Lubrication Layer Perturbations in Chemical-Mechanical Polishing

Dr. Len Borucki
CTO, Araca, Inc.

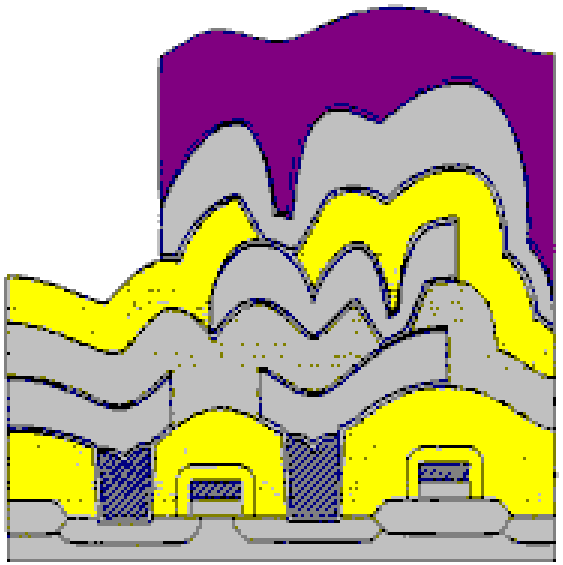
Outline

- A quick tutorial on chemical-mechanical polishing (CMP).
- Elastohydrodynamic lubrication with a pure lubricant.
- Questions posed by the presence of slurry particles.

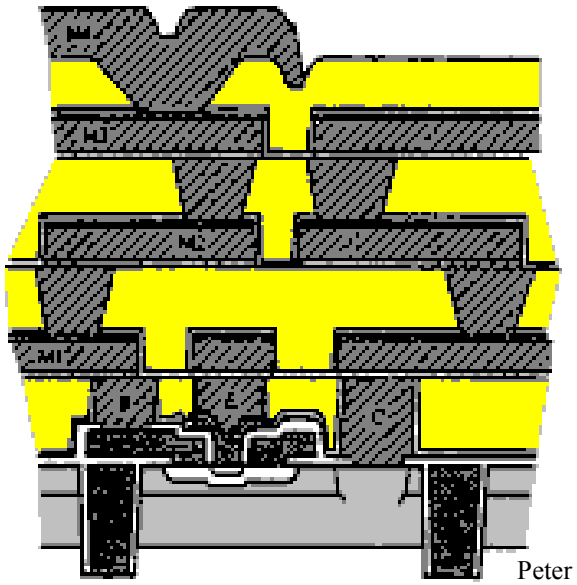
Quick CMP Tutorial

Wafer Planarization in Integrated Circuit Fabrication

- Integrated circuits are made by deposition and modification of numerous material layers.
- Photolithography, the main method of creating patterns, works best on flat surfaces.
- Chemical-Mechanical Polishing (CMP) is currently the leading method for planarizing surfaces.



Schematic of an integrated circuit produced without CMP

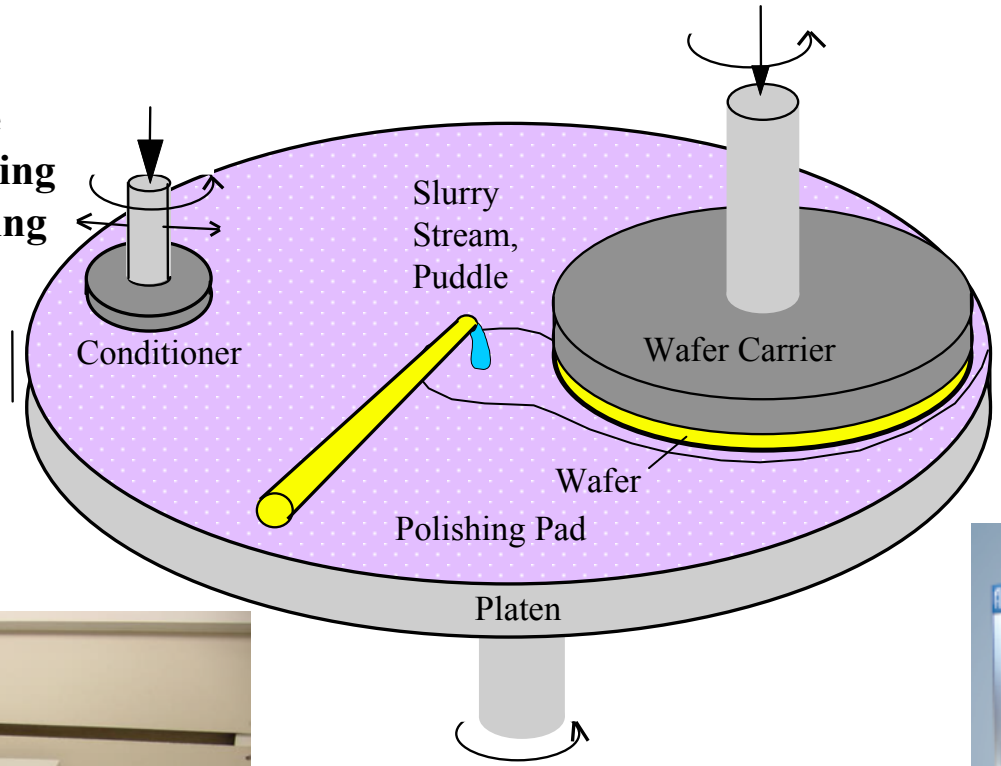


Peter Wolters

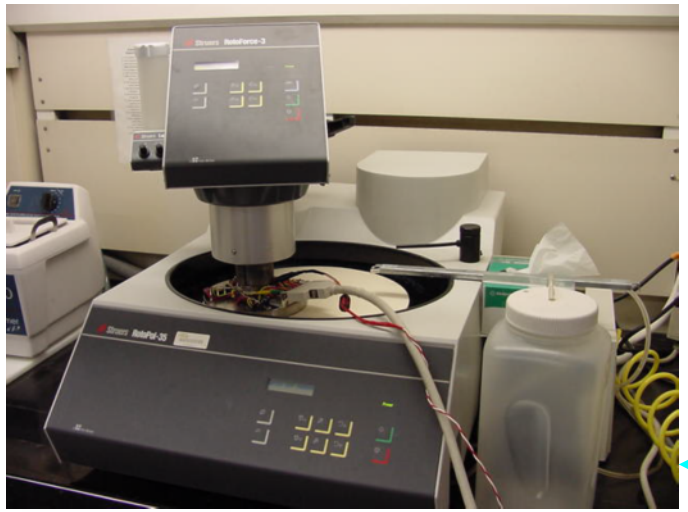
Schematic of an integrated circuit produced with CMP

Generic Rotary Polishing Tool

A rotating tool with a diamond-covered face maintains pad surface roughness, counteracting abrasive wear, removing debris, exposing new pad surface.



The wafer is held upside down by a rotating carrier. The wafer surface reacts with chemicals in the slurry and is abraded by slurry particles. The pad also experiences abrasive wear.



