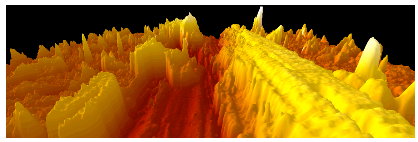
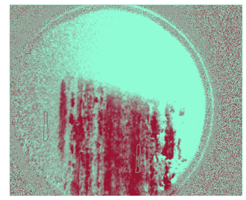
Friction at the Nanometer Scale: Recent Experimental Advances





Prof. Robert W. Carpick
Dept. of Engineering Physics, University of Wisconsin-Madison
carpick@engr.wisc.edu
http://mandm.engr.wisc.edu
KITP Room 2108

Acknowledgements

Nanomechanics Group:
A. V. Sumant, Erin E. Flater, David Grierson, Andrew Konicek, Gelsomina "pupa" De Stasio
U. Wisconsin-Madison

Silicon MEMS:
Maarten P. de Boer, Alex D. Corwin, E. David Reedy, Tom Mayer, M. Dugger, T. Scharf
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Auburn University

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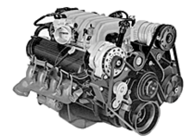
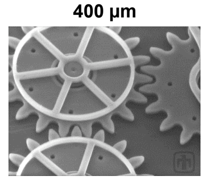
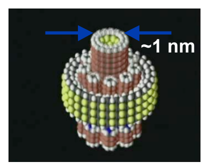
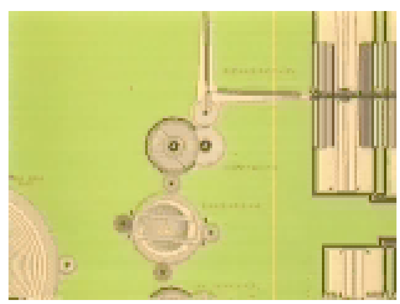
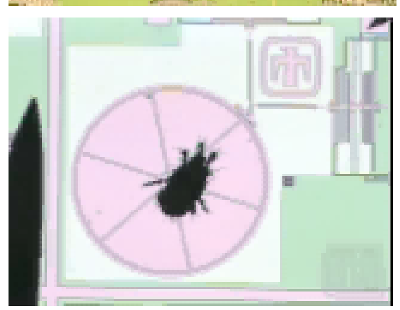
Surface forces (adhesion, friction) are increasingly important at small scales

$\frac{\text{surface}}{\textbf{VOLUME}}$	macro	
$\frac{\textbf{surface}}{\textbf{volume}}$	micro	 (c) Sandia National Laboratories
$\frac{\textbf{SURFACE}}{\text{volume}}$	nano	 Nanomachine image (c) Foresight Institute

Micro-electro-mechanical systems (MEMS)

Examples:
- air bag accelerometers
- digital micromirror device (DMD)
- resonators & switches

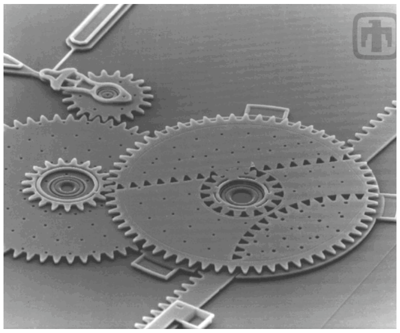


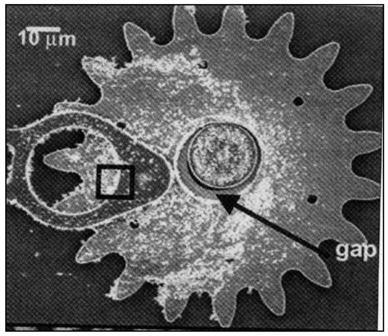


Images (c) Sandia National Laboratories

Small is beautiful….. but complex as well

Images (c) Sandia National Laboratories



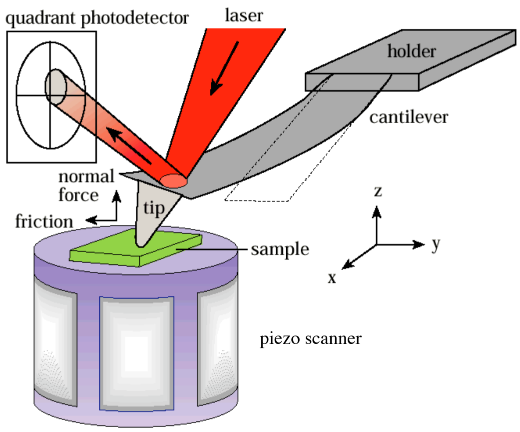


Problems with Silicon:

