SAND2007-3487C

Towards reliable and predictable MEMS

Alex Corwin

June 8, 2007

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

My Roles at Sandia

- Reliability and Characterization (Thermal rotary actuator, Pistoning mirrors)
- Predictable microsystems (friction)
- Parametric Test (interferometry)
- Tools and Software Development (MEMScript, WaferScript, automated interferometeric test setups)

All of these roles involve working closely with many team members including processing, design, modeling and packaging

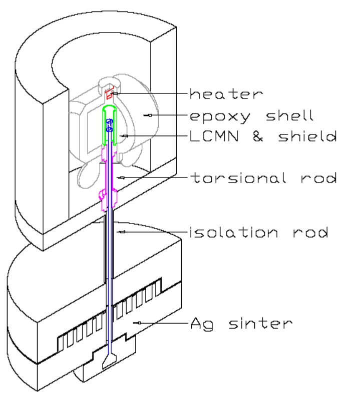
Acknowledgements

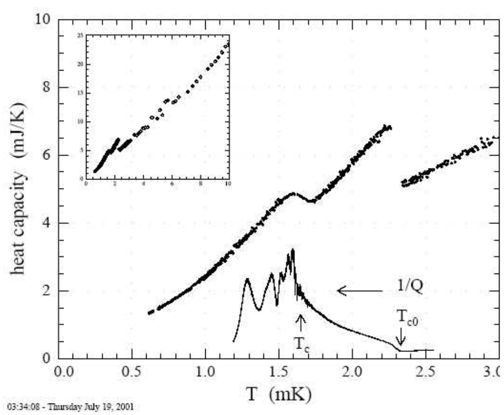
Working at Sandia has been a great experience. I have gotten to work with and learn from an incredible team of people. Here are just a few of them:

Maarten de Boer (design / characterization)
Bob Ashurst (chemical engineering of coatings)
Mike Shaw (process engineer)
Danelle Tanner (reliability)
Mike Rightley (packaging)
David Luck (testing)
Mike Baker (modeling, design)
Scot Swanson (testing)
Karen Helgesen (testing)
Fred Sexton (manager)
Harold Stewart (manager)
Dave Sandison (manager)
Mark Platzbecker (team lead)
Frank delRio (modeling, characterization)
Matt Hankins (process engineer, coatings)
Ernie Garcia (project lead)
and many more …..

Graduate work in ultra low temperature helium physics

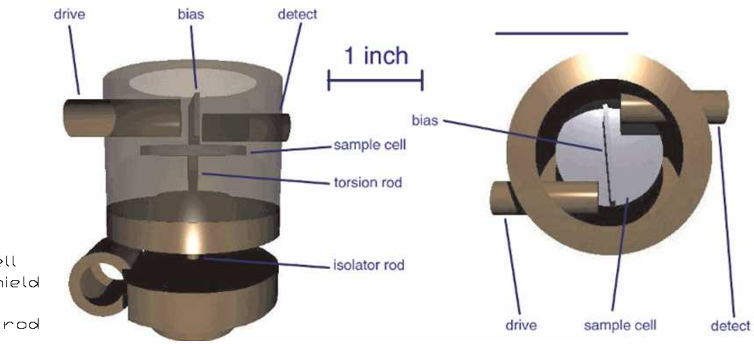
Heat capacity of He3 in aerogel

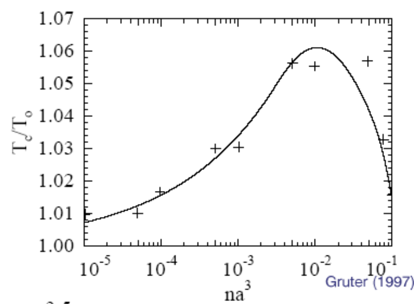


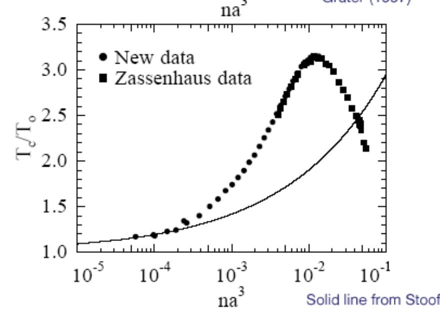


He, JZ; Corwin, AD; Parpia, JM; Reppy, JD, *Heat capacity of He-3 in aerogel*, Physical Review Letters, Sep 9 2002; v.89, no.11, p.115301-5301

BEC of He4 in vycor



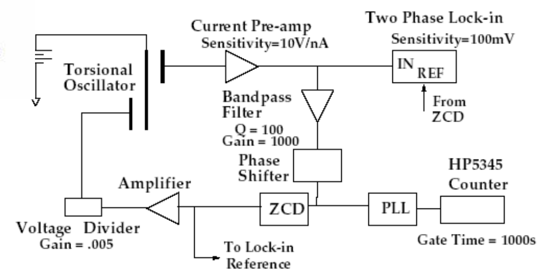


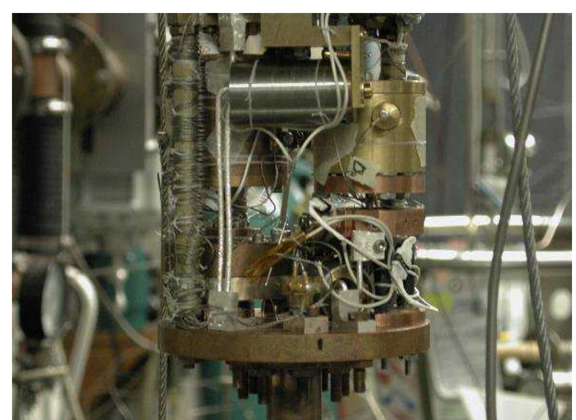


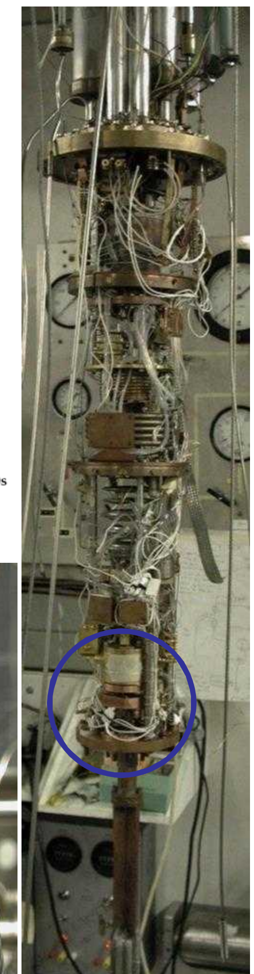
Corwin, AD; He, JZ; Zassenhaus, G; Reppy, JD, *Density dependence of transition temperature of He-4 films in vycor glas,* Journal of Low Temperature Physics; Dec 2000, v.121, no.5-6, p.525-530

PrNi5 demag fridge with 0.3 mk base temperature

Torsional oscillator used to detect superfluid transitions with lock-in resonance technique



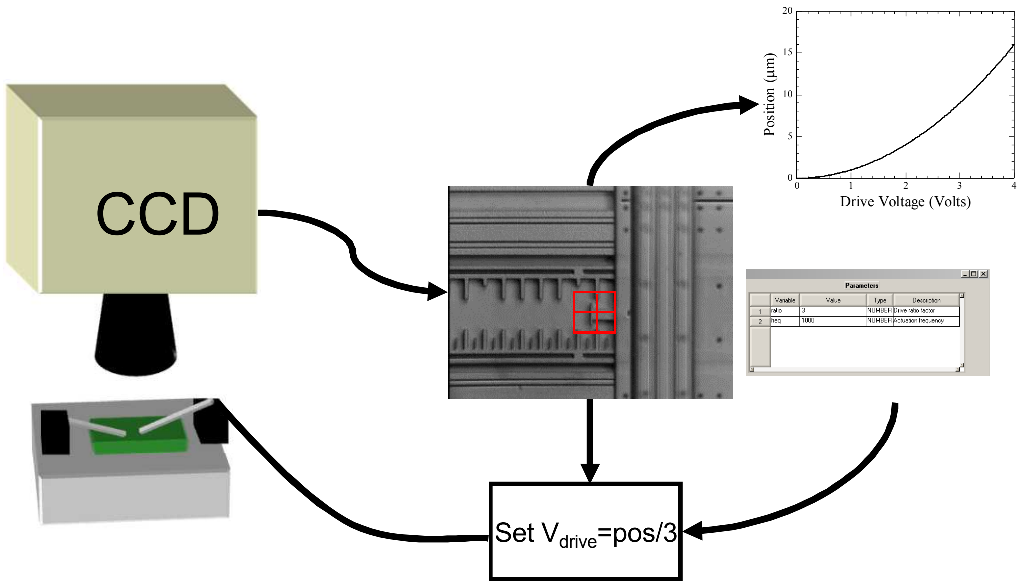




Microsystem Reliability and characterization:

Tools and techniques

MEMS*cript* An integrated vision and actuation automation tool for MEMS



Extensively used at Sandia in many MEMS reliability and characterization applications as well as in parametric testing.

Pattern matching allows nm scale position measurements

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)

20,000 lines of code. Written by Alex Corwin

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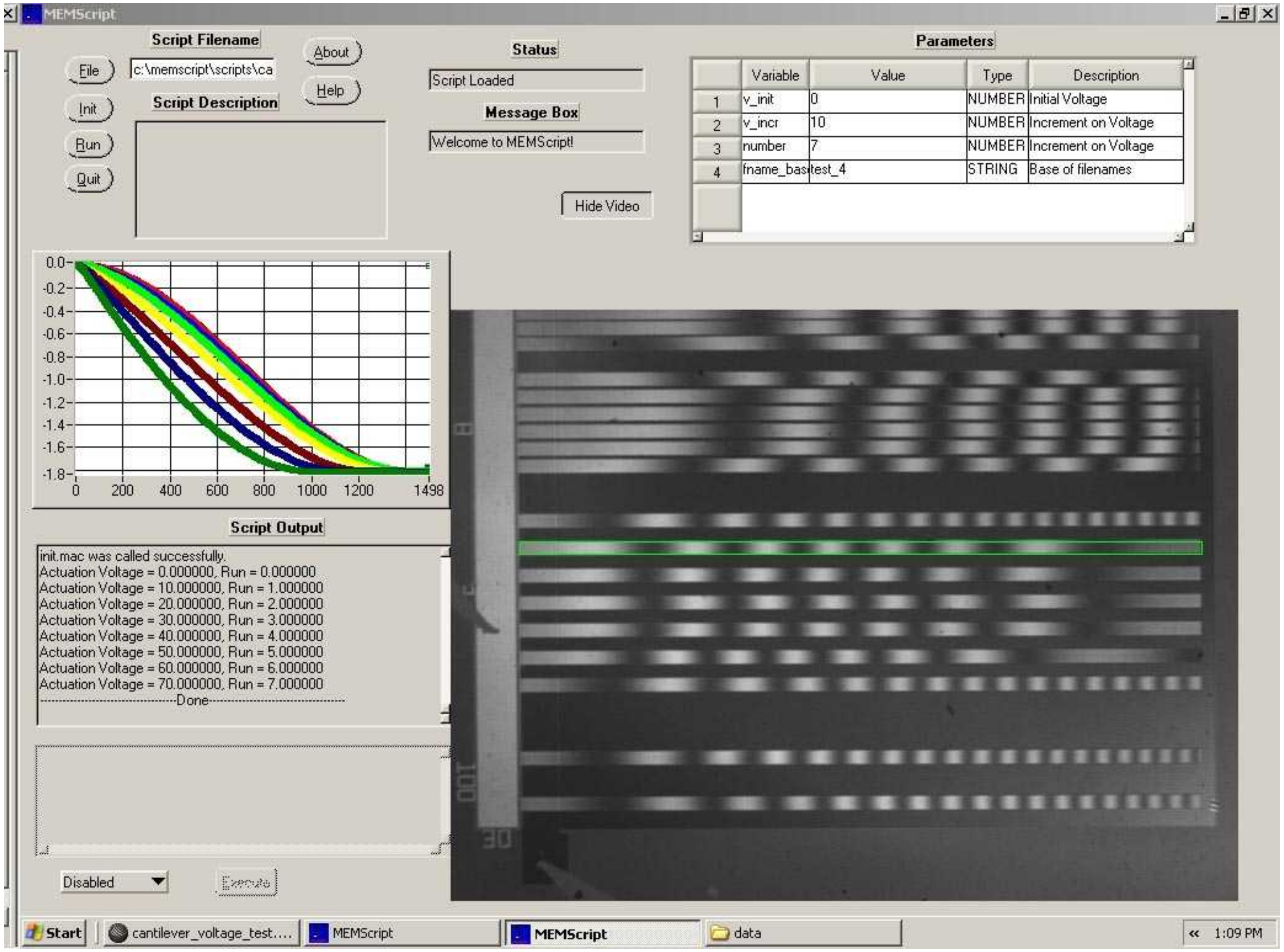
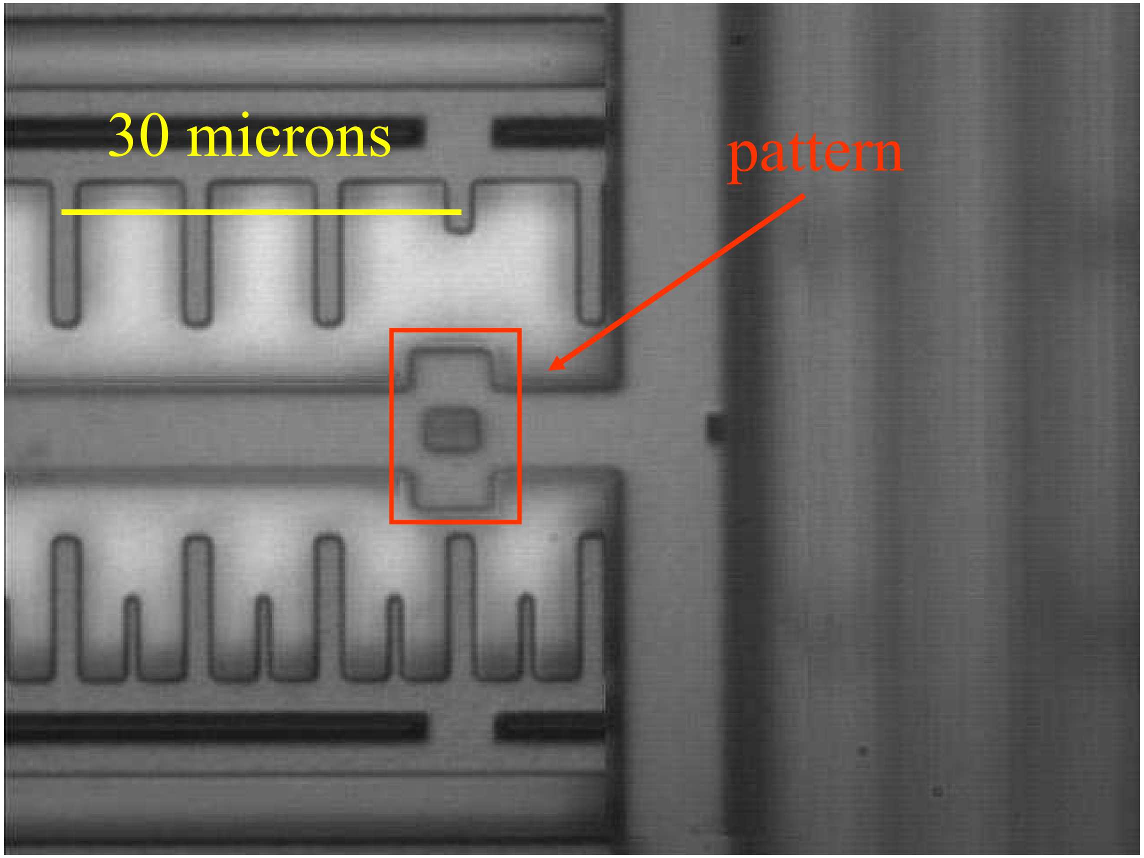
Screen capture of MEMScript



Uniform interface for all scripts allow wide variety of measurements

Automation allows large number of measurements over large number of devices to get statistical reliability data

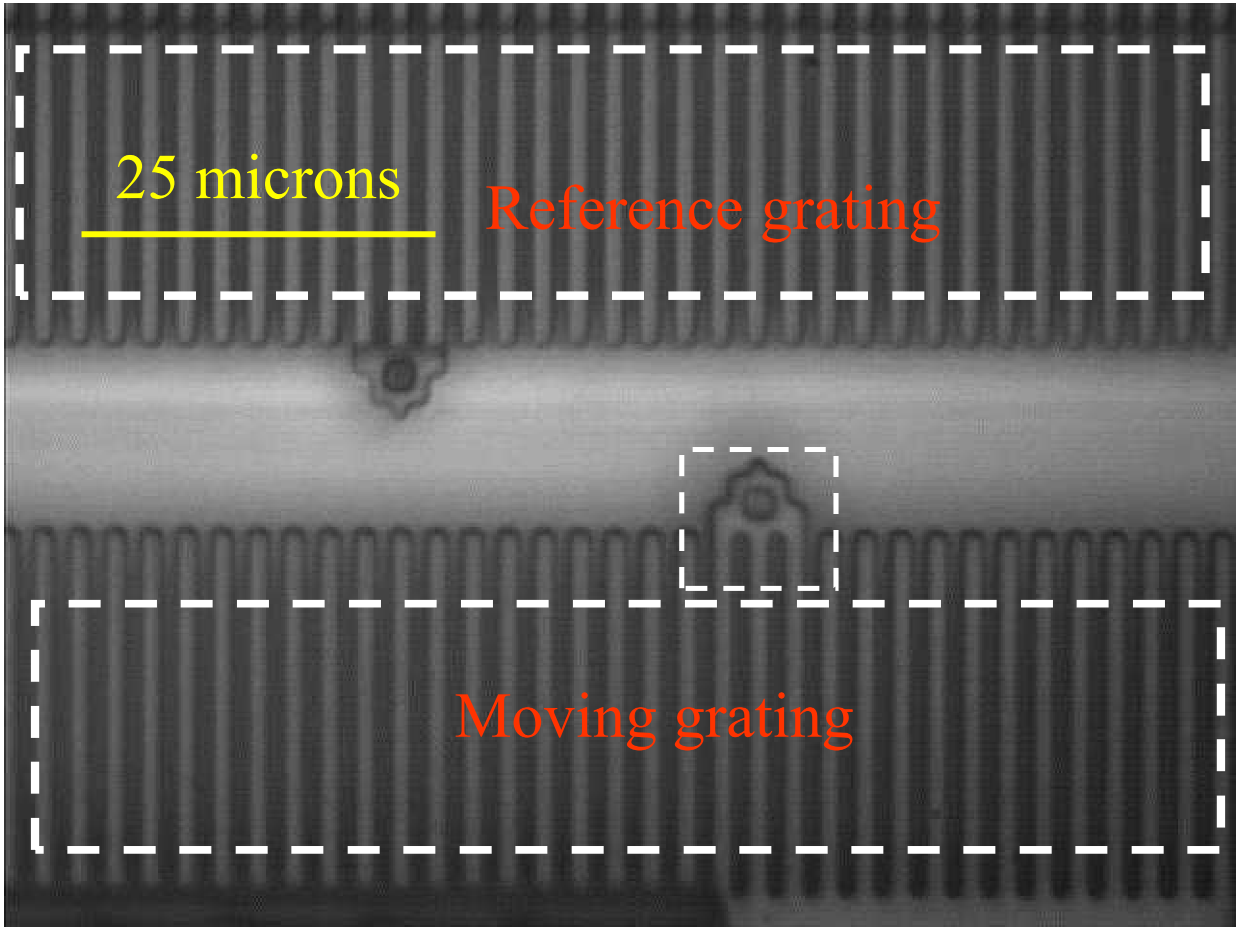
Optical Metrology – Pattern matching



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

Optical Metrology – Grating

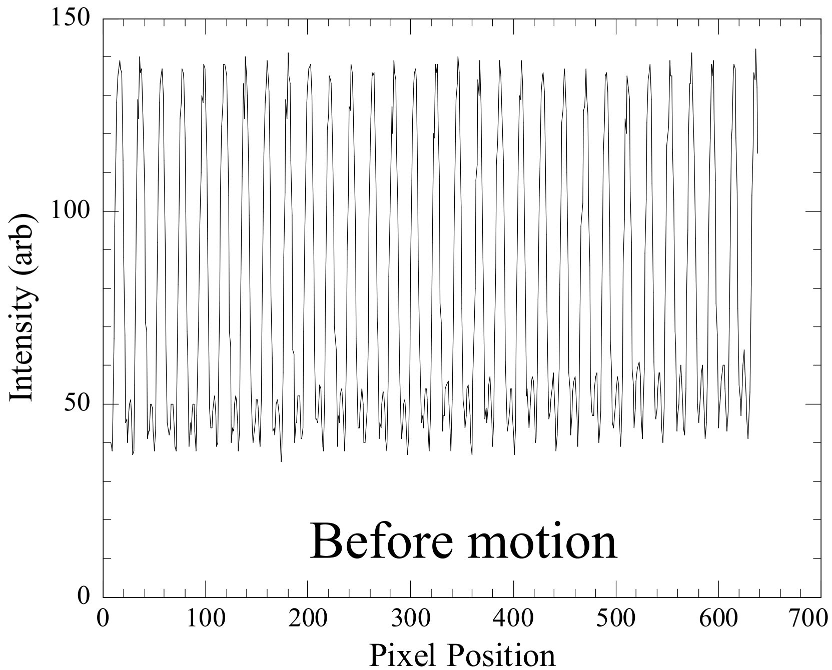
We can do better using a periodic grating

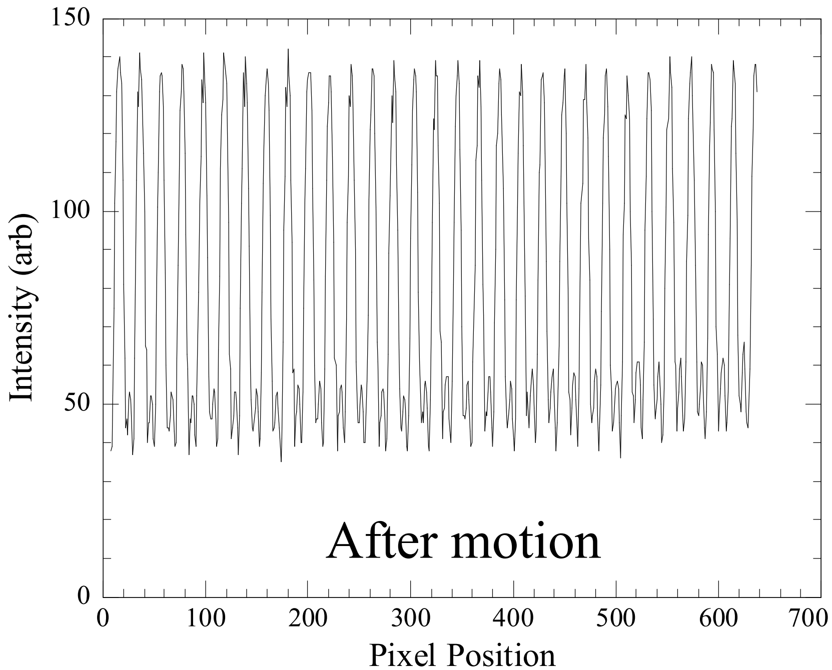


Technique allows hi-resolution (~1 nm) in plane displacement measurements through full range of motion using pattern matching to correct for phase jumps

Optical Metrology – Grating cont.