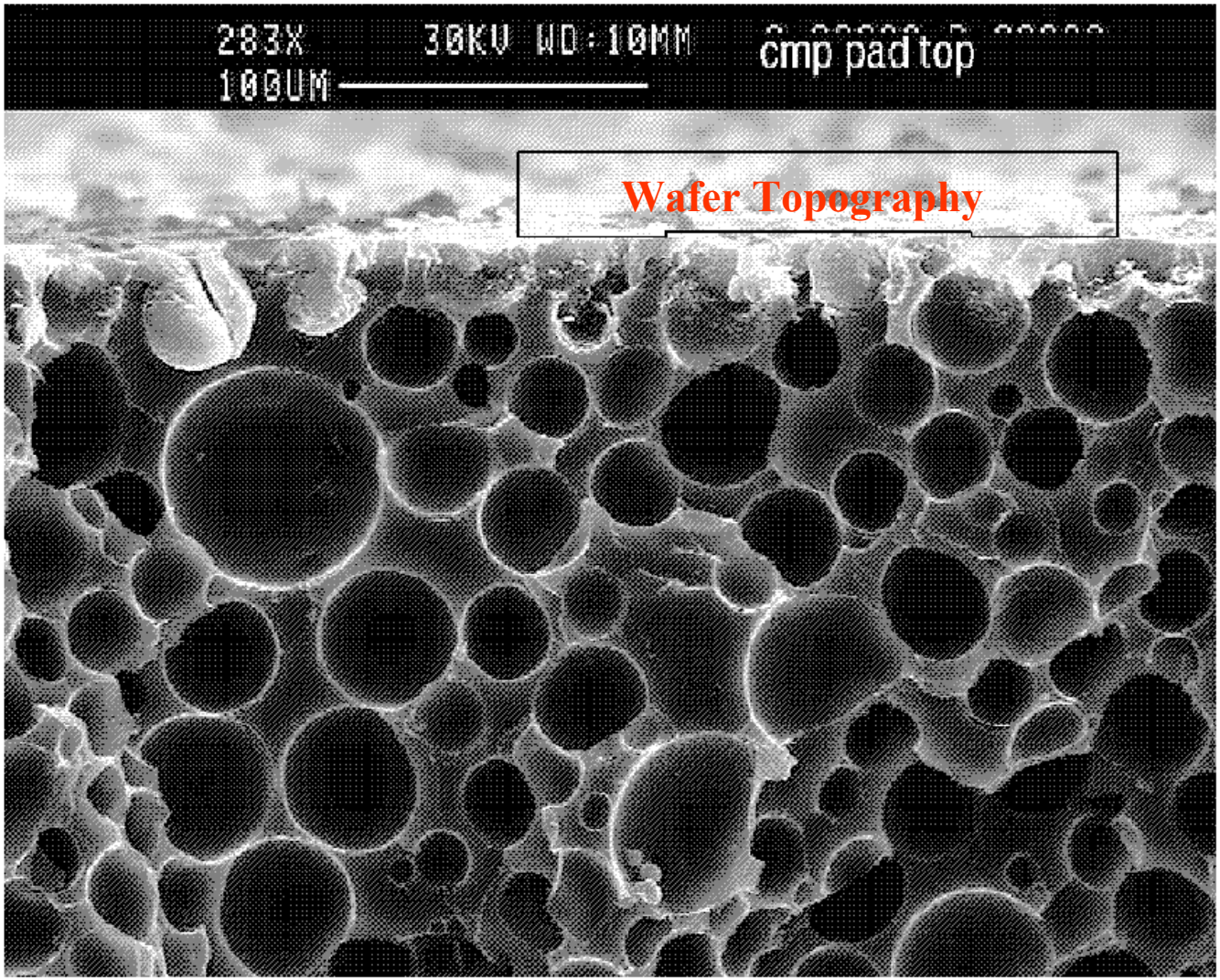
Bench top polisher
Struers. Photo by Rob Hight
Georgia Tech.

Commercial tool
AMAT Reflexion

Polishing Pads

The most commonly used pad, IC-1000™, (Rohm and Haas) is a closed cell polyurethane foam with a mean void diameter of about 30 microns. Voids occupy about 35% of the volume and are not interconnected except at the surface.

The pad is shown here next to a scaled drawing of a 100 μm wide, 2 μm deep trench. The pad surface roughness is large compared with typical wafer features.

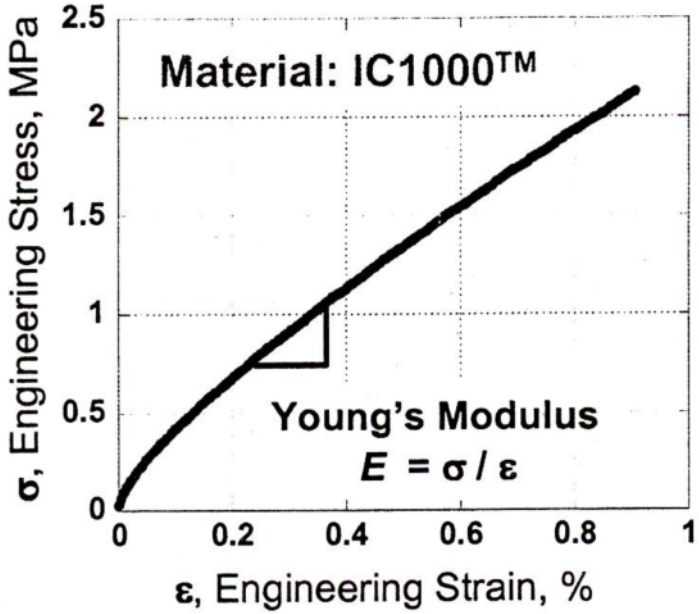


Letitia Molina, Motorola

ROHM HAAS ELECTRONIC MATERIALS CMP TECHNOLOGIES

Measured CMP Pad Properties

C.Elmufdi *et al.*, 2004 CAMP Symposium.



Material	Young's Modulus, *E* (MPa)
IC1000	285 ± 5
PSA	765 ± 45
SUBA IV (x direction)	80 ± 8
SUBA IV (y direction)	232 ± 20
Ungrooved IC1000 Stack (50 mil)	230 ± 10

Polishing pads are soft compared with most of the materials they polish.

Copper: 110 GPa Silicon Dioxide: 43-77 GPa

The pad elastic modulus generally decreases with increasing temperature and water content. A wide range is possible: ~100-550 MPa.

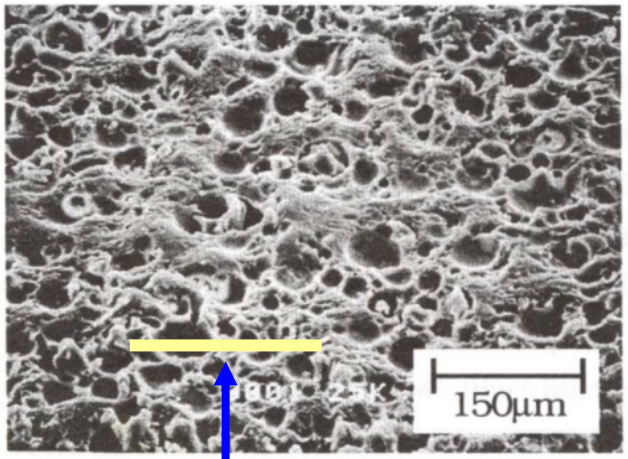
Polishing Pad Surfaces

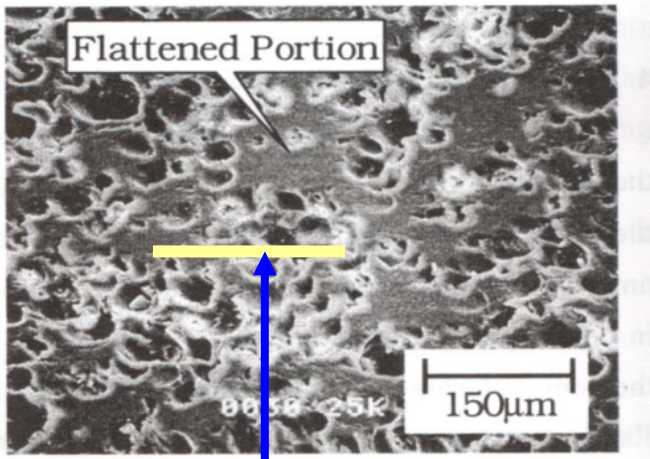
The pad surface is not static, but evolves under conditioning and abrasive wear.

