A Model of
Chemical Mechanical Polishing

Ed Paul

Stockton College
Pomona NJ   08240   USA

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Outline

Goal

- Explain how the polishing rate depends on slurry formulations and mechanical conditions.

Model

- Chemical and Mechanical Balance
- Chemical Formation
  - Oxidizer concentration
- Mechanical removal
  - Pads, polishing pressure and speed
  - Abrasive loading, abrasive diameter
- Inhibitors

Extensions

Conclusion

Investigation of the Kinetics of Tungsten Chemical Mechanical Polishing in Potassium Iodate-Based Slurries

I. Role of Alumina and Potassium Iodate

David J. Stein, Dale L. Hetherington and Joseph L. Cecchi

Journal of the Electrochemical Society **146** 376-381 (1999)

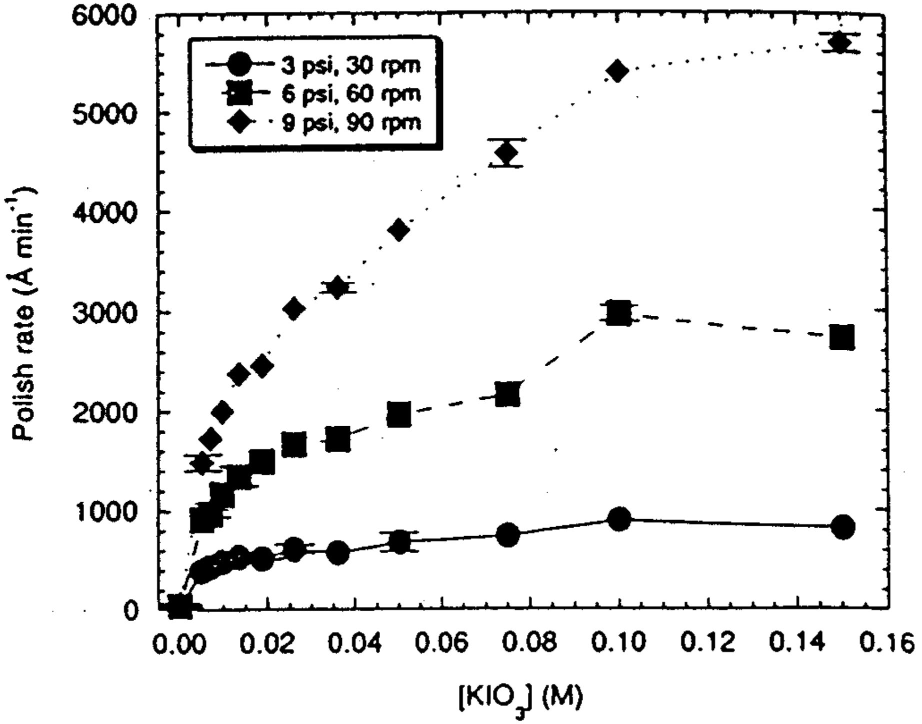

Figure 5. The polish rate at the three settings of polish pressure and rotation rate is shown as a function of KIO_3 concentration. The concentration of PHP was 0.05 M and the slurry contained 5 wt % alumina.

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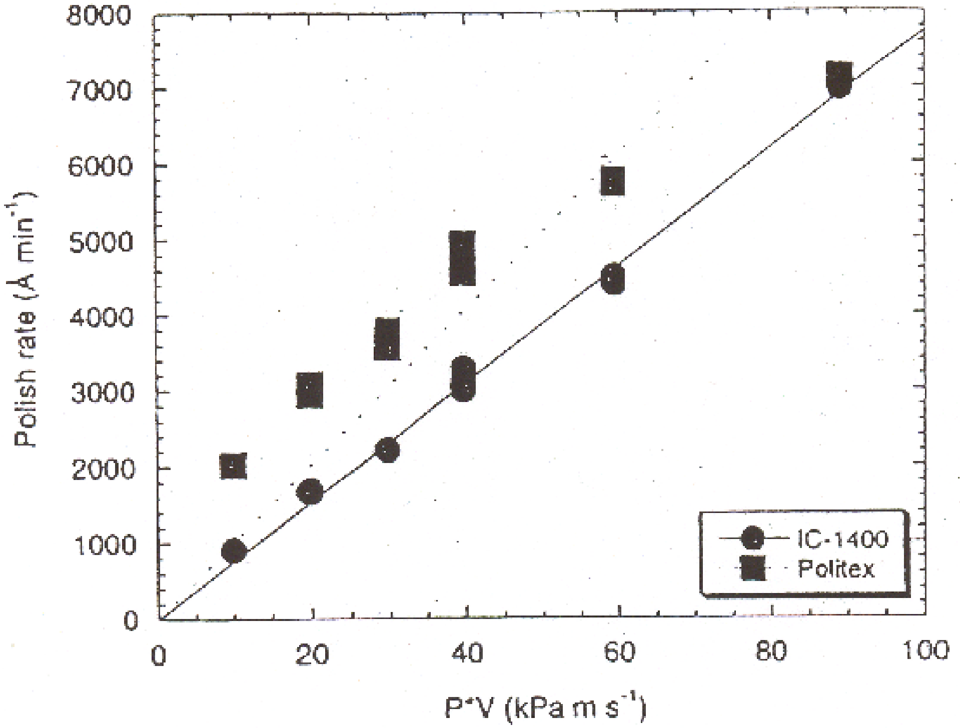

Figure 2. The polish rate data for both the IC-1400 and Politex regular pads are shown. The lines represent the best fit of the data to the Preston equation (Eq. 1).

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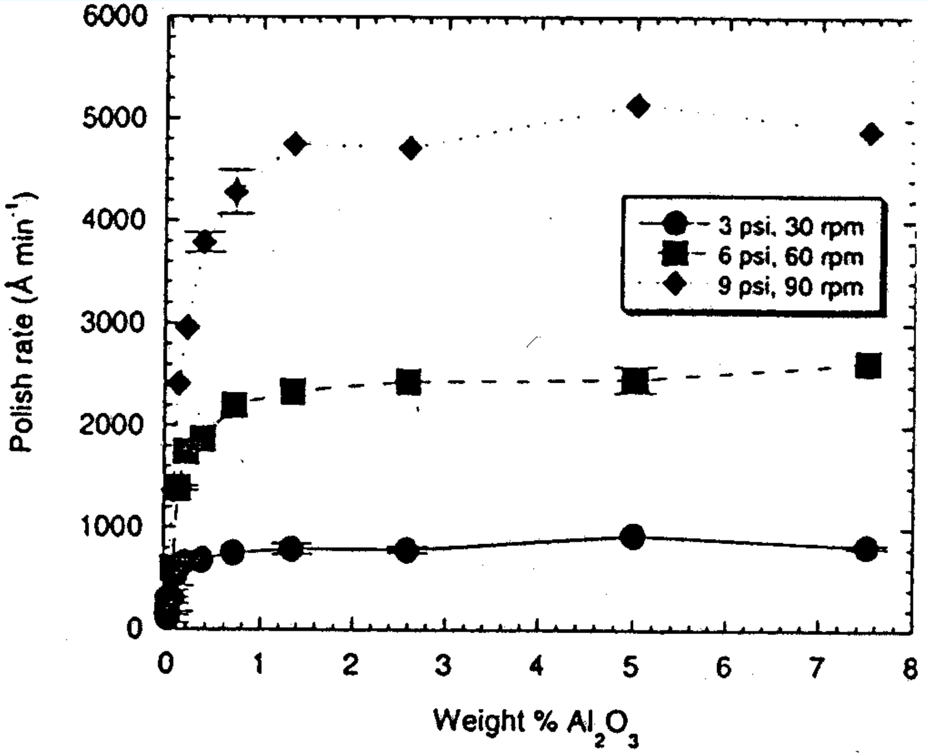


Figure 3. The polish rate at the three settings of polish pressure and rotatio rate is shown as a function of alumina concentration. The concentration o KIO_3 was 0.1 M and PHP was 0.05 M.

