The Mechanics of CMP and Post-CMP Cleaning

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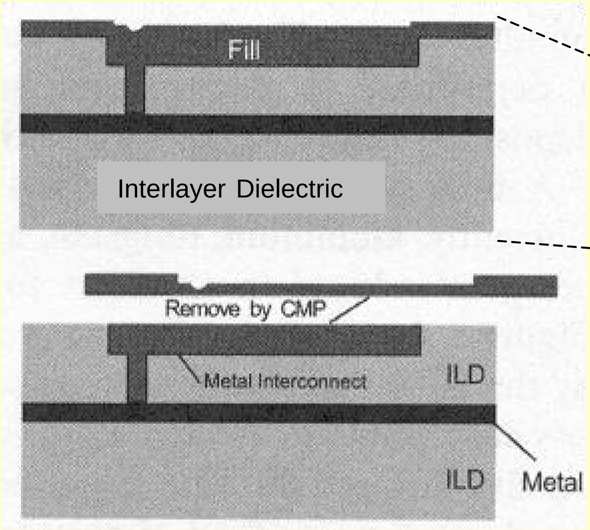
Outline

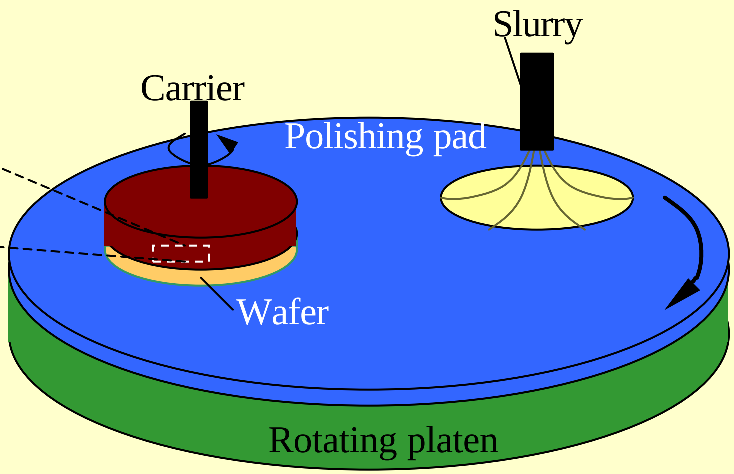
- Introduction
- Objective
- Brief description of proposed modeling work
- Previous work on material removal rate (MRR)
- Mixed lubrication in CMP and tape recording!
- Summary

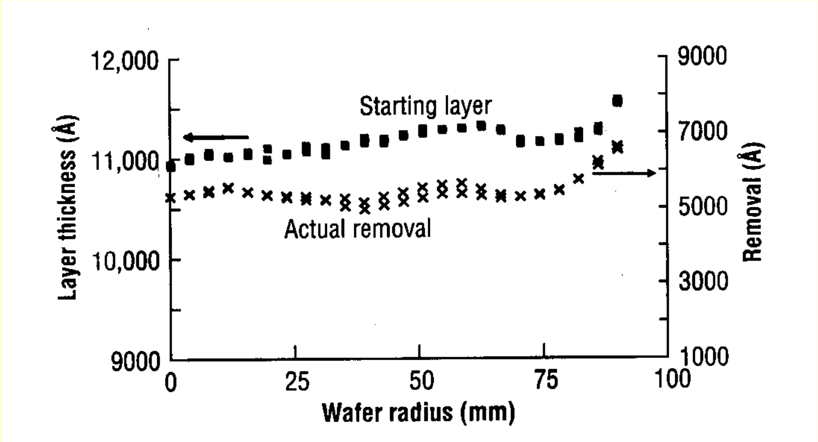
Chemical Mechanical Polishing (CMP)

Goal is to remove excess material to ensure:
- Reliable interconnects between multilayers
- Uniform thickness of dielectric materials

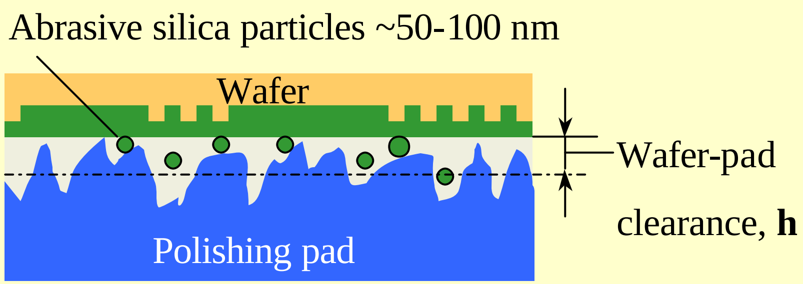


Source: J.A. Hopwood, *Thin Films*, Vol. 27, 2000.



