KITP Workshop on Friction, Fracture and Earthquake Physics
Santa Barbara, CA

Friction and Adhesion in MEMS

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- U. Wisconsin
  - Rob Carpick

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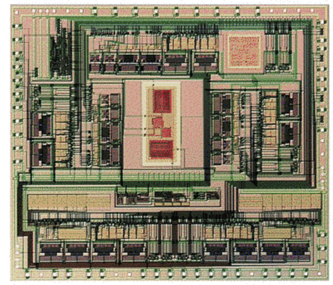
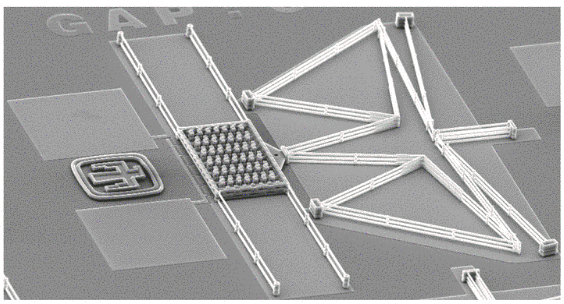
With polysilicon MEMS we can reliably accomplish electromechanical and optical functions

-thousands of devices simultaneously
-no assembly required
-hundreds of device concepts explored

Integrated inertial sensor

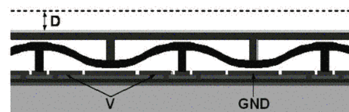


High performance comb drive with mechanical amplifier



Polychromator :

programmable diffraction grating



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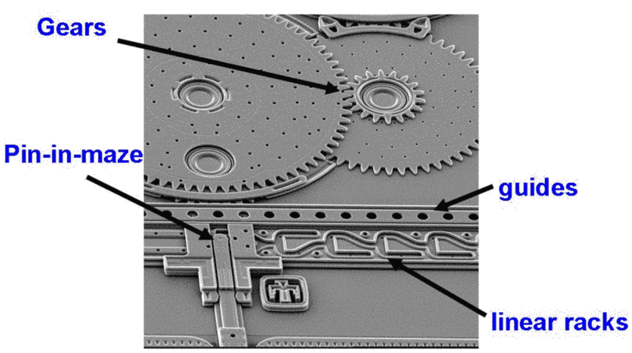
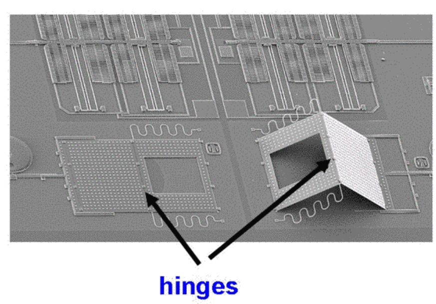
Allowing contact between MEMS surfaces significantly broadens the design space

Complex Mechanical Logic



Pop-up Mirrors



but …
static friction can dominate the forces required
dynamic friction can dominate energy loss
adhesion, friction and wear become the most important failure mechanisms of contacting MEMS

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MEMS – surface micromachining implementation

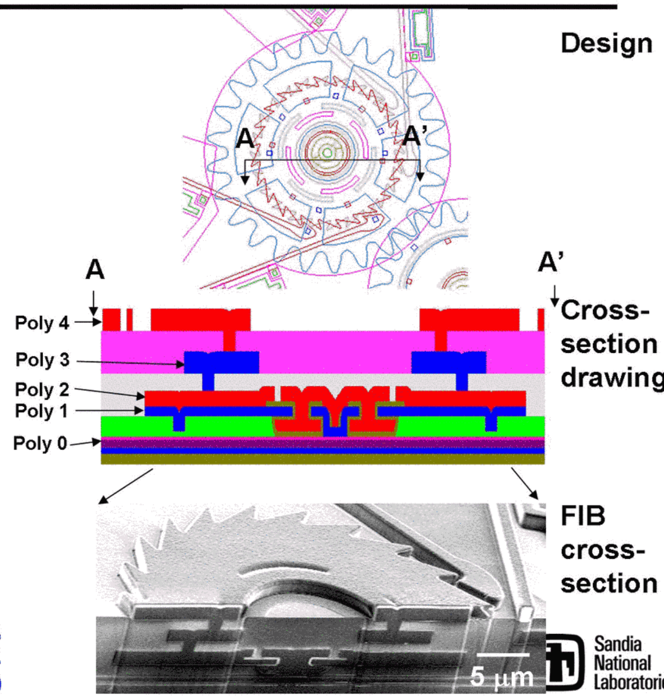
A series of structural and sacrificial layers are deposited

Ground plane layer (Poly 0)
4 structural levels
(Poly 1 - Poly 4)

Chemical Mechanical Planarization (CMP)