Effect of Particle Size during Chemical Mechanical Polishing

M. Bielmann, U. Mahajan, R.K. Singh

Electrochem. Solid-State Lett. **2,** 401-403 (1999)

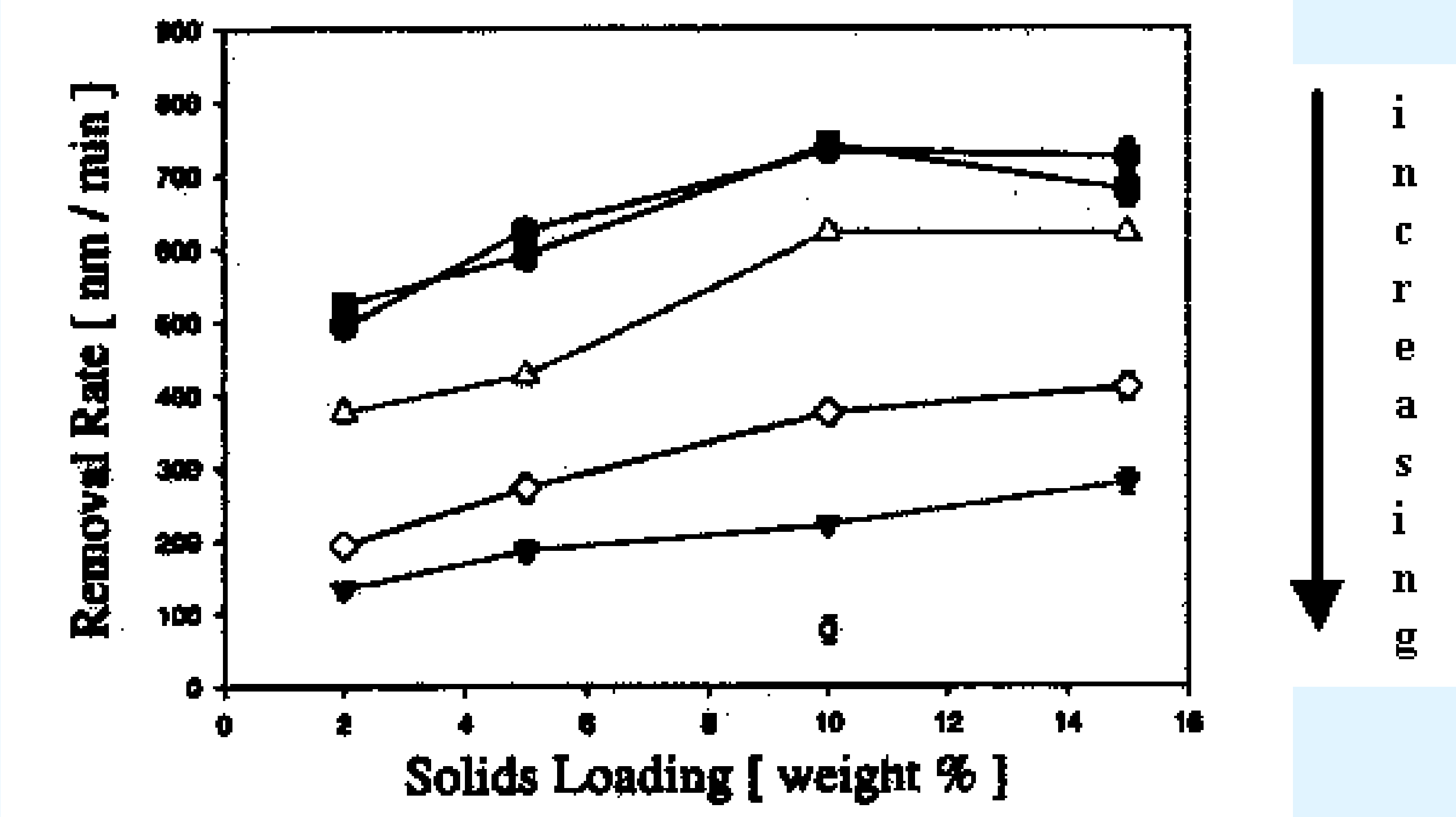
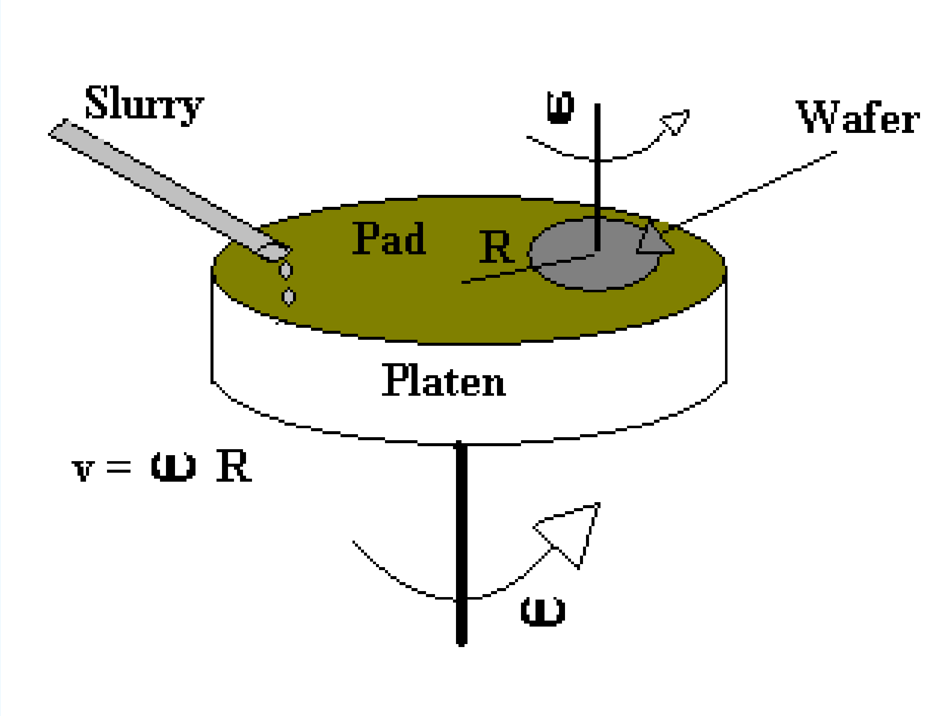


Figure 4. Tungsten removal rate vs. solids loading for different particle size distribution.