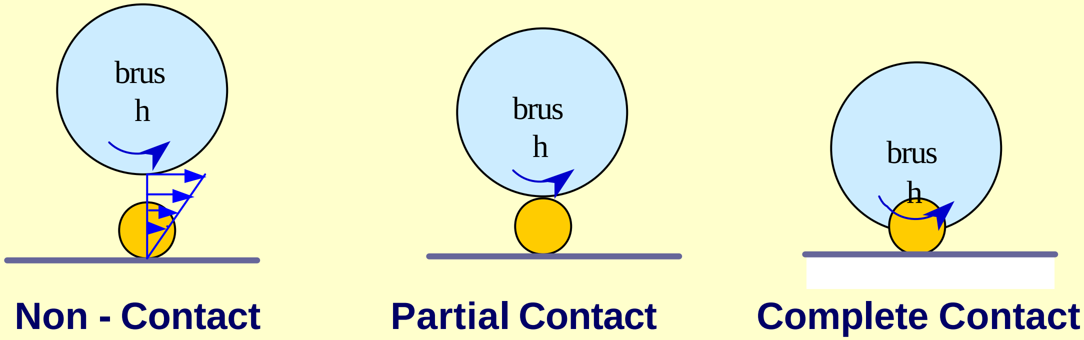


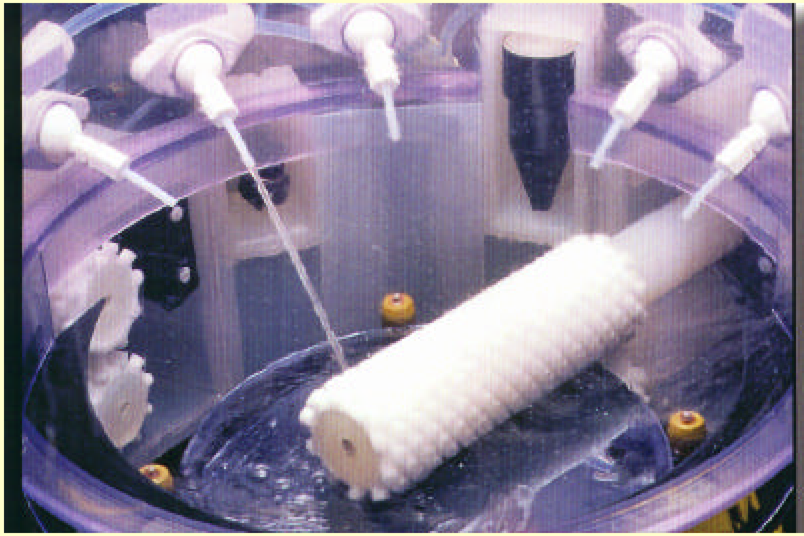
Source: A. Jensen et al., *Solid State Technology*, June 2001



Source: A. Philliposian, Uinv. of Arizona, 2001

Post-CMP Brush Cleaning Operation



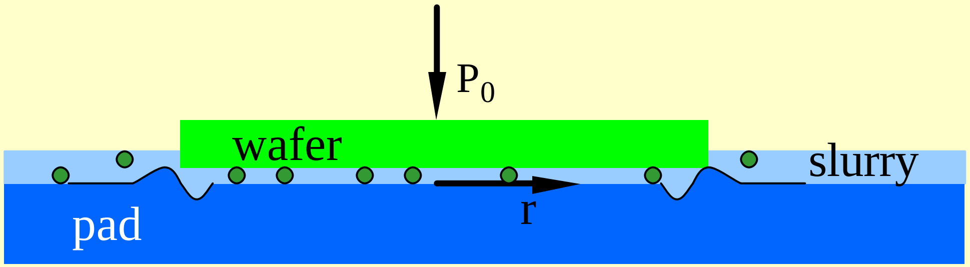


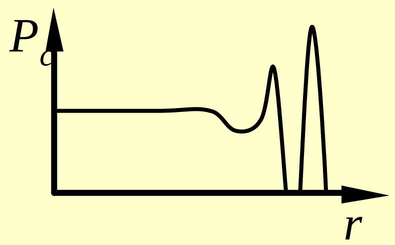
- ❑ **Results**
- ❑ **In brush cleaning, contact between the particle and the brush is essential to the removal of submicron particles.**
- ❑ **In non-contact mode, 0.1-micron particle are difficult to remove when the brush is more than 1 micron above the particle. In full contact mode, RM>>1 for typical brush rotating speeds investigated.**

Objective

- Investigate the mechanics of contact and wear in CMP (post-CMP cleaning) by studying the simultaneous effects of:
  - deformation of the polishing pad (scrubbing brush),
  - lubrication due to cleaning slurry (liquid) and
  - deformations of surface asperities and abrasive particles.

Effect of pad deformation and lubrication





- Pad deformation redistributes the load P_0 non-uniformly
- Lubrication carries part of the load, 0_0

} Elastohydrodynamic lubrication

The ***contact pressure*** distribution on the wafer surface is non-uniform, $P_c = P_c(r, q)$.

As contact is responsible for the material removal (I.e., M in CMP,) it is important to know how the mechanics of lubrication, pad, asperity and abrasives affect it.

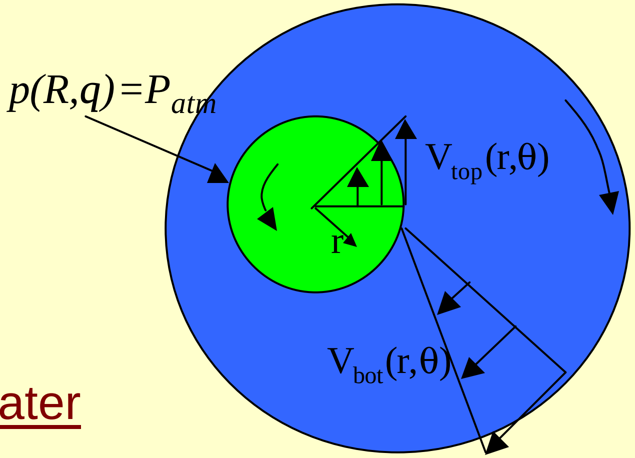
Factors that Influence Material Removal Rate and Quality