Look at phase shift after motion and convert to displacement



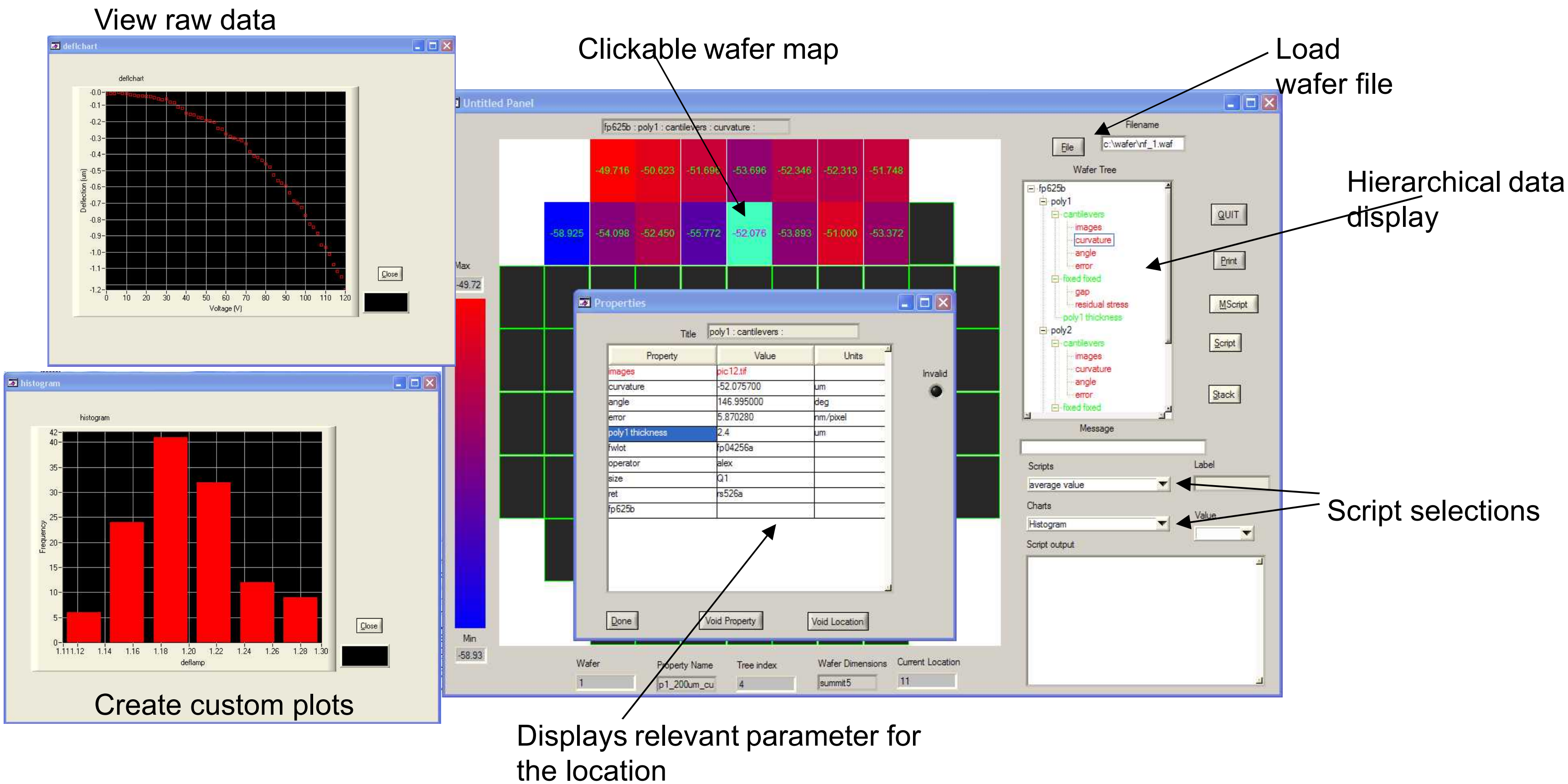


$$\Delta x = \Delta x_{move} - \Delta x_{ref} = \frac{\Delta\phi_{move} - \Delta\phi_{ref}}{2\pi f} S$$

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

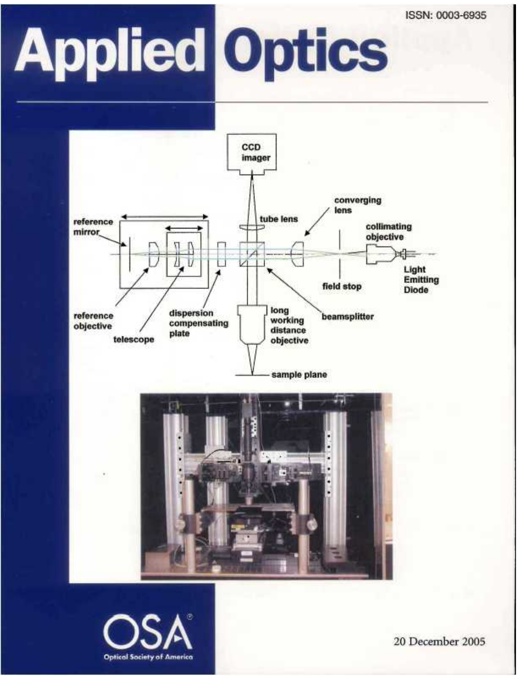
Technique allows phase detection to 2π/2500 and yields resolution of ~ 1 nm (grating pitch/2500)

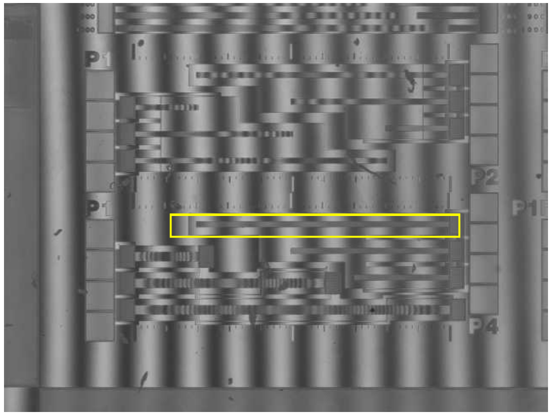
WaferScript

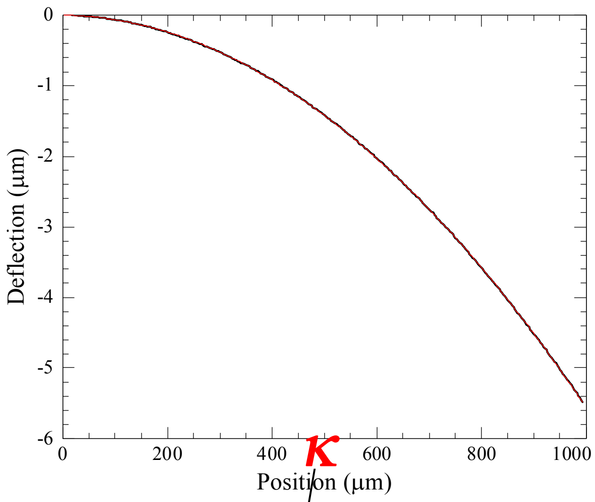


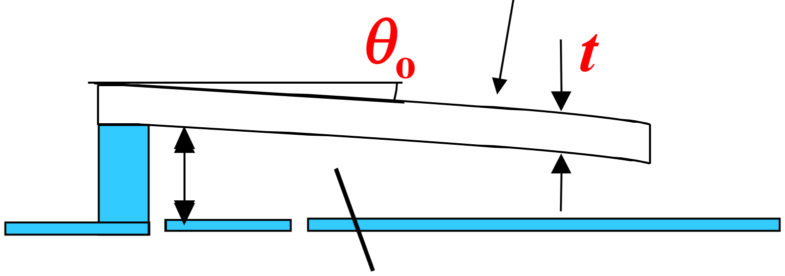
- Fully scriptable data mining and analysis tool
- High level wafermaps (i.e. deflections, stresses) linked to underlying raw data
- All analysis and graphical output accomplished through simple plug-in scripts
- Can generate automated reports included statistical analysis
- Sharead code-base with MEMScript package

Collaborated in designing long working distance interferometer









Allows out of plane measurements of MEMS devices

Incorporated into many of the test setups I have built

Can measure take-off angle and radius o curvature to track process variations

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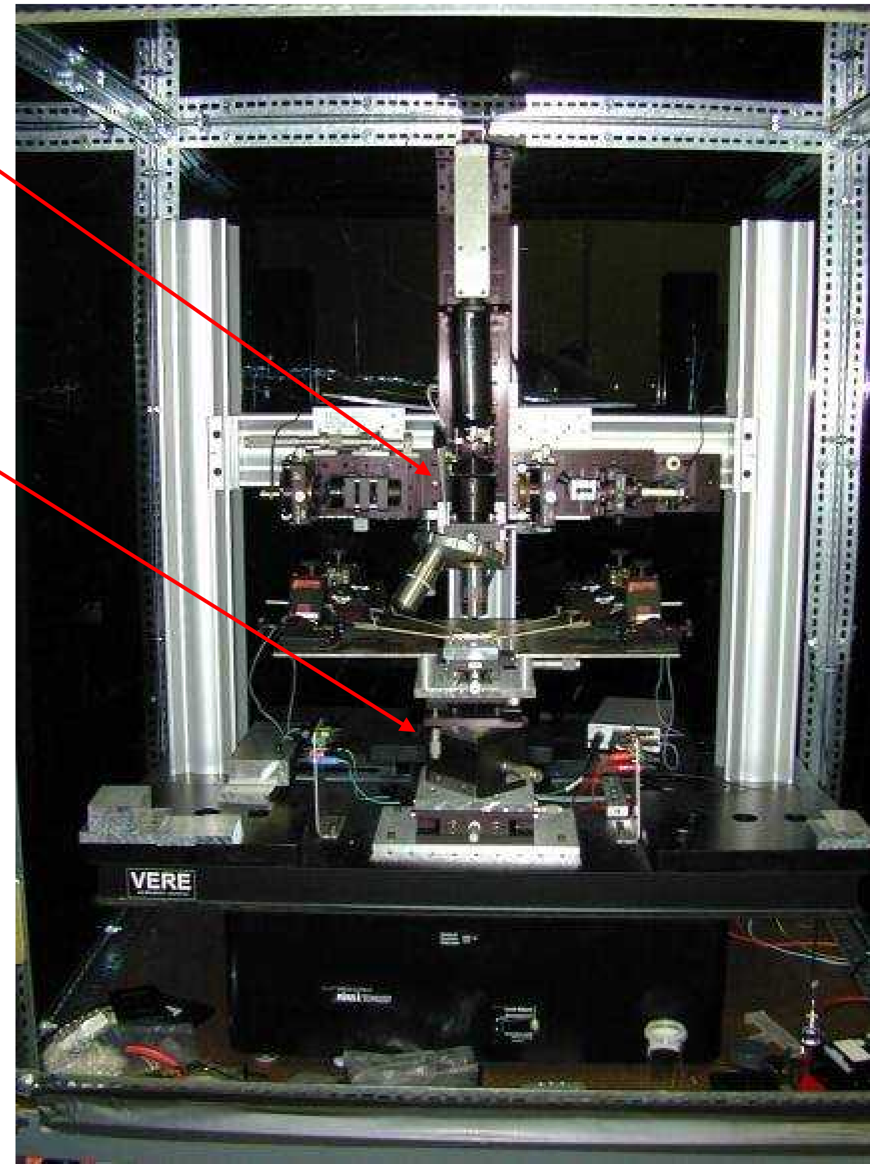
Built dual use high resolution probe station

Combines interferometer with turret and with solenoid to switch between interferometery and standard microscopy

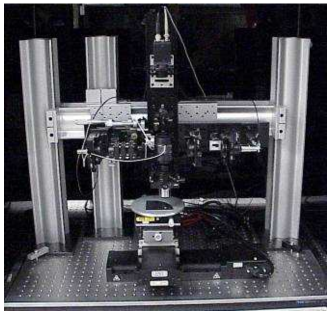
Stage stack allows for movement of part relative to probes as well as part + probes relative to microscope

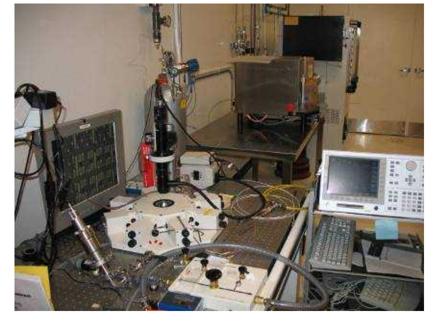
Used to take much of the data I will be presenting

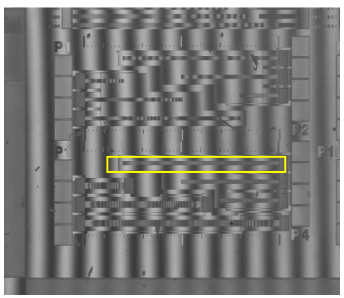
Modified version used for fully automated testers



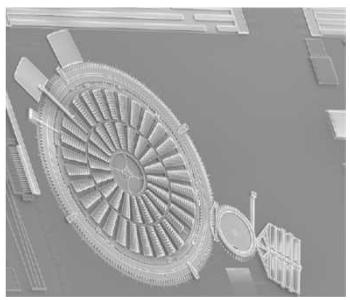
Microsystem Parametric testing:
Process control and parameters for designers



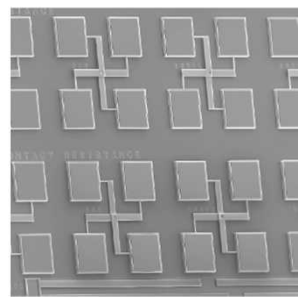





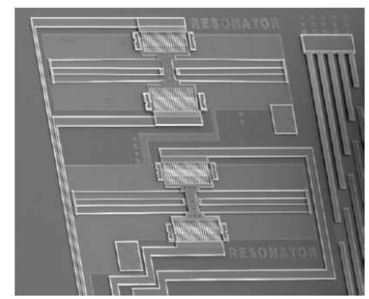
Residual stress stress gradiant



Device functionality



Sheet & contact resistance



Resonance (line width)

Lead group of 1 technologist and 2 contractors working on wide range of test hardware

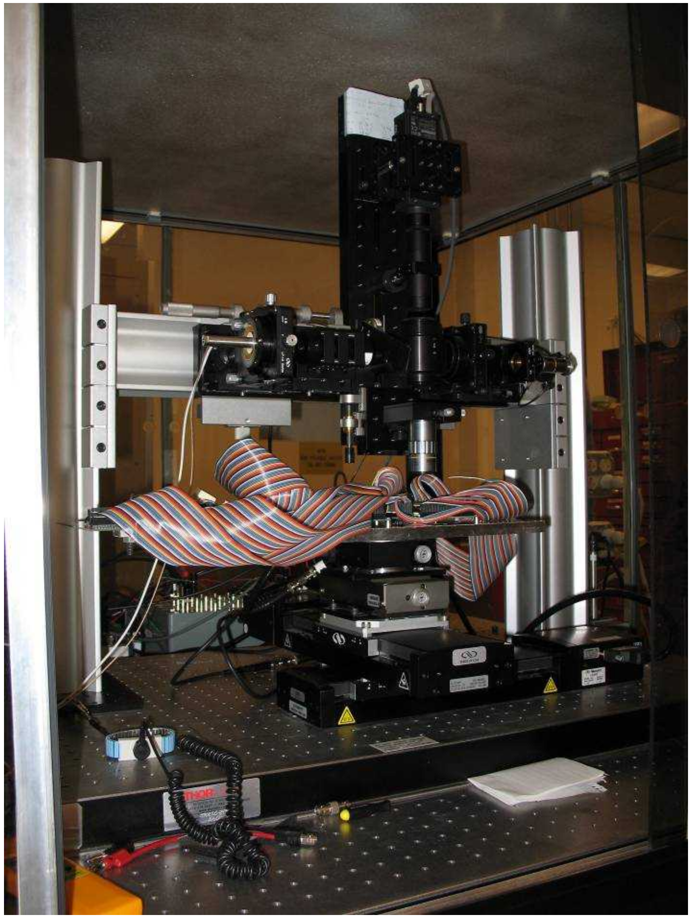
Measure electrical and mechanical test structures from every standard SUMMiT run.

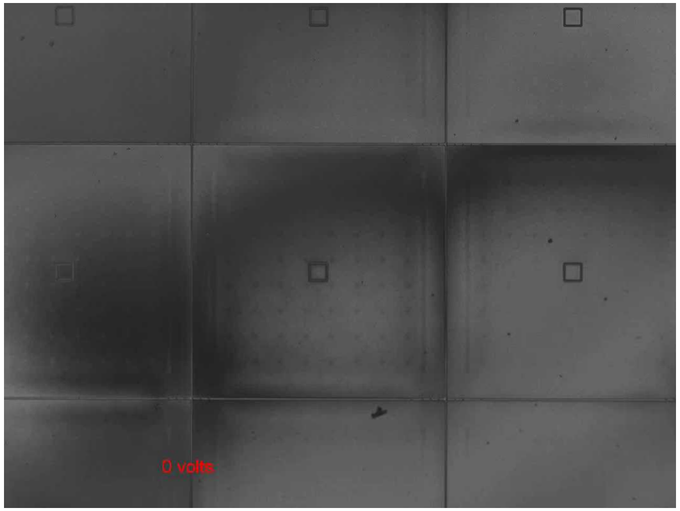
Monitor process bounds to aid process engineers (and enable them to qualify new equipment)

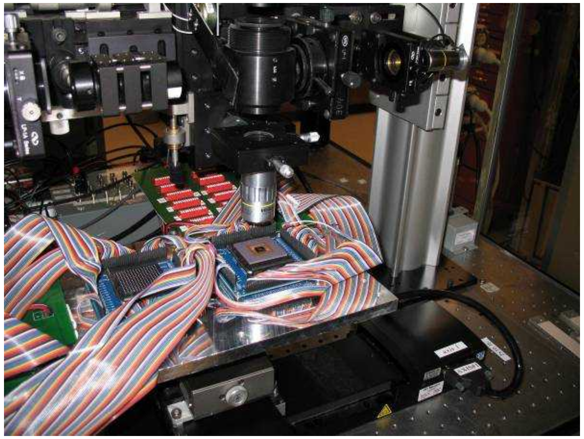
Provide property averages and standard deviations for designers and modelers

Microsystem Reliability: How do we determine reliability of large array of pistoning mirrors?

Build a fully automated x,y,z,theta scanning interferometer



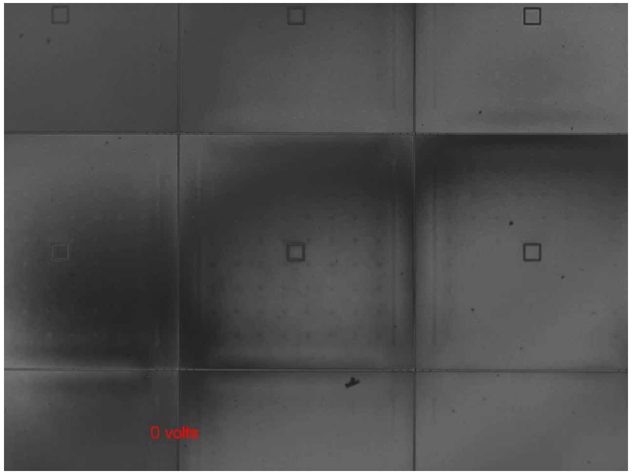


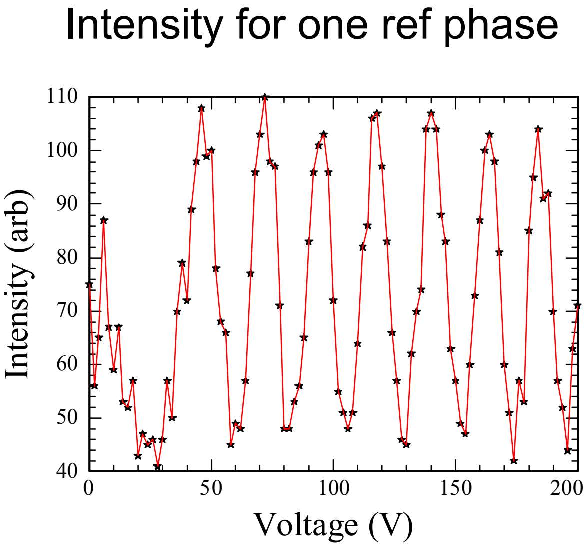


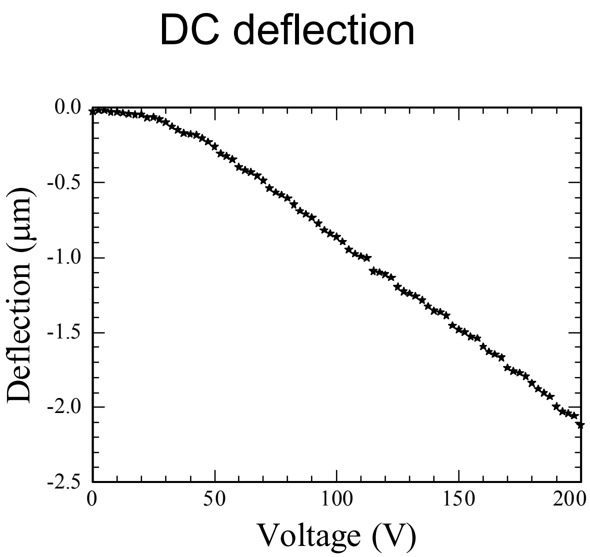
How can we capture and mine the necessary performance data?

Develop technique to allow both DC and dynamic measurements of displacement

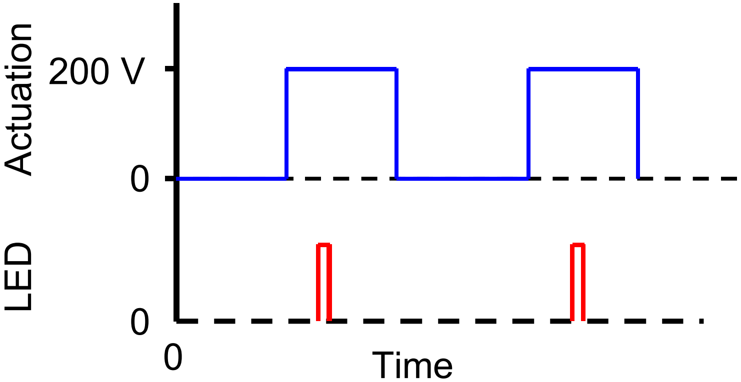
Use PSI (Hariharin algorithm), but stitch together points over time instead of space.

