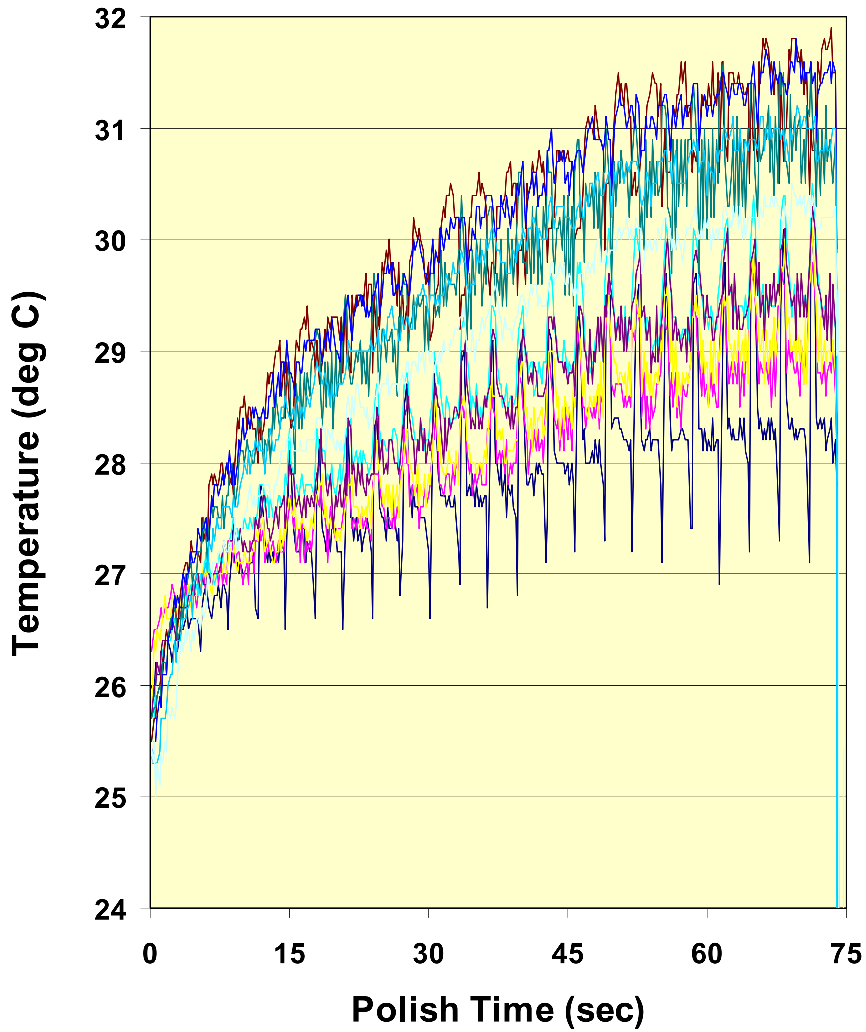


Source: Lu, Rogers, Kaufman & Philipossian … MRS, SF (2001)

Example of Temperature Transients during Cu CMP

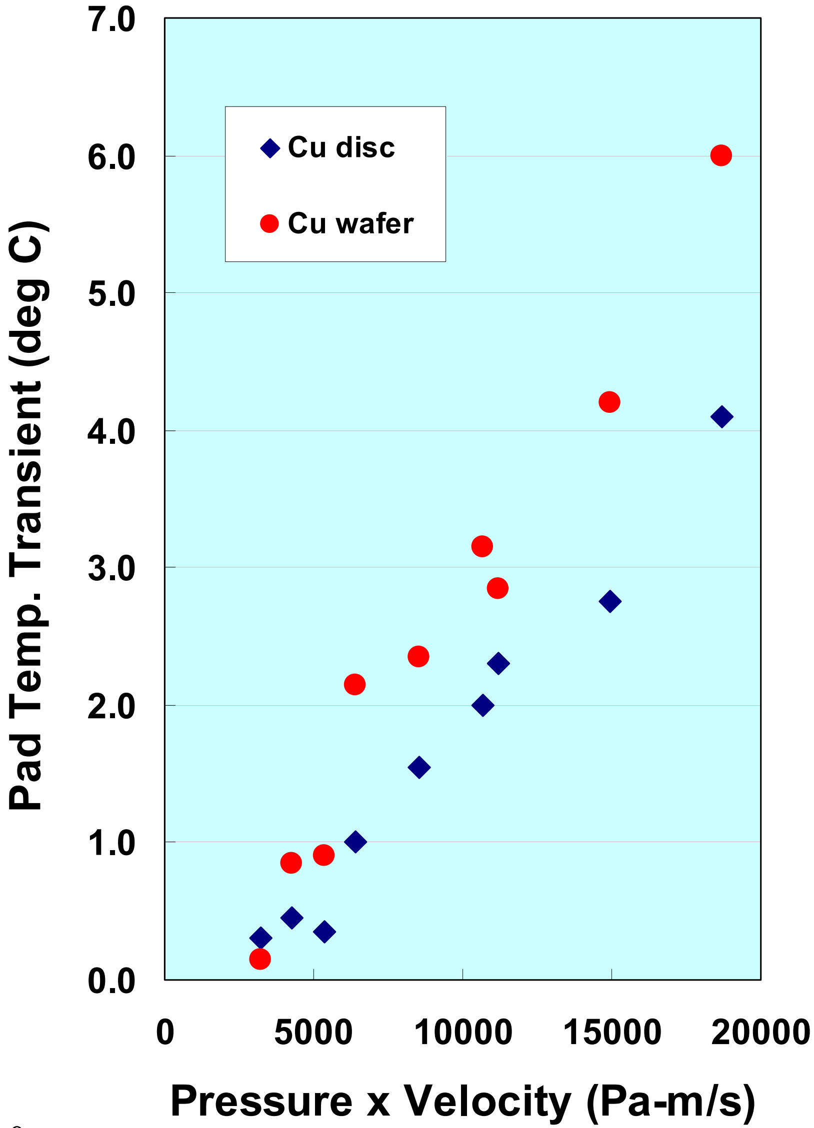
(2.5 PSI & 1.09 m/s)

