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Using Casimir and capillary forces to model adhesion of MEMS cantilevers

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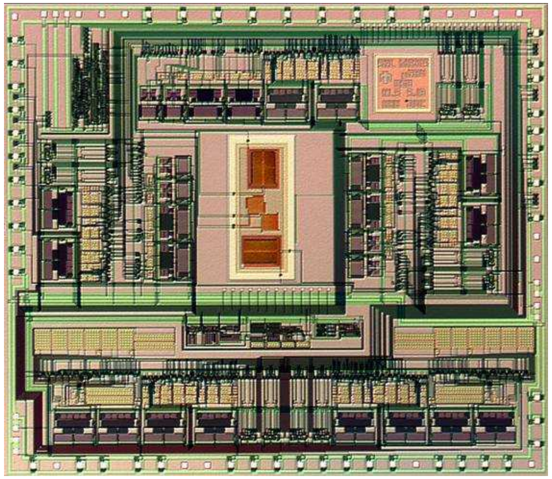
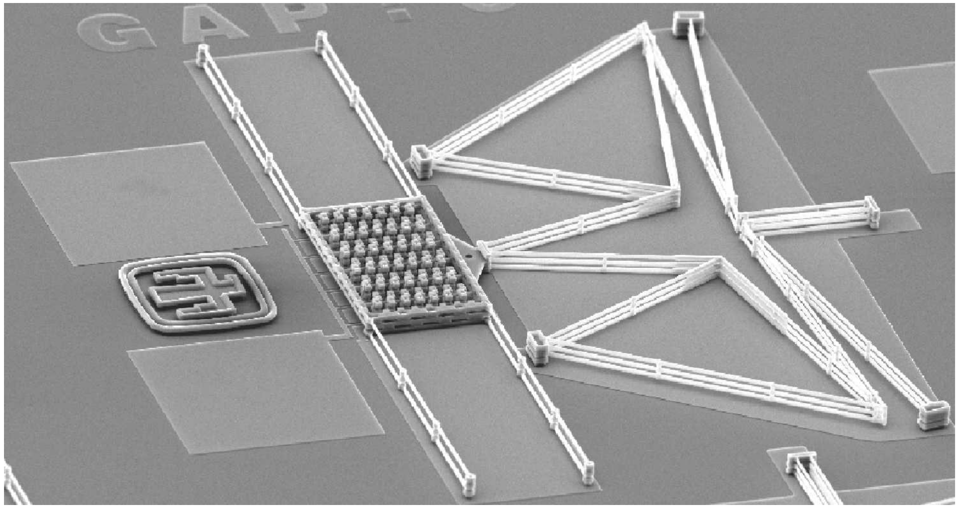
With polysilicon MEMS we can reliably accomplish electromechanical and optical functions

Integrated inertial sensor



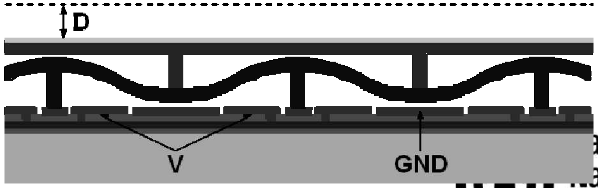
- **-thousands of devices simultaneously**
- **-no assembly required**
- **-hundreds of device concepts explored**

High performance comb drive with mechanical amplifier



Polychromator :

programmable diffraction grating



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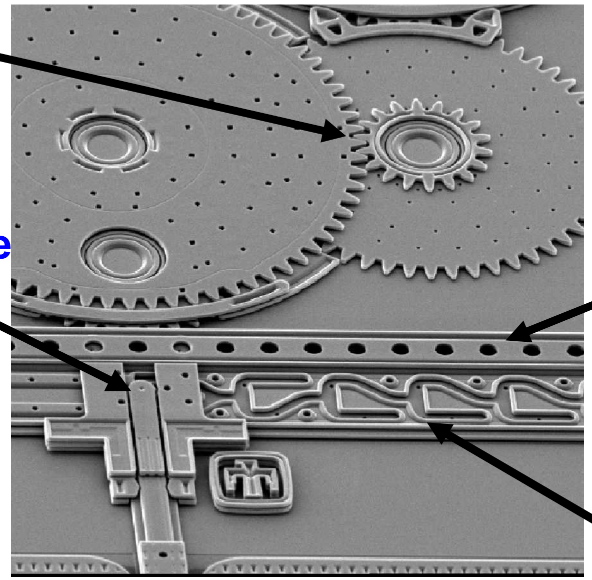
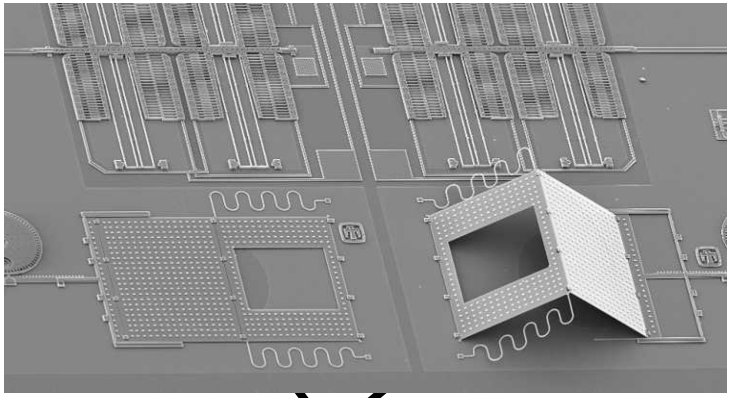
Allowing contact between MEMS surfaces significantly broadens the design space

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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MEMS – surface micromachining implementation

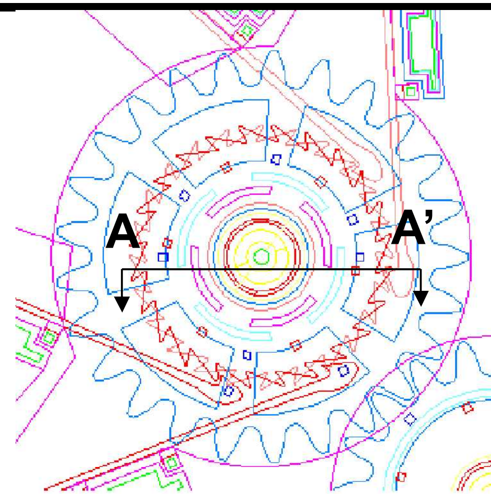
A series of structural and sacrificial layers are deposited

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

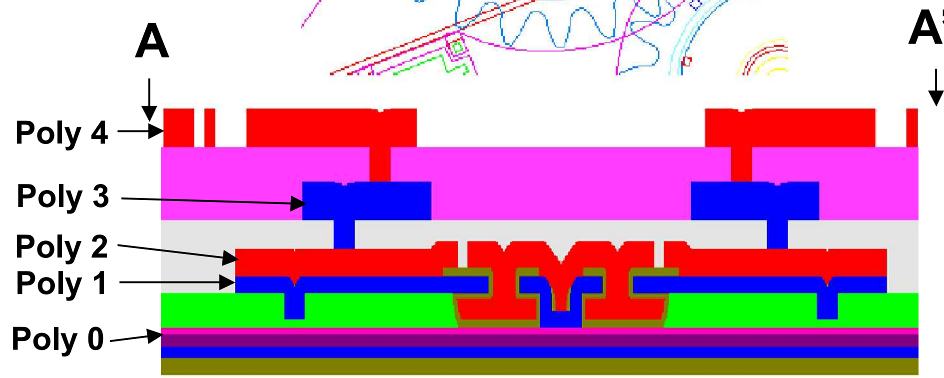
Chemical Mechanical Planarization (CMP)

1 μm design rule

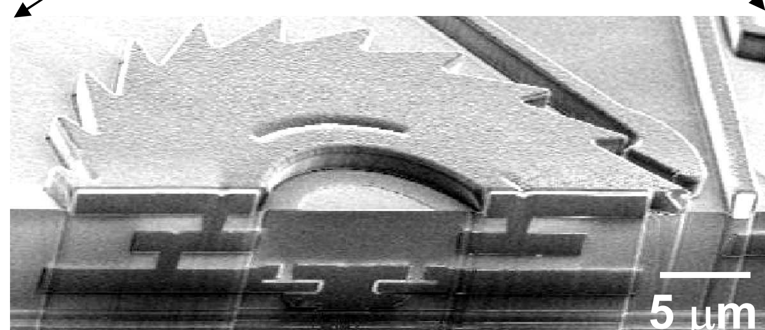
Create freestanding thin film structures by "release" process