Multiscale Processes, Part I

Fluid Dynamics 1 mm

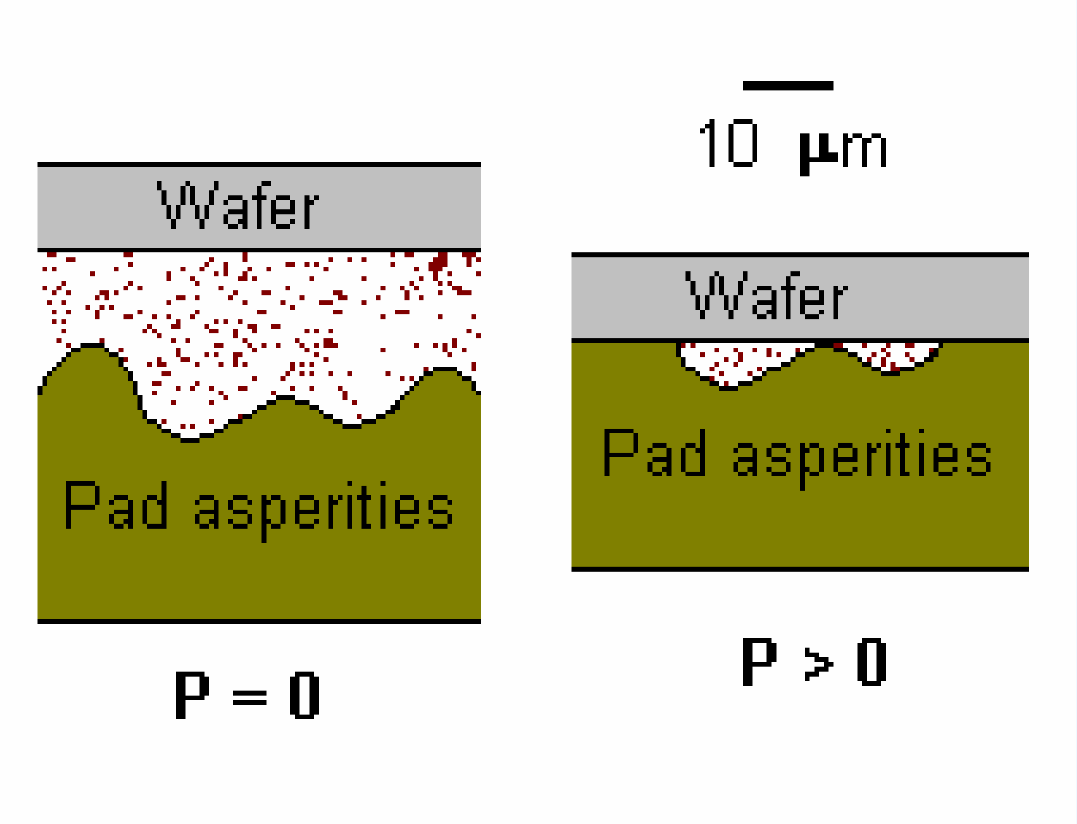
- slurry thickness
- partial lubrication
- coefficient of friction



Multiscale Processes, Part II

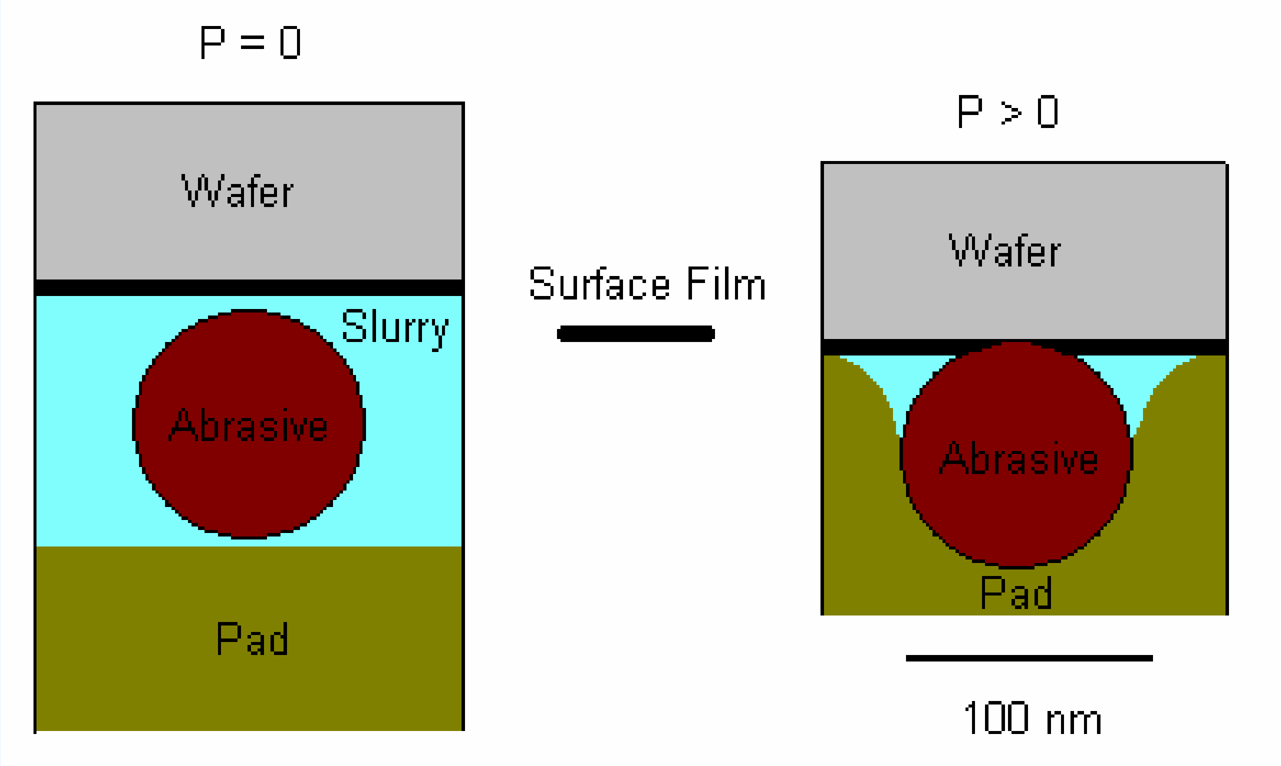
Pad Asperity Flattening 100 μm

Abrasive – Pad Loading 10 μm



Multiscale Processes, Part III

Abrasive – Pad Interactions	100 nm
Abrasive – Wafer Interactions	10 nm
Wafer – Slurry Reactions	1 nm

