New Frontiers in Casimir Force Control
Sept. 27-29, 2009, Santa Fe, New Mexico
http://cnls.lanl.gov/casimir/

Surface Forces in MEMS – Adhesion and Friction Experiments

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MEMS – surface micromachining implementation

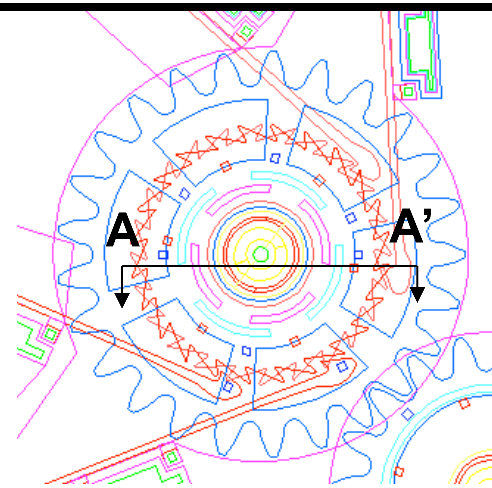
A series of structural and sacrificial layers are deposited

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

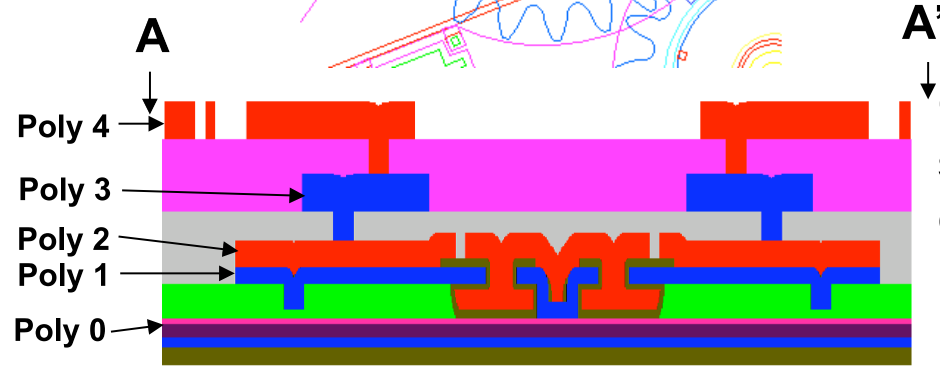
Chemical Mechanical Planarization (CMP)

1 μm design rule

Create freestanding thin film structures by “release” process



Design



Cross-section drawing

FIB cross-section

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

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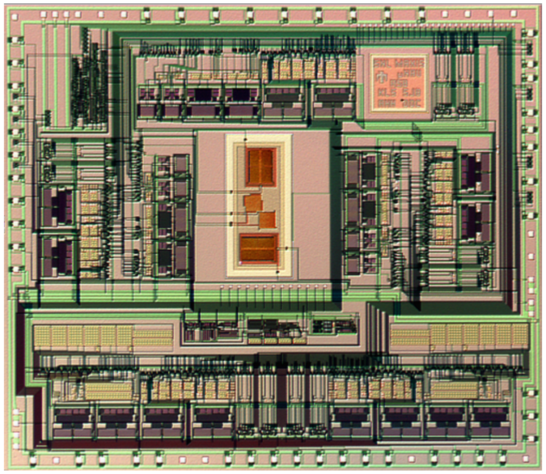
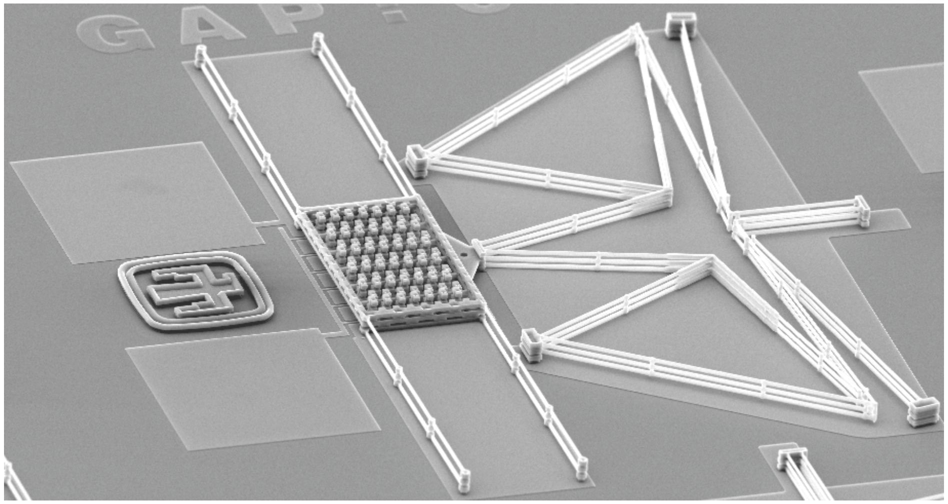
With polysilicon MEMS we can reliably accomplish electromechanical and optical functions

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

Integrated inertial sensor

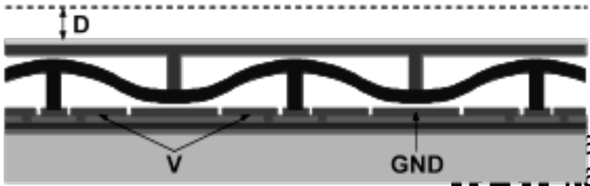


High performance comb drive with mechanical amplifier



Polychromator :

programmable diffraction grating



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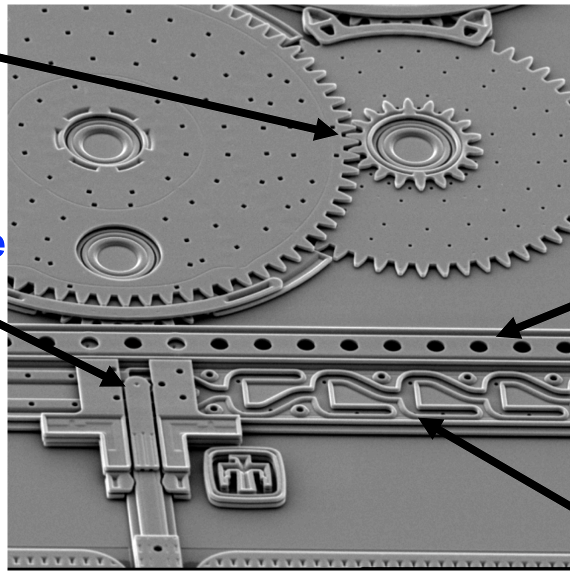
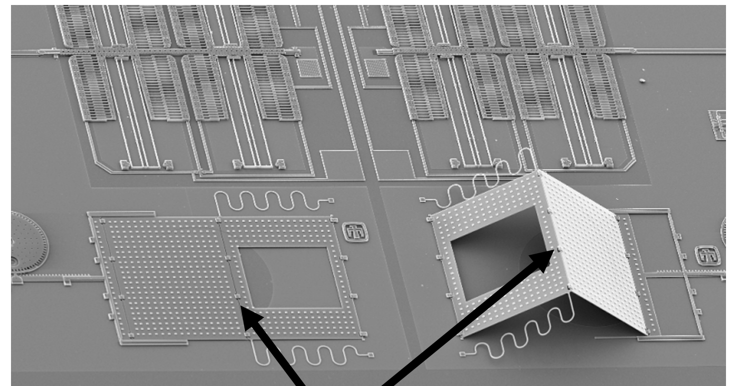
Allowing contact between MEMS surfaces significantly broadens the design space

Complex Mechanical Logic



Pop-up Mirrors



<u>but</u> …

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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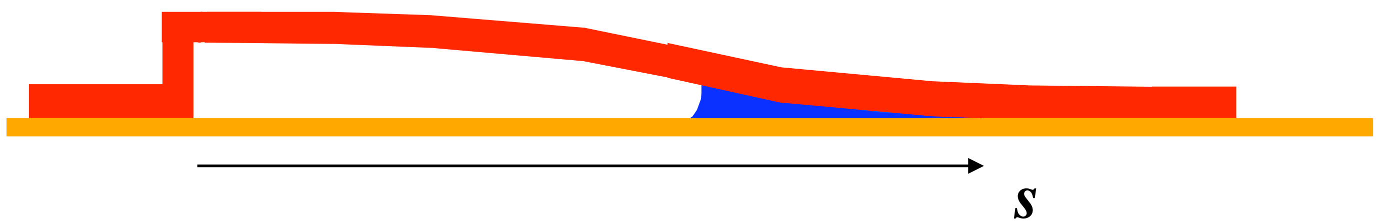
Adhesion ("stiction") is a big problem in micromachining

Initially free beam, but still in water

Drying leads to "stiction"



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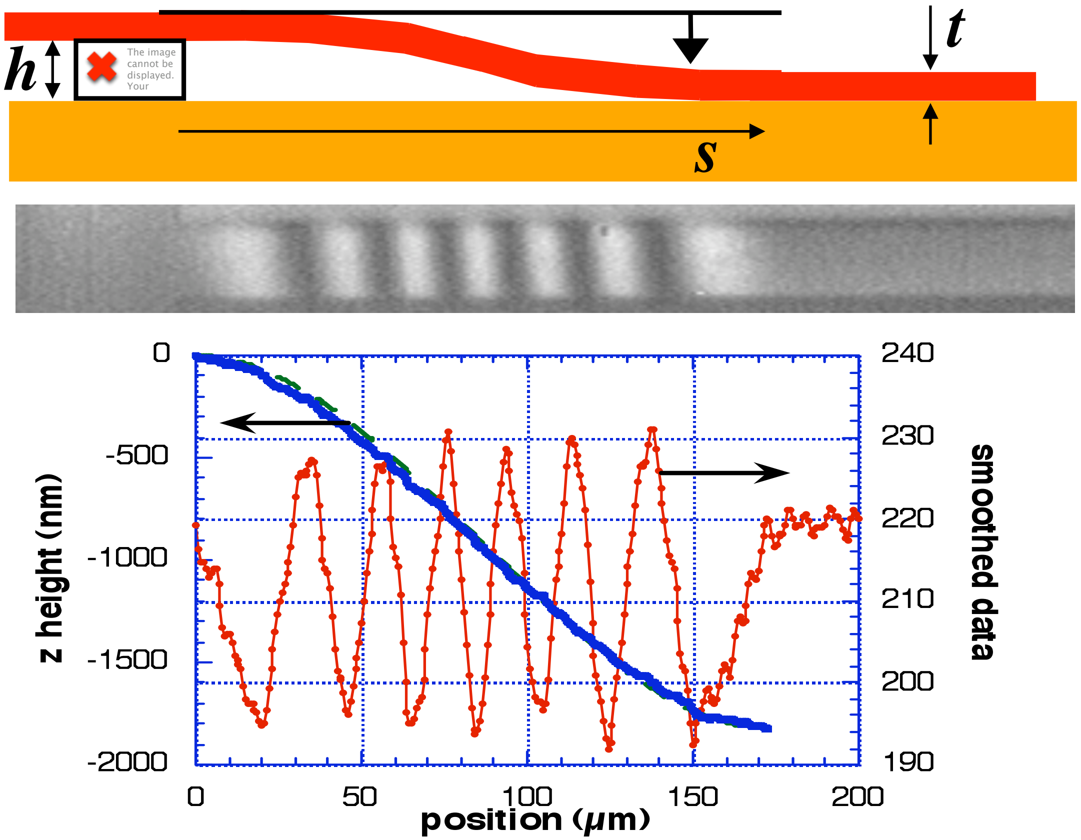
We can use cantilevers to quantify the adhesion, Γ



