Kavli Institute for Theoretical Physics Conference on Friction, Fracture and Earthquake Physics
Santa Barbara, CA, Aug. 15-19, 2005

Friction in surface micromachined interfaces

Aug. 18, 2005

Maarten P. de Boer
Sandia National Laboratories, Albuquerque, NM
MEMS Devices & Reliability Physics Dept.

Collaborators

Sandia National Labs

- Alex Corwin
- David Luck
- Mike Starr
- Dave Reedy

University of Wisconsin

- Rob Carpick
- Erin Flater

Auburn U.

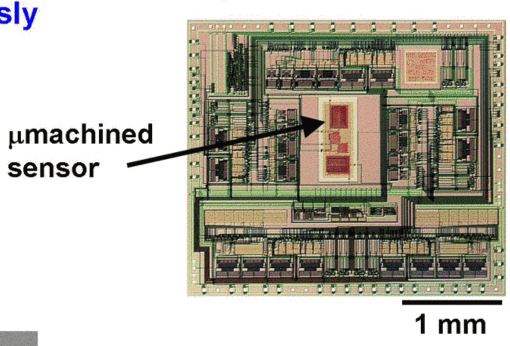
- Bob Ashurst

Funding:
Sandia LDRD programs (DOE)
DOE/BES Center for Excellence in Nanotribology

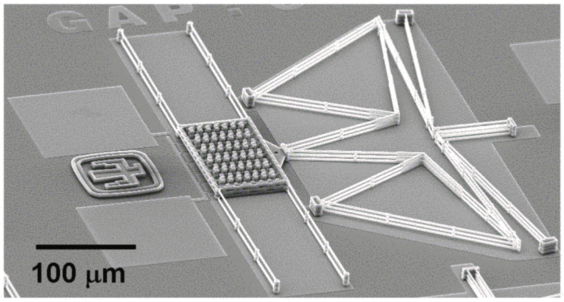
With polysilicon MEMS we can reliably accomplish electromechanical and optical functions

