PENNSTATE

SAND2007-6952C

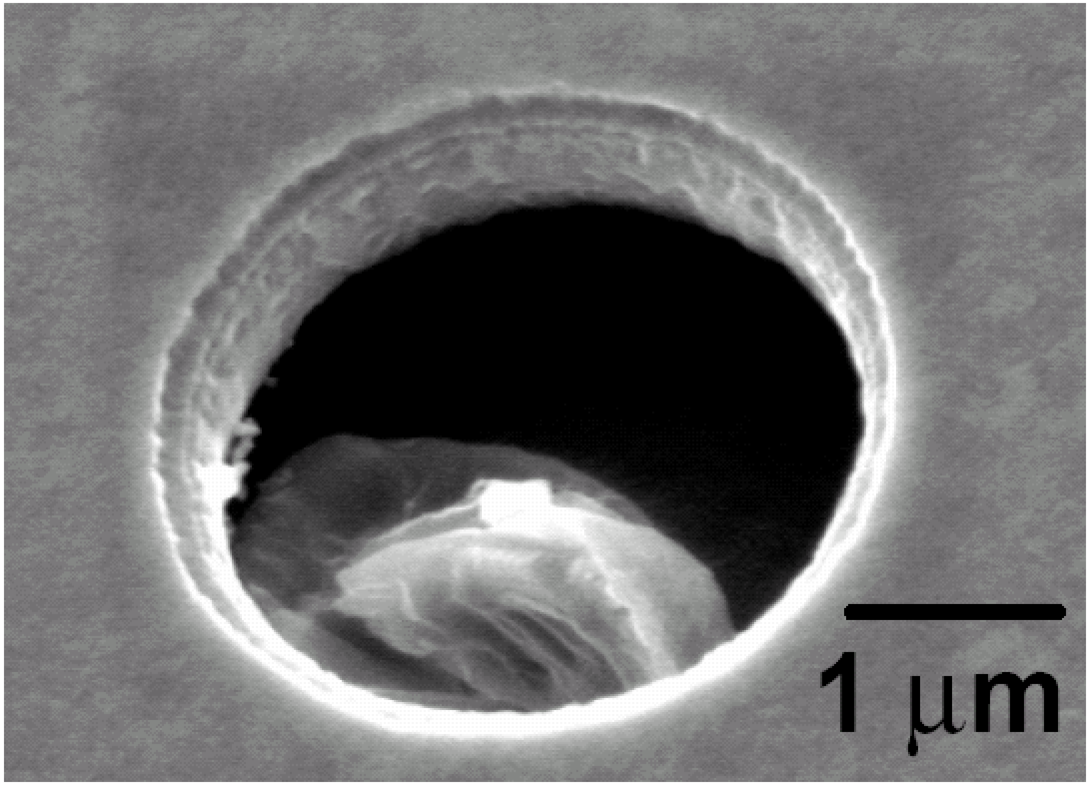
Effects of Gas Adsorption in Nanotribology and Demonstration of in-situ Vapor Phase Lubrication of MEMS Devices

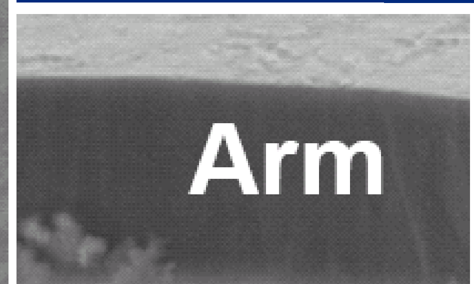
David B. Asay,[1)] Michael T. Dugger,[2)] Seong H. Kim

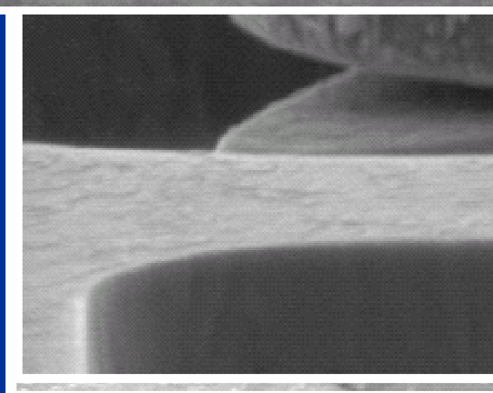
1) Department of Chemical Engineering
The Pennsylvania State University
2) Sandia National Laboratory

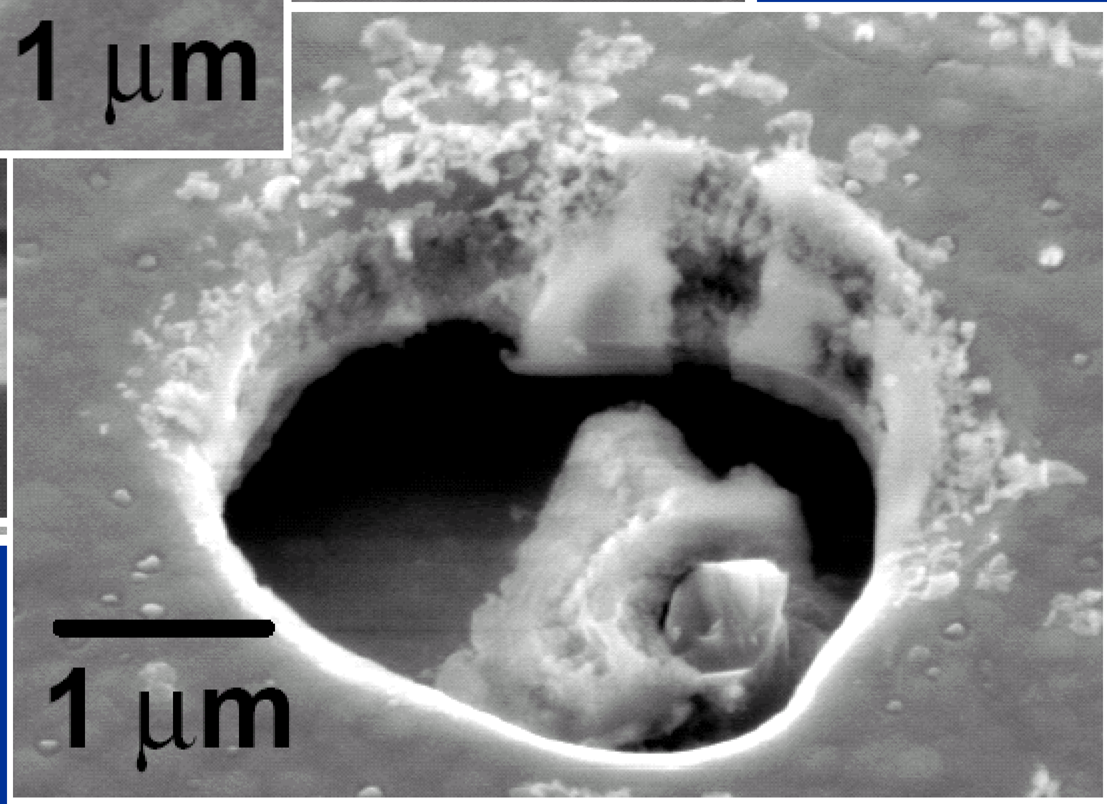
ASME/STLE International Joint Tribology Conference
October 22-24, 2007, San Diego, CA

D.M. Tanner, *et. al.* IEEE (1998)







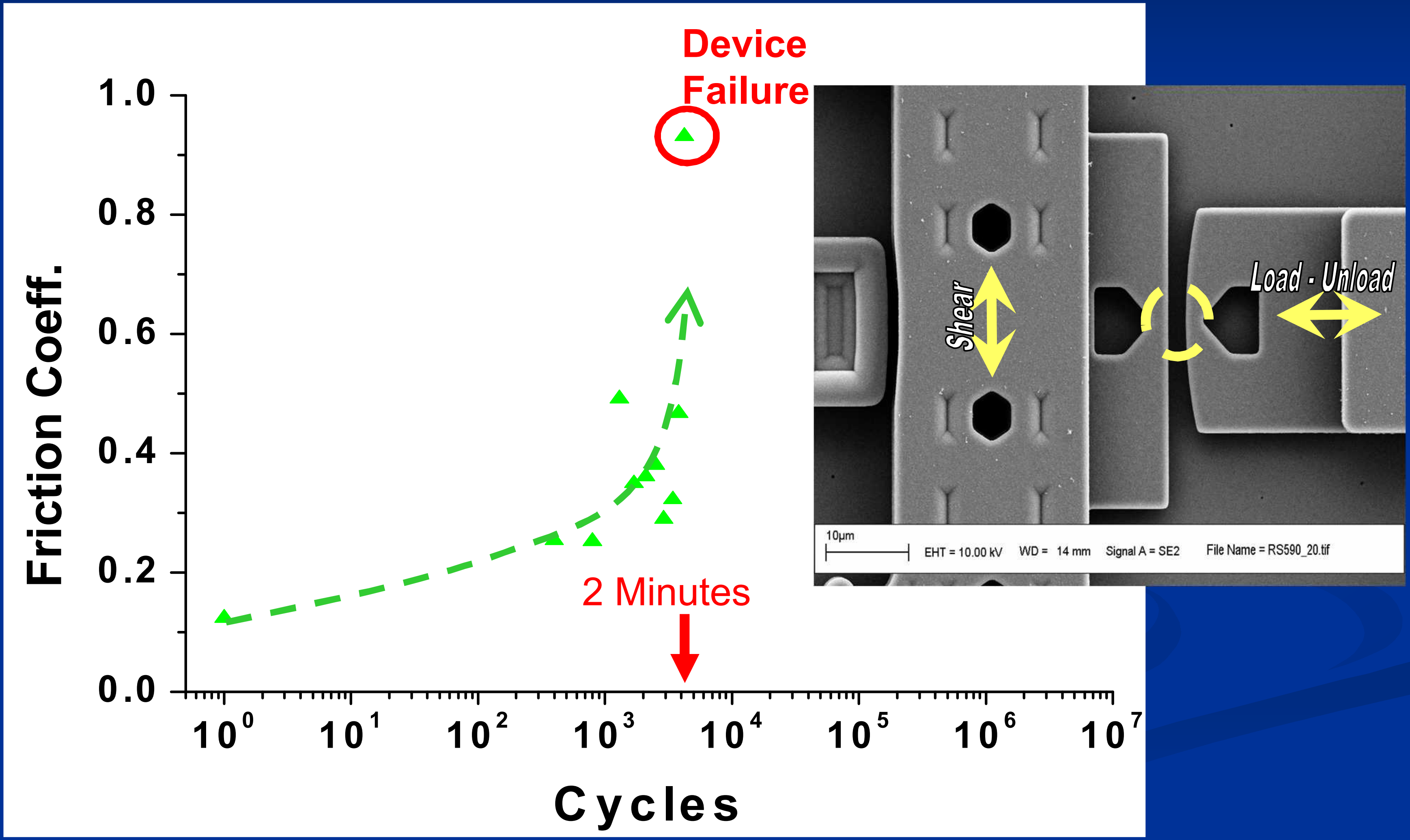


Wear in nanoscale

$$\text{wear life} \propto \frac{\text{thickness}}{\text{erosion rate}} \propto L$$

→ a centimeter-scale part having a 10 year lifetime would be expected to have a 30 sec lifetime if scaled to nanometer dimensions.

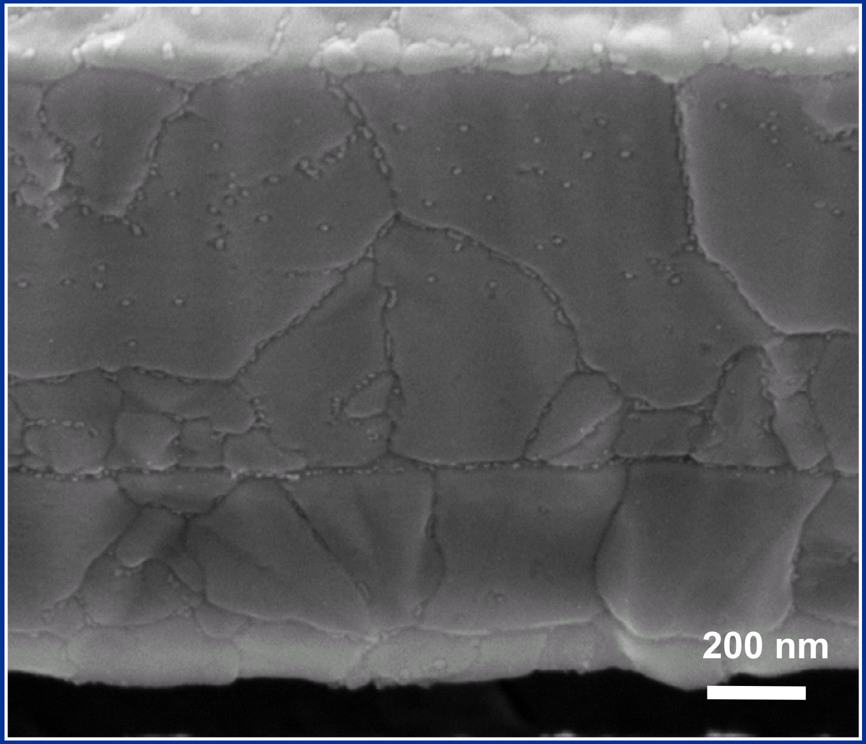
Lifetime depends on wear…

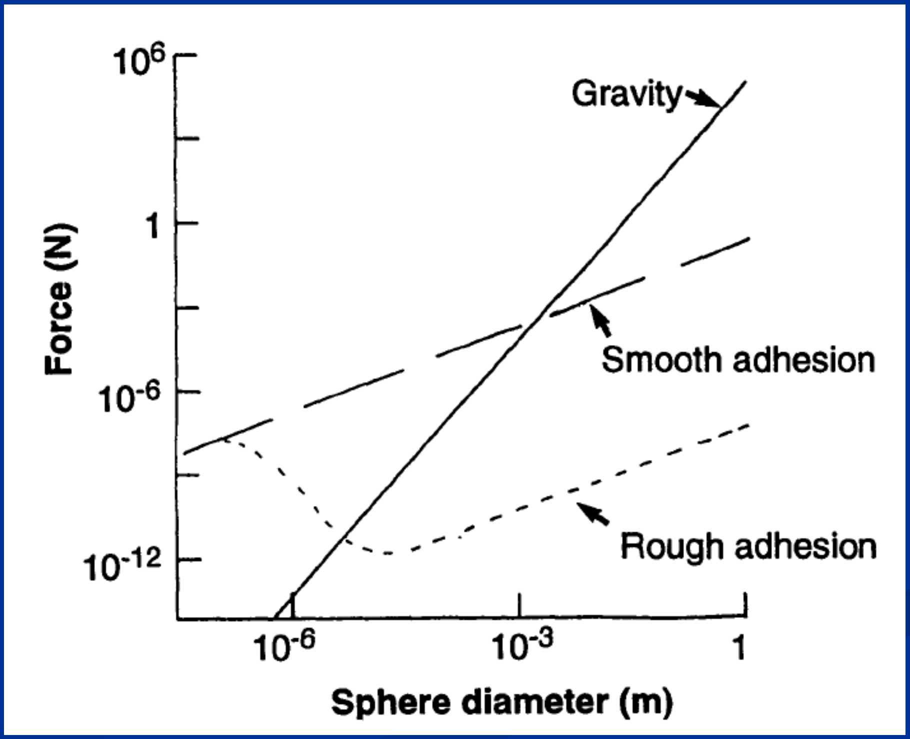


Needs for nano-scale tribological study
(adhesion, friciton, wear)