Design



Cross-section drawing



FIB cross-section

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

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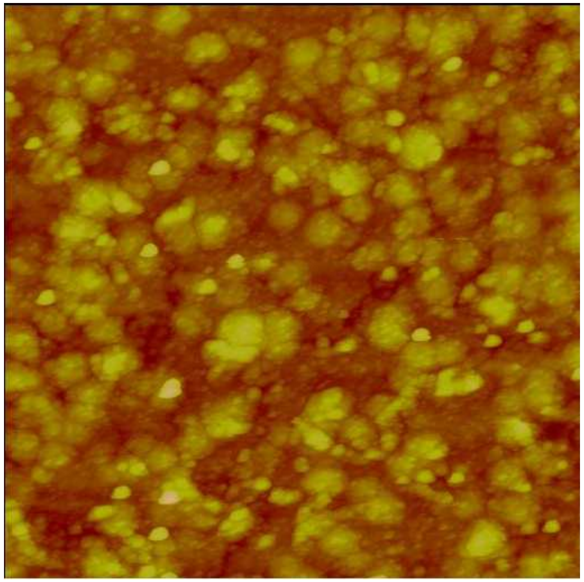
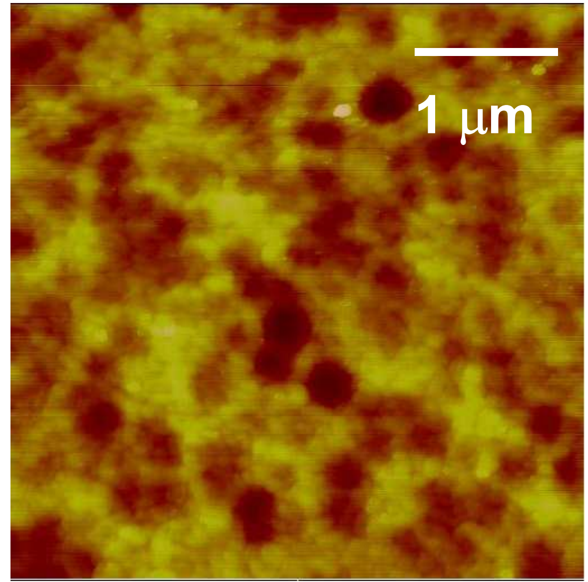
Surface contact is an aggregate of asperities



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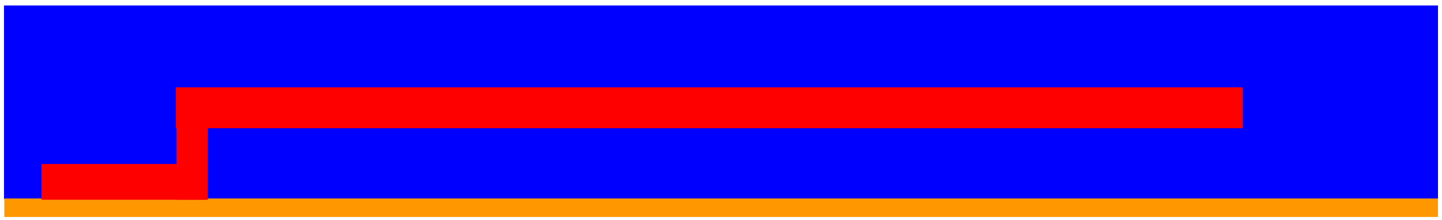
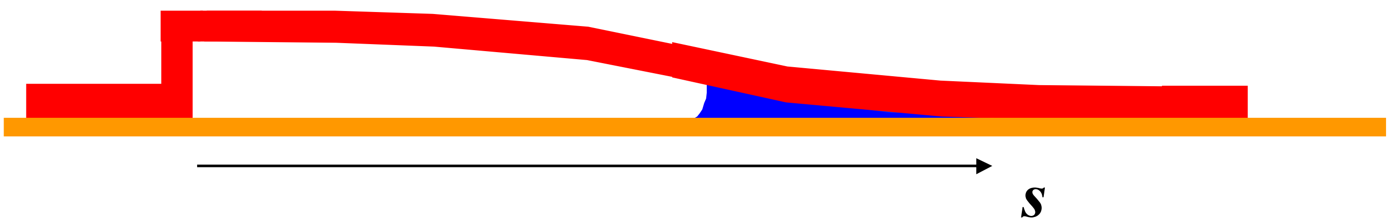
Adhesion (e.g., "stiction") is a big problem in micromachining

Initially free beam, but still in water



Drying leads to "stiction"



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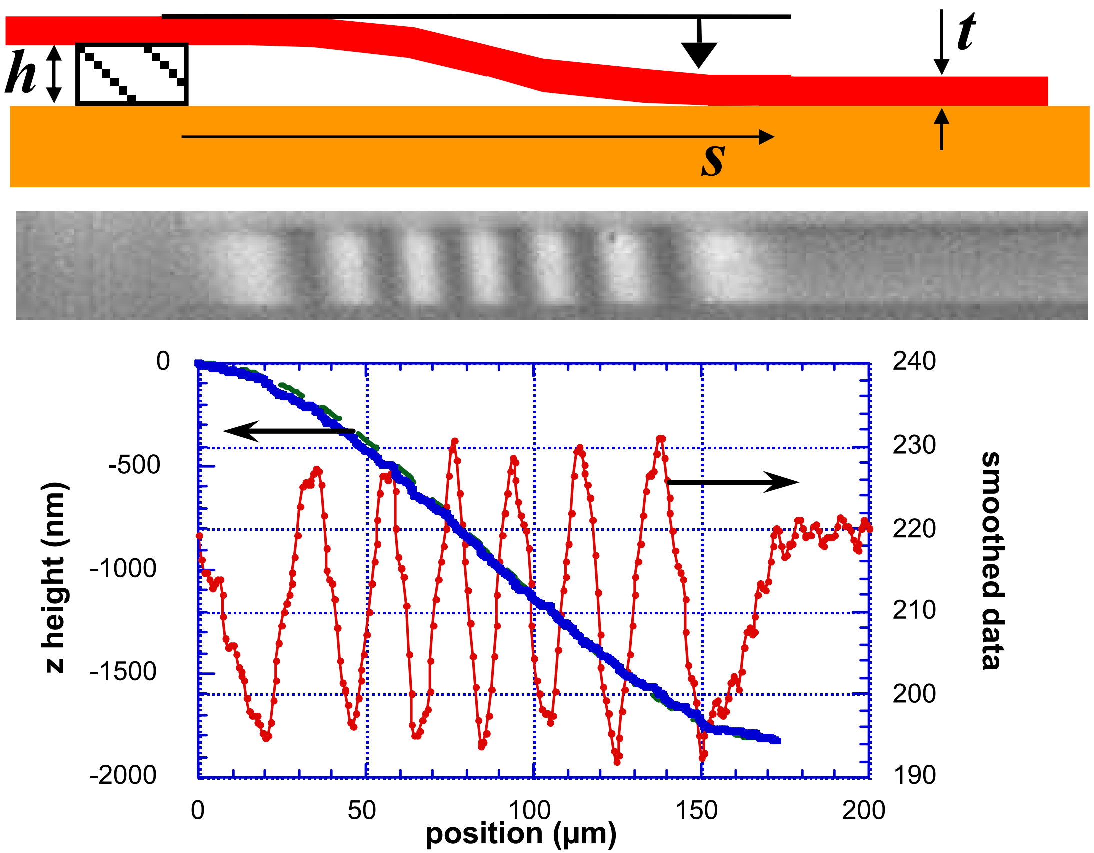
We can use cantilevers to quantify the adhesion, Γ



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

$$G = -\frac{dU_E}{wds} = \frac{3}{2} E \frac{h^2\ t^3}{s^4} = \Gamma = 10\ \frac{\mathrm{mJ}}{\mathrm{m}^2}$$

(drying from water)

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

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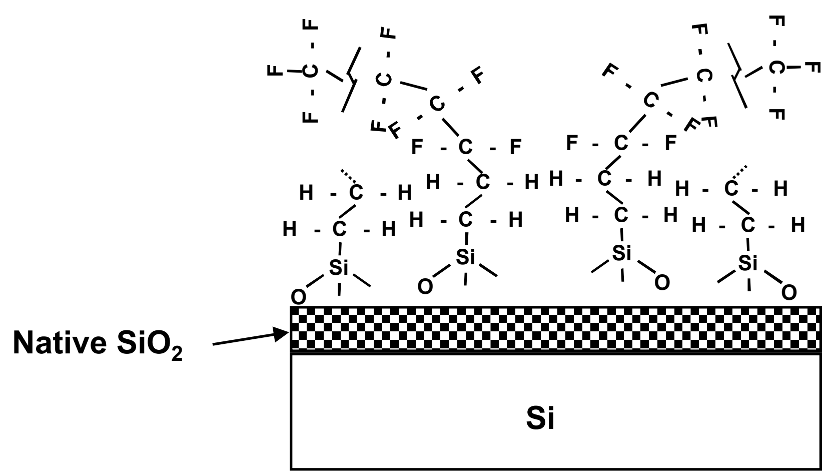
MEMS monolayer coupling agent