-thousands of devices simultaneously
-no assembly required

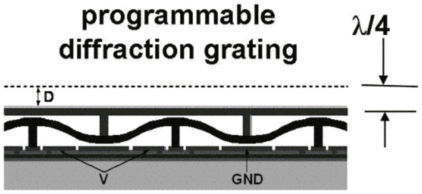
Integrated inertial sensor



High performance comb drive with mechanical amplifier

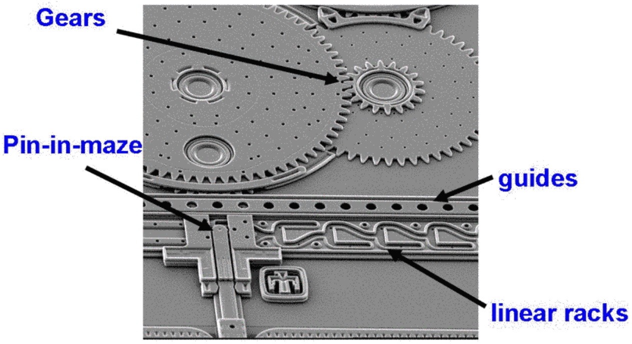


Polychromator : programmable diffraction grating

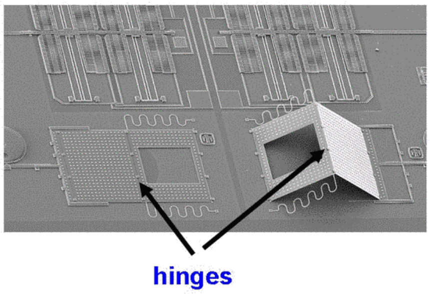


Allowing contact between MEMS surfaces significantly broadens the design space

Complex Mechanical Logic



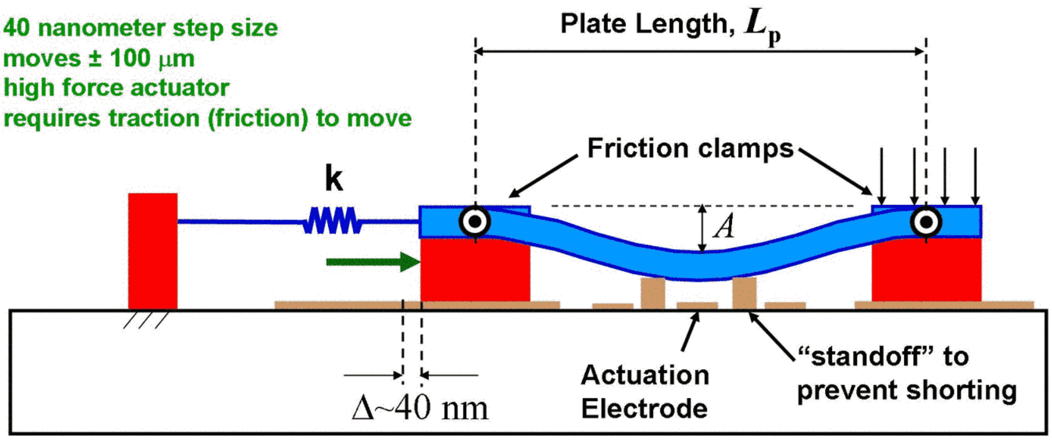
Pop-up Mirrors



<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

Friction can be good: We developed a high-performance friction-based actuator

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



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

large tangential force range

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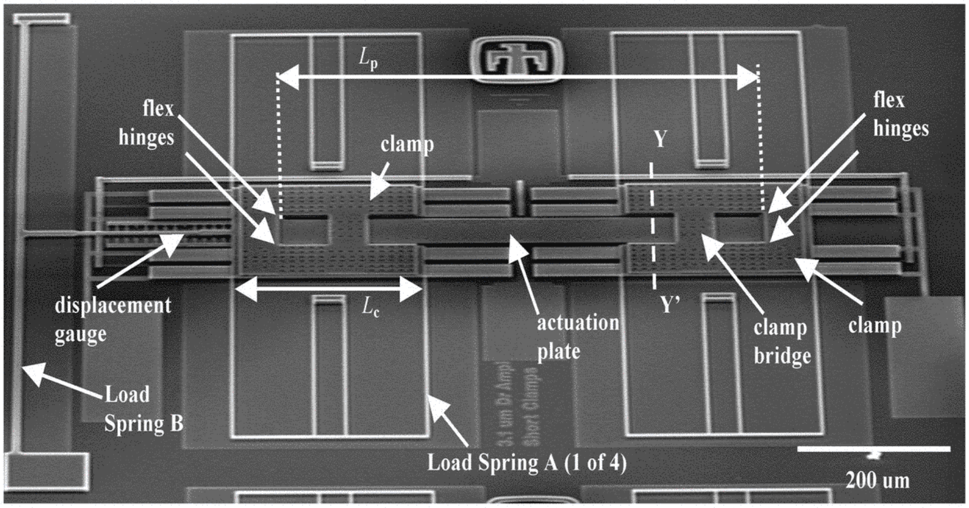
Nanotractor - SEM



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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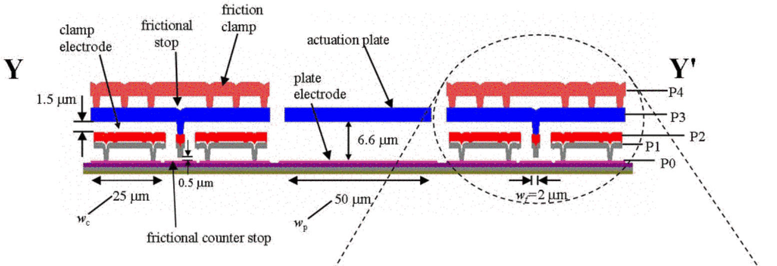
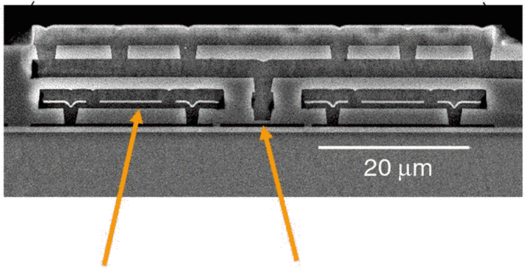
Nanotractor – clamp cross section





