Discovery at the Interface of Science and Engineering: Science Matters!

SAND2006-5236P

Future Engineering Challenges for MEMS and NEMS

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“There’s plenty of room at the bottom.”

– Nobel Laureate Richard P. Feynman, 1959

Micro- and nano-scale devices can revolutionize engineering

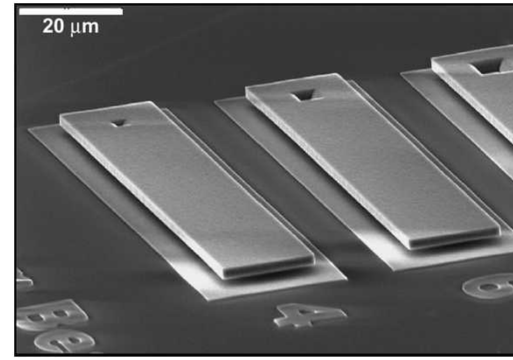
Manufacturing micro-scale devices may require nano-scale assembly

But...such small scales challenge conventional engineering approaches

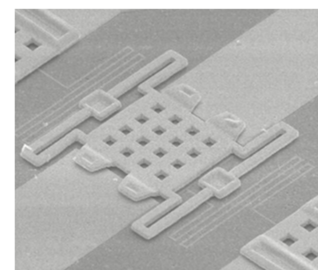
- **Unexpected physical behaviors**
- **Experiments are difficult**
- **Intuition is suspect**
- **Can’t just scale down from macro-scale**

A bottom-up approach is required - micro- and nano-enabled solutions

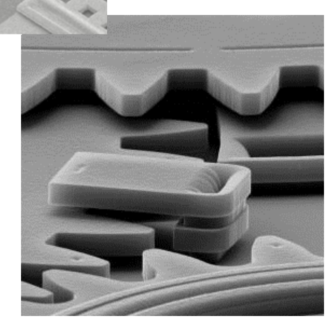
Profound implications for engineering education in the 21st century



Micro-beams



Micro-switch



Micro-gears

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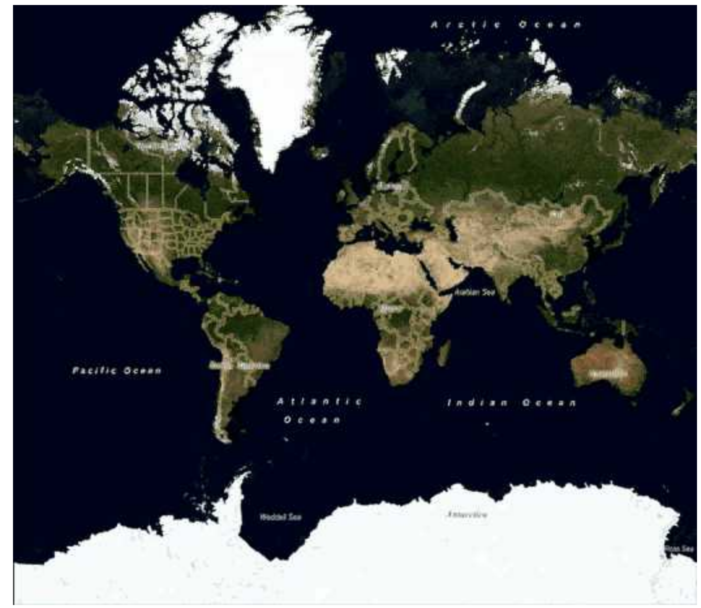
Physical Models Must Change as Length Scales Shrink

Moving from macro to micro to nano

- Gravity is overcome by adhesion (van der Waals, electrostatic)
- Surface and interfaces are critical
- Friction models break down
- Solids melt at lower temperatures
- Transport models break down
- Quantum effects emerge
- Ballistic transport of energy
- Increasingly coupled physics leads to highly nonlinear behavior