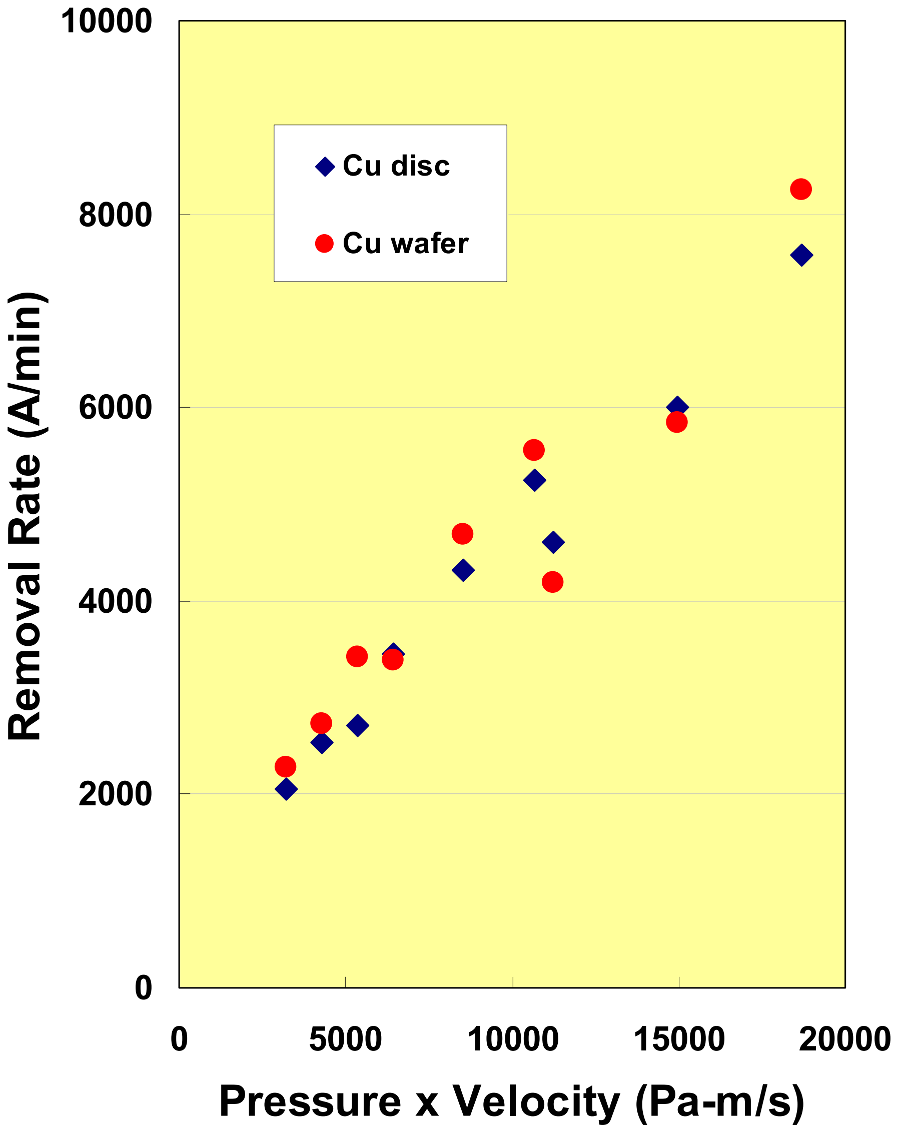




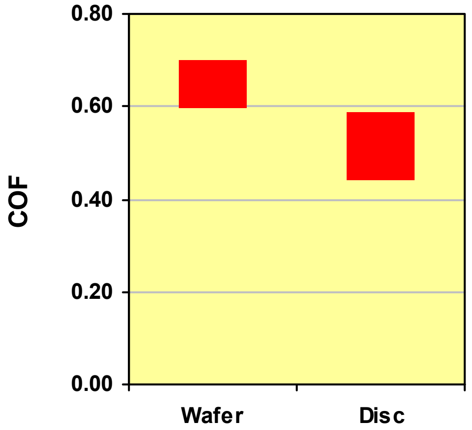
Temperature of the pad can increase by ~ 6 ^{o}C during a 75 second polishing process

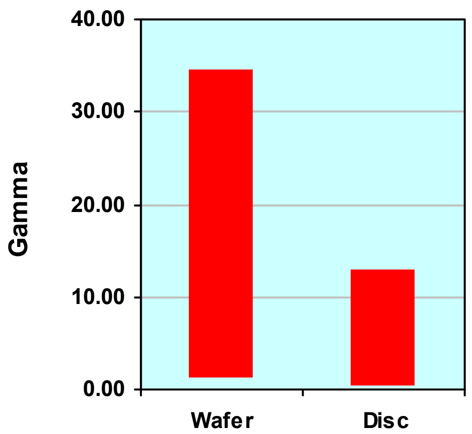
Pad Temperature Transients and Removal Rate





Qualitative Model Explaining Differences in Frictional, Thermal & Kinetic Attributes of Discs & Wafers





Frictional heating due to shaft work …
Pad temperature is proportional to power per unit area …

$$T_{pad} \propto COF \times P \times u \propto T_{substrate}$$

$$\Delta T \equiv T_{pad}\big|_{wafer} - T_{pad}\big|_{disc} \sim 1.03 \ {}^{o}\mathrm{C}$$

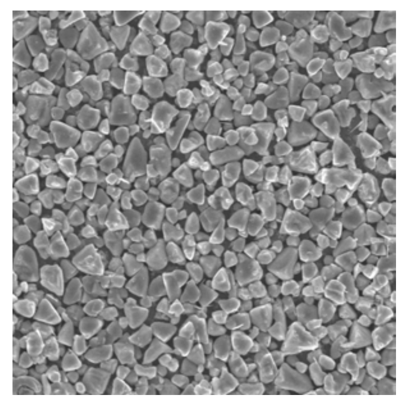
$$\Delta RR \equiv RR_{wafer} - RR_{disc} \sim 204 \ \mathrm{A/min}$$

Other Possible Causes of Observed Trends

- **Other geometric differences**
  - **Substrate thickness and its position relative to the plane of the retaining ring**
    - **Wafer thickness ~ 500 micron**
    - **Disc thickness ~ 400 micron**
  - **No 'primary flat' for copper disc**

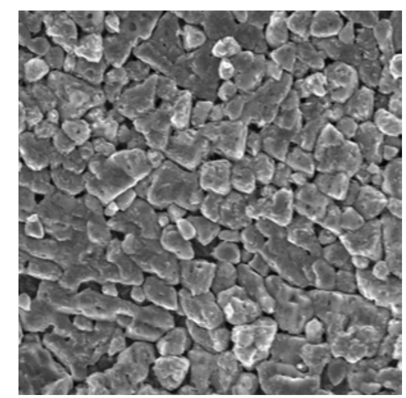
- **Differences in grain size**

Disc



2 microns

Wafer



2 microns

- **Differences in thermal conductivity between copper disc and copper deposited silicon wafer**
  - **Numerical simulations indicate that, on the average, copper discs will run ~ 0.5 °C cooler than copper wafers**

Concluding Remarks

- **Lubrication mechanism (wafer = disc = 'boundary lubrication')**
- **Average COF (wafer > disc)**
- **Extent of 'stick-slip' (wafer > disc)**
- **Pad temperature (wafer > disc)**
- **Removal rate (wafer > disc)**

- **Above differences likely due to drift in the geometric features of the two substrates:**
  - **Thinning of the edges of discs**
  - **Discs becoming more convex in shape**