Freshly conditioned

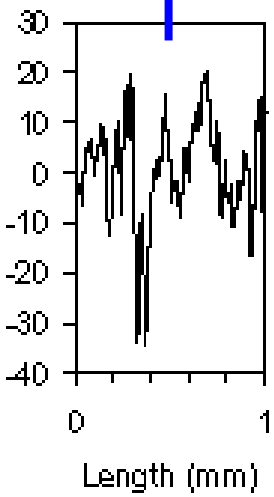
After polishing without conditioning

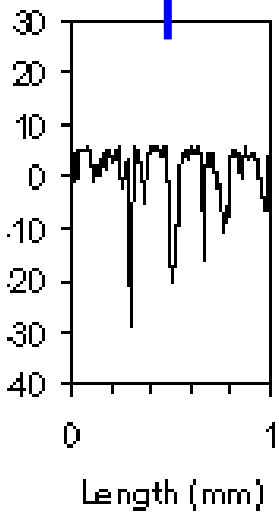
Kojima and Nishiguchi, 2003 CMP-MIC.





Scott Lawing, Rohm and Haas ECS 2003



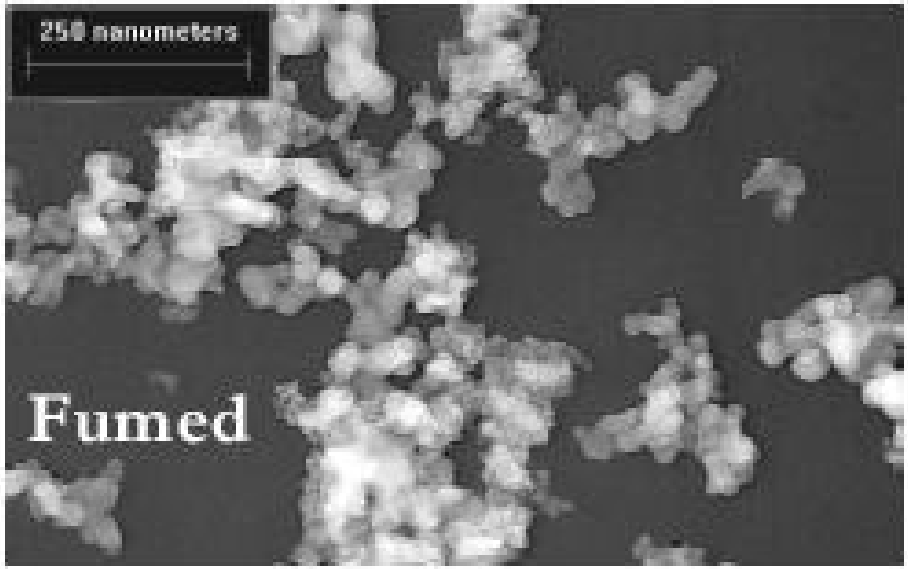


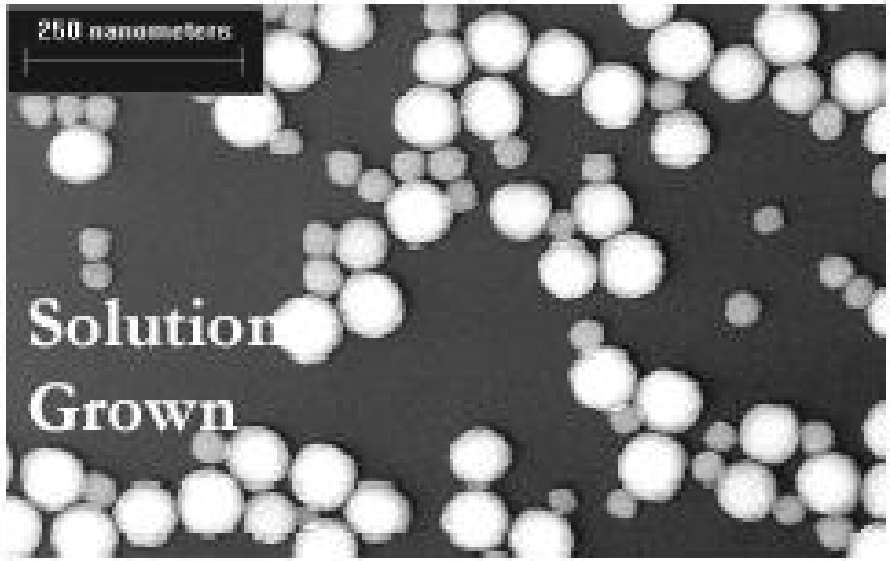
This shows that there is pad/wafer contact. The wear rate varies with the abrasive type. Spherical particles produce less wear, irregular particles more wear.

Slurry Particles

Slurry particles are very much smaller than pad asperities. Typical mean diameters for spherical colloidal particles range from a few tens to a few hundreds of nanometers. Solid loadings vary from ~0.3% to ~30% by weight. Slurry viscosity is similar to water.