1 μm design rule

Create freestanding thin film structures by "release" process

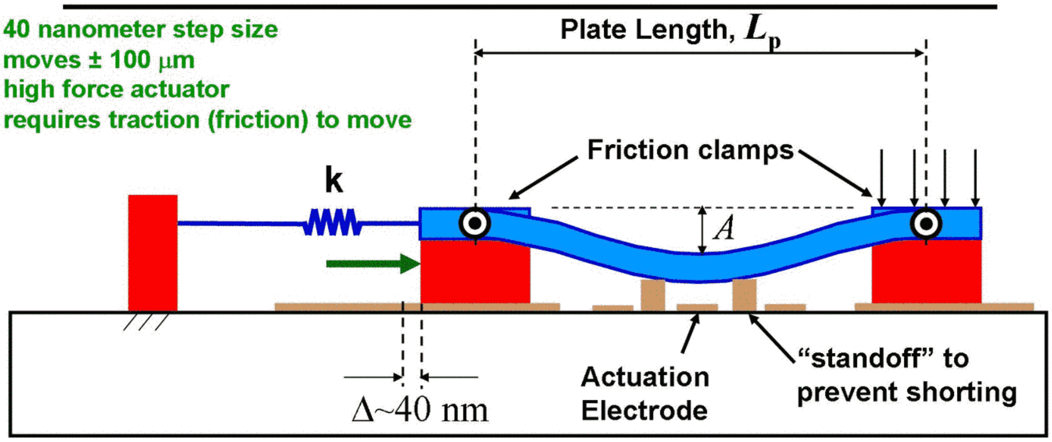


Sniegowski & de Boer, Annu. Rev. Mater. Sci. (2000)

slide 5

Taking advantage of friction, we developed a high-performance actuator

- 40 nanometer step size
- moves ± 100 μm
- high force actuator
- requires traction (friction) to move



$$F_{max} \sim 2Ewt\left(\frac{A}{L_p}\right)^2 \approx 1\,\text{mN}$$

large tangential force range

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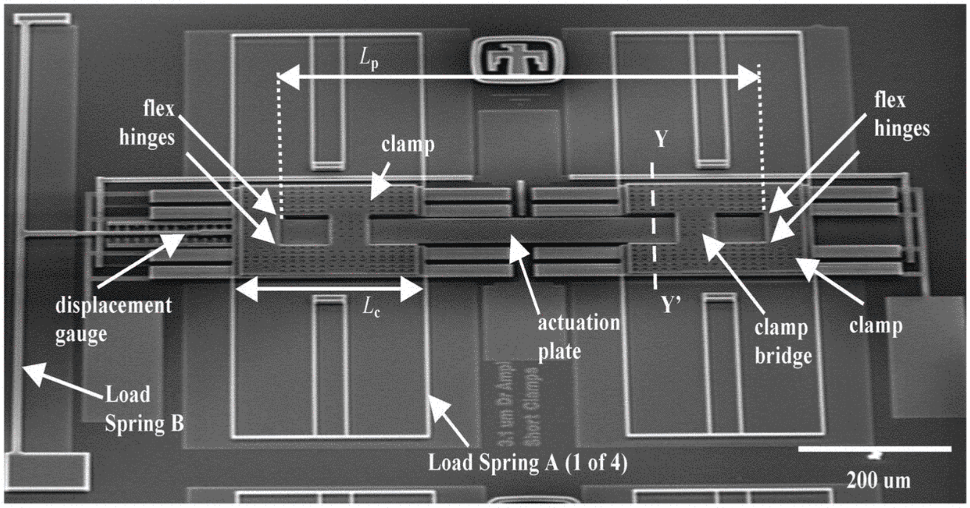
Nanotractor - SEM



M. P. de Boer, D. L. Luck, W. R. Ashurst et al.
"High Performance Surface-Micromachined Inchworm Actuator"
J. MicroElectroMechanical Systems, Feb. 2004

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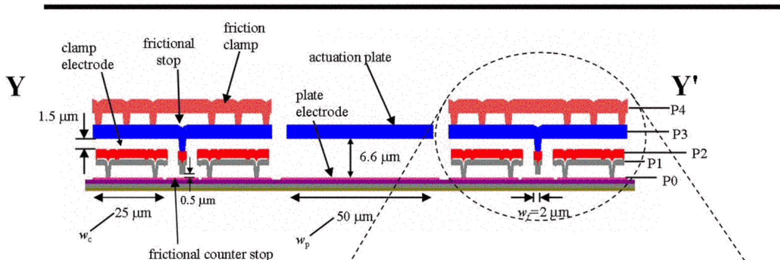
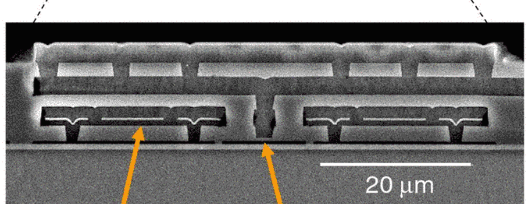
Nanotractor – clamp cross section



SEM cross-section (before release)



Normal force is applied electrostatically and borne mechanically

We can apply normal force from 1 µN to 10 mN with this arrangement

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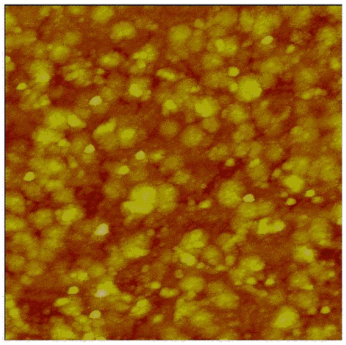
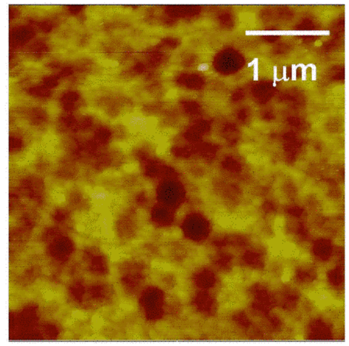
Surface contact is an aggregate of asperities



bottom counterface
(top of P0, 8 nm rms)



top counterface
(bottom of P12, 5 nm rms)