Modeling & simulation must play an integral role in system design

View from the World to Sandia Labs



Scale changes above by a factor of ~10^5 - between 1 meter and 1 nm is 10^9

Welcome to the Noncontinuum World

Macro-scopic World Built from Smaller Constituents

- Gas transport by molecules
- Heat transport by phonons

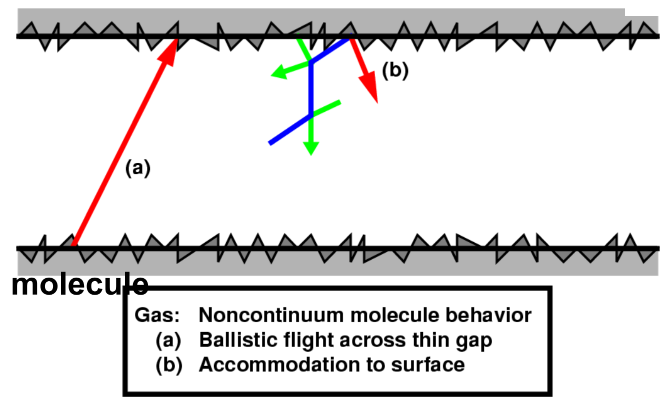
Continuum World View

- Average over space
- Average over time
- Much of engineering science built on these assumptions

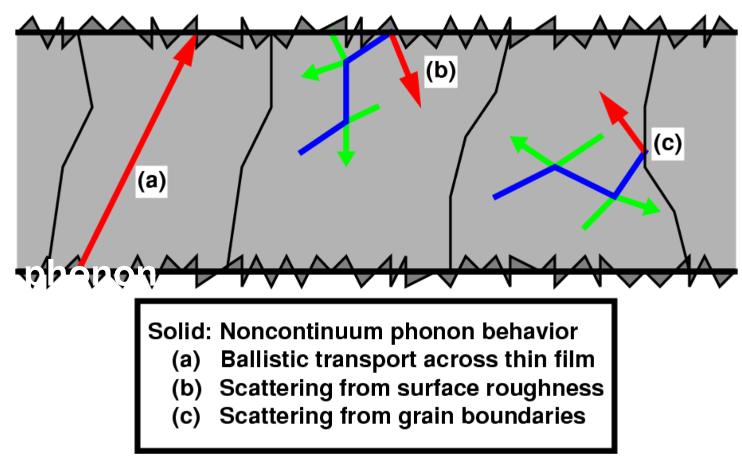
Micro- and Nano-Worlds

- System length scale shrinks to molecular scales
- Discrete physics important
- Example: gas molecules collide with walls more often than each other