We'll assume spherical colloidal particles

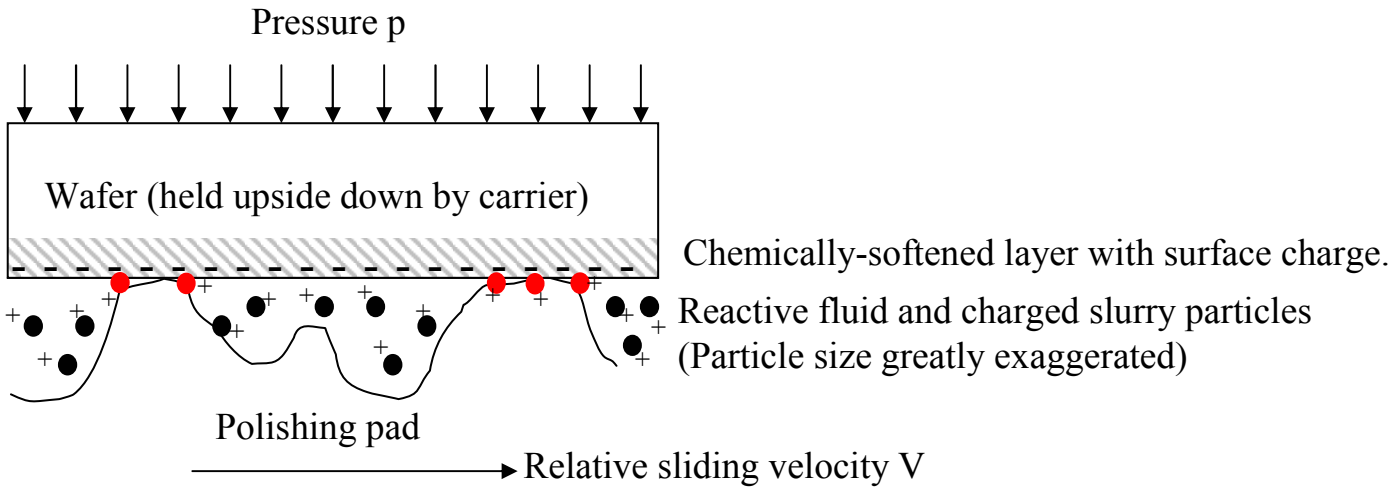




S. Lawing, ECS 2003

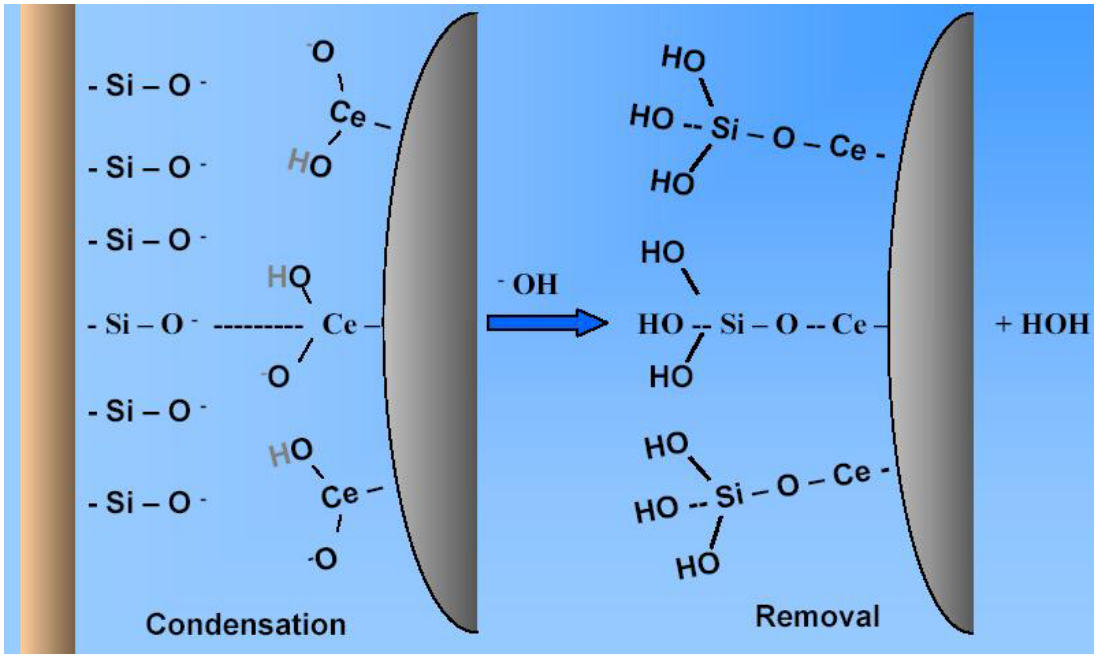
Polishing Mechanisms (SiO_2)

Chemical reaction/softening and mechanical removal.

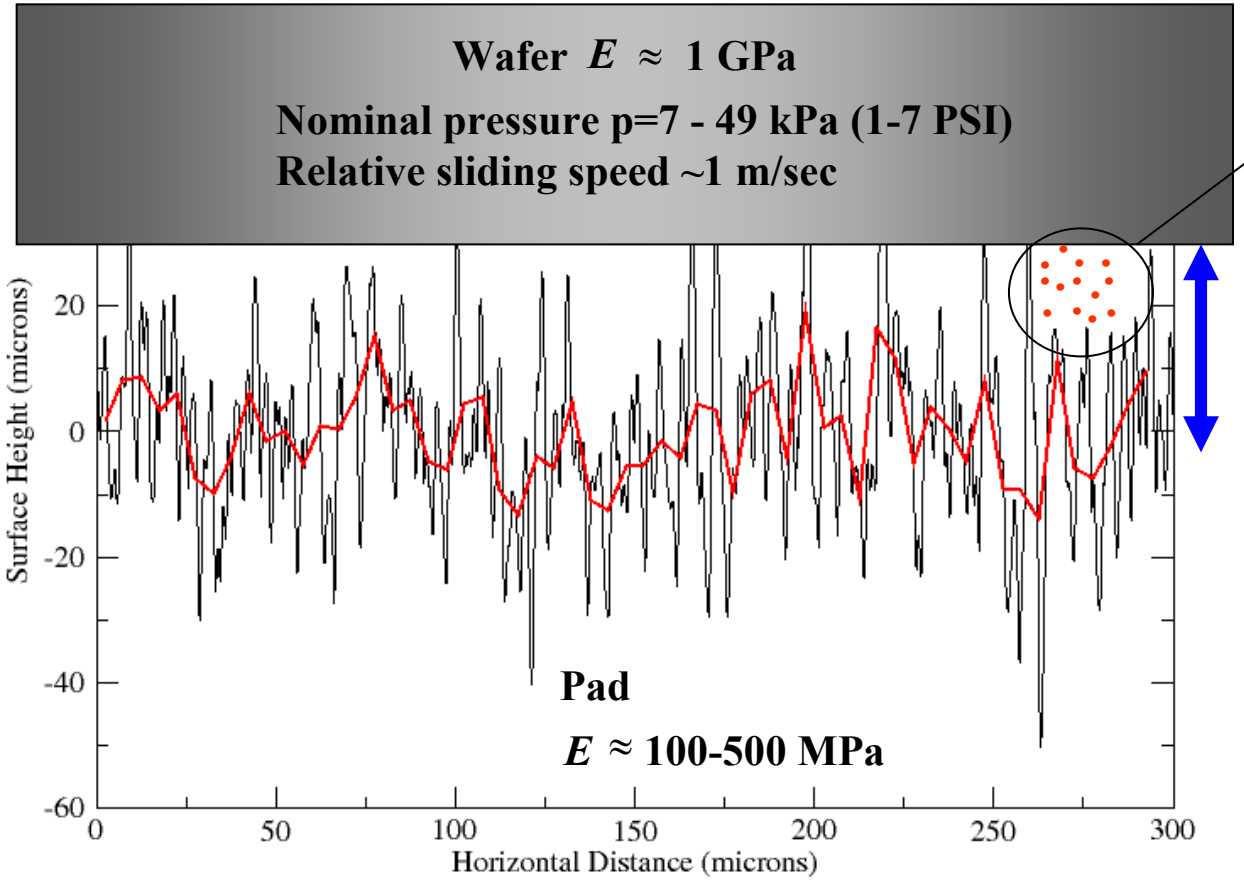


Hypothesized mechanism for SiO_2 removal by ceria. Most removed silica is found on the slurry particles and in colloidal suspension. (W. America, CAMP 2003).