- **Other considerations:**
  - **Thickness of substrates**
  - **Grain size**
  - **Differences in thermal conductivity**

- **Bottom-line … Discs are viable replacements for wafers for initial 'screening' experiments**
  - **Overall trends (wafer = disc)**
  - **Differences do not alter conclusions regarding the effect of process parameters on COF and RR**
  - **One disc can be used up to 5 times (~ 4X savings in substrate cost)**

Consumables Reduction in Cu CMP

Part 2: Determining the Effect of Slurry Flow Rate on the Tribological, Thermal and Removal Rate Attributes of Cu Polishing

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NSF/SRC ERC for Environmentally Benign Semiconductor Manufacturing

Motivation

- **Driving force**
  - **A serious cost and EHS concern**
    - **In copper CMP applications, slurry costs per wafer are responsible for more than one-third of the total COO**
    - **Reducing slurry flow rate without compromising polish performance will reduce:**
      - **COO**
      - **Solid and liquid waste**
      - **The burden on copper waste treatment**

- **Goal**
  - **Determine the effect of slurry flow, wafer pressure and relative wafer-pad velocity rate as it relates to:**
    - **COF**
    - **Lubrication mechanism**
    - **Material removal**
    - **Temperature**

Apparatus

Parameter	Scaling Factor	Speedfam-IPEC 472	Scaled Polisher
Down Pressure	1	4 PSI	4 PSI
Platen Speed	Reynolds Number	Relative pad-wafer velocity of 0.5 m per second (30 RPM)	Relative pad-wafer velocity of 0.5 m per second (55 RPM)
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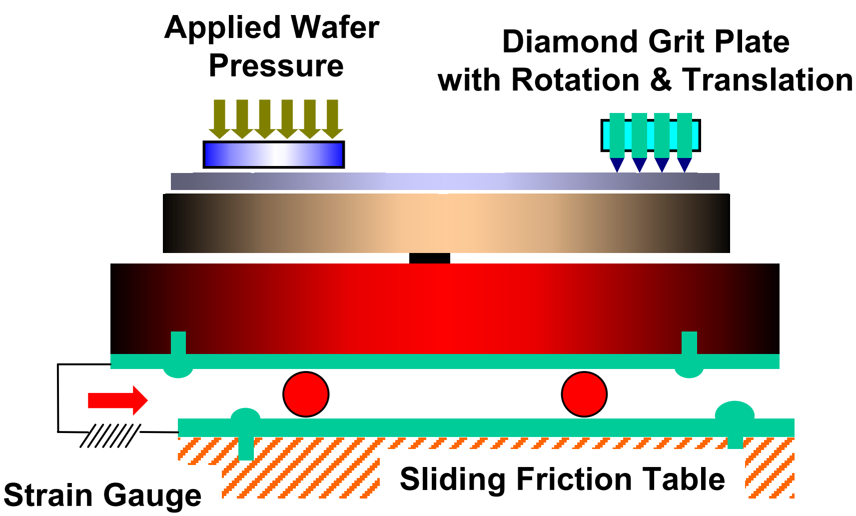

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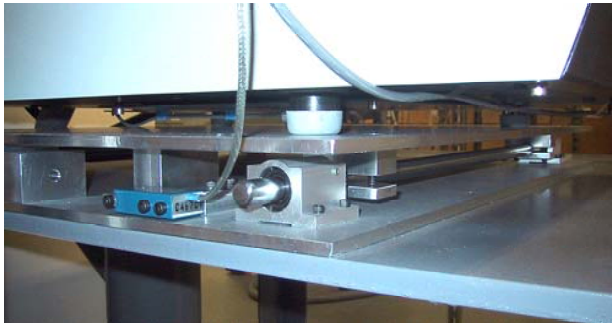

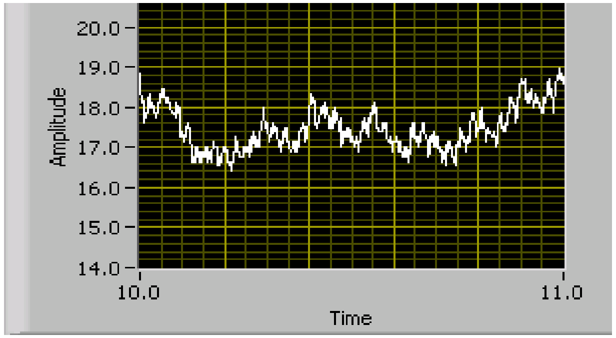

Experimental Conditions

- **Constants:**
  - Conditioning
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  - Wafers
    - Cu disc (purity of 99.99%)
  - Pad type
    - Rodel IC-1000 k-groove

- **Variables:**
  - Slurry flow rate
    - 80 cc per minute
    - 140 cc per minute
  - Relative pad-wafer velocity (m/s)
    - 0.31
    - 0.62
    - 1.09
  - Wafer pressure
    - 1.5 PSI (~ 10 kPa)
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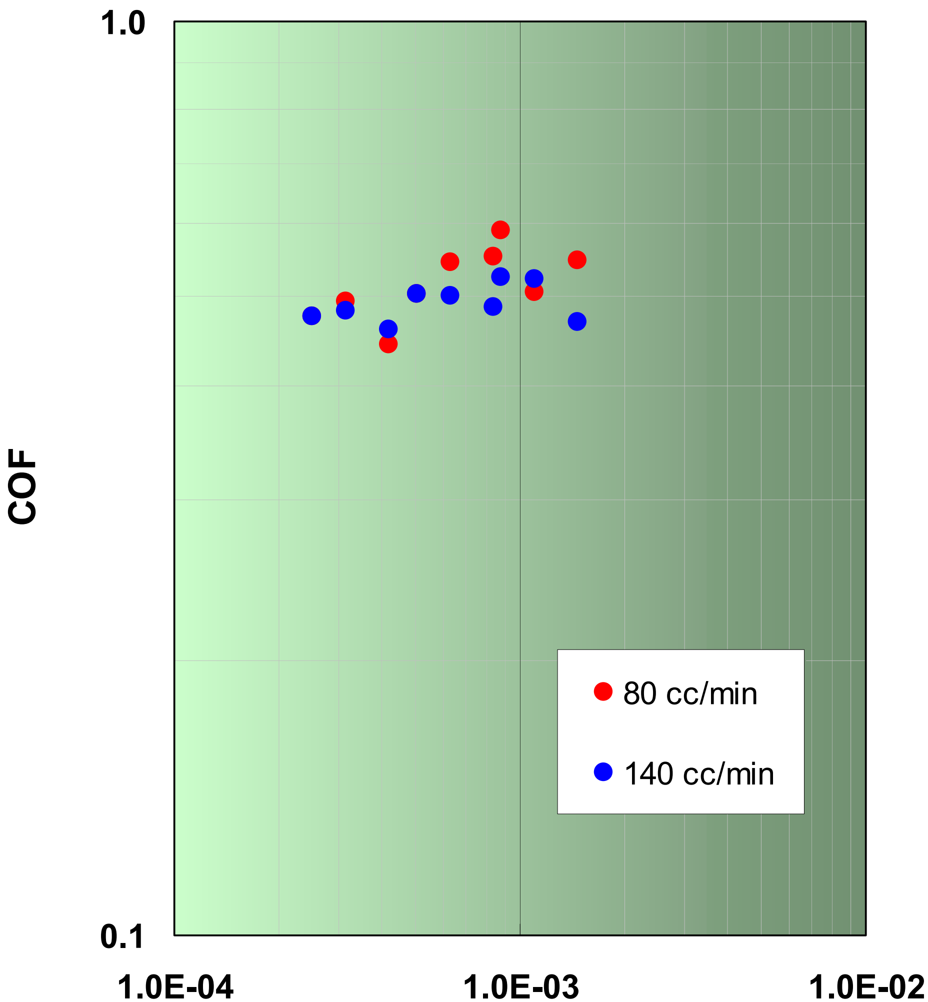
Effect of Slurry Flow Rate on COF and Lubrication Mechanism