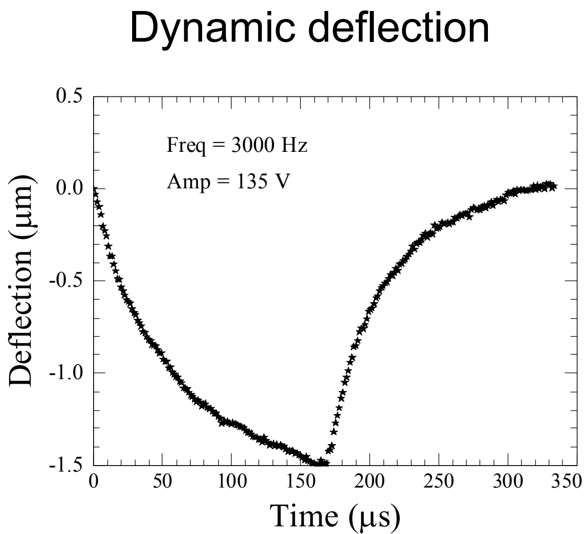




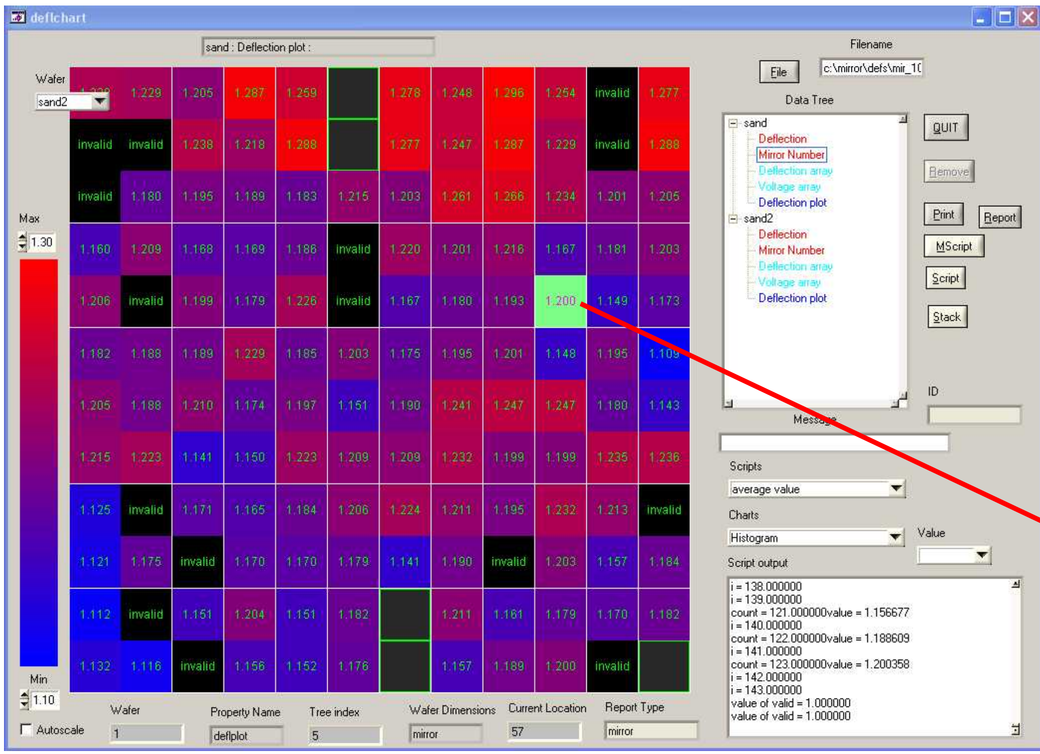


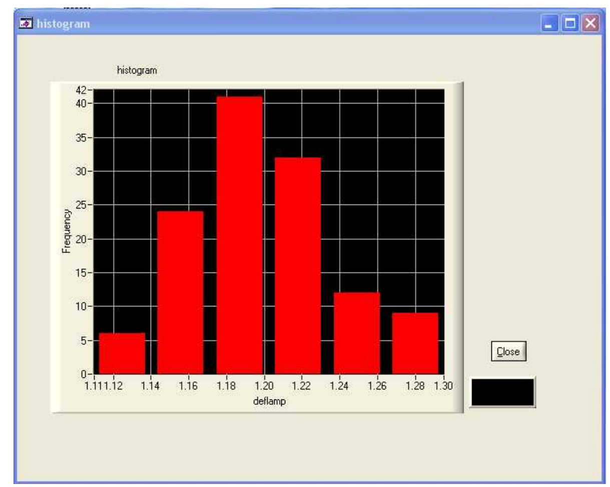
Strobe LED with delay box and vary phase to acquire dynamic deflection data



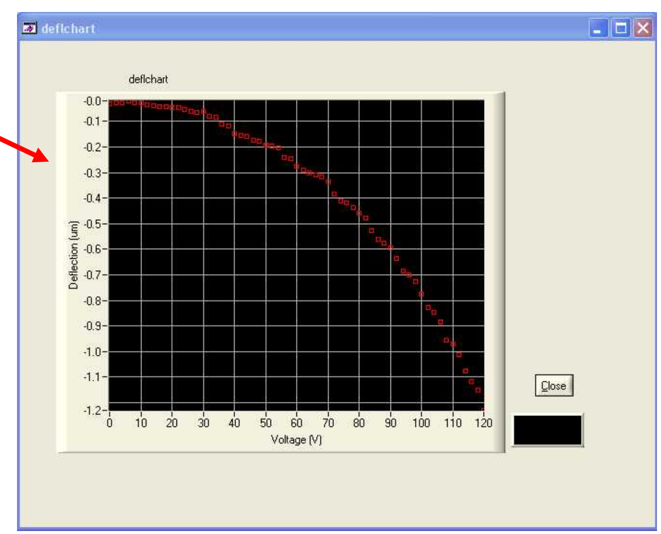


Use WaferScript to visualize and analyze data





Easily generate plots summarizing complete data set



Can drill down into data and look at individual deflection curves

Reliability analysis

Mirrors have shown no failures to data. Can predict lifetimes with exponential distribution (assumes random failures).

$$F(t) = 1 - e^{-\lambda t}$$

We can place an upper bound on the failure rate, λ, with confidence α as:

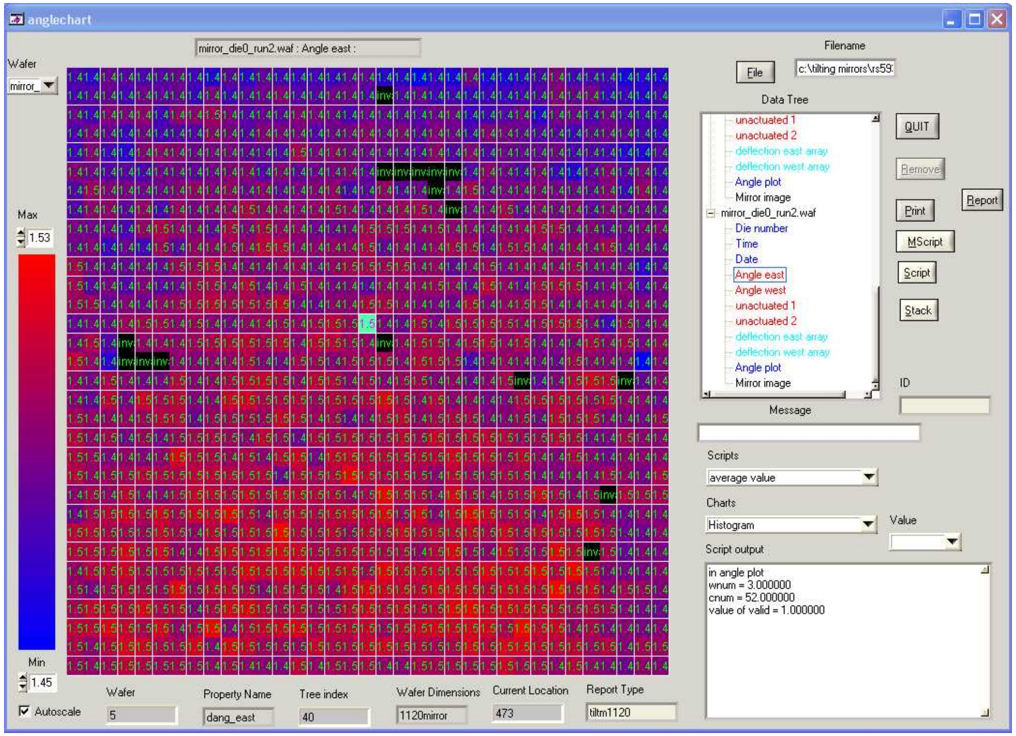
$$\lambda_{100(1-\alpha)} = -\frac{\ln(\alpha)}{n \times AF \times T}$$

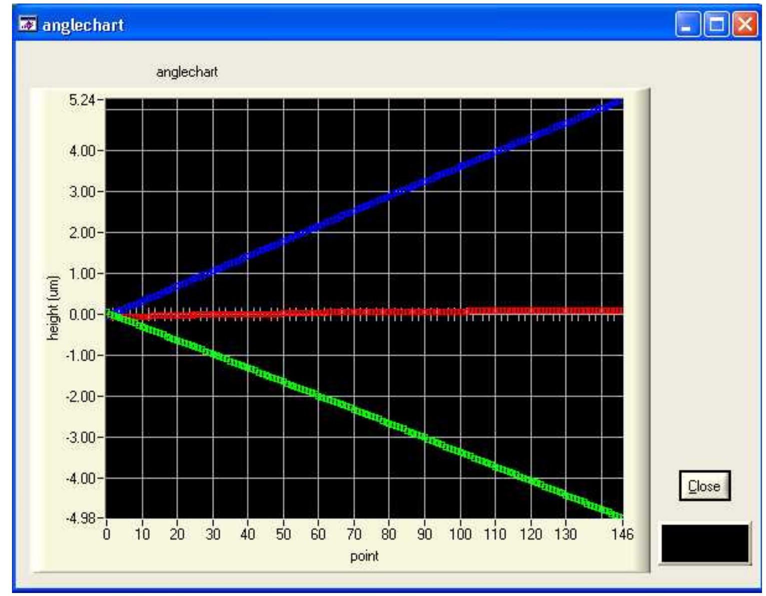
Where n is the number of mirrors, AF is the acceleration factor (as we can test the mirrors at a higher frequency than needed for the application), and T is the total number of days on test

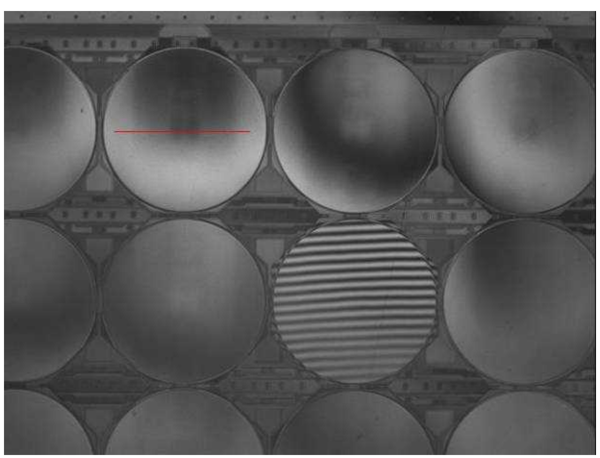
We can then compute the expected lifetime for a 1-F_mirror probability of a mirror working as

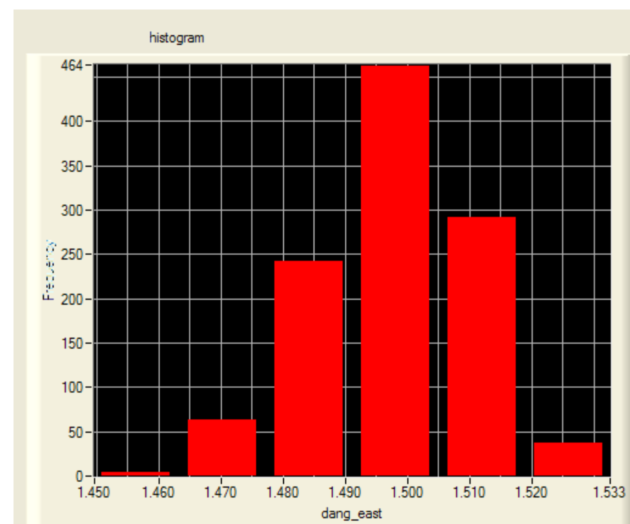
$$t = -\frac{\ln(1 - F_{mirror})}{n\lambda_{100(1-\alpha)}}$$

Build similar system for characterization / acceptance testing of tilting mirror for whitecell

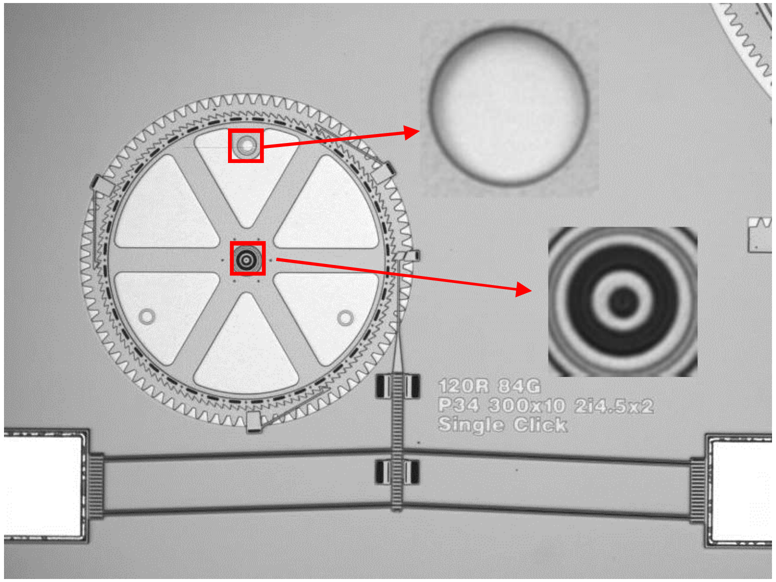


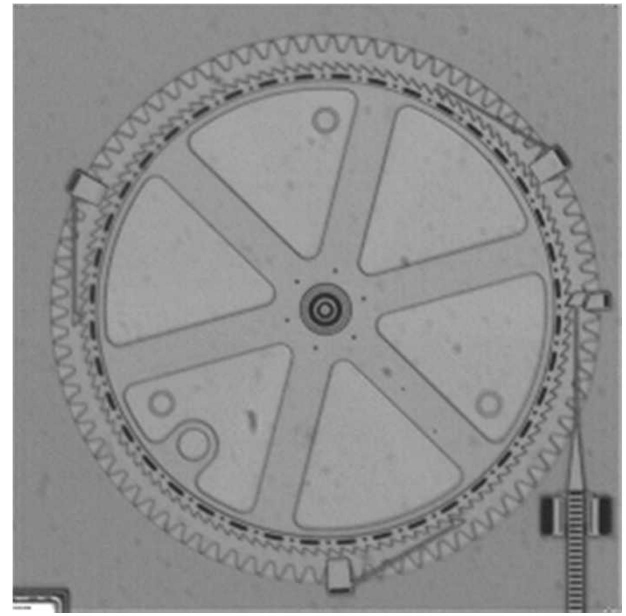






Microsystem Characterization and failure mechanism ID: Thermal Rotary Actuator (ThRA)





ThRA in operation

Used pattern matching to find center and circle on gear, and from locations, deduced angle of gear. Pattern matching also performed on stroboscopic video

Thermal actuator uses thermal expansion to create linear motion, which is then translated into motion of the gear

When will this actuator skip, and what can we do to improve performance?

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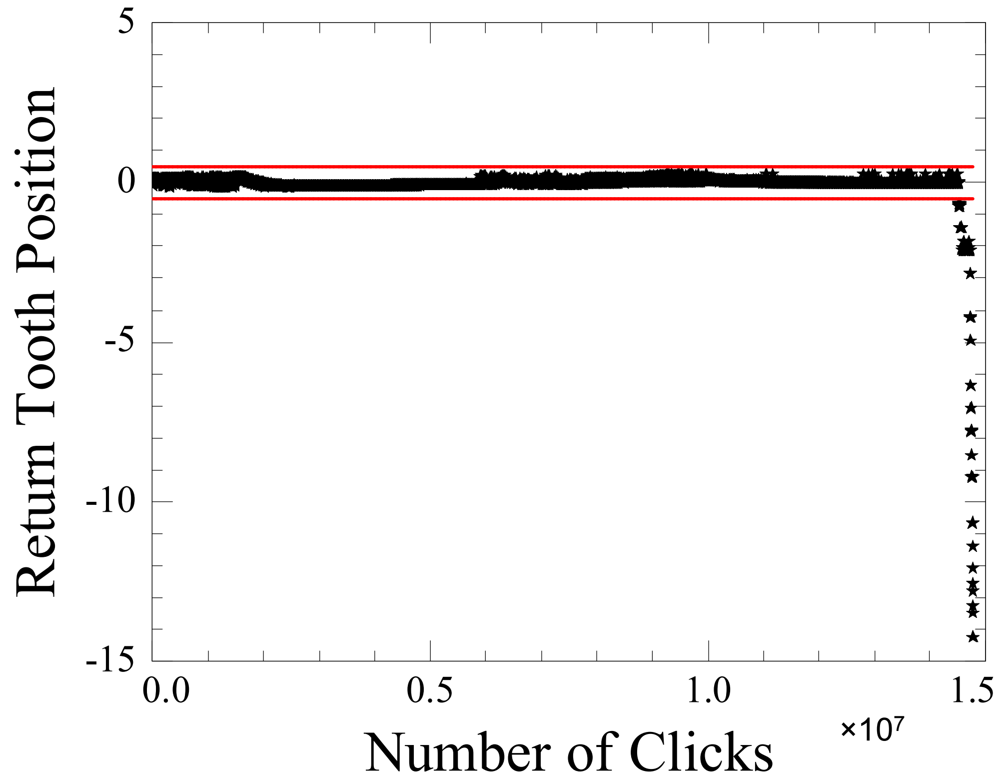
Integrate actuation and pattern matching

Use pattern matching to record position of gear after each complete rotation

Device skips after ~ 14 million clicks



Can characterize skip free operation

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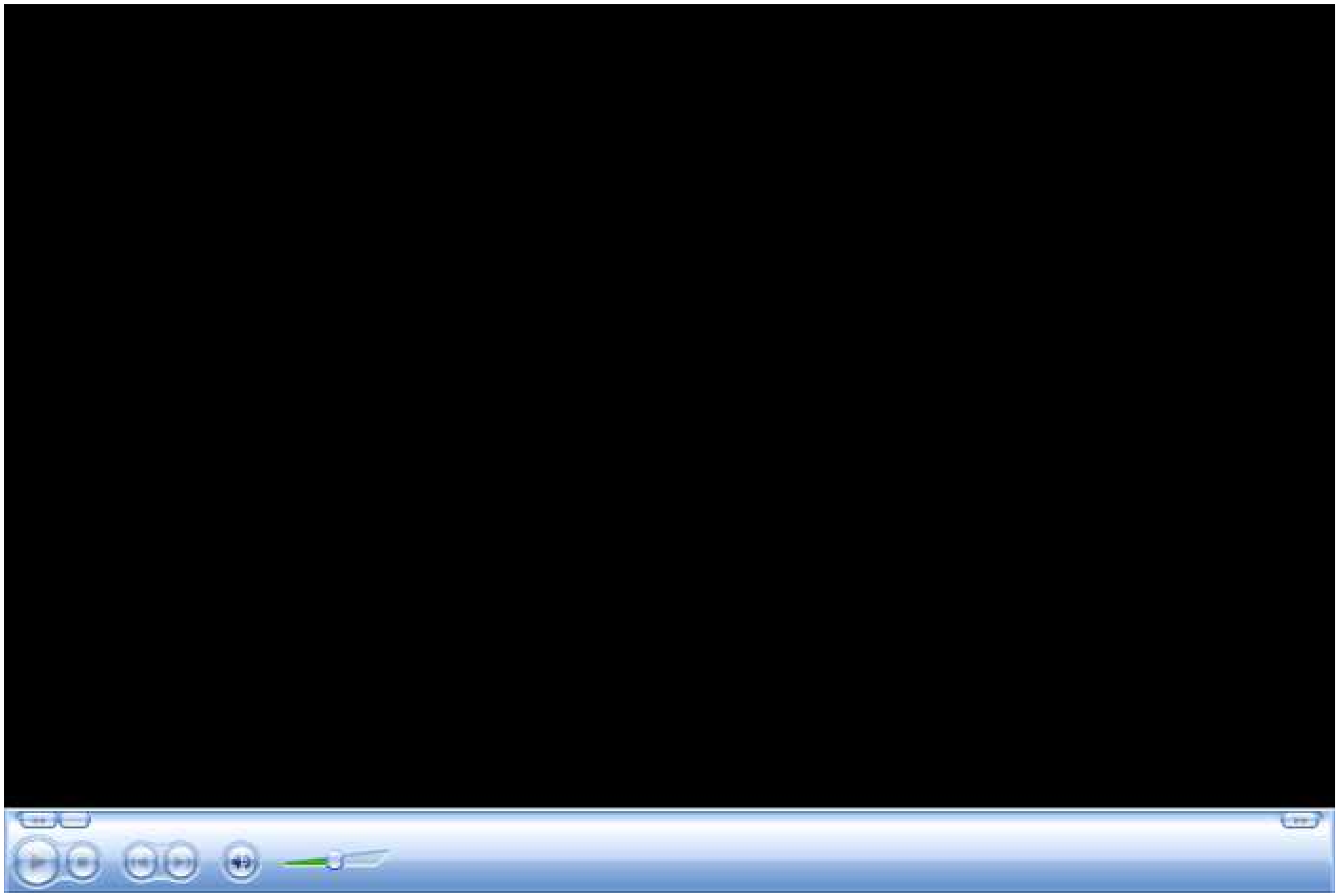
ThRA stroboscopic video – Investigate operation