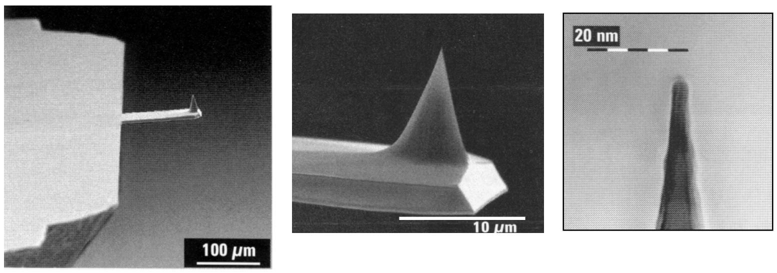
- •Hydrophilic, reactive surfaces (adhesion)
  - •Part stuck together after processing, during operation
  - •High friction
- •Low fracture toughness
  - •Fracture, wear

Strategies: ***(1) Tailor Si surface to reduce friction/adhesion/wear***
(2) Replace silicon with diamond

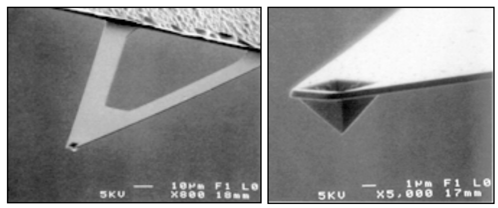
The atomic force microscope senses force in nano-contacts at the nanoNewton level



The AFM probe is a microfabricated cantilever (~100 µm) and tip (<50 nm radius)



Images from NT-MDT, Inc.

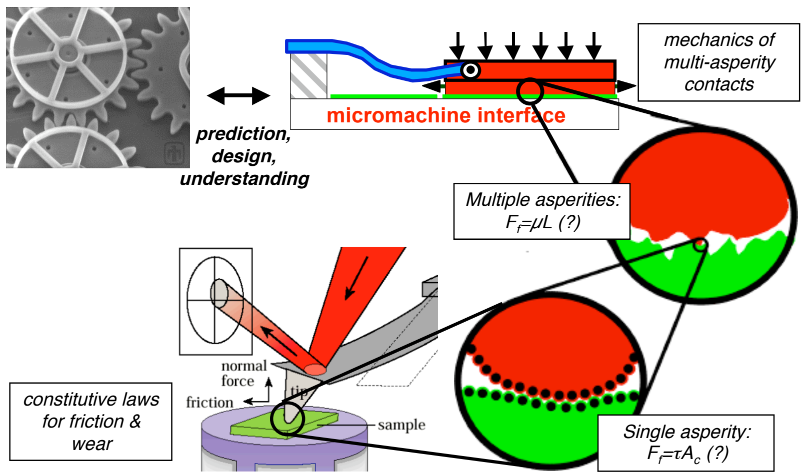


Images by J. VanLangendon, UW-Madison.

Quantitative AFM experiments are carried out

- Si tips: uncoated, *or* with a monolayer coating prepared identically with the samples at the same time
- Normal forces calibrated using the "resonance-damping method"
  - *Sader (RSI, 1999)*
- Lateral forces calibrated using the "wedge" technique
  - *Ogletree, Carpick, Salmeron (RSI, 1996), Varenberg (RSI, 2003)*
- Tip shape checked before and after using "inverse imaging" and TEM
  - *Villarrubia (JVST, 1996), P.M. Williams (JVST, 1999)*
- Experiments repeated (back and forth between the two samples)
- Friction measured as a function of load, fit to continuum adhesive contact model with variable range of adhesion
  - *Carpick, Ogletree, Salmeron (J. Coll. Int. Sci., 1998)*
- ***Note: MatLab scripts for appying our calibration methods to DI AFM measurements are available on our website***

We seek to understand MEMS friction through multi-scale experiments and modeling



Strategy (1): Tailoring the surface of silicon

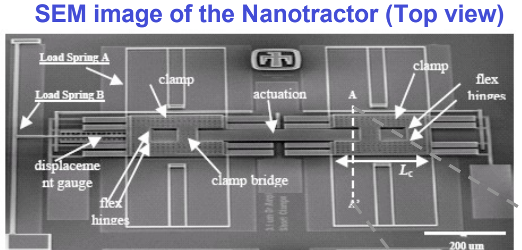
- How do tailored silicon surfaces behave in MEMS devices?
- How do tailored silicon surfaces behave at the nano-scale?

Strategy (1): Tailoring the surface of silicon

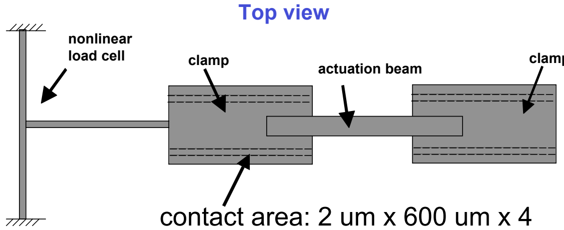
- **How do tailored silicon surfaces behave in MEMS devices?**
- **How do tailored silicon surfaces behave at the nano-scale?**

Sandia's nanotractor is designed to study friction and wear mechanisms at nanoscale

SEM image of the Nanotractor (Top view)