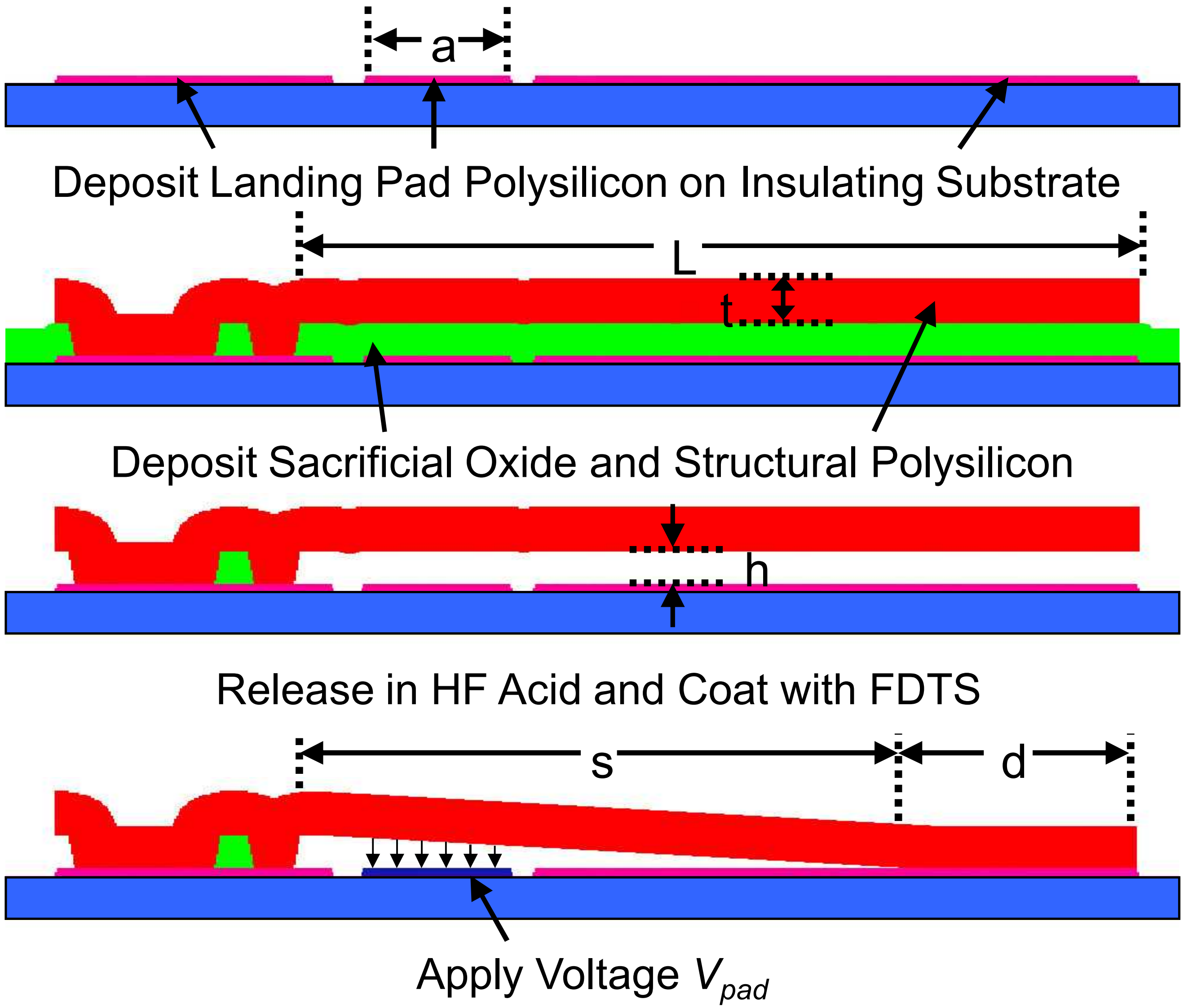
FOTAS (tridecafluoro-1,1,2,2-tetrahydrodecyltris(dimethylamino)silane)

- 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)



Microcantilever process and test flow



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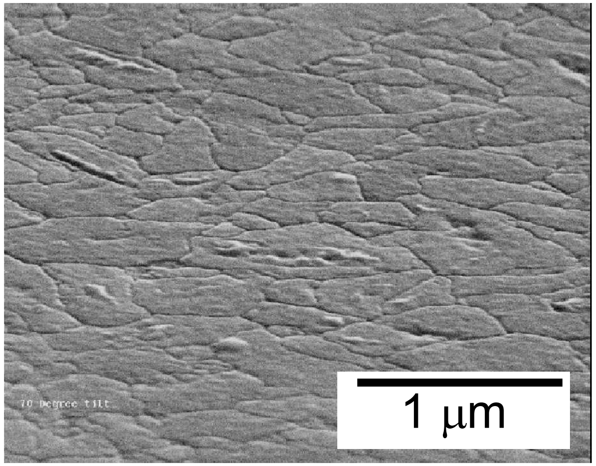
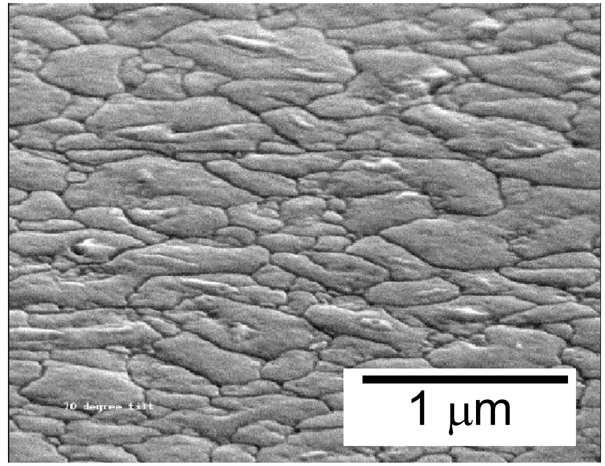
Oxidize the Poly 0 Surface to change surface roughness



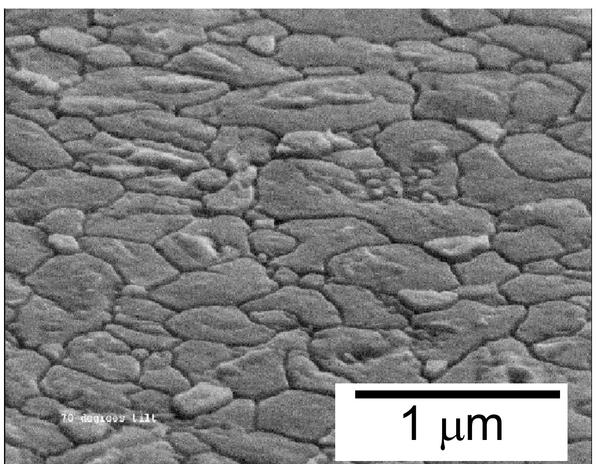
No oxidation, 2.6 nm rms



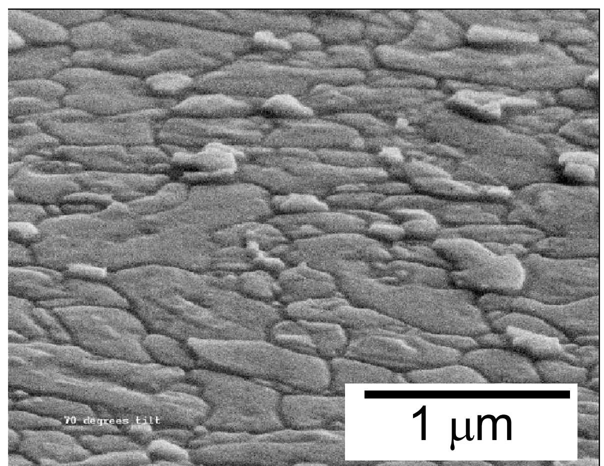
100 Å oxidation, 4.4 nm rms

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



300 Å oxidation, 5.6 nm rms



600 Å oxidation, 10.3 nm rms

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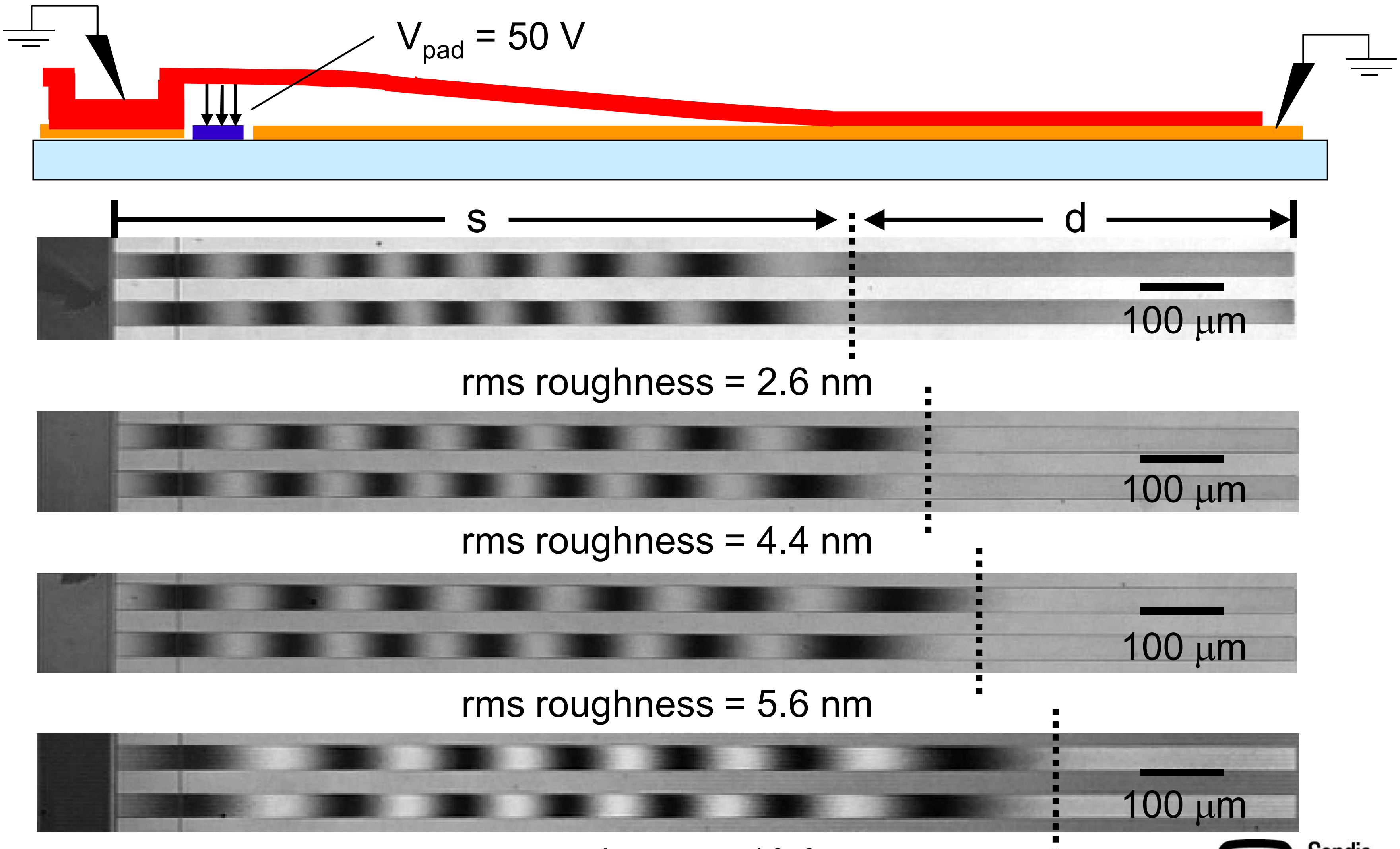
Interferograms show qualitative relationship between surface roughness and crack length