Strobe can catch periodic motion

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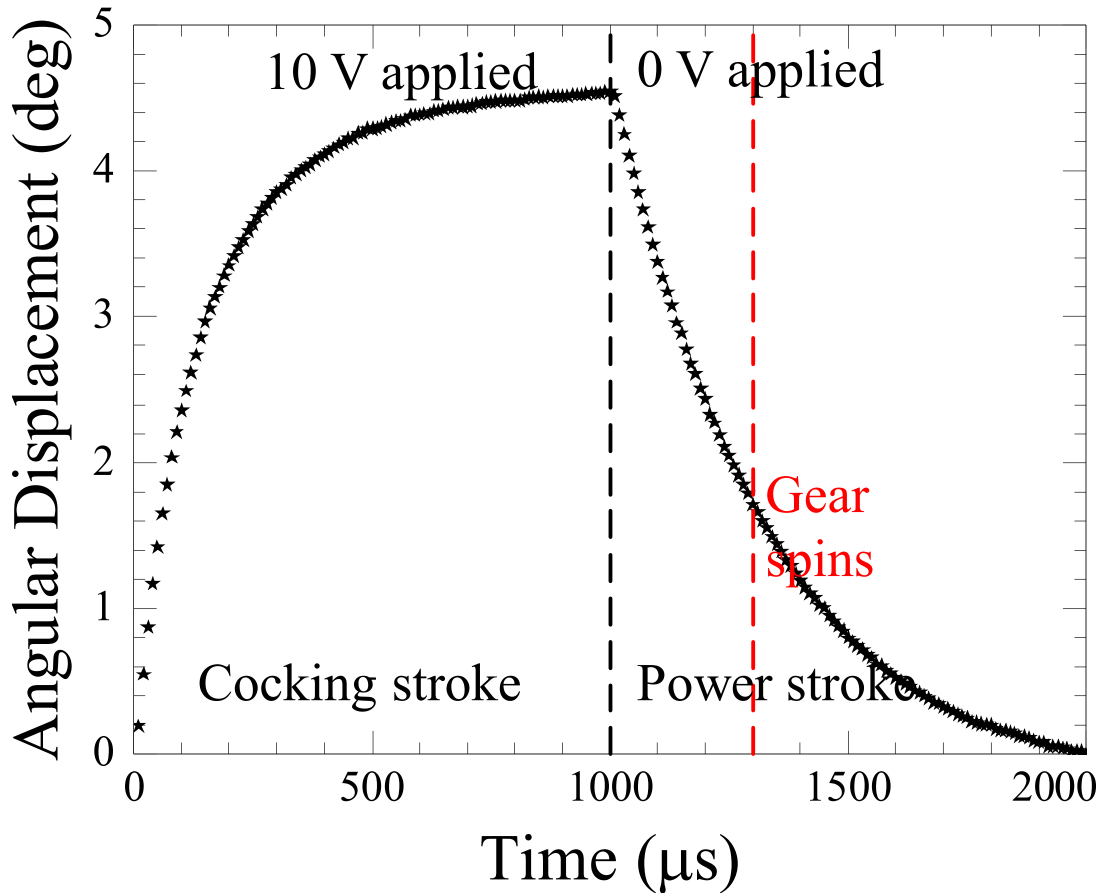
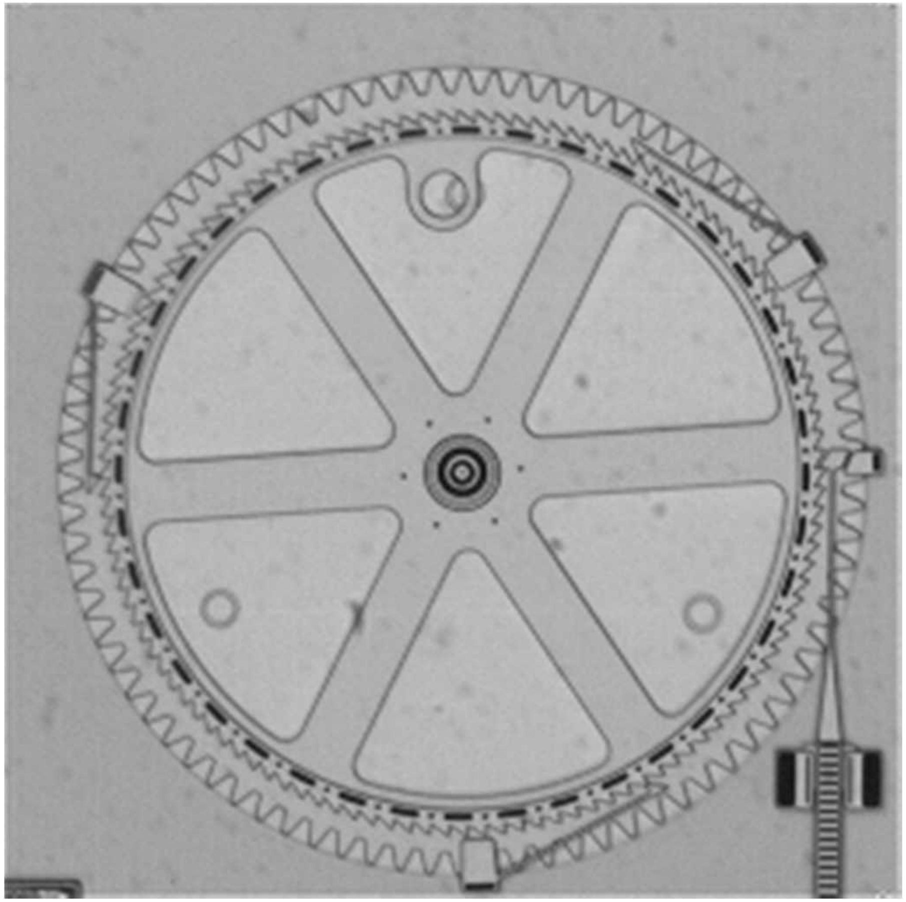
ThRA stroboscopic video diagram

Can combine pattern matching with stroboscopic video to determine device operation



Intentionally overdriving ThRA will help us identify failure modes earlier and address them through more robust design

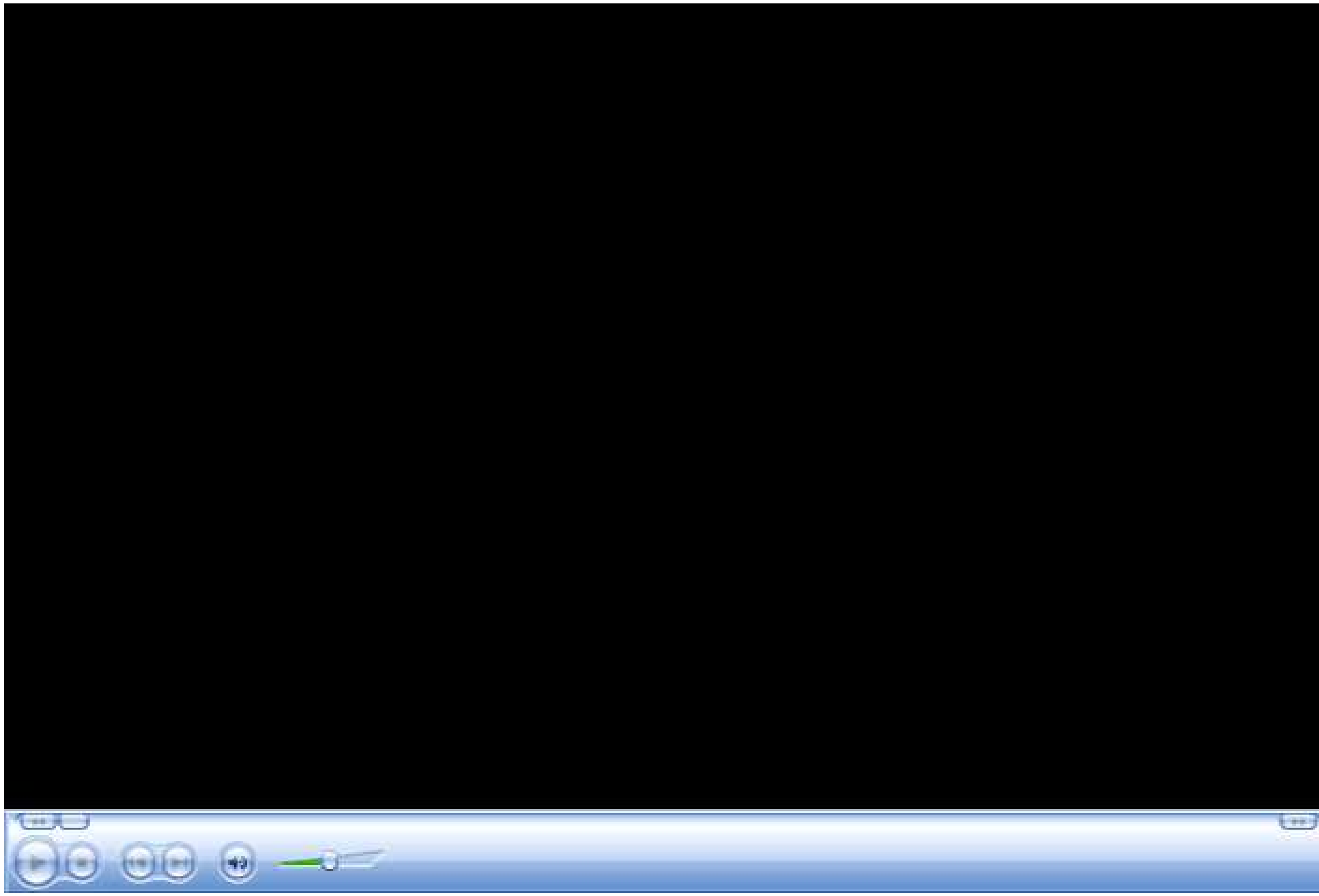
ThRA – Hi Speed video



Hi-speed video can capture transient (non-periodic events) that cannot be captured with strobe such as intermittent failure

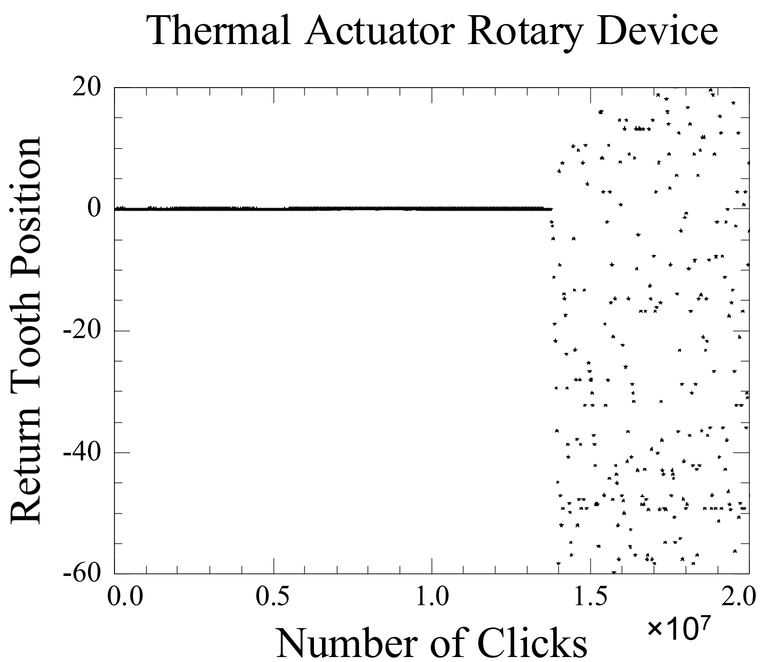
ThRA (failed) stroboscopic video

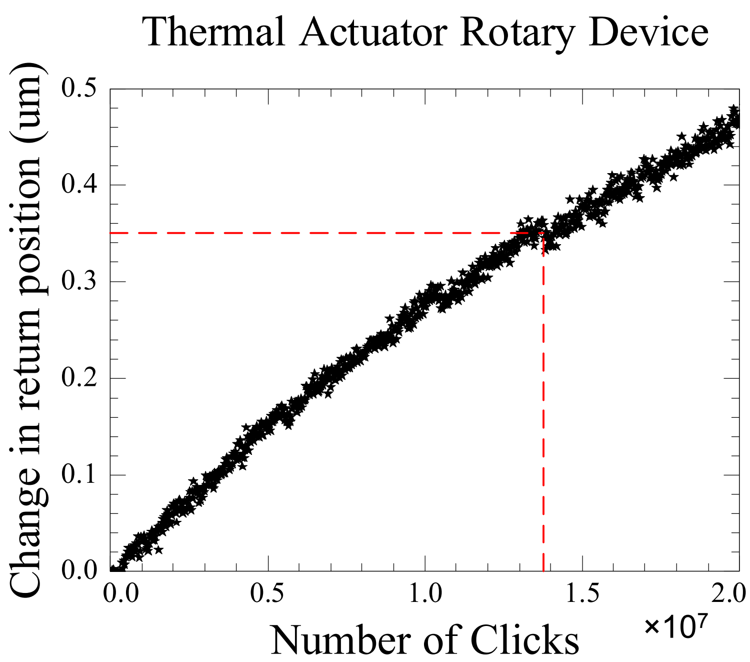
ThRA not returning far enough back in return position



Total device failure can be captured with strobe

Look for changes in return position





Heating of ThRA under load may be stretching device over time (modeling shows temperature of ~ 650 C)

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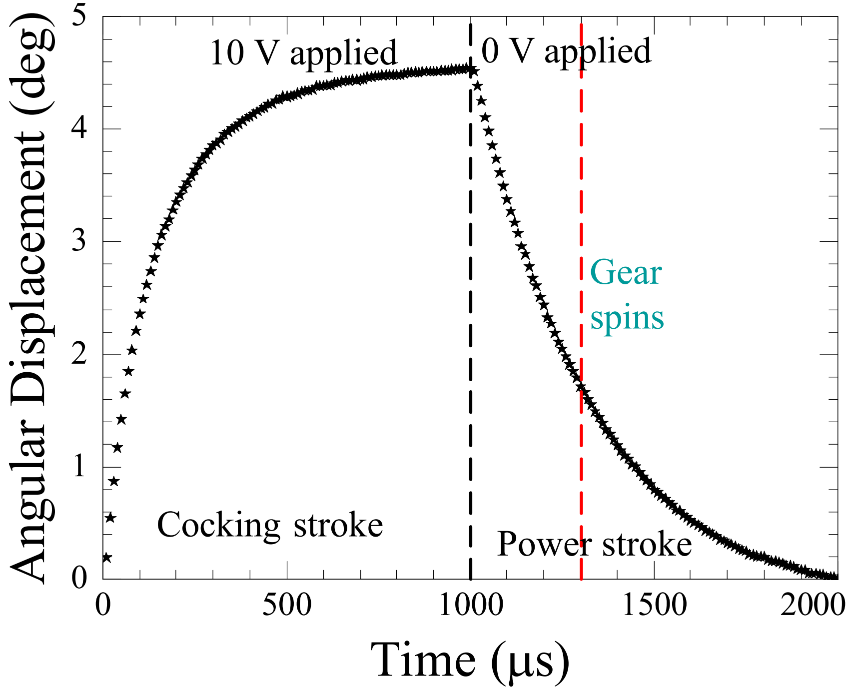
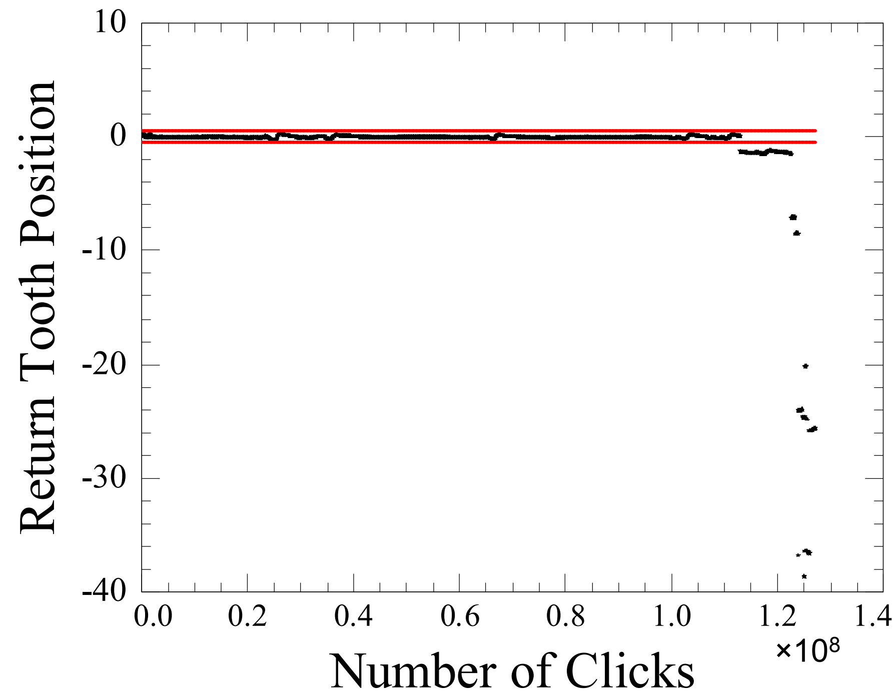
Try running ThRA and lower voltage

Recall from stroboscopic study that we had more than enough throw and can reduce voltage and still turn gear





Reducing voltage lowers temperature allows over 100 million skip free clicks!

New ThRA was designed to operate at even lower temperature. To data has accumulated over .5 billion clicks!

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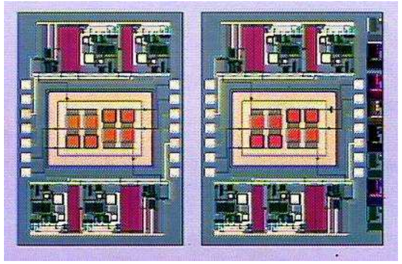
Microsystem Reliability Challenge:

Friction between contacting surfaces

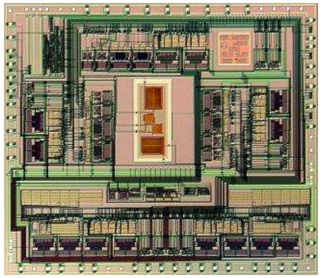
MEMS are RELIABLE – Industry chooses simpler devices

Class I
No Moving parts



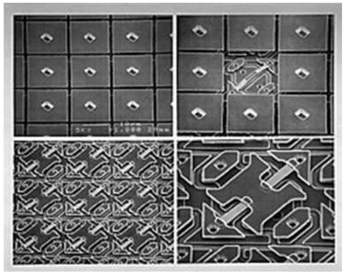
Accelerometers
Pressure Sensors
Inkjet Print Heads
Strain Gauge

Class II
Moving Parts, No Rubbing or Impacting Surfaces



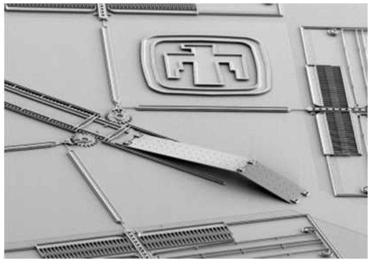
Gyros
Comb Drives
Resonators
Filters

Class III
Moving Parts, Impacting Surfaces



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

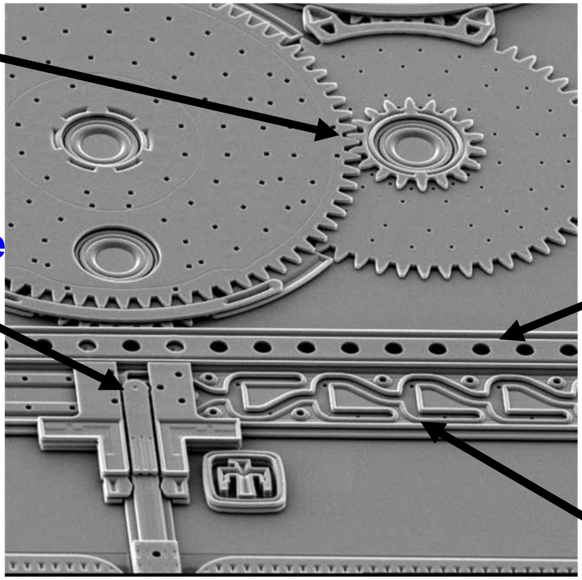
Class IV
Moving Parts, Impacting and Rubbing Surfaces

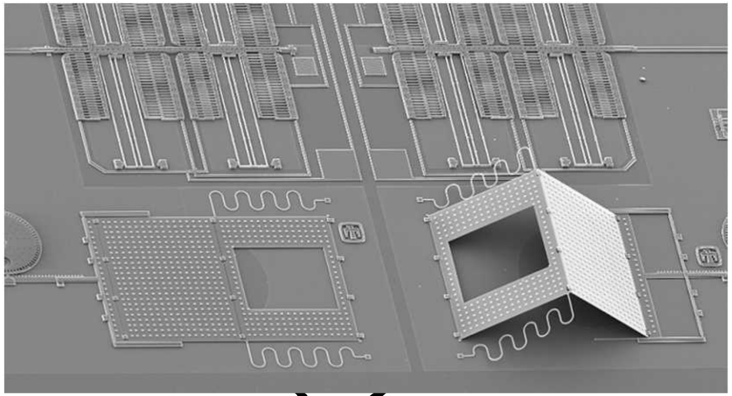


Optical Switches
Shutters
Scanners
Locks
Discriminators

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

Allowing contact between MEMS surfaces significantly broadens the design space





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

How can we understand these mechanisms better?