GAS

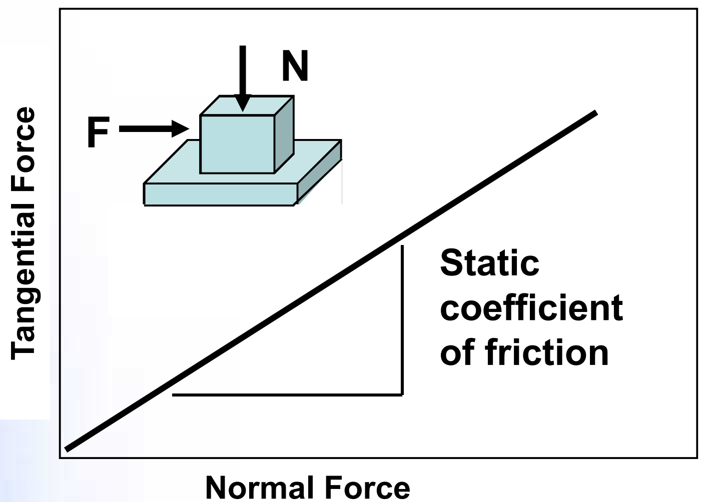


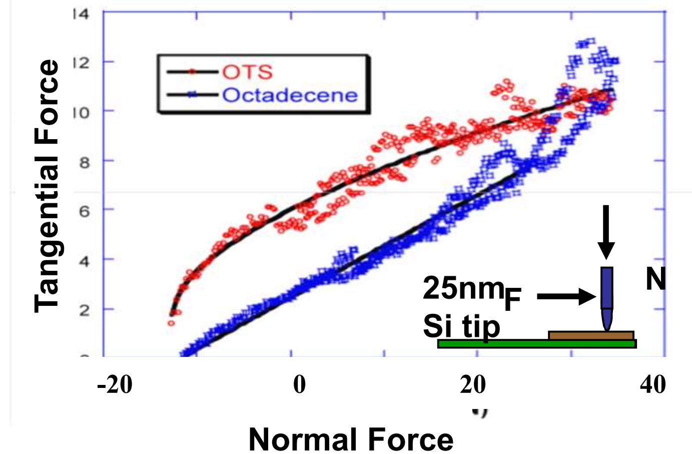
SOLID



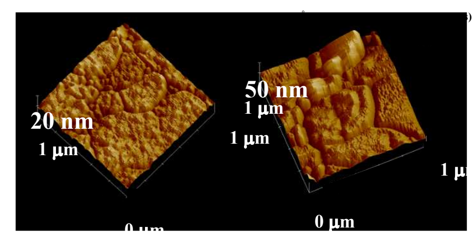
Friction Behavior at the Micro-scale Depends on Discrete Contacts

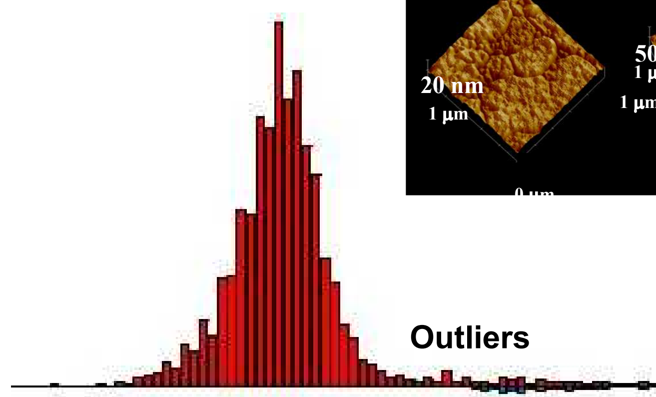
Macroscale surfaces have many contacting asperities – real contact area scales with load





Single asperities friction exhibits effect of molecular interactions



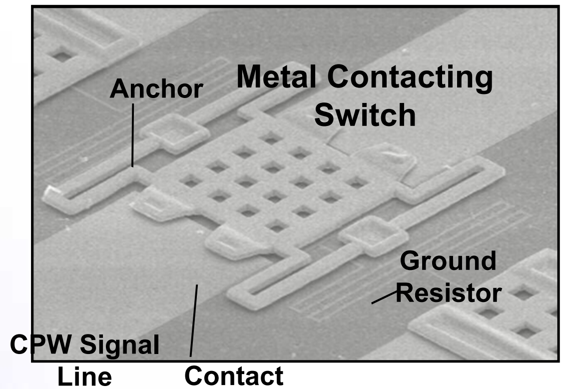


Measured Distribution of Summit Heights

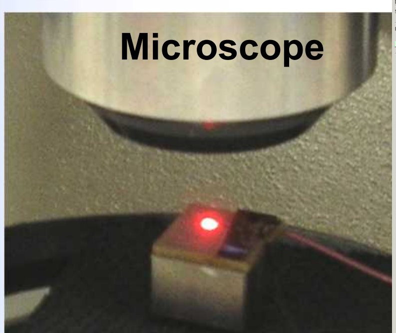
On the microscale, relatively small number of asperities interact - outliers initially dominate.

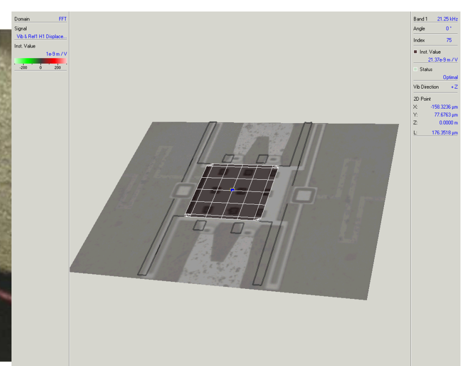
Gas Damping Critical to Structural Response at the Micro-scale

Small gas gaps between structures and substrate generate large squeeze-film effects…