Rough surface contact mechanics considerations ...

asperity radius of curvature R ~ 20 to 500 nm (typically ~50 nm)
rms roughness 1.5 to 10 nm
contact diameter ~10 nm, pressure ~10 GPa
real contact area << 10^{-3}•(apparent contact area)

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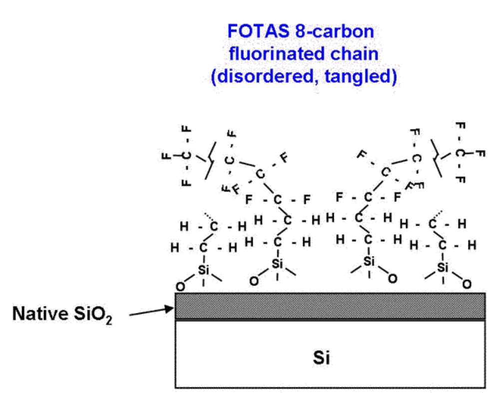
MEMS monolayer coupling agent

FOTAS (tridecafluoro-1,1,2,2-tetrahydrodecyltris(dimethylamino)silane)
- vapor deposition
- 8 carbon chain
- van der Waals forces not strong enough to self assemble (tangled)
- contact angle ~ 110°



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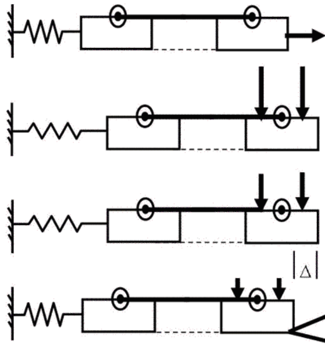
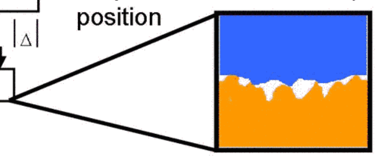
Static friction measurement



Walk out nanotractor against load spring

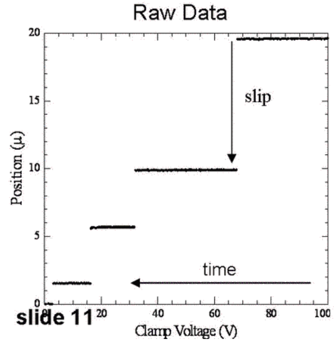
Apply large normal force (voltage)

Step down normal force (voltage) and record position



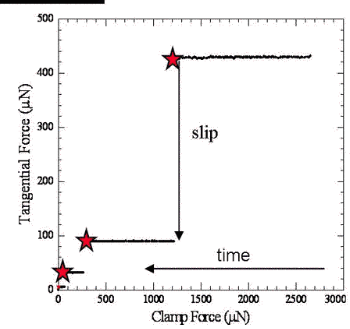
Contacting Asperities

Raw Data



Convert clamp voltage to clamp force and position to tangential force

Force Data



Identify equilibrium points right before jumps where

$F_{Tan} = \mu_s F_N$

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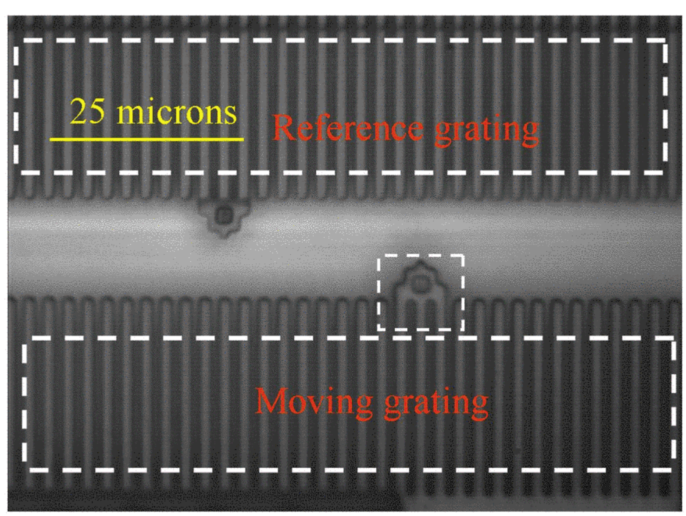
Highly resolved slip measurements: we measure position to 1 nm

Use periodic grating and measure relative phase to 1 part in 2500



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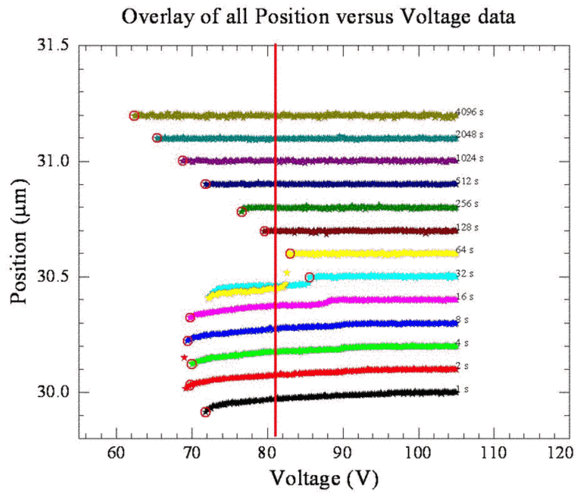
As hold time increases, static friction increases. For short hold times we get small-scale sliding.