- **Independent parameters:**
  - External pushdown pressure, P_0
  - Relative sliding speed, V
  - Slurry
    - Liquid
      - Chemistry
      - Flow rate
      - Viscosity, *m*
    - Abrasive
      - Size distribution, ☞
  - Material properties
    - Polishing pad, E_p, ■$_p$, H_p
    - Wafer, E_w, ■$_w$, H_w
    - Abrasive, E_a, ■$_a$, H_a
    - Friction coeffcients
  - Pad and wafer geometry
  - Pad and wafer surface topography

- **Dependent parameters:**
  - Contact pressure distribution, P_c***(r, ❑)***
  - Liquid pressure distribution, P_l***(r, ❑)***
  - Deformation distribution,
    - Pad, U_p
    - Wafer U_w and
    - Asperities U_a
  - Real Contact area
  - Wafer-to-pad clearance distribution, ***h(r, ❑)***

- ***These will control***
  - ***Material removal rate***
  - ***Polishing uniformity,***
  - ***Surface quality***

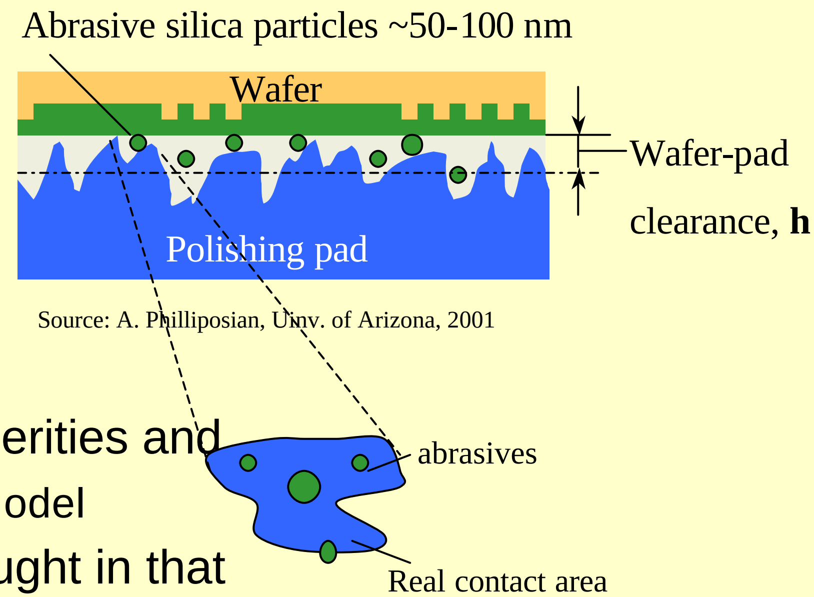
Detailed Modeling the Mechanics of CMP



- The 3D model will consider
  - Pad deformations (FEM)
    - Three dimensional large deformation elasticity
    - non-linear material behavior
      - Poroelasticity can be addressed later
  - Wafer deformations (FEM) can be addressed later
  - Slurry lubrication (FEM and FDM)
    - Incompressible, viscous fluid with low Reynolds Number
    - Steady state
      - Chemical reactions,
      - Effects of abrasive particles on the fluid flow, and
      - Transient effects can be addressed later
  - Mechanics of deformation of abrasives and pad surface roughness

Detailed Modeling the Mechanics of CMP

- Contact can occur
  - on the tips of wafer asperities and
  - on the abrasive particles embedded in the pad

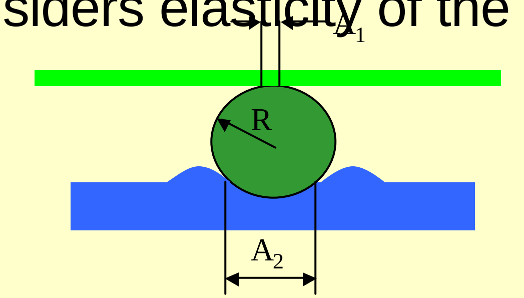


Source: A. Philliposian, Uinv. of Arizona, 2001

- A combined model to predict
  - the real contact area due to pad asperities and
    - such as Greenwood & Williamson Model
  - the number of abrasives that are caught in that contact area
    - Abrasive density and size distribution

  is necessary
- A model for three body contact that considers elasticity of the
  - upper and lower planes and
  - the abrasive

  is necessary (especially as $R \rightarrow 0$).



Detailed Modeling the Mechanics of CMP

- <u>Wear</u>
- Dominant contact related wear mode is abrasion
- Third bodies (abrasives) act like two body …
- Adhesive wear typically modeled by