Physical contacts in MEMS are composed of many nano-asperity contacts…

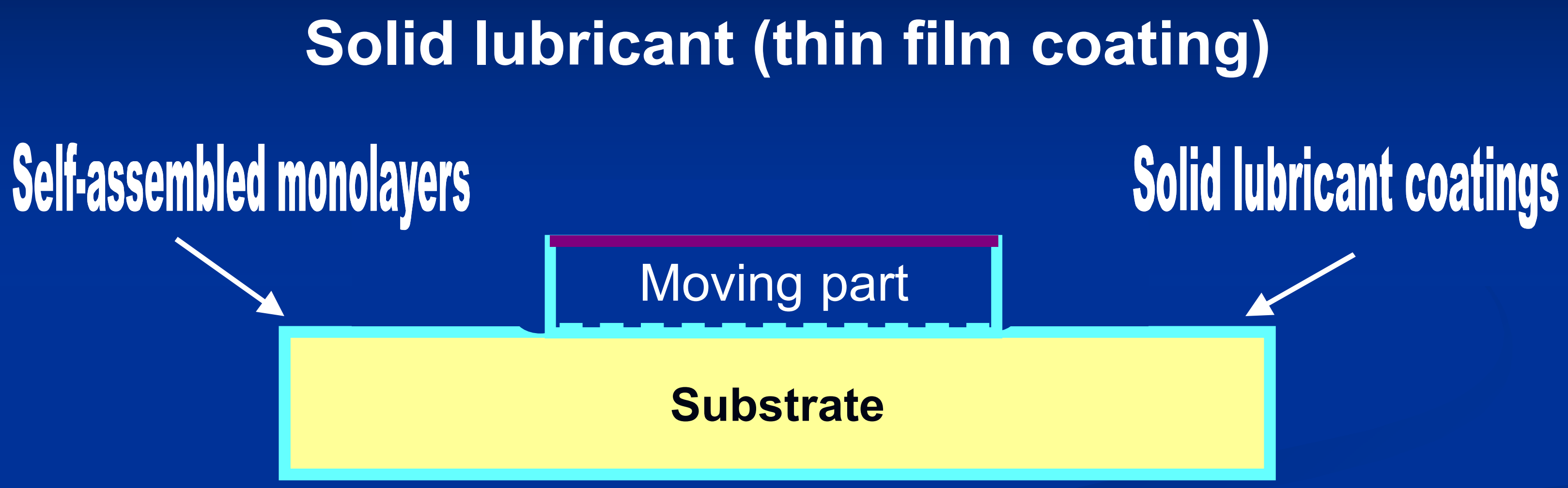
At nanoscale, forces that are negligible at the macro-scale become comparable to the actuation forces provided with on-chip actuators.





Kendall, *Science* **263**, 1720 (1994)

Current "State-of-the Art"



Advantages:

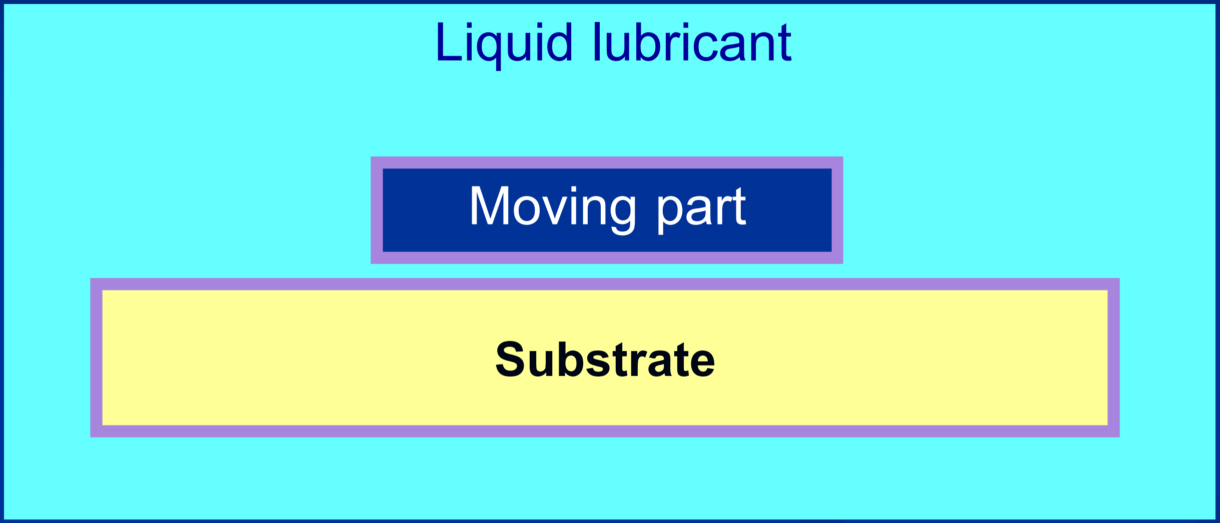
- Easily incorporated into device while being fabricated
- Reduces friction

Disadvantages:

- Not always conformal (cover all surfaces)
- Doesn't last forever → lubricant is not replenished

Kim SH, Asay DB, & Dugger MT, "Nanotribology and MEMS" *NanoToday 2* (5): 22-29, **2007**

Wisdom from conventional liquid-phase lubricants



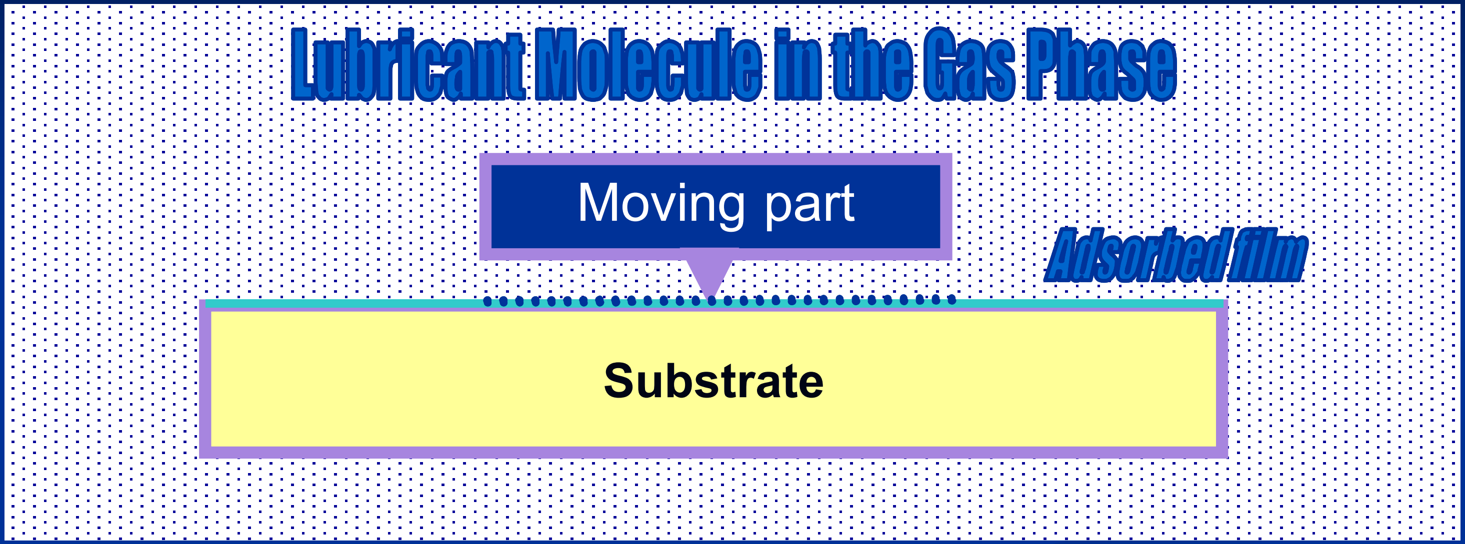
Advantages:

- Continuously replenish lubrication film
- Liquid is fully conformal → works on buried surfaces

Disadvantages esp. at micro- and nano-scales:

- ✘ Dragging of viscous liquid cause power dissipation problems

In-situ Vapor Phase Lubrication



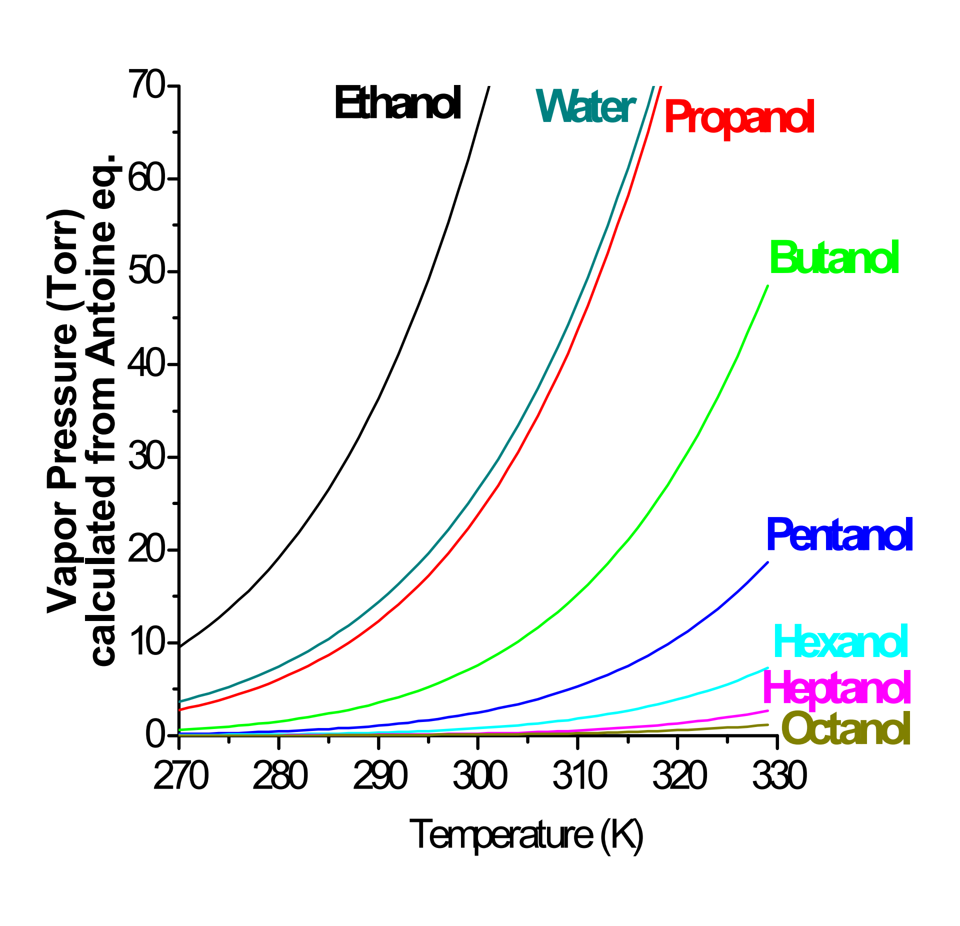
Advantages:

- Lubricant is continuously replenished
- Coats all surfaces exposed (Totally Conformal)
- No Power Dissipation (vs. liquid lubricants)

Gas Phase Lubricants

Primary Alcohols (Ethanol – Pentanol)

- Relatively high vapor pressure
- Few monolayers of water on hydrophilic surfaces
- Hydrogen bond with Si-OH surface groups
- LOW SURFACE ENERGY



Key concept:

K. Strawhecker, D. B. Asay, J. McKinney, and S. H. Kim, *Tribol. Lett.* **2005**, *19*, 17-21.

KEY QUESTION

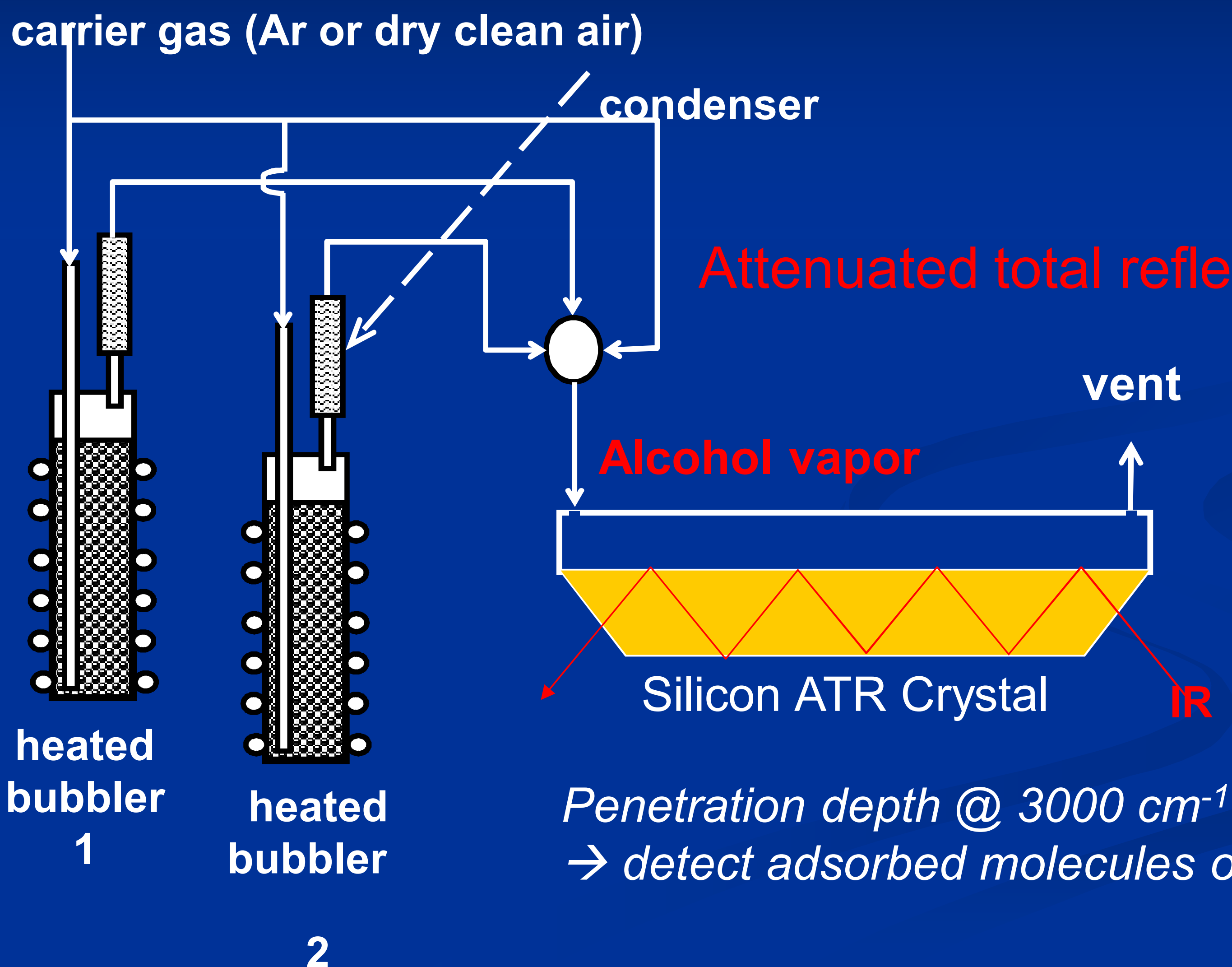
How does gas-adsorption affect the tribological properties of the surface?

- Effect on Adhesion
- Effect on Friction
- Effect on Wear

1. Adsorption Isotherm

How thick is the adsorbed film, $f(P/P^{sat})$?

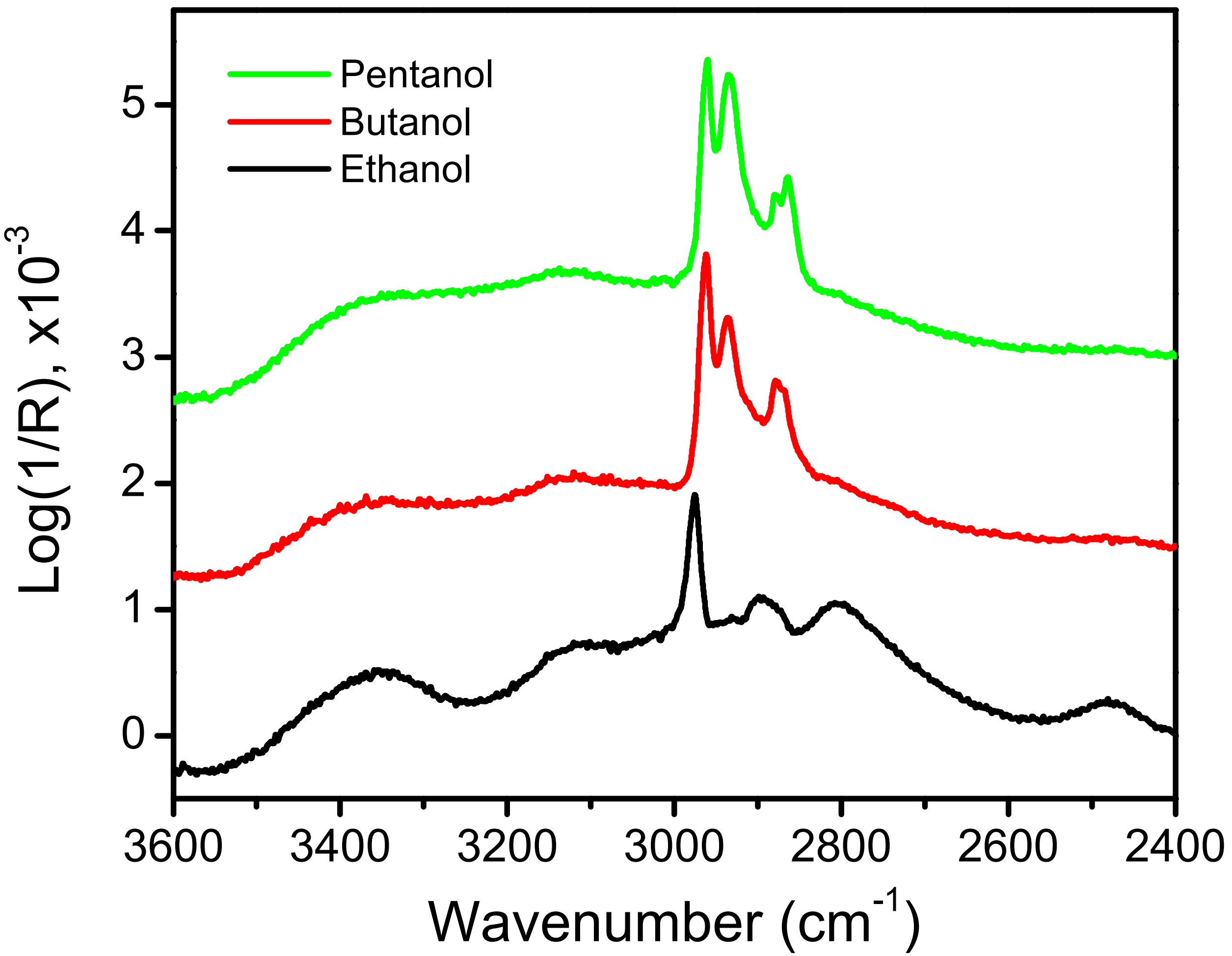
ATR-IR → adsorption isomtherm



Attenuated total reflection FTIR

Penetration depth @ 3000 cm^{-1} = ~ 300 nm
→ detect adsorbed molecules only

ATR-IR @ 65% P/P^{sat}

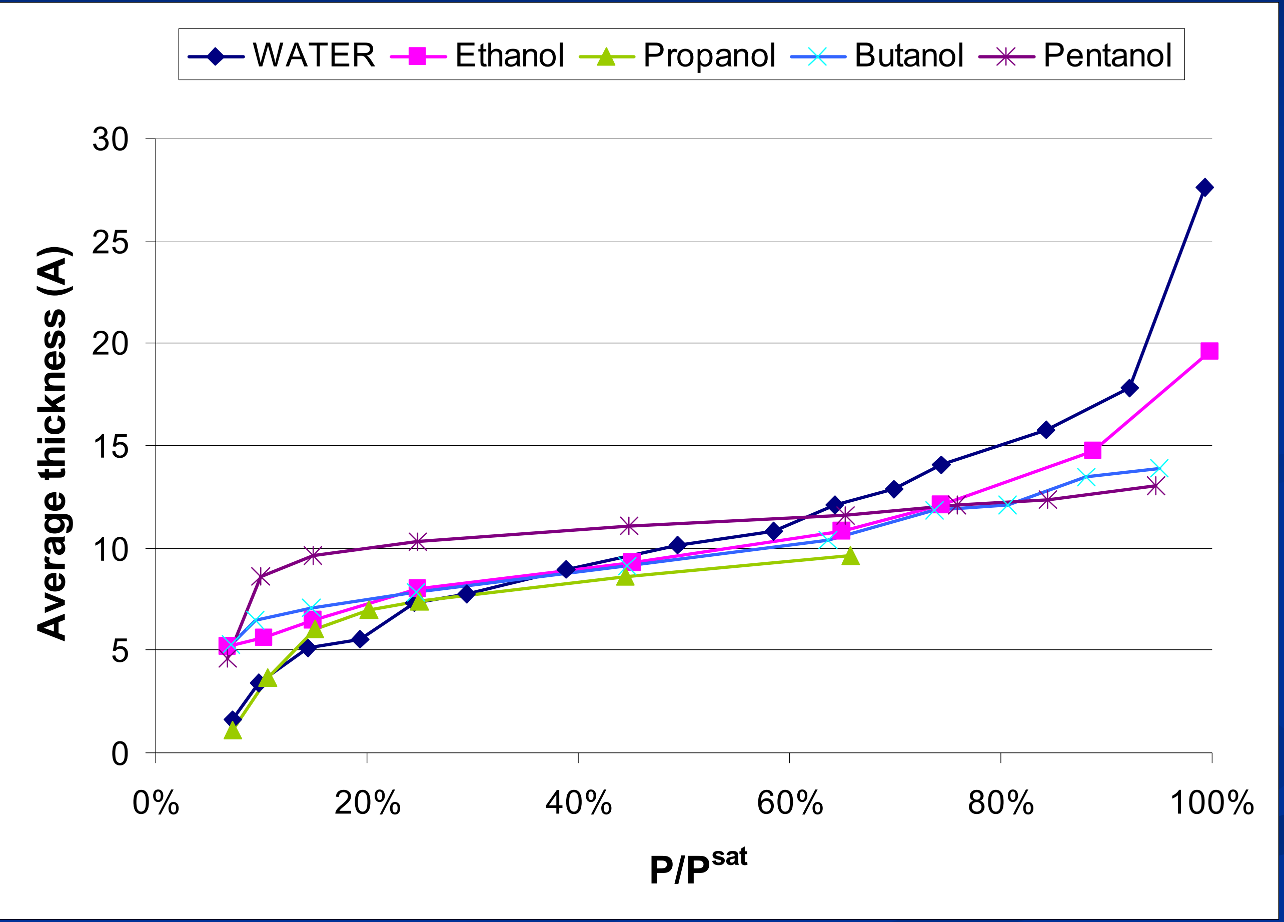


Adsorption on Silicon

Carrier Gas:
Argon

Temperature:
21-23 °C

Error:
± 2 -3 Å
± 3% P/Psat



Measured via: ATR-FTIR

2. Tribological Properties

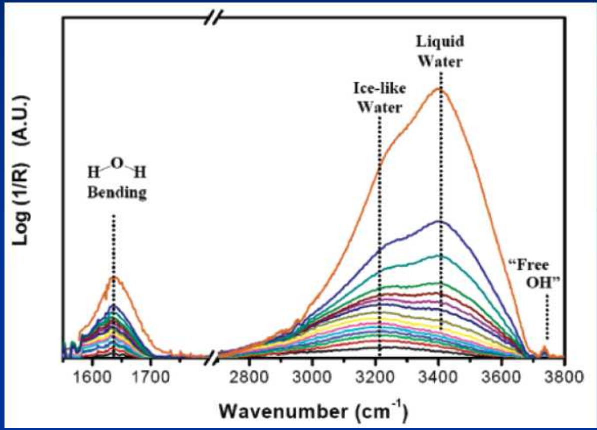
Nano-scale study : Atomic Force Microscope (AFM)

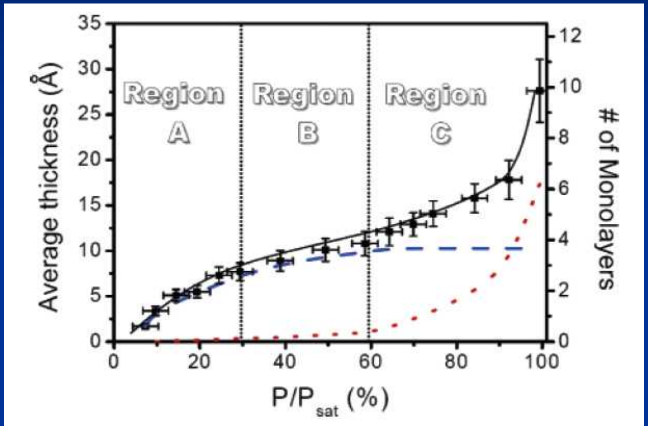
Micro-scale study : MEMS

Macro-scale study: Linear Wear Test

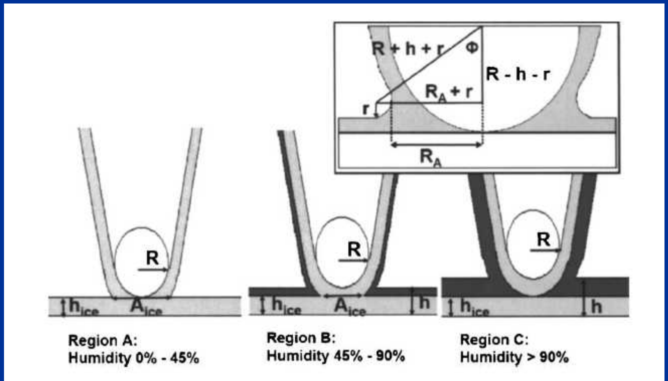
Effects of water adsorption

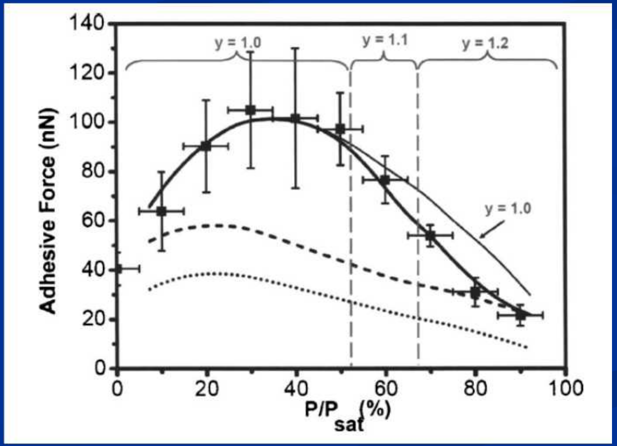
- Adsorption isotherm and structure





- Adhesion and structure





D. B. Asay and S. H. Kim, *J. Phys. Chem. B* **2005**, *109*, 16760-16763.
D. B. Asay and S. H. Kim, *J. Chem. Phys.* **2006**, *124*, 174712-1 - 174712-5.