Jumps that occur above this critical voltage Vc (lower apparent friction) end up with sliding, while those released with voltage below it (higher apparent static friction) end up jumping

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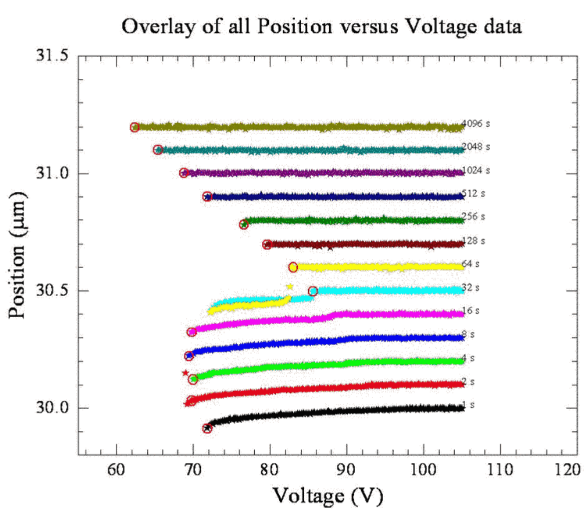
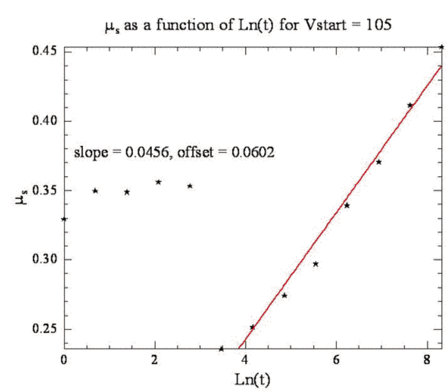
At longer hold times, we obtain a typical u_s time-dependence





From the plot on the left, we should only consider times of 32 seconds or longer as having well defined jumps

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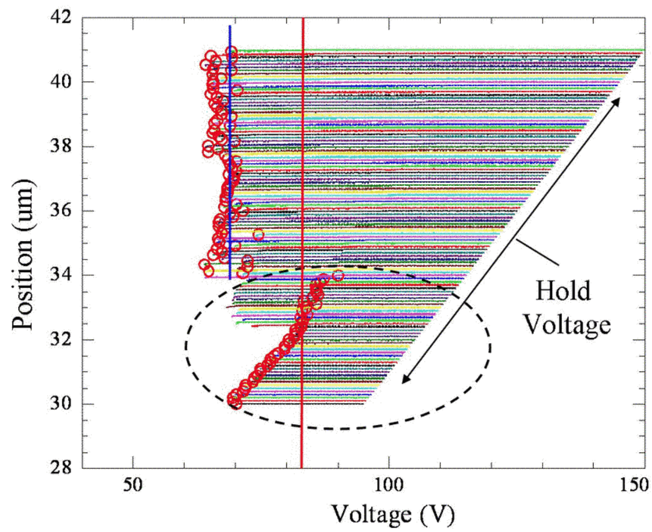
When we hold the clamp with a larger normal force, we experience a correspondingly lower friction force



(64 sec hold)

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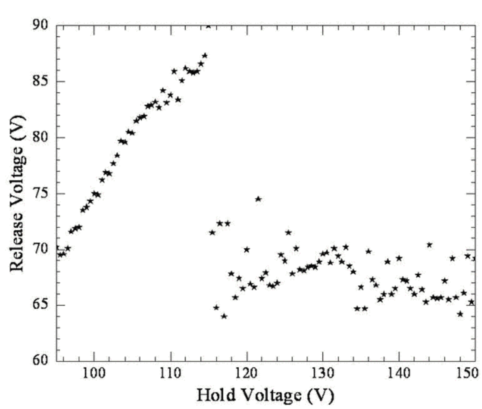
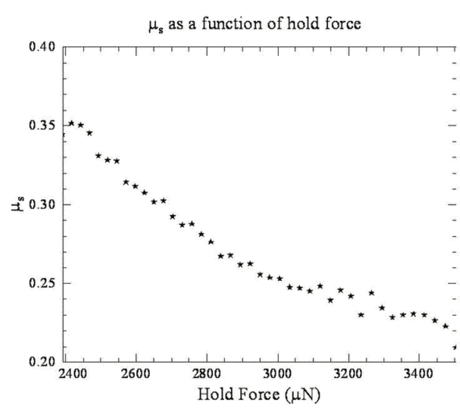
u_s decreases with hold force