$$\tilde{V}_r = k \frac{L}{H} F_r$$

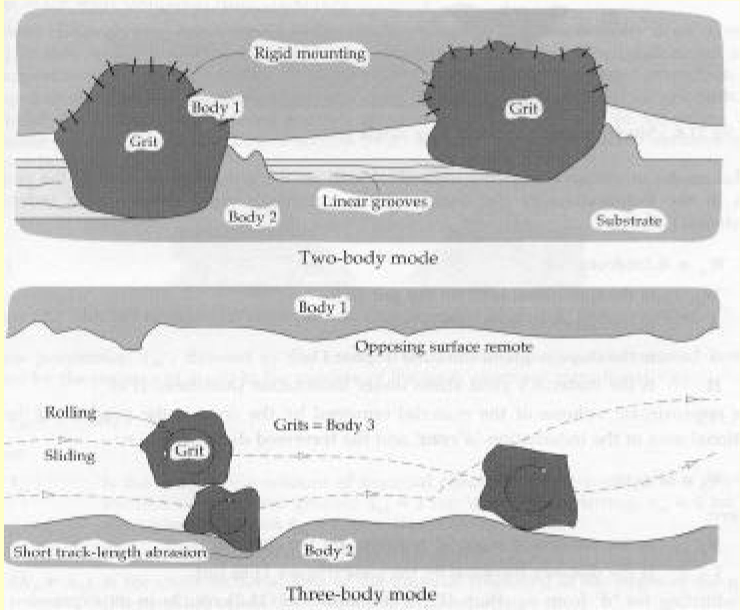
$\tilde{V}_r$: wear volume

k : geometric constant

L : sliding length

H : Hardness

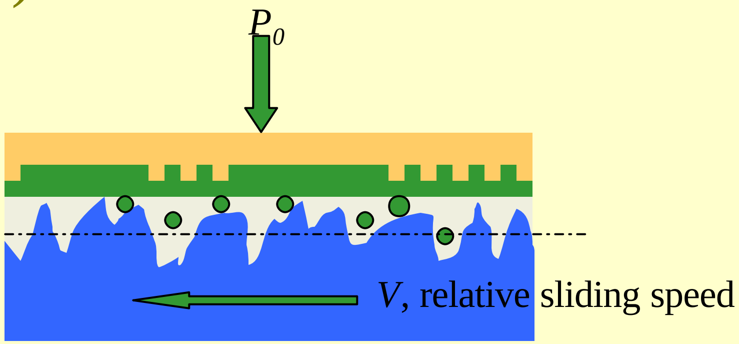
F_r : Normal force



Source: Stachowiak and Batchelor, *Engineering Tribology*, 2001.

Material Removal Rate (MRR)

- Material removal occurs as a result of:
  - Chemical etching and
  - Mechanical wear
    - Abrasive wear
    - Three body abrasion



Source: A. Philliposian, Uinv. of Arizona, 2001

- **<u>Material removal rate</u>** is critical to control the CMP

Preston's equation (1927): $$MRR = K_P P_0 V$$

Modified Preston's equation: $$MRR = K_P P_0 V + MRR_{init}$$

Zhang and Busnaina (1999): $$MRR = K_P \sqrt{P_0 V}$$

Zao and Shi (1998, 1999): $$MRR = K_P V \left(P_0^{3/2} - P_{th}^{3/2} \right)$$

K_p is empirically determined

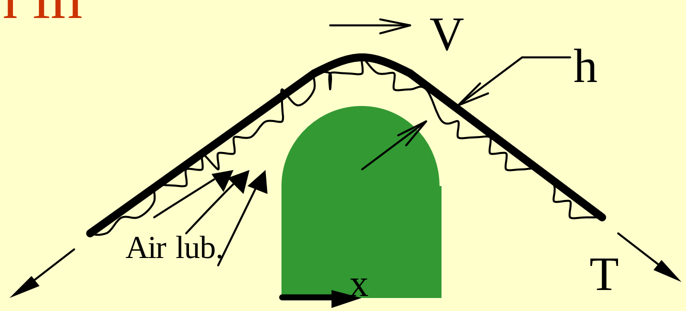
Work of Luo and Dornfield (2001)

$$MRR = C_1\left(1-\Phi\left[3-C_2P_0^{1/3}\right]\right)\sqrt{P_0}V$$

- $C_{1,}$ C_2 deterministic functions of
  - slurry chemicals,
  - slurry abrasives,
  - wafer size,
  - wafer density,
  - wafer hardness,
  - pad hardness
  - pad material and
  - pad roughness
- ☞ is probability density function

The effect of local equilibrium due to pad deformation and lubrication are not included

Elastohydrodynamic lubrication in tape recording



Moment and out-of-plane equilibrium:

$$D w_{,xxxx} + kw + \left(\rho c V_t^2 - N \right) w_{,xx} - N_{,x} w_{,x} = \left(p + p_c - p_a \right) - \frac{N}{R}$$

In-plane equilibrium:

$$N_{,x} + \tau = 0$$

with

Coulomb friction (in case of sliding)

$$\tau = f p_c \begin{cases} -1 \text{ if } V_t > 0 \\ 1 \text{ if } V_t < 0 \end{cases}$$

Rigid body contact pressure:

$$p_c = p_c\left(h, \sigma_0, P_0\right), \text{ e.g., } = P_0 \left(1 - \frac{h}{\sigma_0}\right)^2$$

Air lubrication:

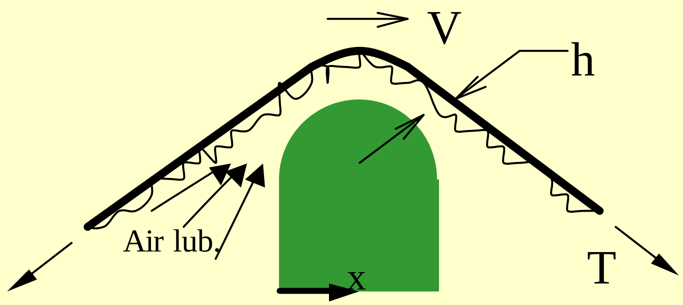
$$\frac{d}{dx}\left[\left(p h^3 + 6 \lambda\, p_a h^2 \right) \frac{dp}{dx} \right] = 6 \mu \left(V_t + V_r \right) \frac{dph}{dx}$$