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

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

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

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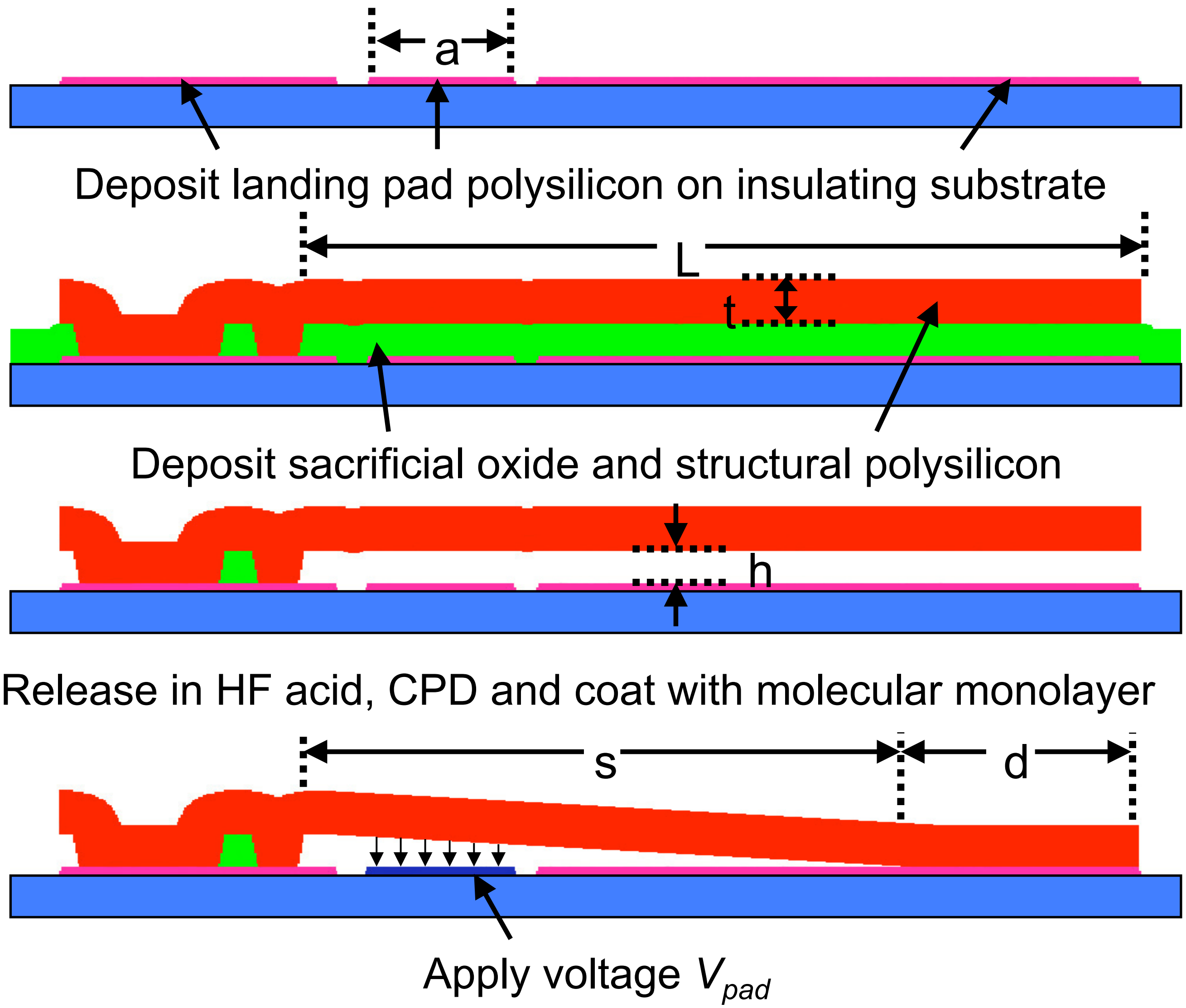
Microcantilever process and test flow



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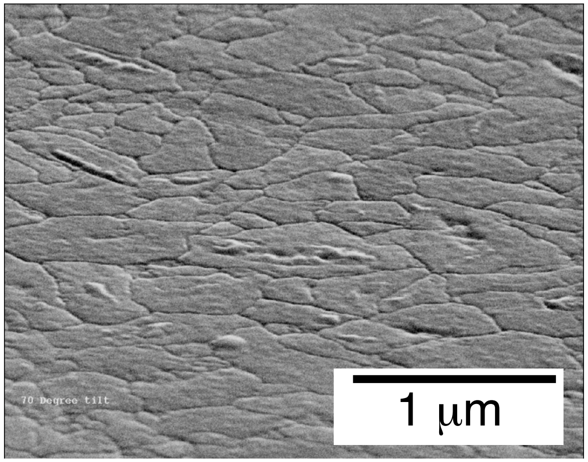
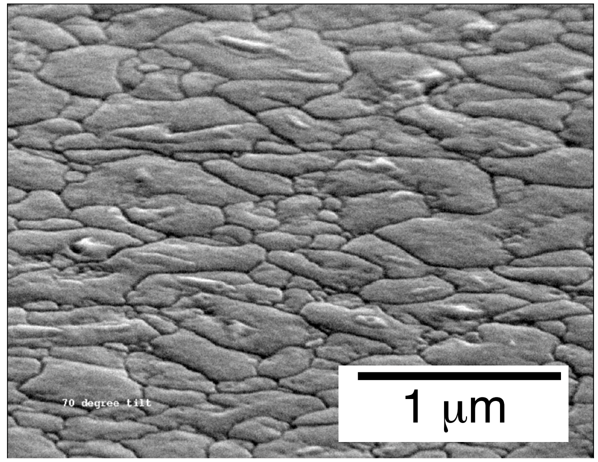
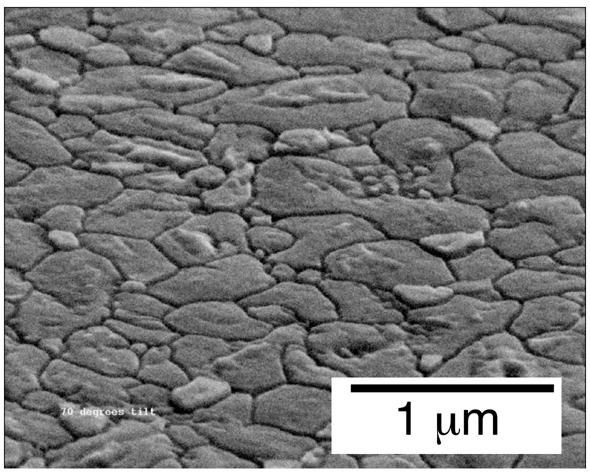
Oxidize the Poly 0 Surface to change surface roughness



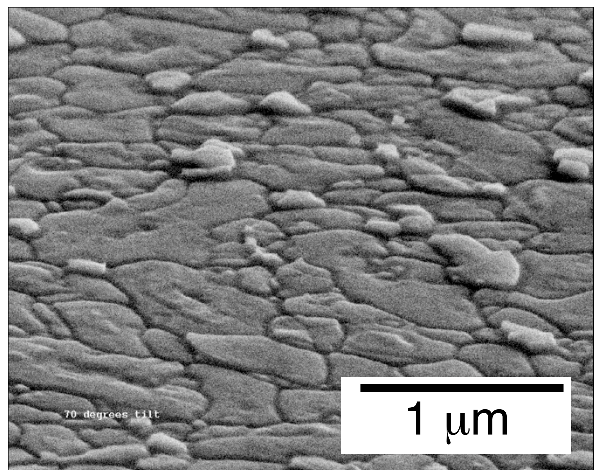
No oxidation, 2.6 nm rms



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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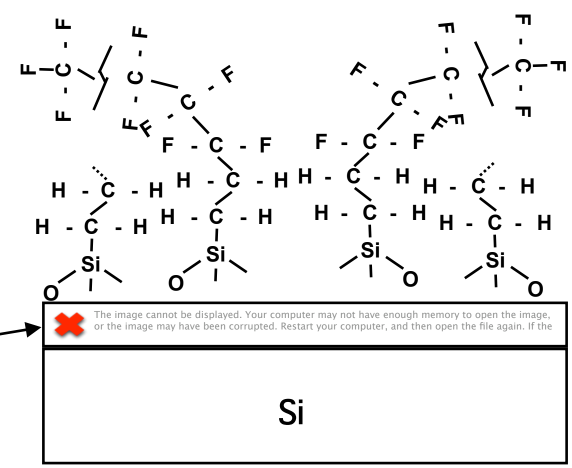
MEMS monolayer coupling agent

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°

FOTAS 8-carbon fluorinated chain (disordered, tangled)



Native SiO_2

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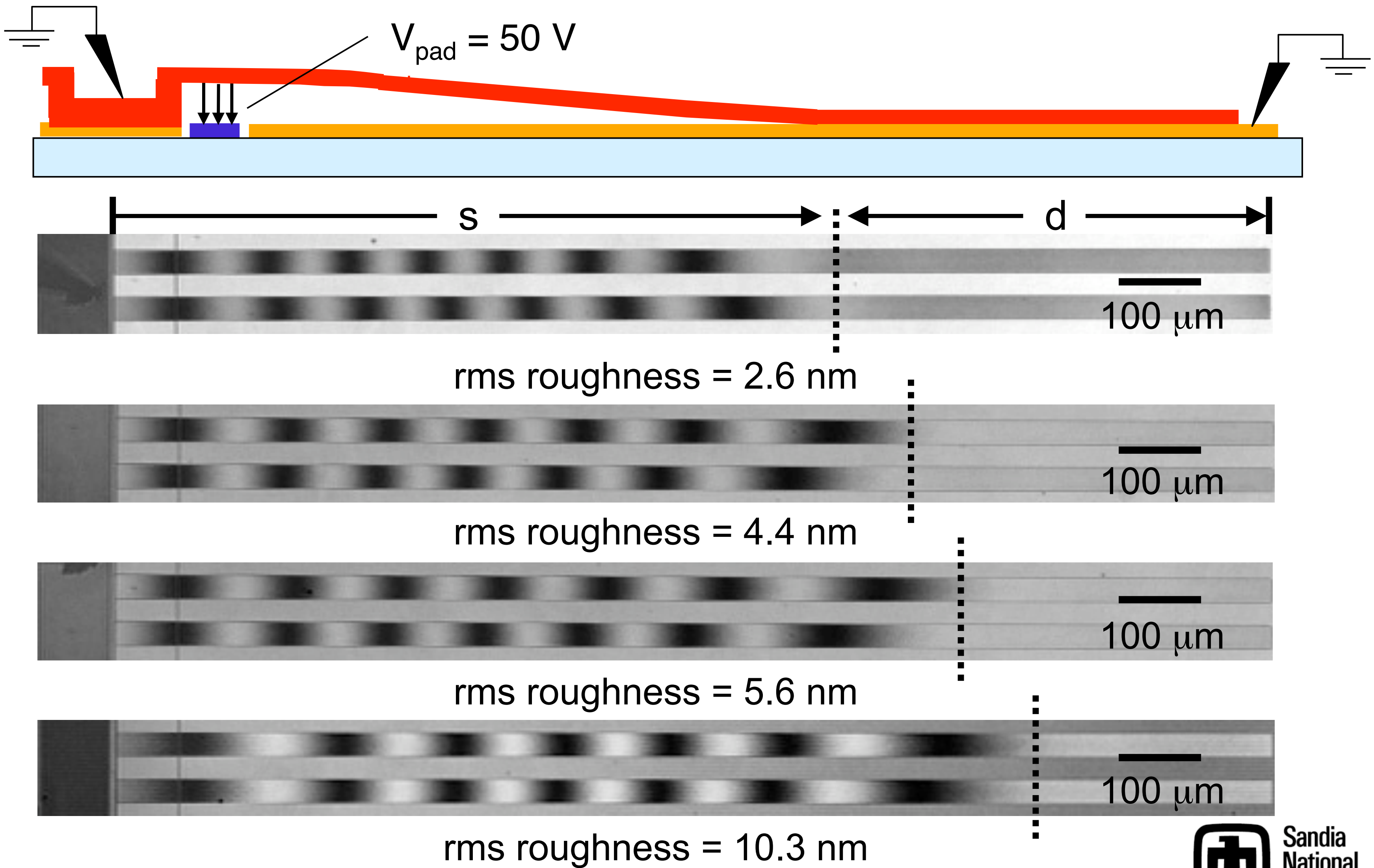
Interferograms show qualitative relationship between surface roughness and crack length