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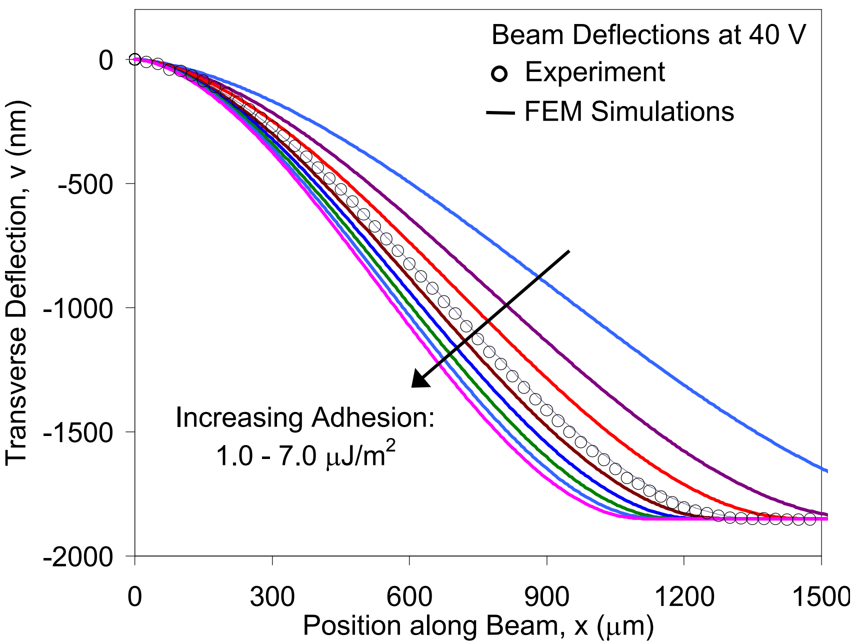
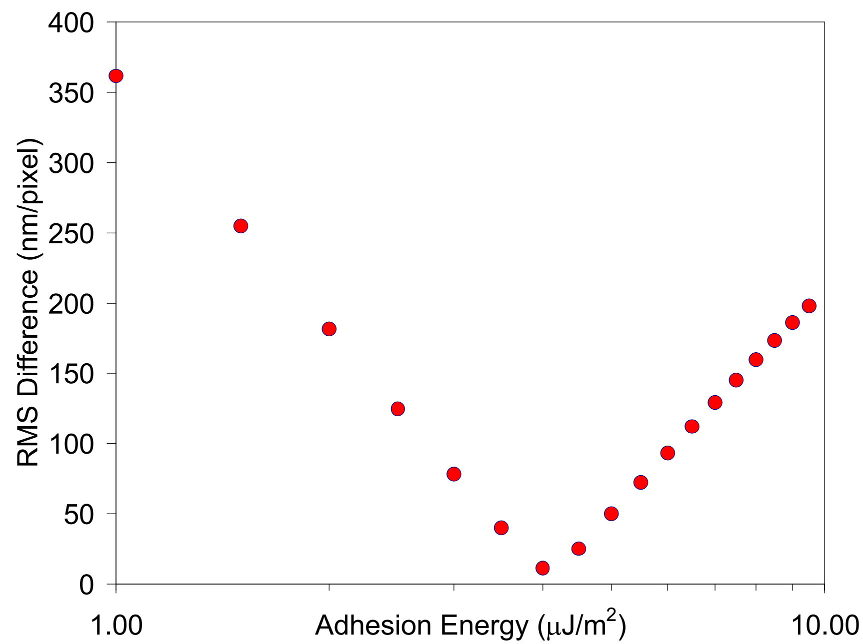
Adhesion measurement with applied voltage

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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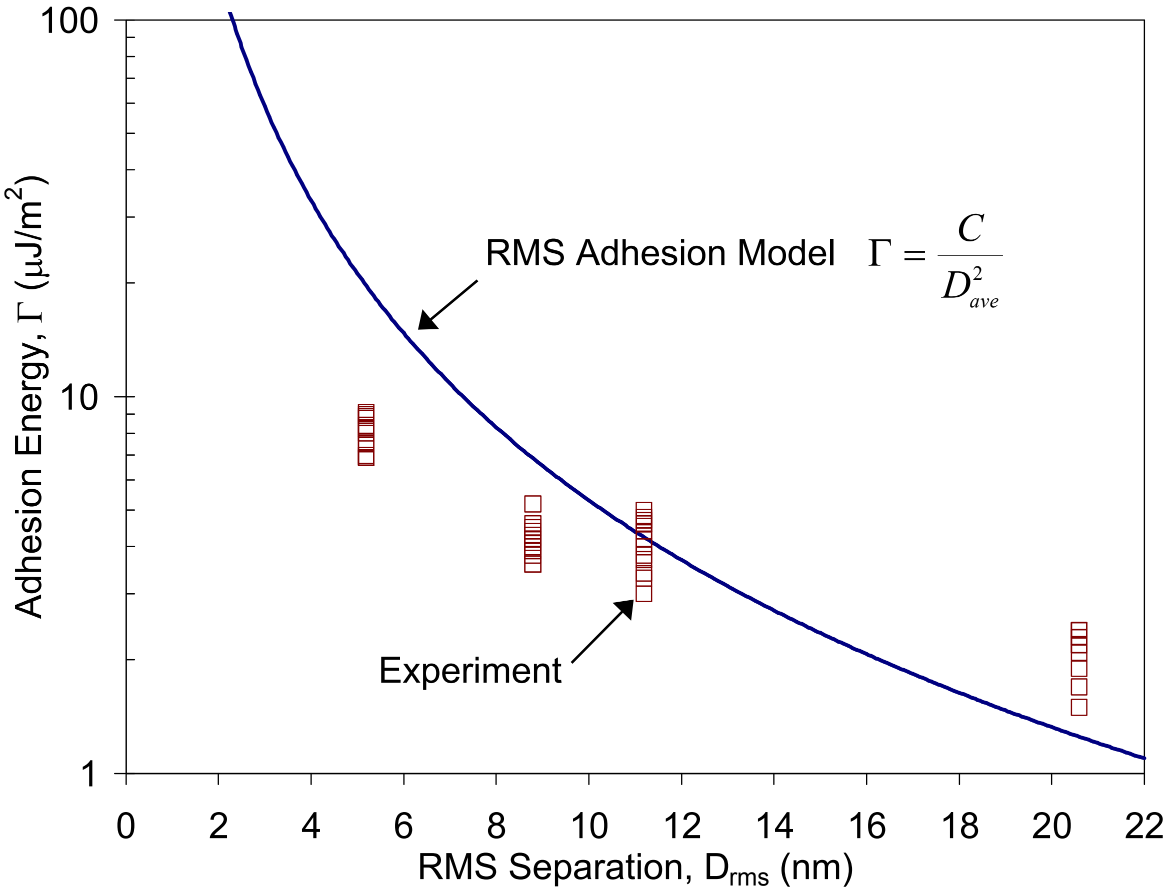
Experimental values of adhesion for each surface roughness

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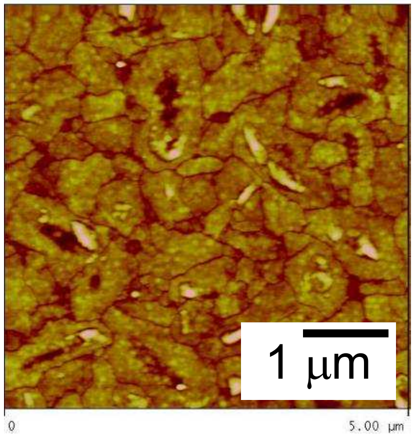
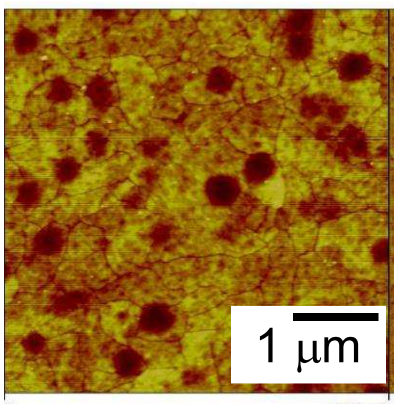
AFM topography data is analyzed using a numerical force-displacement routine