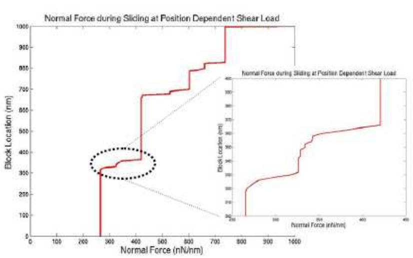
Large effort at Sandia to understand and mediate effects of contacting MEMS

Vital for many projects across the lab

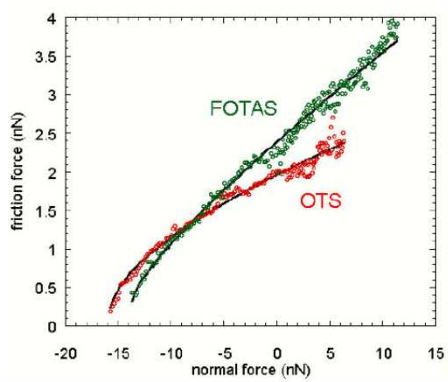
Effort includes designers, process engineers, packaging engineers, modelers, characterization and reliability physicists

Desire reliable and predictable device performance

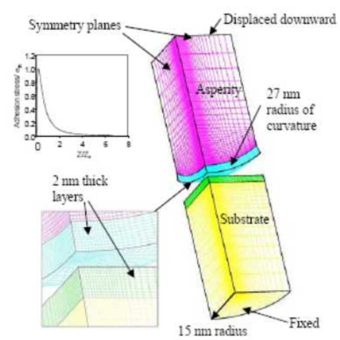
Rough surface contacting a flat plane – R.E. Jones, Sandia



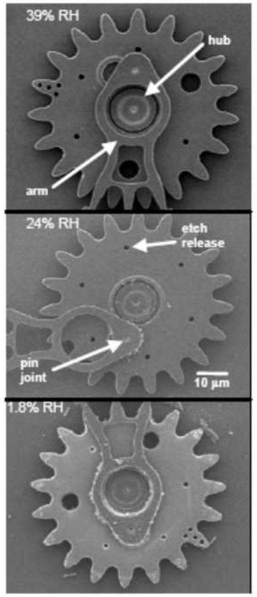
Discrete simulations of polysilicon frictional sliding, M.J. Starr, Sandia



AFM friction force measurements on polysilicon surfaces – E.E. Flater, R.W. Carpick, U. Wisc., R.W. Ashurst, Auburn



Finite Element simulation of a single asperity – N.D. Reedy, Sandia



SEM of μengine gears stressed at various humidity's – D.M. Tanner et al, Sandia

I will focus on work I have done to understand frictional contact between planar surfaces

MEMS – surface micromachining implementation

A series of structural and sacrificial layers are deposited

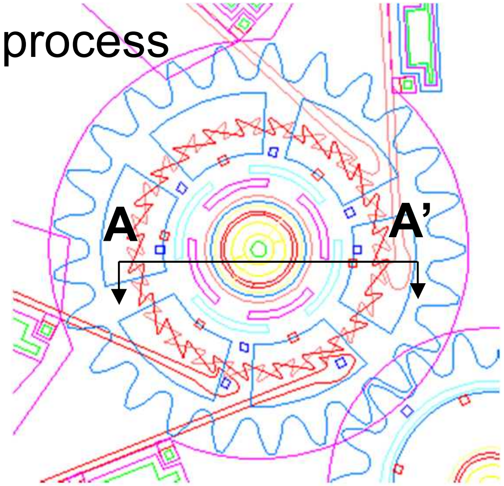
Ground plane layer (Poly 0)
4 structural levels
(Poly 1 - Poly 4)

Chemical Mechanical Planarization (CMP)

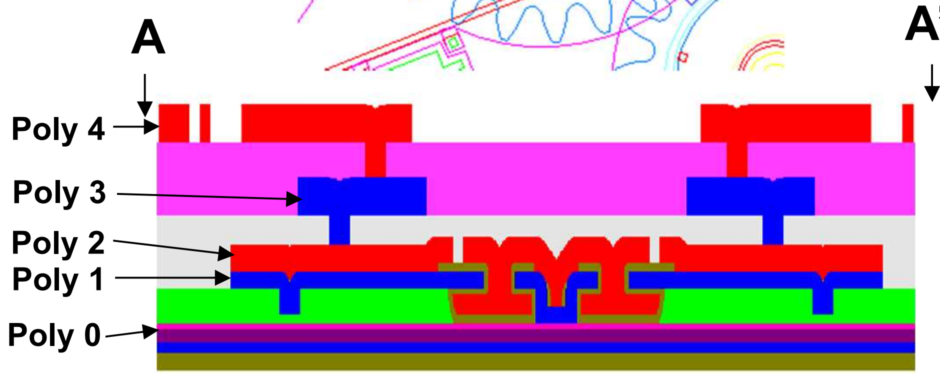
1 μm design rule

Create freestanding thin film structures by "release" process

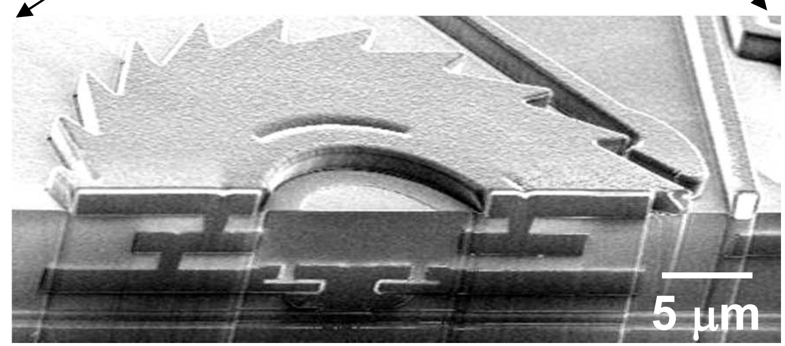
SUMMiT V™ process



Design



Cross-section drawing

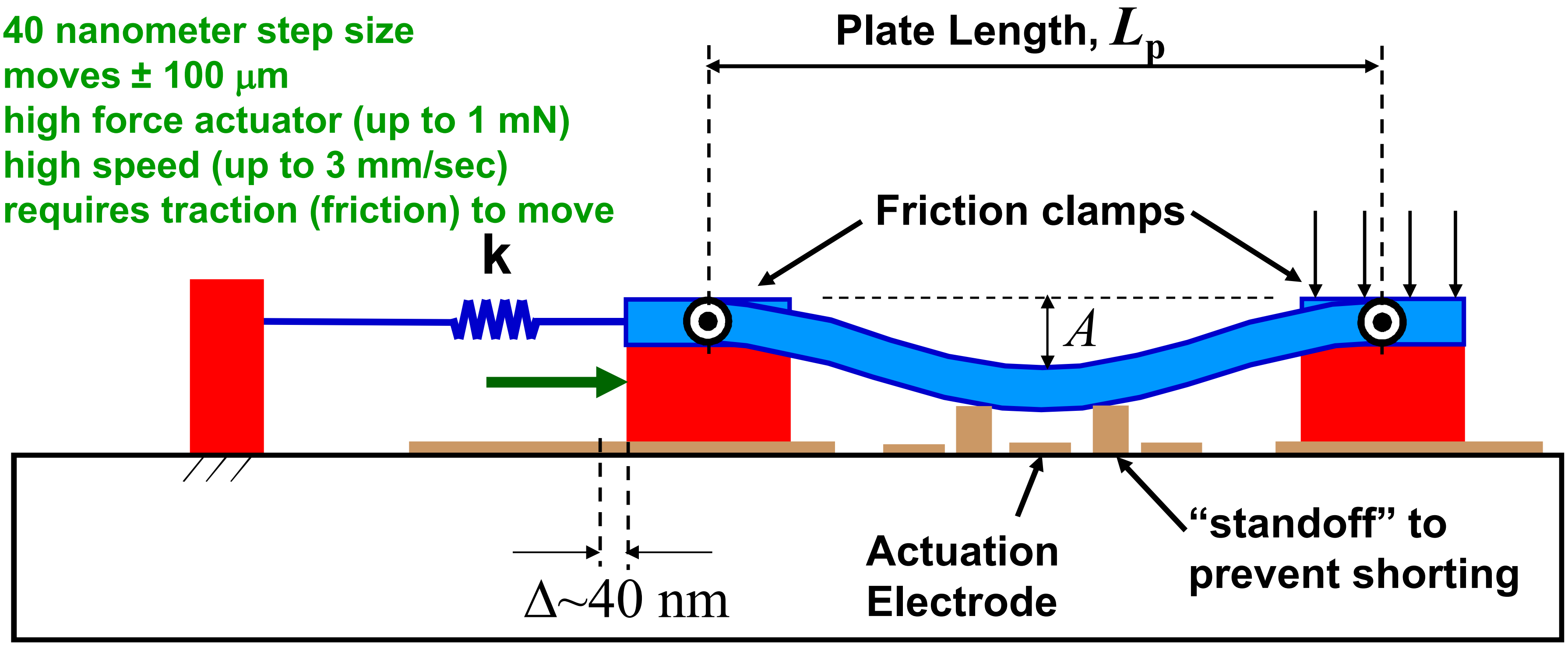


FIB cross-section

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

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

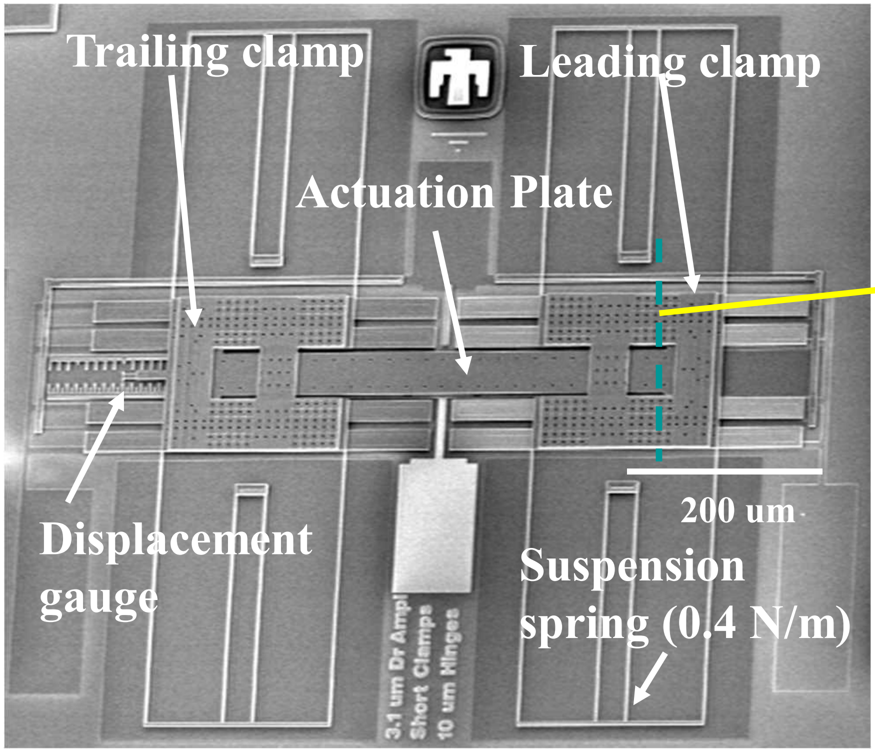
- 40 nanometer step size
- moves ± 100 μm
- high force actuator (up to 1 mN)
- high speed (up to 3 mm/sec)
- requires traction (friction) to move

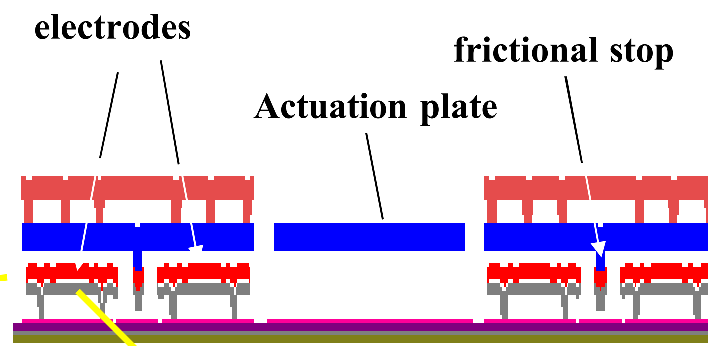


$$F_{\max} \sim 2Ewt\left(\frac{A}{L_p}\right)^2 \approx 1\,\mathrm{mN}$$

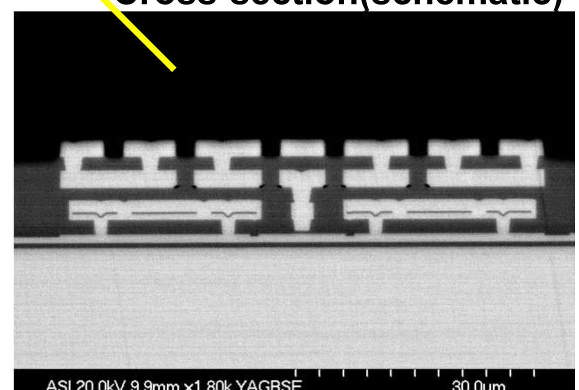
large tangential force range

The Nanotractor Device





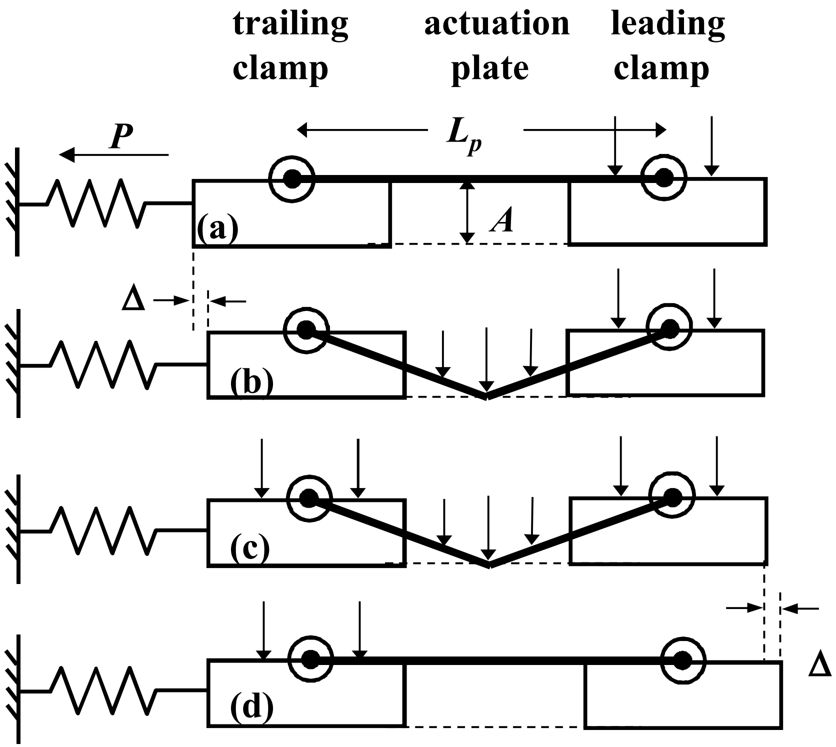
Cross-section(schematic)

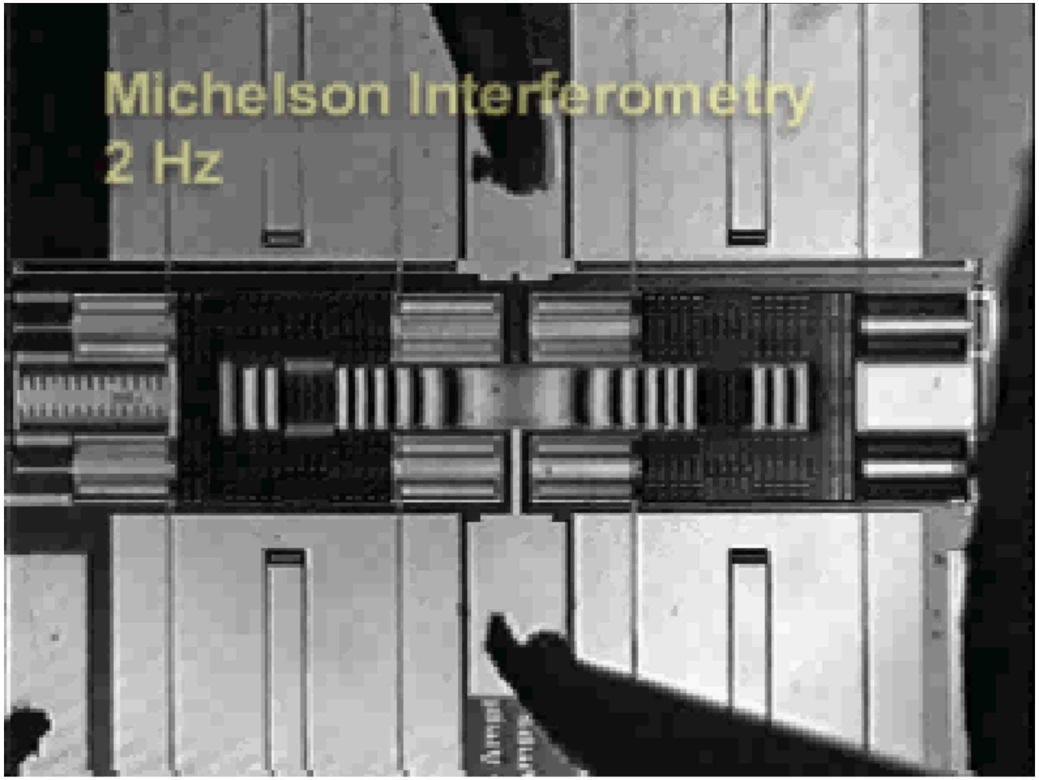


SEM of Friction Clamp

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

Driving the Nanotractor

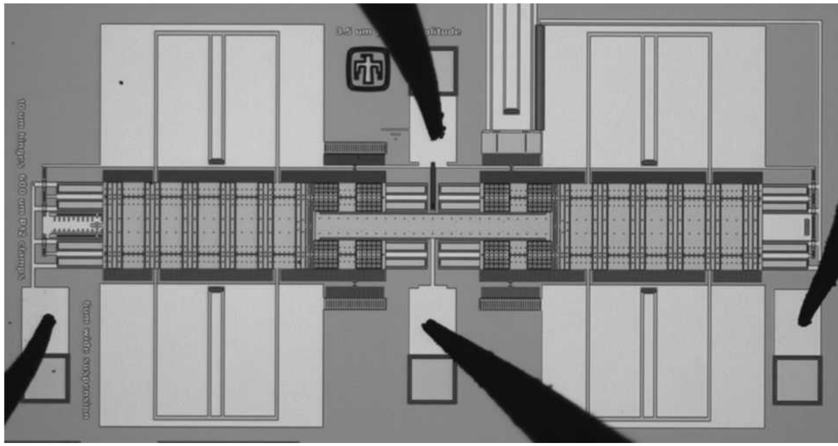




(a) Clamp RHS
(b) Pull down driver beam
(c) Clamp LHS
(d) Relax RHS & driver beam

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



Maybe replace with picture or video showing nanotractor pulling against fixed-fixed load cell

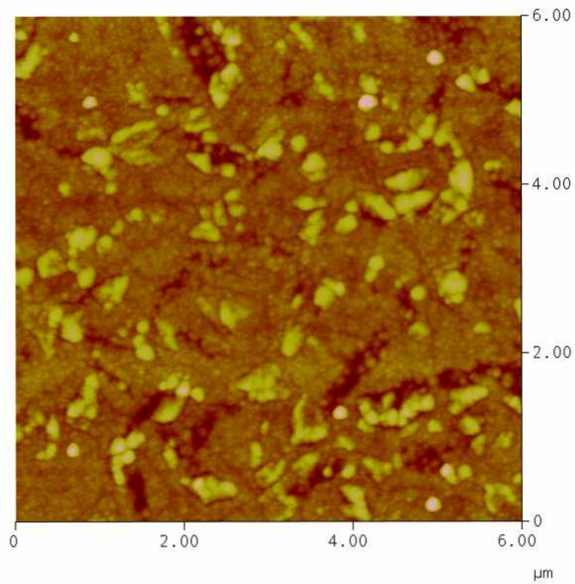
The nanotractor depends on friction for its operation

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



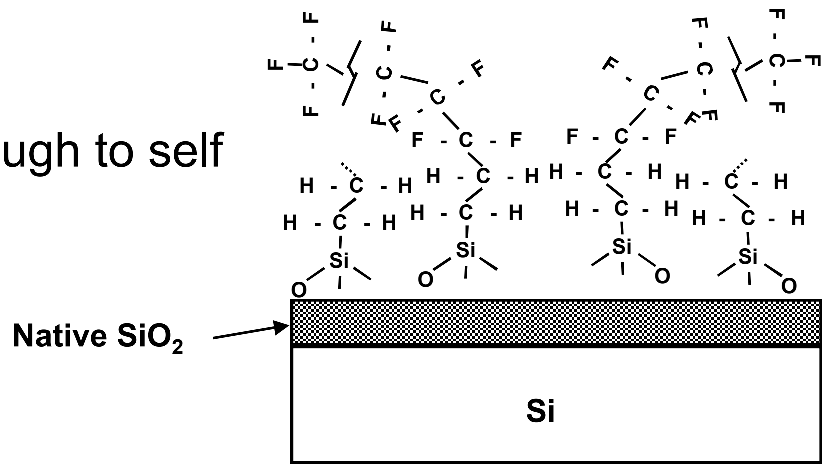
FOTAS (tridecafluoro-1,1,2,2-tetrahydrodecyltris(dimethylamino)silane)

•vapor deposited 8 carbon chain

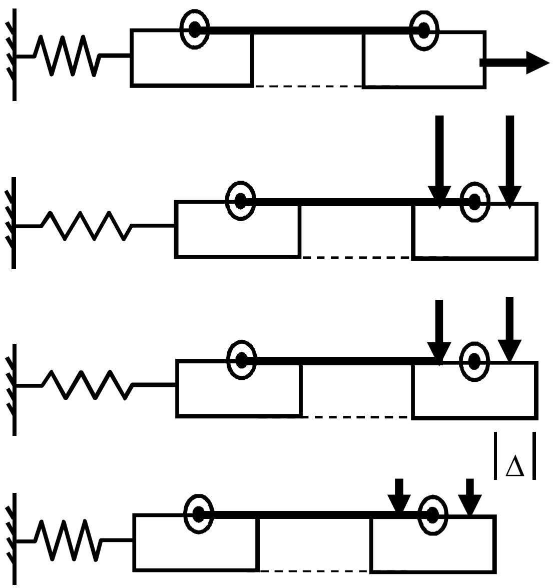
•van der Waals forces not strong enough to self assemble (tangled)

•contact angle ~ 110° (hydrophobic)

FOTAS 8-carbon fluorinated chain (disordered, tangled)