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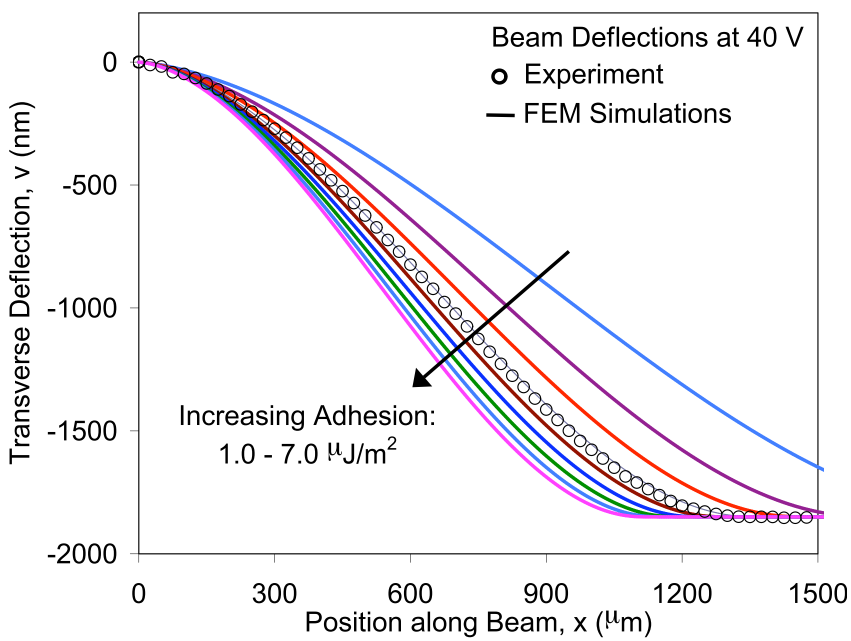
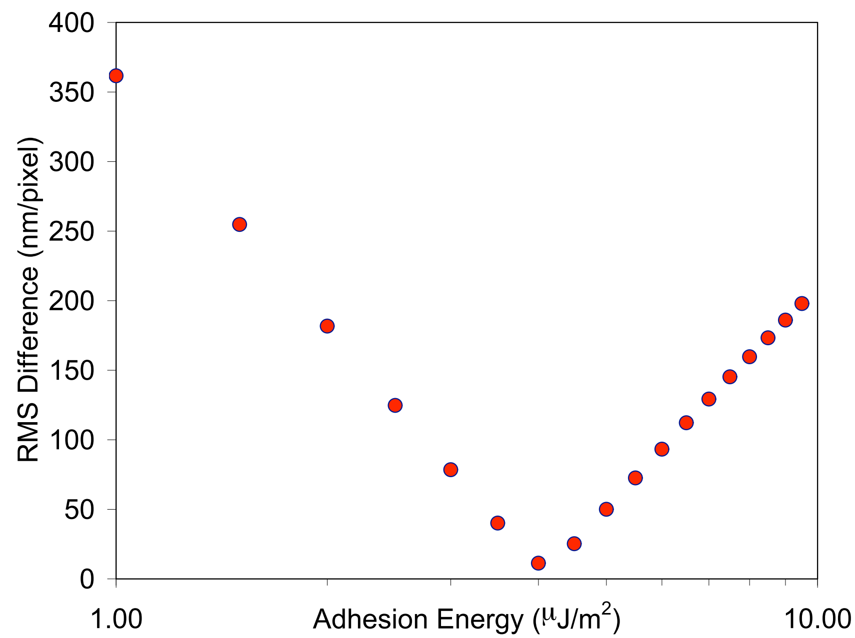
Adhesion measurement with applied voltage

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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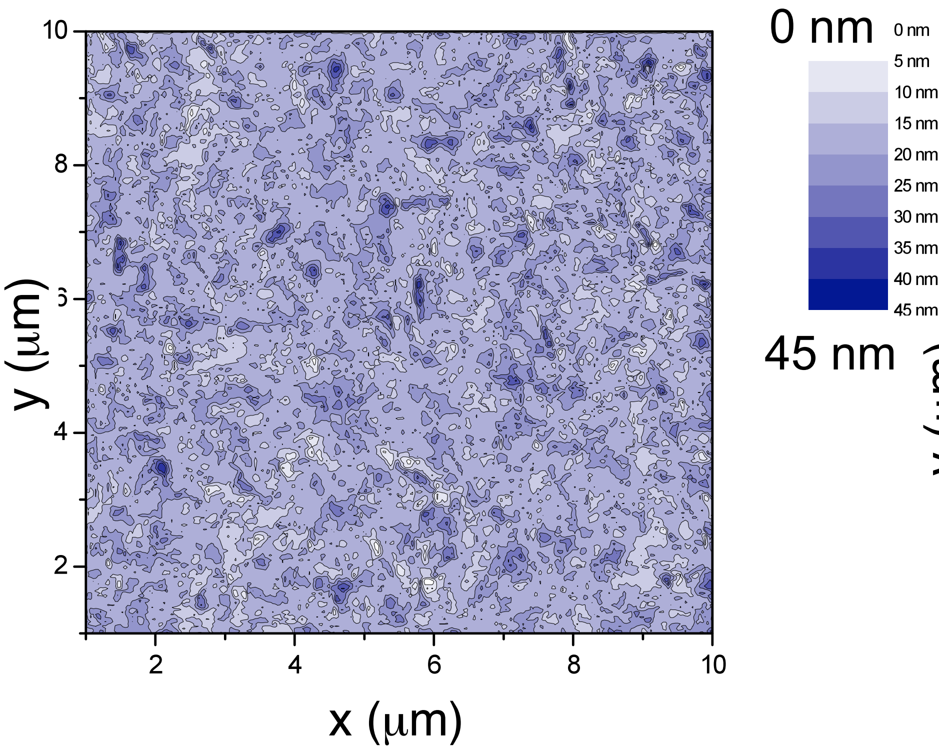
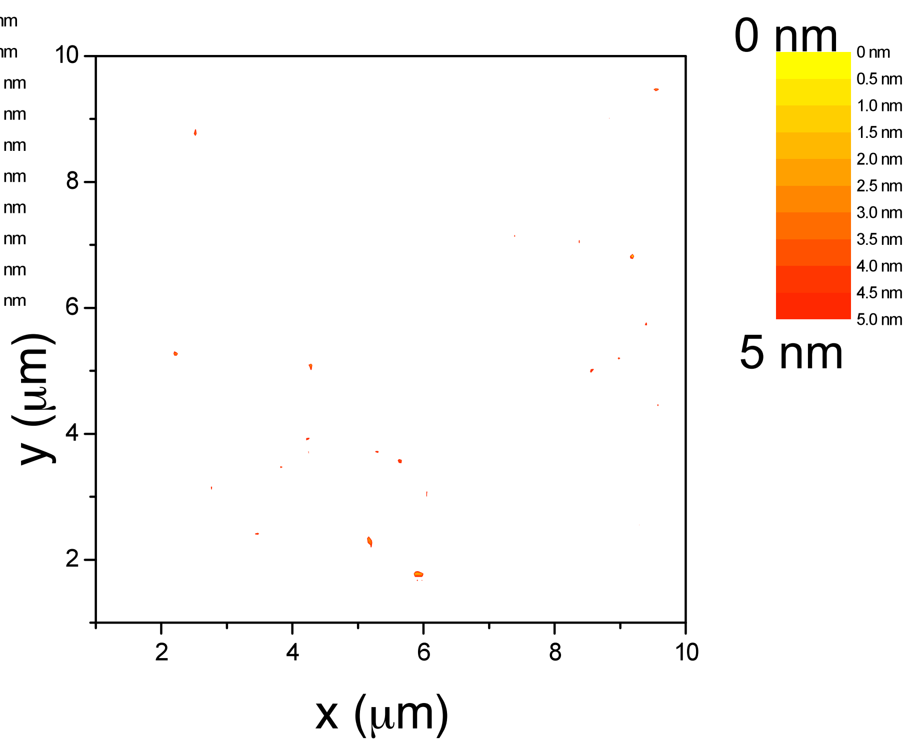
The surfaces separation is everywhere less than 100 nm.

Contour map of gap separation between the two surfaces

All separations



Small separations



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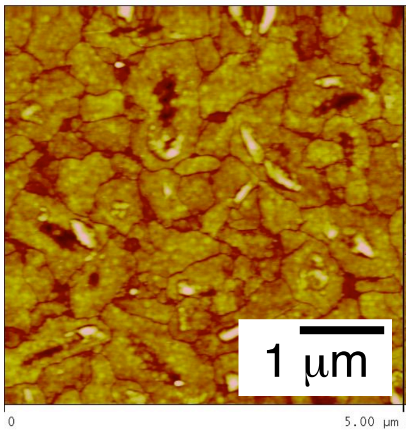
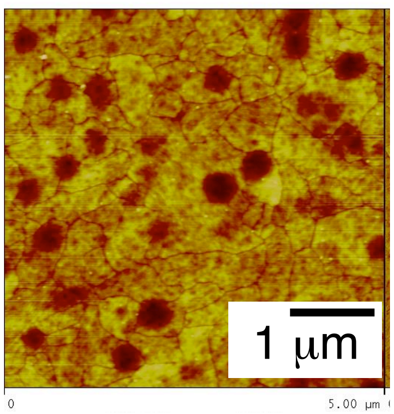
AFM topography data is analyzed using a numerical force-displacement routine

AFM Images

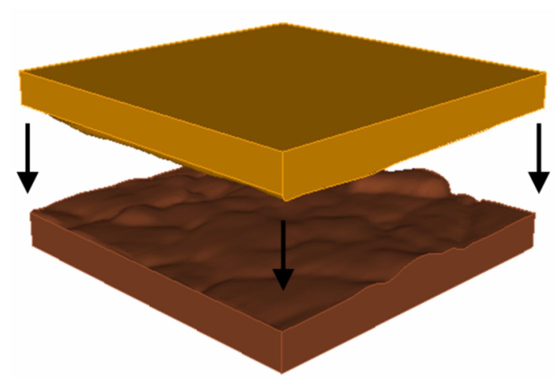




512 x 512 matrix with surface heights entered into force displacement routine

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



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

Anandarajah and Chen 1995

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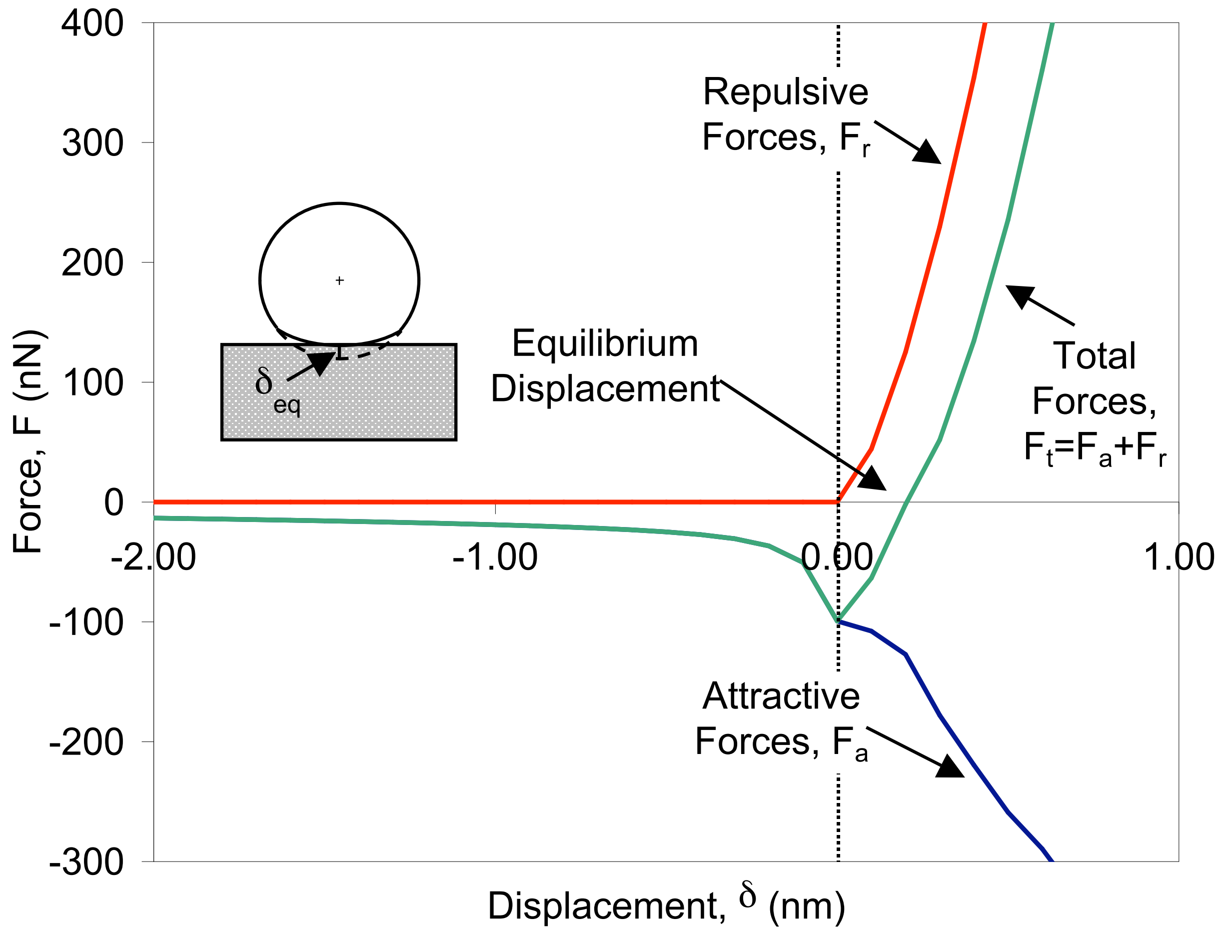
Calculate the total force-displacement curve using the AFM analysis and Hertzian mechanics