AFM Images

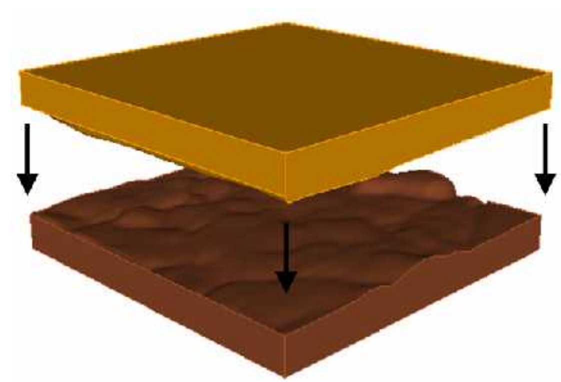




512 x 512 matrix with surface heights entered into force displacement routine

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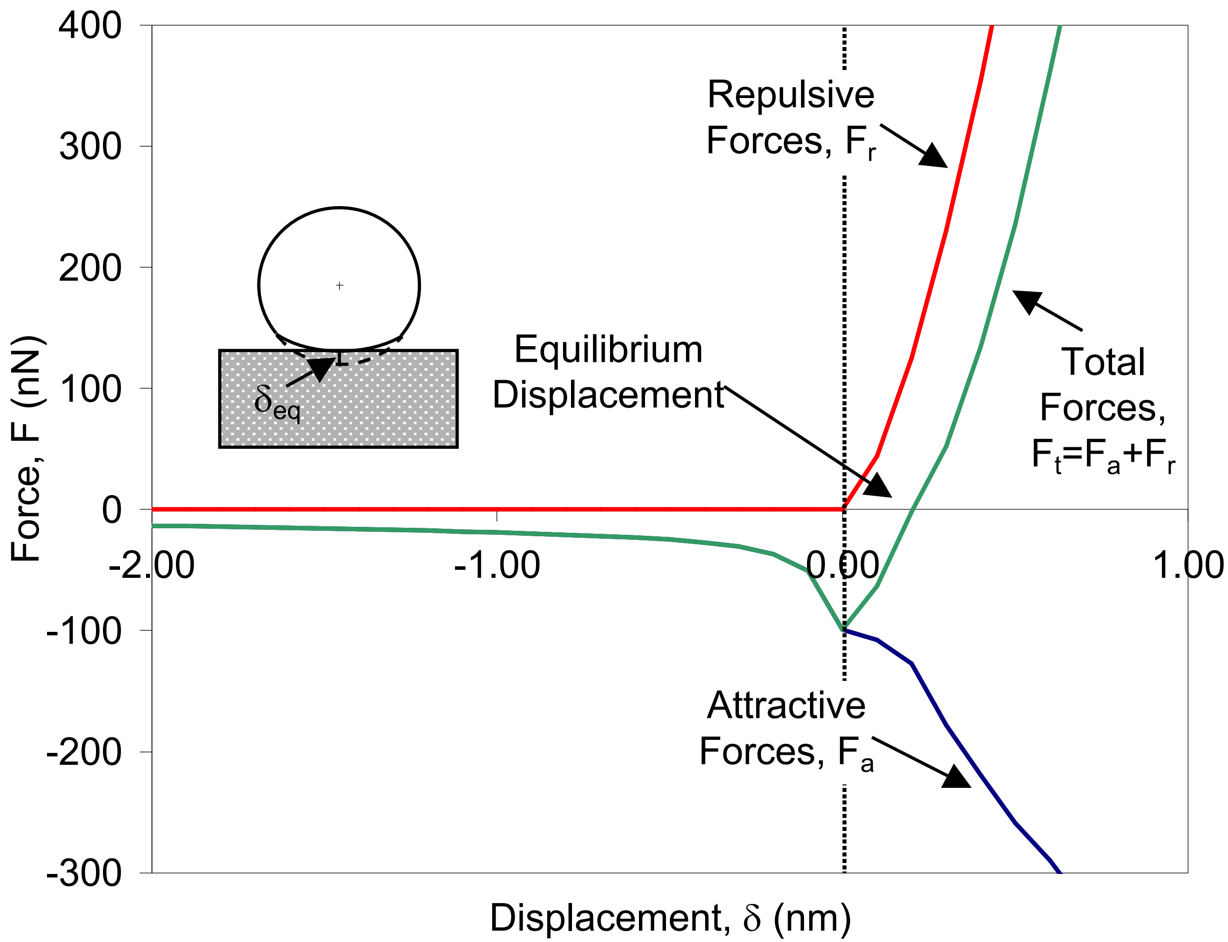
Calculate the total force-displacement curve using the AFM analysis and Hertzian mechanics

Attractive force-displacement curve based on AFM analysis

Repulsive force-displacement curve based on Hertzian mechanics

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

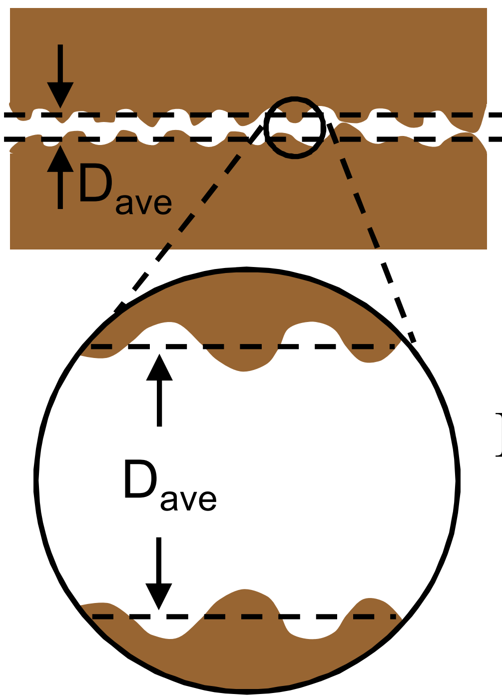
DMT Adhesion Model



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

Two extreme models for adhesion

Smooth Surface



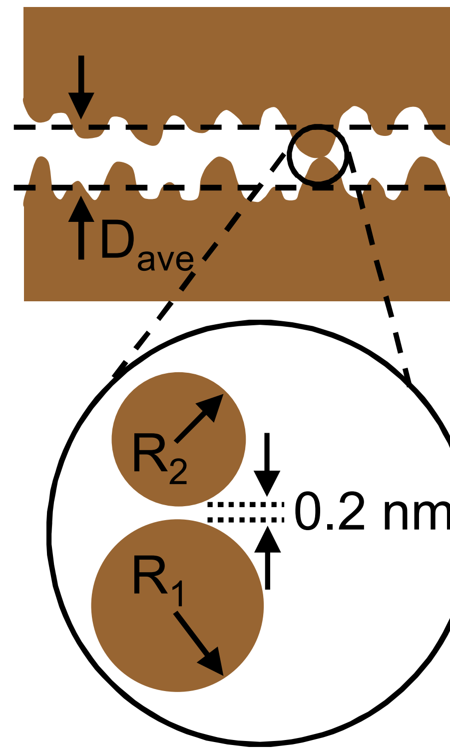
Parallel Plate Model

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

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.

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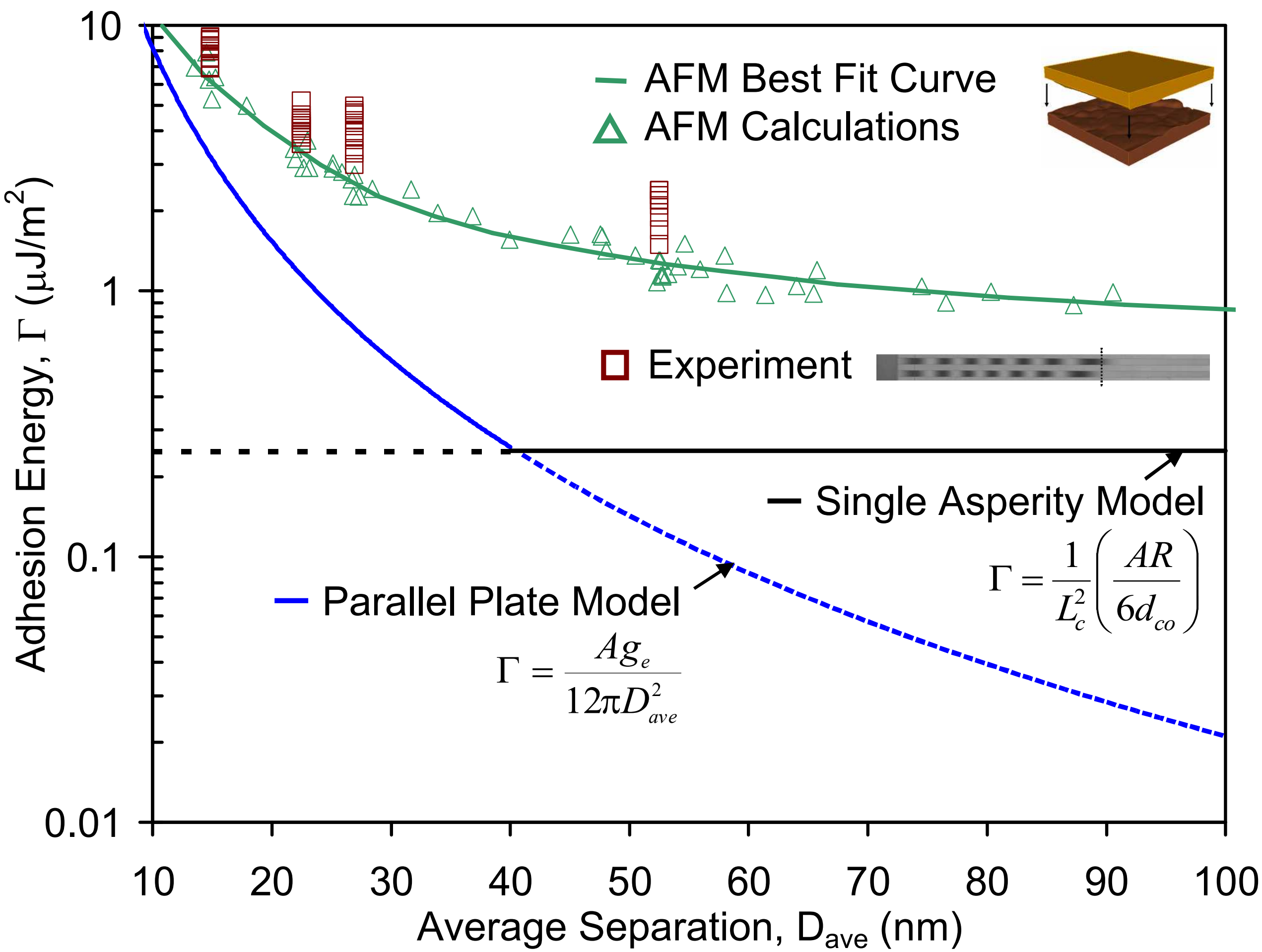
Predicted values of adhesion with AFM data