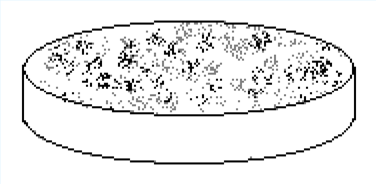


Chemical Formation and Mechanical Removal of a Surface Complex

Chemical Formation $W + C \rightarrow WC$ $r_C = \kappa_C n_W$

Mechanical Removal $WC \rightarrow W + Y$ $r_M = \kappa_M n_{WC}$

W	Wafer material (Tungsten)
C	Chemical in reaction (Oxidizer)
WC	Surface complex formed by reaction (Oxide)



n_W Unreacted Sites n_{WC} Reacted Sites

Total Sites $n_{oW} = n_W + n_{WC} = A_W / d_W^2$

Removal Rate

$$R = \tau_1 \kappa_M n_{WC} / A_W$$

A_W Wafer area

τ_1 removal depth

τ removal depth per site area

At steady state $\kappa_C n_W = \kappa_M n_{WC}$

$$n_{WC} = \frac{n_{oW}\kappa_C}{\kappa_C + \kappa_M}$$

CMP Polishing Rate

$$R = \frac{\tau\kappa_C\kappa_M}{\kappa_C + \kappa_M}$$

chemical rate constant $\kappa_C = k_C [C]$

Removal Rates - Oxidizer Concentration

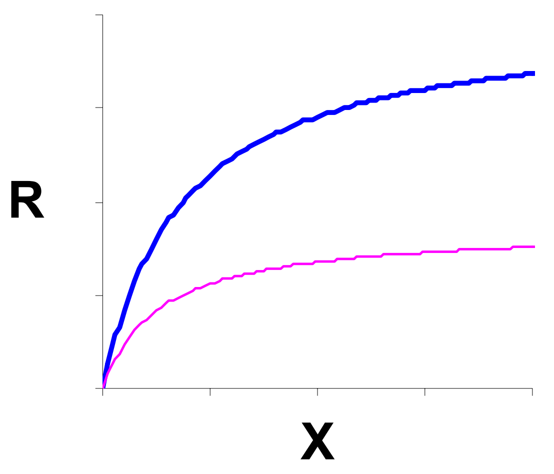
$$R = \frac{\tau \ \kappa_M k_C [C]}{k_C [C] + \kappa_M}$$

$$= \frac{\left(\tau \ \kappa_M\right)[C]}{[C] + \left(\kappa_M / k_C\right)}$$

$$= \frac{a_C X}{b_C + X}$$

R(X)

$$R = \frac{a\,X}{b + X}$$



Maximum Rate = a

Initial Slope = a / b

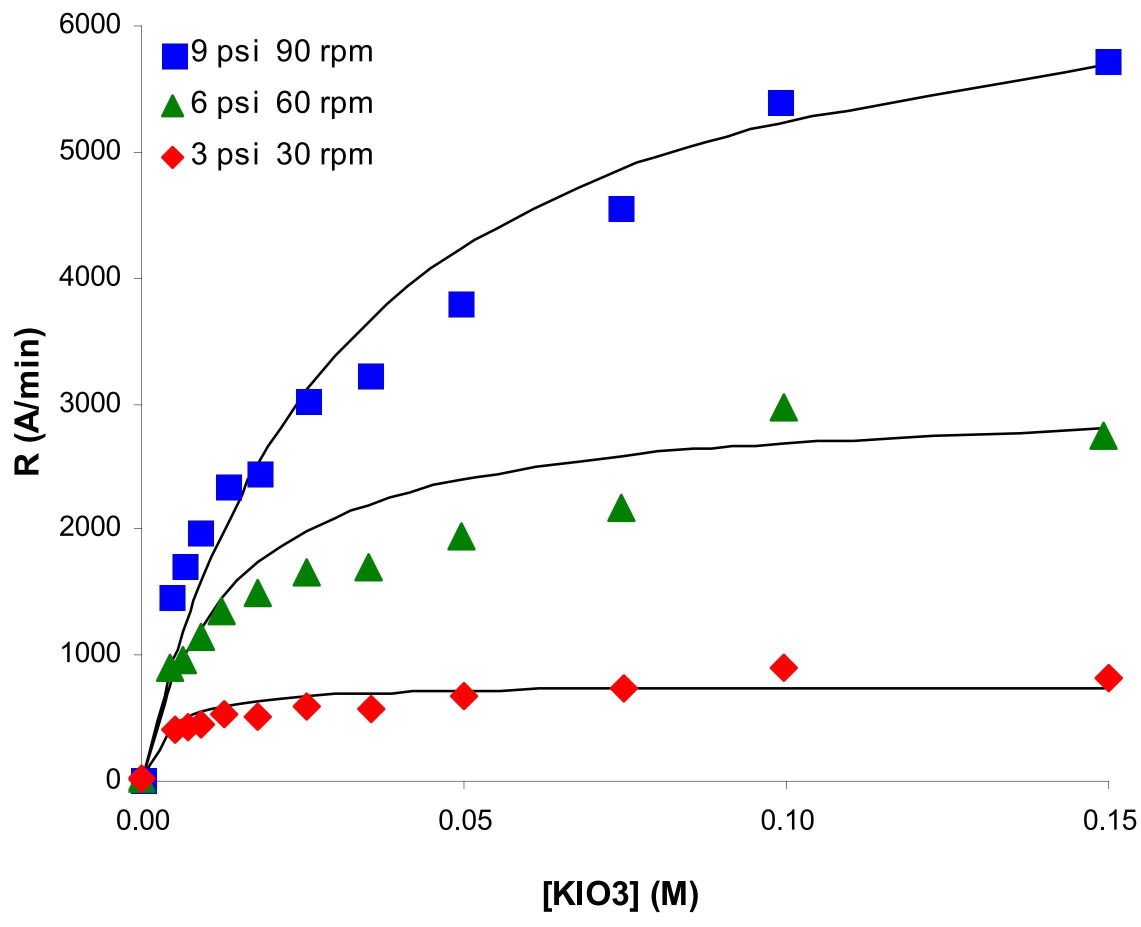
a and b depend on variables other than X

W-CMP   R([C])