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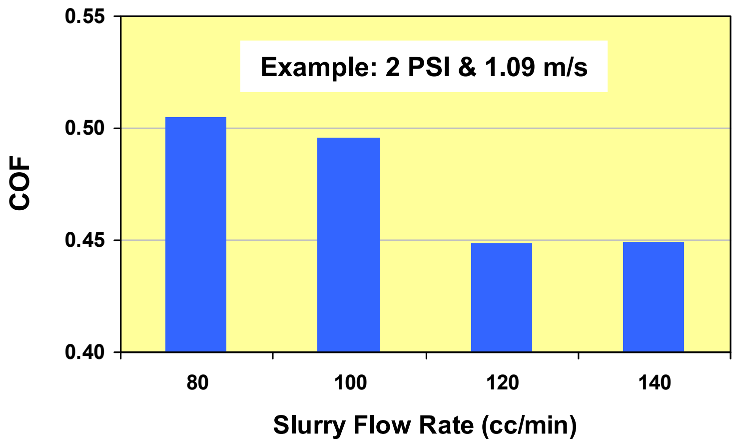
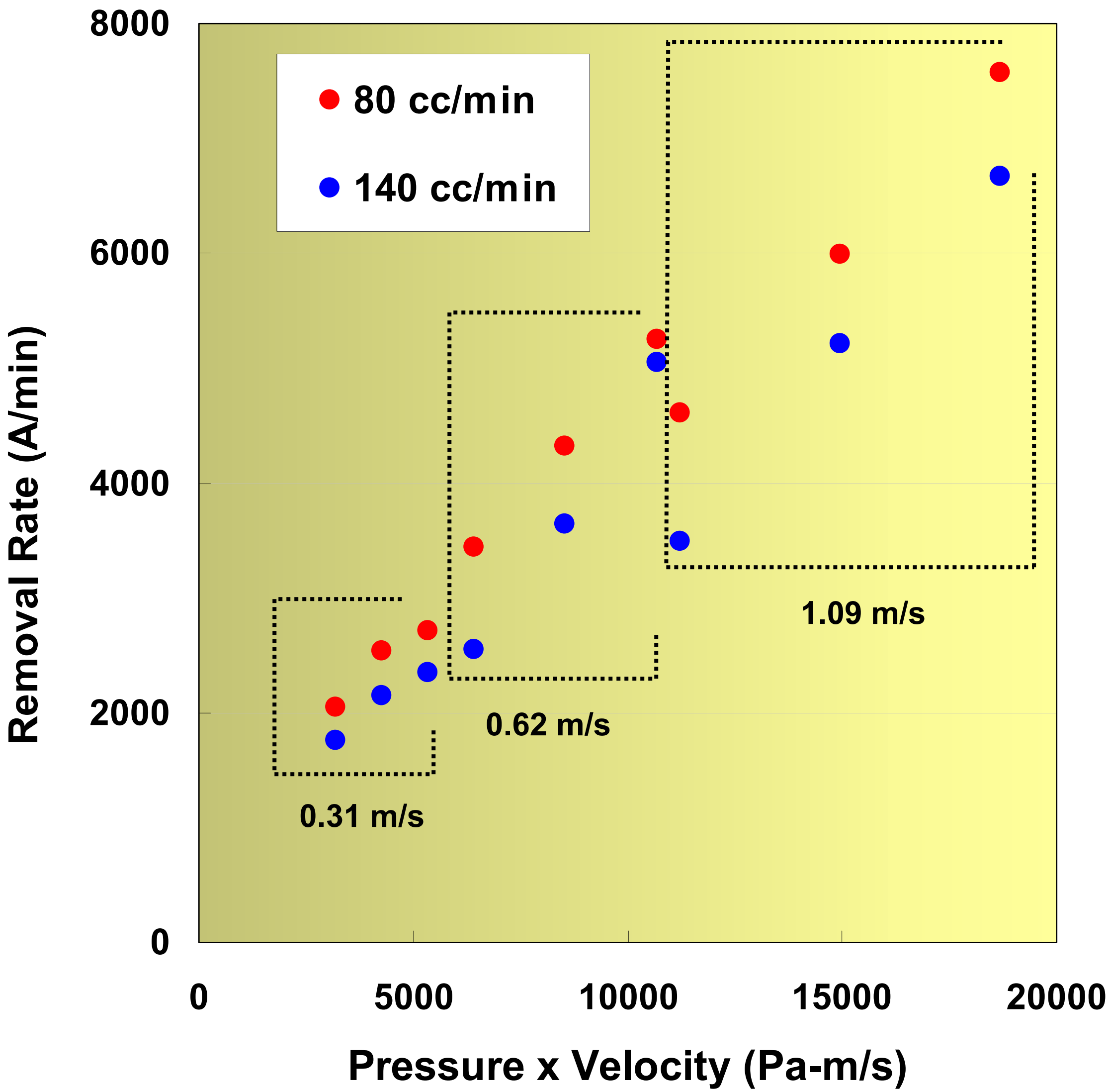


- **Slurry flow rate affects average COF**
  - **0.5167 … 80 cc/min**
  - **0.4913 … 140 cc/min**
- **Slurry flow rate does not affect the lubrication mechanism**
  - **'boundary lubrication' in both cases**
- **Slurry flow rate can be used to modulate average COF without changing the lubrication mechanism**
  - **Key to studying effect of COF on RR without having to worry about changes in the the lubrication characteristics of the process**

Removal Rate Studies



- Slurry flow rate affects RR:
  - RR at 80 cc/min is 10 to 20 percent higher than RR at 140 cc/min
- When transitioning from 2.5 PSI & 0.62 m/s to 1.5 PSI & 1.09 m/s the following are nearly constant:
  - COF
  - Lubrication mechanism
  - P x u

  Yet there is a significant drop in RR at 1.5 PSI & 1.09 m/s (drop is more pronounced at higher flow rate)
- What is the reason for the observed non-Prestonian behavior ?