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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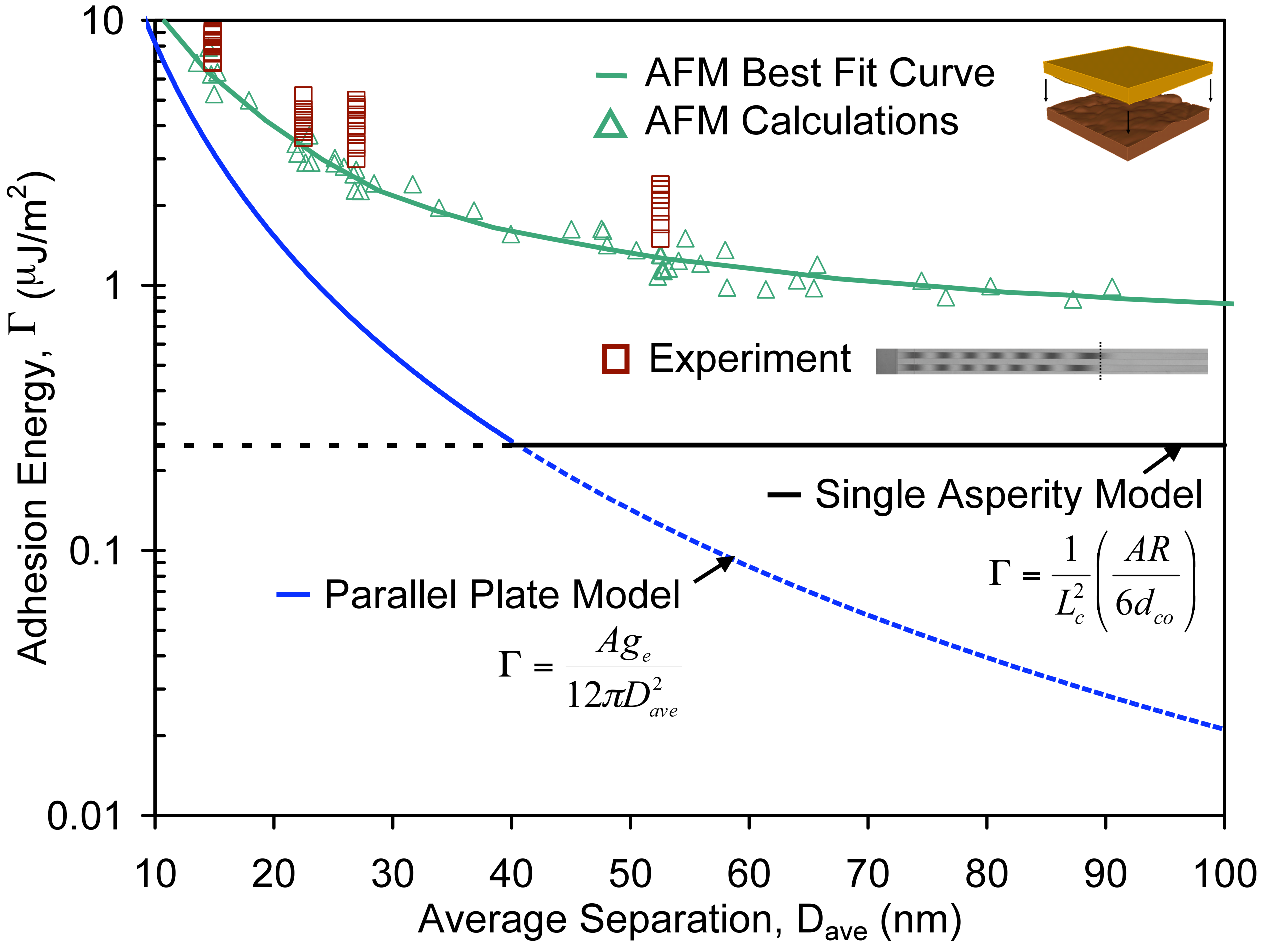
Predicted values of adhesion with AFM data

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., Nature Materials (2005)

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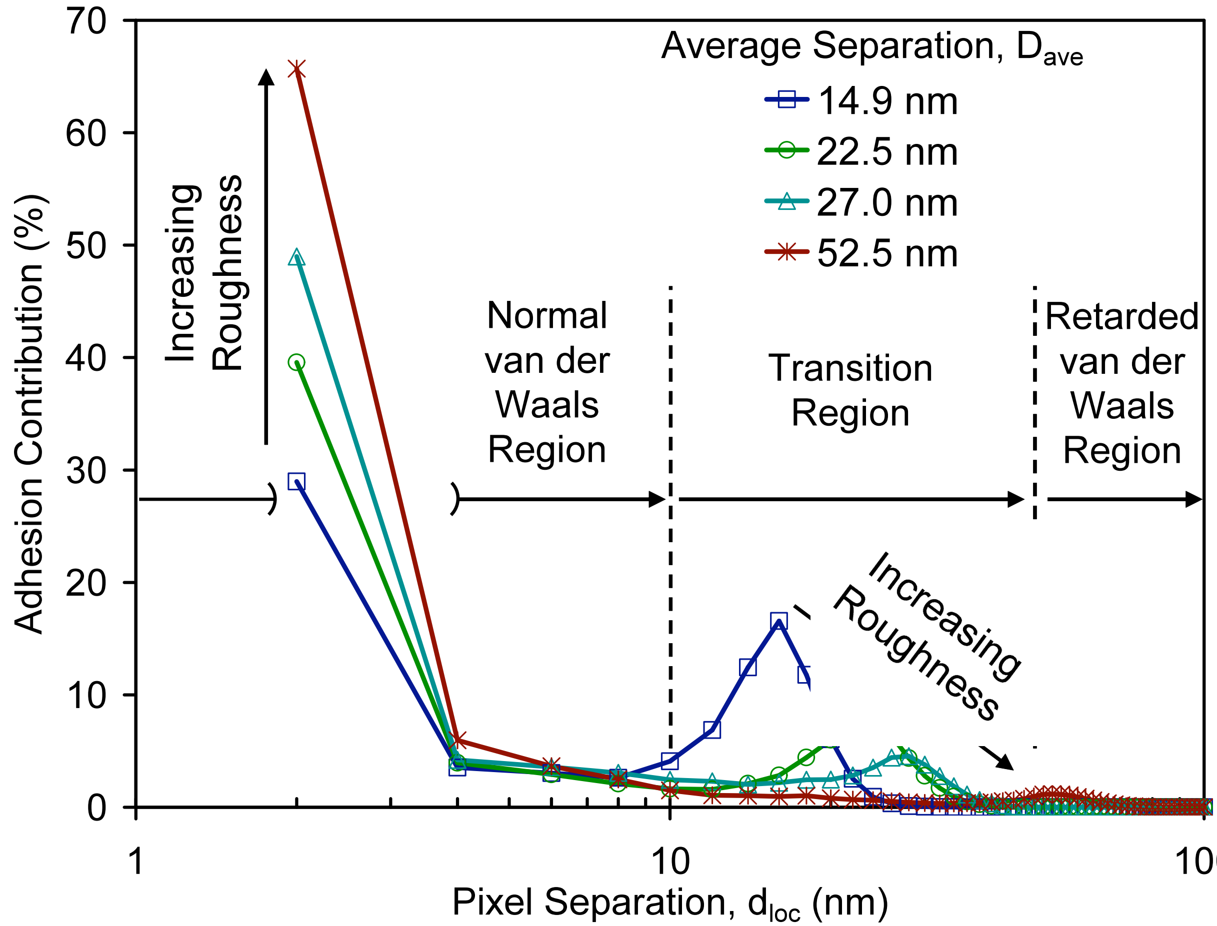
Histogram of adhesion contributions vs. pixel separation

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).



DelRio, de Boer et al., Nature Materials (2005)

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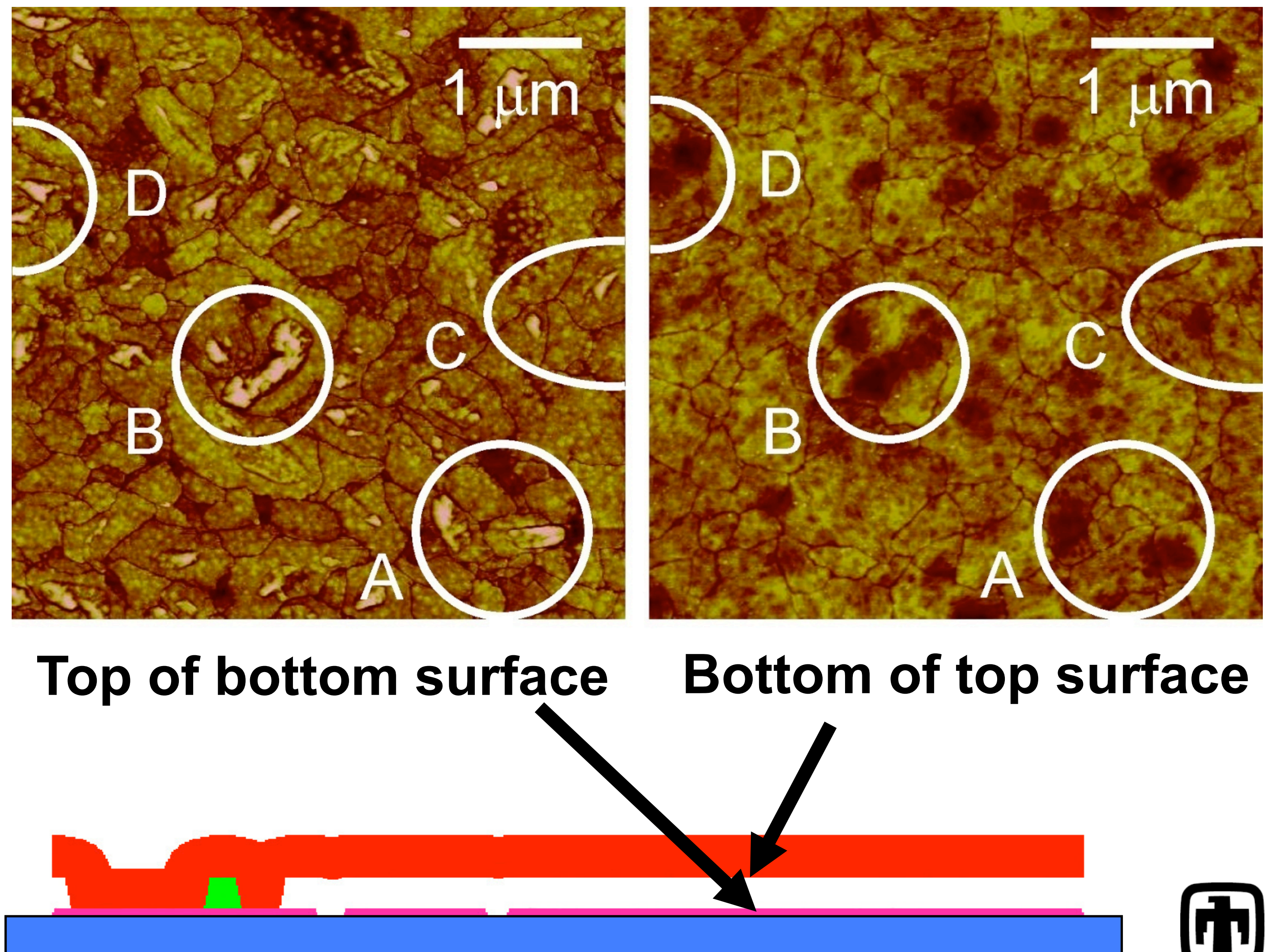
Roughness on top and bottom surfaces is correlated!



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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 (Casimir forces)

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

Surface topography correlations between upper and lower surfaces play an important role

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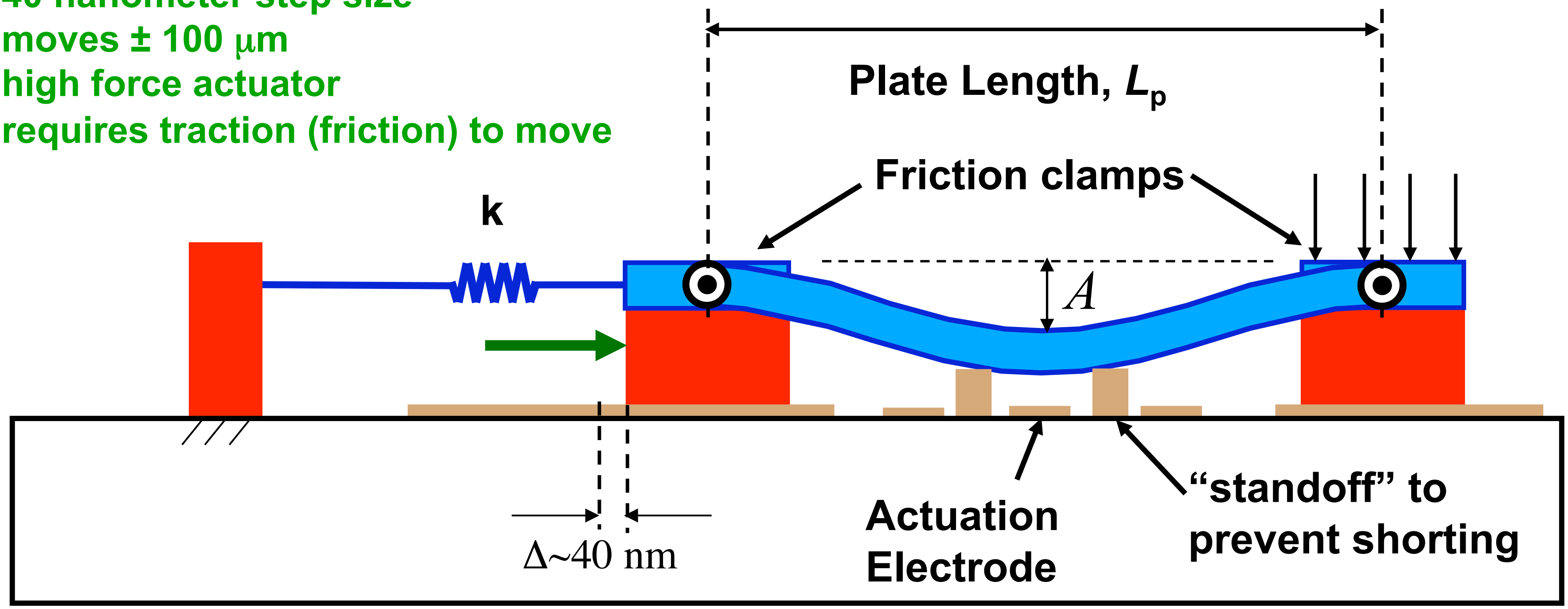
Nanotractor for on-chip actuation - a stepper motor with 50 nm steps