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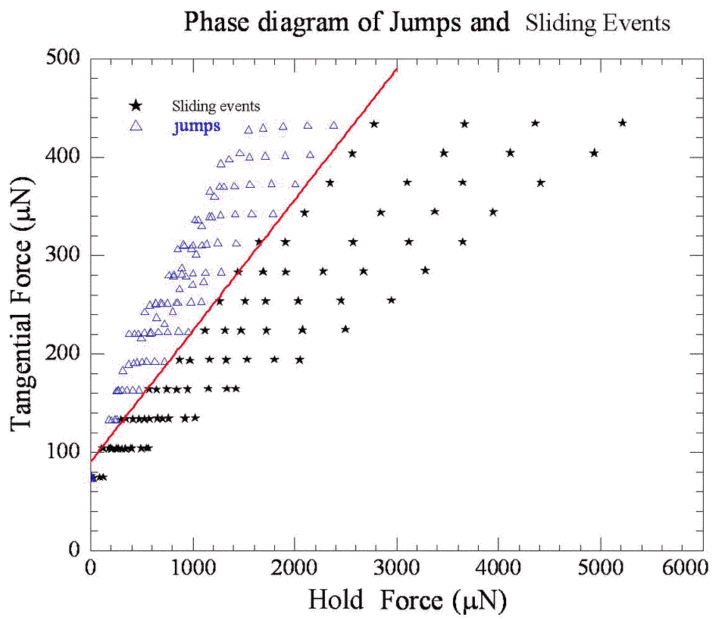
We observe a bifurcation in the jumps versus sliding events



(256 second hold)

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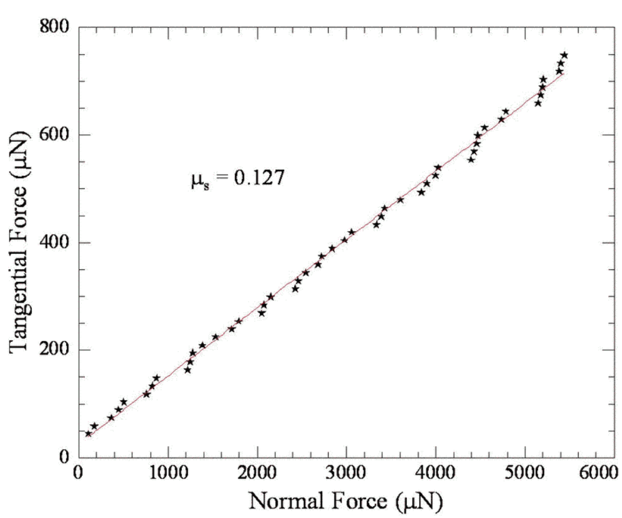
If we approach the static friction limit from "below", we get a low u_s (corresponding to short time)



No hold after walking out

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Summary of friction data

The nanotractor can be used to study friction of surface-micromachined interfaces

<u>With FOTAS coating:</u>

$u_s(t) = \alpha + \beta \ln(t)$

u_s decreases with increasing hold voltage (counter-intuitive)

If motion begins above (below) a certain critical voltage, sliding (a jump) is observed.

Phase space can be mapped out – this behavior occurs independent of tangential load

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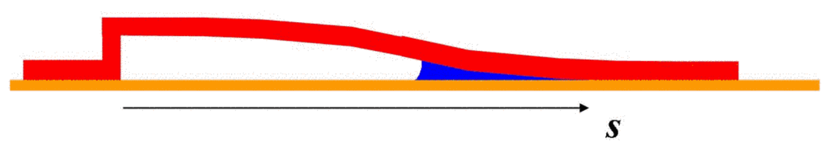
Adhesion (e.g., "stiction") is a big problem in micromachining

Initially free beam, but still in water

Drying leads to "stiction"



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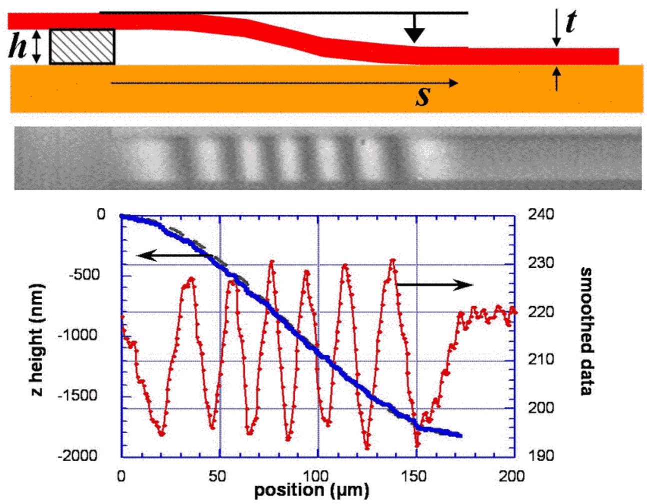
We can use cantilevers to quantify the adhesion, Γ



Capillary adhesion can be avoided by critical point drying or by applying monolayer coatings

$$G = -\frac{dU_E}{wds} = \frac{3}{2} E \frac{h^2 t^3}{s^4} = \Gamma = 10\ \frac{\text{mJ}}{\text{m}^2}$$ (drying from water)

(de Boer and Michalske, Journal of Applied Physics, 1999)

