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Frictional studies of a monolayer coated micromachined actuator: Beyond Amontons laws

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Sandia National Labs

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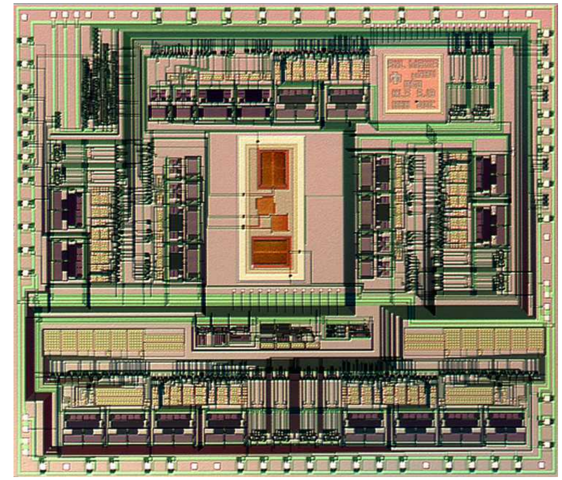
Brief outline

- Reliability challenges in MEMS
- Our optical metrology
- The nanotractor as actuator
- The nanotractor as research instrument
  - Static friction and adhesion
  - Dynamic friction and adhesion
  - Frictional aging – rate-state friction
- Summary of what we have learned

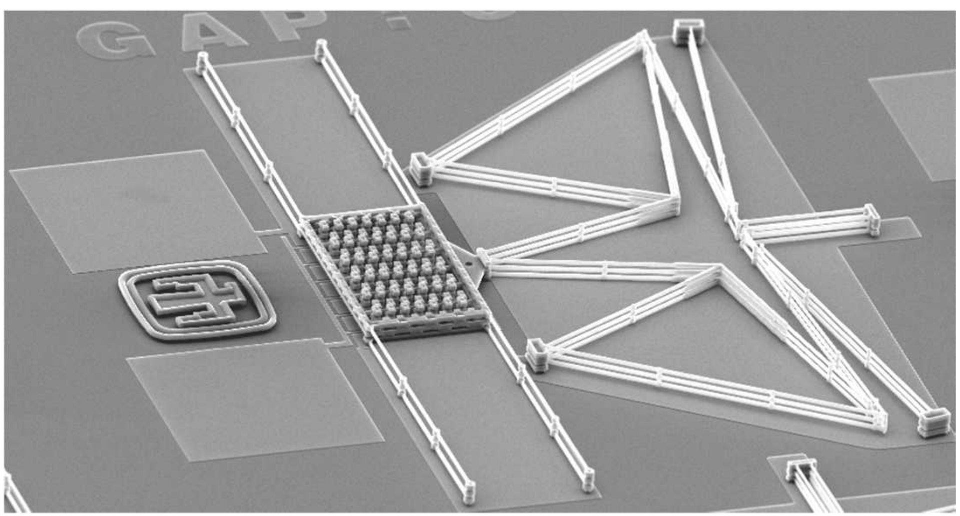
With polysilicon MEMS we can reliably accomplish electromechanical and optical functions

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

Integrated inertial sensor

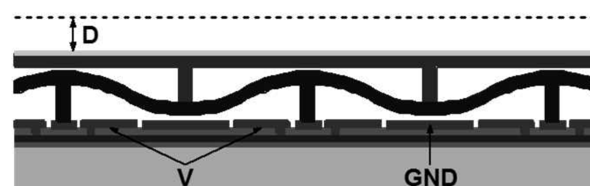


High performance comb drive with mechanical amplifier



Polychromator :

programmable diffraction grating



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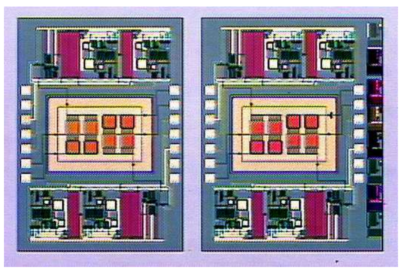
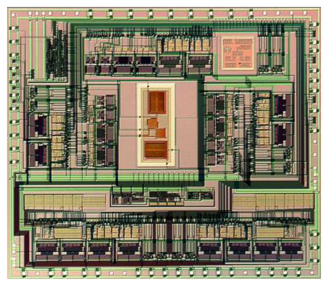
MEMS are RELIABLE – Industry chooses simpler devices

Class I
No Moving parts



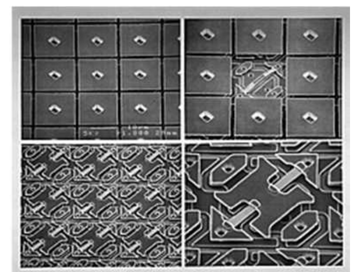
Accelerometers
Pressure Sensors
Inkjet Print Heads
Strain Gauge

Class II
Moving Parts, No Rubbing or Impacting Surfaces



Gyros
Comb Drives
Resonators
Filters

Class III
Moving Parts, Impacting Surfaces



TI DMD ($ 1B)
Relays
Valves
Pumps
Optical Switches

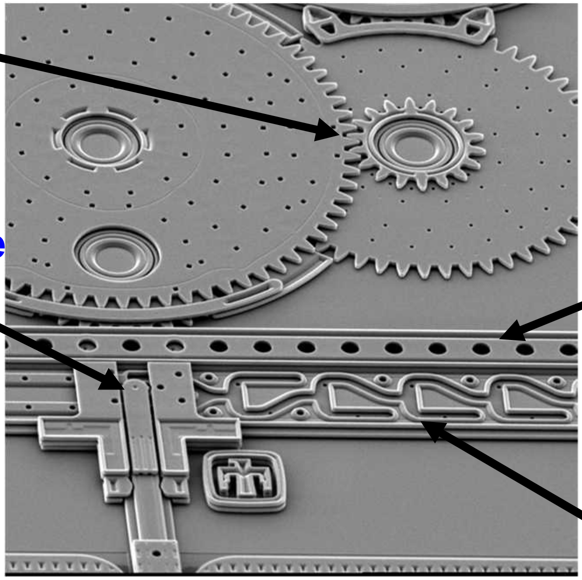
Class IV
Moving Parts, Impacting and Rubbing Surfaces

Optical Switches
Shutters
Scanners
Locks
Discriminators

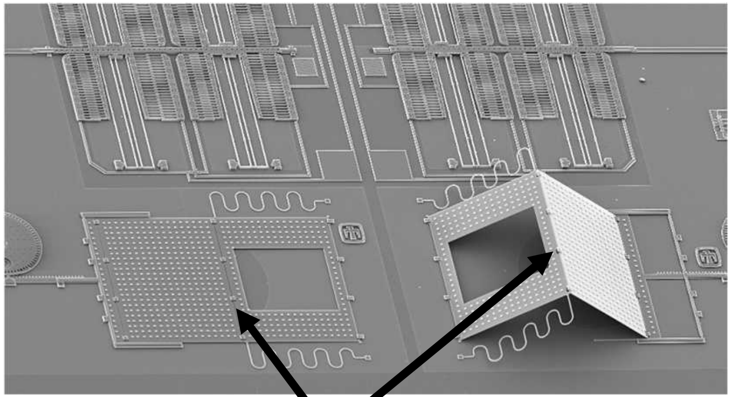
Billions of inkjet print cartridges produced using HP technology!
Analog Devices ships 1 million MEMS accelerometers a week!
Texas Instruments has shipped over 2 million DLP subsystems!

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

How can we understand these mechanisms better?

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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)

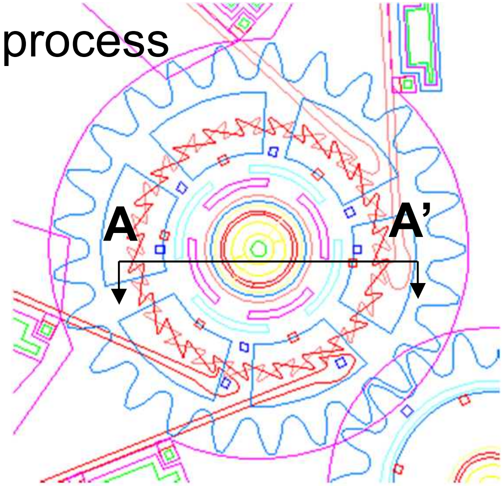
Chemical Mechanical Planarization (CMP)

1 μm design rule

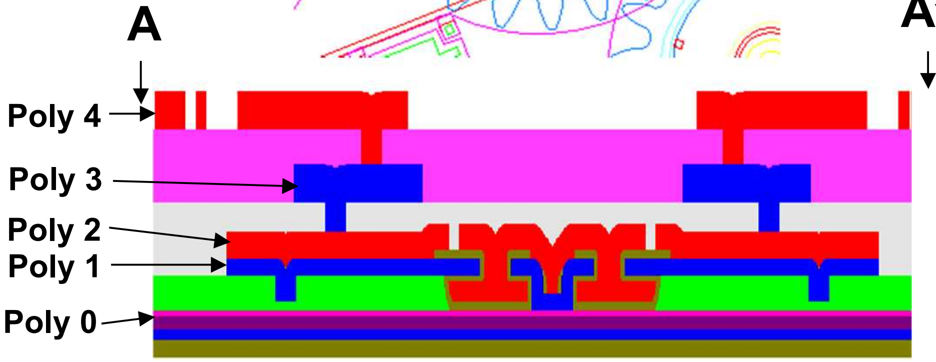
Create freestanding thin film structures by "release" process