Nano-asperity adhesion in alcohol vapor environment

Single Asperity Adhesion

Young's Equation

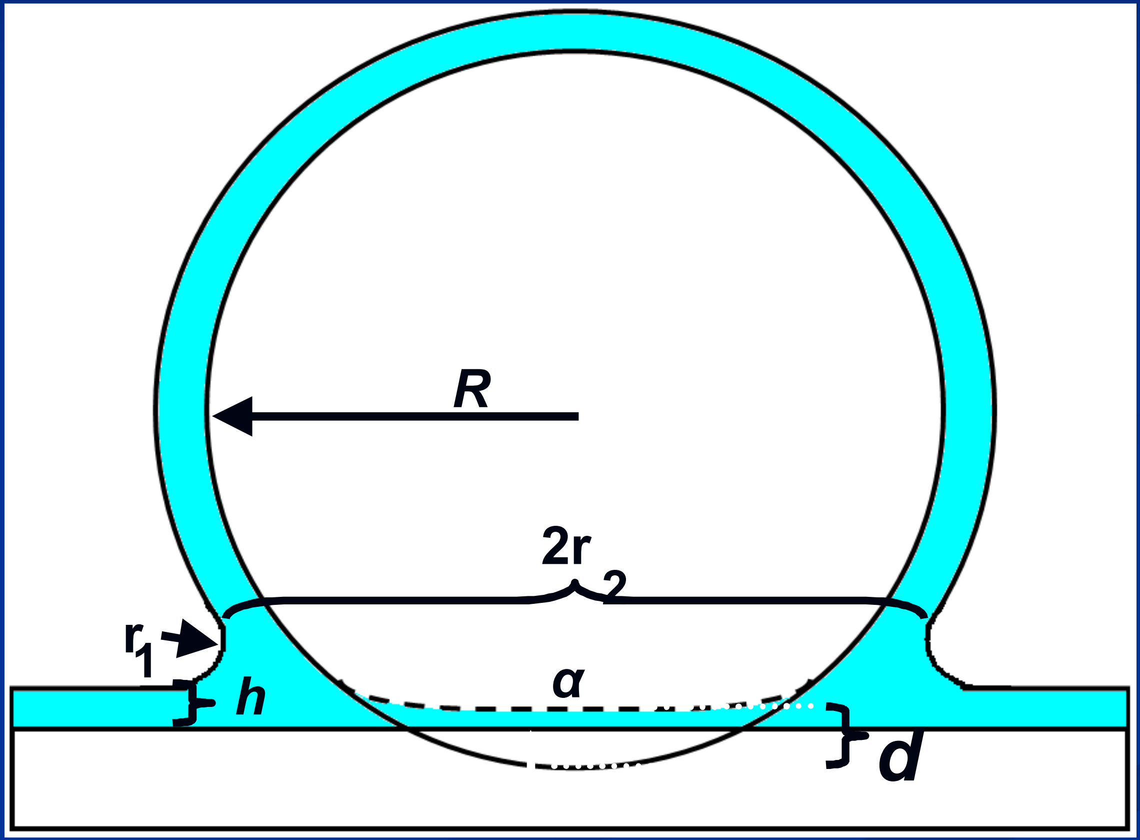
$$P_{Laplace} \equiv \gamma_L \left(\frac{1}{r_1} + \frac{1}{r_2} \right)$$

Mechanical Equilibrium

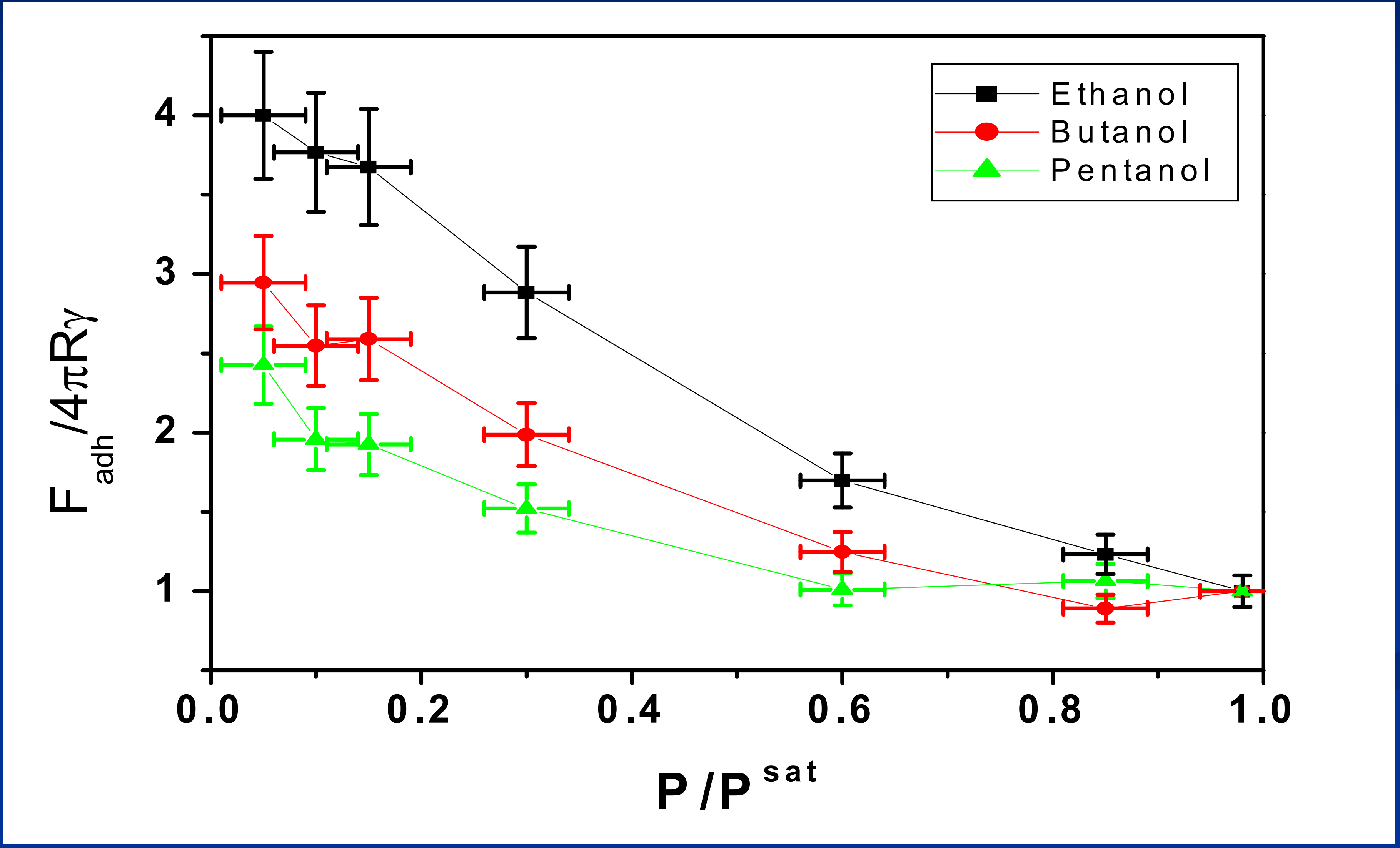
Kelvin Equation

$$P_{Laplace} \equiv \frac{R_g T}{V} \ln\left(\frac{P}{P^{sat}} \right)$$

Chemical Equilibrium



Capillary force in alcohol vapor environment



Why the difference?

Macroscopic view of capillary force

→ A liquid with a higher surface tension gives a larger capillary force.

	γ (erg/cm^2)
Ethanol	22.8
1-butanol	24.6
1-pentanol	24.9

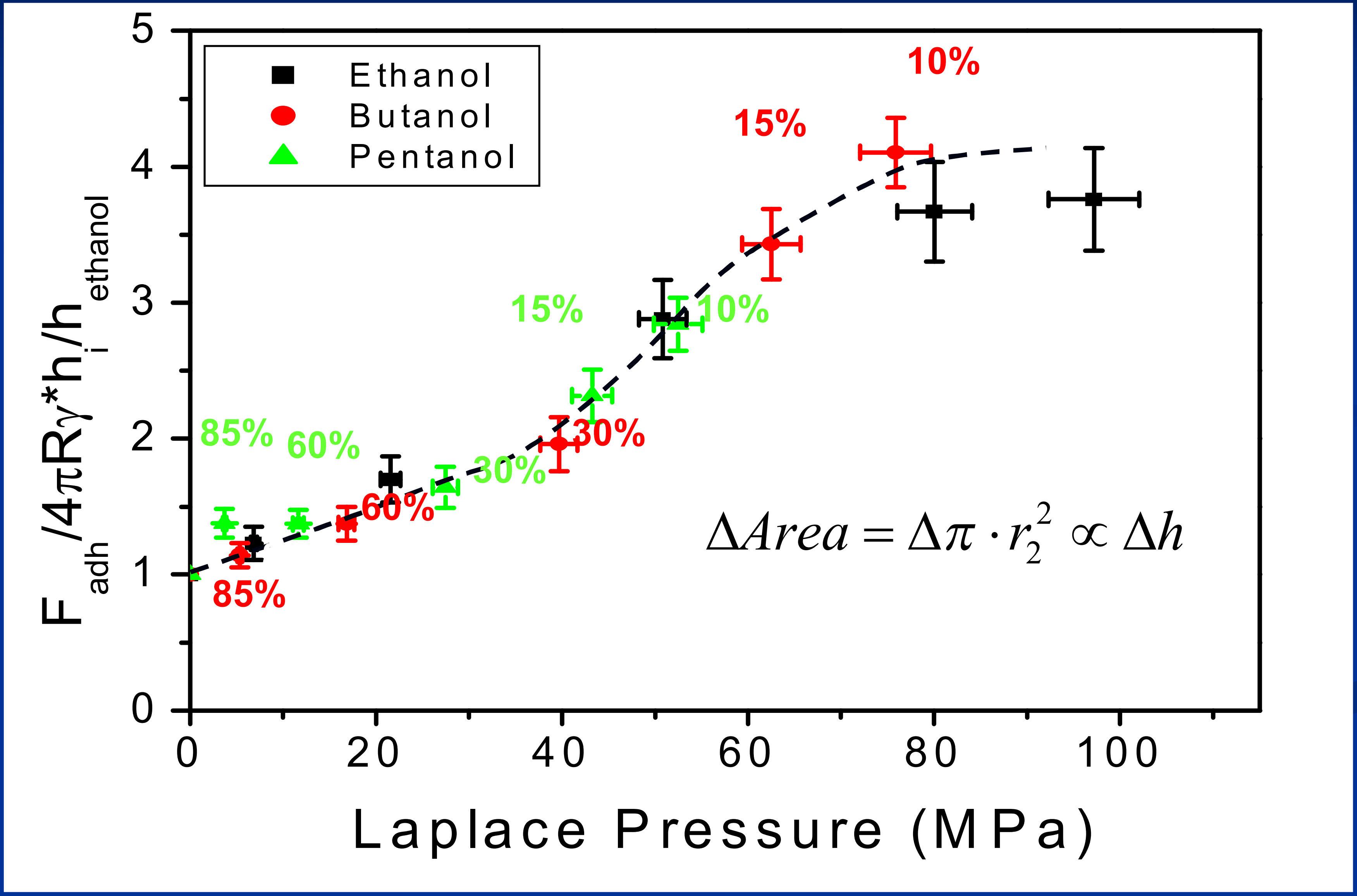
But, each alcohol has virtually the same surface tension (γ) and adsorption isotherm (h)…

The difference is related to the molar volume of the condensed phase…

$$P_{Laplace} \equiv \frac{R_g T}{V} \ln\left(\frac{P}{P^{sat}}\right)$$

	V (cm^3/mol)
Ethanol	58.7
1-butanol	91.2
1-pentanol	108.7

Capillary Force vs. Laplace Pressure (Normalized for h and V)



What's the big deal?