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.

large normal force range

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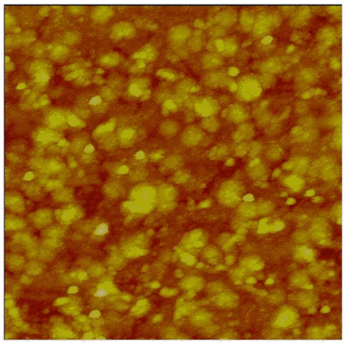
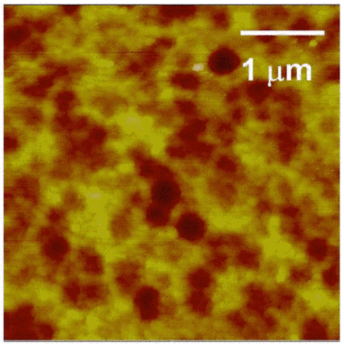
Surface contact is an aggregate of asperities



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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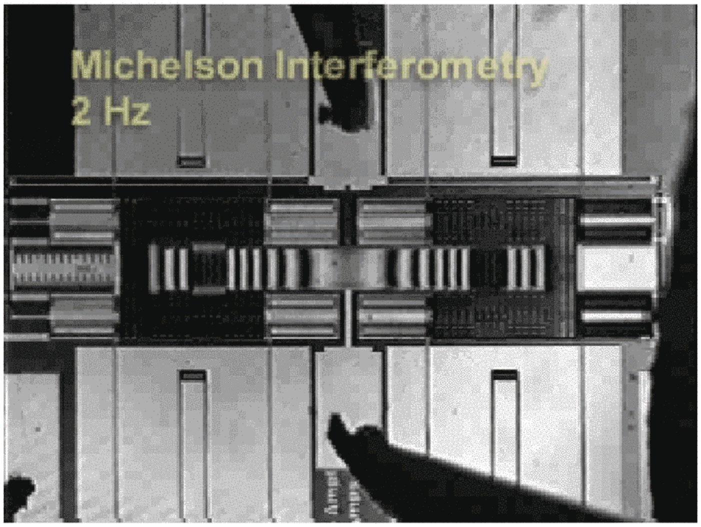
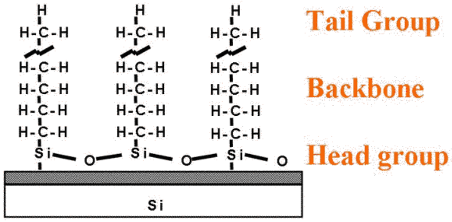
Nanotractor in operation



Monolayer coatings strongly affect frictional behavior

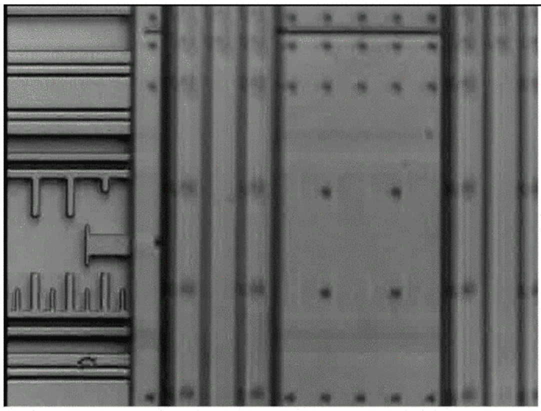
FOTAS (tridecafluoro-1,1,2,2-tetrahydrodecyltris(dimethylamino)silane)
- vapor deposition
- 8 carbon chain
- van der Waals forces not strong enough to self assemble (tangled)
- contact angle ~ 110°