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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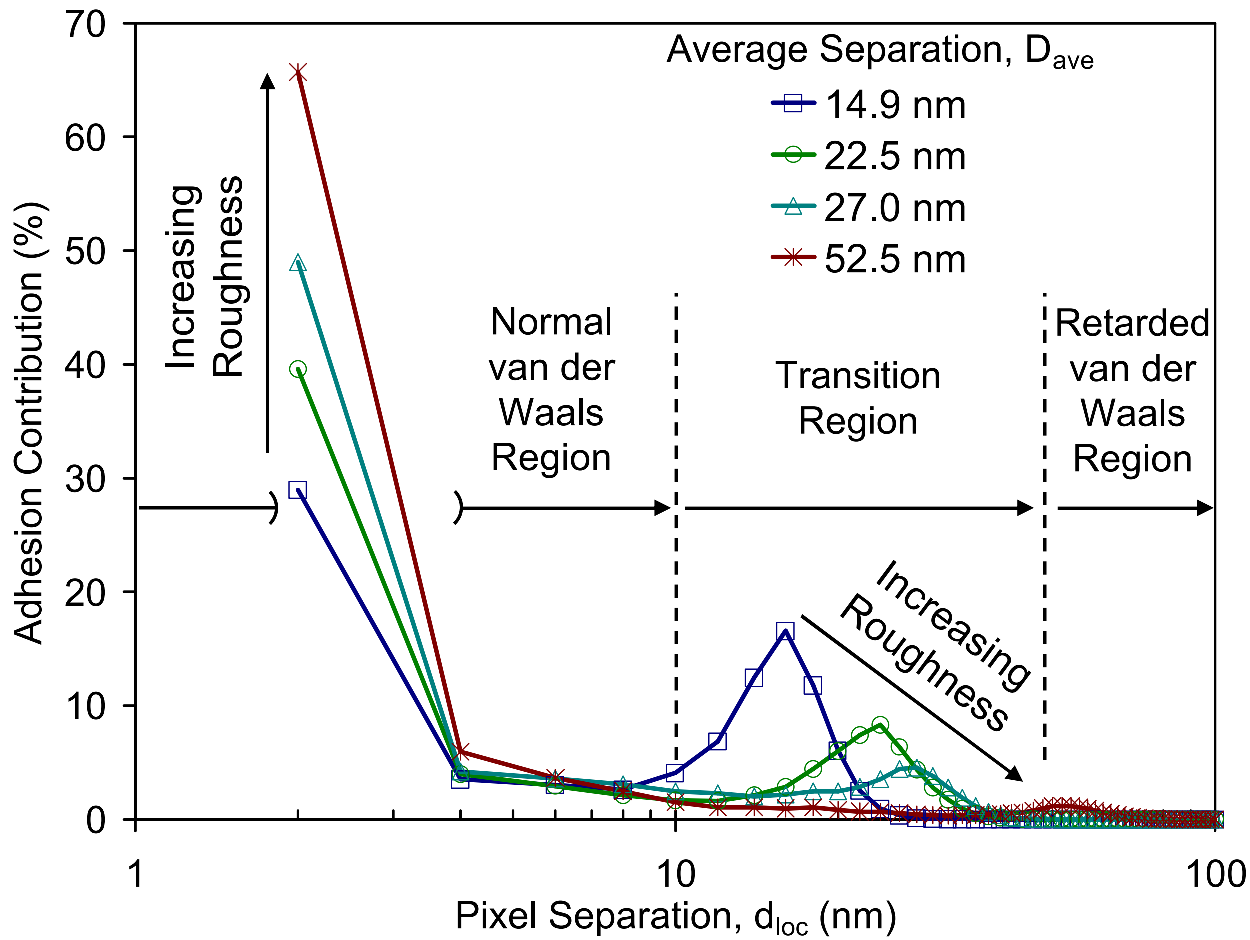
Histogram of adhesion contributions vs. pixel separation

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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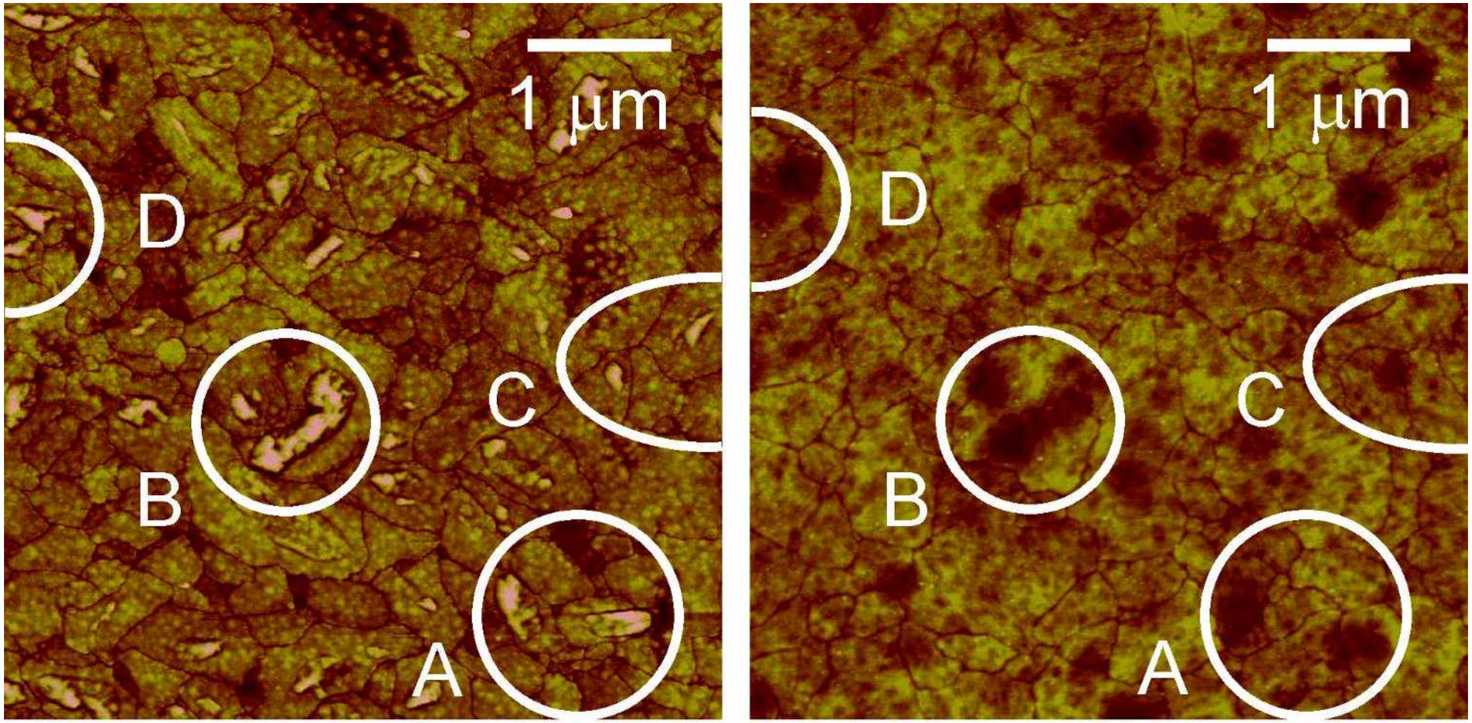
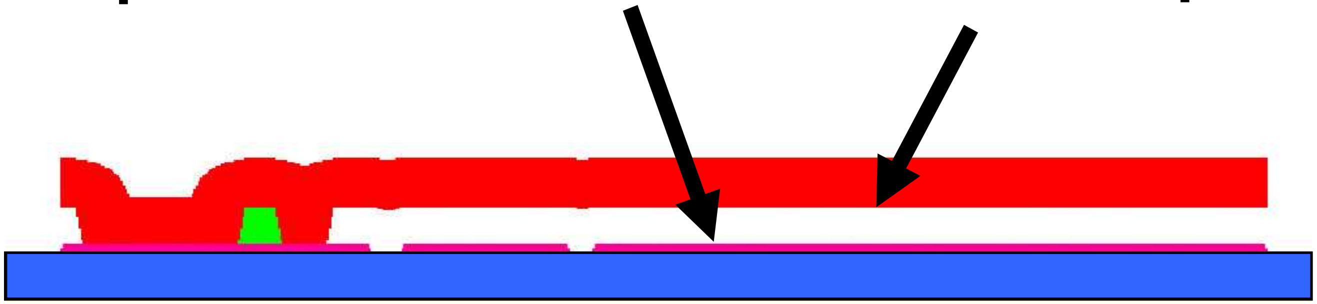
Roughness on top and bottom surfaces is correlated!