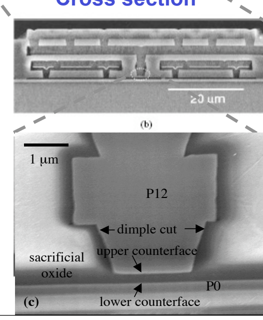
Top view



contact area: 2 um x 600 um x 4 = 2400 um^2

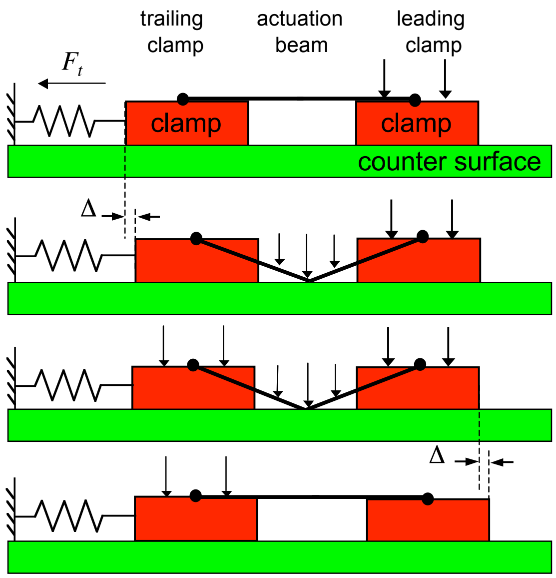
top view

Cross section



de Boer M. P. *et al.*, J. MEMS 13 (1) 2004

The "nanotractor" has been designed to quantify surface forces in MEMS



Schematic of the nanotractor (SIDE VIEW)

M.P.de Boer, D.L.Luck, W.R.Ashurst, R.Maboudian
J.MEMS **13**(1) 2004

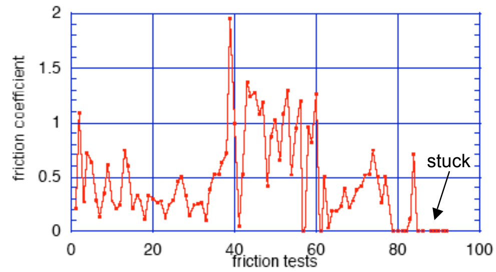
E.E.Flater, A.D.Corwin, M.P.de Boer, R.W.Carpick
Wear 2005 **in press**

The Nanotractor in action...

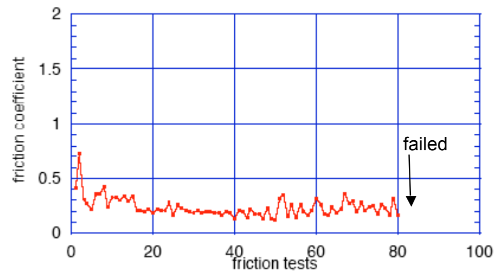
Movie courtesy of Sandia National Laboratories

Self-assembled monolayers improve the performance and lifetime of the device

uncoated



coated

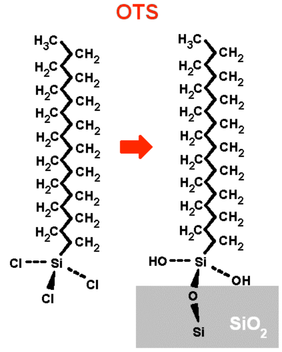


E.E.Flater, A.D.Corwin, M.P.de Boer, R.W.Carpick *Wear*, in press (2005)

We study two monolayers which are successfully integrated into the MEMS process flow

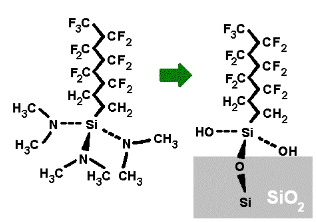
Hyrdogenated **Fluorinated**

OTS



Part of a joint friction experiment collaboration

FOTAS



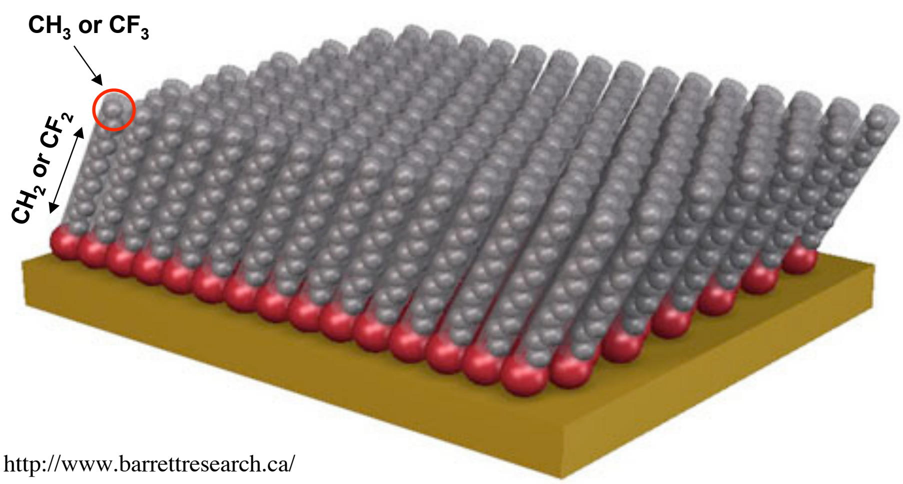
OTS=OctadecylTrichloroSilane

FOTAS=(tridecaFluoro-1,1,2,2-tetrahydroOctyl)Tris(dimethylAmino)Silane

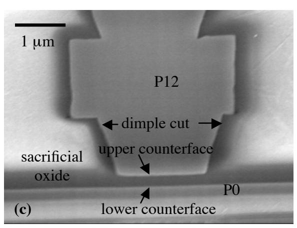
OTS prepared by W. Robert Ashurst
(UC Berkeley, now at Auburn University)
using solvent deposition