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

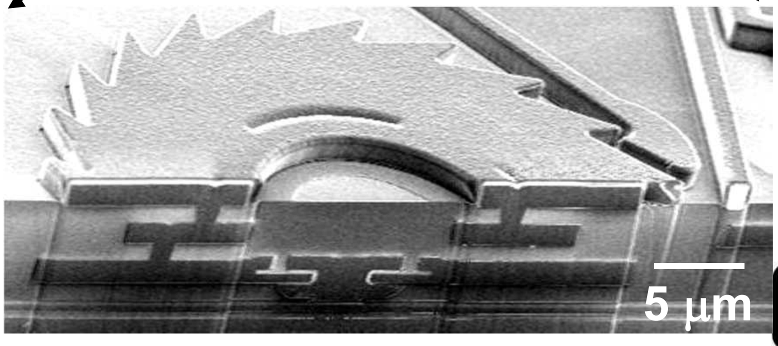
SUMMiT V™ process



Design



Cross-section drawing



FIB cross-section

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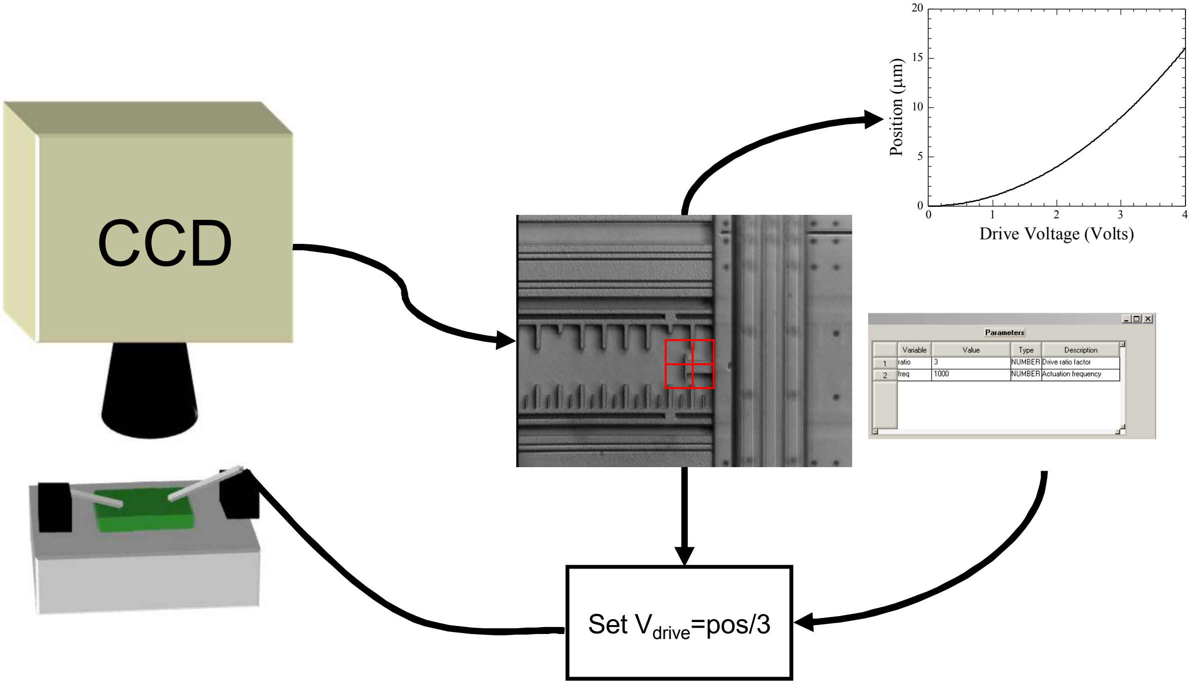
MEMScript An integrated vision and actuation automation tool for MEMS



Licensed to EM Optomechanical, Inc. (EMOM) for commercial sale. Used extensively at Sandia for a wide range of MEMS measurements for a wide range of technologies

Intelligent Actuation: Combine real time in-plane, interferometric, and stroboscopic vision capabilities with full scripting power to allow actuation to respond to vision data in real time

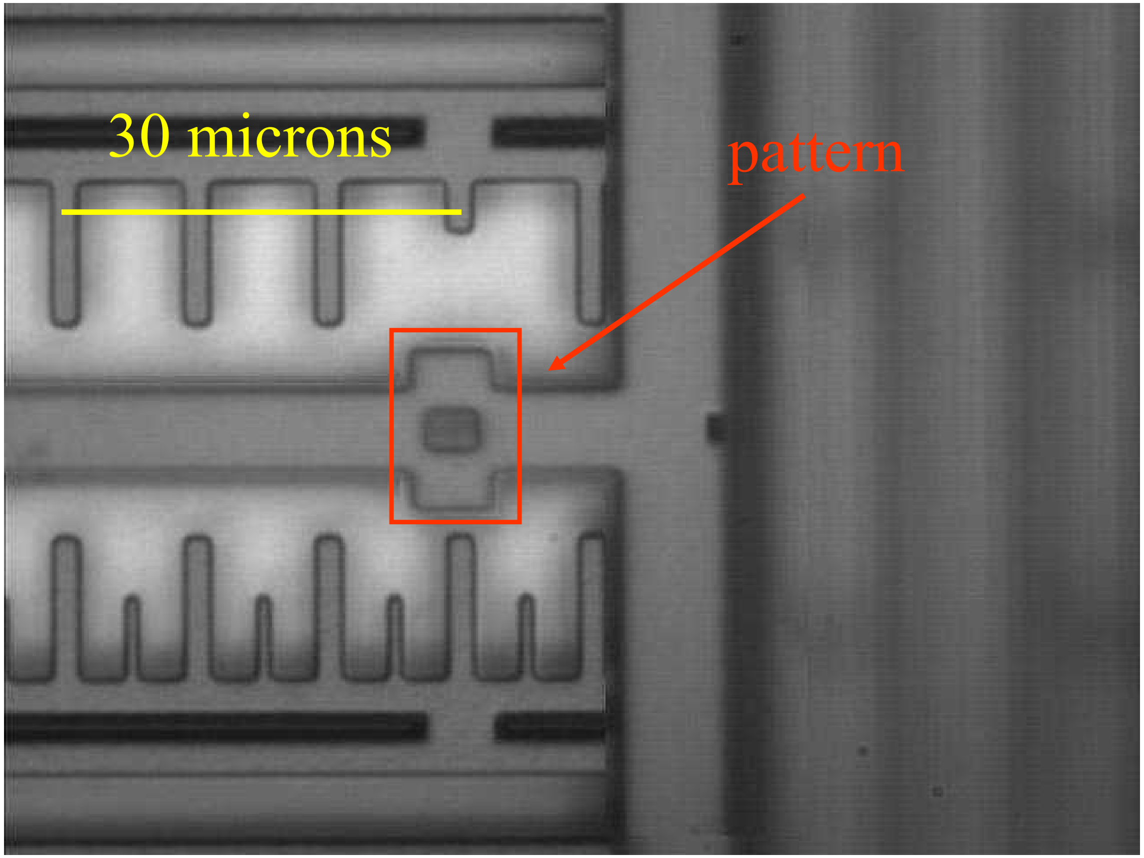
Flexibility: Works with a variety of National Instruments image capture and digital to analog boards, as well as GPIB and serial devices. Interface to external programs via DDE (i.e. LabView)

Simplicity: Presents simple user interface to allow use without knowing scripting language

Power: Full featured scripting engine written in C includes full branching (make decisions on the fly), arithmetic function evaluation (calculate on the fly), graphing (display on the fly), file output (save data and images for further analysis/presentation)

Currently licensed to E M Optomechanical, Inc. (EMOM)

Optical Metrology – Pattern matching

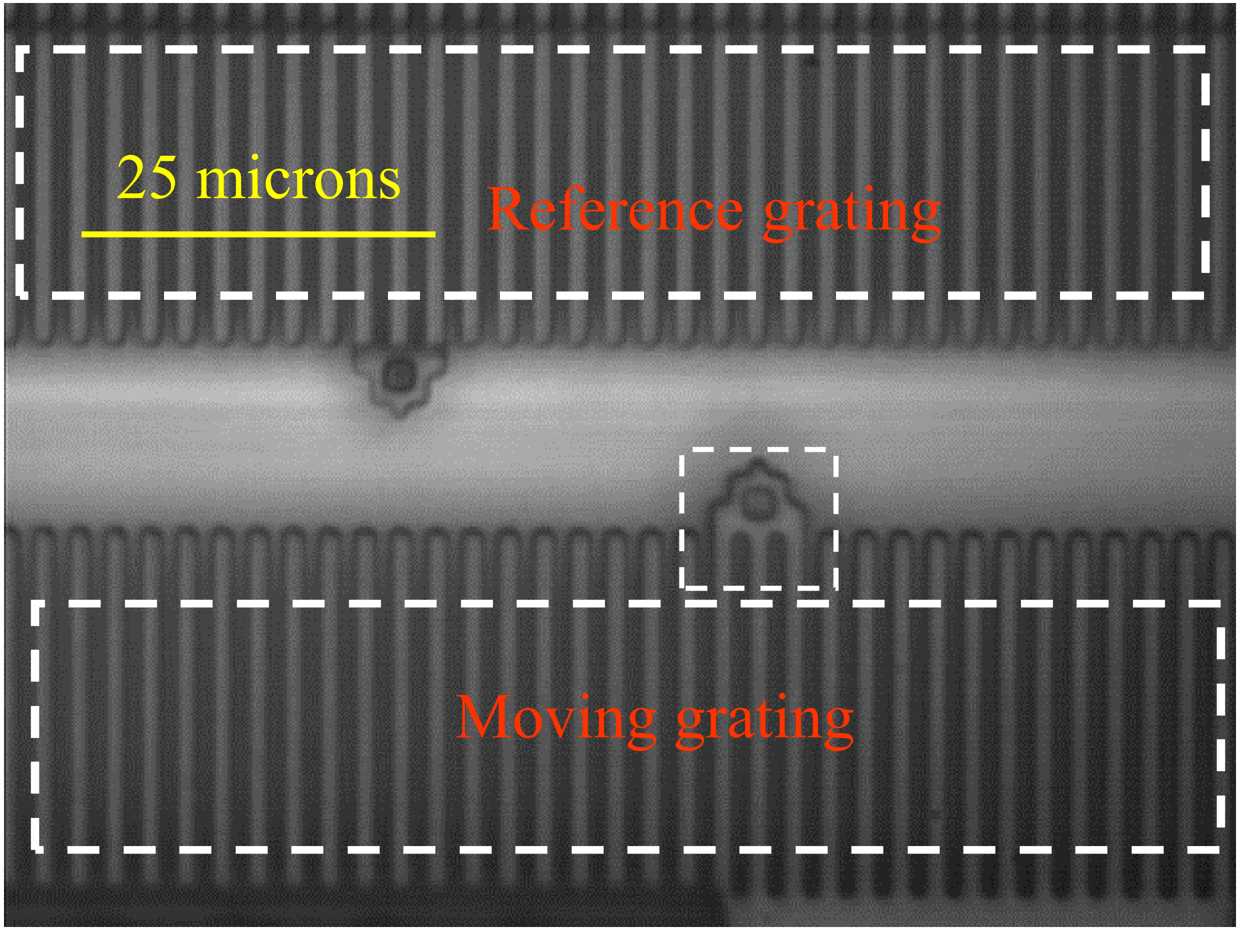


Sub-pixel pattern matching using a 100X mitutoyo objective yields about ±4 nm resolution

Optical Metrology – Grating

We can do better using a periodic grating

Technique allows hi-resolution (~1 nm) in plane displacement measurements through full range of motion using pattern matching to correct for phase jumps