Top of bottom surface **Bottom of top surface**



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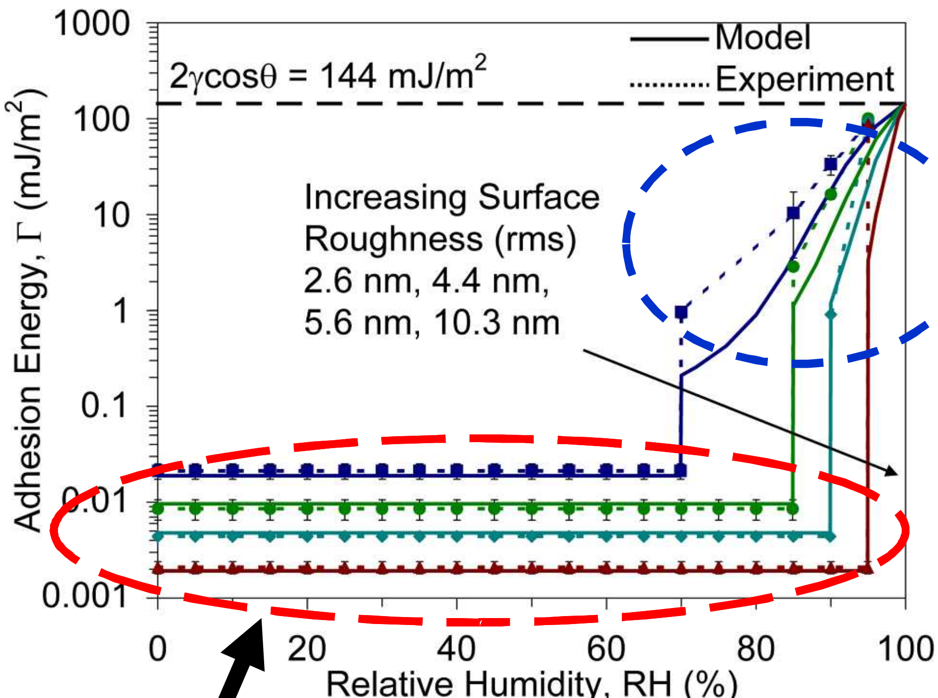
Taking correlation into account makes model/experiment agreement nearly perfect



Capillary forces can dominate vdW forces!

Model and measurement accounting for surface correlations

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

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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

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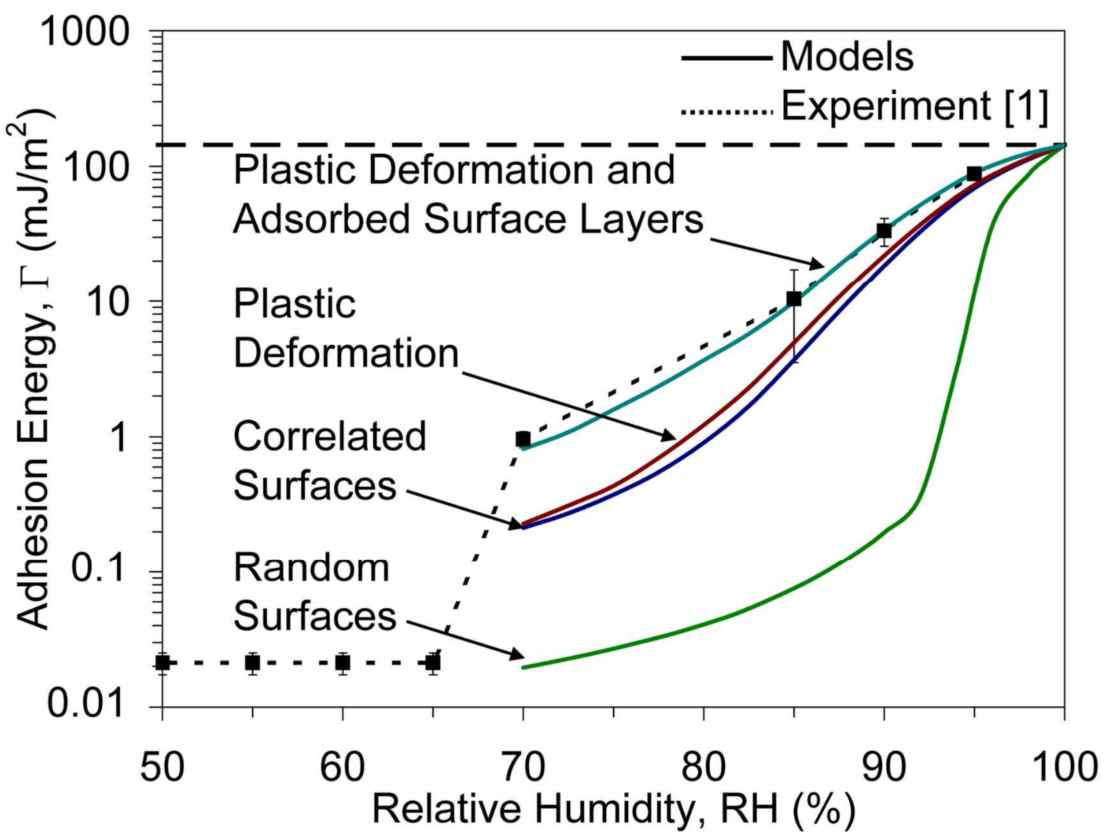
Relative importance of surface correlations, plasticity, and disjoining pressure



DelRio, Dunn and de Boer, Scripta Materialia (2008)

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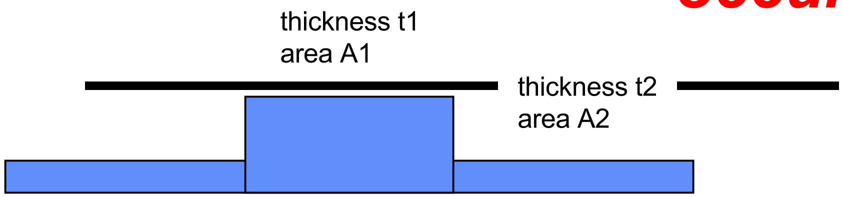
Disjoining Pressure of a liquid film on a surface - occurs when vdW force is repulsive



Imagine that the liquid is surrounded by two flat plates. One is the substrate. The other is a distance t above the substrate - in reality, this is ambient air. Ignoring for the moment capillary effects, we have two regions A1 and A2 of liquid thicknesses t1 and t2, respectively. Will the system spread the liquid uniformly over the substrate or will t2 grow at the expense of t1?

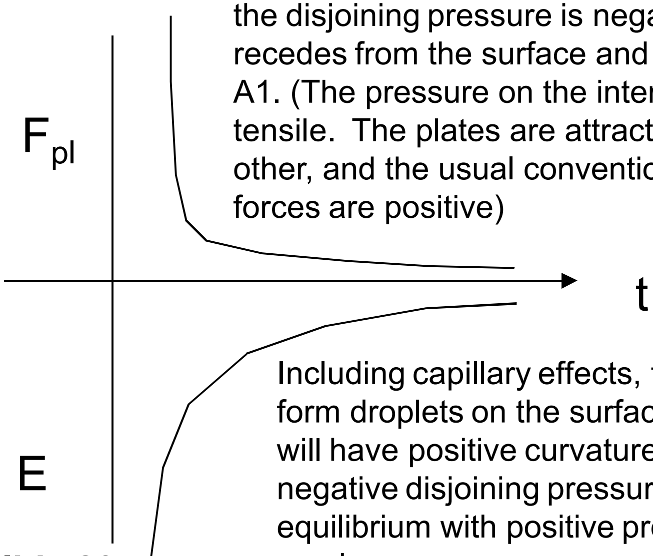
Hamaker Eqn. E is liquid energy/unit area. F_{pl} is force/area two plates would feel if surrounding anintervening liquid

$$E = -\frac{A}{12\pi} t^{-2}$$

$$F_{pl} = \frac{dE}{dt} = \frac{A}{6\pi} t^{-3}$$

A>0

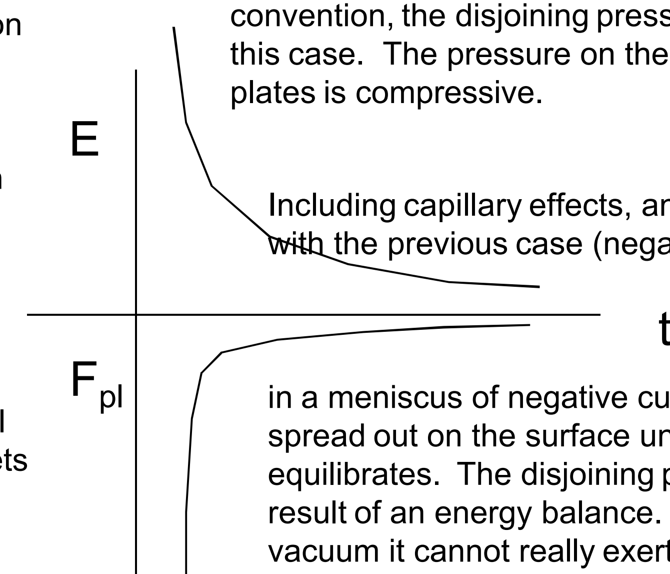
Assuming constant volume of the liquid, by considering the system energy, thickness t1 in area 1 grows at expense of t2 in area 2. Thickness t2 will approach zero. By convention the disjoining pressure is negative because it recedes from the surface and collects in area A1. (The pressure on the intervening liquid is tensile. The plates are attracted towards each other, and the usual convention is attractive forces are positive)



Including capillary effects, the liquid film will form droplets on the surface. These droplets will have positive curvature, and therefore negative disjoining pressure films are in equilibrium with positive pressure in the meniscus.