Simple Reaction Rate Model

- **Copper RR & the sequential <u>Langmuir-Hinshelwood</u> model:**
  - ***n*** **moles of reactant** ***R*** **in the slurry react at rate** k_1 **with copper film on the wafer to form a product layer** ***<u>L</u>*** **on the surface**

$$\underline{Cu} + nR \xrightarrow{k_1} \underline{L} \qquad \boxed{k_1 = A\exp(-E/kT_w)} \qquad \boxed{RR = (M_w/\rho)k_1}$$

  - **Product layer** ***<u>L</u>*** **subsequently removed by mechanical abrasion with rate** k_2

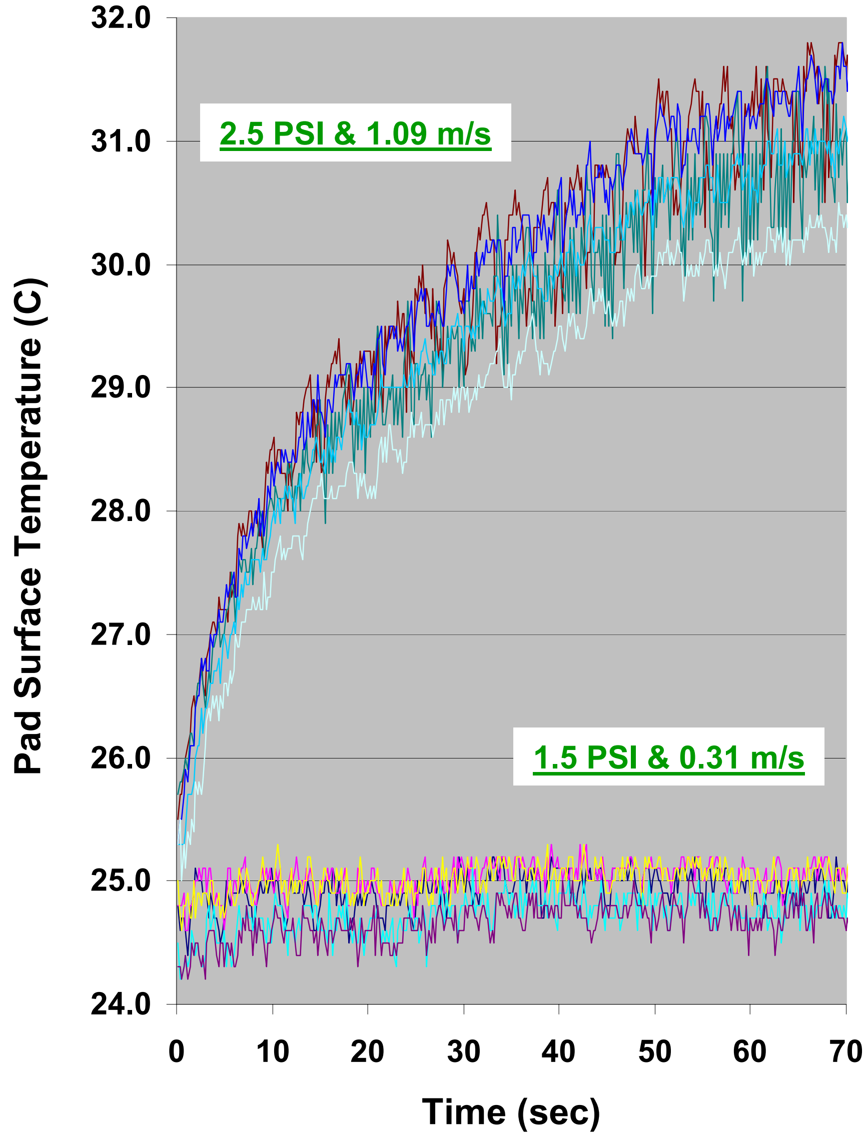
$$\underline{L} \xrightarrow{k_2} L \qquad \boxed{k_2 = c_p \times pV} \qquad \boxed{RR = (M_w c_p/\rho)pV}$$

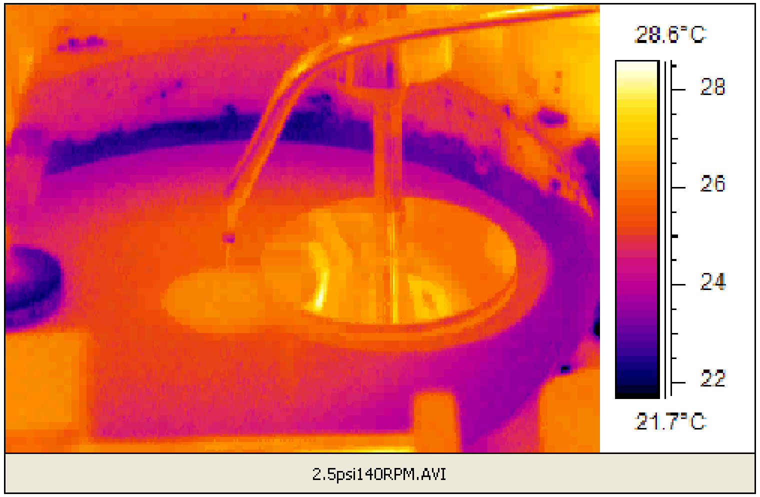
  - **Abraded material** ***L*** **carried away by the slurry**

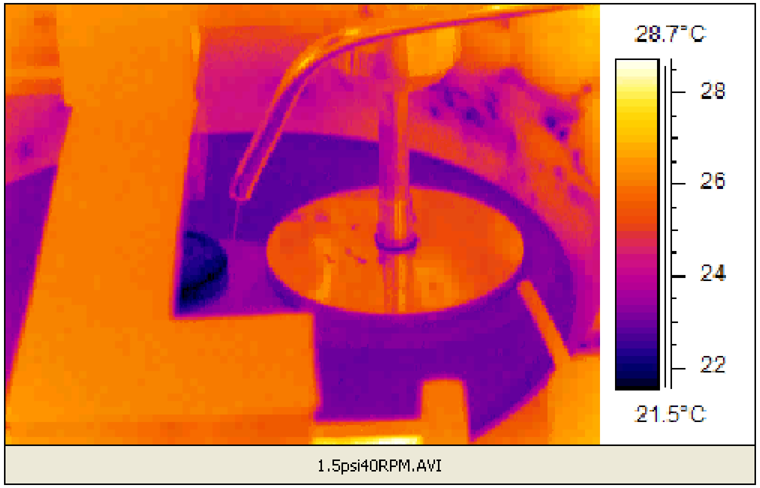
- **The local removal rate in this sequential mechanism therefore <u>is a function of both thermal and mechanical attributes of the process</u>**