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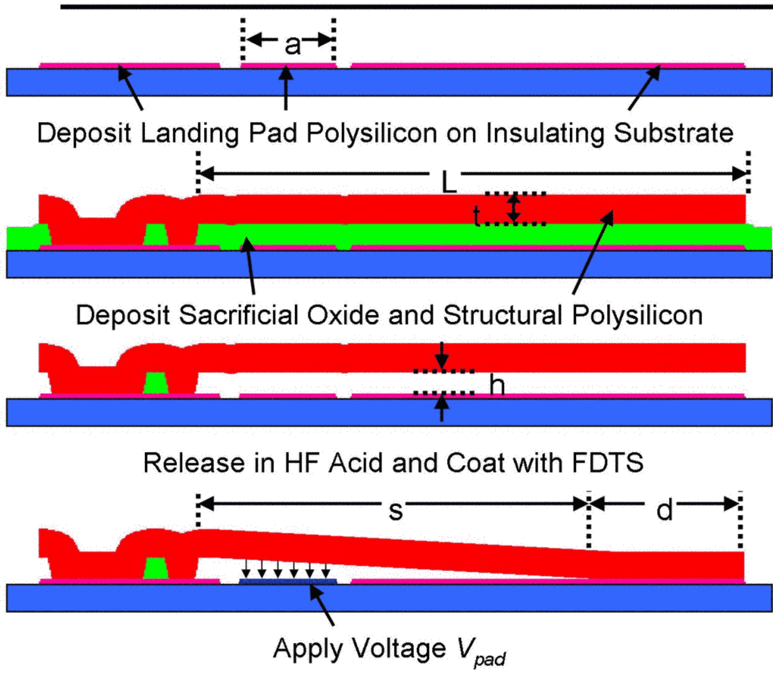
Microcantilever process and test flow



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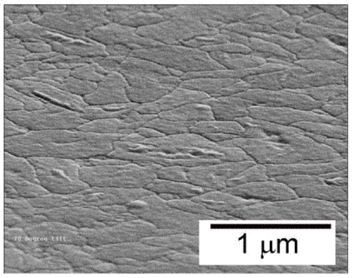
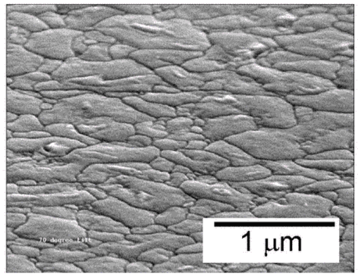
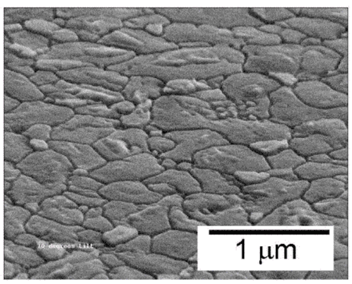
Oxidize the Poly 0 Surface to change surface roughness



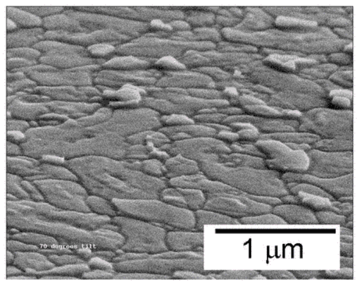
No oxidation, 2.6 nm rms



100 Å oxidation, 4.4 nm rms



300 Å oxidation, 5.6 nm rms



600 Å oxidation, 10.3 nm rms

Nanotexturing of the lower layer or polysilicon (P0) was accomplished via thermal oxidation in dry O_2 at 900° C for increasing times.

t (min)	tox (Å)	rms (nm)
0	--	2.6
20	100	4.4
136	300	5.6
400	600	10.3

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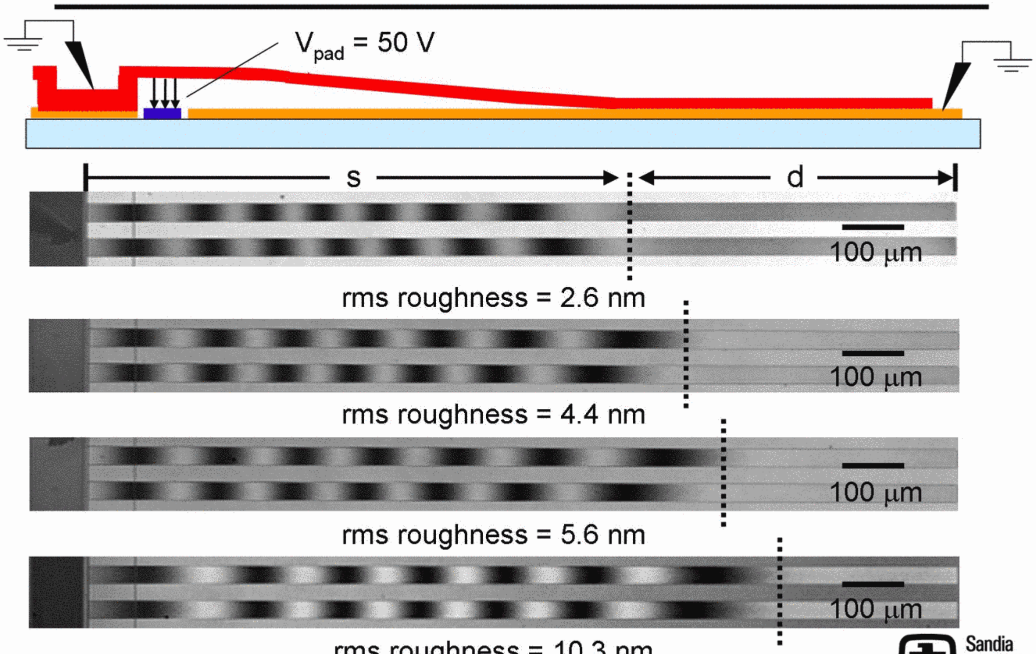
Interferograms show qualitative relationship between surface roughness and crack length