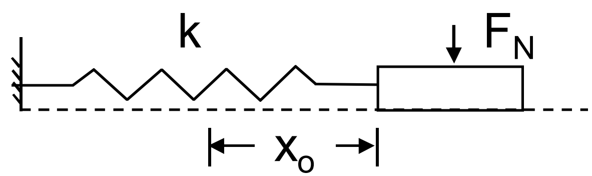
Static friction measurement

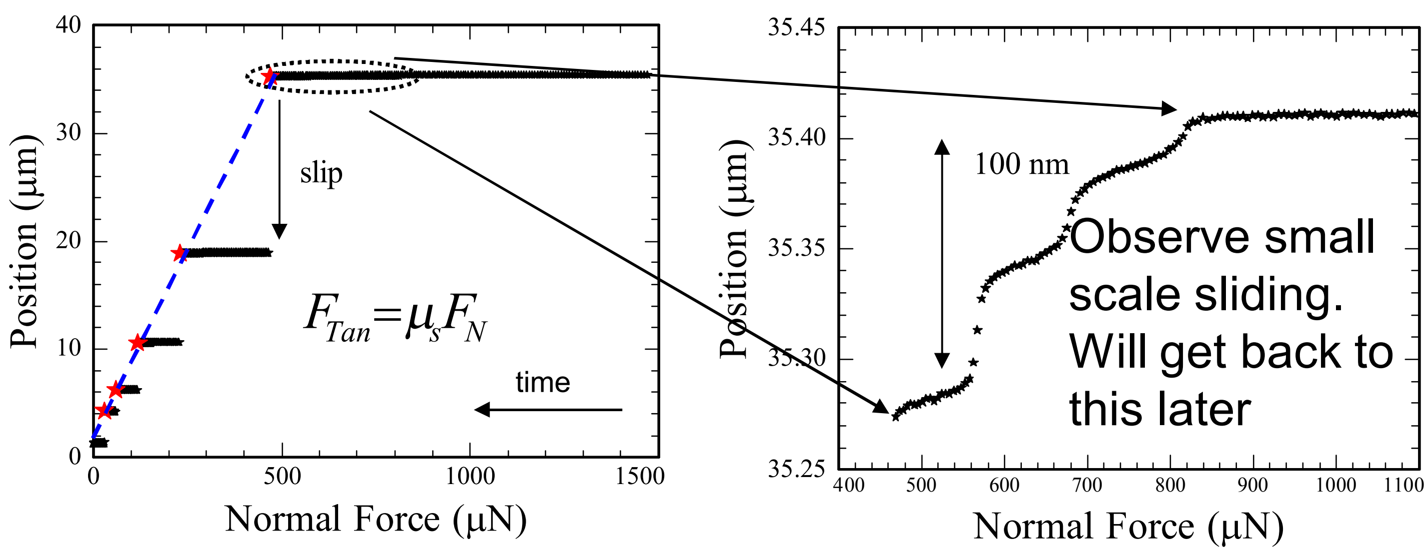


Walk out nanotractor against load spring

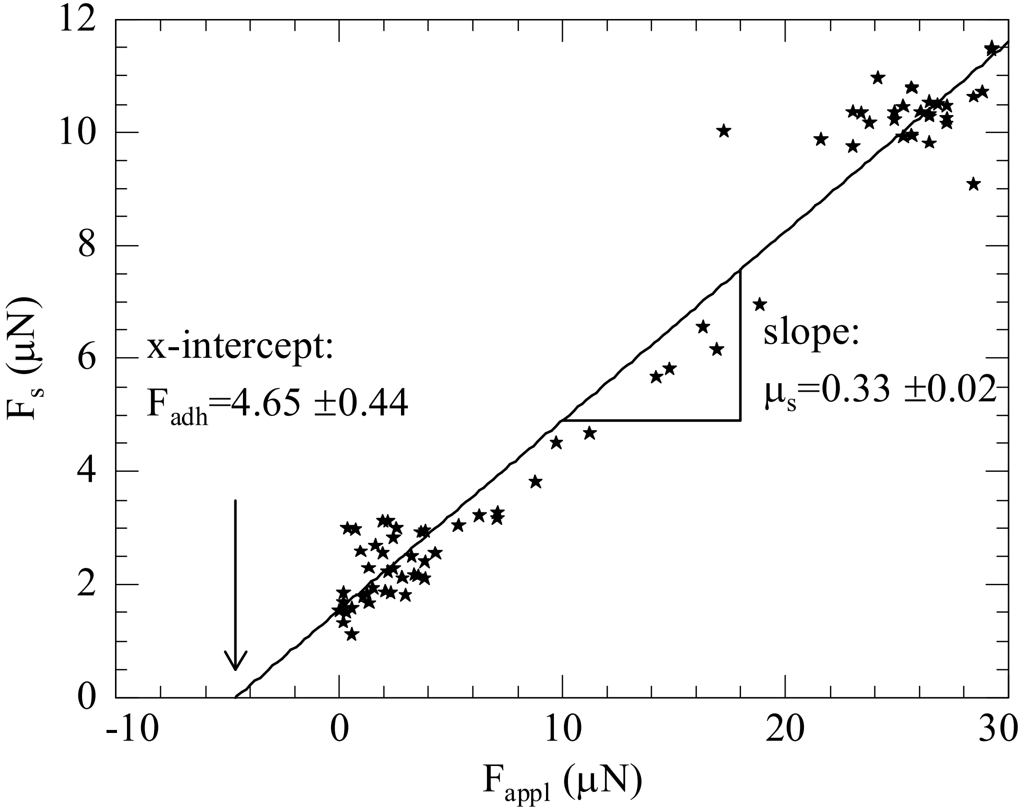
Apply large normal force (voltage)

Step down normal force (voltage) and record position





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

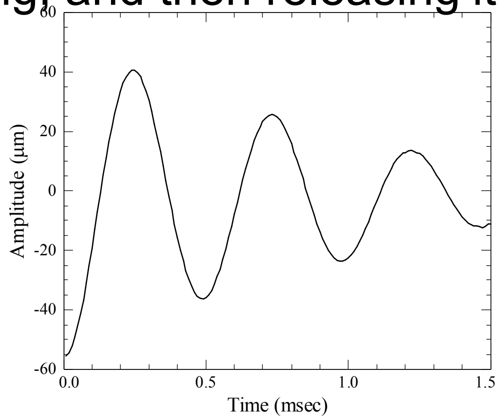
$$F_s = \mu_s F_{appl} + \mu_s F_{adh}$$

Capturing Dynamics

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

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

Resonant frequency ~ 2 KHz

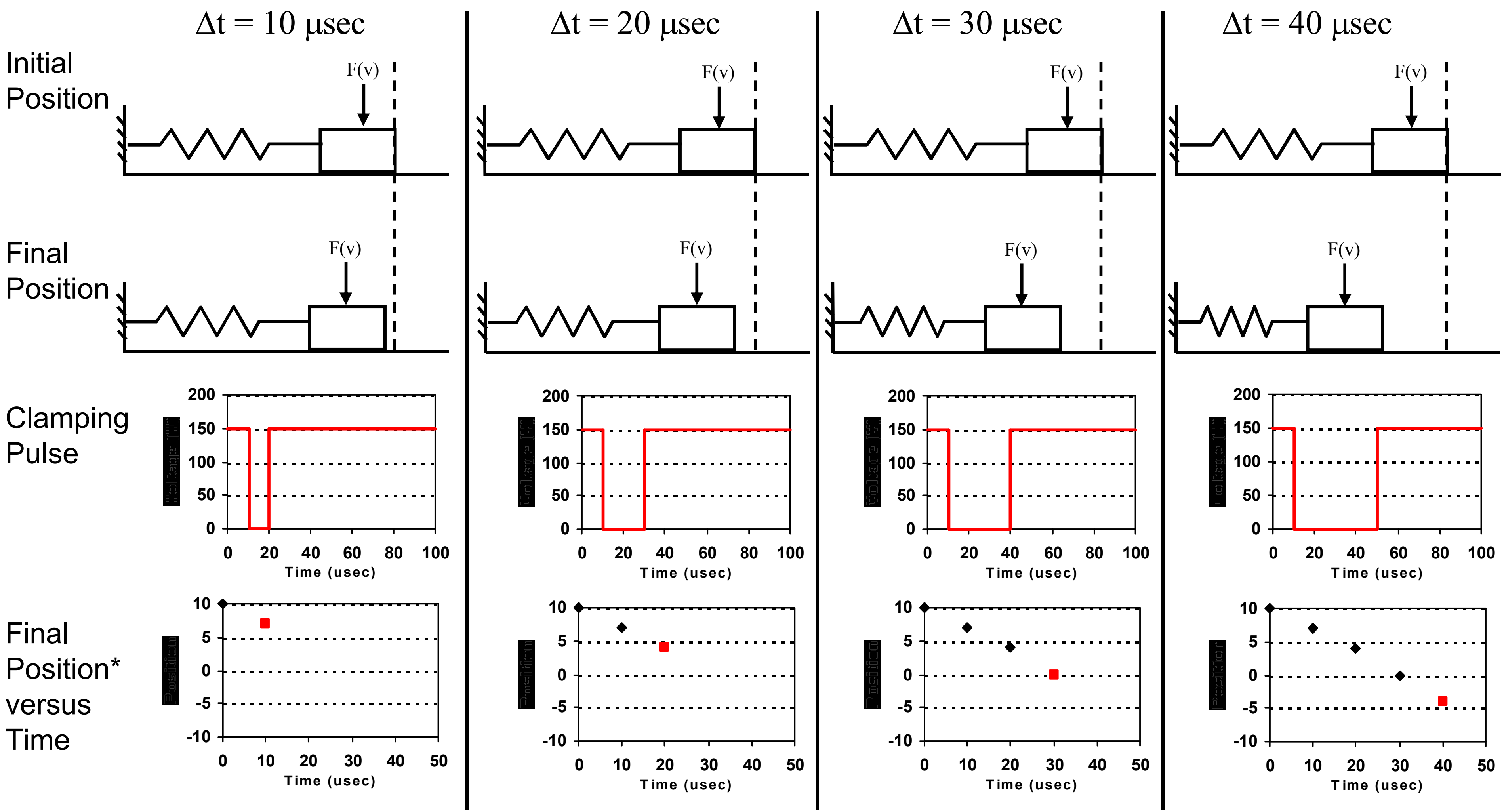


How can we measure this with high resolution?

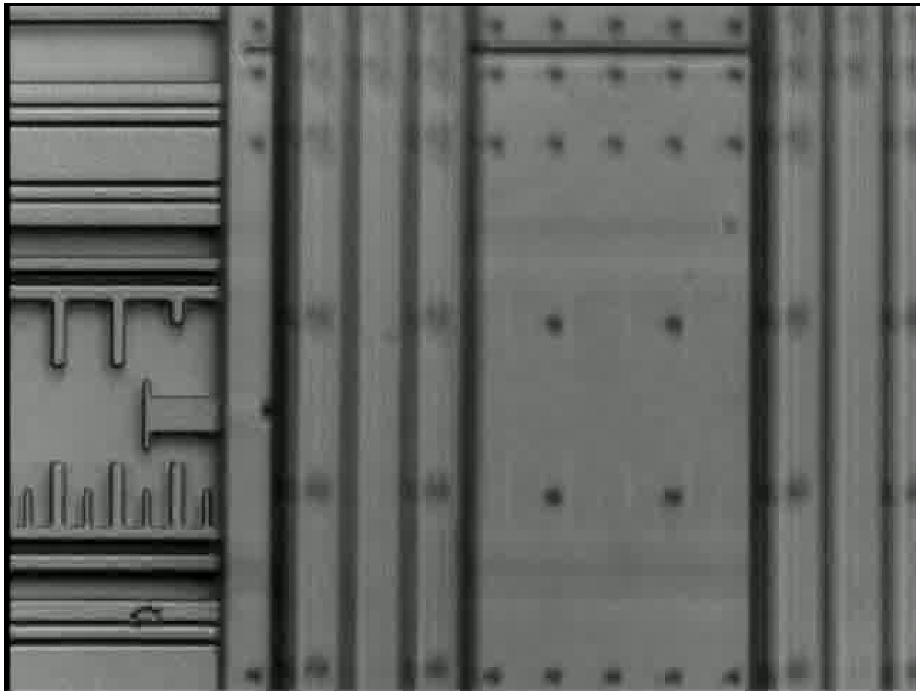
- High speed camera has light issues at high mag
- Strobing also presents high mag light problem
- Piezo resistance in the spring related deflection, but low signal to noise, and calibration issues

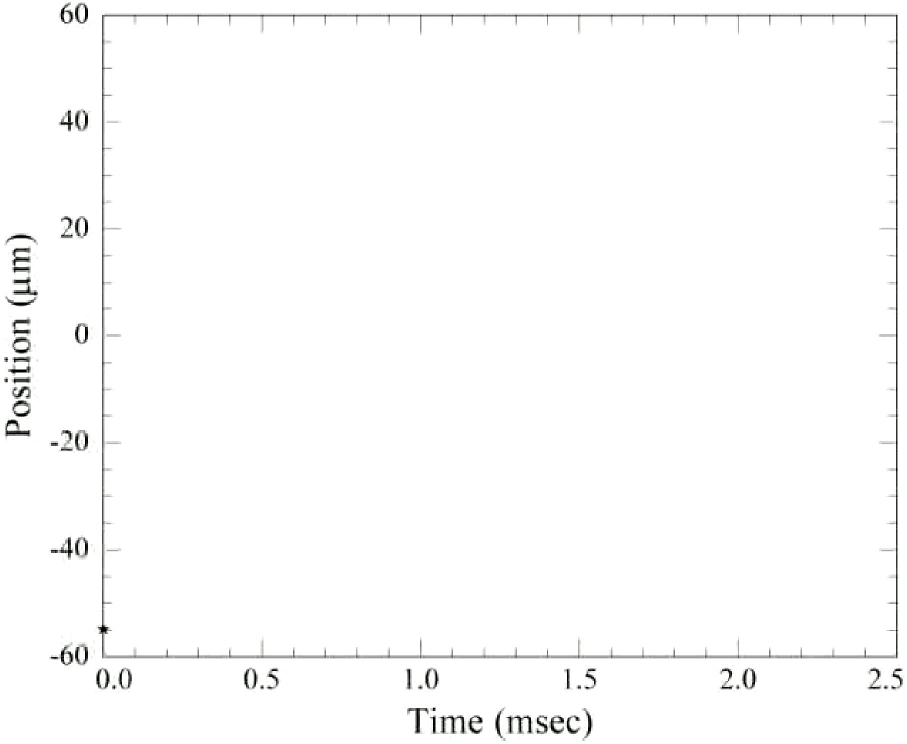
Instead, we have implemented an electro-mechanical strobing technique.

Electro-Mechanical Strobing Diagram



Electro-Mechanical Strobing in Action





600 um clamps, FOTAS coating

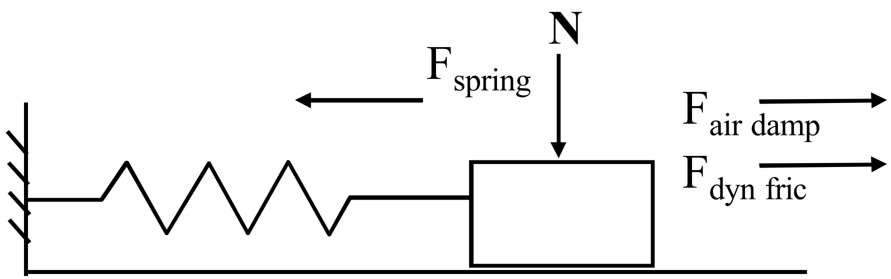
Data taken with no electrostatic normal load

Modeling: Force Diagram

$$\mathrm{F}_{\mathrm{spring}} = k\dot{x}$$

$$\mathrm{F}_{\mathrm{dyn\ fric}} = \mu_d N \,\mathrm{sgn}(\dot{x})$$

$$\mathrm{F}_{\mathrm{air\ damp}} = b\dot{x}$$



Writing the sum of the forces:

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

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

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

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

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

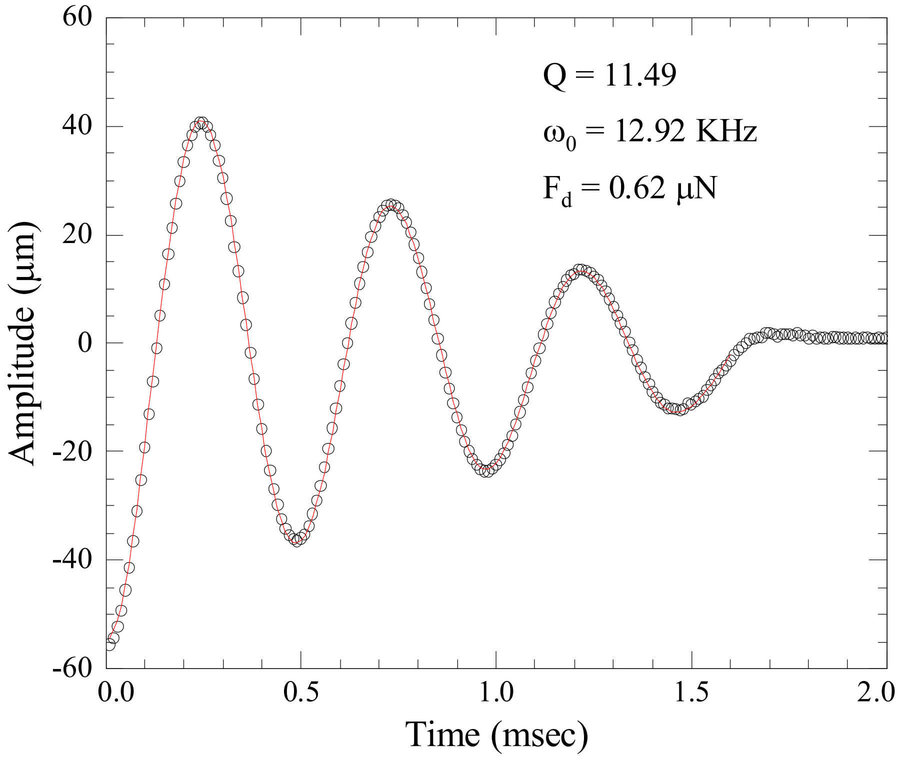
$$x'_{n+1} = \left[-x'_n + (-1)^n F_d / k\right]e^{-\gamma\pi/2\omega} + (-1)^n F_d / k$$

and with the definitions $\omega^2 = {\omega_0}^2 - \gamma^2/4$

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

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

$$\mu_d = 0.24 \pm 0.02$$

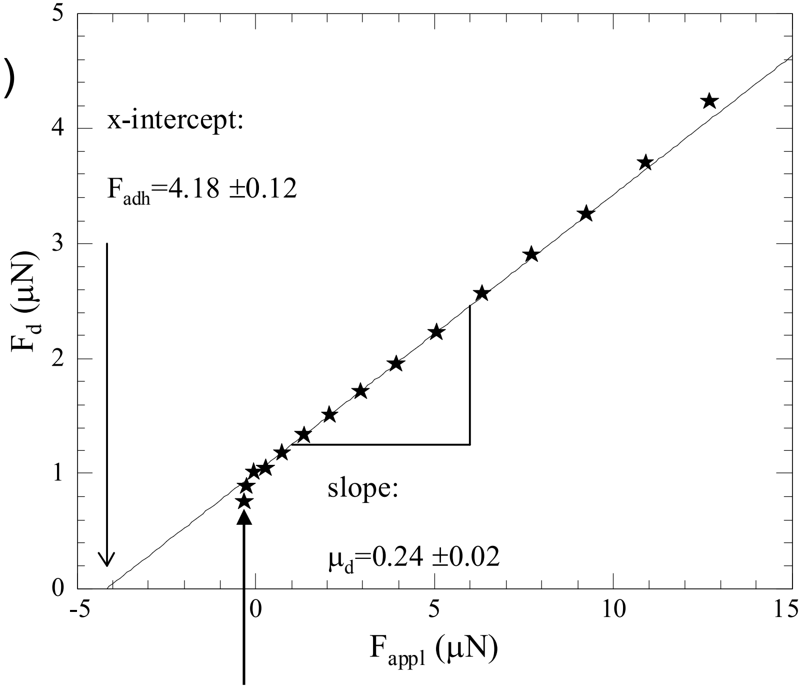
$$F_{adh} = 4.2 \pm 0.15\ \mu N$$

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

Show pull behind device as new design to make future measurements

Is rate-state friction important for MEMS

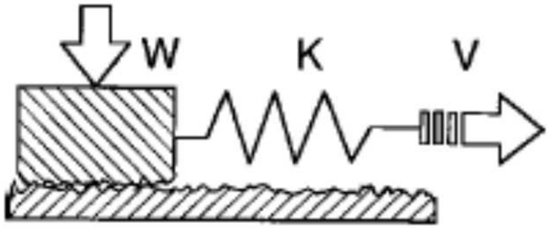
Empirical extension to Amontons' laws

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

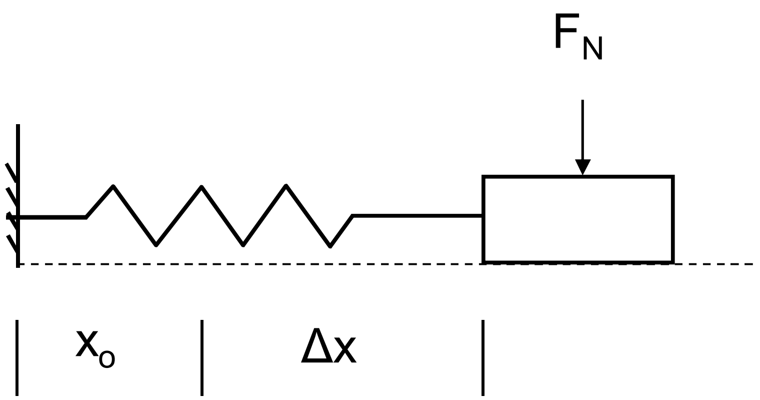


Berthoud et. al, PRB 59 (1999) 313

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

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

Review of static friction measurement



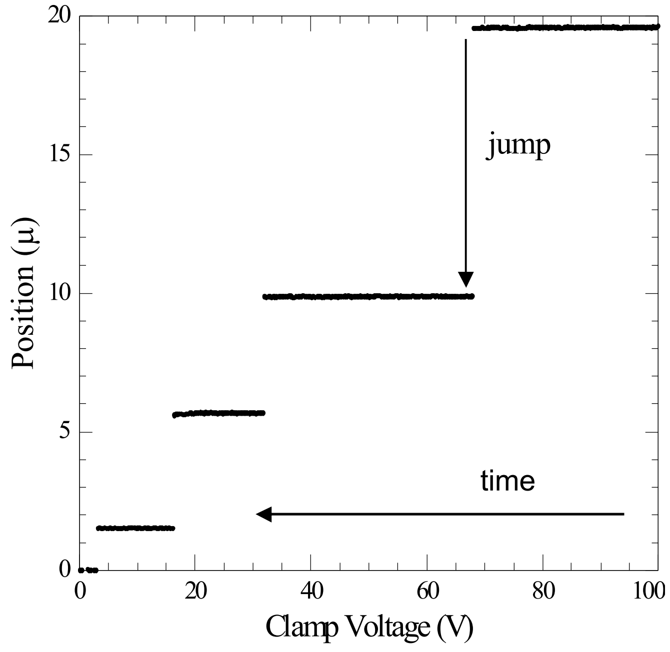
Normal force provided by electrostatics

Start at initial position Δx

Ramp down voltage (normal force) and record position

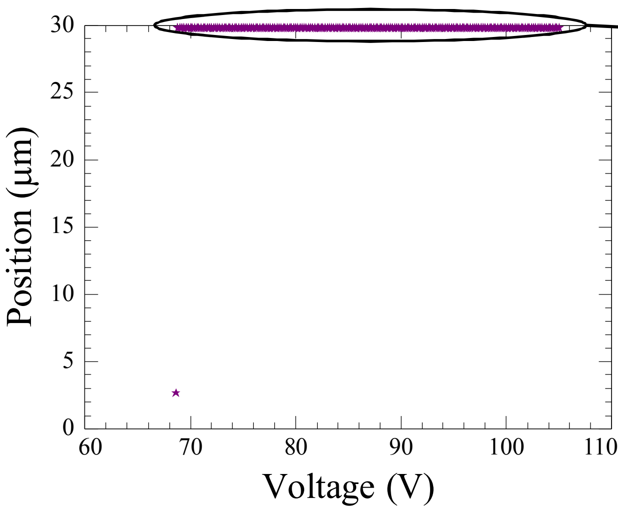
By looking at jumps can determine coefficient of static friction