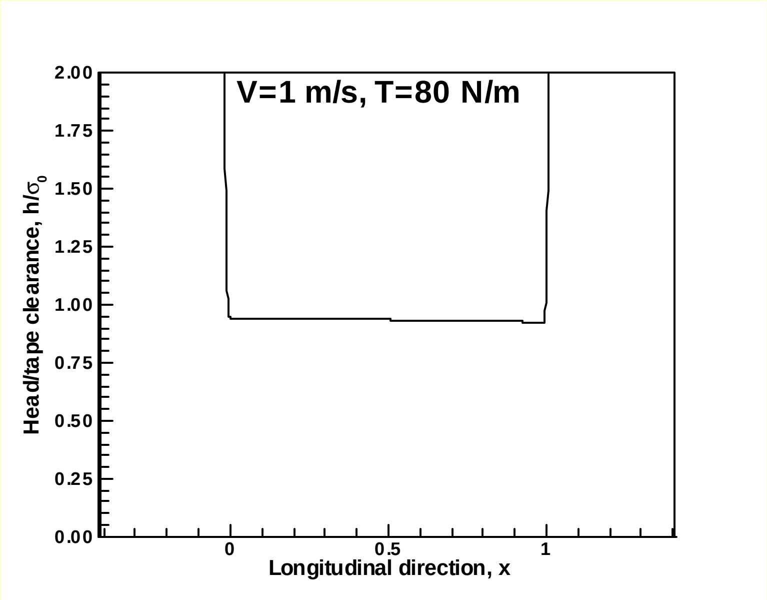
16 parameters control

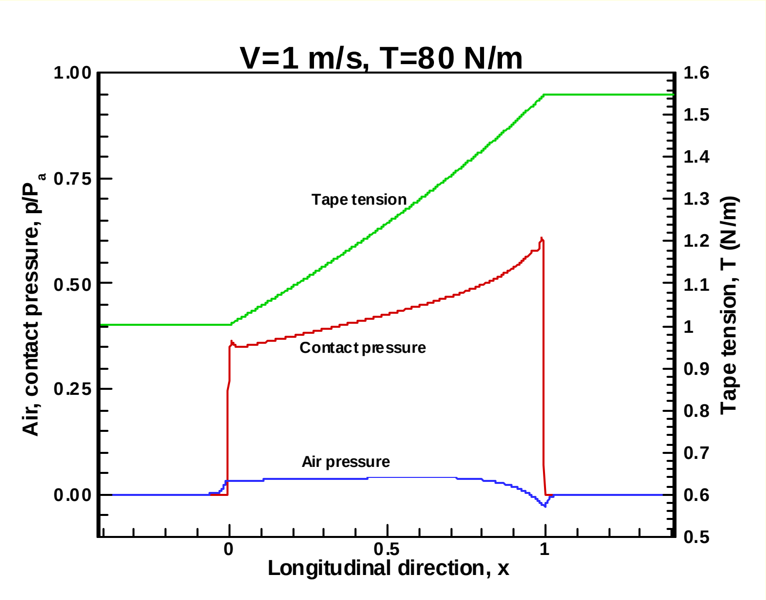
5 dependent variables:

w, h, p_{air}, p_{cont}, N

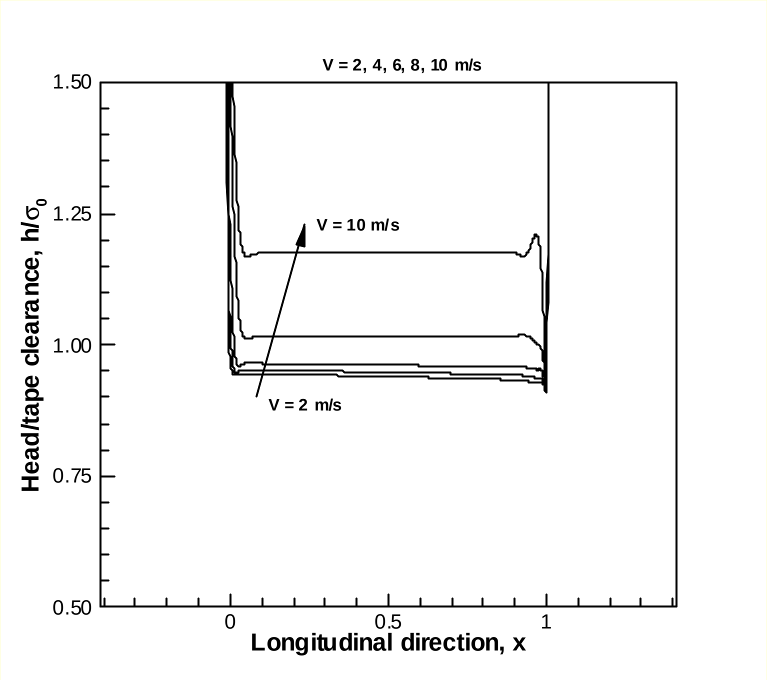
Equilibrium of contact and air lubrication in head/tape interface







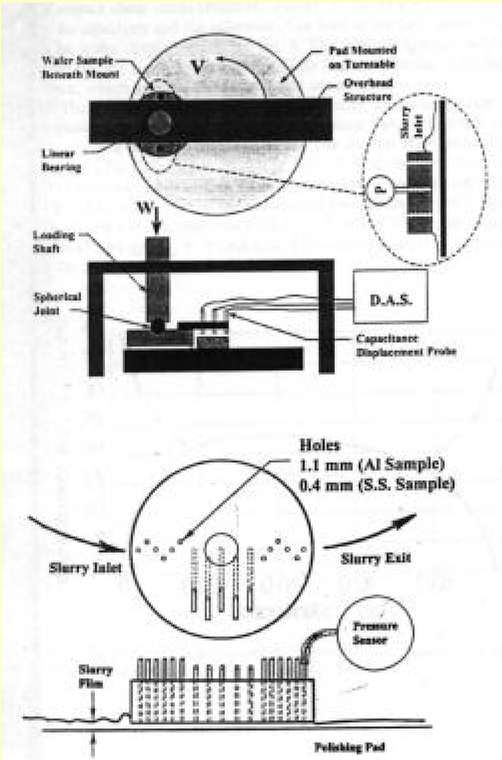
Effect of tape speed on Equilibrium in head/tape interface