D. J. Stein, D. L. Hetherington, and J. L. Cecchi

J. Electrochem. Soc. **146**, 376 (1999)

$$R = \frac{a_c X}{b_c + X}$$



Mechanical Removal of the Surface Complex

$$r_M = \kappa_M n_{WC}$$

κ_M ~ Active abrasives * Area swept ~ $n_A (A_C v)$

Pad properties

Abrasive pad interactions

Abrasive – surface interactions

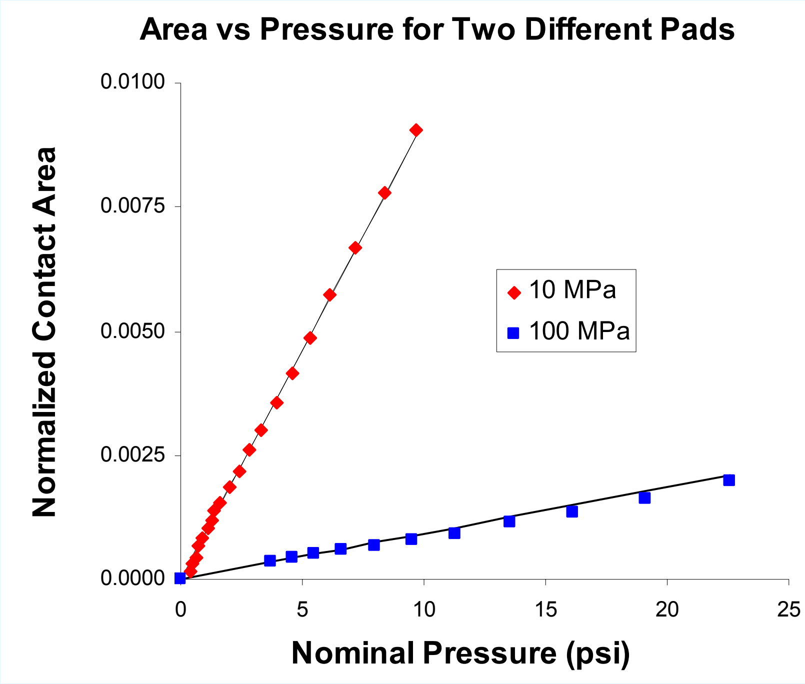
Pad Properties

Pad asperities flatten with pressure

Contact Area

$$A_C / A_W = \alpha P / E$$

$\alpha = 0.00925$



Yu, Yu and Orlowski International Electronic Devices Meeting 1993
Quoted as Fig. 4.27 in Steigerwald, Murarka and Guttman
Chemical Mechanical Planaization of Microelecgtronic Materials

Preston Equation $\kappa_M \sim (A_C v) = (k'_M \alpha/E) Pv = k_M Pv$

Nominal Pressure and Effective Pressure

$$F_{\text{on Pad}\ =} = P\,A_W = P_{\text{effective}}\ A_C$$

$$P_{\text{effective}} = E / \alpha$$

$F_{\text{on Pad}}$	force on pad	A_W	wafer area	A_C	contact area
P	polishing pressure	$P_{\text{effective}}$	effective pressure		
E	Young’s modulus	α	proportionality constant		

Removal Rates – Pressure and Speed

$$R = \frac{\tau\ \kappa_M k_C[C]}{k_C[C] + \kappa_M} = \frac{\tau\ k_M Pv\, k_C[C]}{k_C[C] + k_M Pv}$$

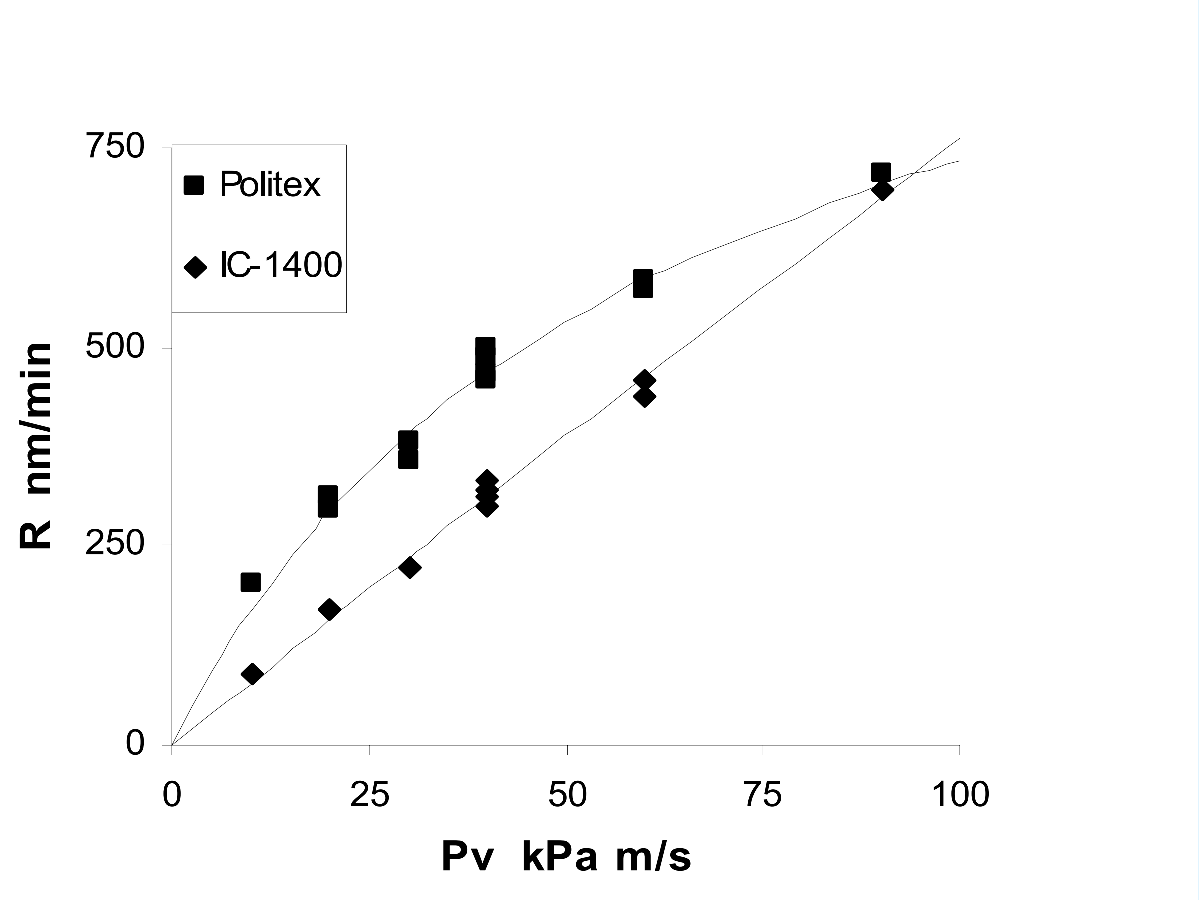
$$= \frac{(\tau\ k_C[C])Pv}{\left(k_C[C]/k_M\right) + Pv} \quad = \frac{a_{Pv}\ Pv}{b_{Pv} + Pv}$$

$$a_{Pv} = \tau\ k_C[C] \qquad b_{Pv} = \frac{k_C[C]}{k_M} = \frac{k_C[C]\, E}{k'_M \alpha}$$

W-CMP   R(Pv) for Two Pads

D. J. Stein, D. L. Hetherington, and J. L. Cecchi
J. Electrochem. Soc. **146**, 376 (1999)

$$R = \frac{a_{Pv}\, Pv}{b_{Pv} + Pv}$$

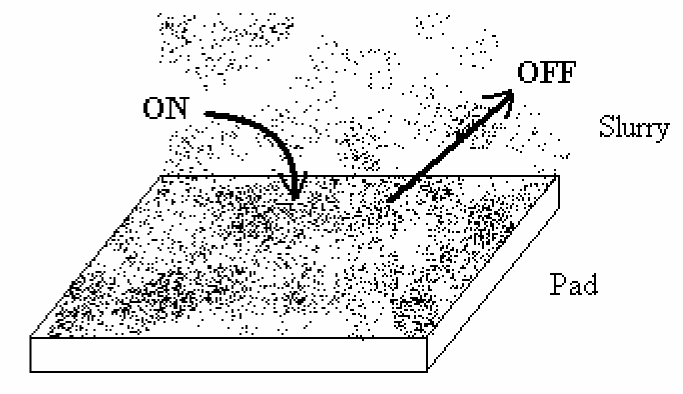


Abrasive – Pad Interactions

Active abrasives n_A

Total abrasive sites $n_{oP} = n_A + n_S$

On – off balance $k_{ON} [A] n_A = k_{OFF} n_S$



$$n_A = \frac{n_{oP}[A]}{[A] + K_{Pad}} = n_{oP}\ f(A)$$

$$K_{Pad} = \frac{k_{ON}}{k_{OFF}}$$

Mechanical Removal Rate

$$r_M = \kappa_M n_{WC} = k_M Pv\, n_{WC} = k_{oM} f(A)\, Pv\, n_{WC}$$

CMP Removal Rate

$$R = \frac{\tau\ k_{oM} f(A)\ Pv\ k_f [C]}{k_f [C] + k_{oM} f(A)\ Pv} = \frac{\tau k_C\ k_{oM} [C]\ [A]\ Pv}{k_C [C]\ K_{Pad} + k_C [C]\ [A] + k_{oM} [A]\ Pv}$$