- **Macroscopic view of capillary force due to Laplace pressure inside the meniscus:**

$$F_{Capillary} = 4\pi R\gamma \cos\theta$$

- **As the contact size shrinks, assumptions that are valid in the derivation for macroscopic contacts break down:**
  - ***MOLAR VOLUME***
  - ***ISOTHERM***

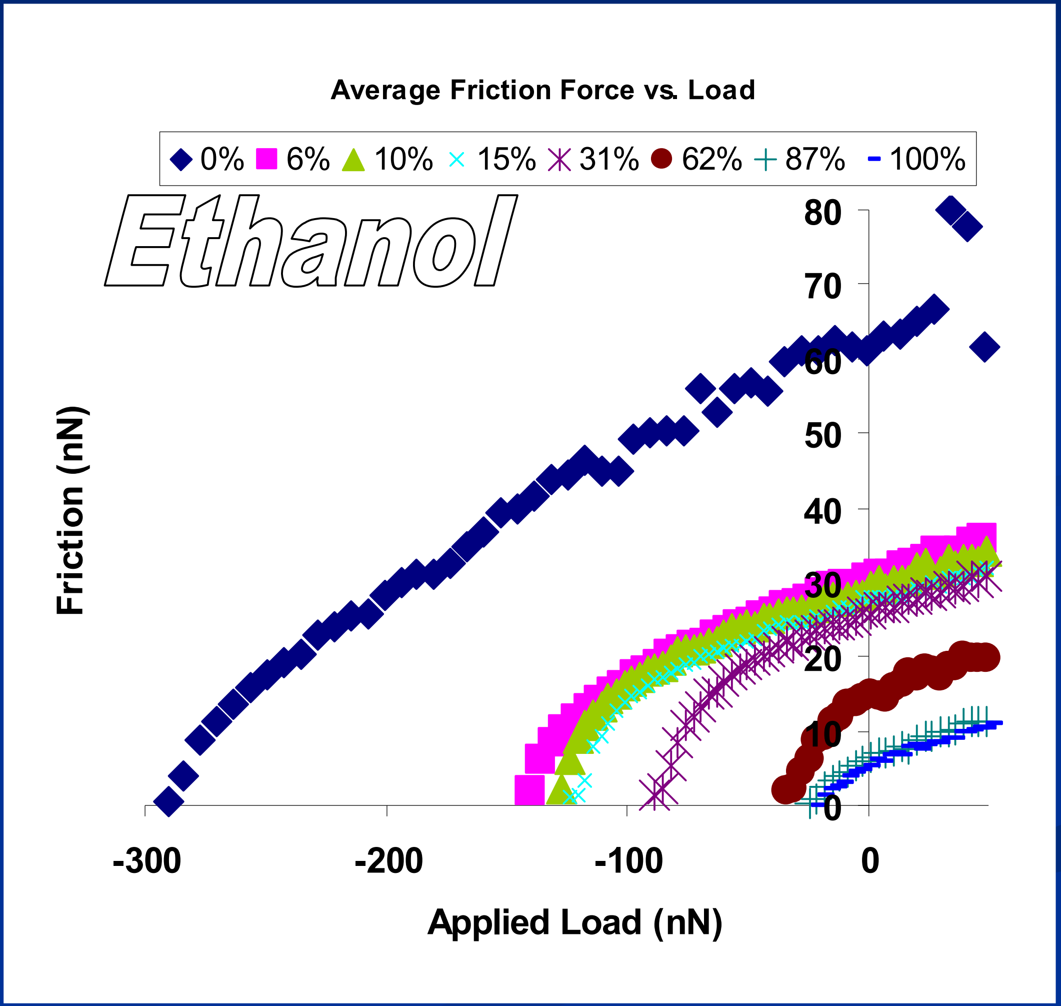
D. B. Asay and S. H. Kim, *Langmuir* (in press)

Nano-asperity friction
in alcohol vapor environment

Friction Load Curves

Reduction in Friction

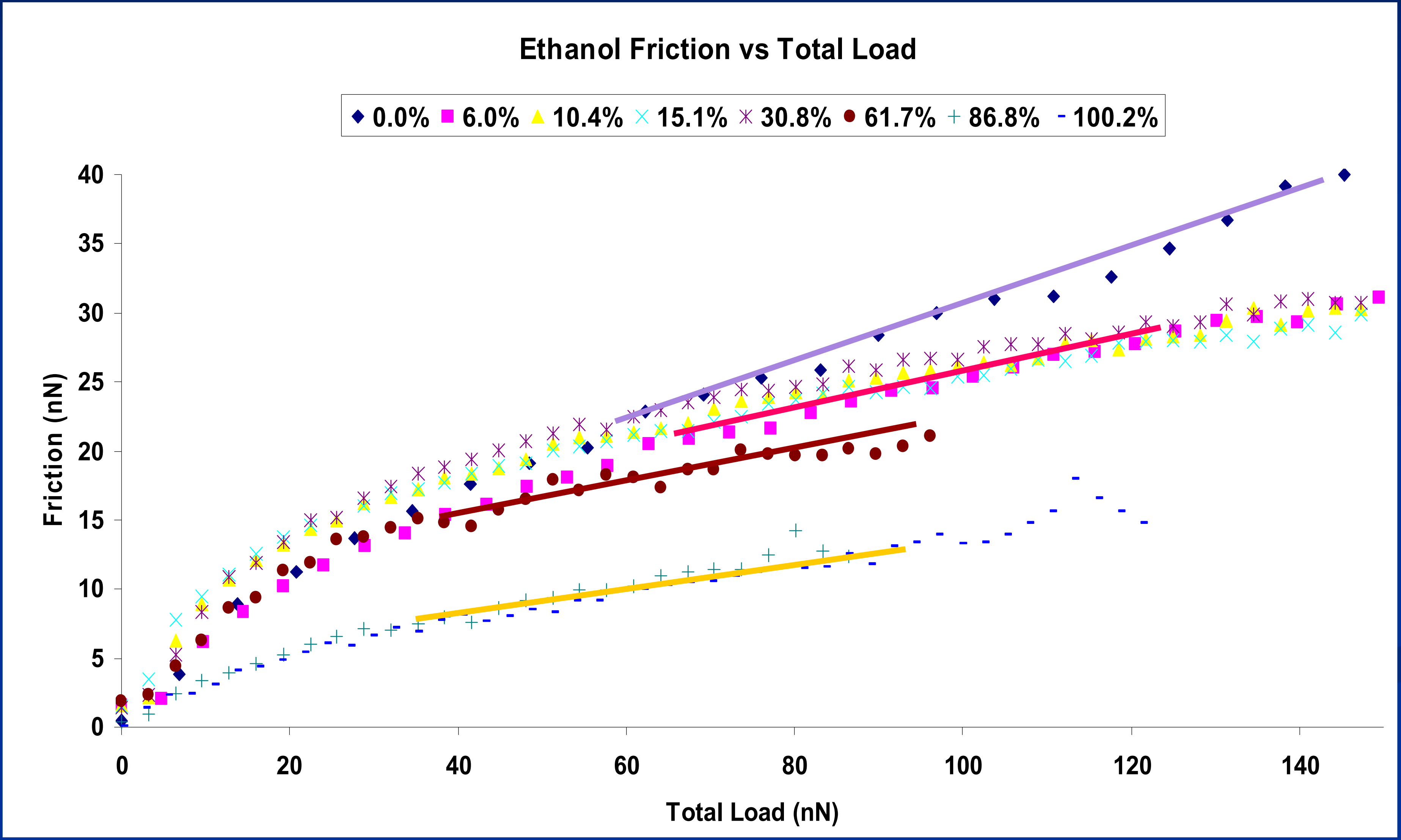
- Reduction in Adhesion?
- Reduction in shear strength?
- Both?



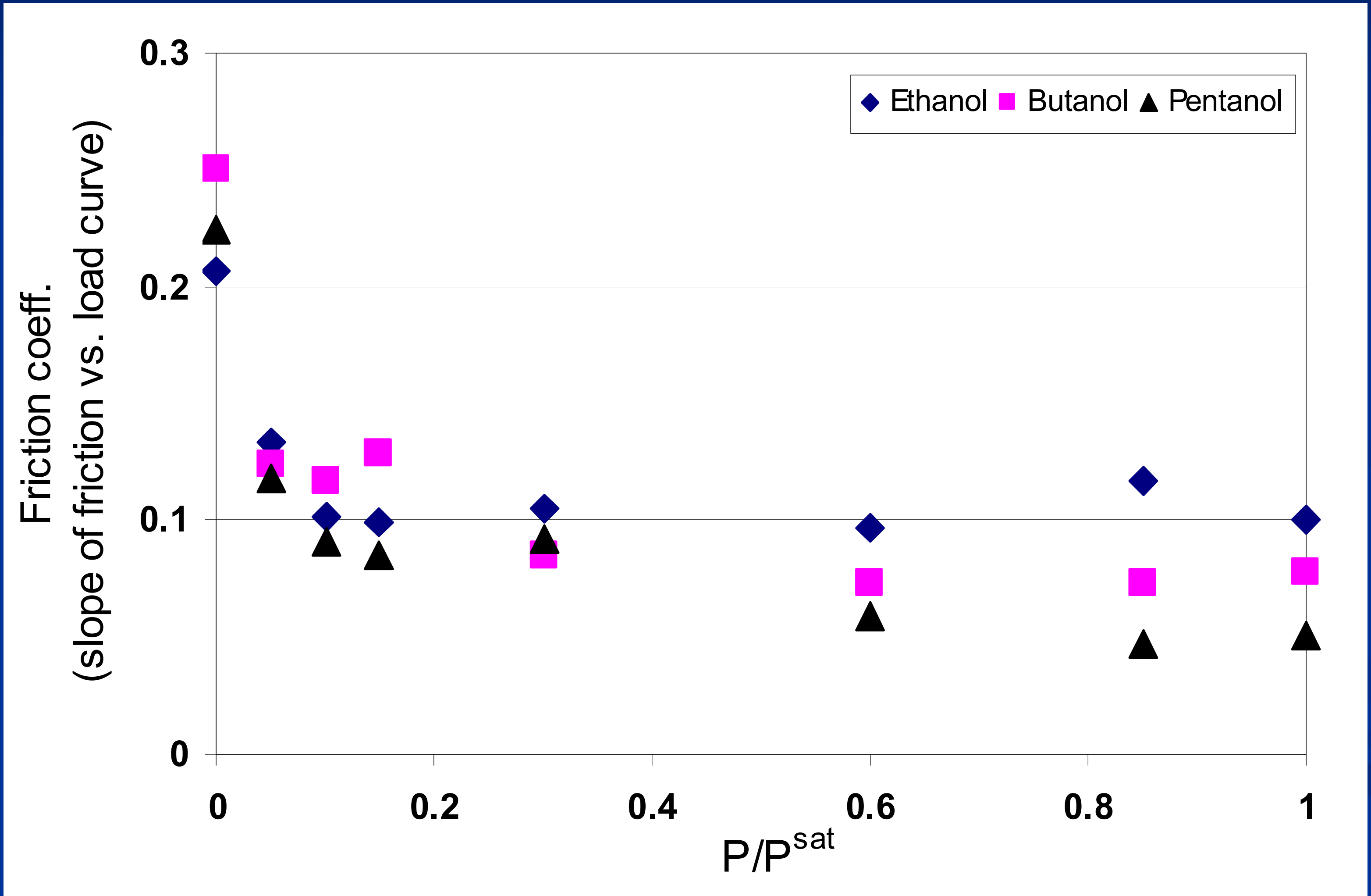
D. B. Asay and S. H. Kim (manuscript in preparation)

Silicon AFM tip on Silicon (100) surface at Room Temp speed 2 μm/sec

Adsorbate Effect on Friction



Friction Coeff. vs. Vapor Pressure

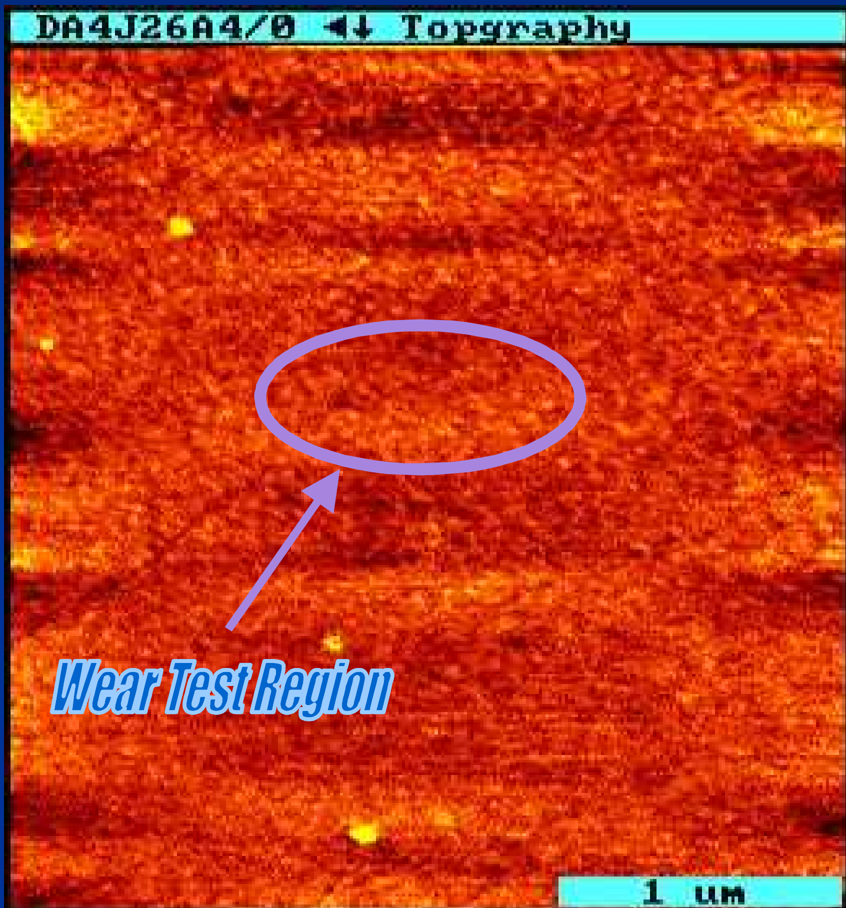


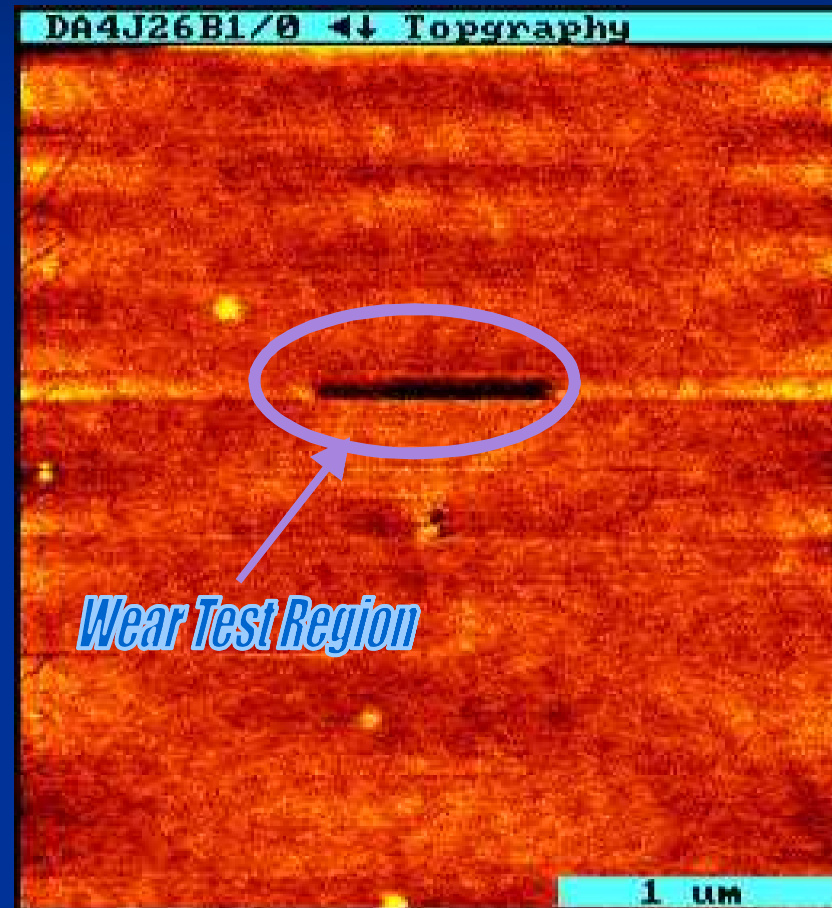
D. B. Asay and S. H. Kim (manuscript in preparation)