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



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

large tangential force range

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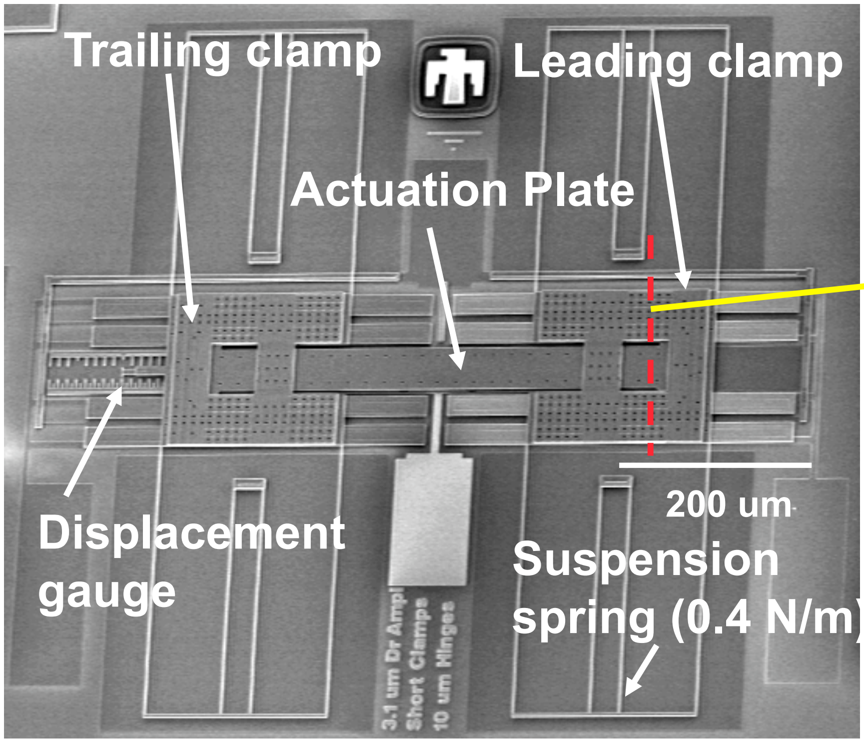
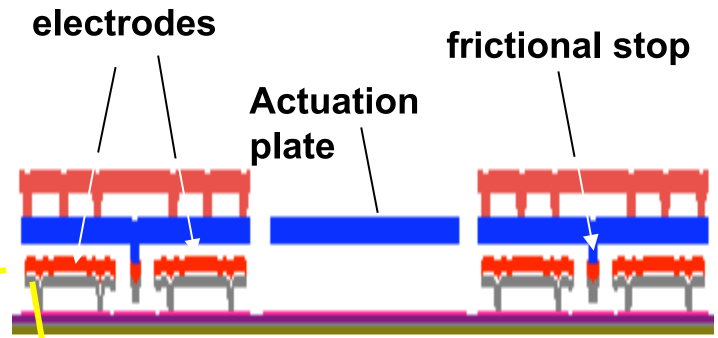
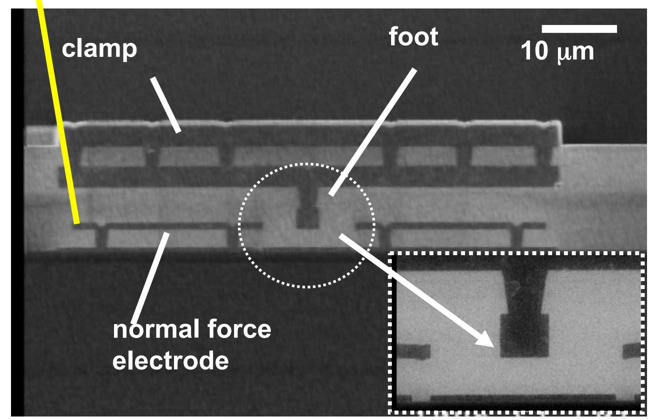
Nanotractor implementation





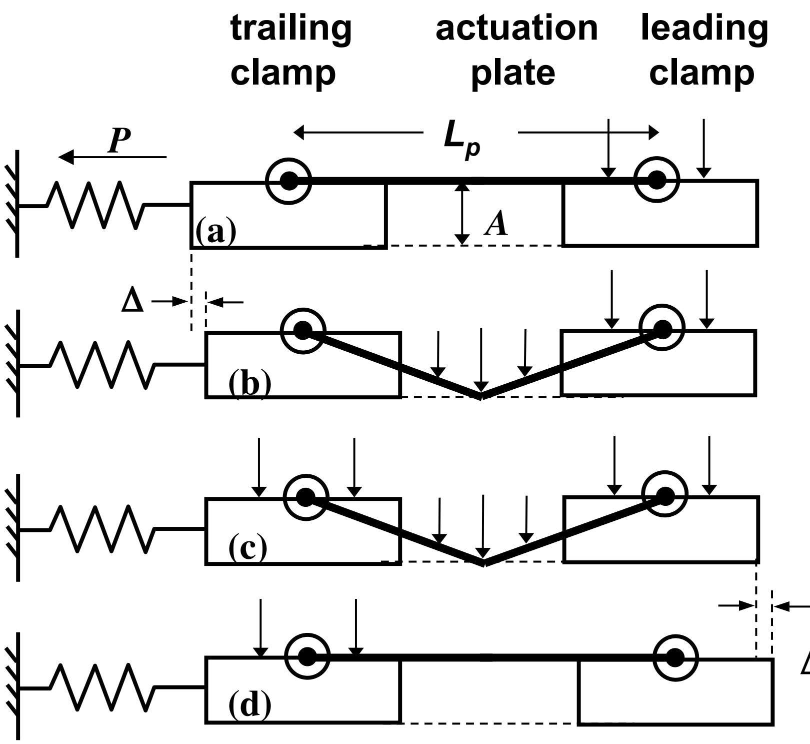
Cross-section(schematic)

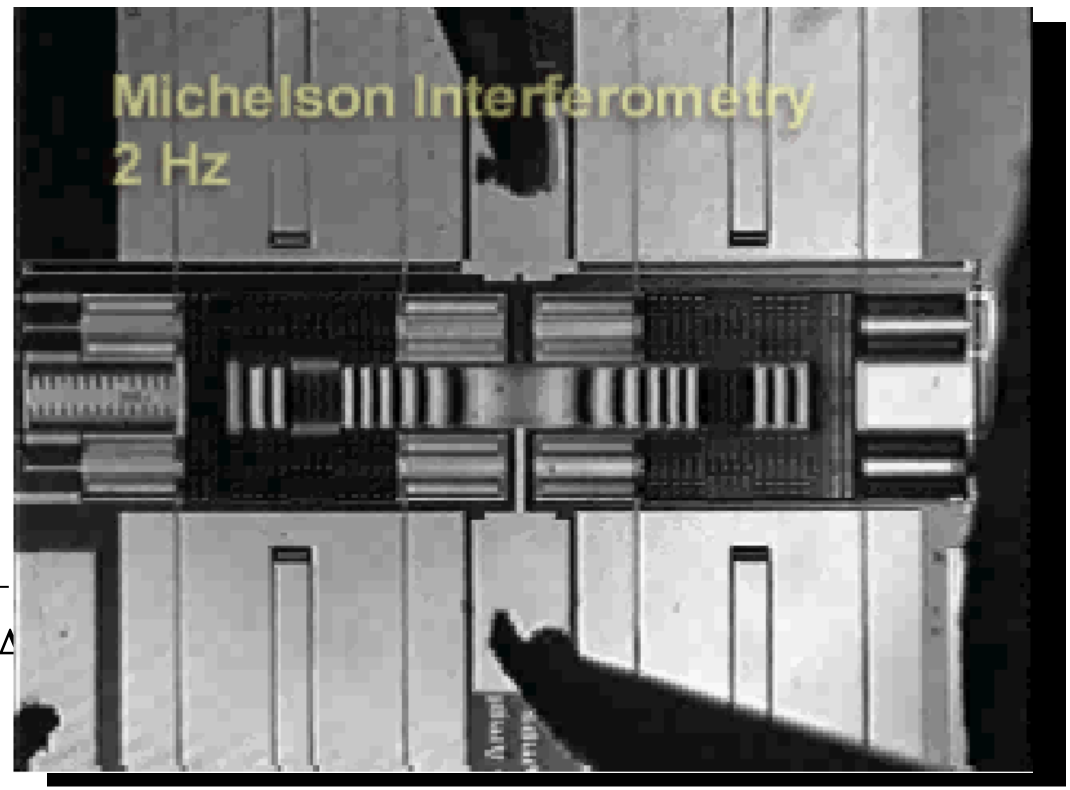


High-performance surface-micromachined inchworm actuator,

de Boer, MP; Luck, DL; Ashurst, WR; Maboudian, R; Corwin, AD; Walraven, JA; Redmond, JM
Journal of Microelectromechanical Systems; Feb. 2004; vol.13, no.1, p.63-74

Driving the Nanotractor





(a) Clamp RHS
(b) Pull down driver beam
(c) Clamp LHS
(d) Relax RHS & driver beam

Operates up to 5 mm/s

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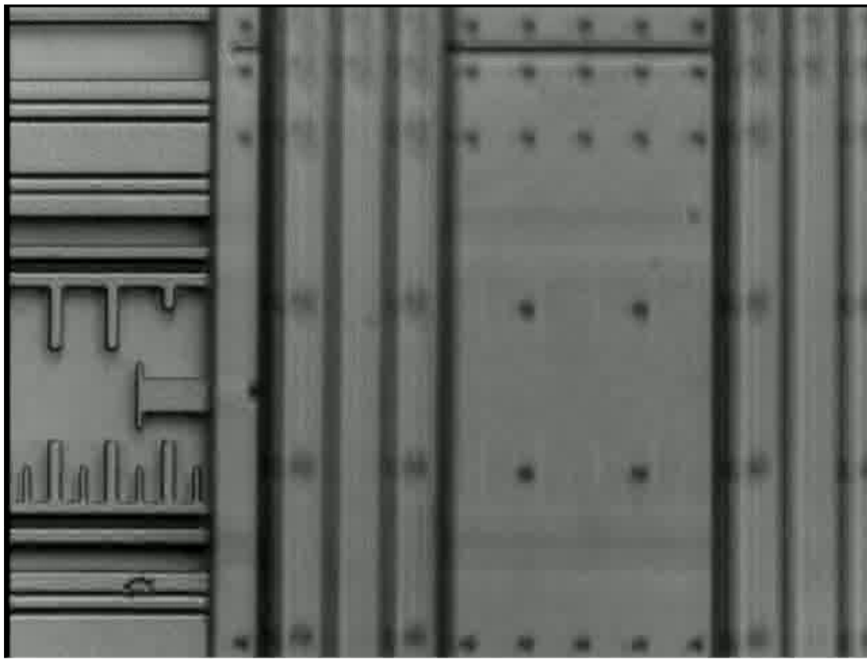
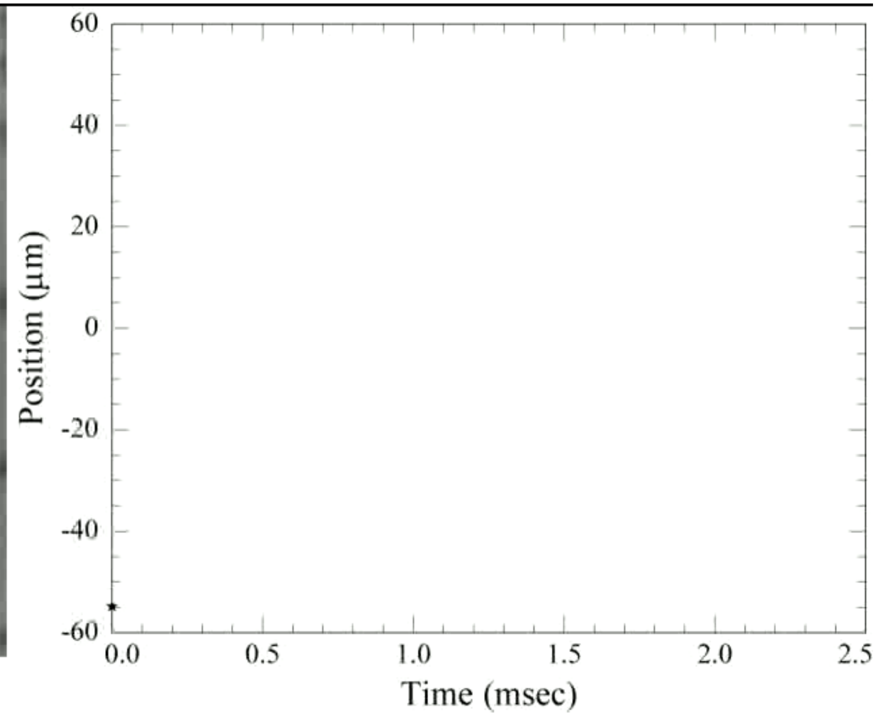
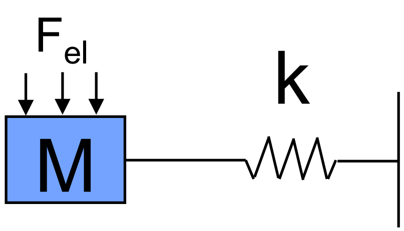
Friction- damped oscillator to measure dynamic friction

dynamic friction test at small tensile load (FOTAS monolayer):







$2.5 \cdot 10^{-9}$ kg   0.4 N/m

dynam_side.mpg

Effect of adhesion on dynamic and static friction in surface micromachining.