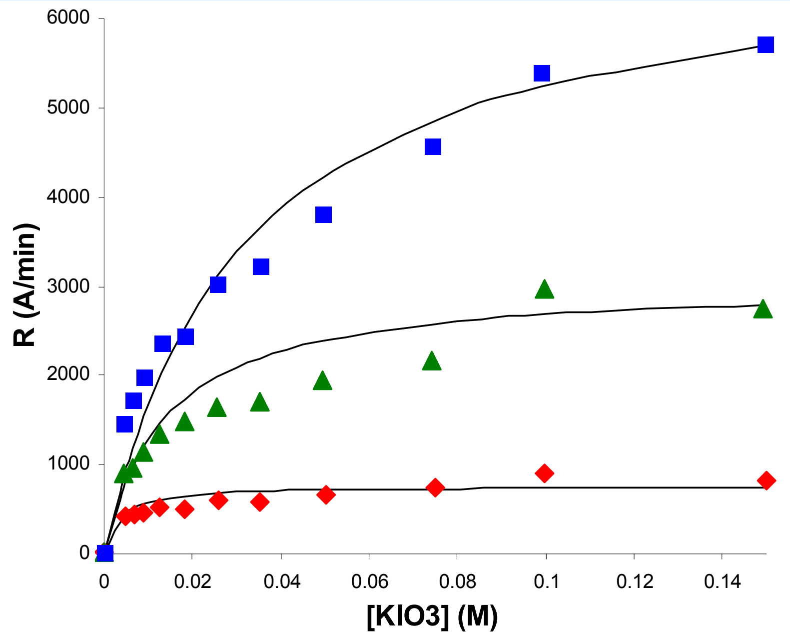
$$R = \frac{[C]\ [A]\ Pv}{a_1 [C] + a_2 [C]\ [A] + a_3 [A]\ Pv}$$

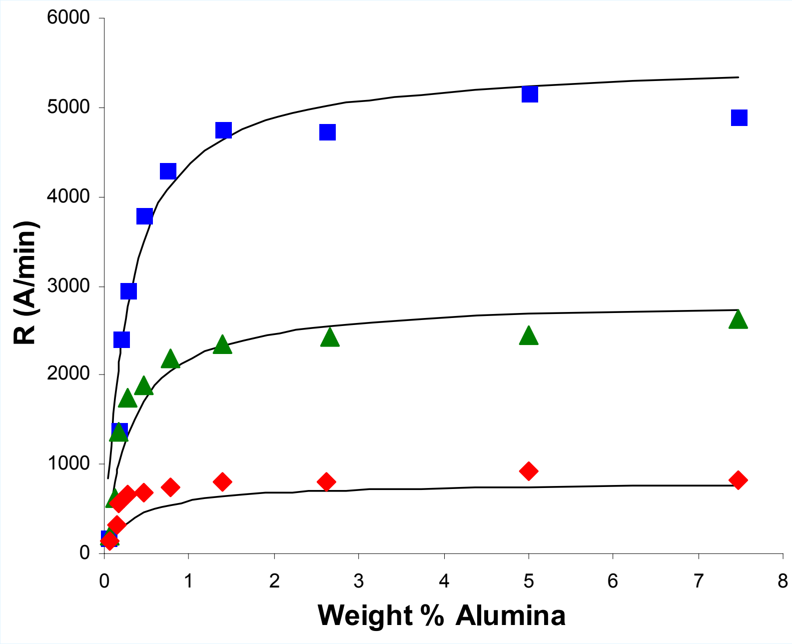
$$R = \frac{a_A [A]}{b_A + [A]}$$ when [C] and Pv are constant

W-CMP R([C], Pv) and R(%A, Pv)

D. J. Stein, D. L. Hetherington, and J. L. Cecchi
J. Electrochem. Soc. **146**, 376 and 1934 (1999)

◆ 3 psi 30 rpm ▲ 6 psi 60 rpm ■ 9 psi 90 rpm





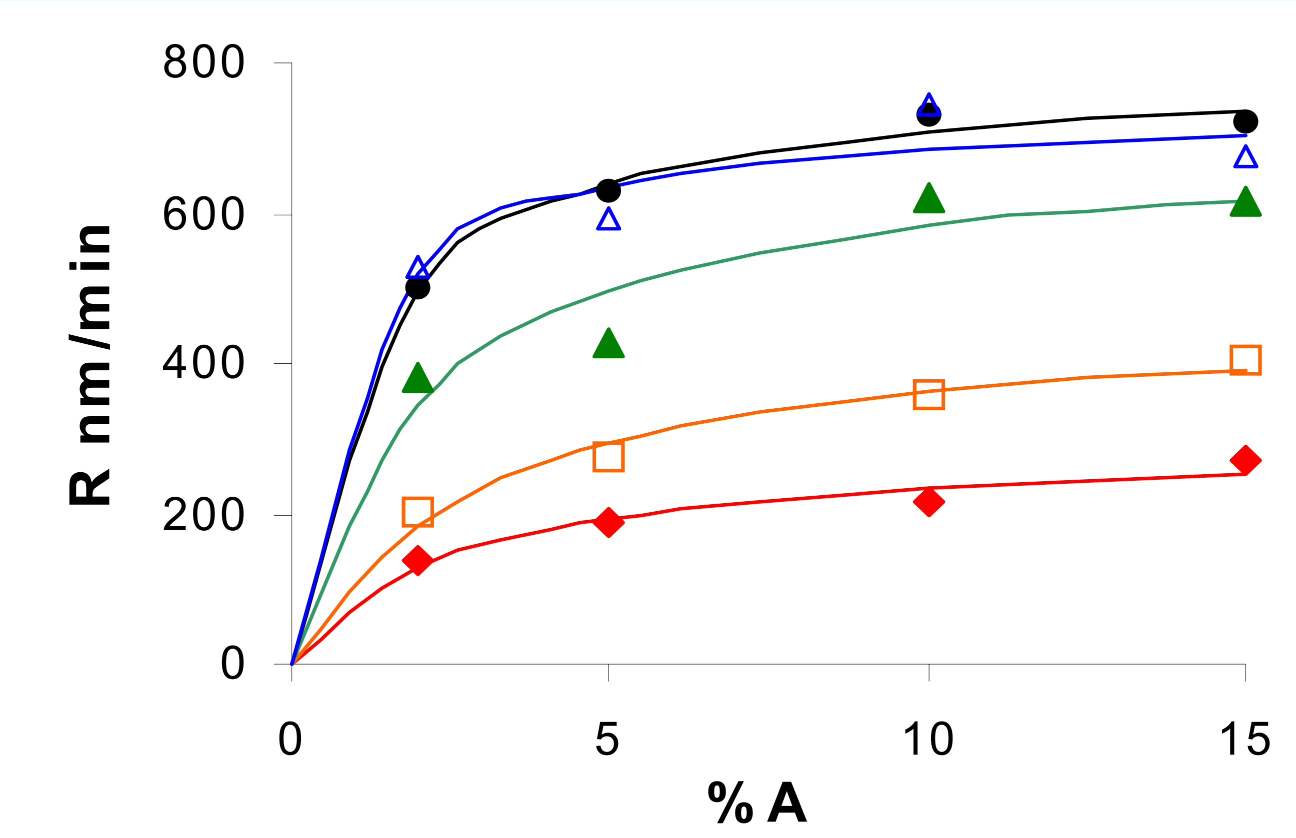
$$R = \frac{[C]\ \%A\ Pv}{a_1[C] + a_2\ [C]\ \%A + a_3\ \%A\ Pv}$$