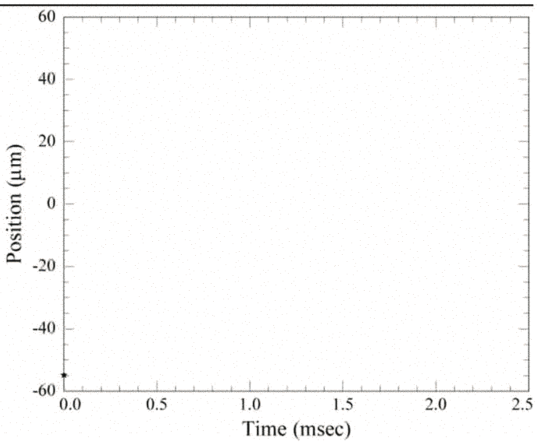
OTS (octadecyltrichlorosilane)
- liquid deposition
- 18 carbon chain
- van der Waals forces strong enough to self assemble.
- contact angle ~ 115°

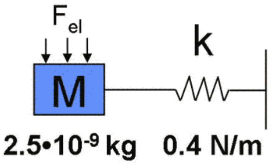


Damped oscillator methodology to obtain true dynamic coefficient of friction

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



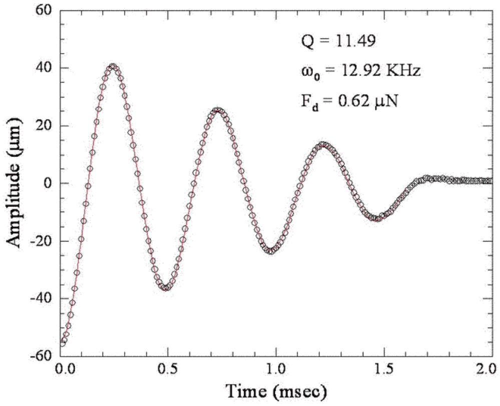




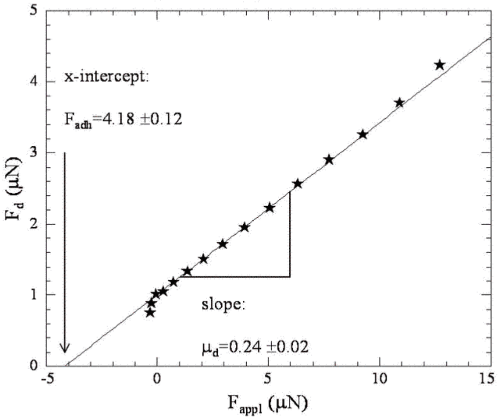
There is friction at zero applied load

FOTAS monolayer

Measured and modeled fit for zero applied load



Dynamic friction over a range of applied loads

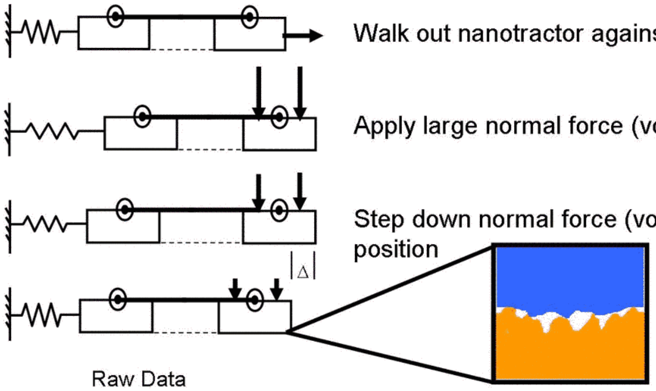


$$F_d = \mu_s \underbrace{(F_c + mg + k_z z)}_{F_{appl}} + \mu_s F_{adh}$$

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

Corwin, AD; de Boer, MP Applied Physics Letters; 29 March 2004; vol.84, no.13, p.2451-3

Static friction measurement



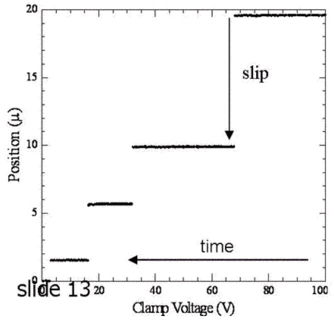
Walk out nanotractor against load spring