Particle surface chemistry matters



Summary of Scales and Numerical Values



Slurry particles tens-hundreds of nm.

Pad asperities and fluid thickness – tens of microns

Elastohydrodynamic Lubrication (EHL)

Dry Contact

Hertzian Theory

o Undeformed asperity tips are spherical.

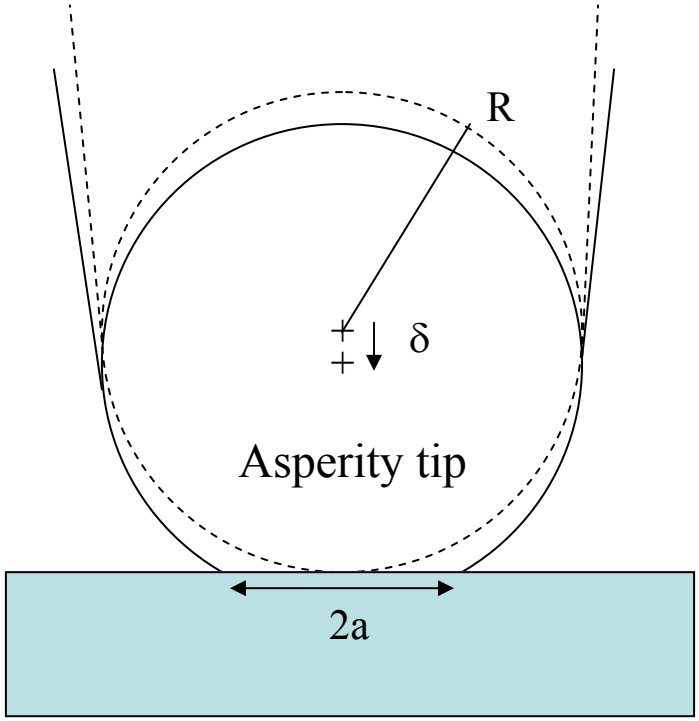
o Contact area is circular.

$$A = \pi a^2 = \pi R \delta$$

o Pressure is elliptic.

$$p = p_0 (1 - (r/a)^2)^{1/2}$$

$$p_0 = \frac{2E}{(1-\nu)\pi R^{1/2}} \delta^{1/2}$$



K.L. Johnson, *Contact Mechanics*

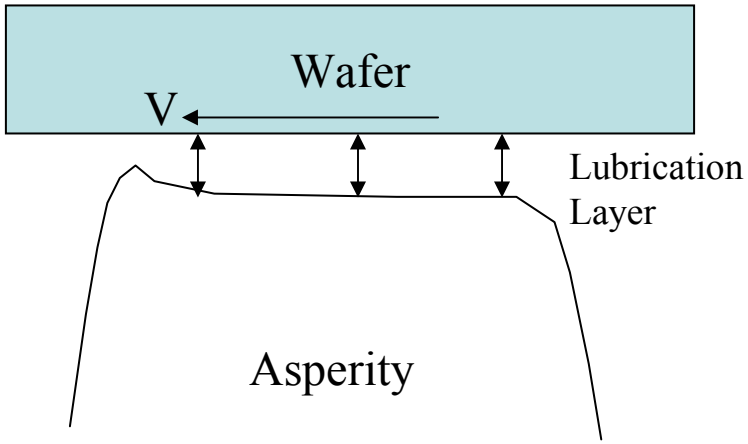
Lubricated Contact

EHL Theory

o A thin lubrication layer forms.

o Hydrodynamic pressures deform asperity tips.

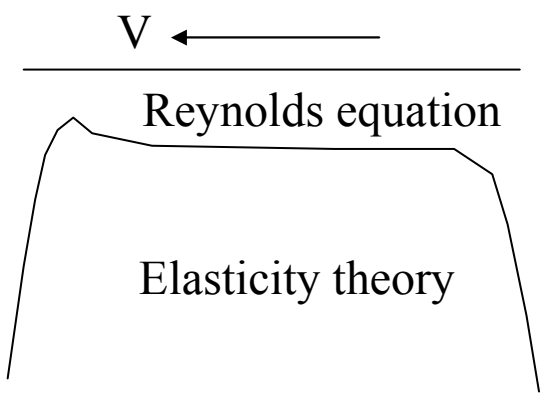
o Positive hydrodynamic pressures in the lubrication layer support the load.

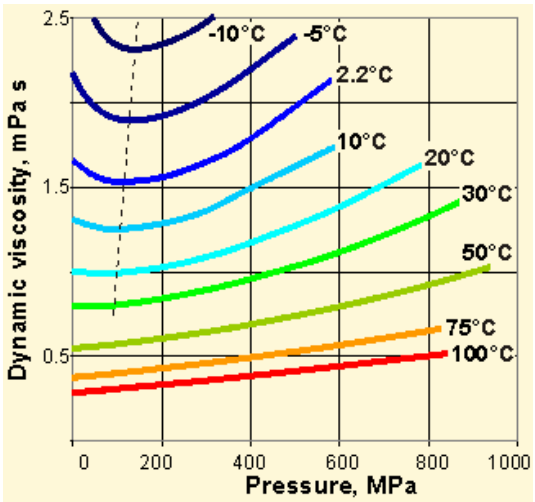


EHL Theories

Elastohydrodynamic lubrication has been studied for almost a century. Some early citations from Szeri, *Fluid Film Lubrication, Theory and Design,* Cambridge (1998) Ch. 8:

1916	H.M. Martin	Assumed rigid bodies. Predicted thinner lubrication layer than observed.
1936	W. Peppler	Allowed contacts to deform elastically.
1945	Gatcombe	Generalized to pressure-dependent viscosity, $\mu=\mu(p)$
1949	A.N. Grubin	First satisfactory solution accounting for elastic deformation and $\mu=\mu(p)$.