FOTAS prepared by Tom Mayer
(Sandia National Labs)
using vapor deposition

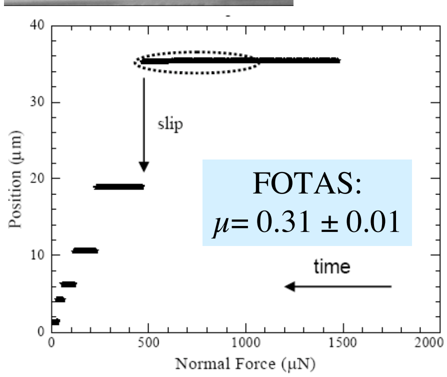
We study two monolayers which are successfully integrated into the MEMS process flow

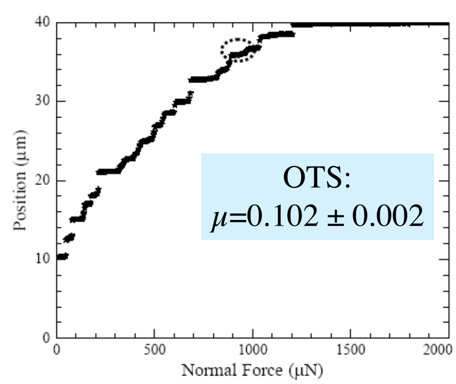


http://www.barrettresearch.ca/



Nanotractor friction measurements reveal contrast between OTS and FOTAS





Proceedings of the 2004 ASME/STLE International Joint Tribology Conference
A.D. Corwin, M.D. Street, R.W. Carpick, W.R. Ashurst, M.P. de Boer

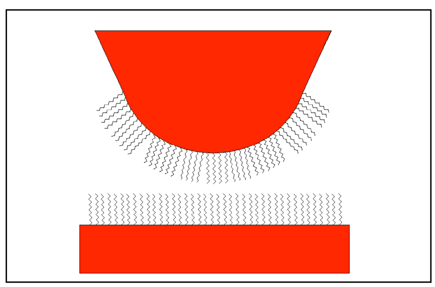
Strategy (1):
Tailoring the surface of silicon

- How do tailored silicon surfaces behave in MEMS devices?
- **How do tailored silicon surfaces behave at the nano-scale?**

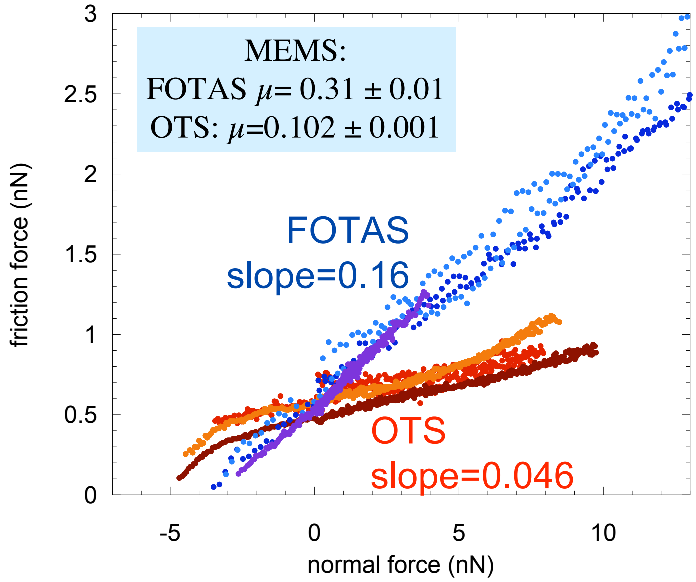
Coated AFM tips and substrates

- tips, flats, and MEMS devices coated at the same time with the same SAMs
  - R. Ashurst* & R. Maboudian, UC Berkeley
  - direct comparisons with nanotractor measurements

  *now at Auburn U.