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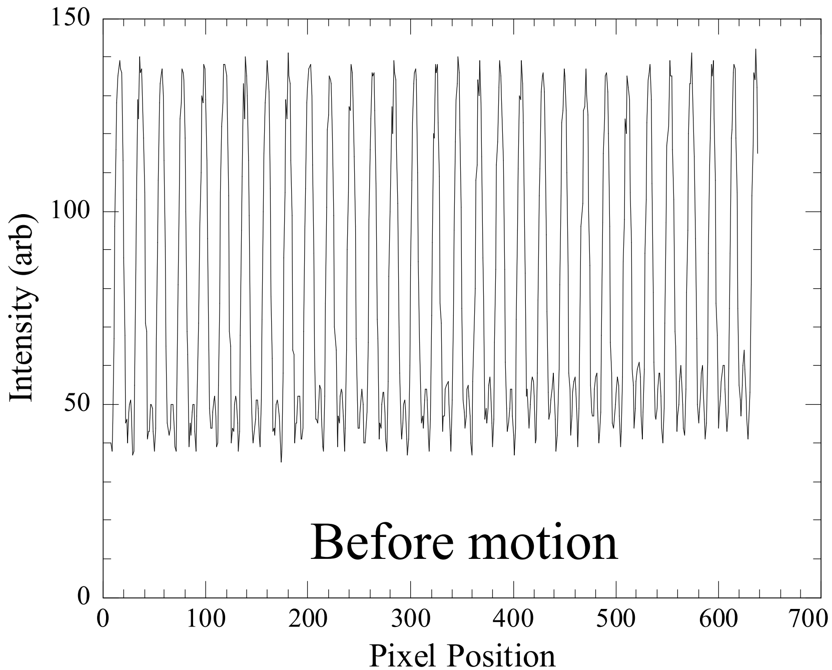
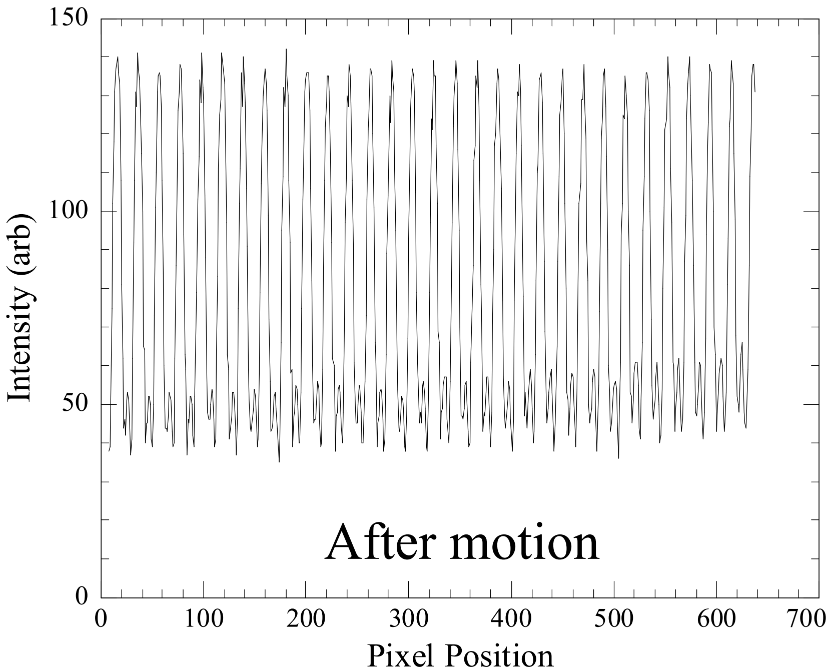
Optical Metrology – Grating cont.

Look at phase shift after motion and convert to displacement





$$\Delta x = \Delta x_{move} - \Delta x_{ref} = \frac{\Delta\phi_{move} - \Delta\phi_{ref}}{2\pi f} S$$

S is scale factor and is a function of pitch of grating

Technique allows phase detection to 2π/2500 and yields resolution of ~ 1 nm (grating pitch/2500)

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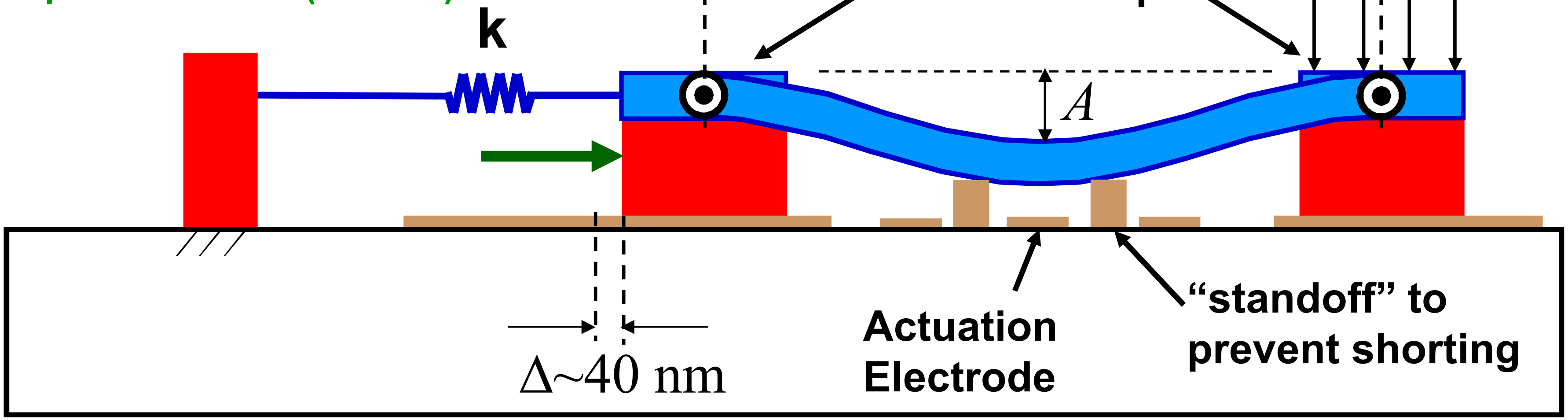
Taking advantage of friction, we developed a high-performance nanotractor actuator

- 40 nanometer step size
- moves ± 100 μm
- high force actuator (up to 1 mN)
- high speed (up to 3 mm/sec)
- 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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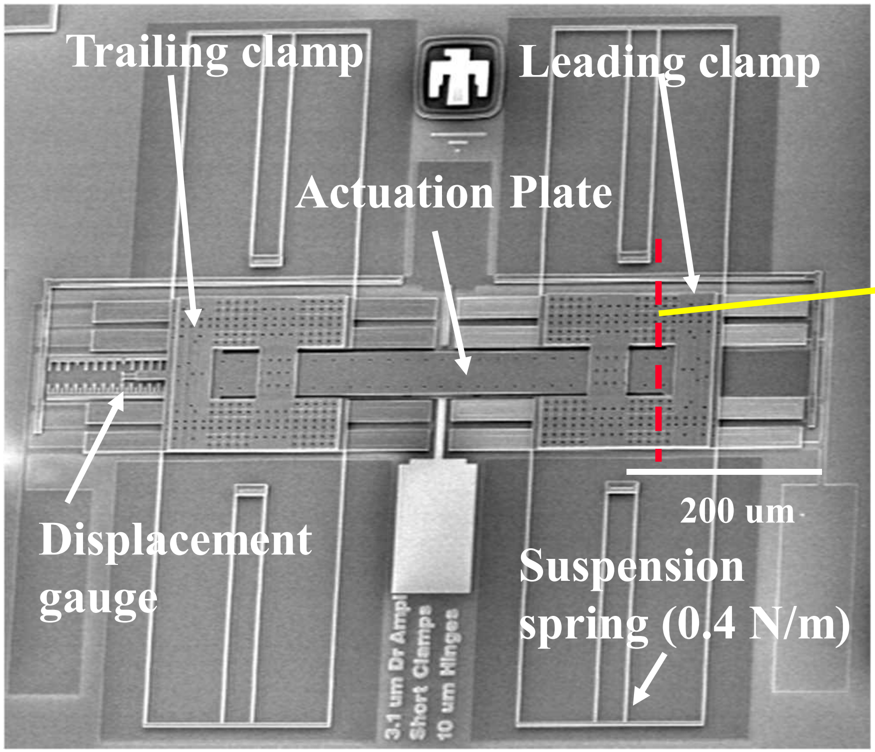
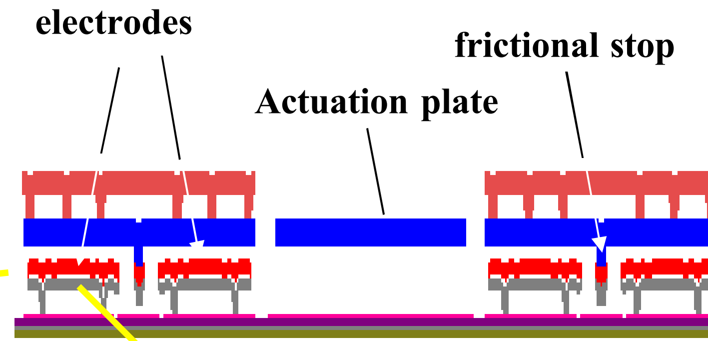
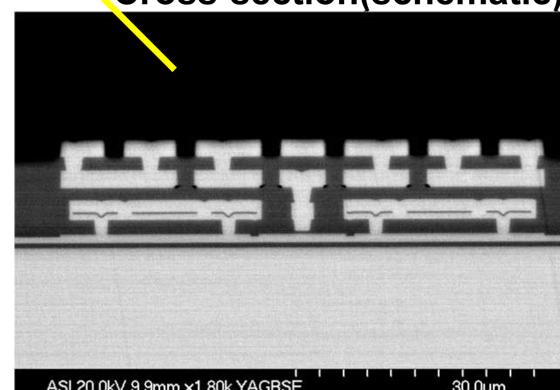
The Nanotractor Device