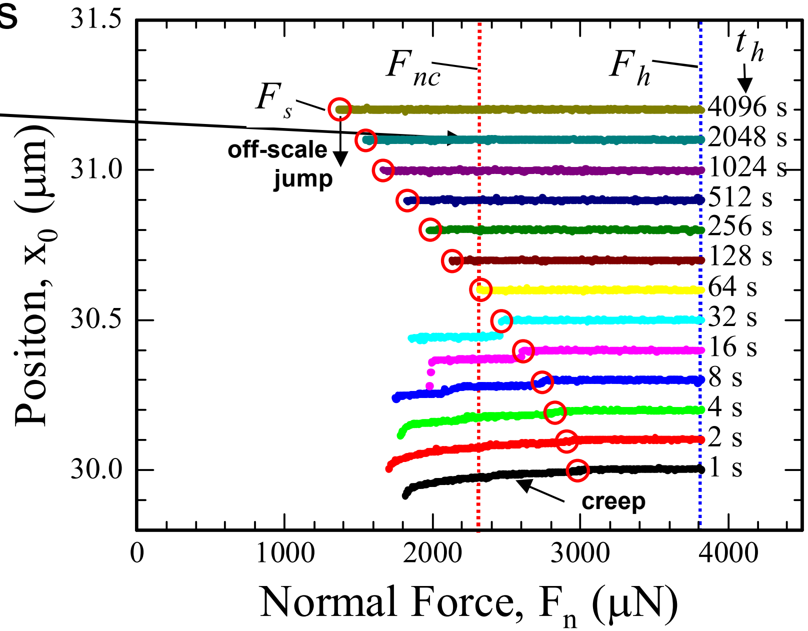
Raw Data



Vary hold time

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





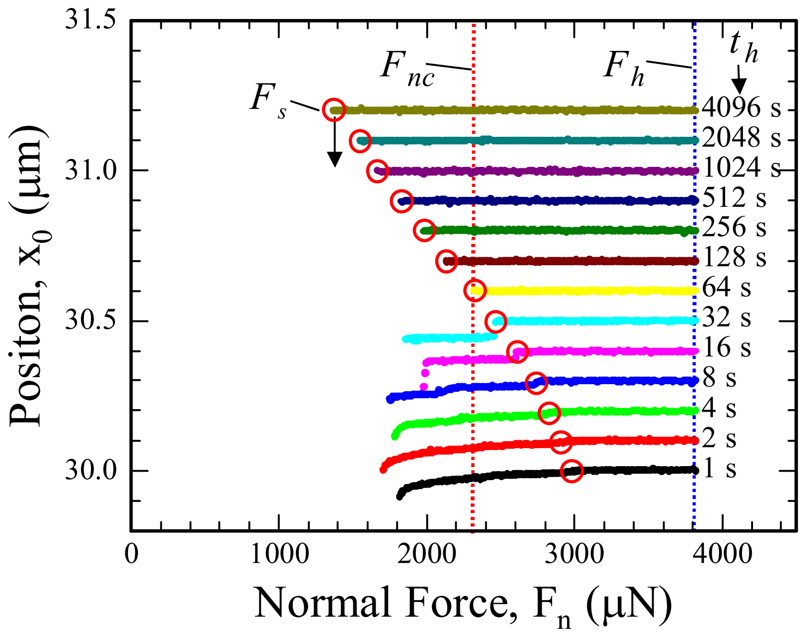
Identify jumps when position changes greatly on release and creep as small position change on release

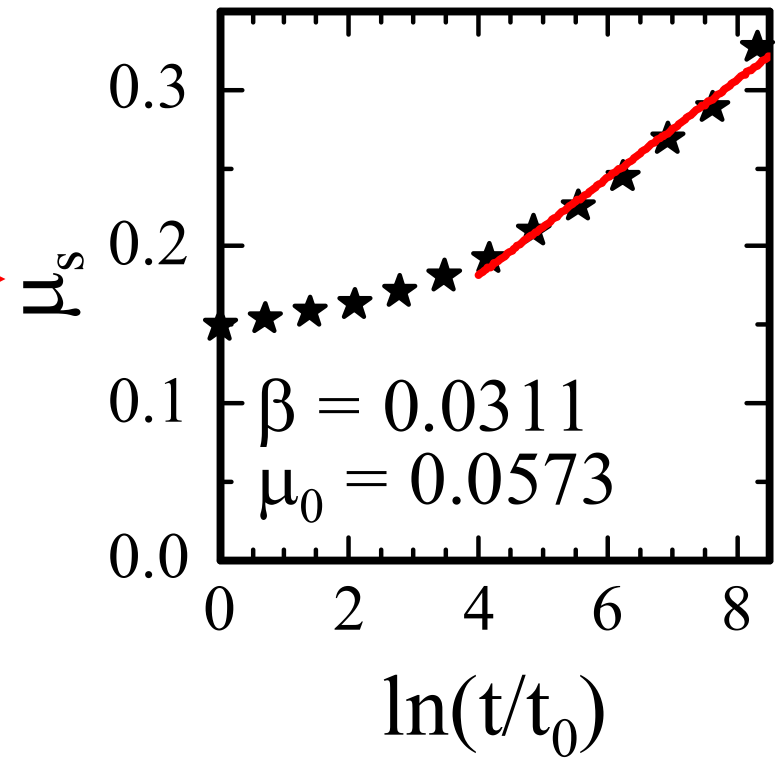
Observe dependence of jump position on hold time

Notice transition between jumps and creep

Analysis of variable hold time data

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



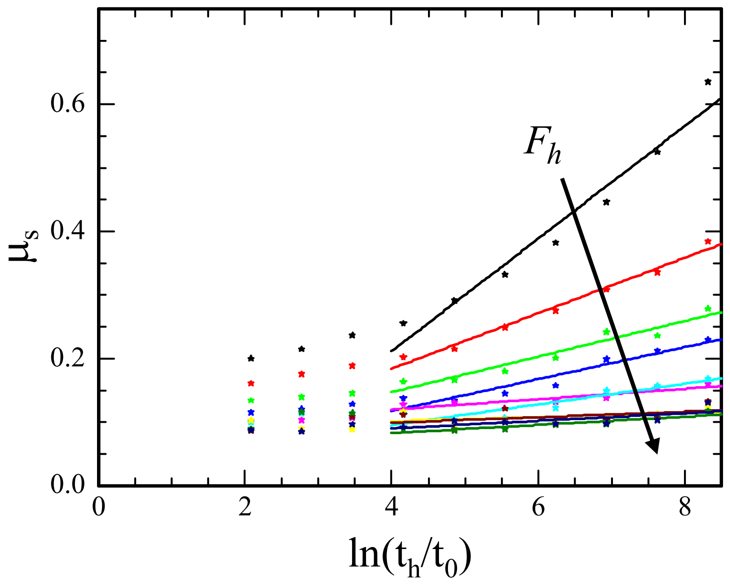


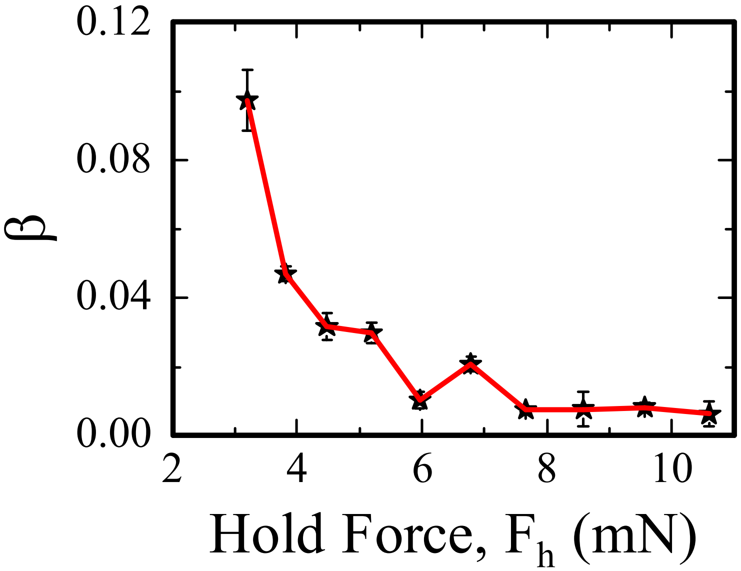
Using spring constant to calculate tangential force, can compute coefficient of static friction for each friction event

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

Friction summary and 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 (issue for dormancy)

Rate of static friction aging reduced with increase in initial loading force (possible solution for dormancy)

We are moving toward the goal of understanding and predicting behavior of contacting microsystems

Summary

I have had the opportunity to work with and learn from exceptional people on a wide variety of MEMS devices and processes

I have performed characterization and reliability work on many systems and through this work have had a large impact on major projects at Sandia

I have learned and implemented many measurement techniques (including novel techniques) to maximize impact of characterization work

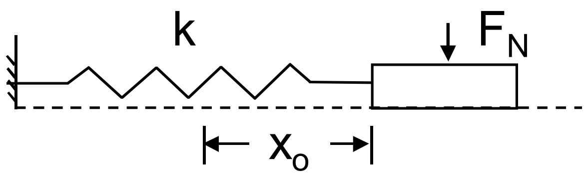
I have performed novel and important research into MEMS friction which is having an impact on some major projects at Sandia

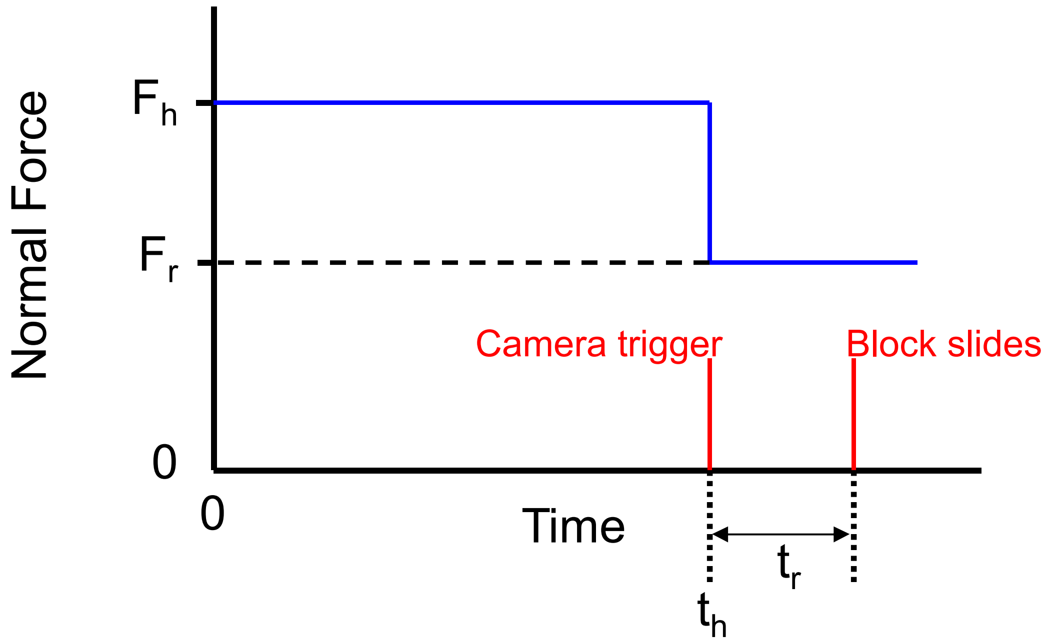
I have created a multi-function MEMS testing software package that is used extensively throughout Sandia (and beyond) for characterization and reliability testingl

I look forward to future challenges and opportunities in MEMS characterization and reliability

Thank you for letting me speak to you today

Will block always release right away





Drop normal force "instantaneously" and see how long it takes block to move

Use high speed camera (Phantom V5.0 at 10,000fps, 100μs / frame).

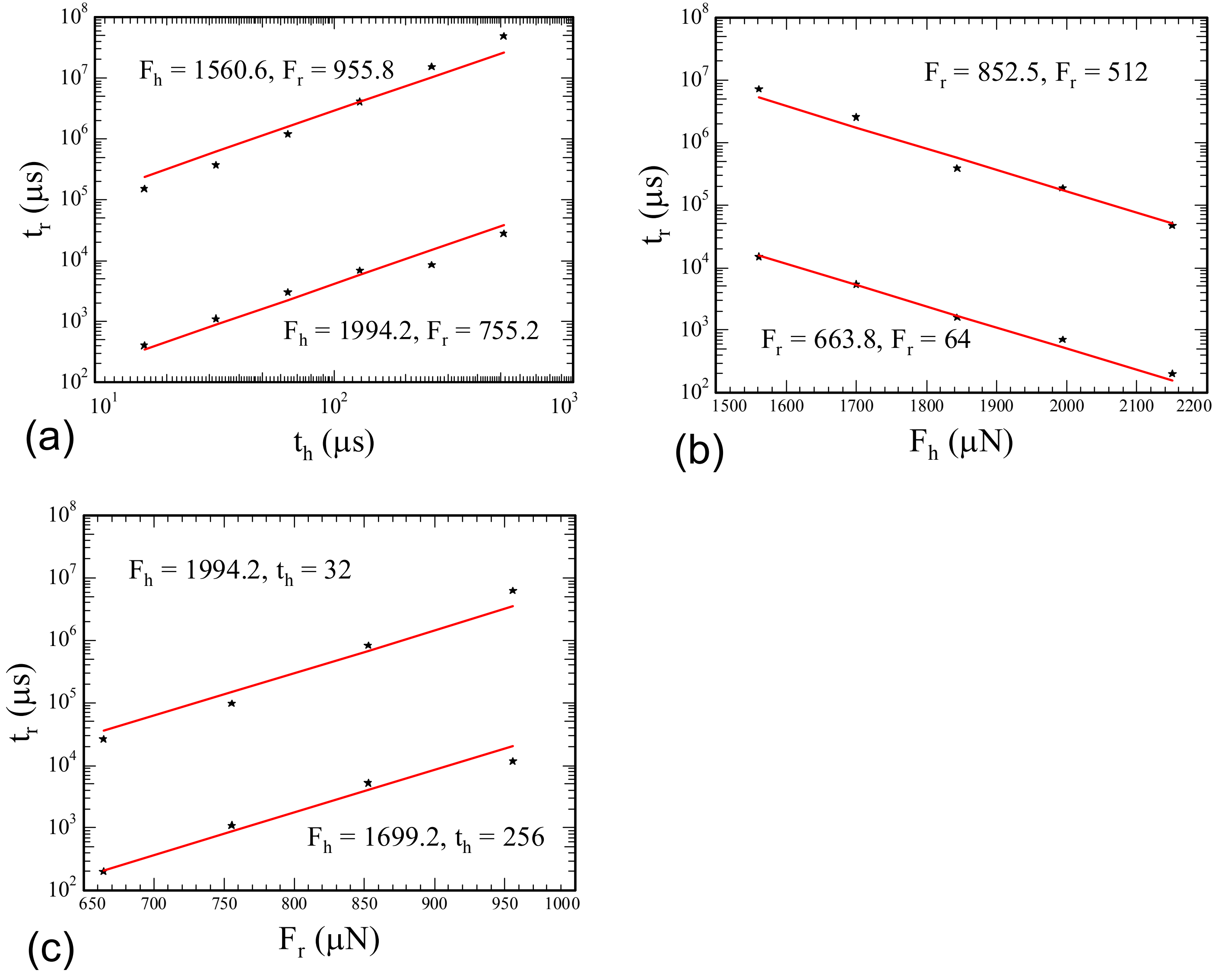
Hold block for 64 seconds at normal force 1814 μN. Then drop normal force to 955 μN in ~ 1 μs (limited by slew rate of amplifier)

Assuming μ_d = .3, given mass of block and stiffness of spring, expect inertial time for motion of ~ 6 μsec

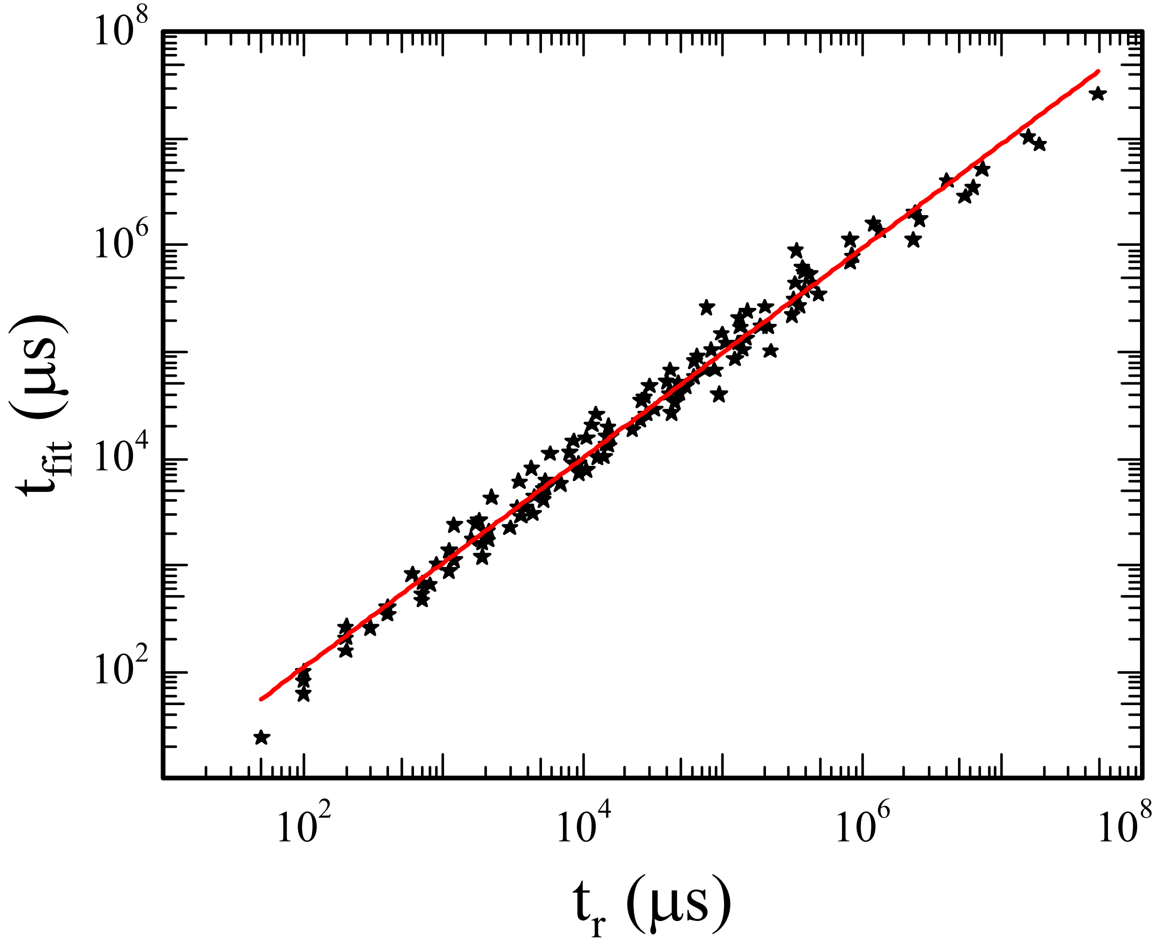
No motion until 80 ms!

Block does not release instantaneously

Release time varies greatly



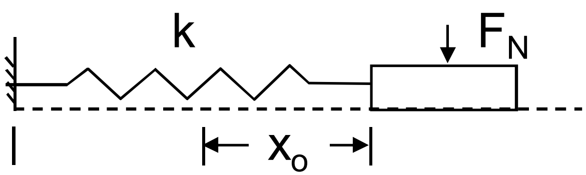
We can empirically model this

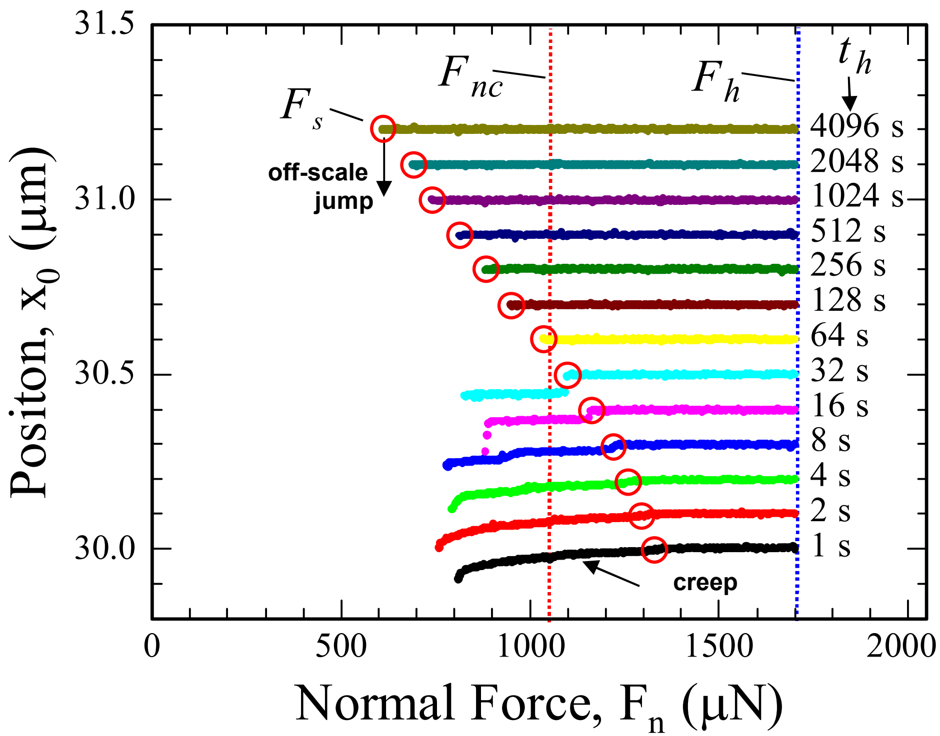


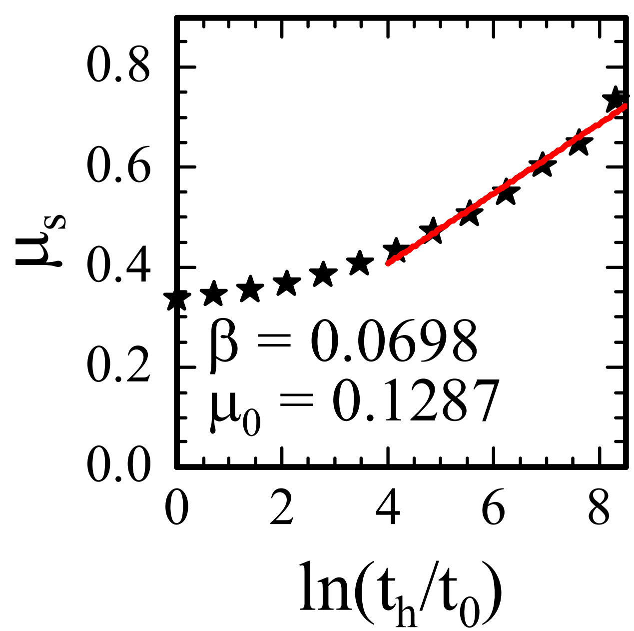
Why does this matter?