$$RR = \frac{M_w}{\rho}\frac{k_1 C}{1 + \dfrac{k_1 C}{k_2}}$$

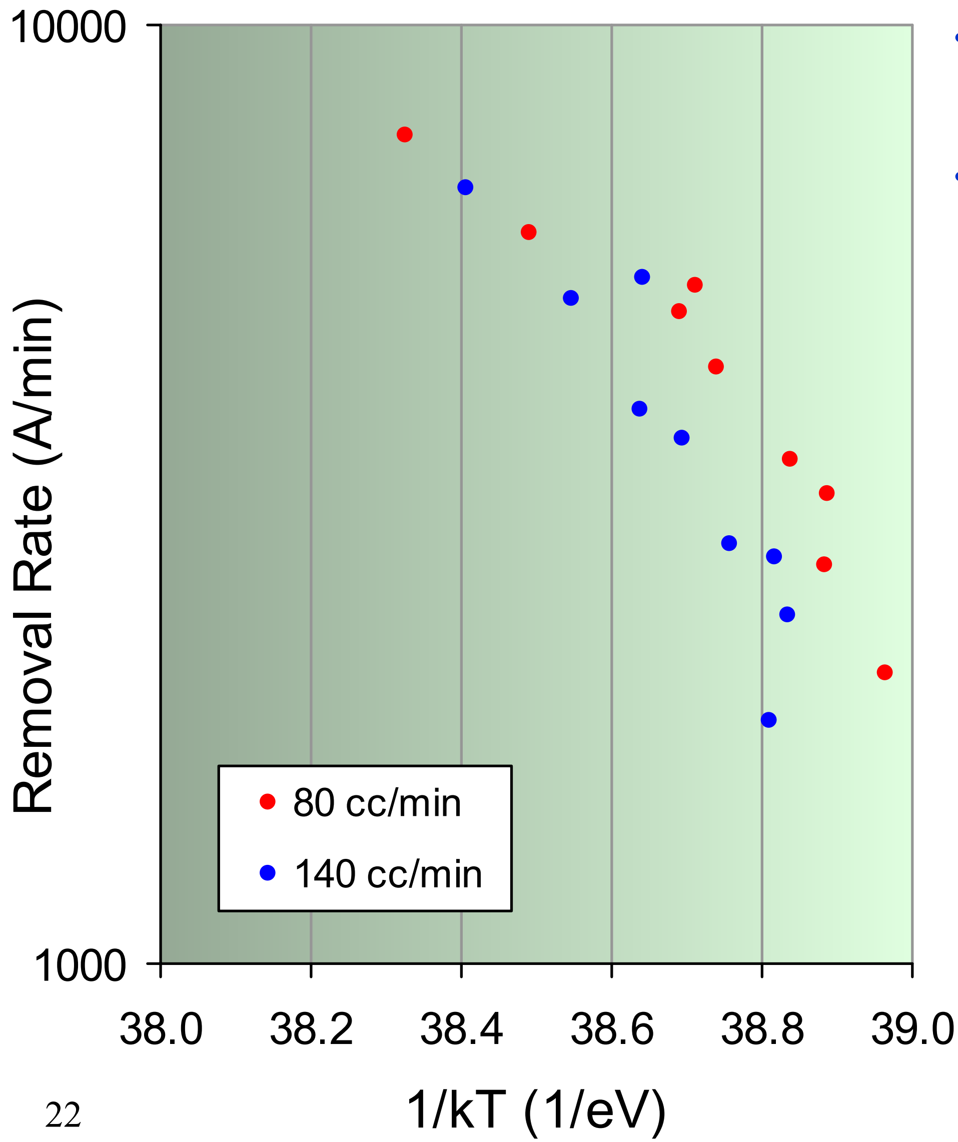
Thermal Analysis During Polish Process



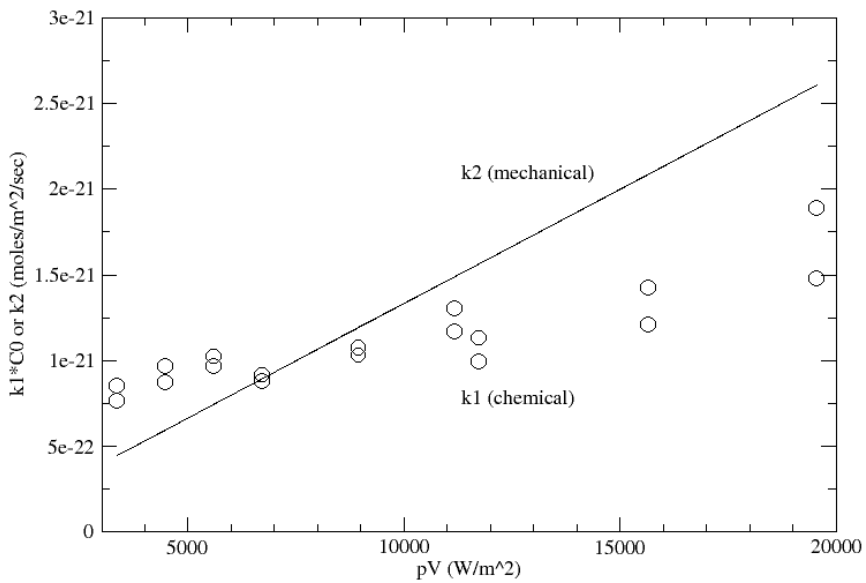




Removal Rate vs. Inverse of Pad Mean Leading Edge Temperature for Various Flow Rates



- Pad temperature, slurry flow rate and RR are all inter-related
- For a given flow rate, departure from a 'classical' Arrhenius relationship is due to several factors:
  - RR is dependent on '1/kT' (thermal) as well as on 'PV' (mechanical)
  - In all cases, mean pad temperature is different from mean wafer temperature