Nano-asperity wear behavior in alcohol vapor environment

Single Asperity Wear

In humid air (RH = 75%)

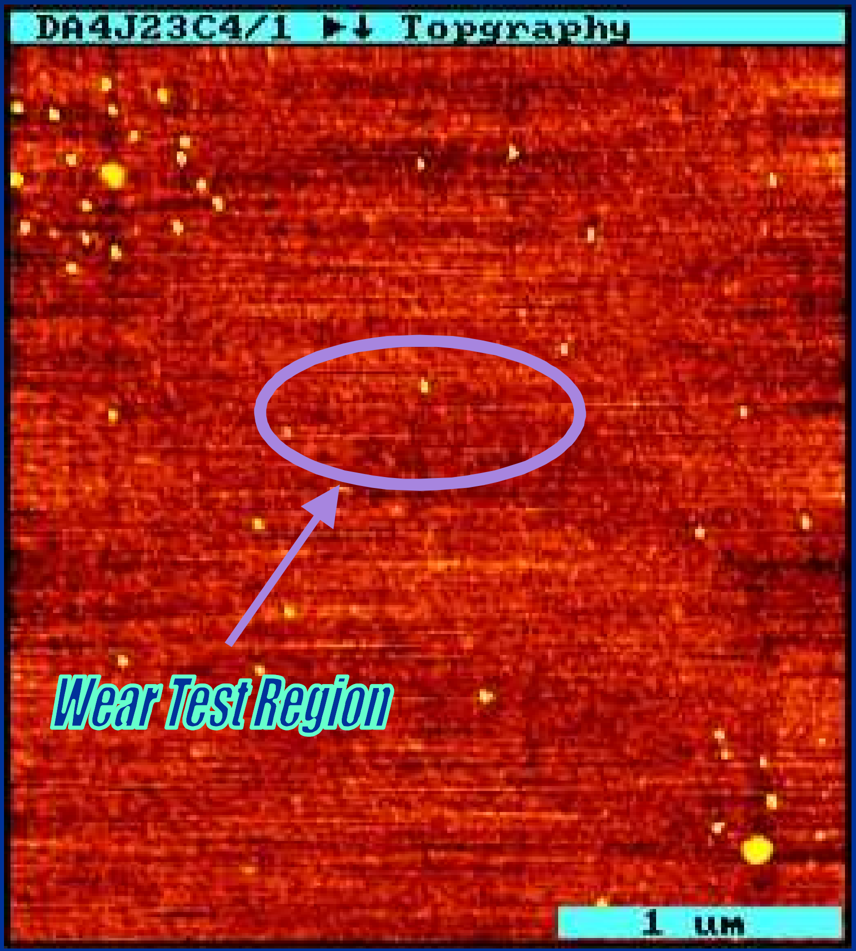


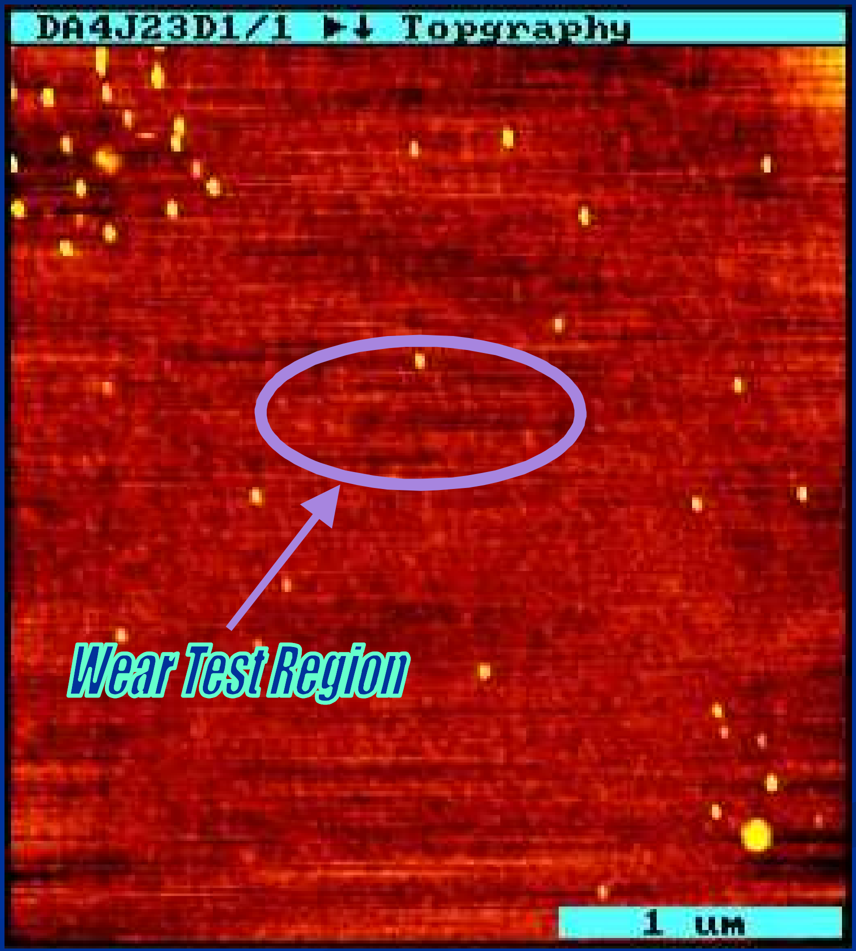


10 Å deep trench

Full Z-scale ~1nm

In 75% P/P^{sat} n-Propanol vapor





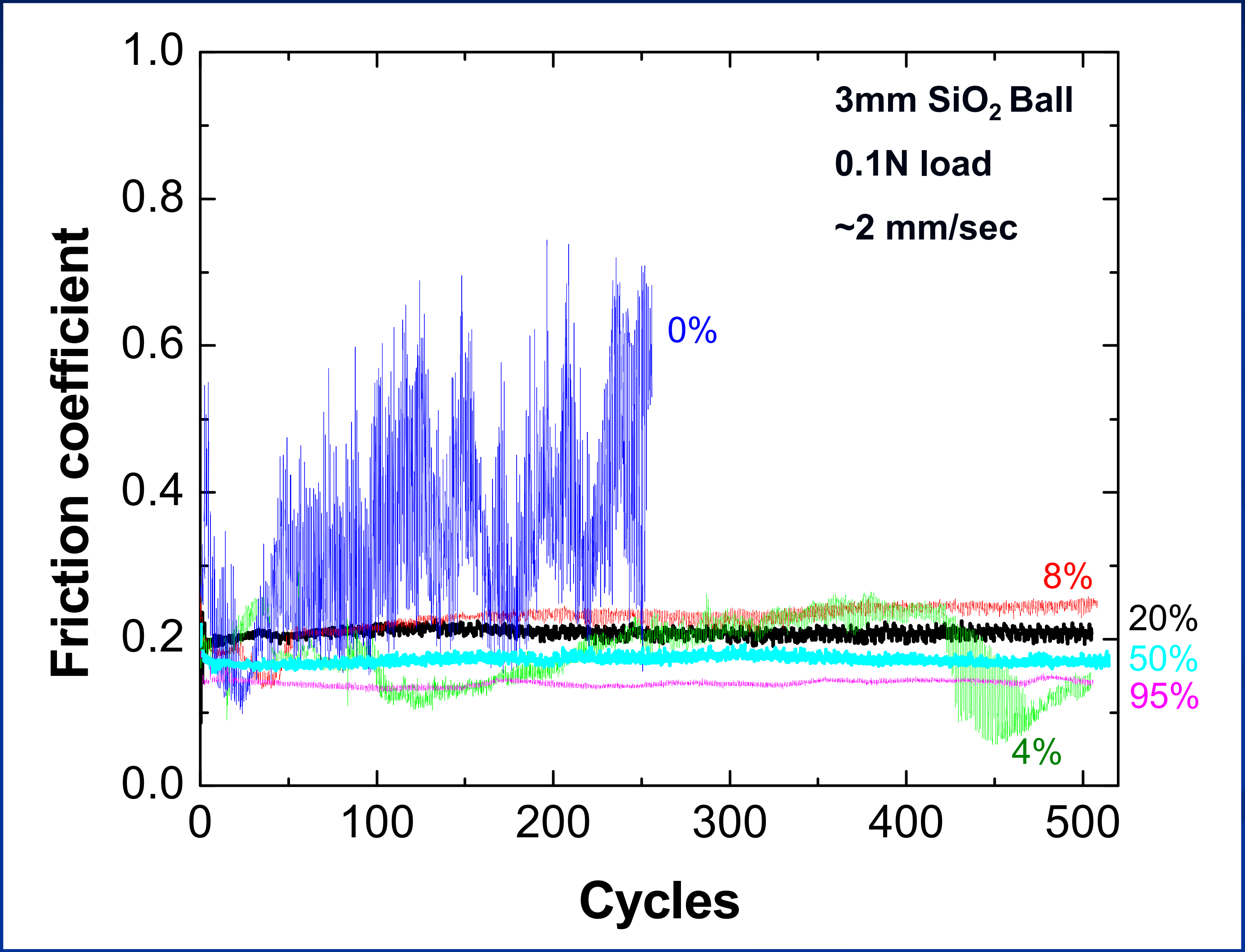
Full Z-scale ~1nm

Asay, Dugger, Ohlhausen, Kim, *Langmuir* (in press)

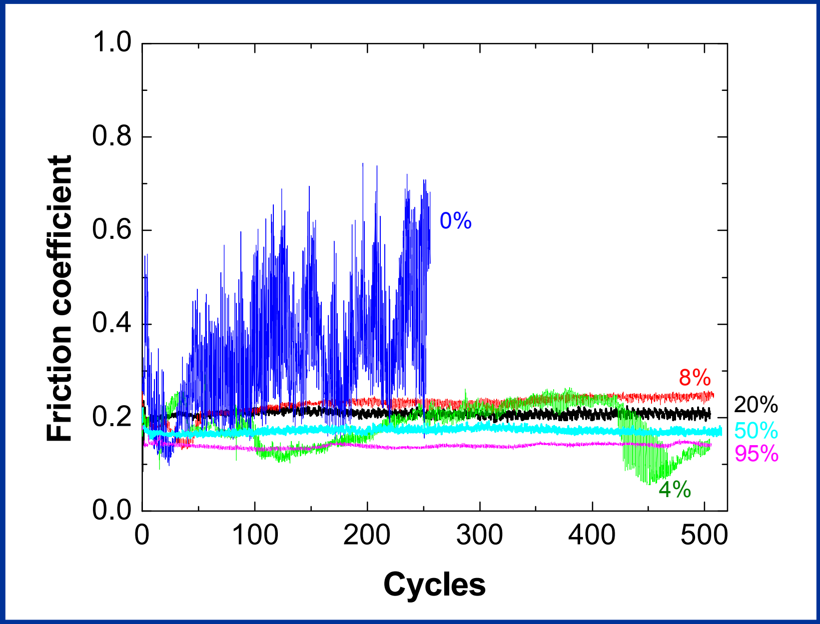
Macroscopic Scale Observations

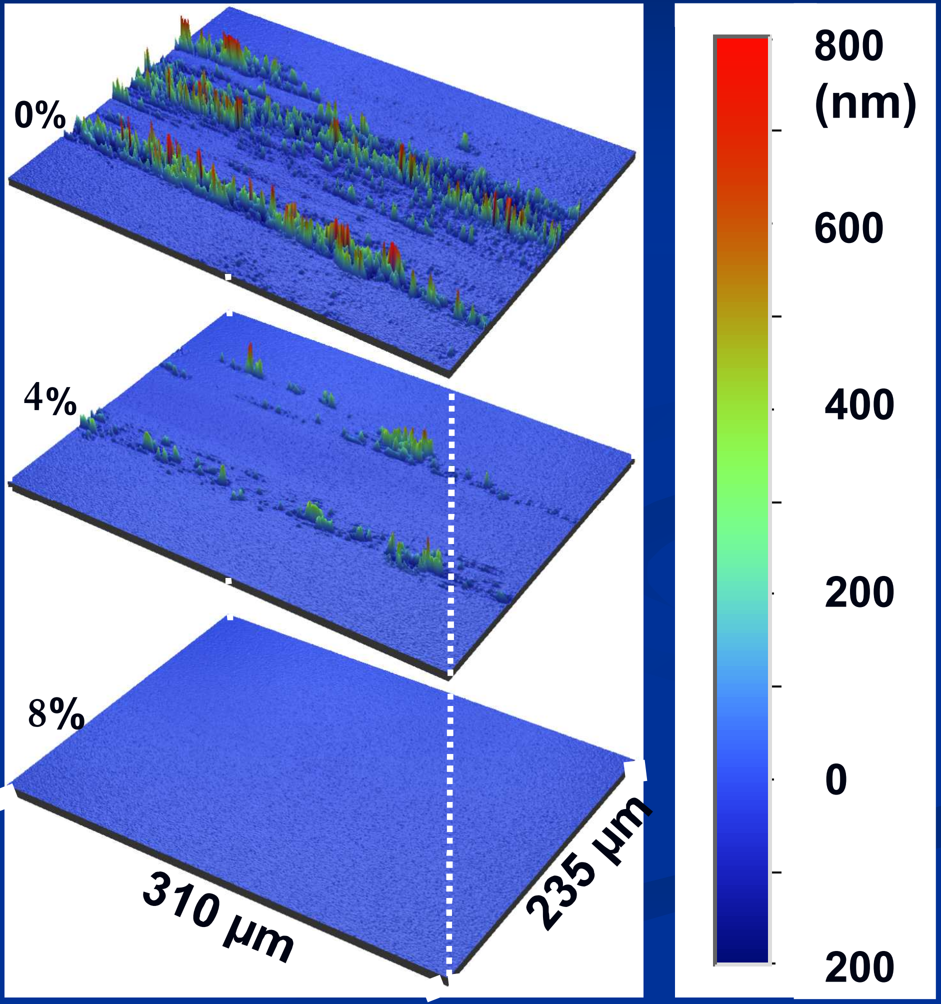
Linear wear tests in n-pentanol vapor environments