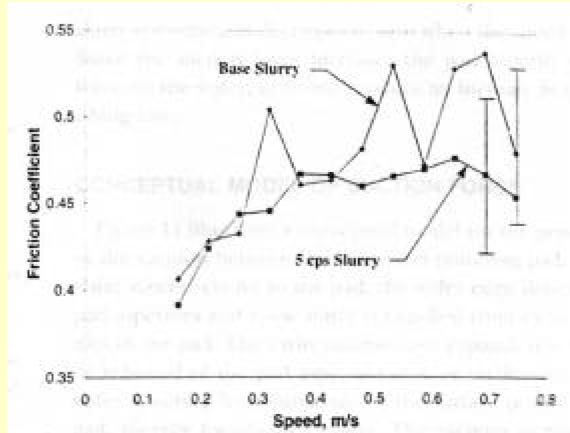


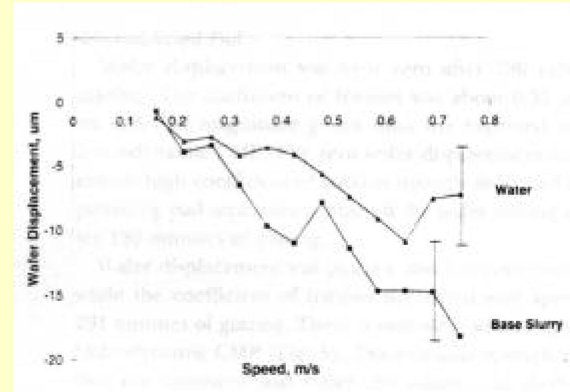
- Head/tape clearance is non-linearly related to tape speed, and tension.
- Software tools are commonly used by tape-recording industry.

Non-uniform pad deformation due to slurry lubrication in CMP

Levert, Danyluk, and Tichy (1997-9)

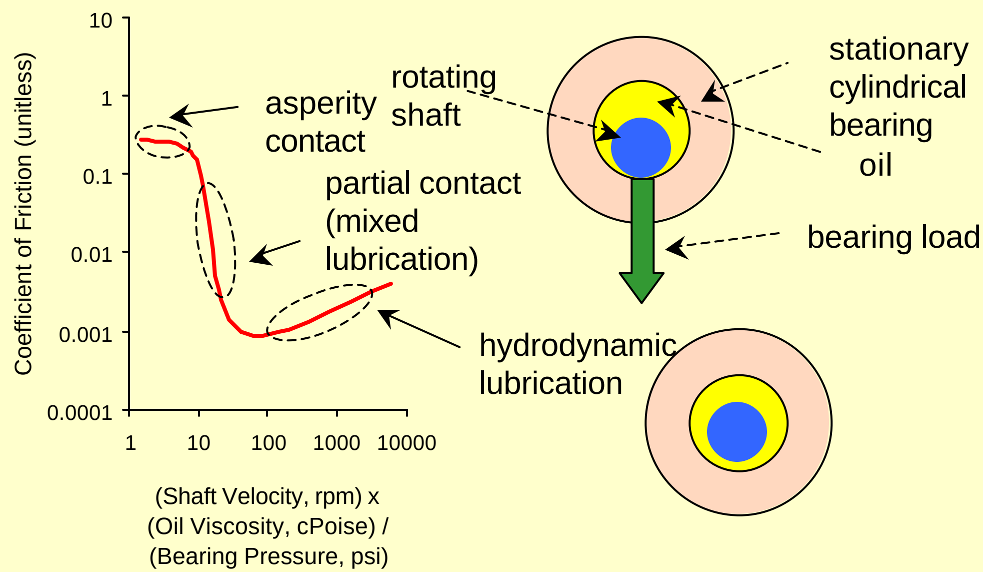






Lubrication in Journal Bearings & the Stribeck Curve

Source: Philliposian (2001)



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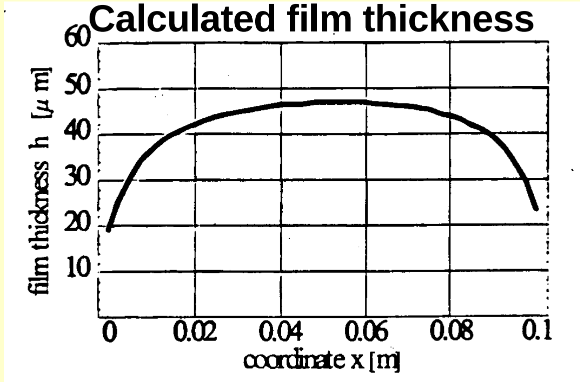
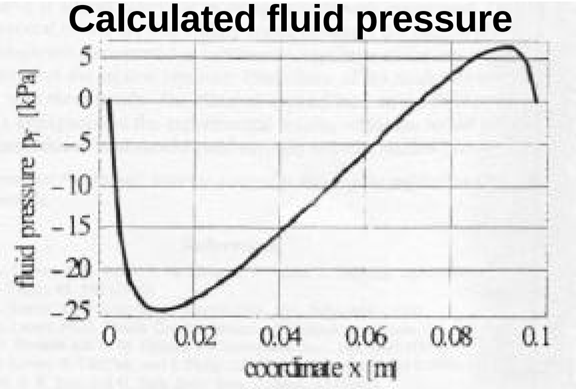
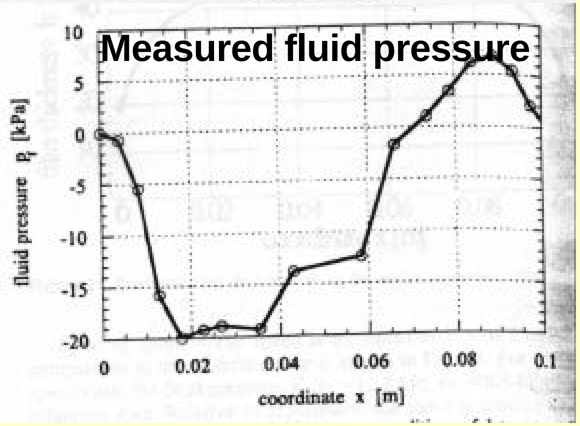