A<0

thickness t1 in area 1 reduces until there is a uniform thickness of the liquid. If t2 is initially zero, liquid will spread over the system. By convention, the disjoining pressure is positive in this case. The pressure on the intervening plates is compressive.



Including capillary effects, and contrasting with the previous case (negative d.p.), liquid in a meniscus of negative curvature will spread out on the surface until the pressure equilibrates. The disjoining pressure is the result of an energy balance. With air or vacuum it cannot really exert a f[illegible]P=0 for a flat surface). However, when dE/dt is minimized, the result is in terms of pressure.

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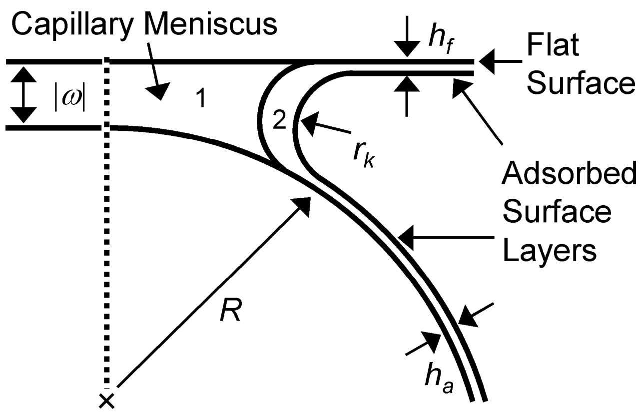
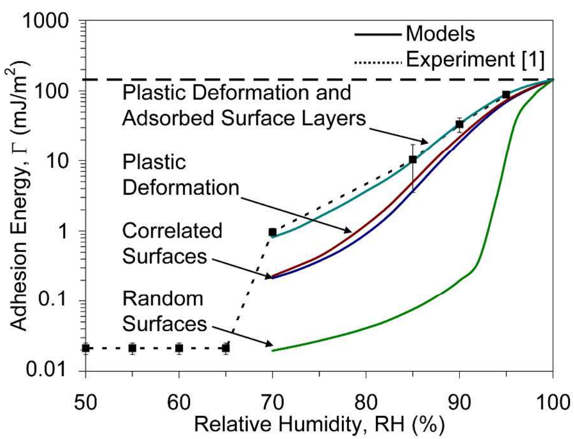
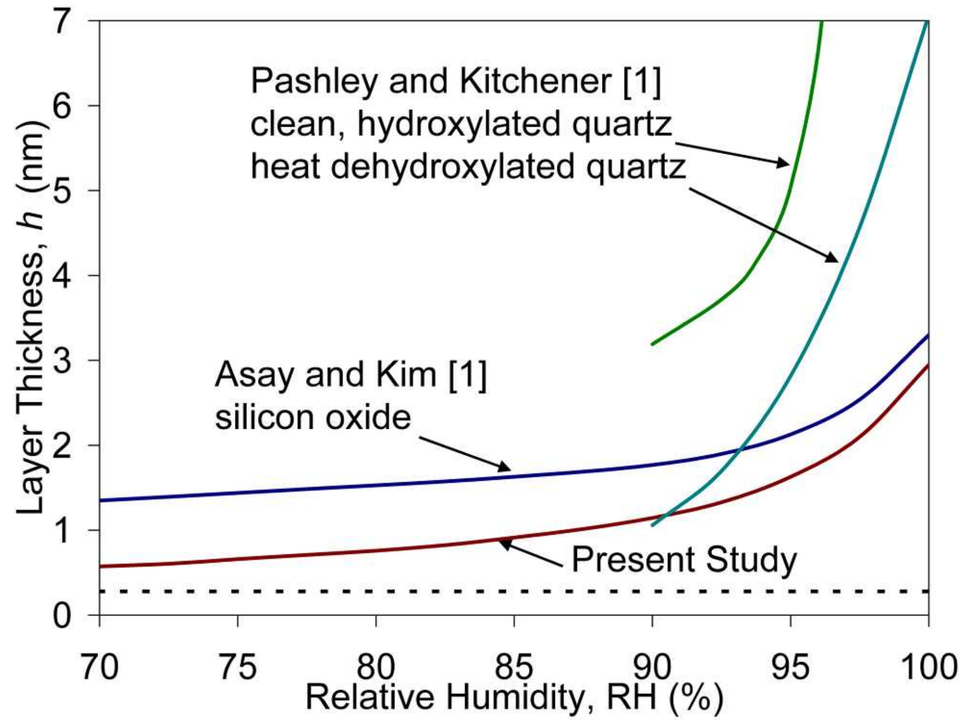
The disjoining pressure is equal to the capillary pressure and increases the effective volume of the meniscus







DelRio, Dunn and de Boer, Scripta Materialia (2008)

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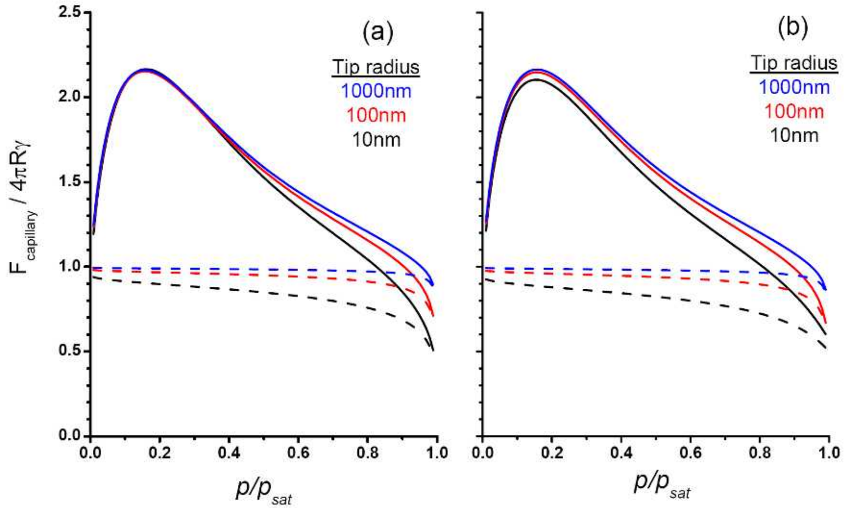
The effect of disjoining pressure on capillary force can be a factor of 2 to 4 for alcohol vapors

Capillary force calculations



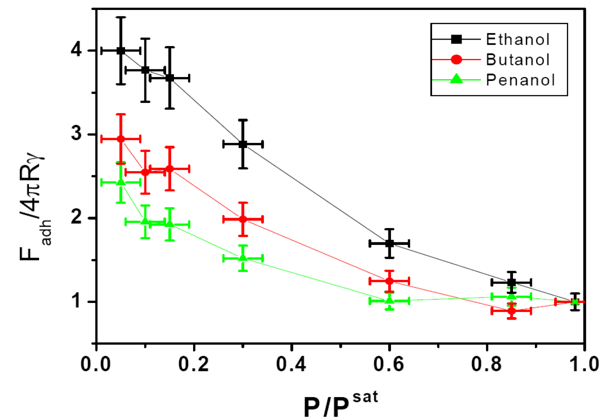
Exact pendular ring calculation

Toroidal approximation

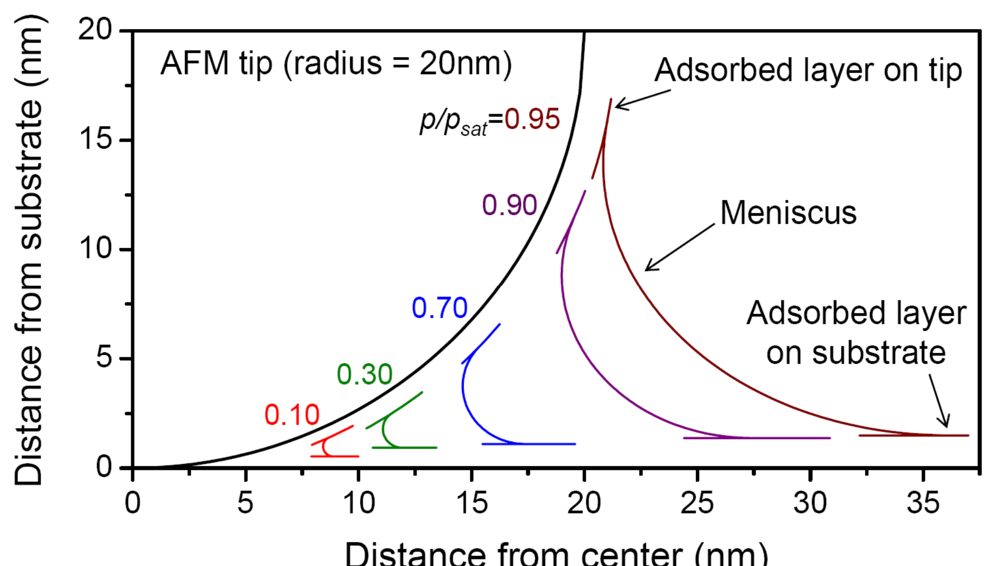
De Boer & de Boer, J. Colloid and Interface Science, (2007)

Asay, de Boer & Kim, J. Adhesion Sc. & Tech. (submitted, 2009)

Single asperity measurements for different alcohol vapors



Calculated Meniscus profiles



Summary - CAPILLARY adhesion in MEMS

Adhesion increases to the mJ/m^2 range for wet systems

Disjoning pressure, due to repulsive vdW forces, significantly increases capillary adhesion

Details of surface roughness are important!