Thermal Model & Energy Balance

frictional energy generated due to abrasion

heat partition factor

$$\gamma_w = \frac{\kappa_w}{\kappa_w + 0.627\,\kappa\sqrt{\frac{V r_w}{D}}} = 1 - \gamma_p$$

$$\kappa \frac{\partial T_p}{\partial z} = \chi(r,t)\gamma_p \mu_k(t) p V_s - h_{ps}(T_p - T_s)$$

$$\kappa_w \frac{\partial T_w}{\partial z} = \gamma_w \mu_k(t) p V - h_{ws}(T_w - T_s)$$

pad

wafer

environment

platen

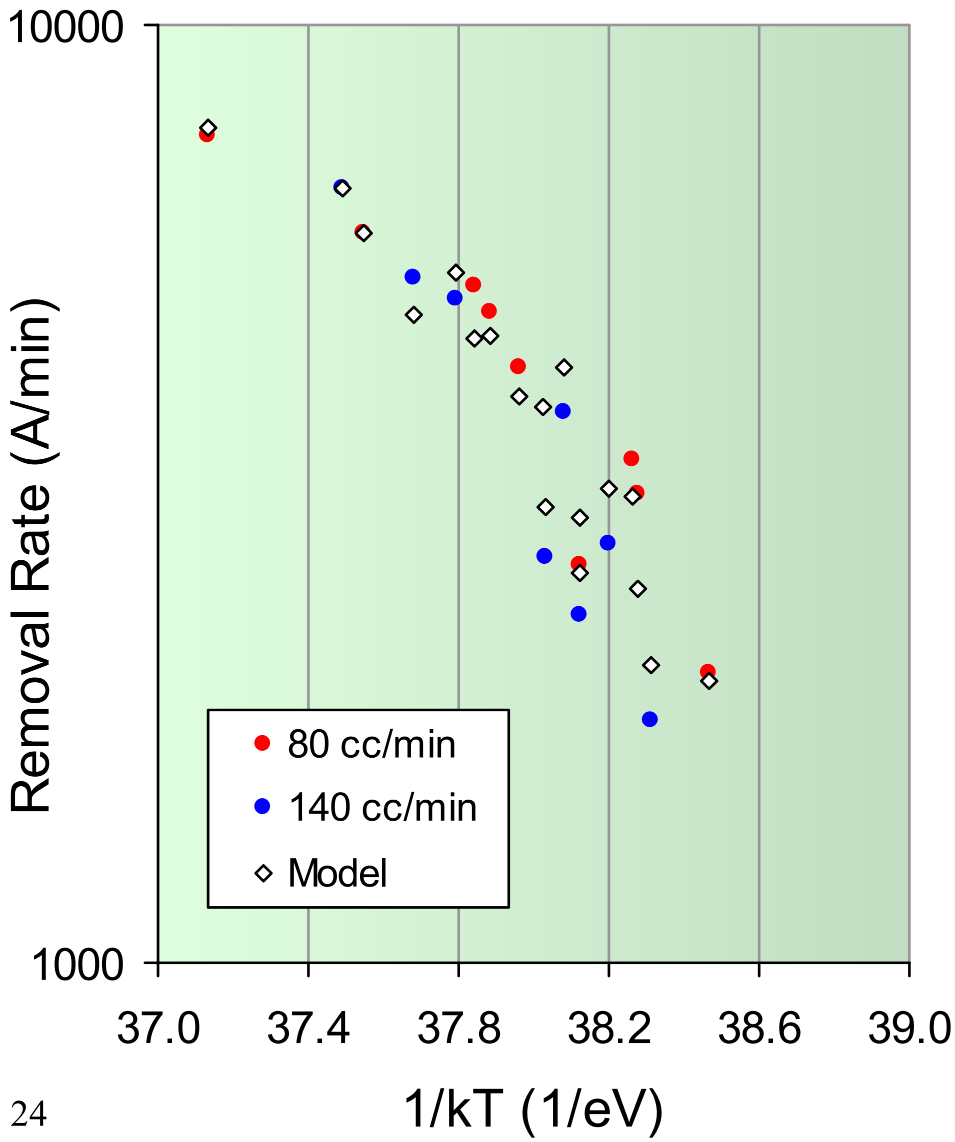
$$V(r) = f_s/(2\pi h_s^0 r)$$

carrier assembly

environment

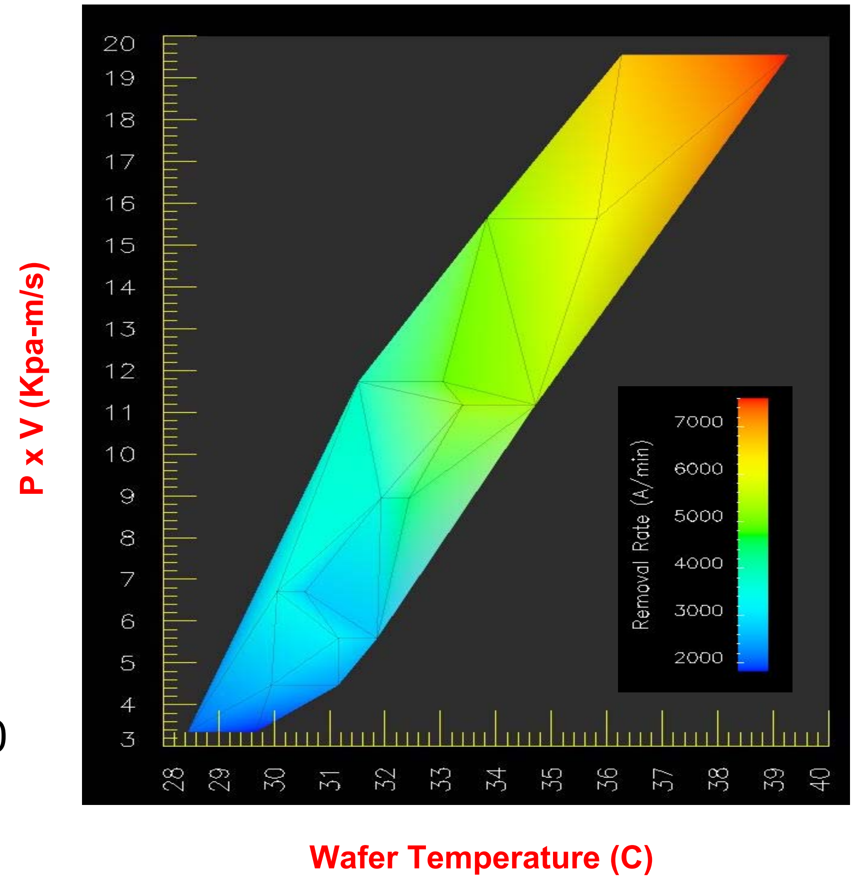
slurry

Removal Rate vs. Calculated Wafer Temperature for Various Flow Rates

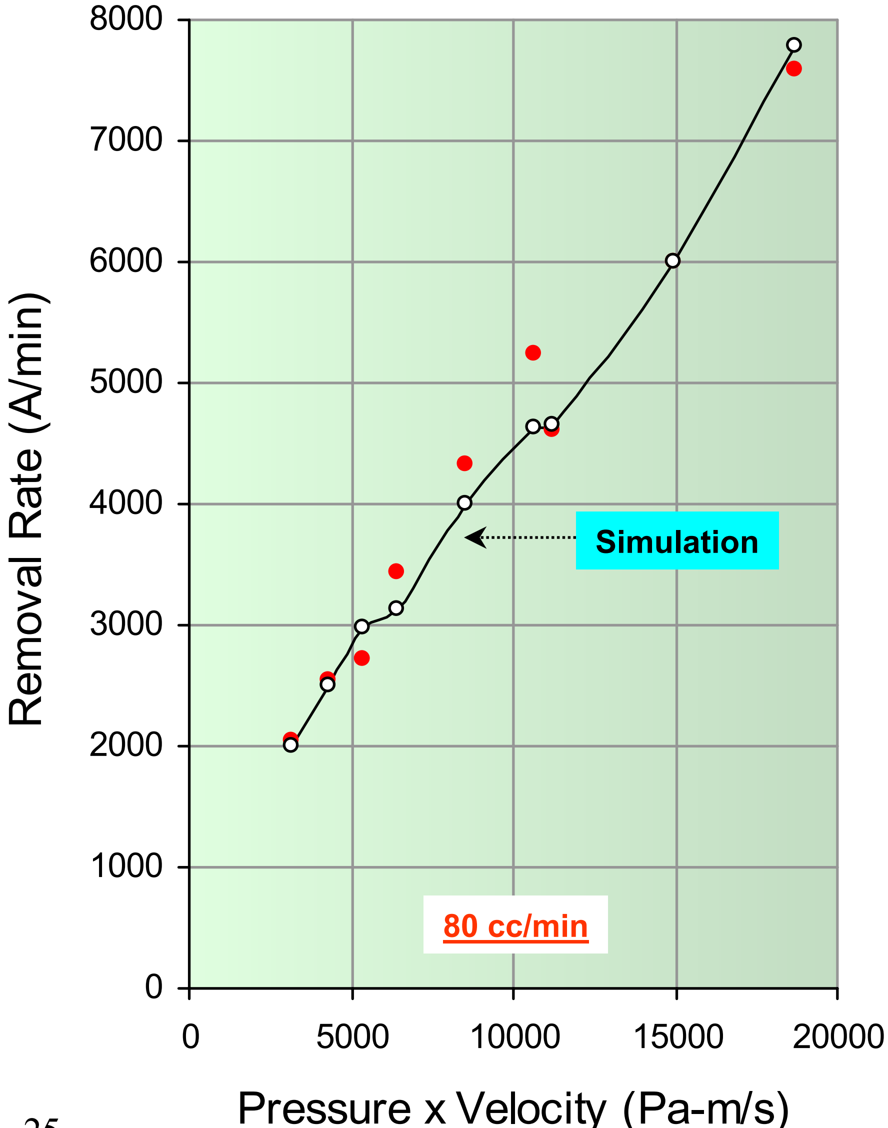


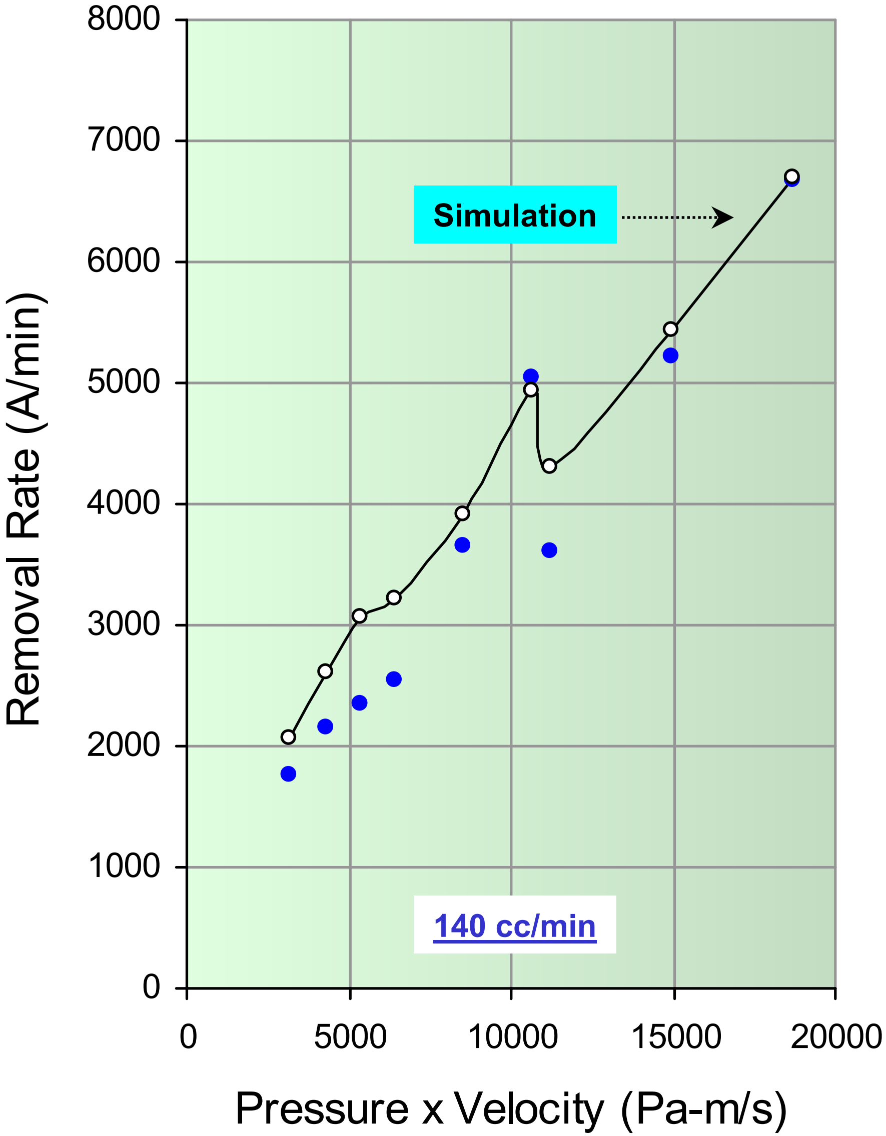
Scatter in data and the model are again due to the fact that RR is dependent on '1/kT' as well as on 'PV'

Under such circumstances, results are best described using contour plots



Removal Rate Studies (Simulation vs. Experiment)





Concluding Remarks

- **Within the range of parameters investigated, increasing slurry flow rate:**
  - **Decreases average COF**
  - **Has no impact on the lubrication mechanism (‘boundary lubrication’)**
  - **Decreases RR due to cooling of the wafer by the slurry**

- **The transition in RR, that occurs when rotation rate is changed at nearly constant P x V, is also due to a combination of changes in:**
  - **COF**
  - **Heat partition factor**
  - **Wafer-slurry heat transfer coefficient (dominant factor)**

- **Trends in RR are explained as a function of P x V and wafer temperature using a model with both chemical and mechanical components**

- **The model is reaction rate limited at higher RRs, emphasizing that removal of copper is generally non-Prestonian**

Questions