a_1	a_2	a_3
0.110	4.53×10^{-6}	0.0388
psi rpm min/A	M min/A	psi rpm % min/A

W-CMP R(%A, d_A)

M. Bielmann, U. Mahajan, and R. K. Singh,
Electrochem. Solid State Lett. **2**, 401 (1999)

● 200 nm △ 400 nm ▲ 700 nm ☐ 1100 nm ◆ 2300 nm



$$R = \frac{a_{\%A}\ \%A}{b_{\%A} + \%A}$$

Abrasive Loading %A and [A]

%A g abrasive / 100 g slurry

[A] abrasive particles / cc slurry

ρ_A abrasive density

ρ_f slurry fluid density

d_A abrasive diameter

$$[\mathrm{A}] = \frac{6}{\pi\, \mathrm{d}_{\mathrm{A}}^{3}} \left[\frac{\%\mathrm{A}}{\left(1 - \rho_{\mathrm{A}} / \rho_{\mathrm{f}}\right)\%A + 100\,\rho_{\mathrm{A}} / \rho_{\mathrm{f}}} \right]$$

W-CMP R([A], d_A)

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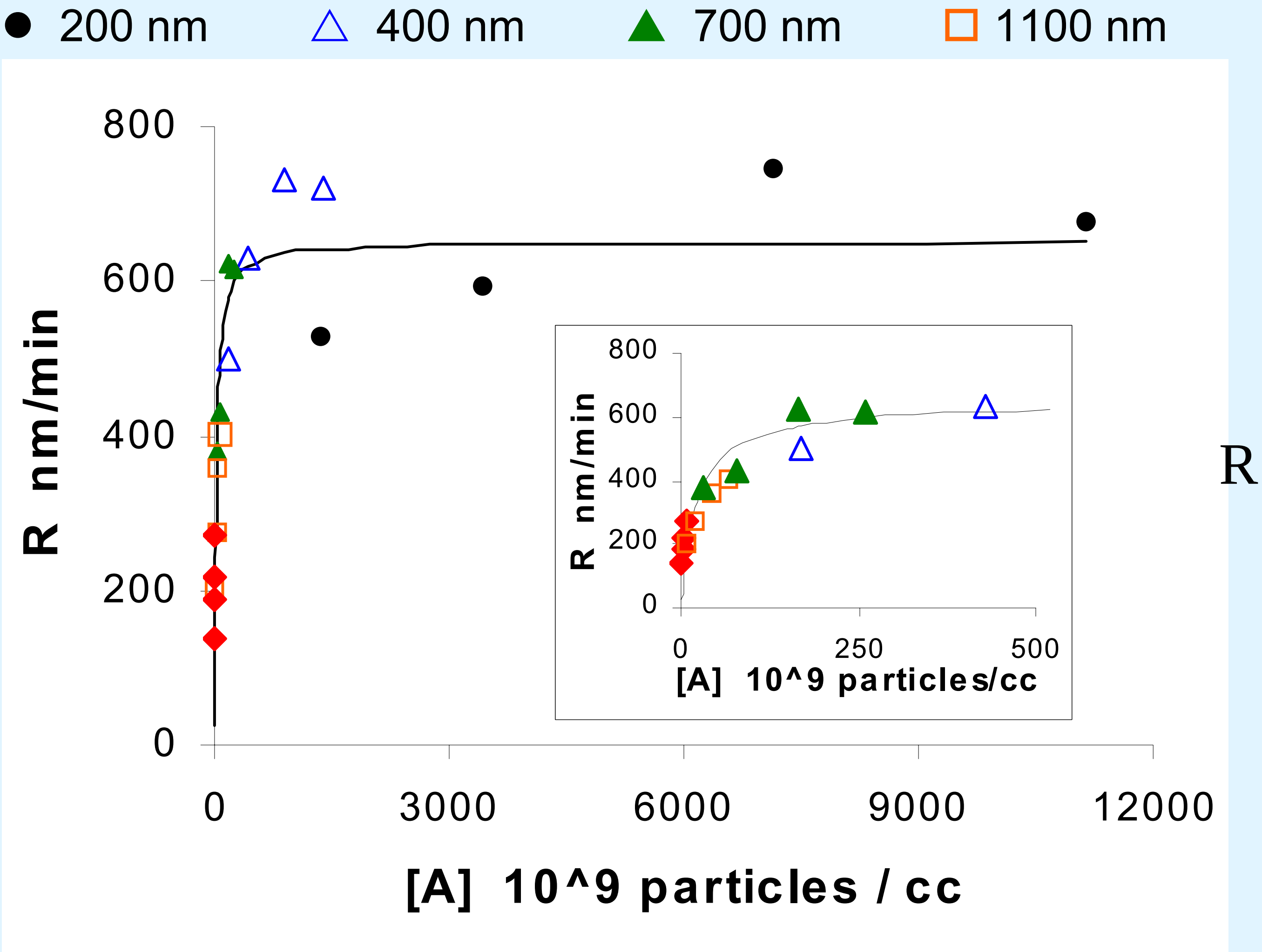