Apply large normal force (voltage)

Step down normal force (voltage) and record position

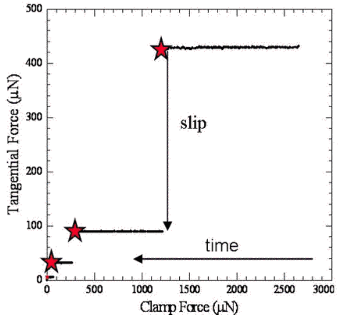
Contacting Asperities

Raw Data



Convert clamp voltage to clamp force and position to tangential force

Force Data



Identify equilibrium points right before jumps where

$F_{Tan} = \mu_s F_N$

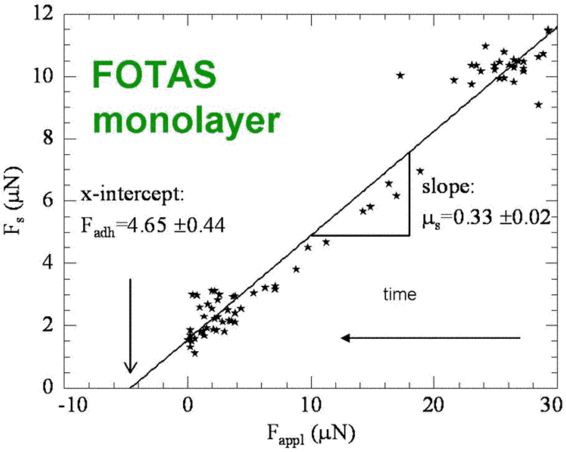
Static Friction Data and Analysis

Plot tangential force as function of applied electrostatic force

Can fit this with Amontons' law if we include adhesive term:

$$\mu_s = 0.33 \pm 0.02$$

$$F_{adh} = 4.6 \pm 0.5\ \mu N$$



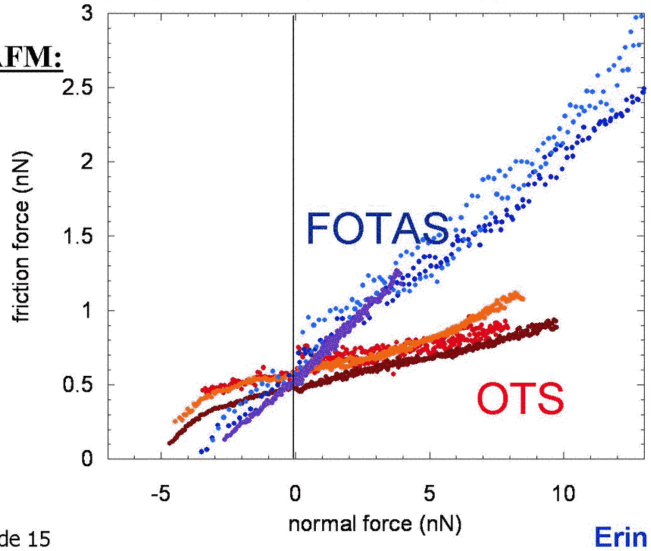
Under static conditions, adhesion also gives rise to friction

Adhesive contribution to force is ~4.7 μN (~1 nN/μm^2)

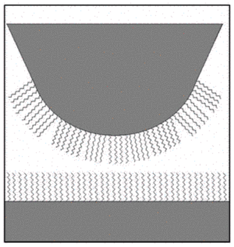
Multi-asperity (MEMS) to single-asperity (AFM) comparison: qualitative agreement

MEMS:	μ_s	μ_d
FOTAS:	0.33 ± 0.01	0.24 ± 0.02
OTS:	0.102 ± 0.001	0.10 ± 0.01

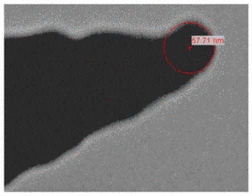
AFM:



AFM: both tip and substrate are coated



TEM of AFM tip



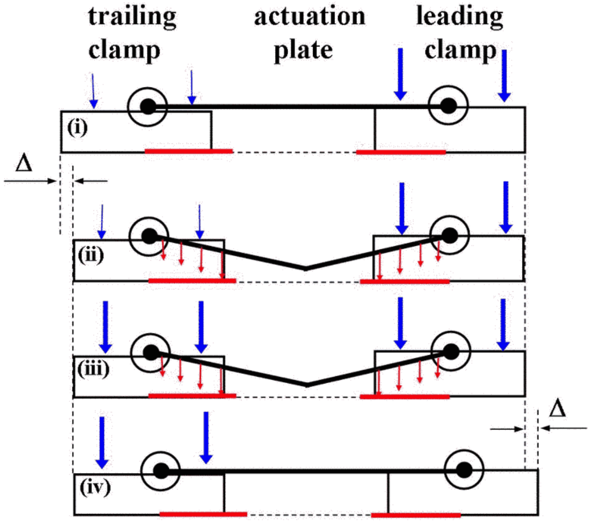
Erin Flater & Rob Carpick, U. Wisc.

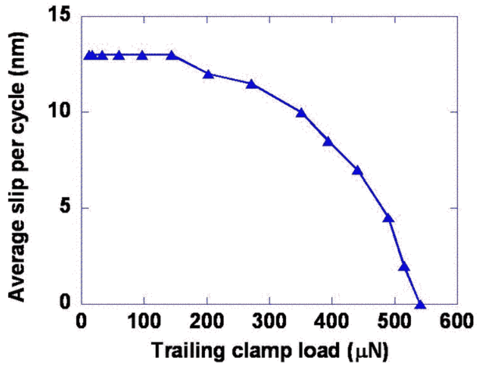
Do μ_s and μ_d describe the nanotractor under operational conditions?

Experiment

FOTAS monolayer

Measured Data





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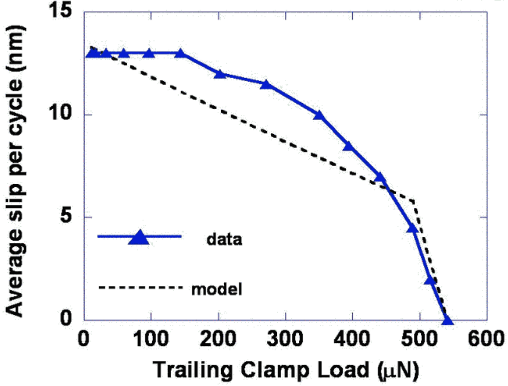
Modeling suggests that μ_s and μ_d CANNOT describe device operation

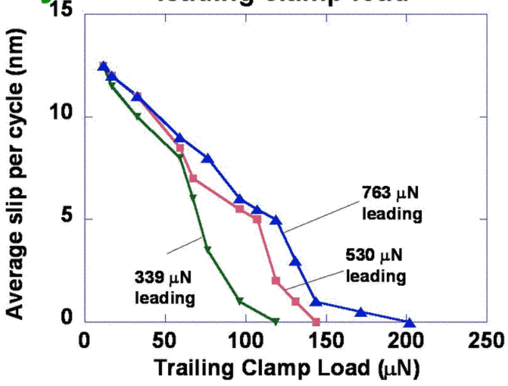
FOTAS monolayer

Model versus experiment



Although agreement may appear reasonable, axial hinge compliance value is unrealistic (value used to fit data is 50 to 100 times too large)

Step size varying the leading clamp load

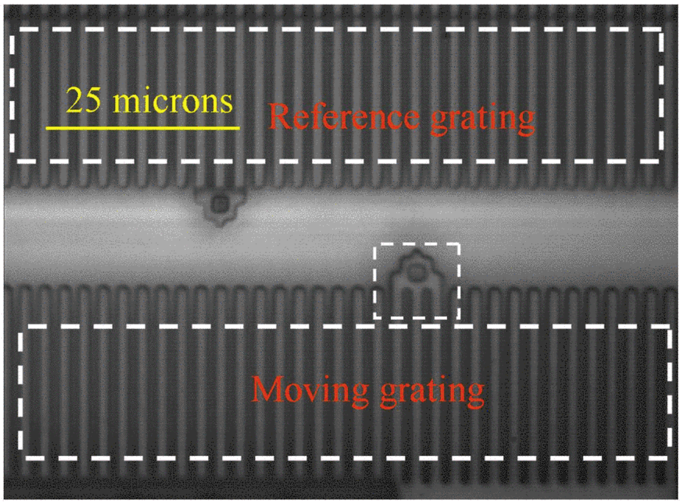


The leading clamp must be slipping backwards!!