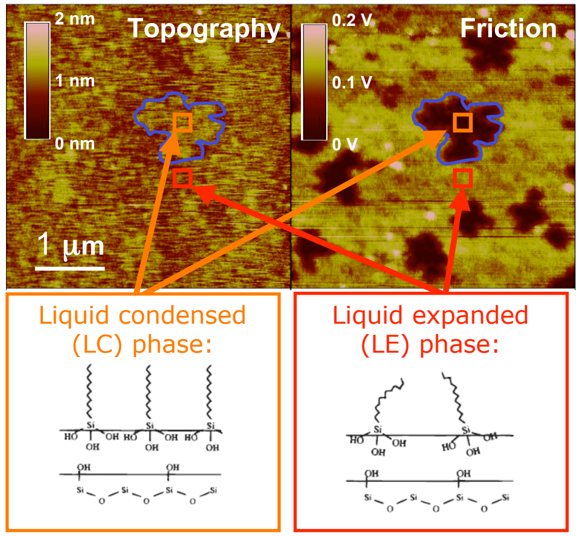
OTS/OTS vs FOTAS/FOTAS



Connection between nano- and micro-scale friction?

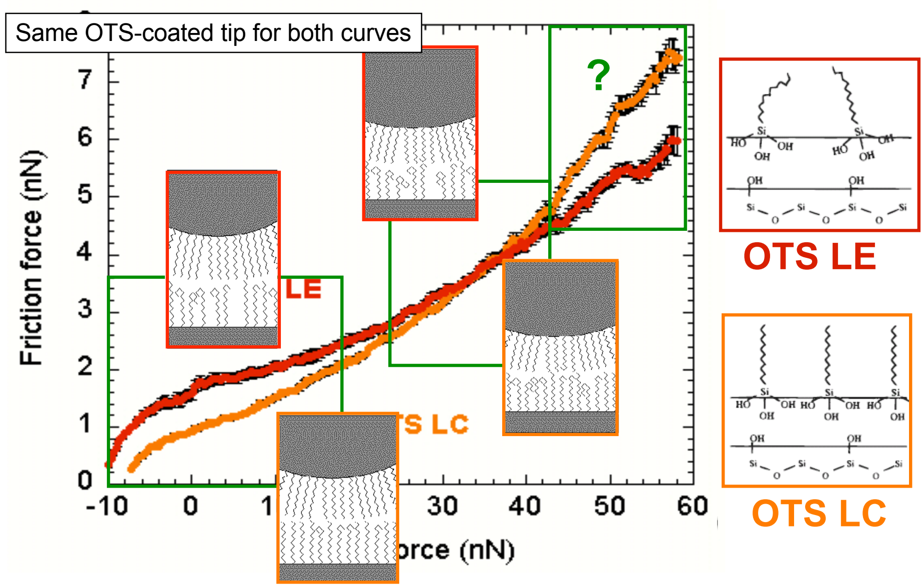
- It is not necessarily the case that the ratio of friction coefficients for rough surfaces should be equal to the ratio of friction slopes in single-asperity contacts
- Our case:
  - From MEMS, the ratio for FOTAS:OTS is ~3.0
  - From AFM, the ratio for FOTAS:OTS is ~3.5

Unique two-phase surface allows for direct analysis of the role of packing density

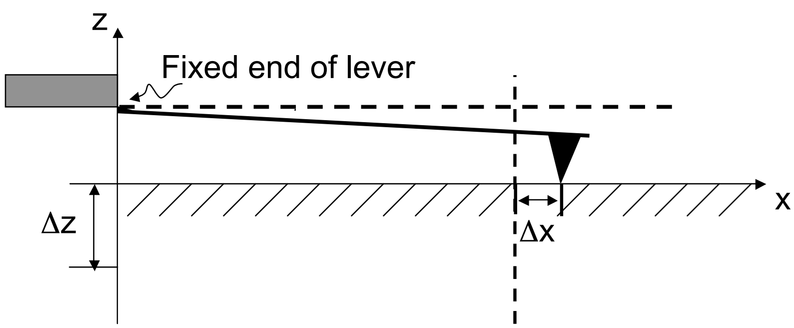


From: Carraro *et al. J. Phys. Chem. B* (1998)

Differences in friction between the OTS phases correlate well with their packing structures