$$R = \frac{a_A [A]}{b_A + [A]}$$

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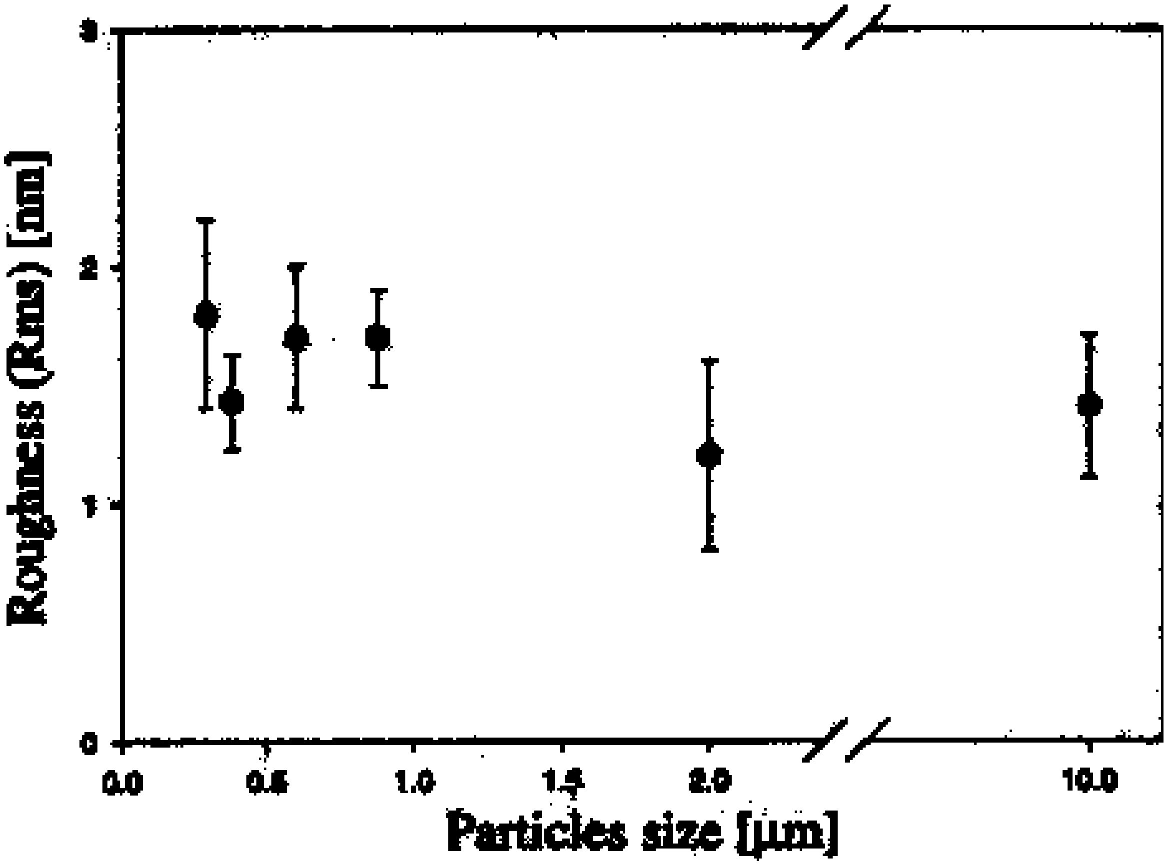


Figure 3. Local roughness of polished surfaces expressed in root mean square value vs. particle size.

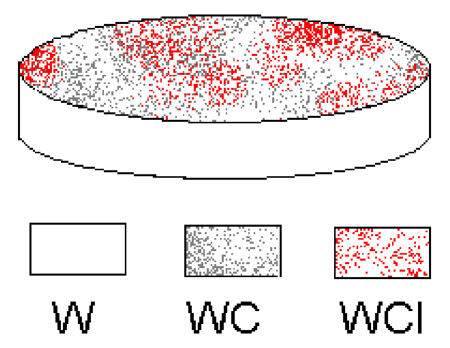
Inhibitors

$WC + I \rightarrow WCI$

$WCI \rightarrow W + Y$

$r = k_{fWCI}\, n_{WC}\, [I]$

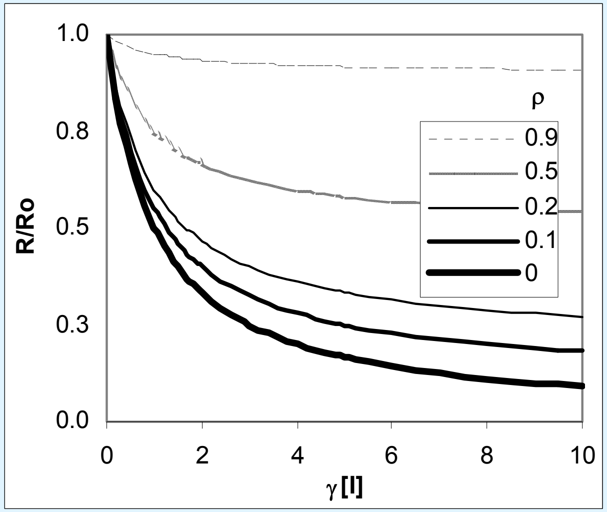
$r = k_{MWCI}\, f(A)\, Pv\, n_{WCI}$

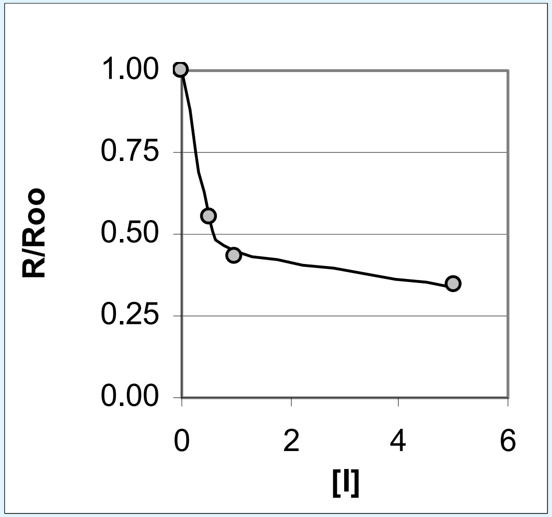


$$\frac{R}{R_o} = \frac{1 + \rho\gamma\,[I]}{1 + \gamma\,[I]}$$

Inhibitors

$$\frac{R}{R_o} = \frac{1+\rho\gamma\,[I]}{1+\gamma\,[I]}$$





R. Vacassy, Cabot Microelectronics

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Clarkson University	**S.V. Babu**

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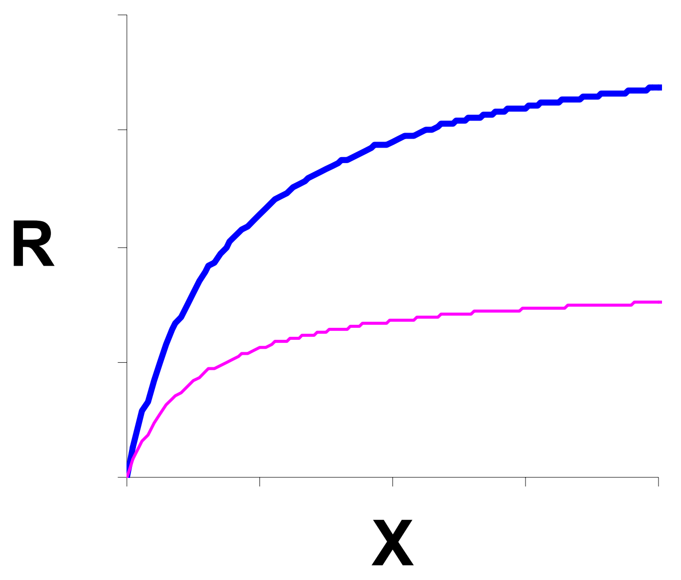
Conclusion

CMP modeling can help understand CMP processes.

R([C], P, v, Pv, %A or [A], d_A , Pads, T, …)



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