D. L. Luck, M. P. de Boer, W. R. Ashurst, A. D. Corwin and M. S. Baker
"Evidence for pre-sliding tangential deflections in MEMS"
Transducers 2003 Conference

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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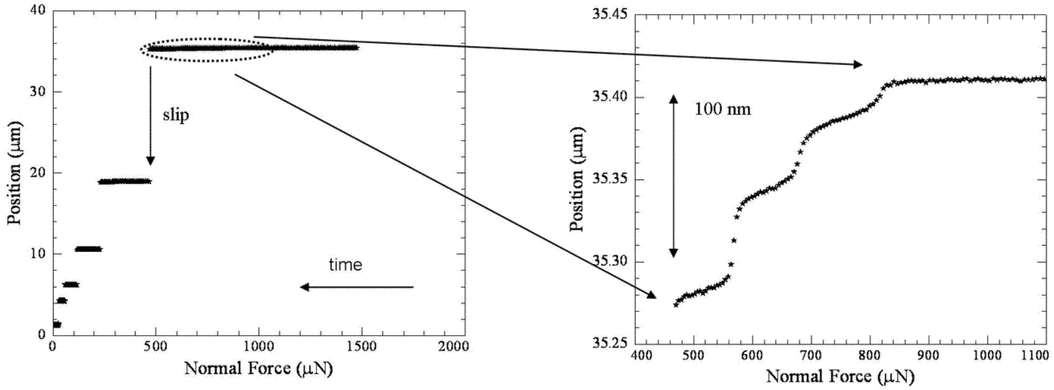
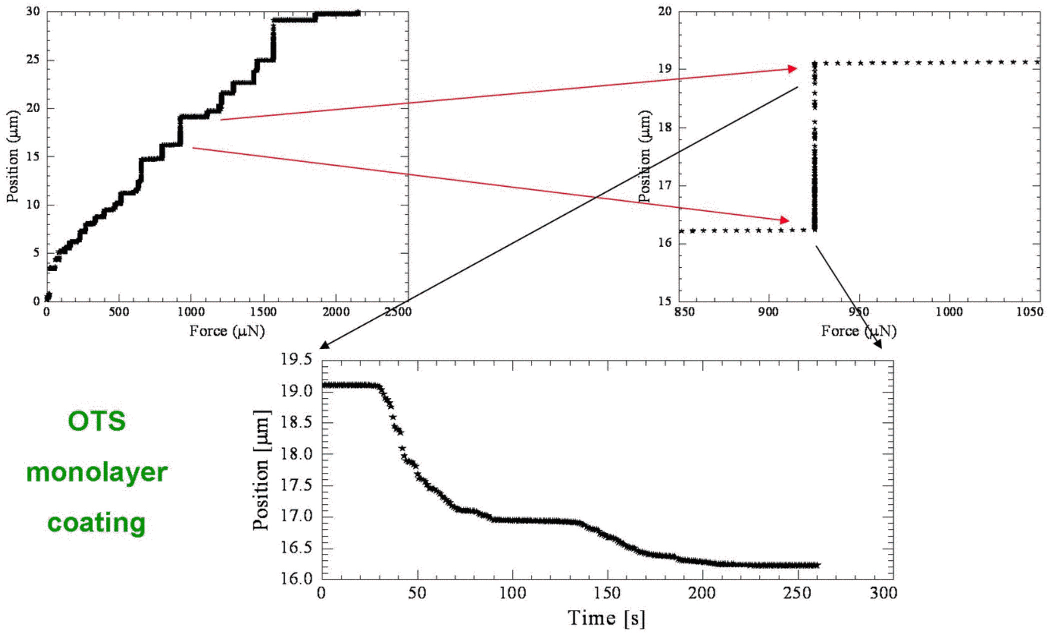
Pre-sliding tangential deflections (PSTD)

FOTAS monolayer coating



Stable in-plane deflections occur before gross sliding event.