Corwin, AD & de Boer, MP Applied Physics Letters (2004)

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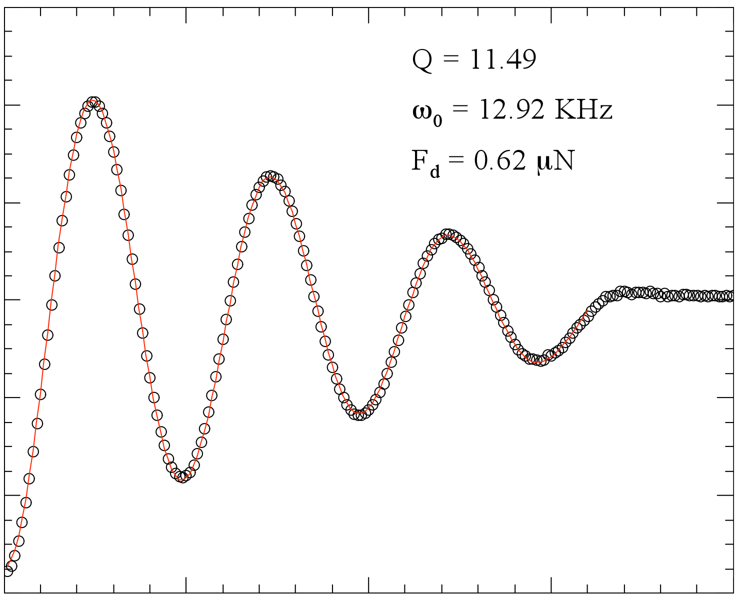
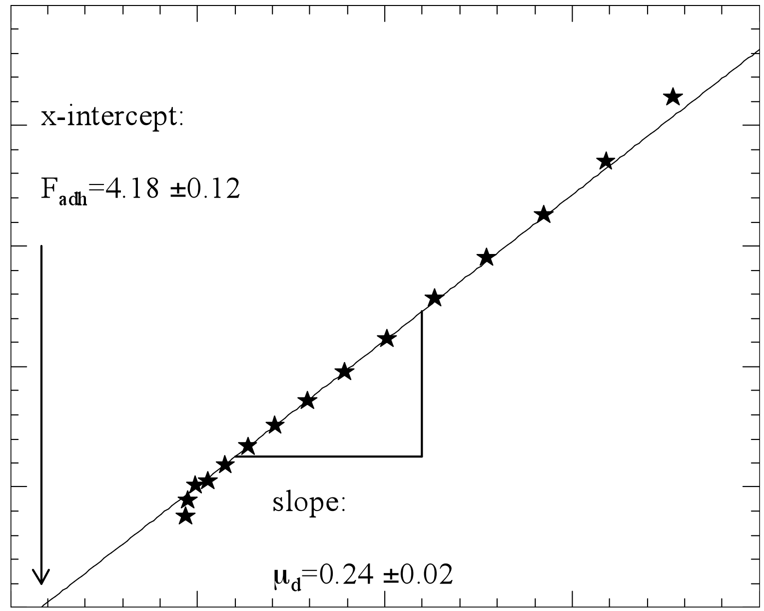
There is dynamic friction at zero applied load

FOTAS monolayer

Measured and modeled fit for zero applied load



Dynamic friction over a range of applied loads



$$F_d = \mu_s \underbrace{(F_c + mg + k_z z)}_{F_{appl}} + \mu_s F_{adh}$$

Effect of adhesion on dynamic and static friction in surface micromachining.

Corwin, AD & de Boer, MP Applied Physics Letters (2004)

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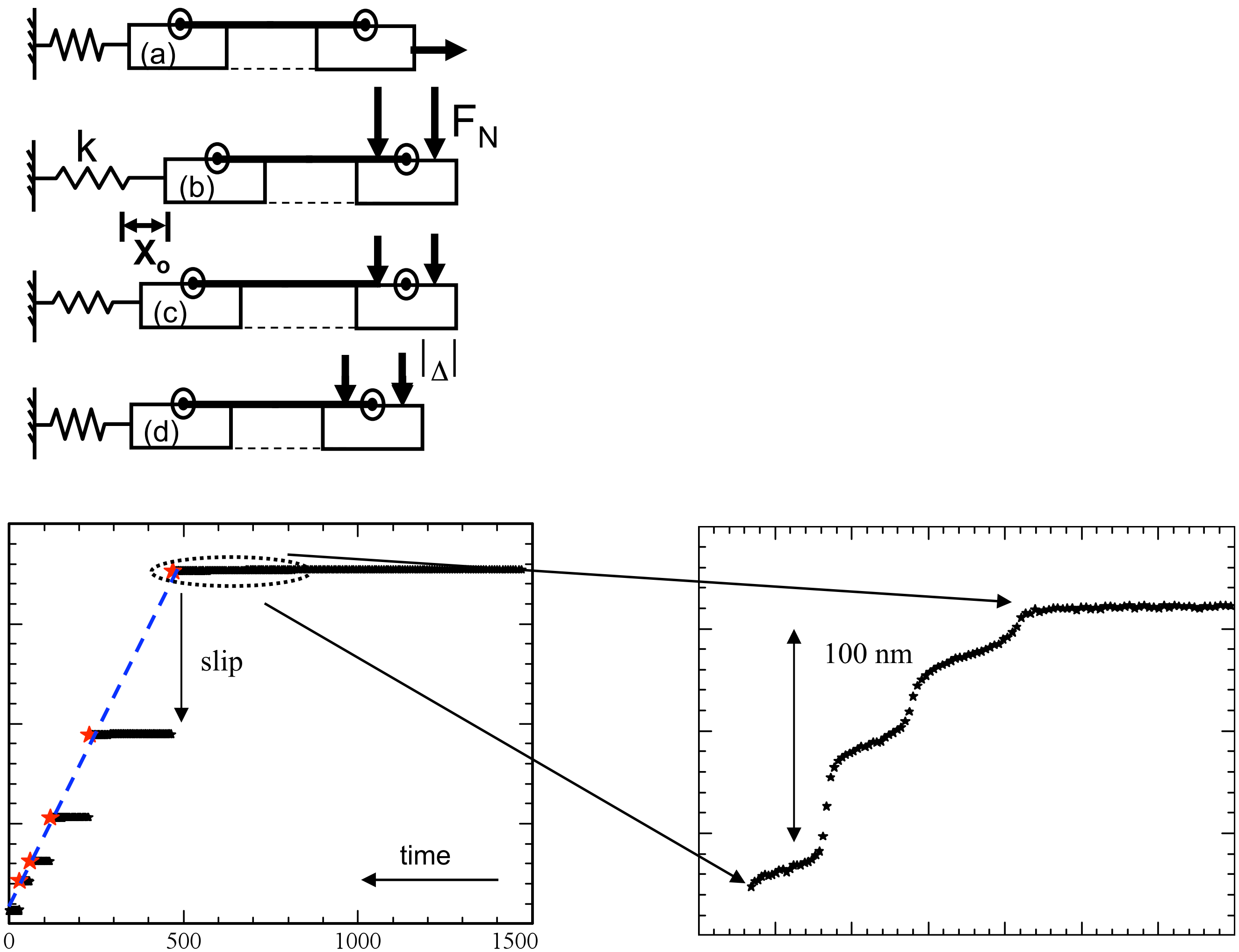
Static friction testing with the nanotractor

a)



b)

c)

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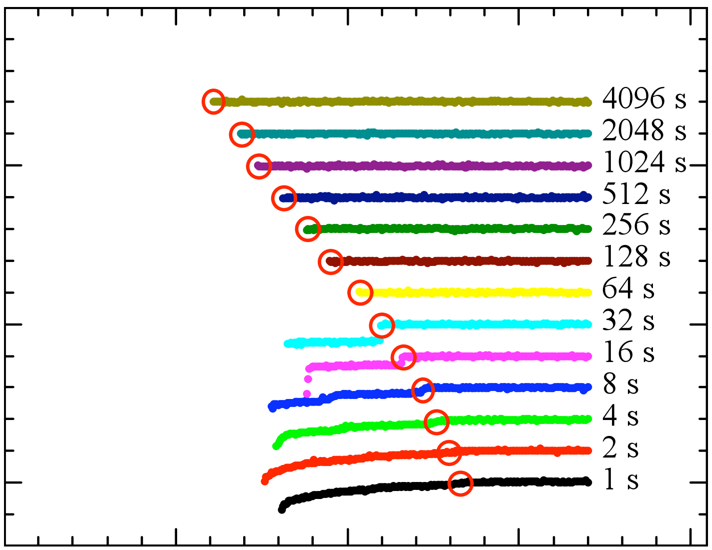
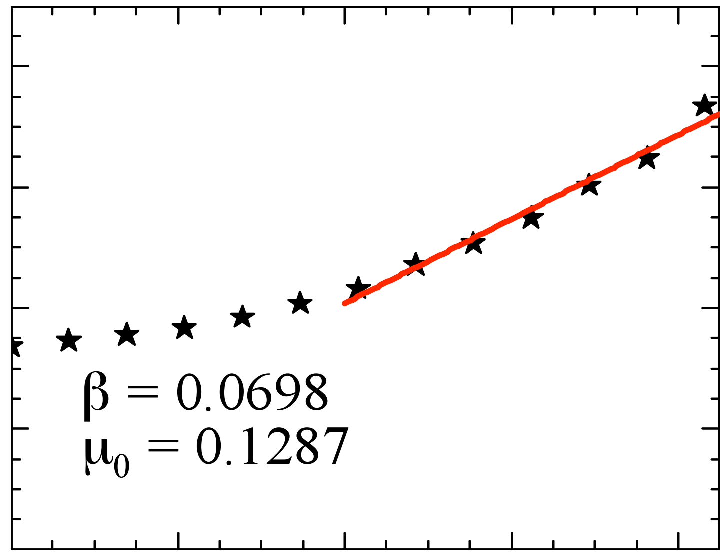
Rich static friction behavior is observed by varying the hold time