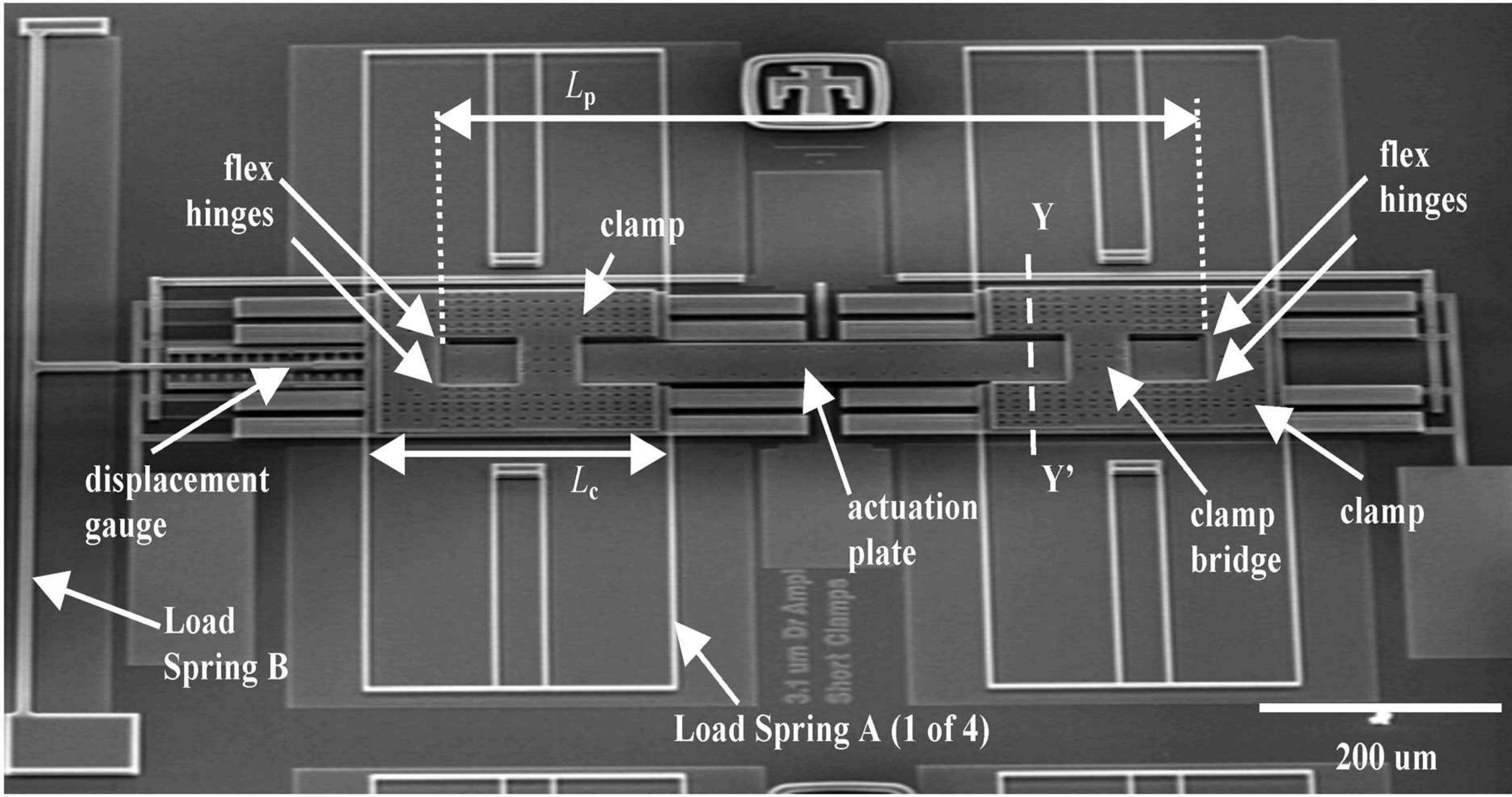
Cross-section(schematic)



SEM of Friction Clamp

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

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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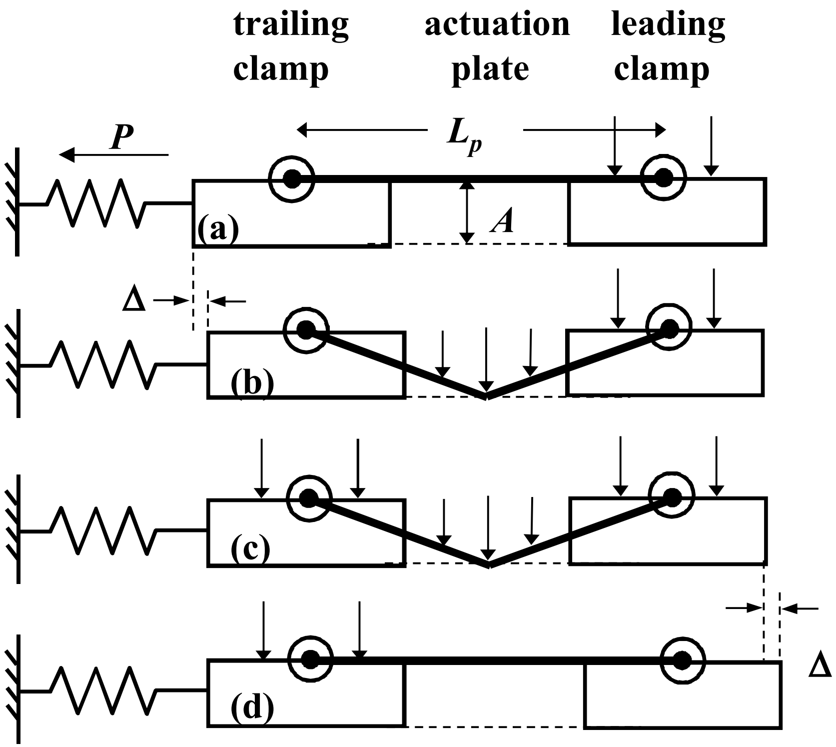
Driving the Nanotractor



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

Nanotractor as research tool

The nanotractor is not only a very useful actuator (high force, large travel, high speed), but is also a very sensitive research instrument

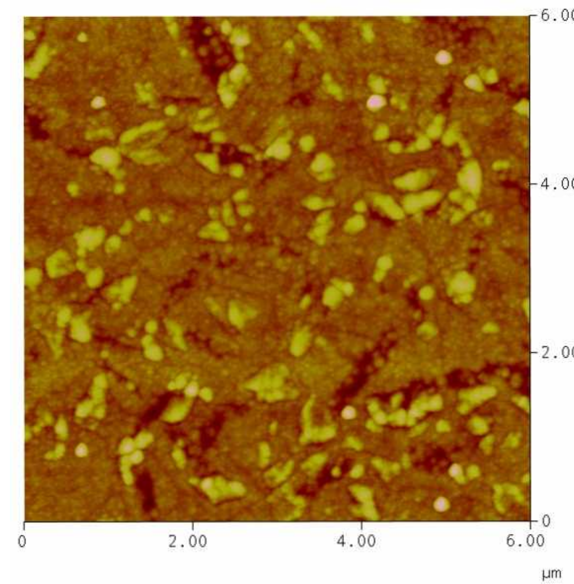
The nanotractor depends on friction for its operation

We can turn this around and use the nanotractor to measure and understand friction between contacting poly-silicon surfaces

Surface

Polysilicon with vapor deposited FOTAS coating

Rms roughness ~ 3.6 nm



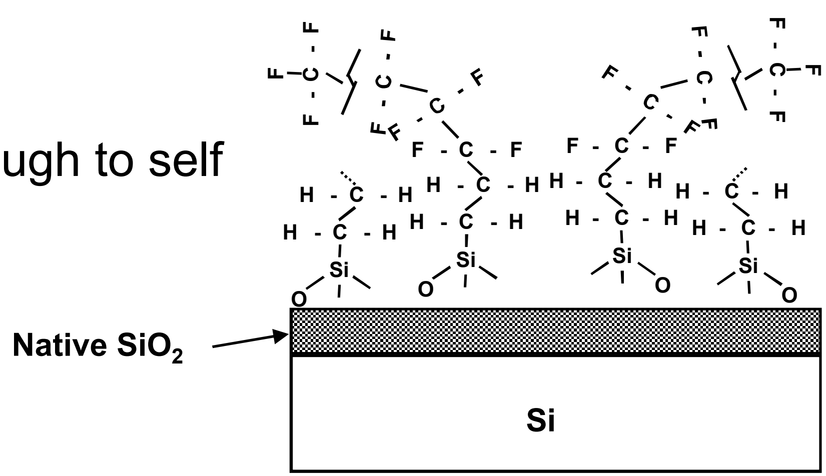
FOTAS (tridecafluoro-1,1,2,2-tetrahydrodecyltris(dimethylamino)silane)

•vapor deposited 8 carbon chain

•van der Waals forces not strong enough to self assemble (tangled)

•contact angle ~ 110° (hydrophobic)

FOTAS 8-carbon fluorinated chain (disordered, tangled)



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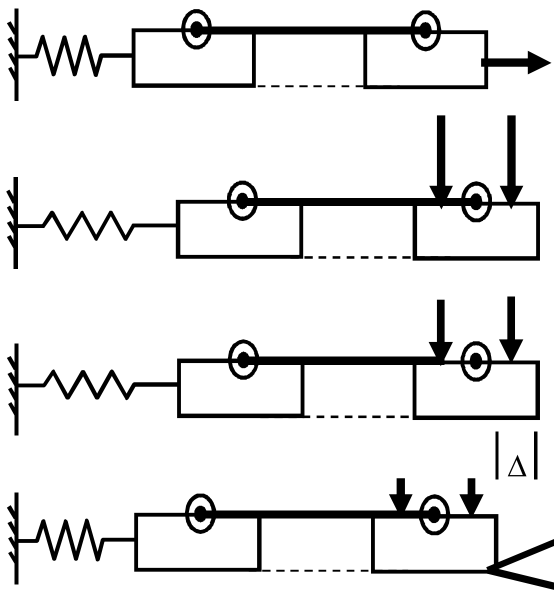
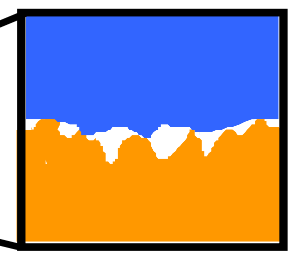
Static friction measurement



Walk out nanotractor against load spring

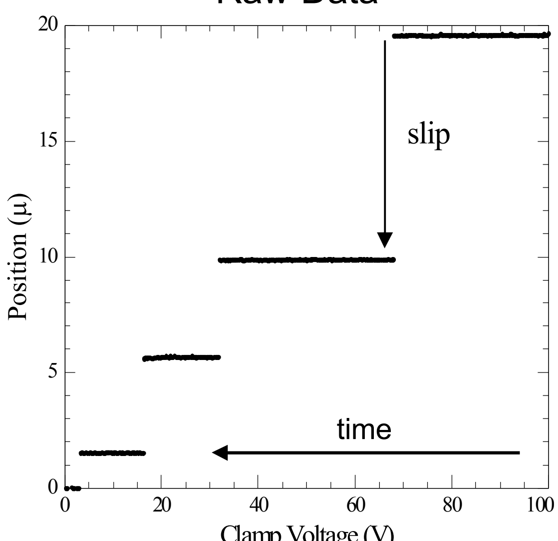
Apply large normal force (voltage)