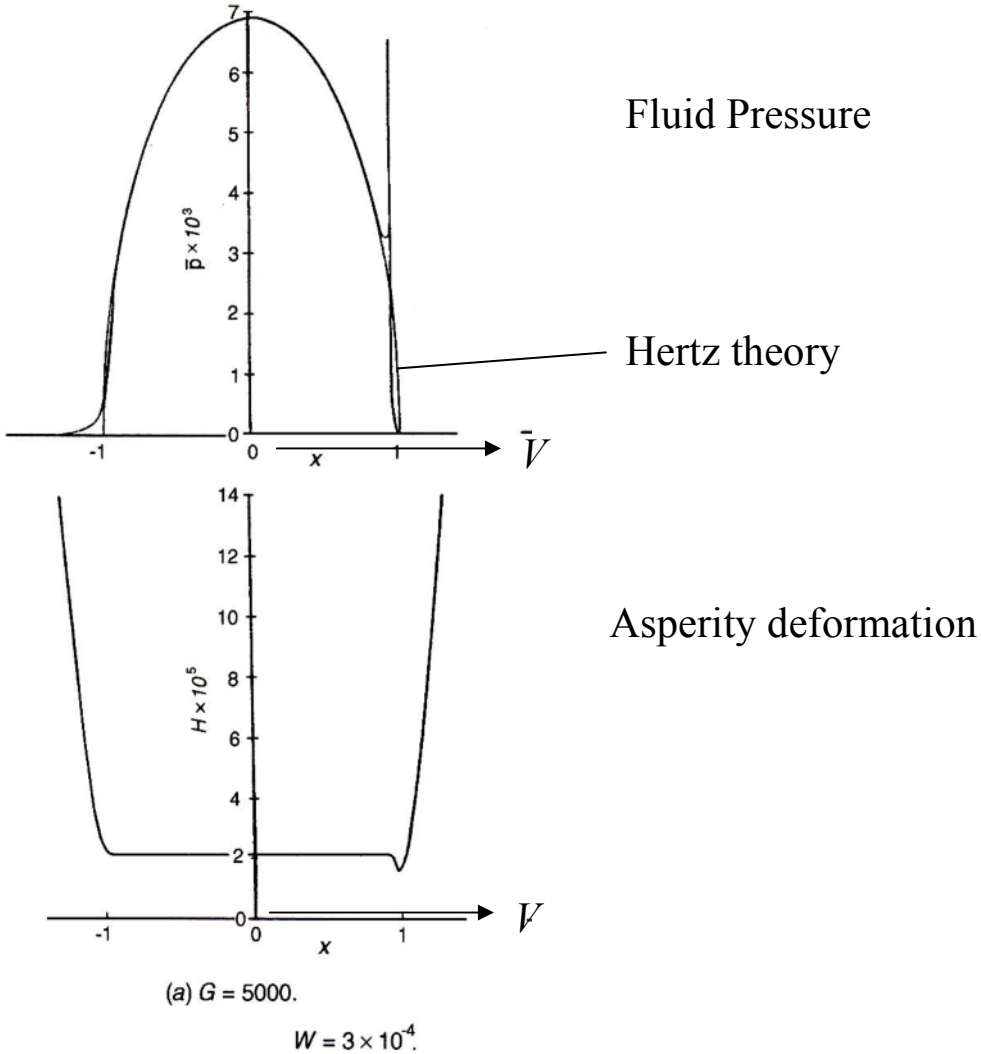


http://www.lsbu.ac.uk/water/explan2.html

EHL Theory Example (Roller)

Fluid pressures are approximately the same as Hertzian pressures except for a pressure spike near the trailing edge. Disagreement becomes more pronounced at lower loads.

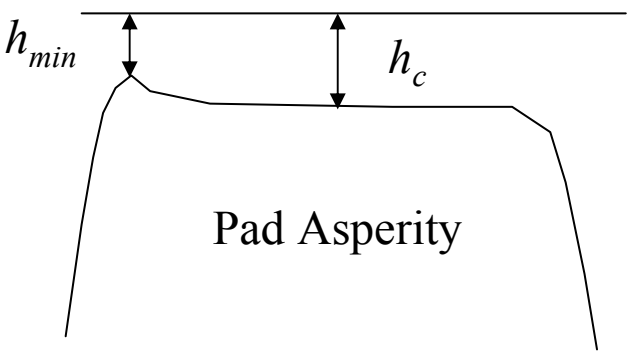
The lubrication layer is nearly uniform in thickness except for a constriction at the trailing edge that produces the pressure spike.



From Szeri, *Fluid Film Lubrication*, Cambridge University Press, 1998

EHL Compact Formulas

Simple formulas are often available for estimating the average lubrication layer thickness. Some fitting to more complex solutions is involved.



$$h_c = 1.5(\mu V)^{0.64} R^{0.8} E^{-0.42} p_{avg}^{-0.22}$$

$$p_{avg} = p / N_c$$

$$N_c = \eta_s \int_d^{\infty} \phi_s(z) dz$$

η_s = summit area density
ϕ_s = summit height PDF.

η_s =2x10^8/m^2
ϕ_s Gaussian with σ=6μm
R=50μm
p=1 kPa
V=1 m/sec
μ=2.5x10^{-3} Pa-sec

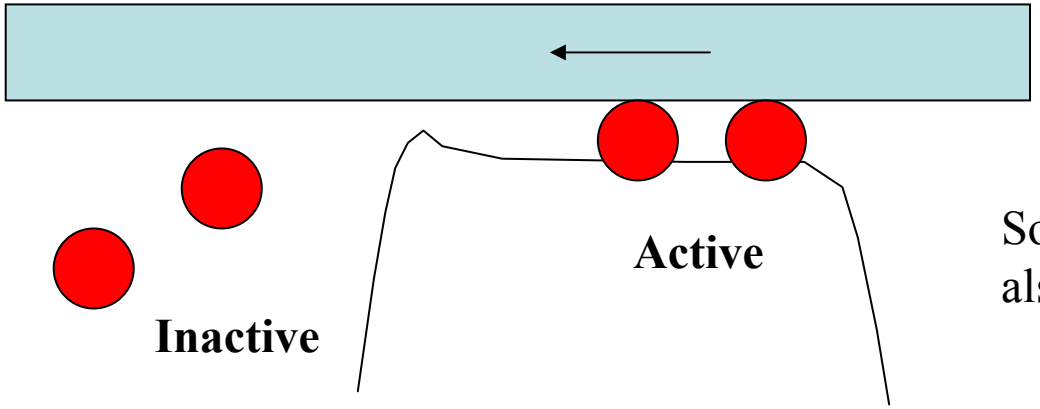
→ h_c=29 nm

about the same as the mean diameter of some types of slurry particles.