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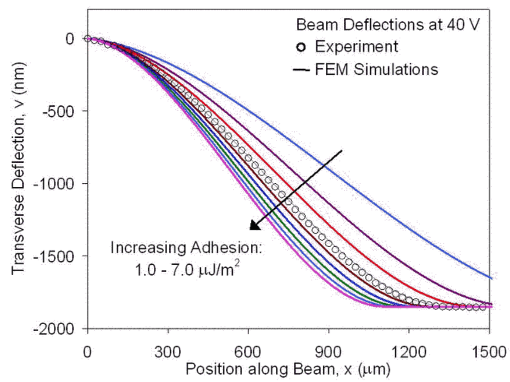
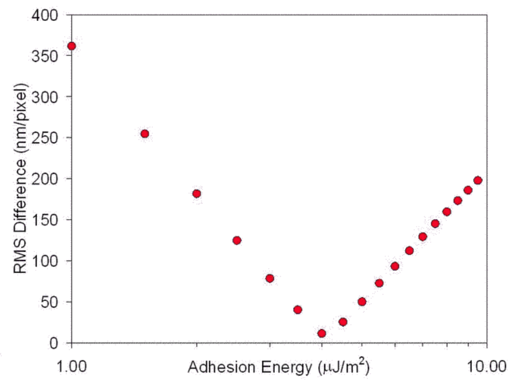
Adhesion measurement with applied voltage

Finite element analysis (ABAQUS) and user subroutines were used to find beam profiles with surface adhesion, electrostatic loading and initial stress gradient.

The only free parameter in the models is the adhesion Γ.

A least squares fit between the model and experiment was used to determine the value at each voltage.





(Knapp & de Boer, JMEMS, 2002)

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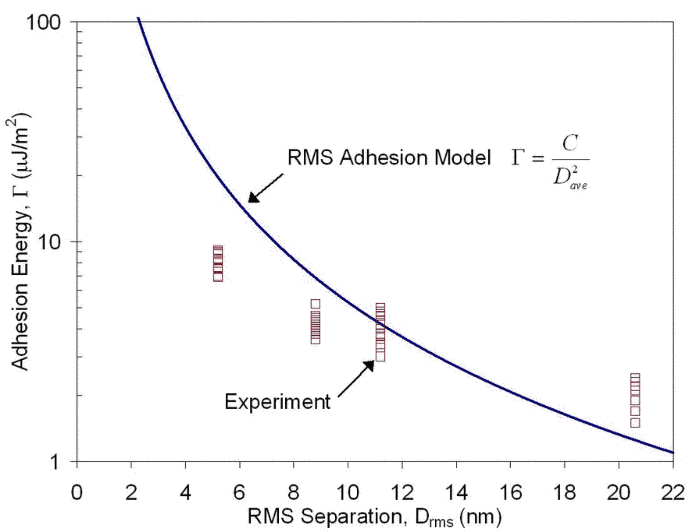
Experimental values of adhesion for each surface roughness

The measured values for adhesion loosely follow the approximation presented by Houston et al. (1996)

$$\Gamma = \frac{A}{12\pi D_{rms}^2}$$

These results raise the following questions:

1. What is the best way to characterize the separation between the two surfaces?
2. Do we have another method to determine if these results are *quantitatively* correct? → Atomic Force Microscopy Imaging with Force Displacement Numerical Analysis



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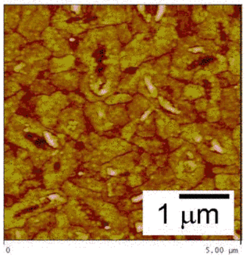
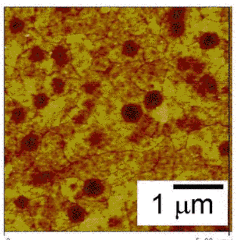
AFM topography data is analyzed using a numerical force-displacement routine

AFM Images

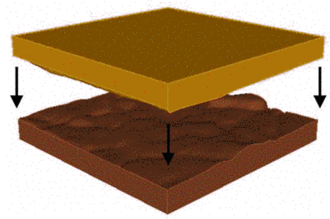




512 x 512 matrix with surface heights entered into force displacement routine

Numerical Force-Displacement Routine

1. Import AFM height data
2. Separate surfaces by initial displacement
3. Calculate separation for each pixel
4. Calculate force for each pixel
5. Find total force (sum)
6. Move surfaces towards each other
7. Repeat steps 3-6 to create attractive load-displacement curve



$$F_a = \frac{L_c^2}{N_{pixels}}\left[\sum_{all\ pixels}\frac{A g_f}{6\pi\left(d_{loc}+d_{co}\right)^3}\right]$$