OTS shows CREEP rather than PSTD

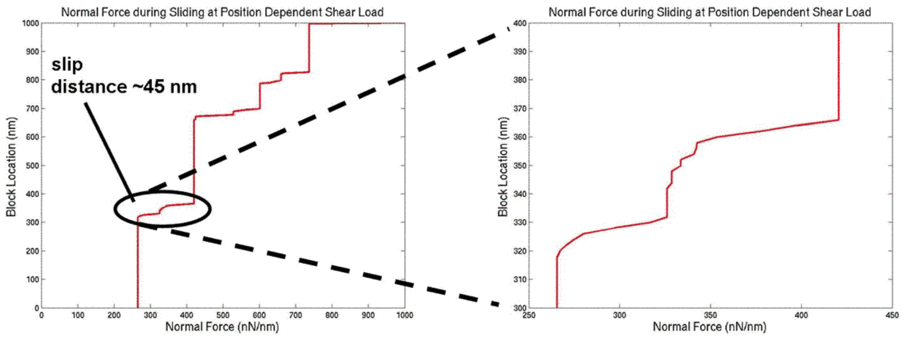


OTS
monolayer
coating

Wait for equilibrium

Simulations indicate PSTD may be stochastic

FOTAS monolayer simulation



Simulation:

2-D linescan of the surface (from real AFM data)

Calculate real contact area at a large normal load (Hertz only)

Reduce load -> contact area reduces until frictional force is surmounted

Clamp moves forward (1 nm), and tangential load reduces slightly

If new position has enough contact area, then new position is stable

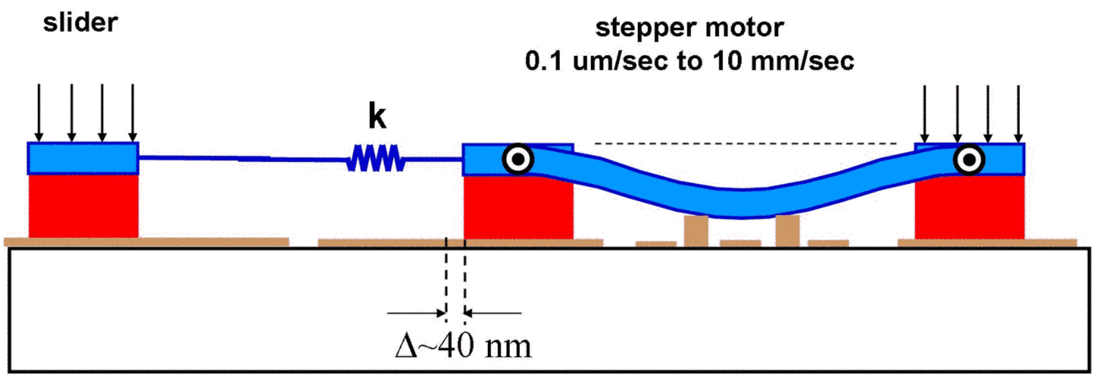
Otherwise get a large position jump

Mike Starr, Sandia

Comparison to Rate & State Phenomenology

Rate & State		**FOTAS**		**OTS**
Do/a~1	pstd:	Do/a~10	creep:	Do/a~300
us > ud		us > ud		us~ud
us=us(t)		unclear		unclear

More direct comparison to rate/state experiments is possible



Summary & Conclusions

- MEMS can serve as a testbed for multi-asperity friction experiments
- At low loads, normal force is dominated by adhesion
- Monolayer static friction correlates from nano to microscale
- PSTD events can govern operation of MEMS nanotractor
- PSTD may be a stochastic effect
- Creep can also dominate and depends on monolayer lubricant