Many applications depend on sliding after contact (i.e. an optical shutter). Depending on specifics of contact (hold time and hold force), could take many seconds for release to occur

Friction test results exhibit aging effect

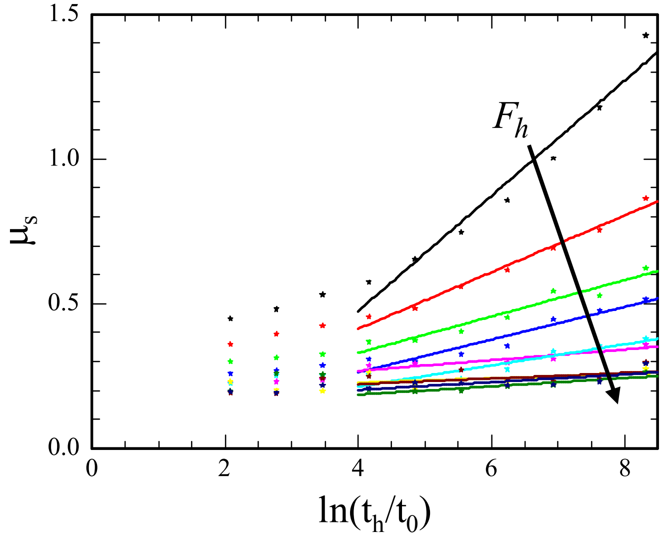


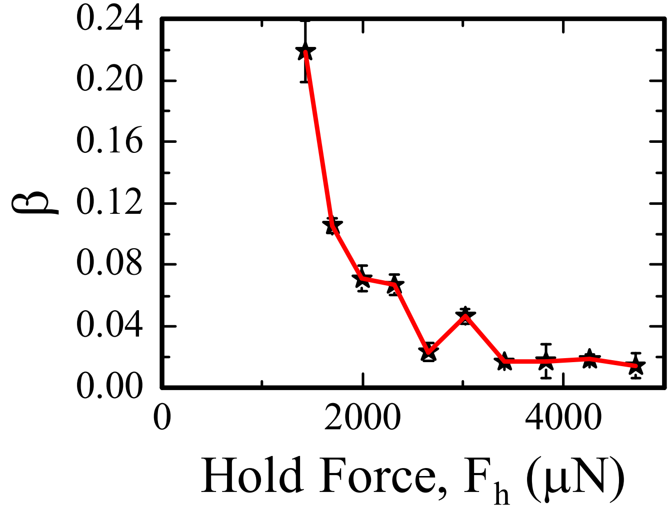




$$u_s = u_o + \beta \ln(t/t_o)$$

As hold time increases, static friction increases.

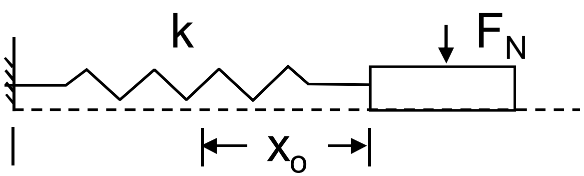


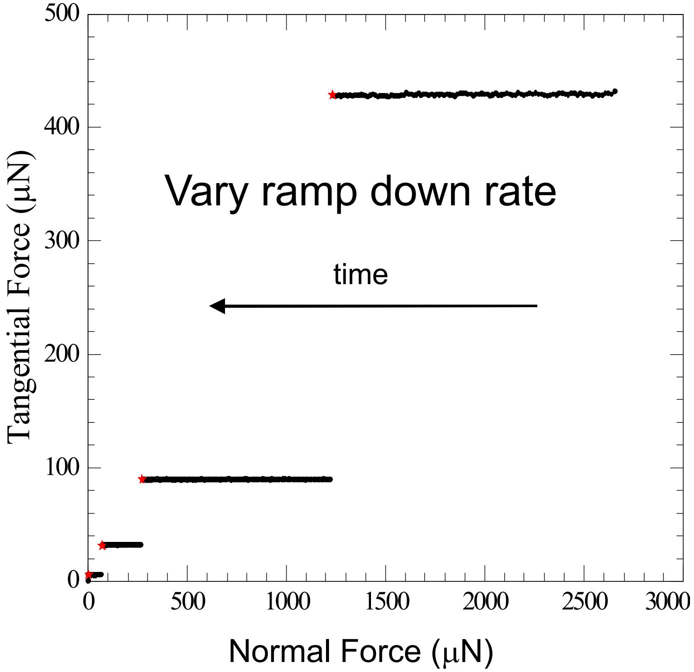


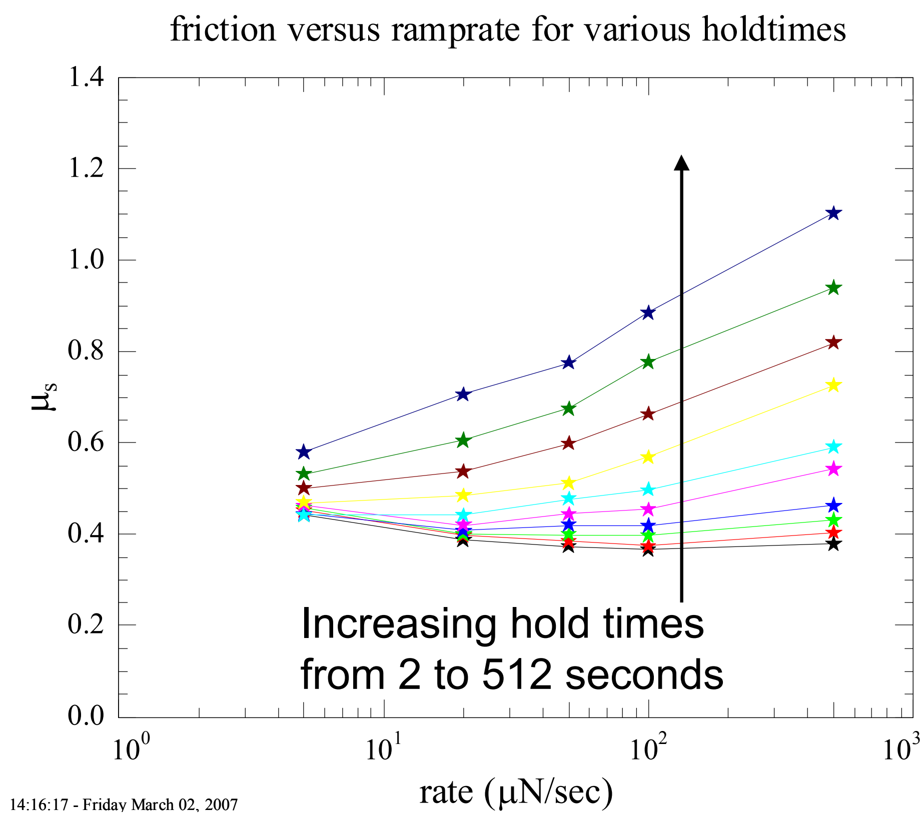
Increasing Fn/Fs leads to decrease in static friction aging. Seen in literature in PMMA and PS

Testing protocol matters

We ramp down normal force until motion is observed. How does this effect our results?







Why does ramp down rate matter so much? Are we seeing the manifestation of more fundamental effect?

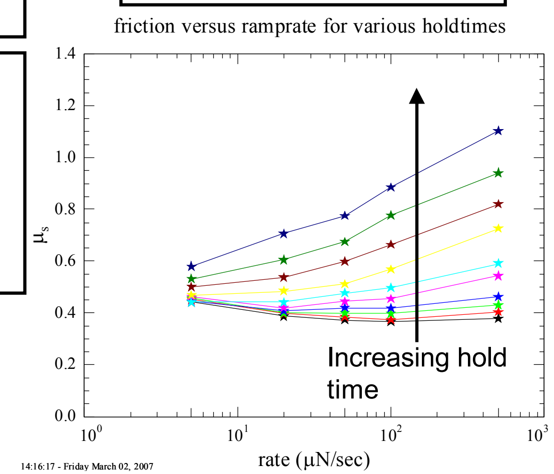
Postulate that block is not released "instantaneously" after normal force is dropped

Surfaces may remain stuck for some time after being pressed together

Ramp down slowly → More time at given normal force to exceed release time → Motion occurs at a higher normal force → Lower μ_s

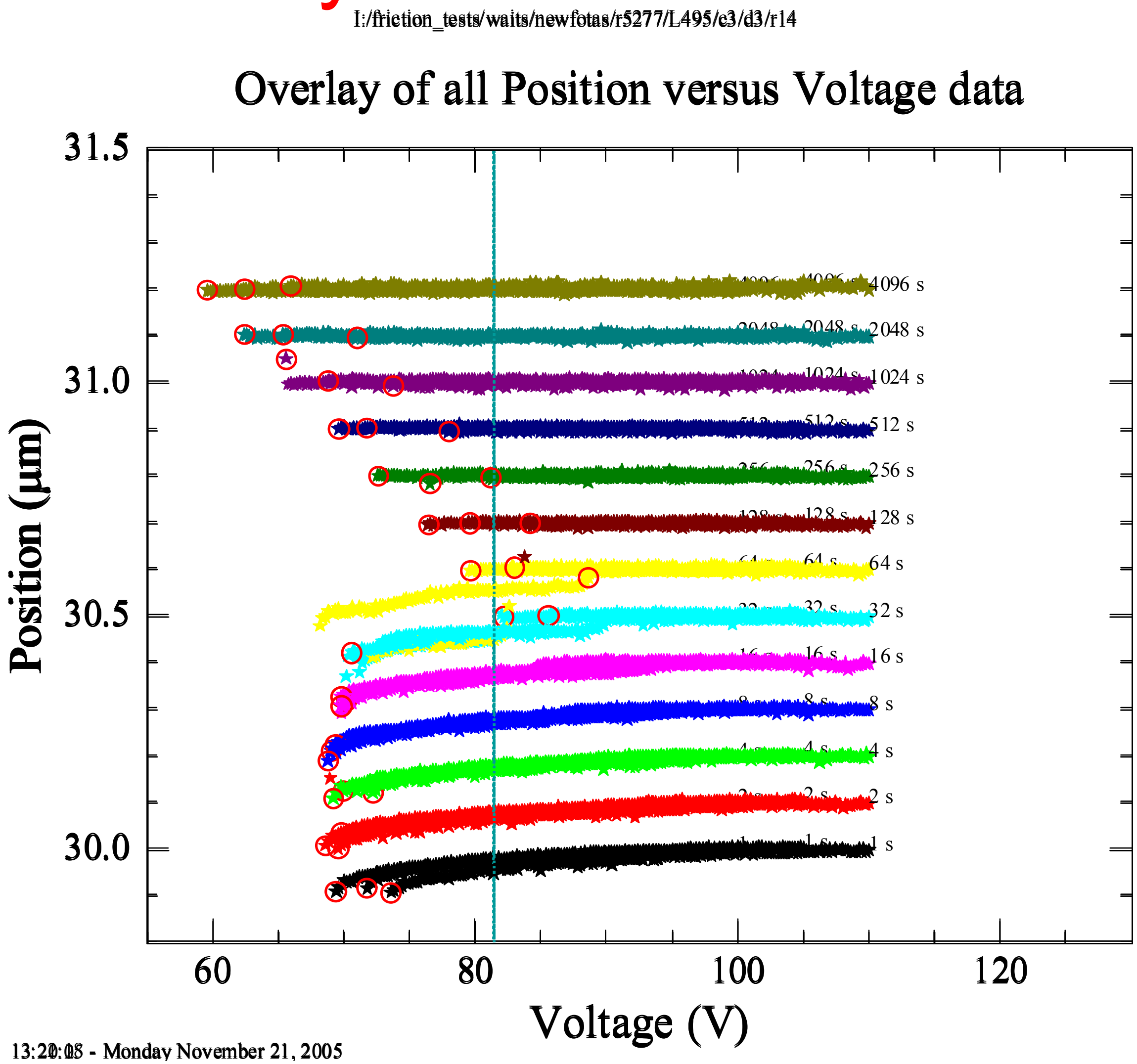
Ramp down fast → Less time at given normal force to exceed release time → Motion occurs at a lower normal force → Higher μ_s

Longer hold times → Longer release times → Larger dependence on ramp rate



Qualitatively, release times could explain ramp rate dependence. How can we measure this?

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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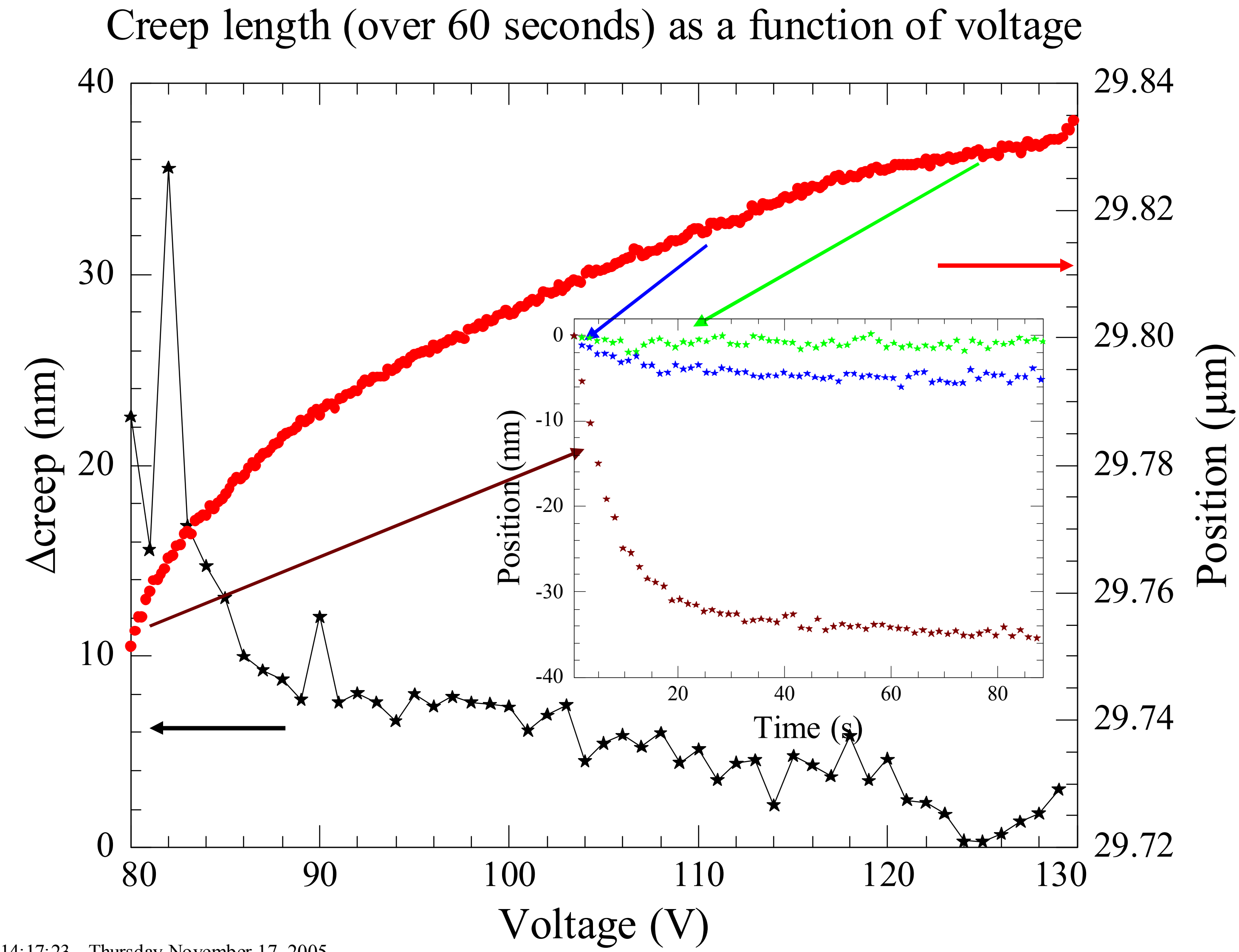
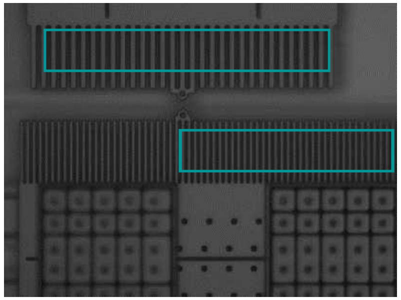
Creep length as a function of voltage

I:/friction_tests/creep_multipos/newfotas/r5277/L495/C6/D3/r8





nm metrology

Repeated measurement so not exactly matched

Creep length grows as jump approached

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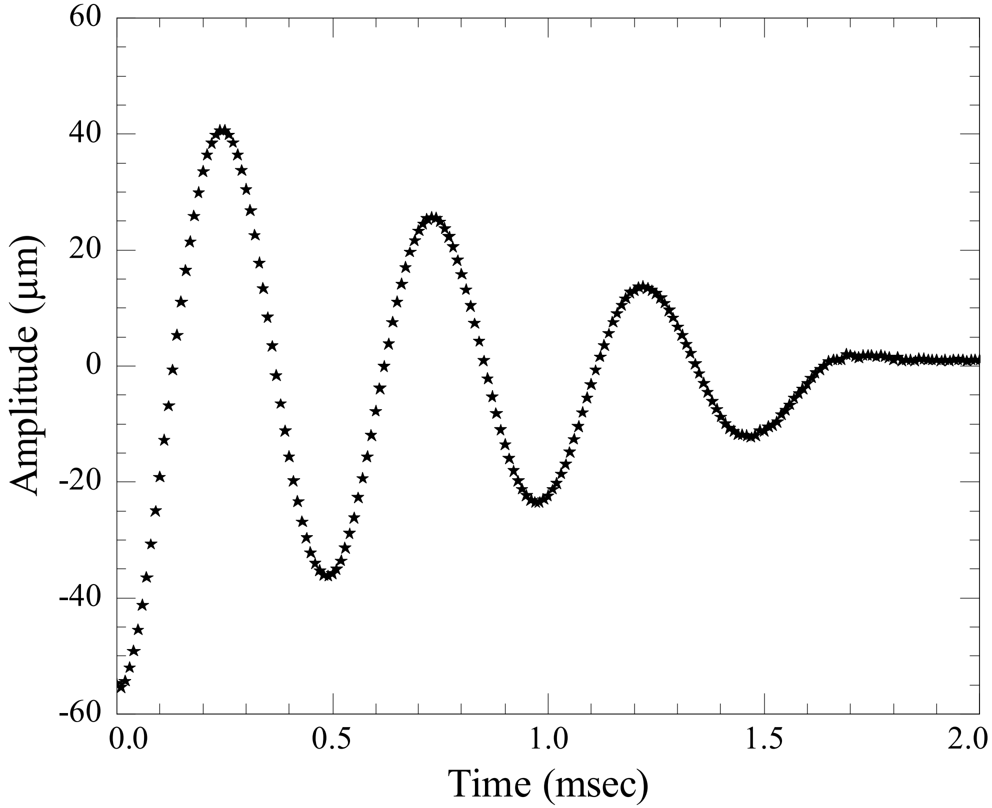
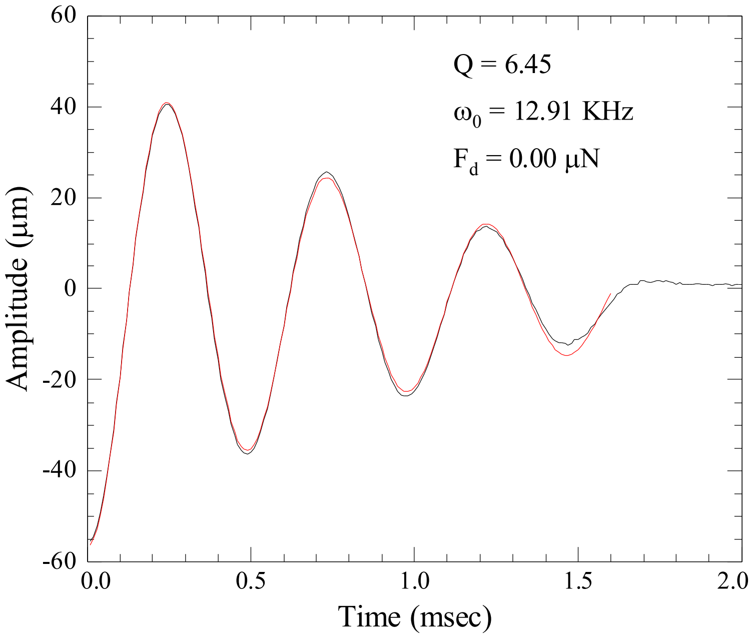
Raw Decay Data



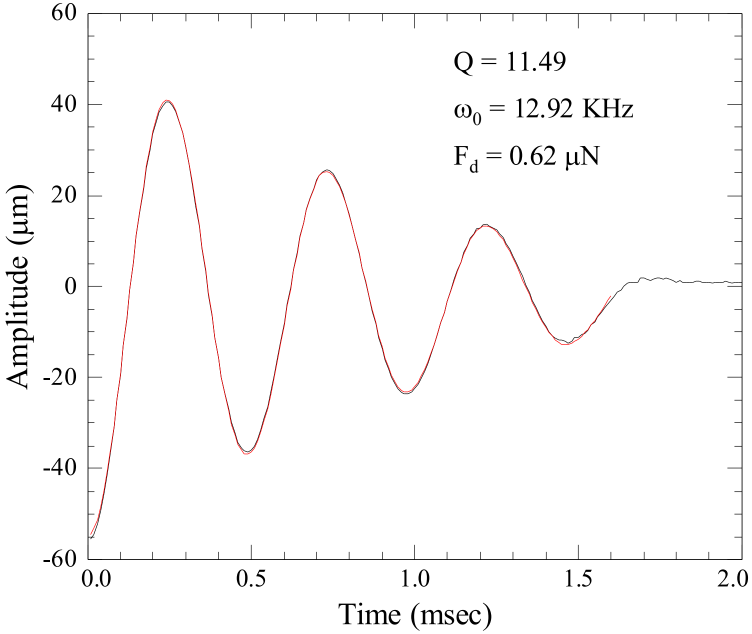
600 mm clamps, FOTAS coating, no electrostatic normal load

Can we model this?

Fit with and without Friction



Fit without friction



Fit with friction

SAND: 2003-2305 P

My Background

Education

Cornell University

Ph.D. in Physics (Low temperature helium), August 2002. GPA 3.9

M.S. in Physics, November 1998.

Wesleyan University

B.A. Math and Physics, High Honors, June 1995. GPA 3.7

Work Experience

Sandia National Laboratories

2005 – Present Senior Member of Technical Staff at Sandia in MEMS Science and Technology group under Harold Stewart (managers). Hold DOE L security clearance. (In June 2006 my group was merged with Dave Sandison and Mark Platzbecker's group)

2002 – 2004 Post Doc at Sandia National Laboratories studying surface interactions in MEMS working with Maarten deBoer in Reliability Physics group under Fred Sexton (manager). Held DOE L security clearance.