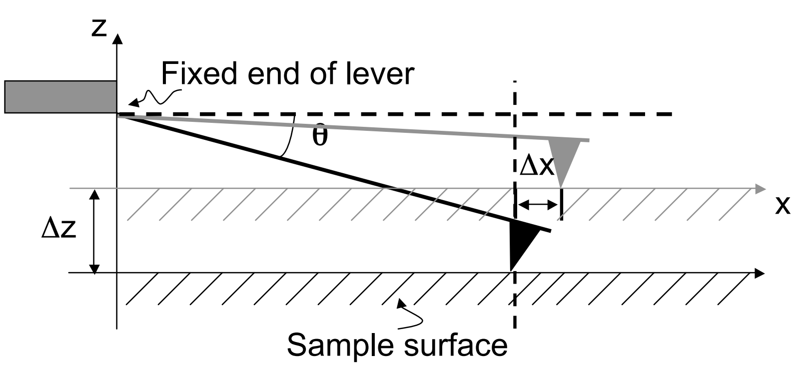


The free end of the lever displaces as the applied load varies



Cannara & Carpick *RSI*, 76(5) 2005

The magnitude of the tilt effect is a simple geometric relation

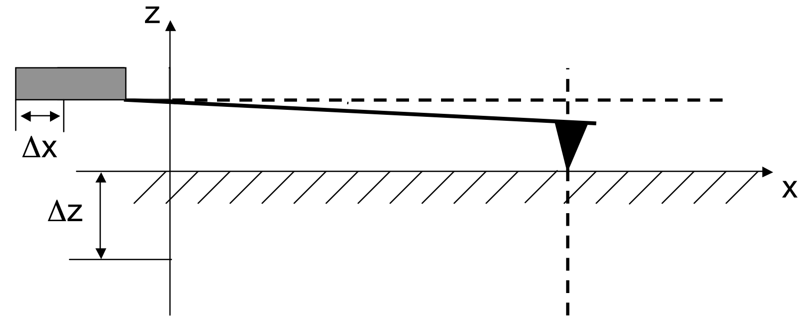


$$\Delta x = \sqrt{L^2 - (L\sin\theta - \Delta z)^2} - L\cos\theta$$

To first order, $\Delta x = \Delta z \tan\theta$

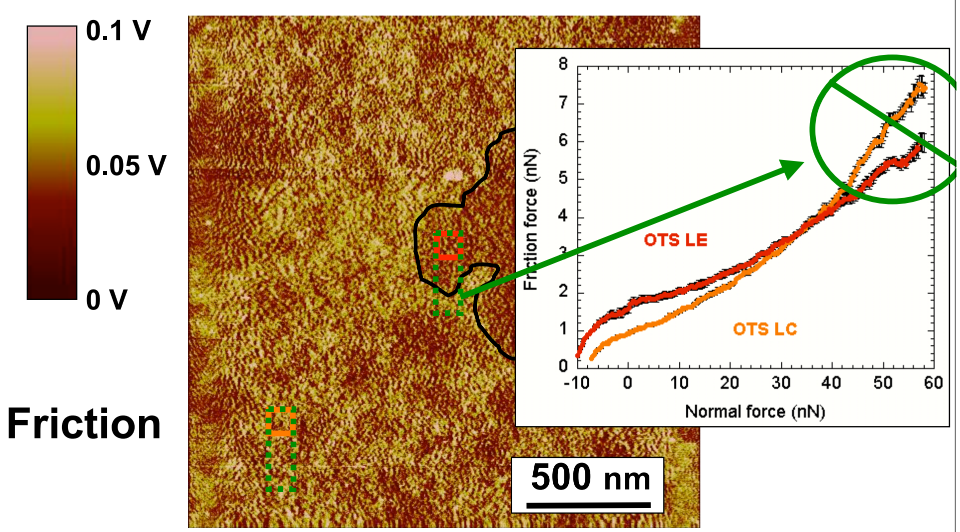
Cannara & Carpick *RSI*, 76(5) 2005

Tilt-compensation allows one to stay within the intended region of analysis

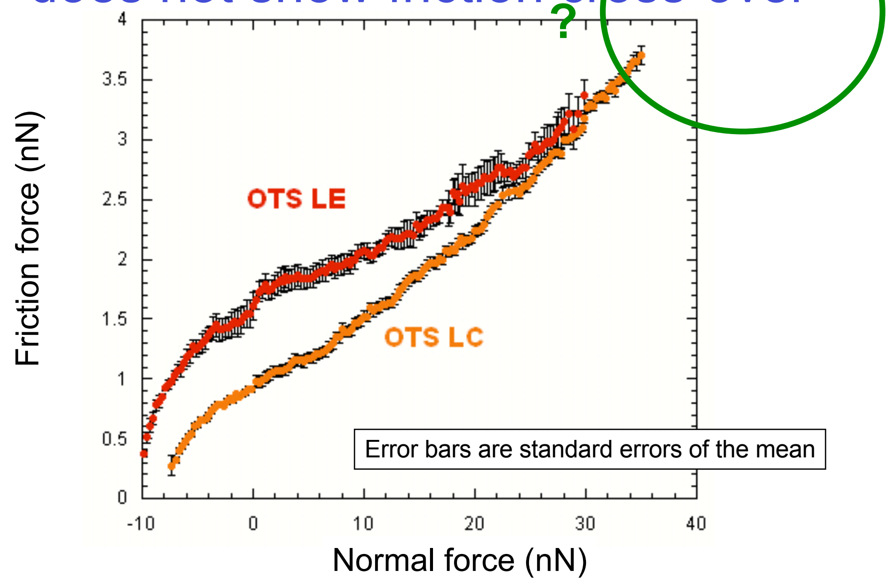


Cannara & Carpick *RSI,* 76(5) 2005

Friction measurements depend on location on sample



Re-analysis of friction measurements does not show friction cross-over



Is it a question of contact area?