Slurry Particles

Active Particles

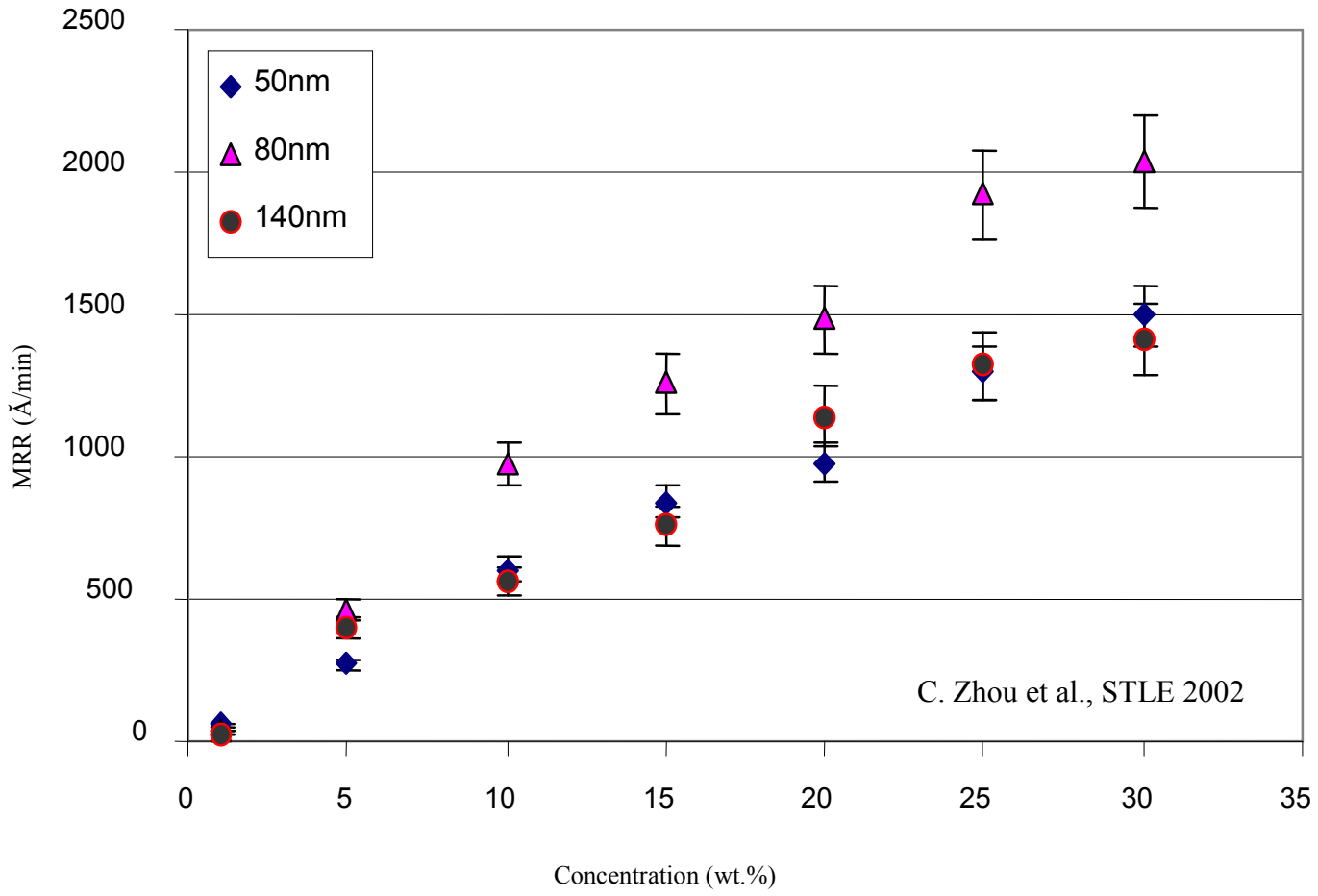
Polish rates are generally low for slurries that do not contain particles. When particles are added, some are evidently trapped between the wafer and pad asperities and increase the removal rate by mechanical or chemical means. These are **active** particles. Experimental estimates of slurry residence time and utilization suggest that most particles never become active.



Some active particles also abrade the pad.

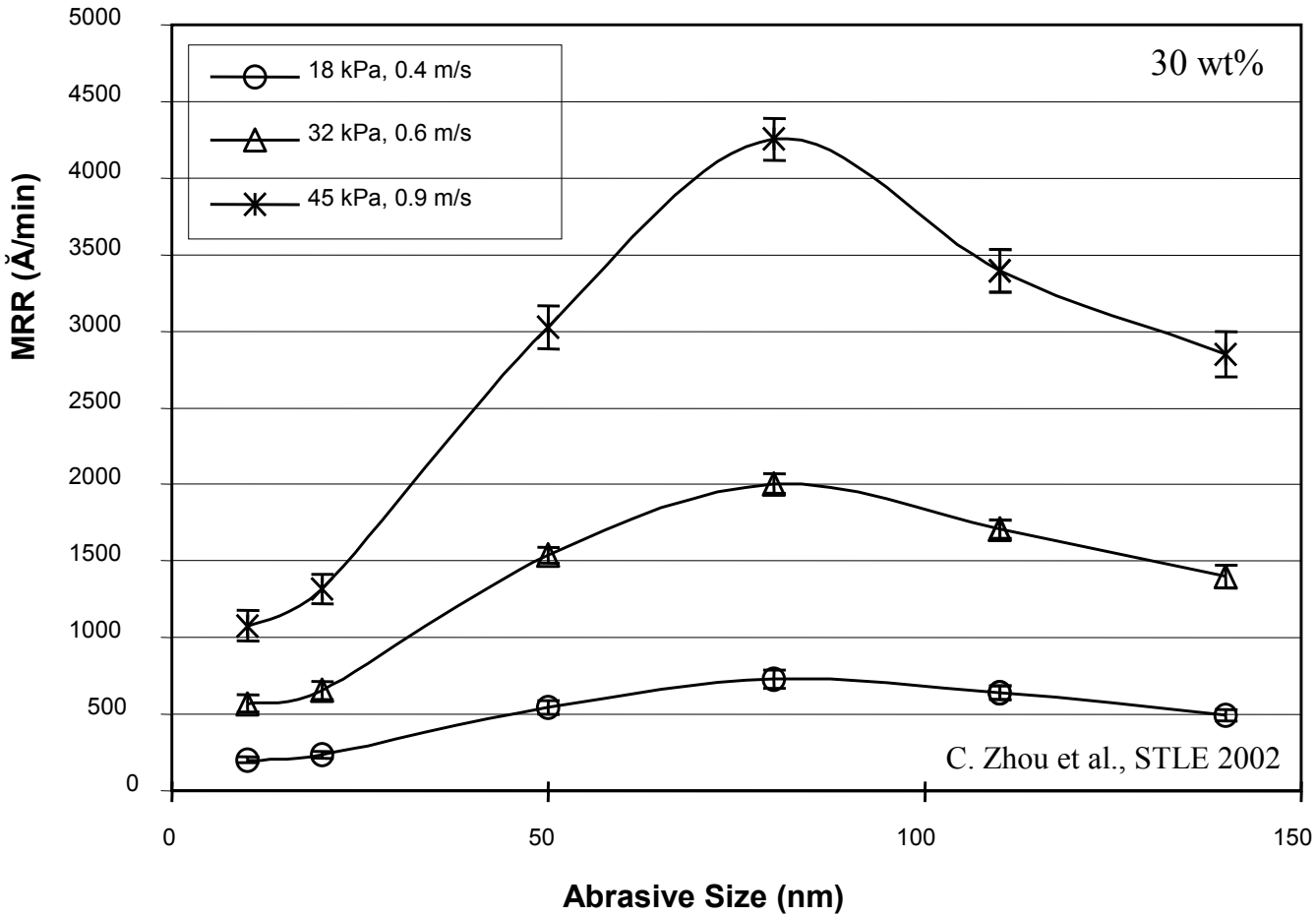
Removal Rate and Solids Loading

Removal rate increases with weight fraction for particles of a given size.



Removal Rate and Particle Size

At a fixed weight fraction, the removal rate has a peak at a size comparable to a possible lubrication layer thickness.



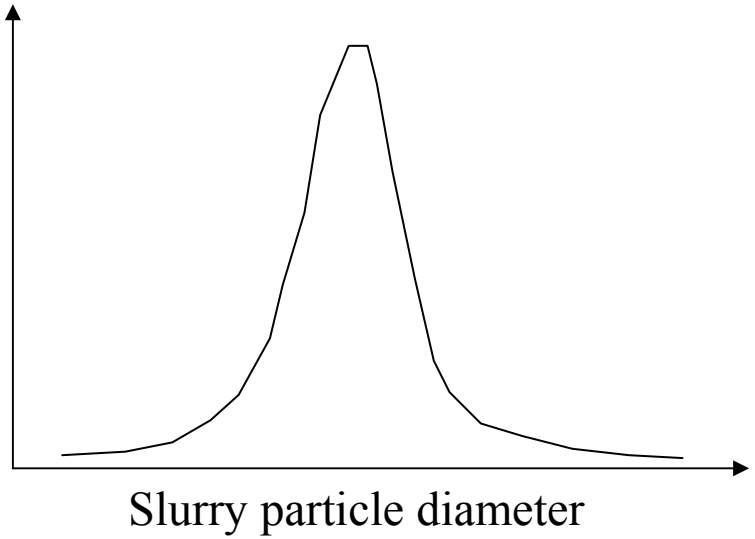
In this figure, the number of abrasive particles decreases as the size increases.