Step down normal force (voltage) and record position



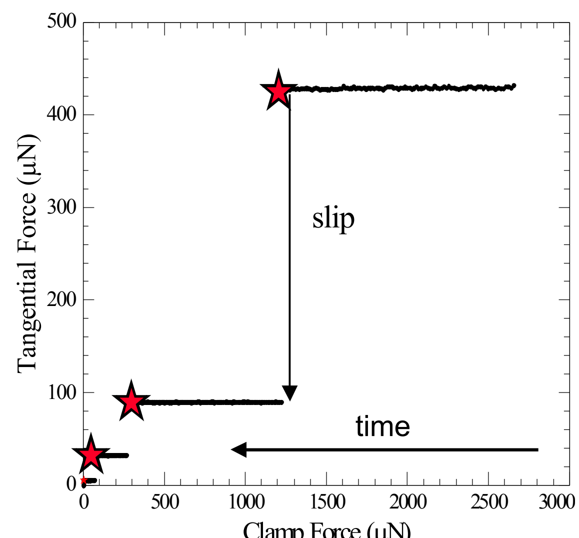
Contacting Asperities

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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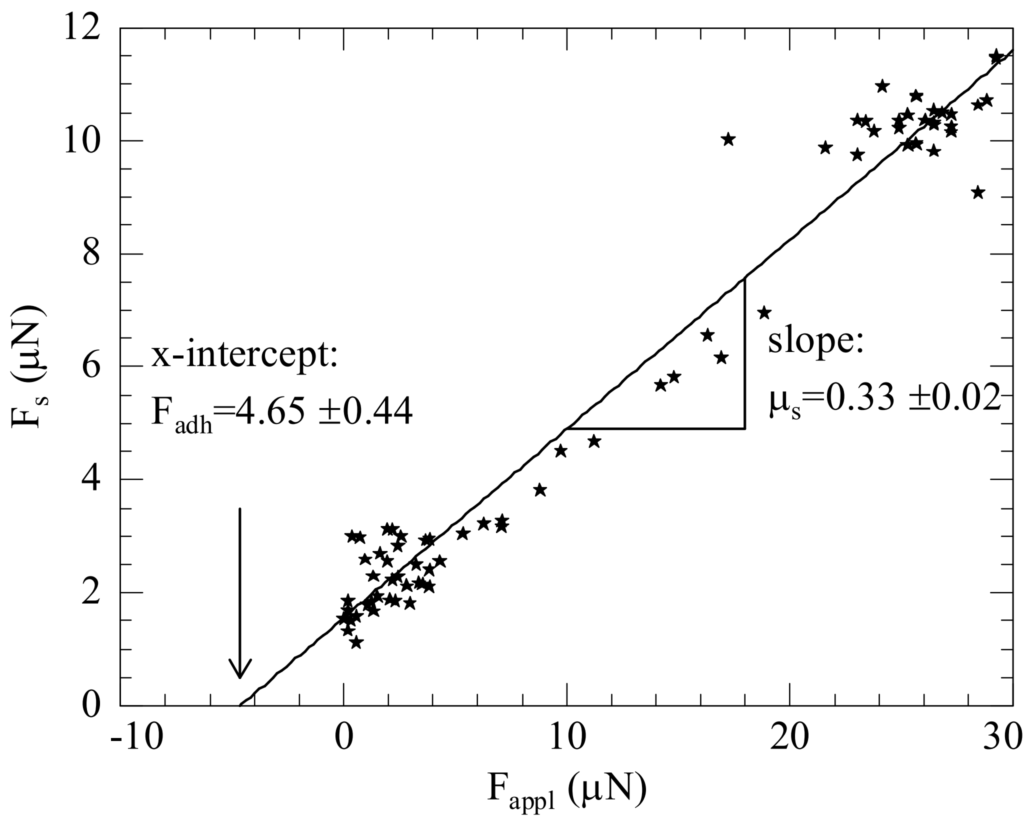
Amontons' Law is not obeyed at low applied force!



Use weak linear load spring A to generate tangential force

Observe non-zero friction at zero applied normal load

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

Simple calculations – expect ~0.1 nN/μm^2 from van der Waals forces

$$F_s = \mu_s F_{appl} + \mu_s F_{adh}$$

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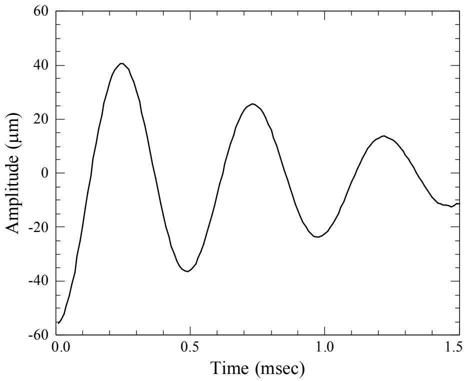
Capturing Dynamics

Can we observe the effect of adhesion on the dynamic operation of the inchworm device?

"pluck" the inchworm by walking it out against the spring, and then releasing it.

Resonant frequency ~ 2 KHz



How can we measure this with high resolution?

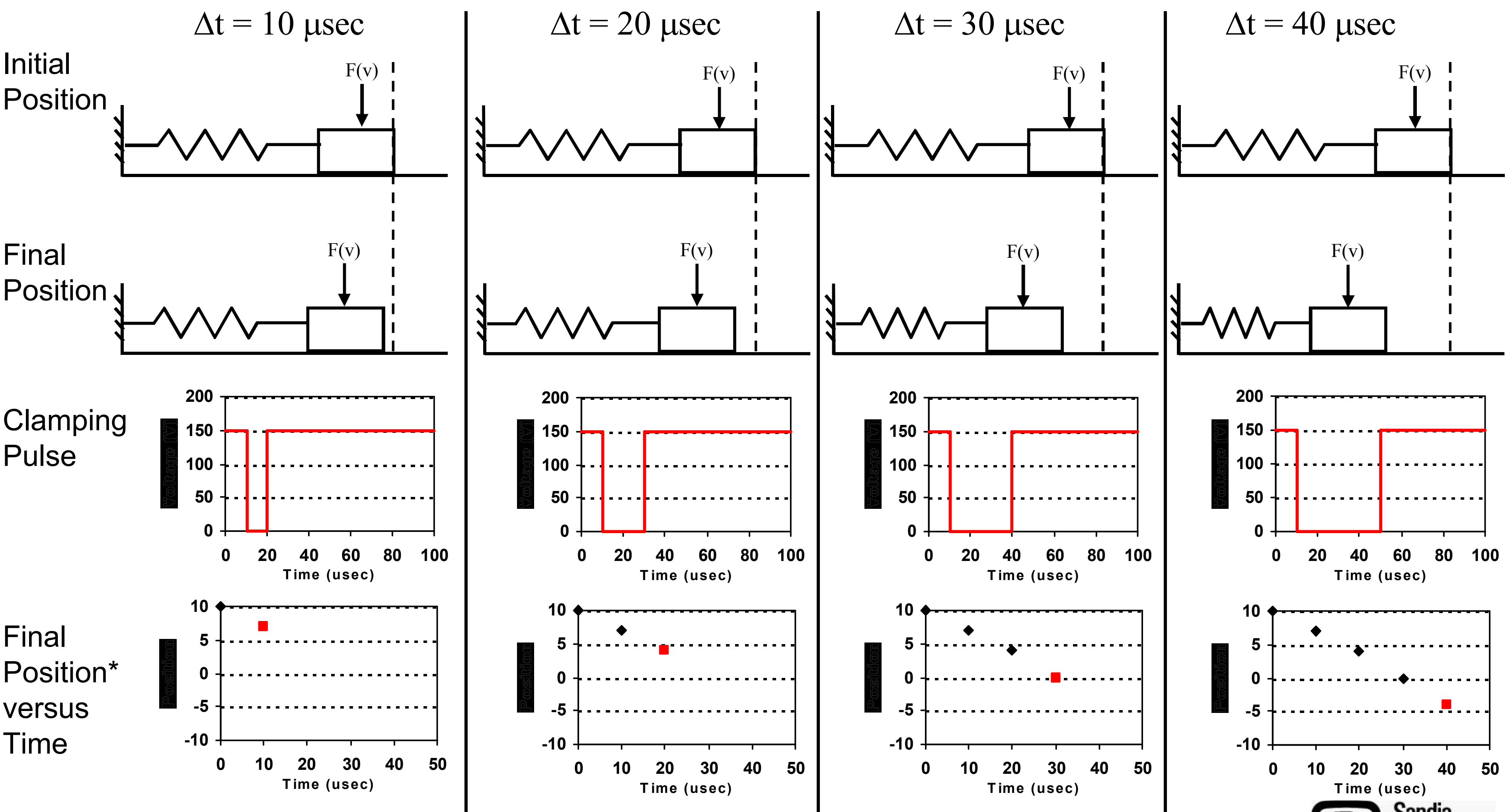
•High speed camera has light issues at high mag

•Strobing also presents high mag light problem

•Piezo resistance in the spring related deflection, but low signal to noise, and calibration issues

Instead, we have implemented an electro-mechanical strobing technique.

Electro-Mechanical Strobing Diagram



*Determined via pattern matching software

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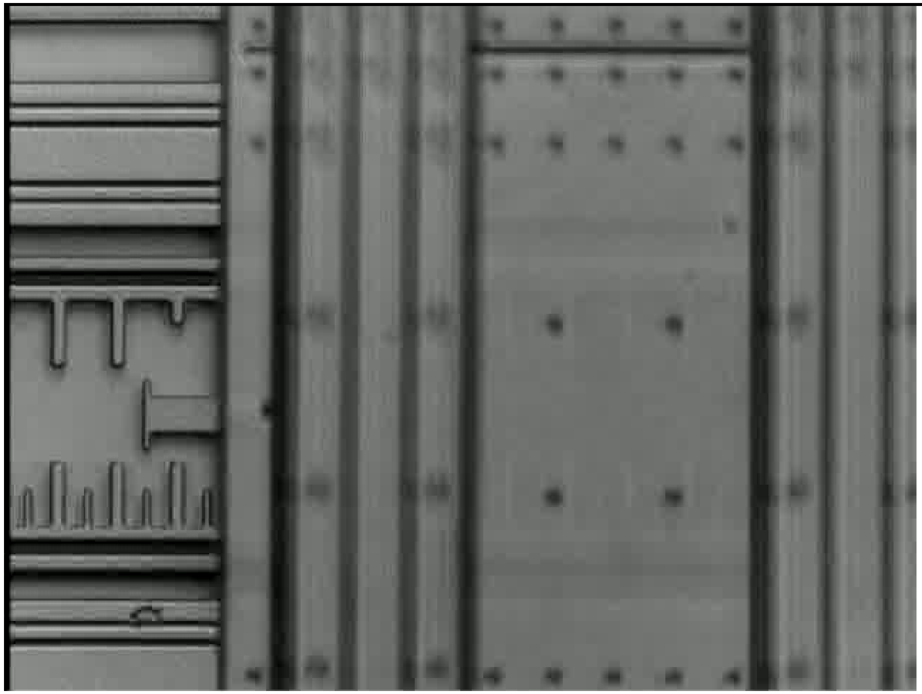
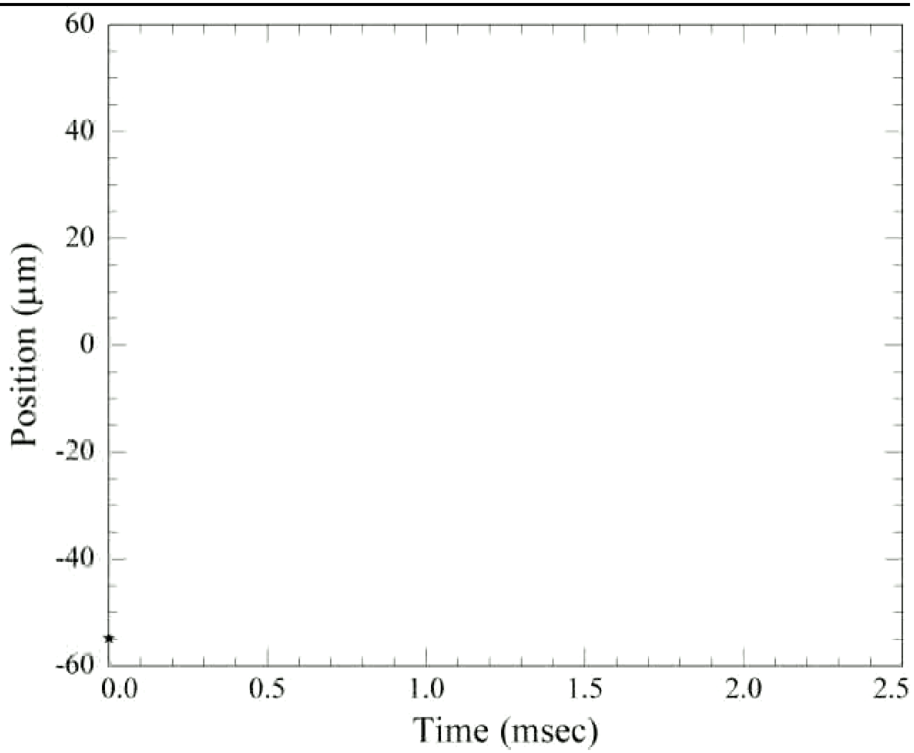
Electro-Mechanical Strobing in Action