sliding bifurcation



static friction aging



A. D. Corwin & M. P. de Boer, J. Microelectromechanical Systems (2009)

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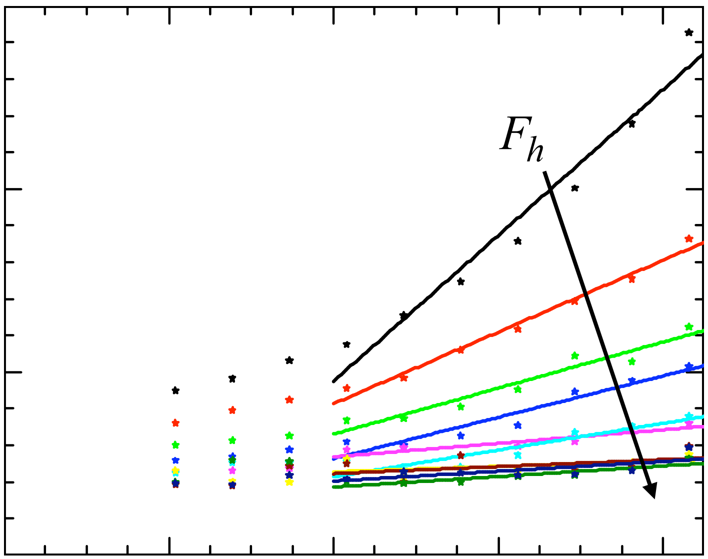
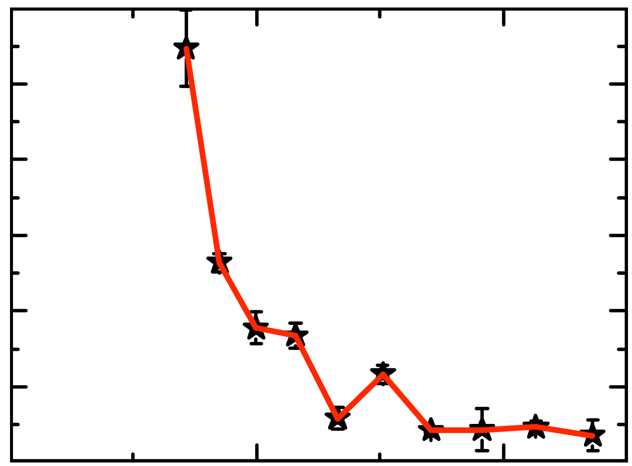
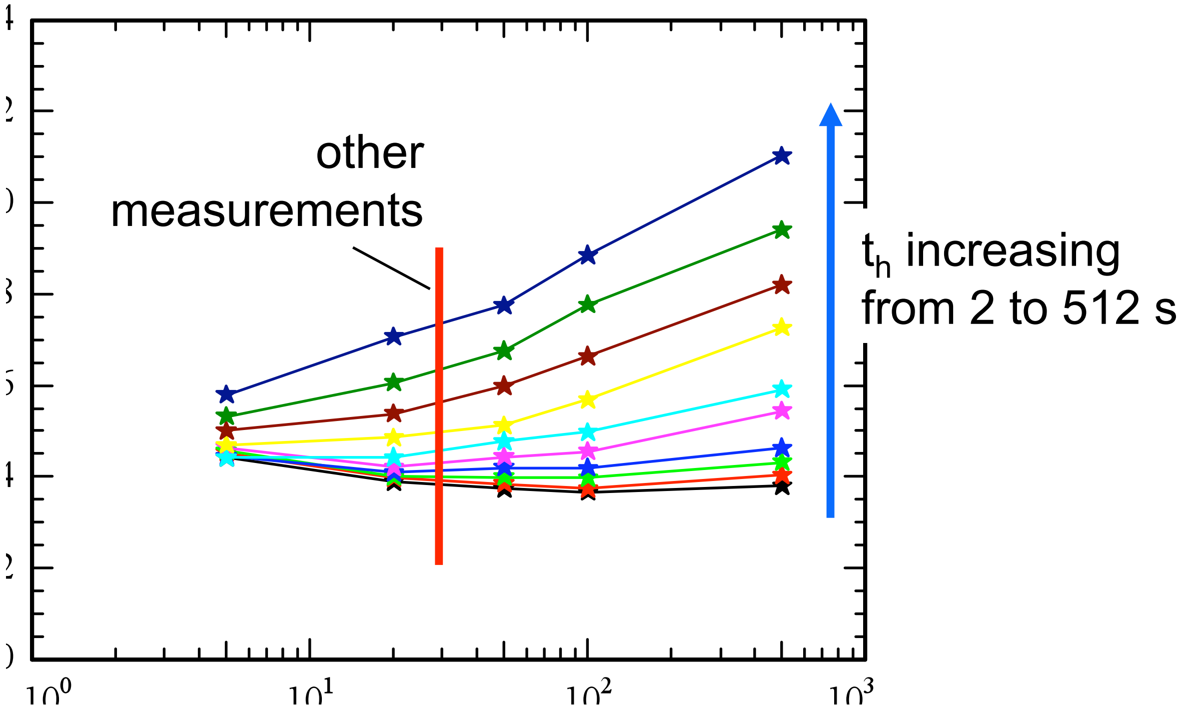
β, the logarithmic rate of aging, decreases with increasing hold force …!!!



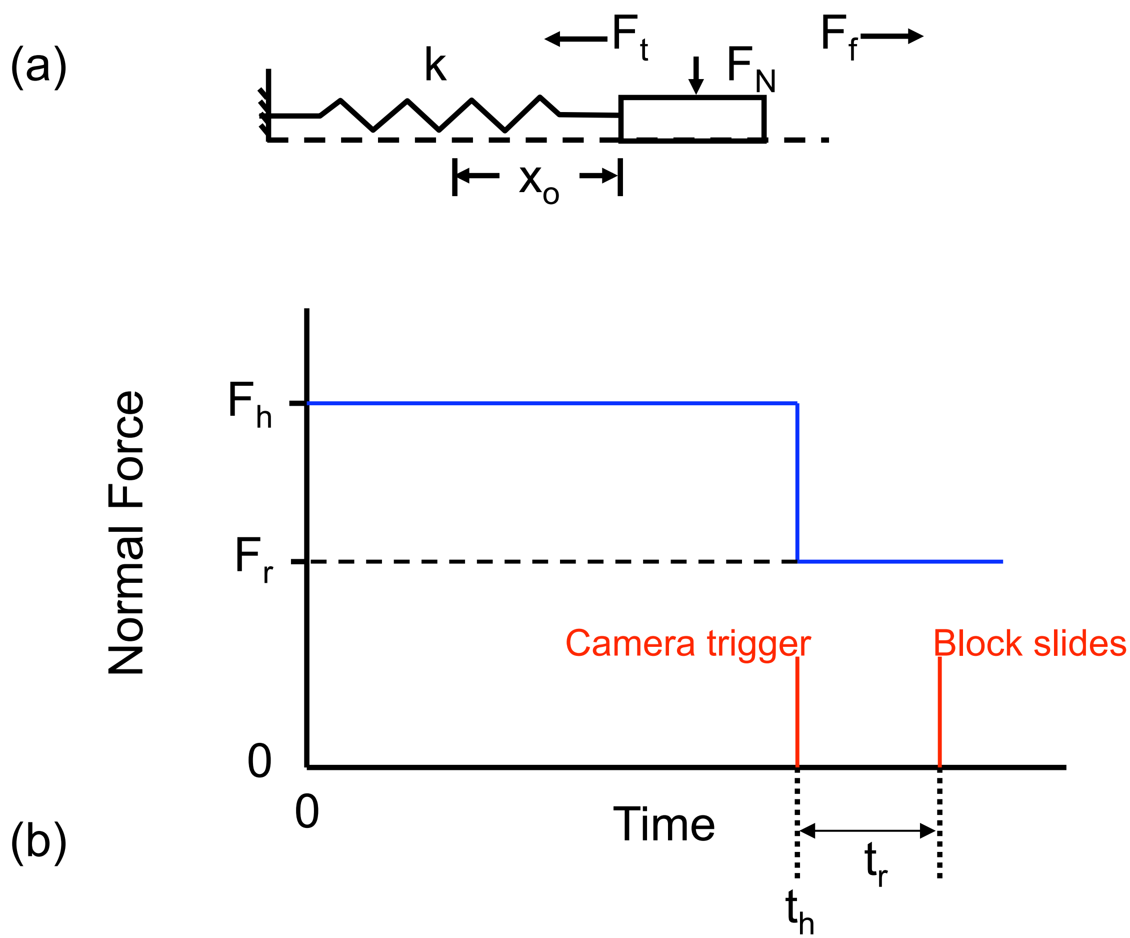


The normal force rampdown rate also affects the static friction value

static friction dependence on ramp-down rate



“Release time” measurement



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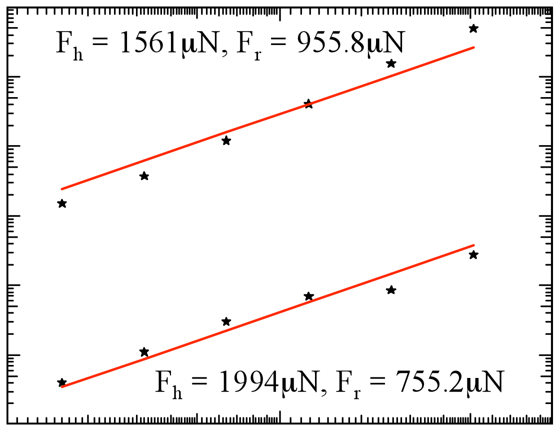
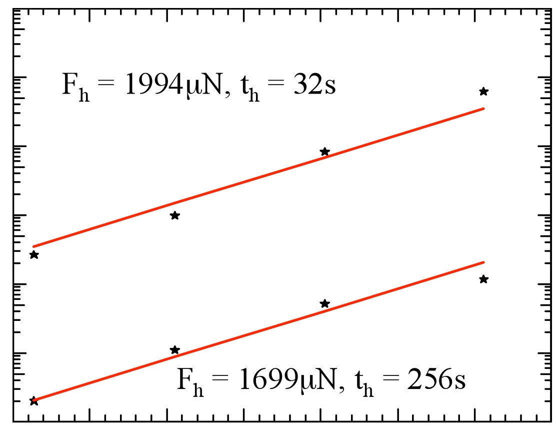
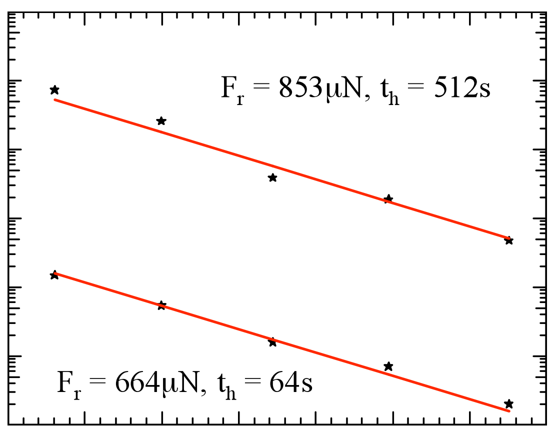
“Release time” is far longer than inertial response time and shows the same qualitative dependencies as static friction



(a)



(b)



(c)

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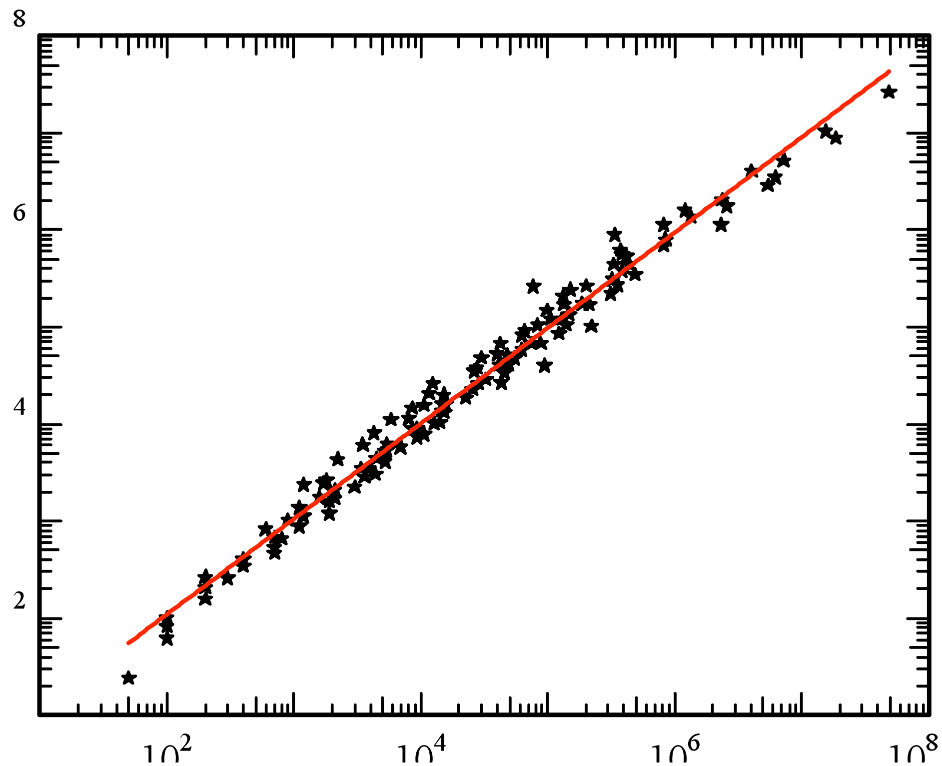
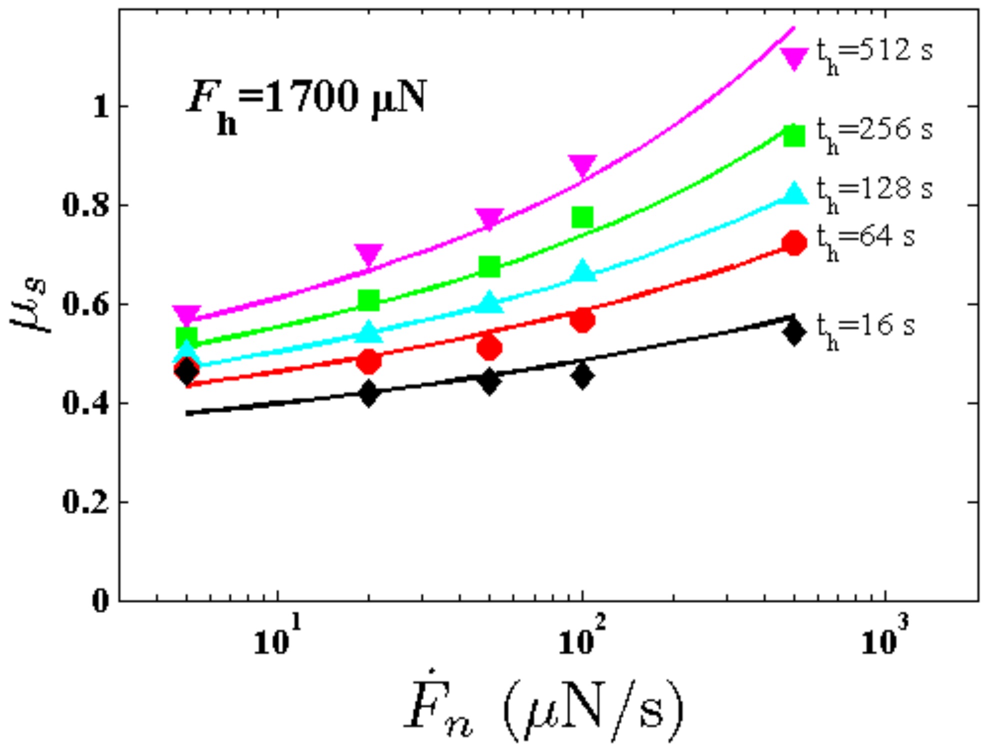
All the release time data collapse onto a single curve