n-Pentanol vapor environment



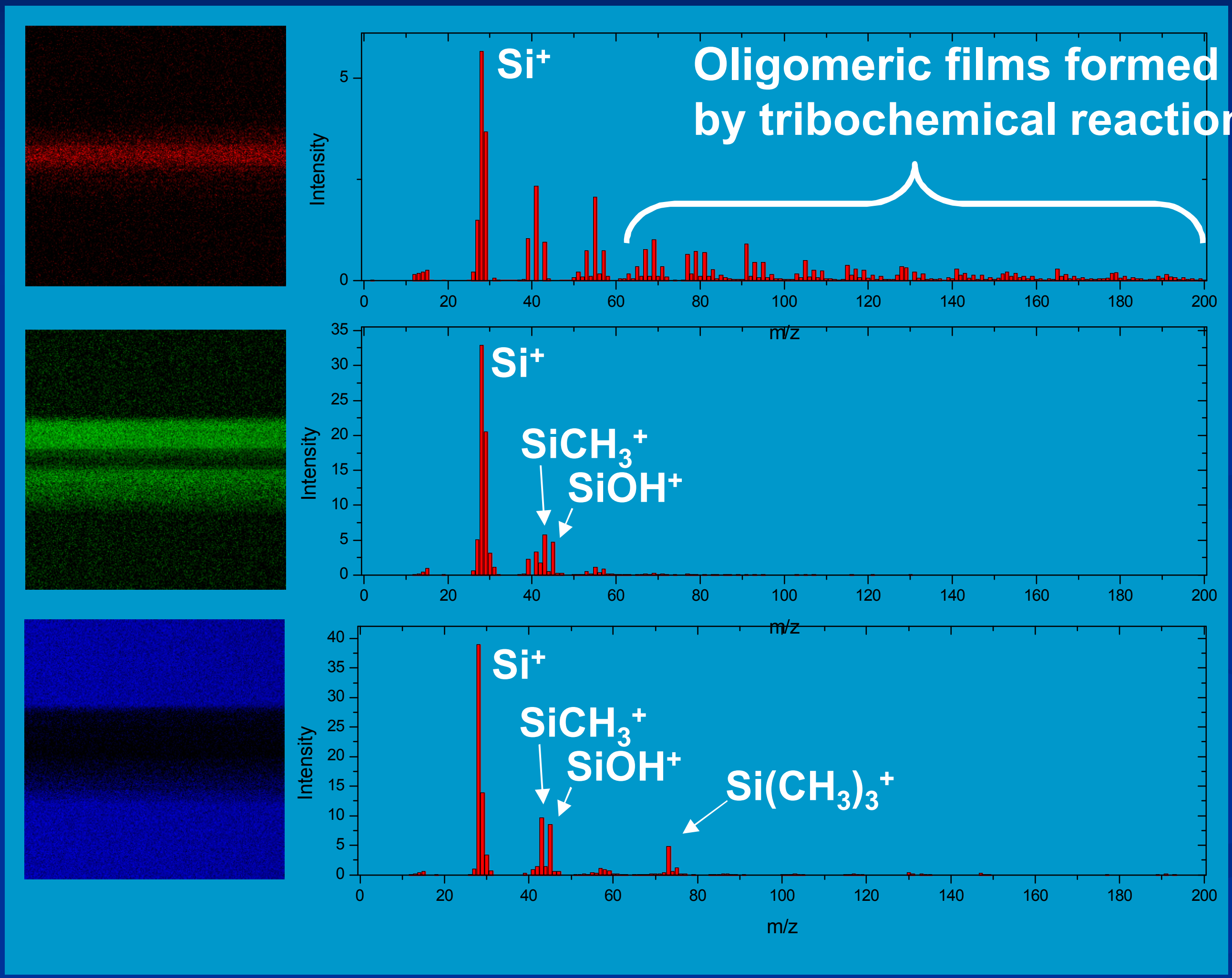
Profilometry of wear track

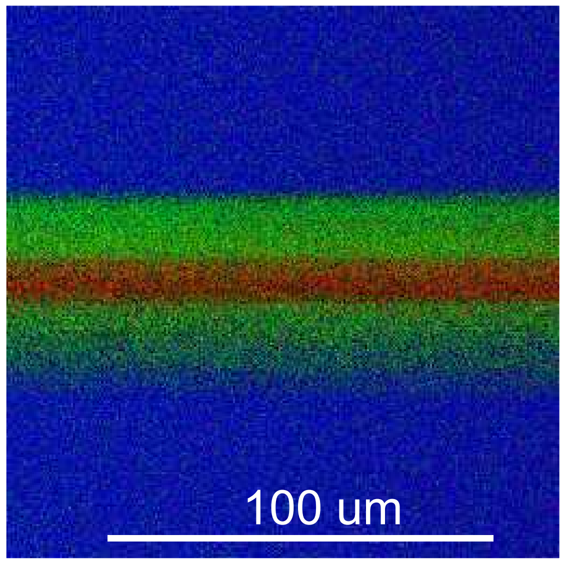




Asay, Dugger, Ohlhausen, Kim, *Langmuir* (in press)

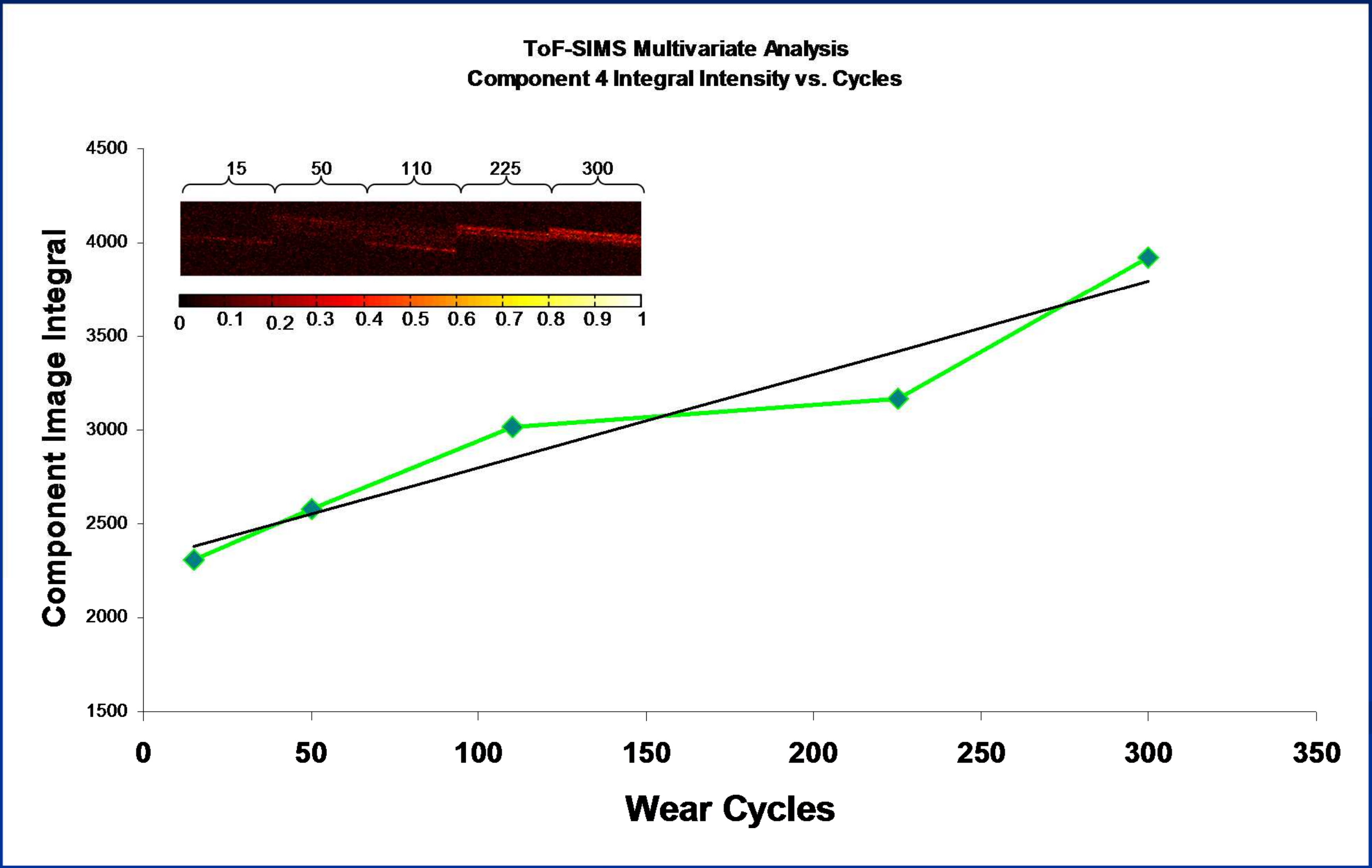
20% P/P^{sat} n-Pentanol
ToF-SIMS Multivariate Image Analysis



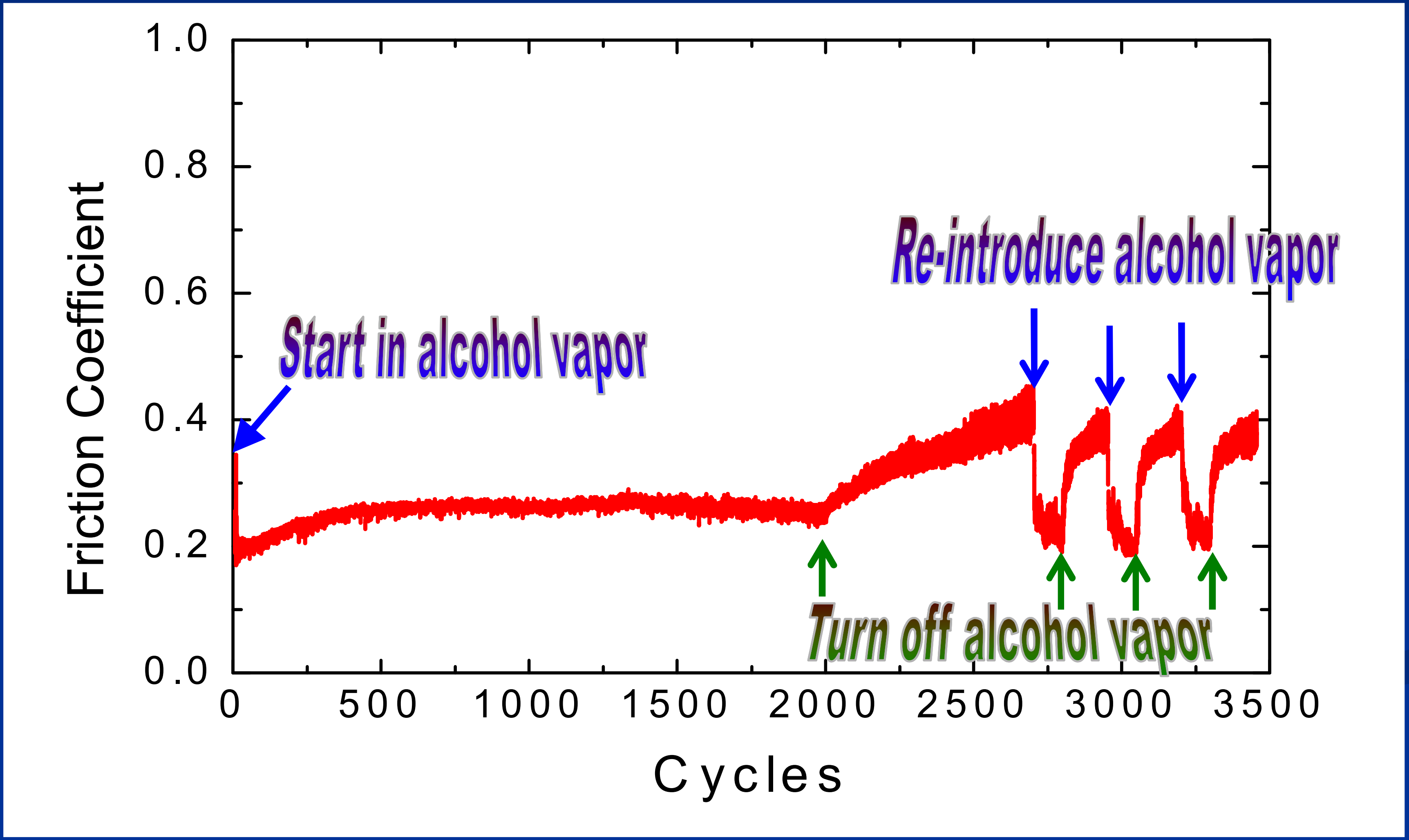


Asay, Dugger, Ohlhausen, Kim, *Langmuir* (in press)