- The equilibrium between;
  - external load,
  - slurry pressure and
  - restoring force of the pad and asperities

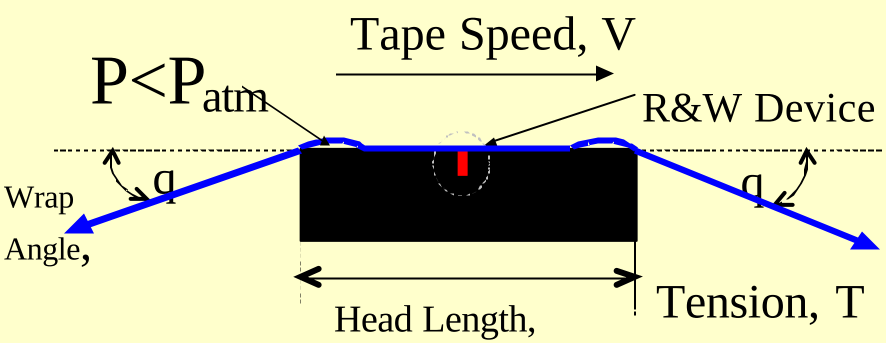
  develop such that the film thickness has a diverging shape on the entry side.

- The fluid film expands into this cavity and develops a subambient pressure

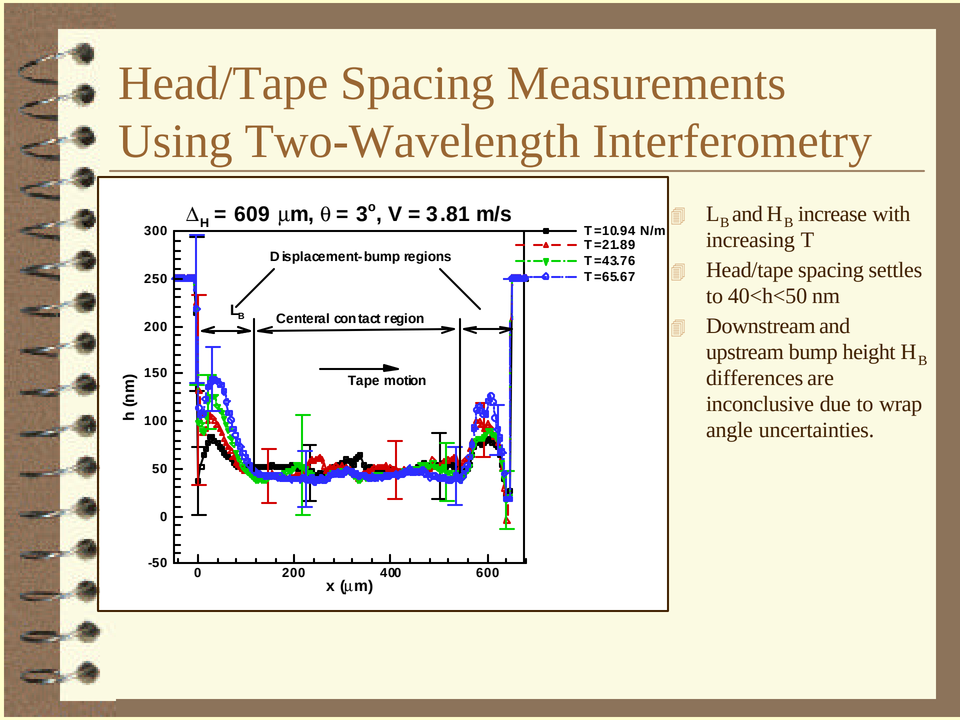
- Net downward force acting on the polishing pad

  = external load + load due to negative pressure!

US Patent 6,118,626 (2000) “Contact Sheet Recording with a Self-Acting Negative Air Bearing”, Sinan Muftu, Hans F. Hinteregger