$$t_r / t_o = (a / t_o)(t_h / t_o)^n e^{F_r b_1 + F_h b_2}$$

A. D. Corwin & M. P. de Boer, PRB (submitted)

The release time equation can be used to directly predict the static friction dependence



A single parameter “b3”, has been introduced.
b3 equates with the logarithmic rate of “re-aging” after the interface de-ages.

$$t_{jmp} = \frac{\ln\left[1 + a(b_1 + b_3)\dot{F}_n t_h^n \exp\left(F_h(b_1 + b_2)\right)\right]}{(b_1 + b_3)\dot{F}_n}$$

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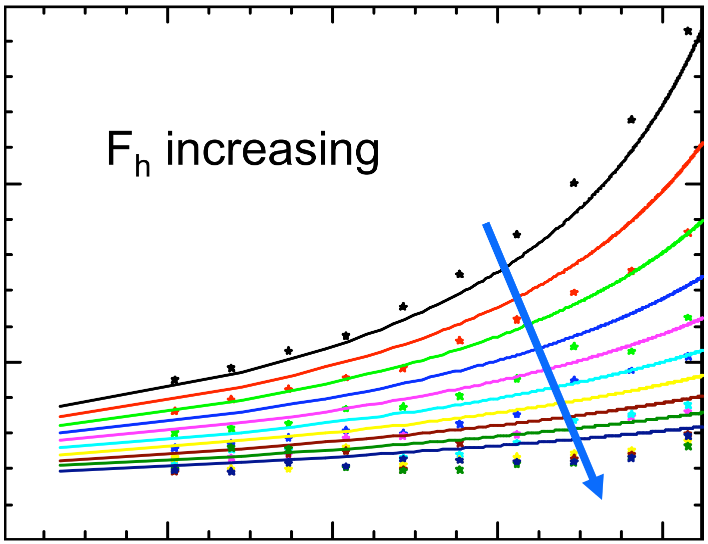
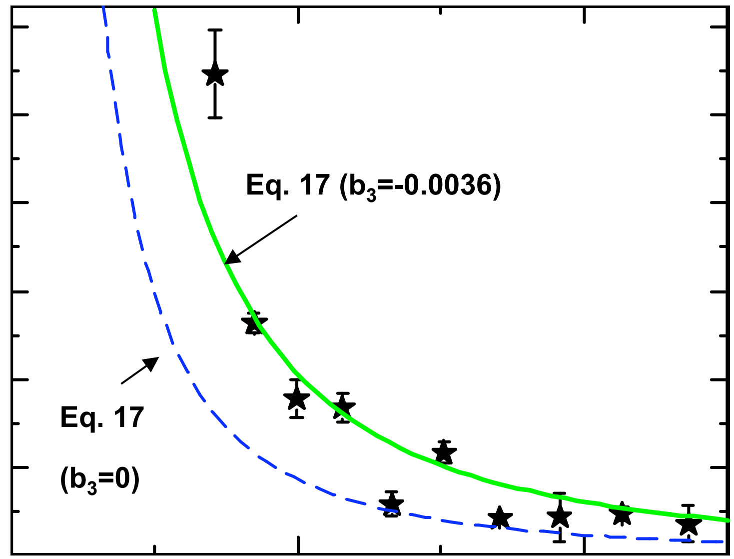
The release time equation also predicts the suppression of β with increasing hold force.





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Summary – Friction effect in MEMS

The nanotractor is a friction-based actuator that produces useful work at the μscale

The clamps form a controlled interface so that friction measurements can be made and modeled

Van der Waals attraction is responsible for dyanmic and static friction in the absence of applied force

Static friction aging effects have been observed

"Release time", much greater than inertial response time, underlies the static friction behavior.

Introducing a re-aging parameter, release time quantitatively predicts static friction aging behavior including aging suppression

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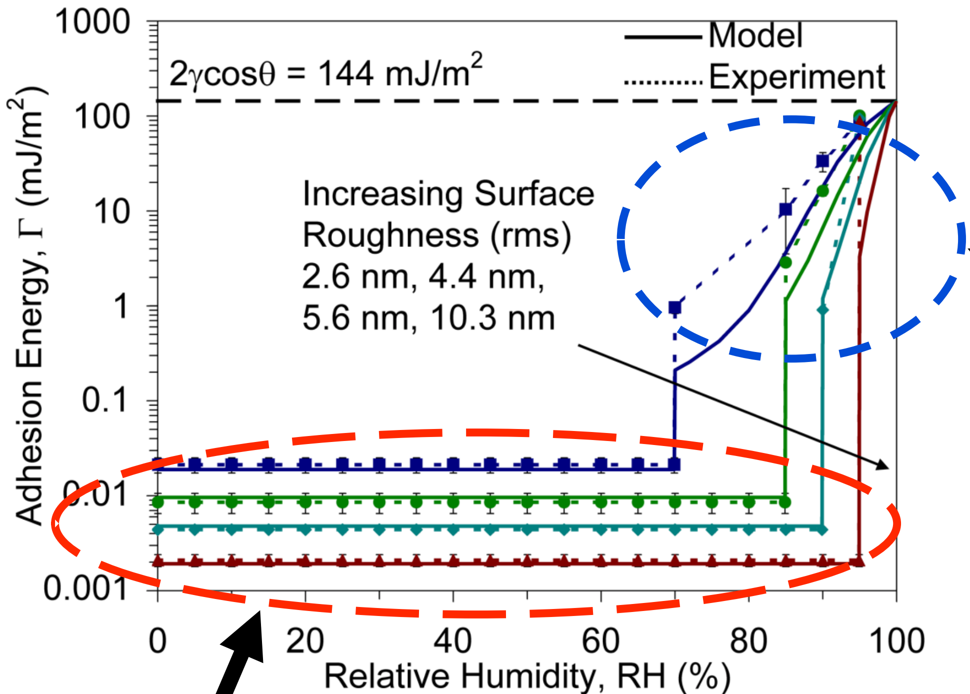
Backup slides

Taking correlation into account makes model/experiment agreement nearly perfect



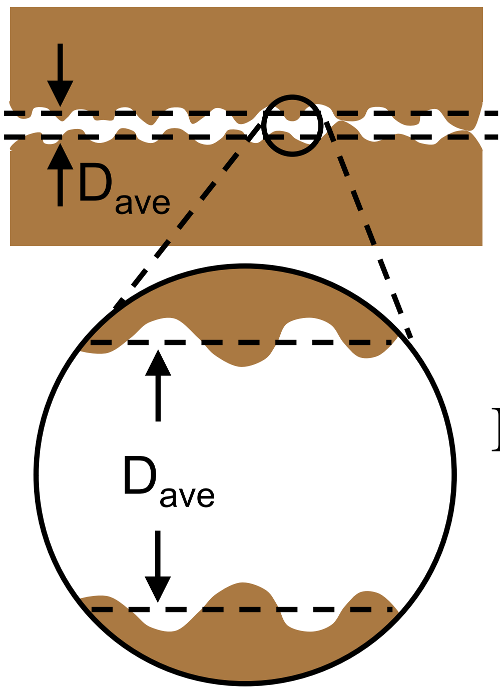
Capillary forces can dominate vdW forces!

Model and measurement accounting for surface correlations

DelRio, de Boer et al., Applied Physics Letters (2007)

Two extreme models for adhesion

Smooth Surface



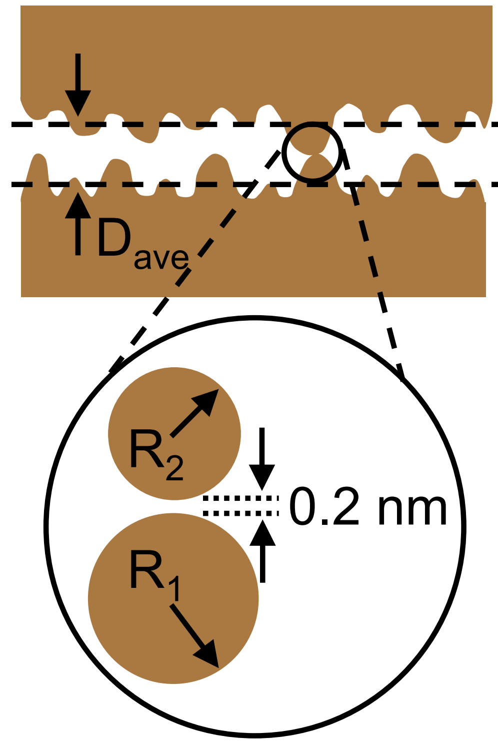
Parallel Plate Model

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

Anandarajah and Chen 1995

The forces across non-contacting portions of the surfaces, whose area is far greater than the contacting area at the one asperity, will dominate the adhesion.

Rough Surface



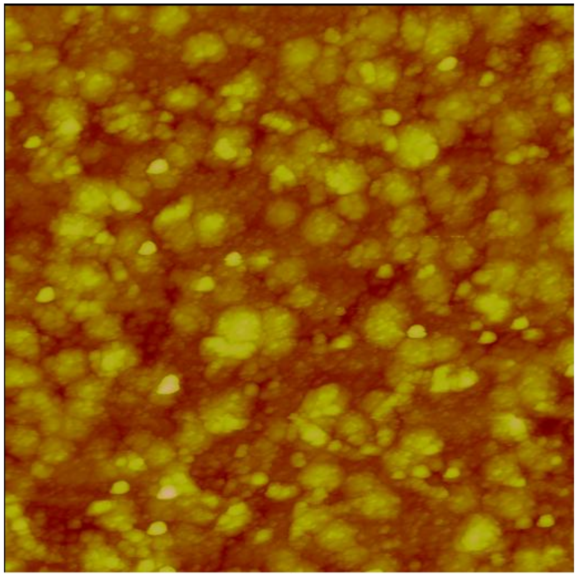
Single Asperity Model

$$\Gamma = \frac{1}{L_c^2}\left(\frac{AR}{6 d_{co}}\right)$$

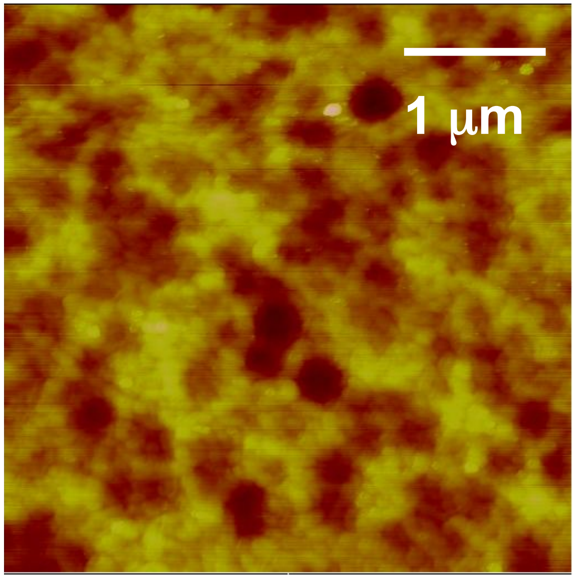
Israelachvili 1992

A significant part of the area is too far apart to contribute to the adhesion; only the van der Waals forces near the single point of contact contribute.

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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