- Junction model (Tabor)

$$F_f = \tau A$$

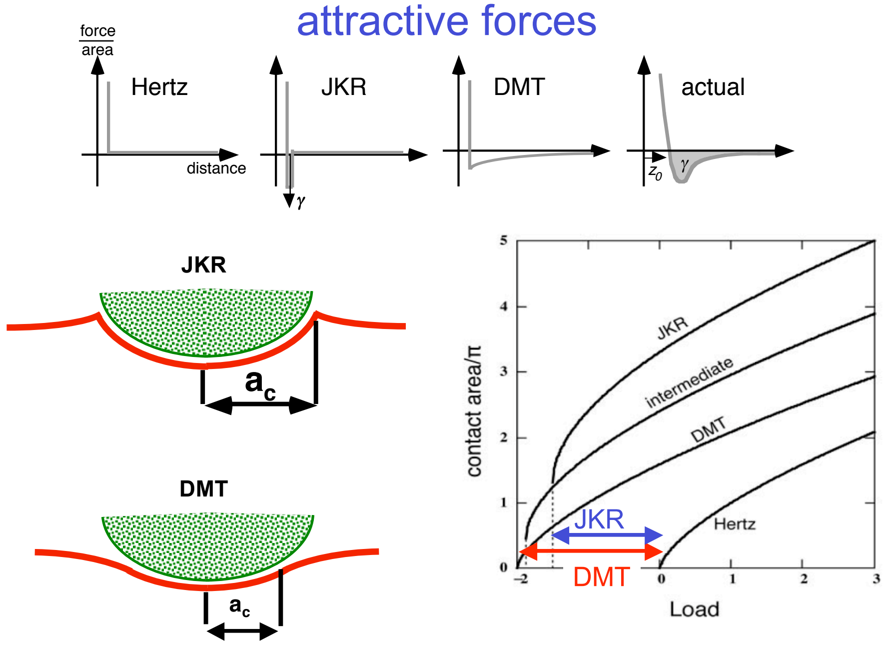
F_f = friction force

τ = interfacial shear strength (units of stress)

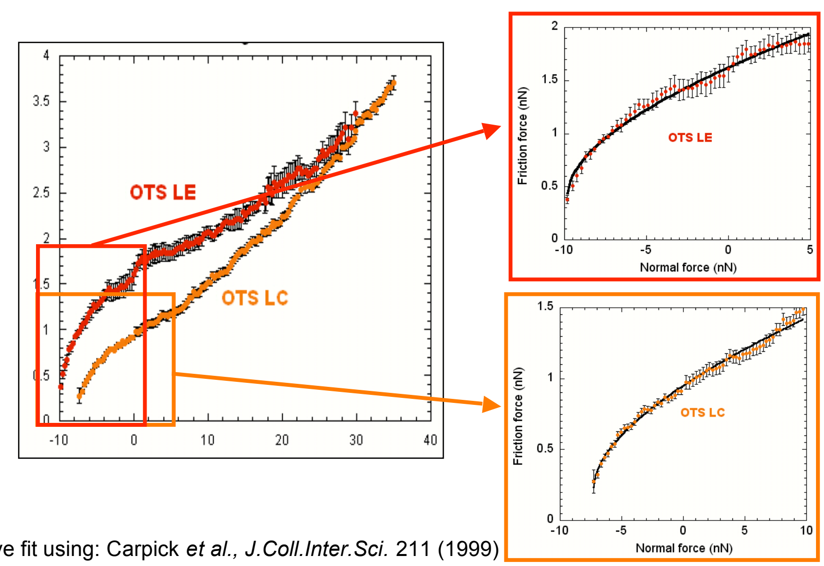
A = contact area at interface

- What is *A*?

Contact properties depend on the range of attractive forces



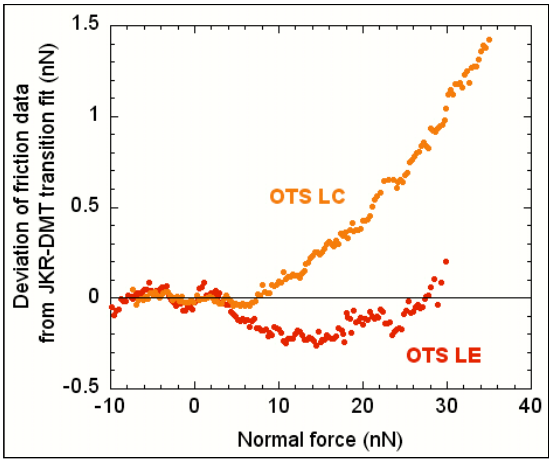
Continuum contact mechanics fits describe frictional behavior at low loads

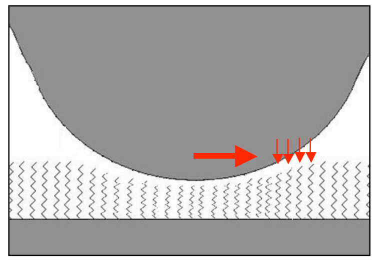


Curve fit using: Carpick *et al., J.Coll.Inter.Sci.* 211 (1999)

Deviations from continuum models at high loads indicate "plowing" behavior

Friction data after subtracting the curve fit





Connection between nano- and micro-scale friction?

Hypothesis only!