Anandarajah and Chen 1995

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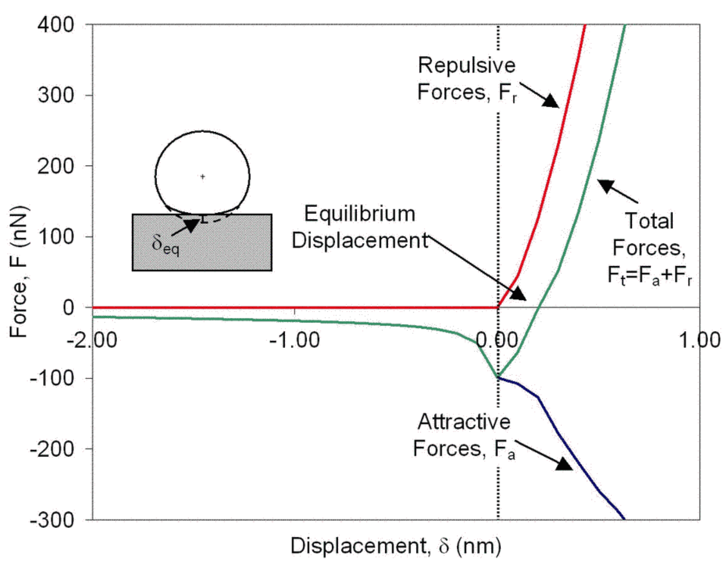
Calculate the total force-displacement curve using the AFM analysis and Hertzian mechanics

Attractive force-displacement curve based on AFM analysis

Repulsive force-displacement curve based on Hertzian mechanics

$$F_r = \frac{2}{3}\left(\frac{E}{1-\nu^2}\right)\sqrt{R\delta^3}$$

DMT Adhesion Model



Calculate adhesion energy by evaluating the area under the total force-displacement curve from the equilibrium displacement to infinity.

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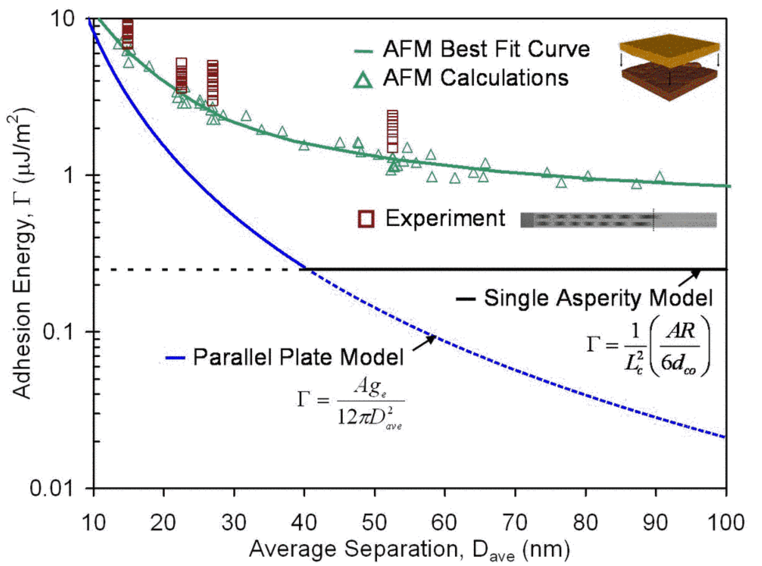
Predicted values of adhesion with AFM data

We placed the surfaces together in the following combinations for each roughness:

- **Poly 0 and Poly 0**
- **Poly 0 and Poly 2**

The average surface separation D_{ave} is calculated for each AFM pair according to

$$D_{ave} = \frac{1}{N_{pixels}} \left[\sum_{all\ pixels} d_{loc} \right]$$



Delrio, de Boer et al., Nat. Mat. (2005)

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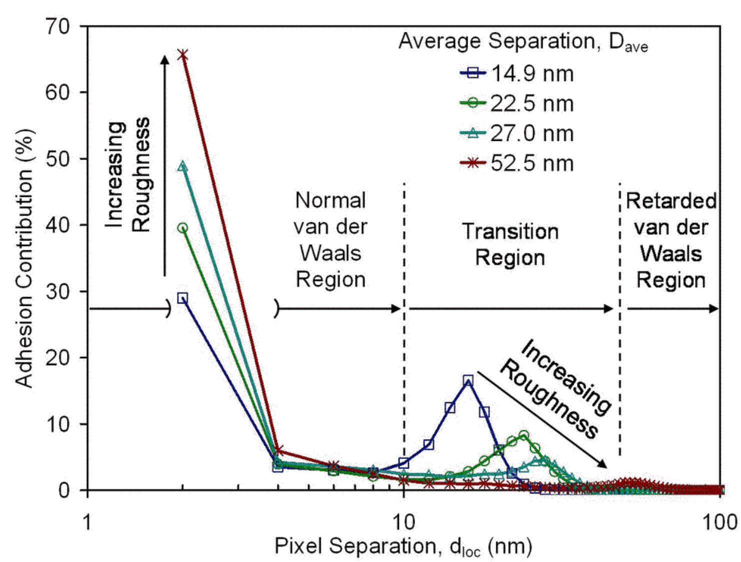
Histogram of adhesion contributions vs. pixel separation

Smoothest Surface

Adhesion contribution from both contacting asperities and non-contacting areas (combination of two extreme adhesion models).

Roughest Surface

Adhesion contribution mainly from contacting asperity (converging to Fuller-Tabor/Maugis model for single asperity).



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Summary - dry adhesion in MEMS

Microcantilevers are used to measure adhesion in MEMS

Adhesion is in the $\mu J/m^2$ range

For low surface roughness, adhesion dominated by retarded van der Waals forces

For higher surface roughnesses, adhesion dominated by normal van der Waals forces

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