600 um clamps, FOTAS coating

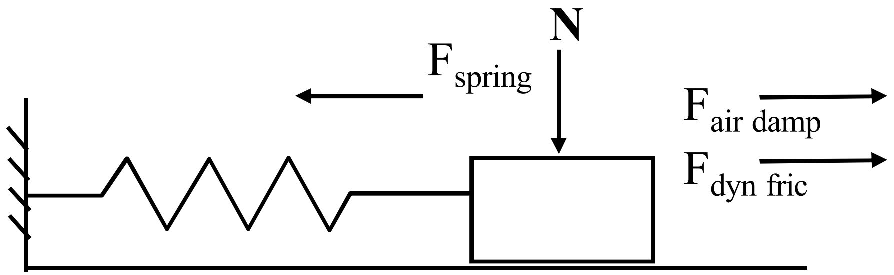
Data taken with no electrostatic normal load

Modeling: Force Diagram

$$F_{spring} = k\dot{x}$$

$$F_{dyn\ fric} = \mu_d N \operatorname{sgn}(\dot{x})$$

$$F_{air\ damp} = b\dot{x}$$



Writing the sum of the forces:

$$m\ddot{x} + b\dot{x} + \mu_d N \operatorname{sgn}(\dot{x}) + kx = 0$$

Where sgn is the sign function:

sgn(x)=1 if x>0

sgn(x)=-1 if x<0

Determining the Equations of Motion

Scale by m and rewrite

$$\ddot{x} + \gamma\dot{x} + \omega_0{}^2 x + \mathrm{sgn}(\dot{x})\frac{F_d}{m} = 0$$

with the definitions

$$\omega_0{}^2 = k/m$$

$$F_d = \mu_d N$$

$$\gamma = b/m$$

Find solution for time t_n such that $\frac{n\pi}{\omega} \le t_n \le \frac{(n+1)\pi}{\omega}$

with initial conditions of zero initial velocity and initial position = x'_0,

$$x_n(t) = \mathrm{A}_n e^{-\gamma t/2}\cos(\omega t + \alpha) + (-1)^{n-1} F_d/k$$

where

$$\mathrm{A}_{n+1} = \left[(-1)^n x'_n - F_d/k\right]\frac{e^{n\gamma\pi/2\omega}}{\cos(\alpha)}$$

$$x'_{n+1} = \left[-x'_n + (-1)^n F_d/k\right]e^{-\gamma\pi/2\omega} + (-1)^n F_d/k$$

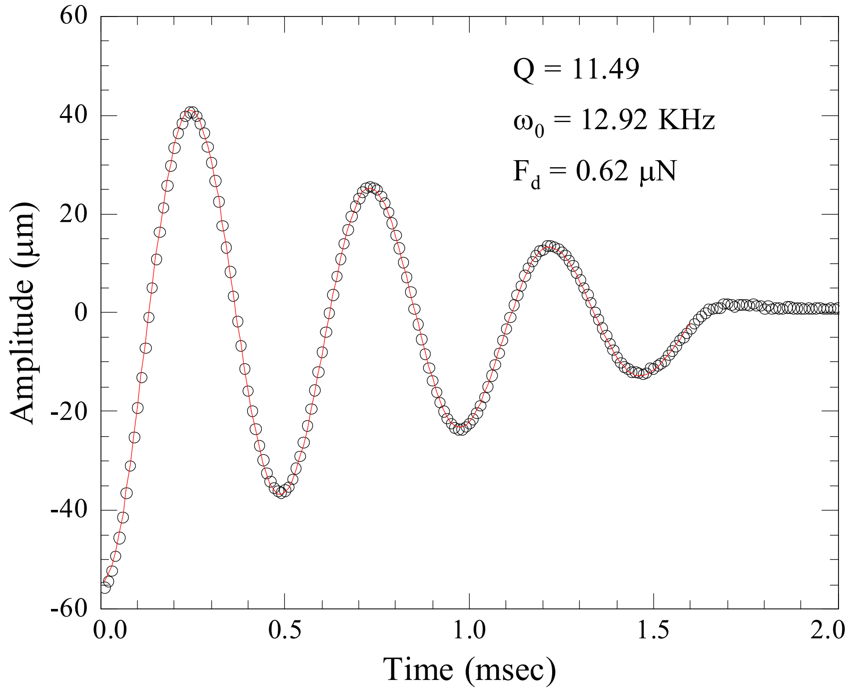
and with the definitions

$$\omega^2 = \omega_0{}^2 - \gamma^2/4$$

$$\alpha = \mathrm{atan}\left(\frac{-\gamma}{2\omega}\right)$$

Fitting the Data

By fitting, can separate air damping contribution from dry friction contribution



600 um clamps, FOTAS coating, V=0

Q (quality factor) is defined as

$$Q = \frac{\omega_0}{\gamma}$$

and is a measure of air damping

Note that F_d (the frictional term) is non-zero, implying a frictional force even in the absence of electrostatic actuation

Dynamic Friction Data and Analysis

Repeat procedure and determine Fd while systematically increasing applied normal load on inchworm during decay

Include an adhesive term (same as static case)

$$F_{fric} = \mu_d F_{elec} + \mu_d F_{adh}$$

Find

$$\mu_d = 0.24 \pm 0.02$$

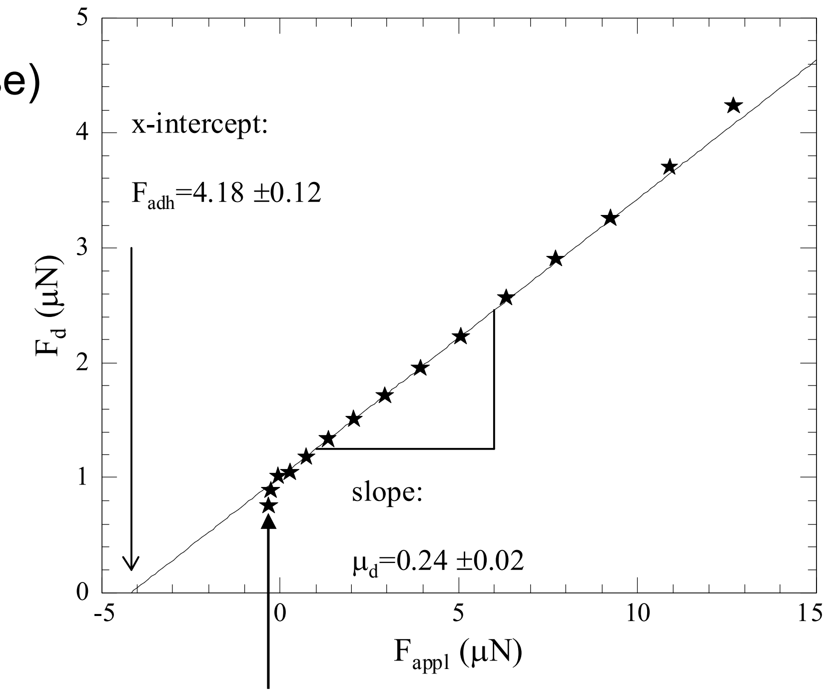
$$F_{adh} = 4.2 \pm 0.15\ \mu N$$

Recall for static case

$$\mu_s = 0.33 \pm 0.02$$

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

so $\mu_d < \mu_s$ as expected



Tensile applied force due to suspension springs

600 µm clamps, FOTAS coating

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Is rate-state friction important for MEMS

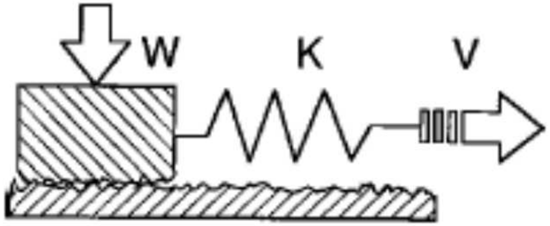
Empirical extension to Amontons' laws

Contact aging causing increase in friction over time for static system

For moving system, friction decreases with velocity as contacts have less time to age

Important over length scales ranging from earth quakes to MEMS (present work)

Typical experimental setup



Berthoud et. al, PRB 59 (1999) 313

Interface ages (strengthens) at rest, while it rejuvenates (weakens) when sliding sets in.

Caroli et. al, J. Phys IV France 12 (2002).

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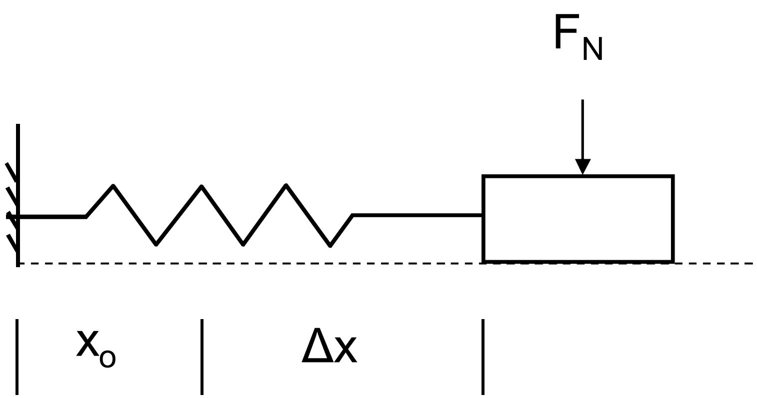
Review of static friction measurement