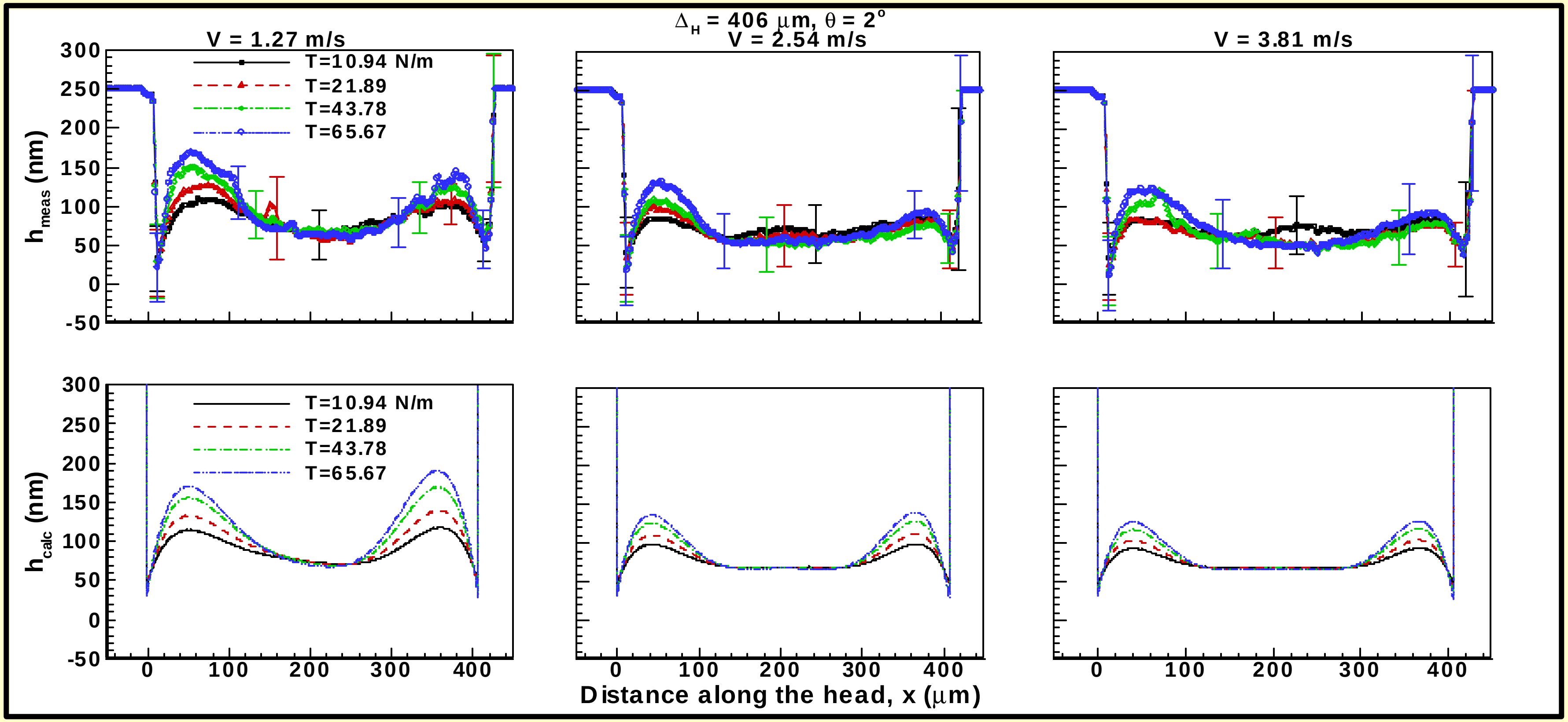


Flat Head Geometry



RESULTS: Head/Tape Spacing Measurements Using Two-Wavelength Interferometry

Typical Measurements and Calculations for: Δ_H,=16 mils, θ = 2°, V =50, 100, 150 ips, T = 1,2,4,6 oz/in



Summary of proposed work

- Goal is to investigate the mechanics of contact and wear in CMP (post-CMP cleaning)
- Develop a model that will include the effects of
  - deformation of the polishing pad (scrubbing brush)
  - lubrication due to cleaning slurry (liquid)
  - deformations of surface asperities and abrasive particles
  - material removal
- There are similarities with the experimental work
  - *Tribology and Fluid Dynamics Characterization of CMP Pads*

    by Dr. A. Philliposian at U.of Arizona.

  which can be advantageous to understanding the fundamentals fo polishing and cleaning.

Outcomes

The modeling tool can be used to:

- Analyze the contact mechanics:

  The contributions of

  -slurry flow,

  -pad elasticity, wafer deformation

  -pad surface roughness

  on contact forces will be characterized.

- Investigate the causes of polishing non-uniformity

- Optimize abrasive density in slurry

- Control (optimize) contact pressure distribution

- The effects of smaller abrasives and different slurry liquids can be analyzed.

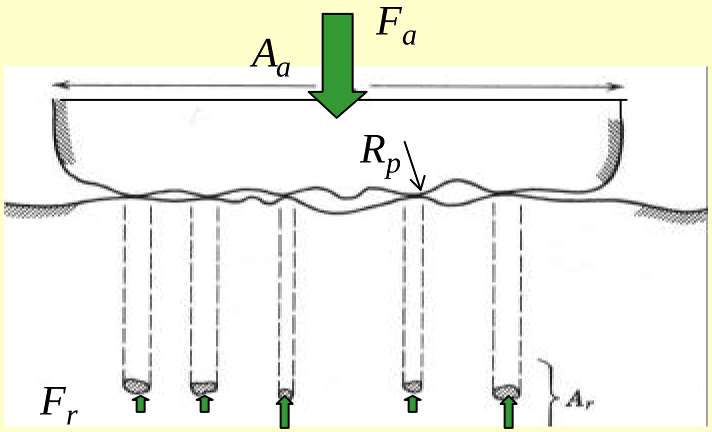
Contact Pressure

- Contact occurs on the asperity tips
- The **real** and **apparent contact pressures**, P_r and P_a, are related:

$$P_a = \frac{F_a}{A_a} = \sum P_r = \sum \frac{F_r}{A_r}$$

- Greenwood and Williamson (1966)

$$p_r = \frac{p_a A_a}{p\, N R_p \int_d^{\infty} (s-d)\, f(s)\, ds}$$



Source: E. Rabinowicz, *Friction and Wear of Materials*, 1995

N: Number of asperities

↗: Probability density function of asperity peak height distribution

d: “Separation” of surfaces