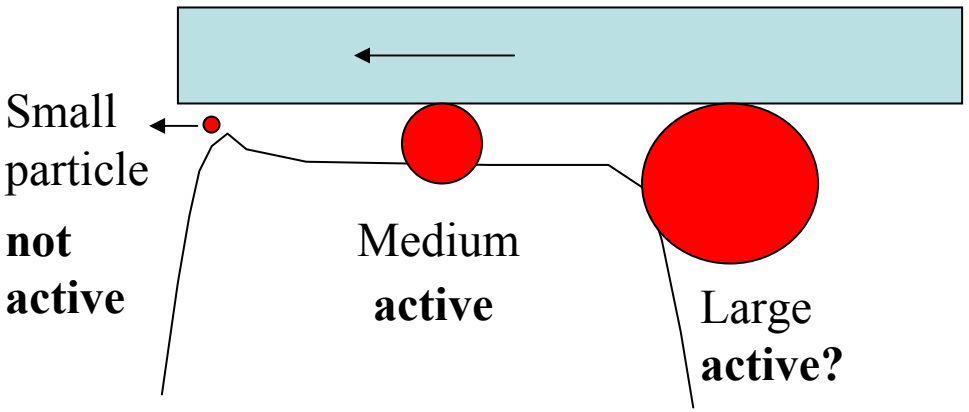
Questions

Which portion of the particle distribution becomes active?

If we start out with no particles in the lubrication layer, then how fast do they accumulate?

How much does the accumulation of a few particles affect the probability of capture of additional particles?





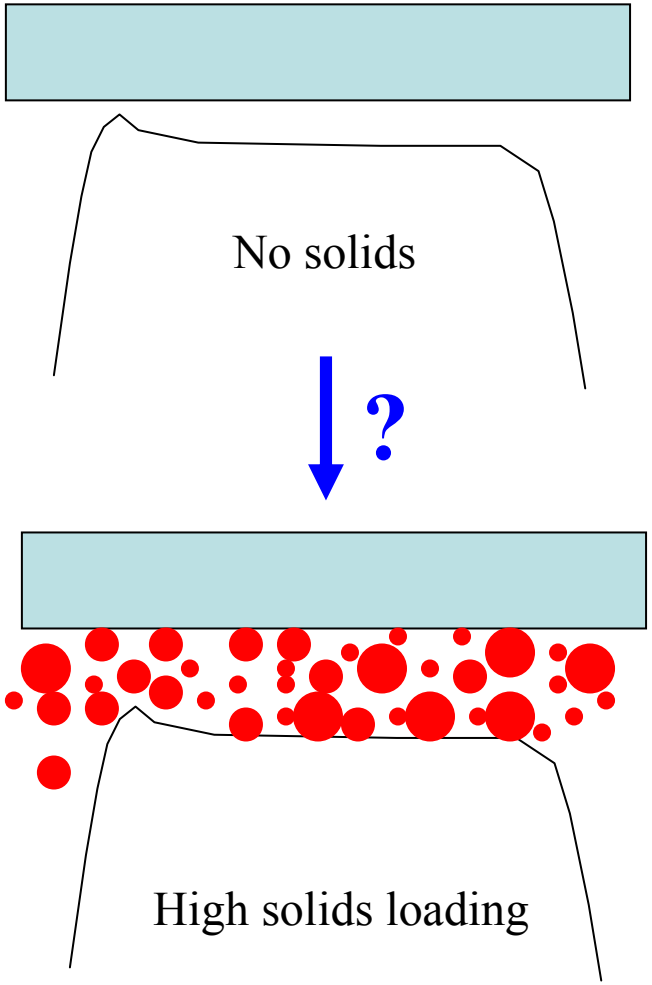
Questions

These are the main questions that I would like to address.

What happens to the thickness and shape of the lubrication layer as the solids loading increases from zero to typical upper weight fraction limits?

Are hydrodynamic pressures the main determinant of the layer geometry or is there a point at which particle size and loading are the main factors?

Can the compact models of lubrication layer thickness be generalized to include slurry particles?



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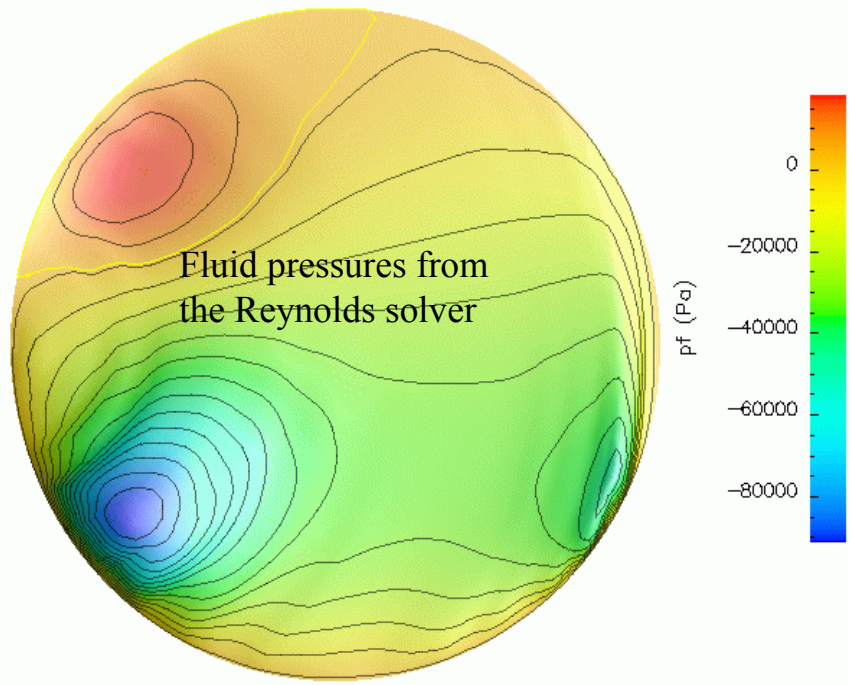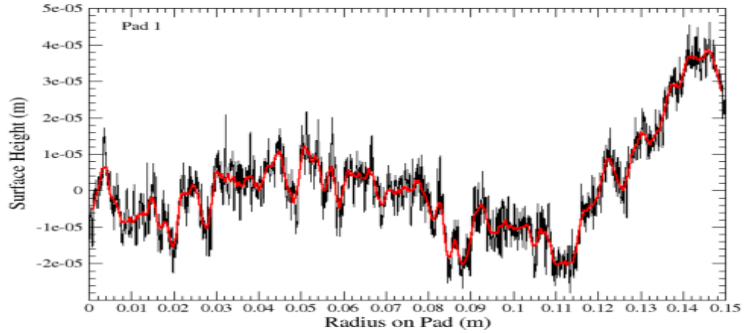
1. A 2D finite element Reynolds equation solver.
2. A 2D/3D linear elasticity solver.
3. Some literature.