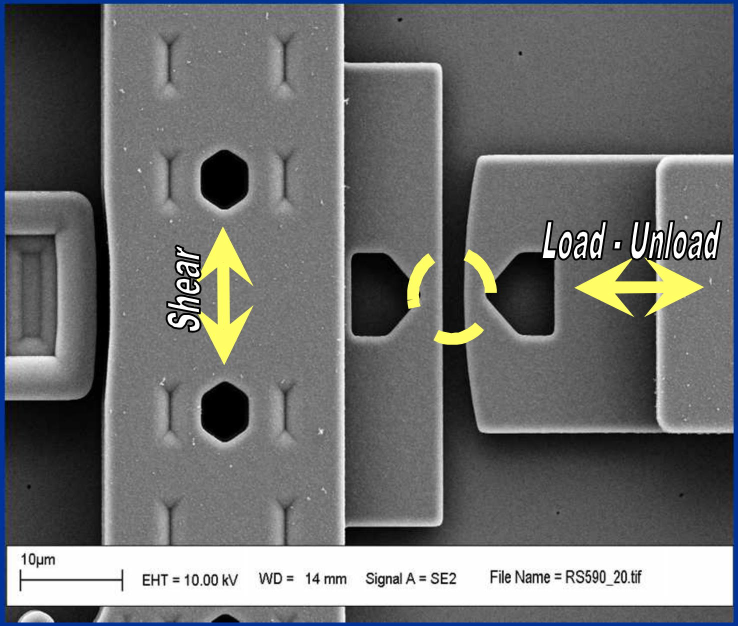
Growth of oligomeric film



Is maintaining the vapor environment important?

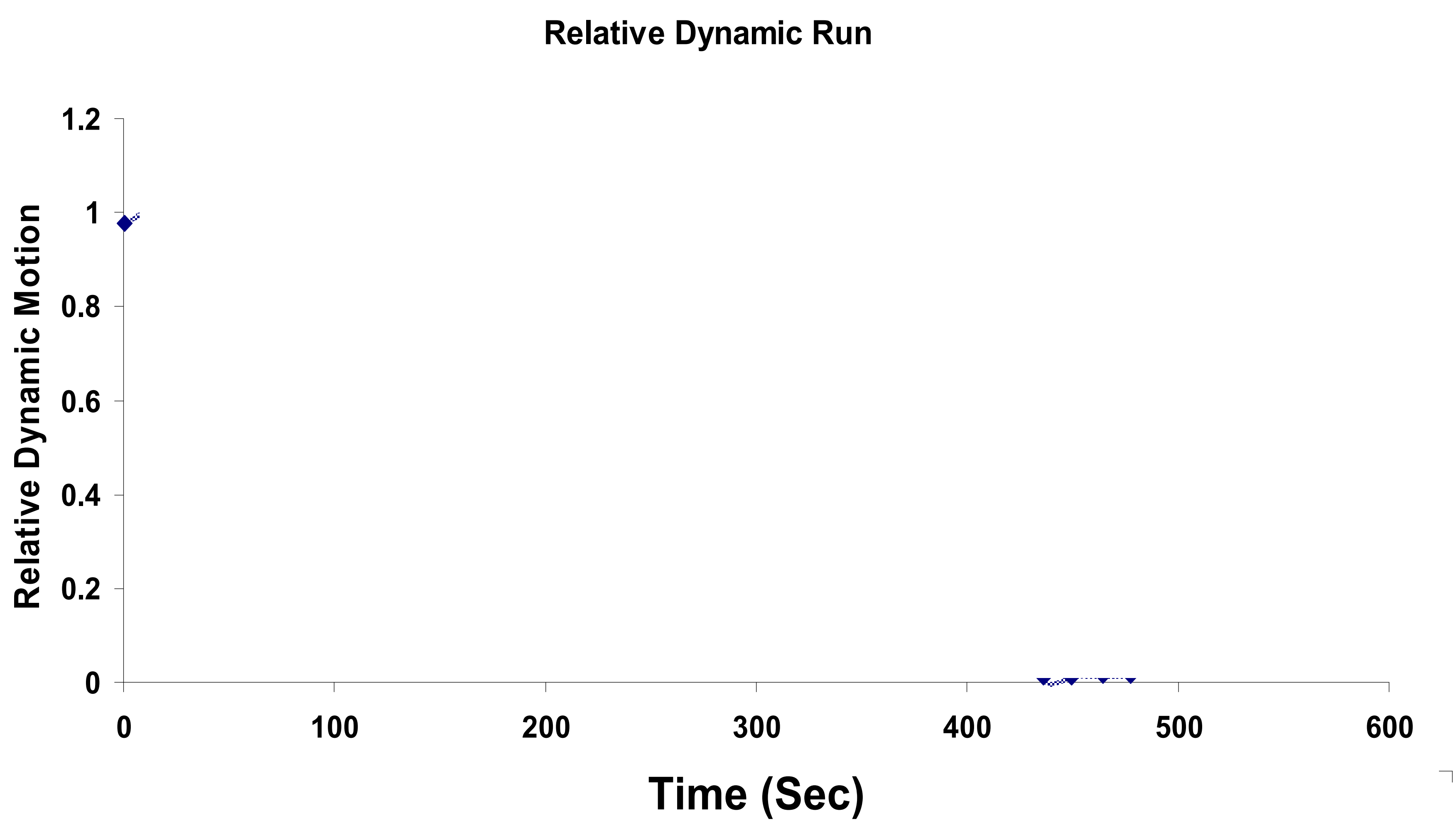


Relevance to MEMS ?

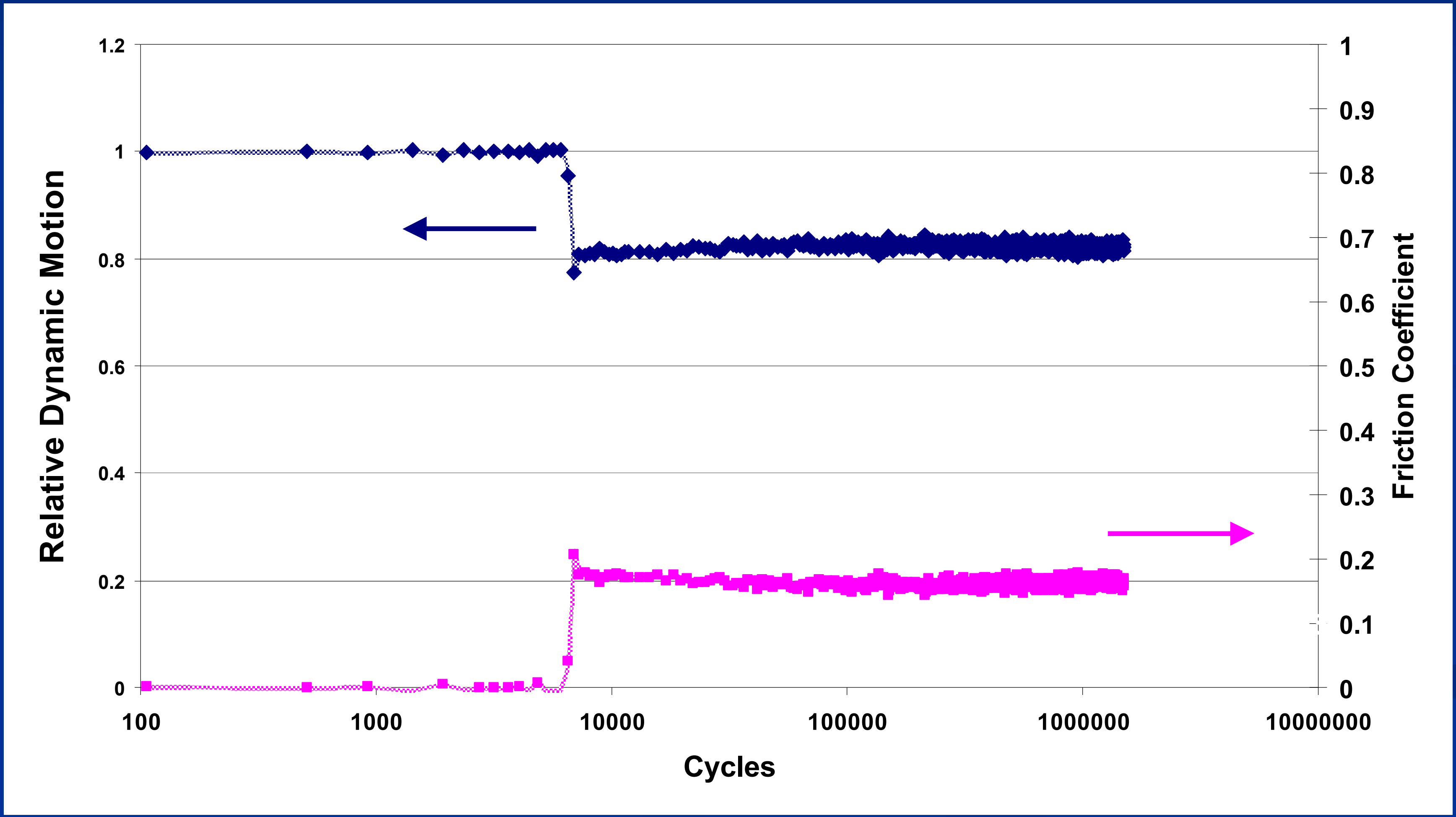


- Sidewall Friction Device
- 500 nN Load
- Oscillations at 100 Hz

Dry N_2 Environment



Dynamic run in 95% P/P^{sat} pentanol vapor

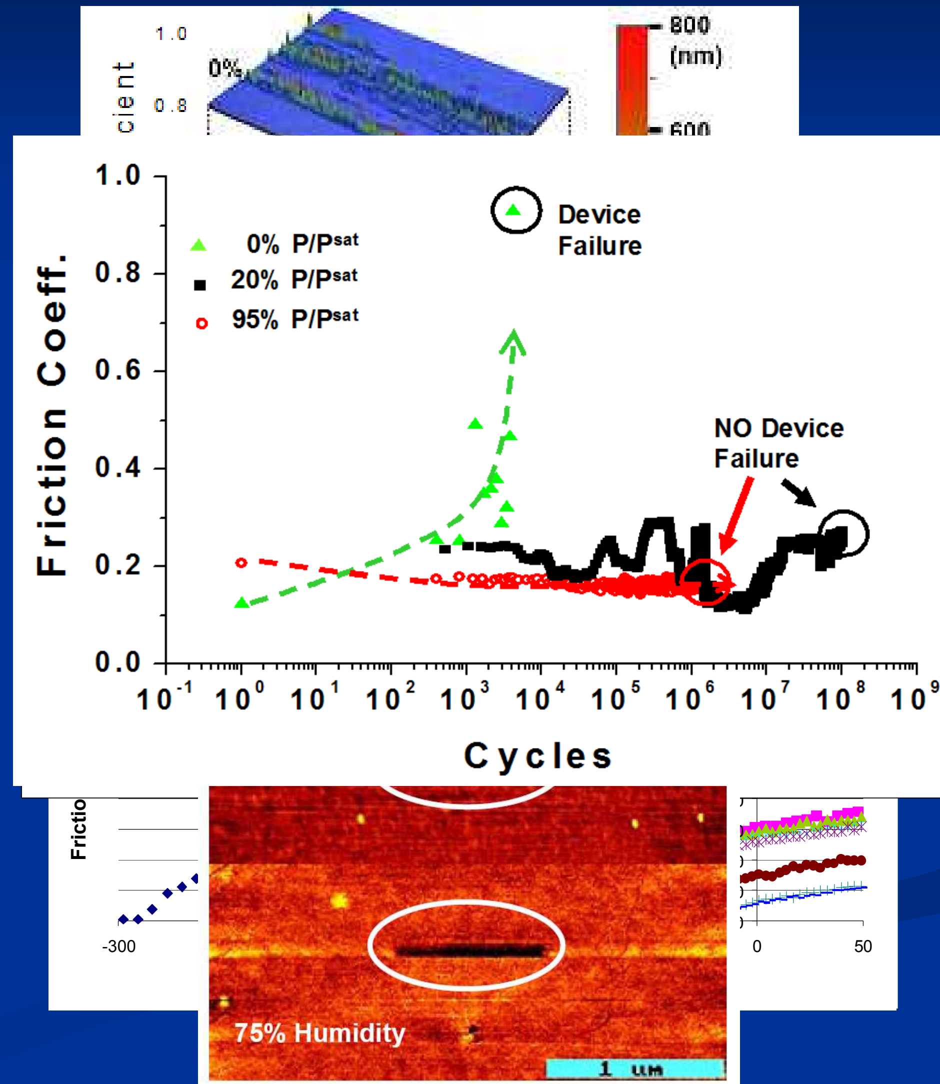


Asay, Dugger, Ohlhausen, Kim, *Langmuir* (in press)

Conclusions

In-situ Vapor phase lubrication

- Alcohol adsorption provides a self-replenishing molecular thick lubricant layer
- Alcohol adsorption reduces Friction at all length scales
- Wear within the contact is dramatically reduced at all length scales
- MEMS failure is prevented



Acknowledgements

Funding

National Science Foundation

(Grant No. CMS-0408369 & CMS-0625493)

Sandia National Laboratory

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000