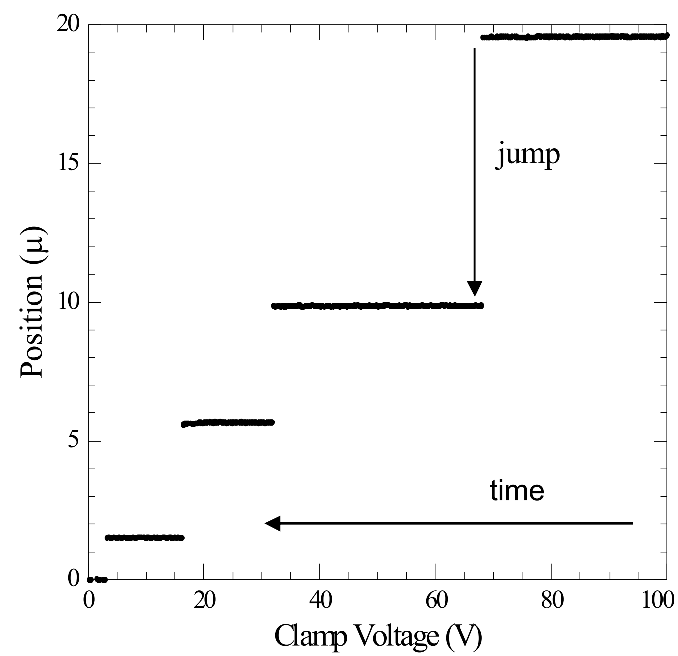
Normal force provided by electrostatics

Start at initial position Δx

Ramp down voltage (normal force) and record position

By looking at jumps can determine coefficient of static friction

Raw Data



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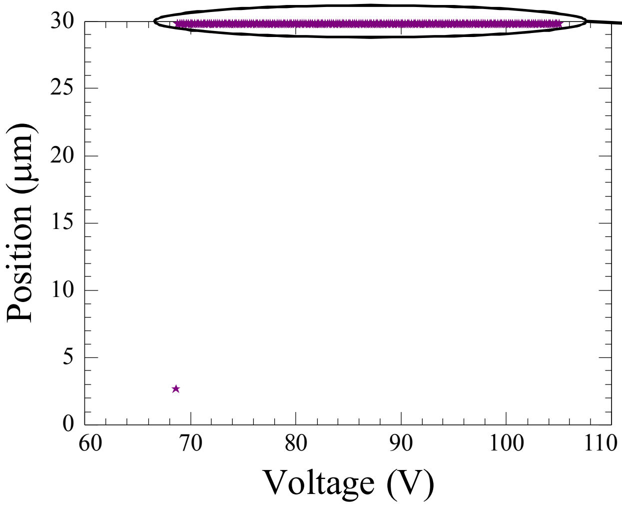
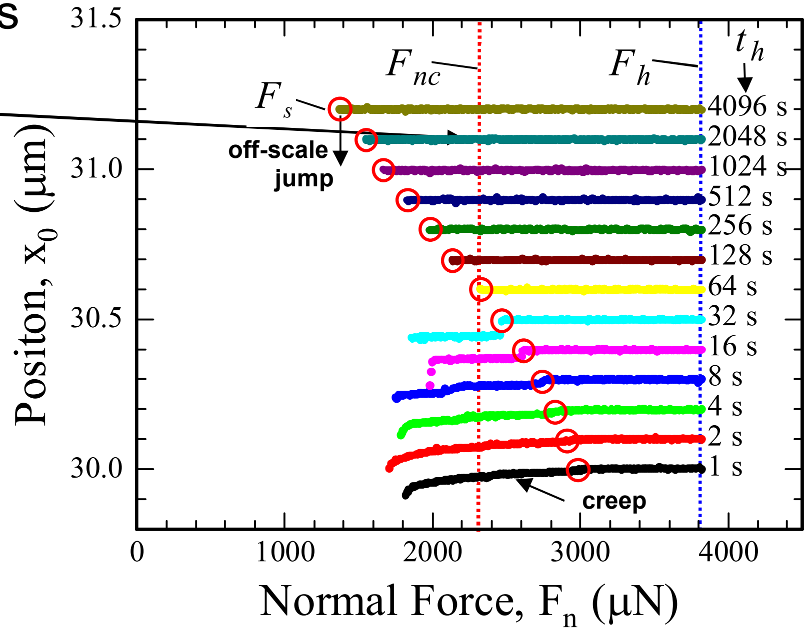
Vary hold time

Hold at initial position for varying amounts of time and then ramp down voltage in .2 volt steps





Identify jumps when position changes greatly on release and creep as small position change on release

Observe dependence of jump position on hold time

Notice transition between jumps and creep

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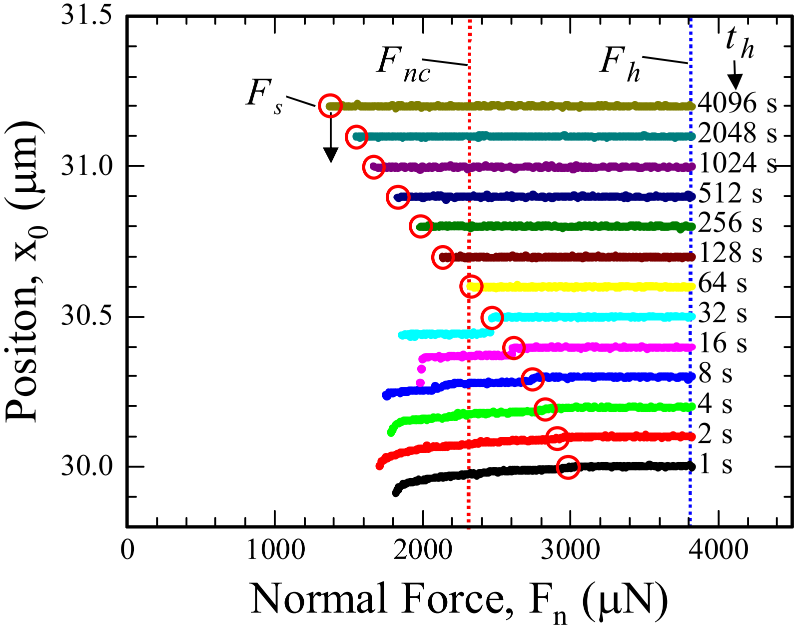
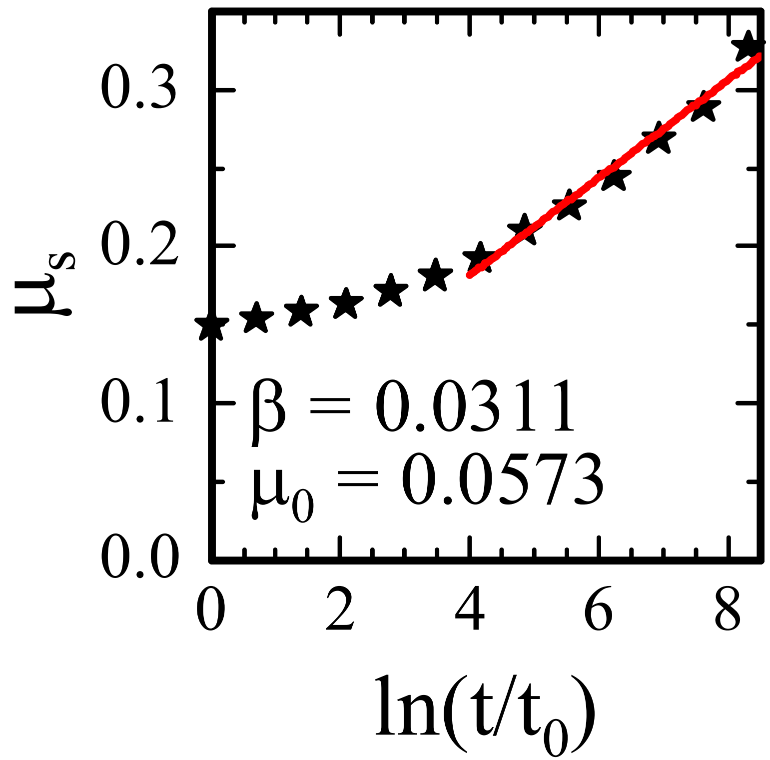
Analysis of variable hold time data

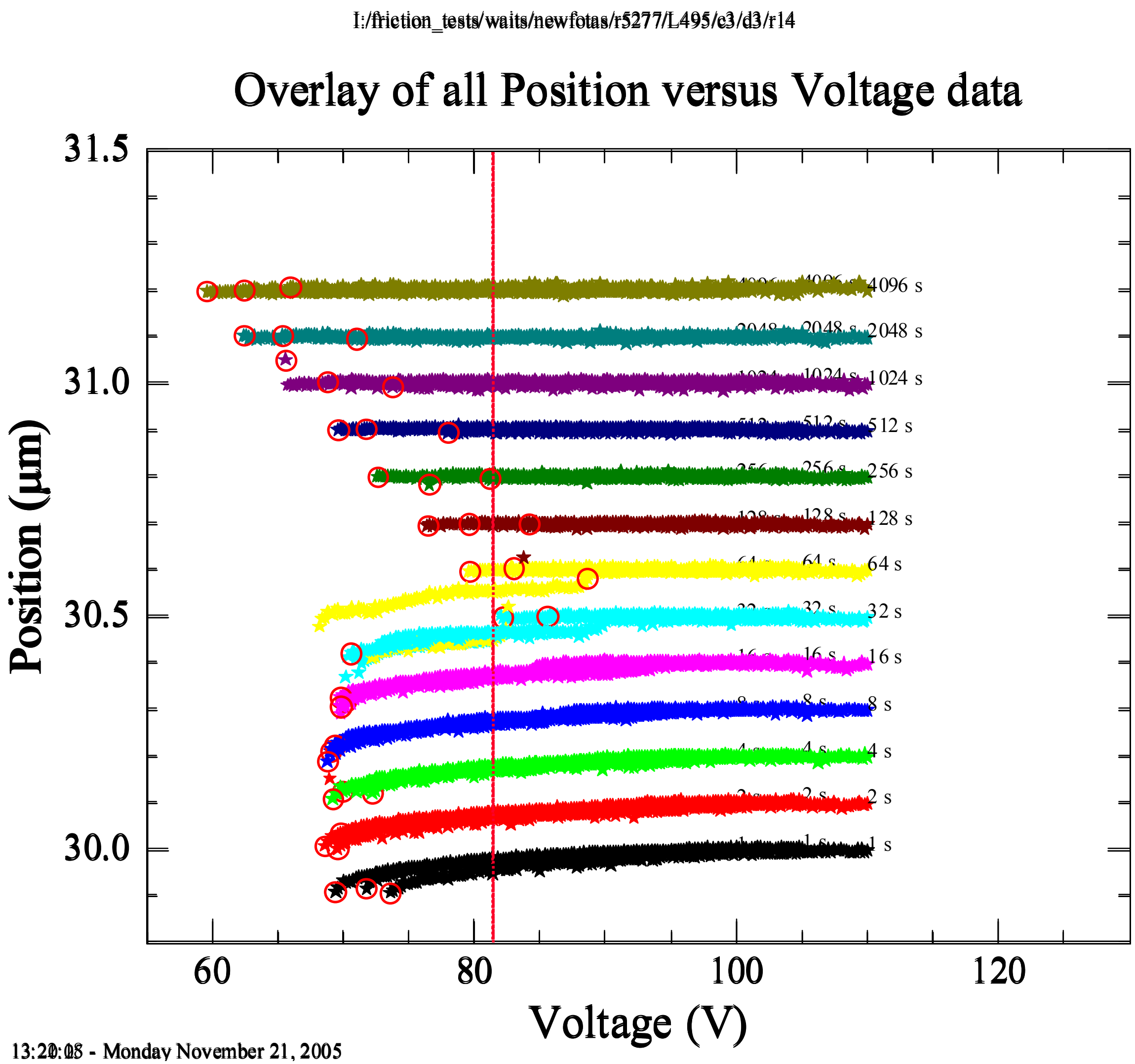
$$\mu_s(t_s) = \alpha_s + \beta_s \ln(t_s / t_0)$$