- *OTS Condensed phase:*

  Low loads: adhesive contact with a well-ordered monolayer with CH_3-CH_3 groups in contact

  Medium loads: pressure-dependent increase as plowing occurs (may include gauche defects formation)

  Higher loads: yet to be determined

- *OTS Expanded phase:*

  Low loads: adhesive contact with a defective monolayer with many CH_2-CH_2 groups in contact - more adhesion & more contact area than for the condensed phase

  Medium loads: simply an increase in contact area, perhaps with stiffening of the layer, but not plowing

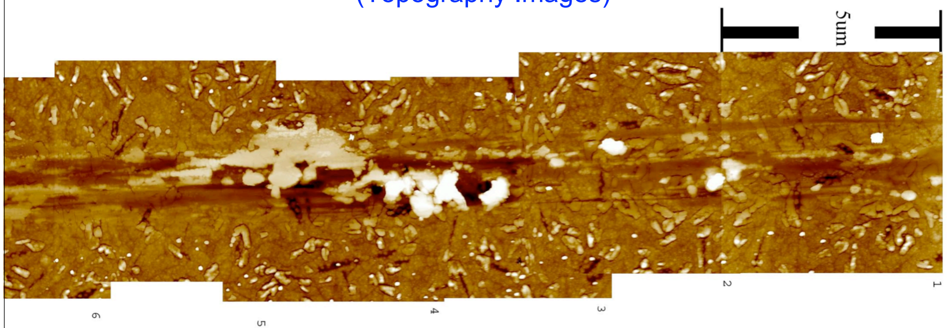
  Higher loads: yet to be determined.

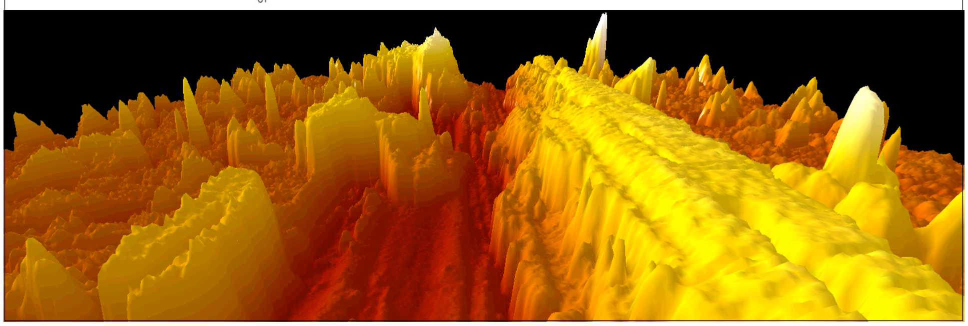
- *FOTAS:*

  Fluorinated films are stiffer - more work required to plow compared to OTS

AFM Investigation of the wear track

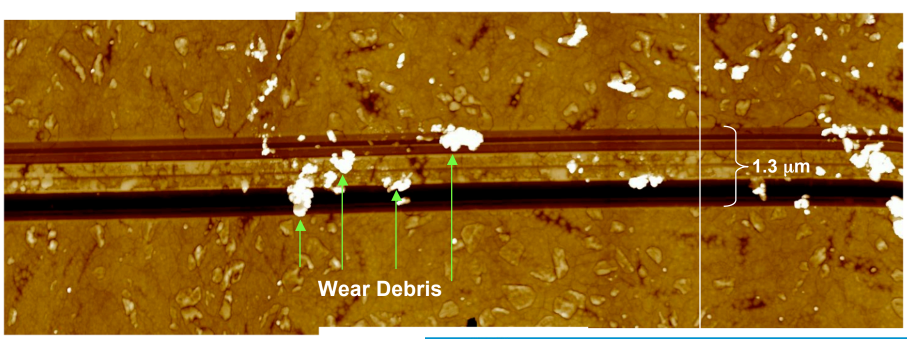
(Topography Images)





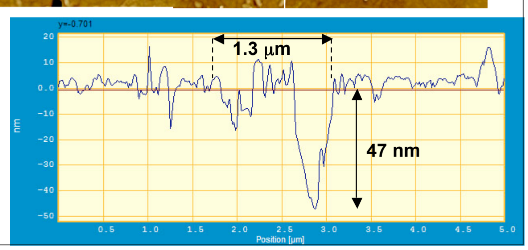
Typical Signs of Wear: Gouging, Polishing, Debris Accumulation

Composite AFM image of the wear track



Ave. RMS roughness on unworn regions: 4.5 nm

Ave. RMS roughness in the wear track: 2.1 nm



Conclusions

- SAM coatings substantially modify friction in MEMS, as determined by their molecular architecture
  - AFM single asperity measurements can be used to understand larger-scale friction behavior in MEMS
  - Tribochemical changes occur during wear processes in MEMS, and we need to study these further

- UNCD is a promising structural material for MEMS
  - Lower friction and adhesion than silicon at the nano-scale
  - Post growth H-plasma improves the surface chemistry and nanotribology of the bottom side. Adhesion approaches the van der waals limit; friction is correspondingly low.

    ⇒ *Is this the ideal tribological surface?*

- Tribology + imaging + spectroscopy = understanding friction?

Thank you