Using spring constant to calculate tangential force, can compute coefficient of static friction for each friction event

Vary initial normal force



More curves exhibit creep as we increase hold voltage. Red dashed line seems to indicate separation between creep and jumps

Friction coefficient decreases as increased hold voltage

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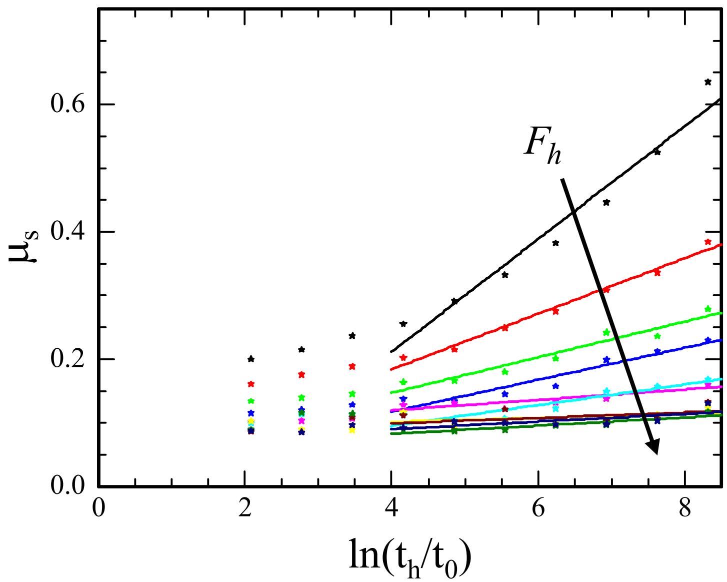
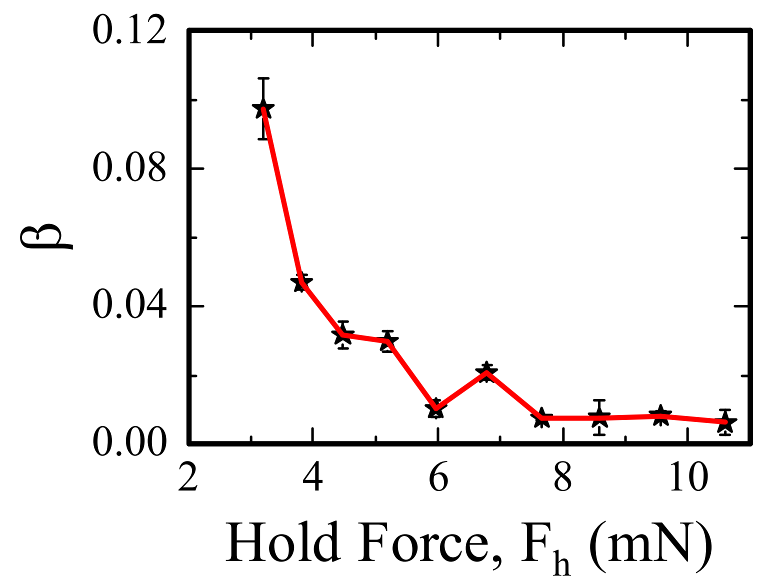
Varying hold force

Can take data for varying hold force

$$\mu_s(t_s) = \alpha_s + \beta_s \ln(t_s / t_0)$$





Rate of static friction aging decreases with increasing hold force

High pressure may reduce interdigitation of monolayer leading to suppression of frictional aging

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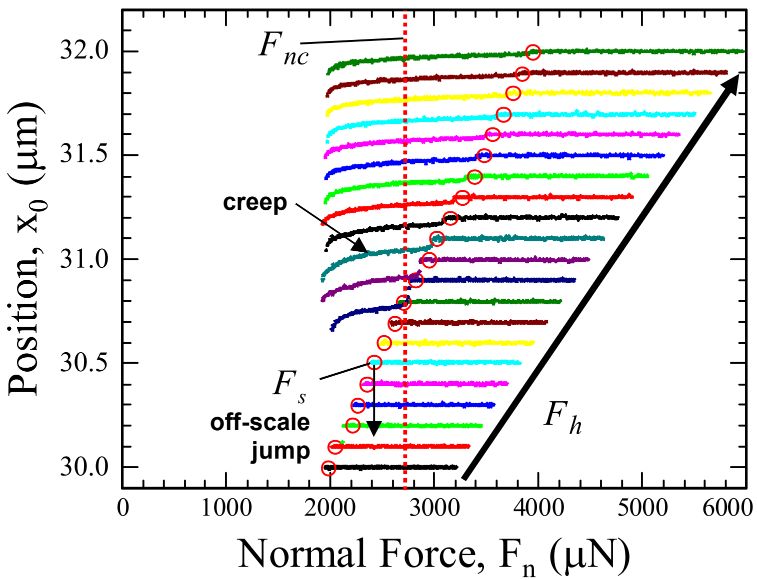
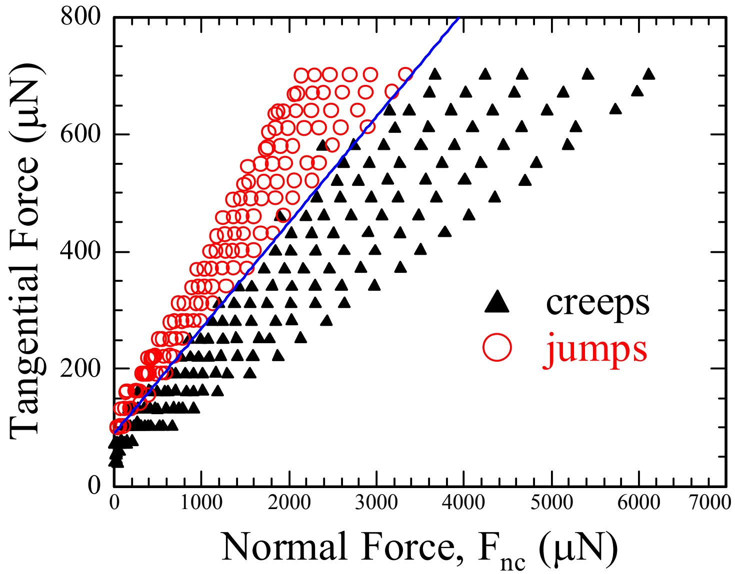
Phase diagram of jumps and creeps





For each tangential force (position) plot type of event as a function of normal force (voltage)

Repeat for many positions to measure boundary as a function of position

Phase boundary exists between creep and jumps (inertial motion)

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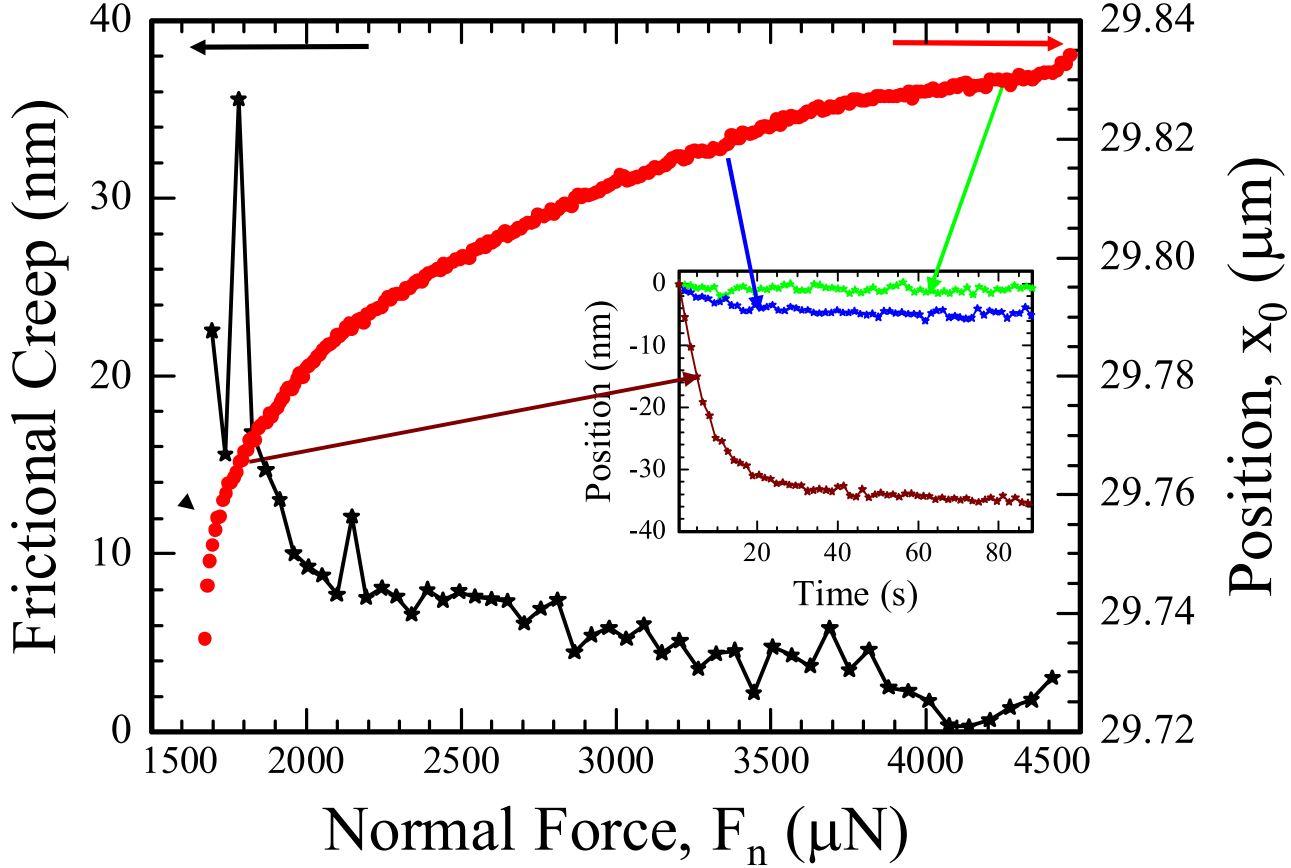
Creep measurements



We observe true creep that increases as we approach the transition to inertial sliding

Conclusions

Adhesion contributes to friction under both static and dynamic conditions even under small tensile normal force

Adhesion is seen to be important in the low force regime

Rate – State is important for our MEMS device

Static friction increases with time

Static friction reduced with increase in initial loading force

Bifurcation between jump and creep behavior as function of tangential divided by normal force

Time dependent creep increases before a jump occurs in the creep regime

The nanotractor device allows us to understand surface interactions in MEMS

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