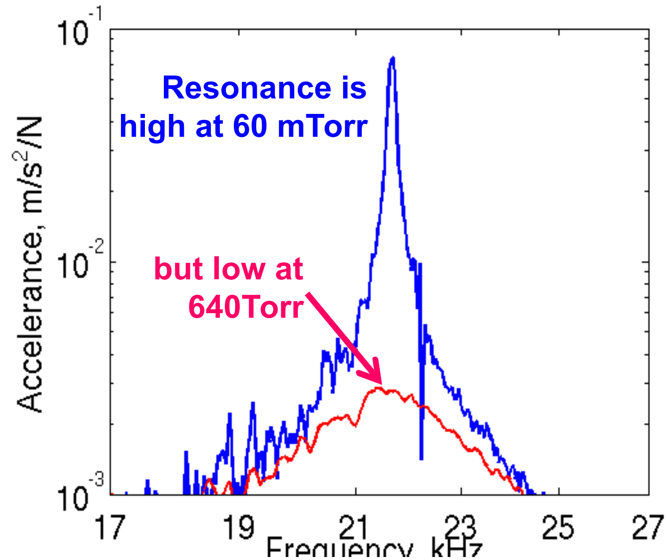


Dynamic testing is challenging due to small time and length scales in controllable environments





Gas damping can change by orders of magnitude and exhibit strong pressure-dependent nonlinearities



Fluid-structure interactions can be tailored for low losses or shock-hardening of components

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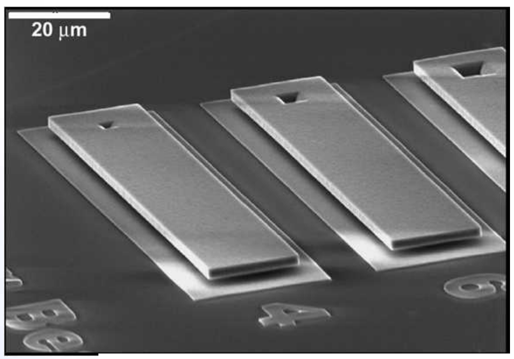
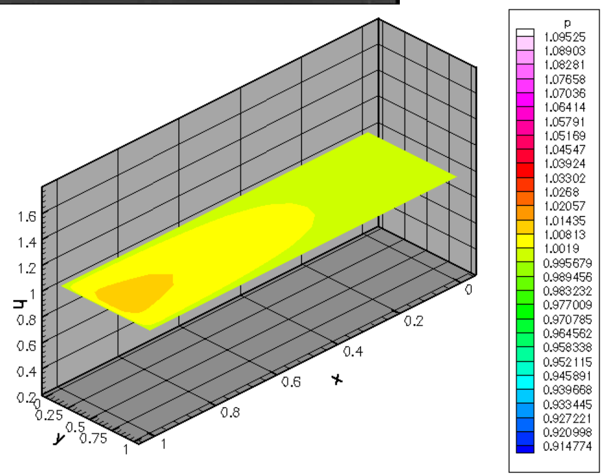
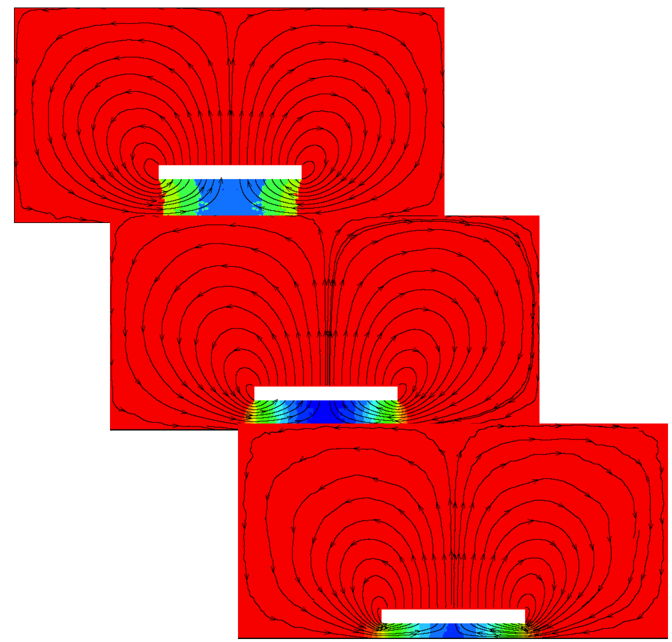
Fluid Response Dominated by Noncontinuum Effects

Molecular mean free path (~0.1 μm at ambient) comparable to gap between beam and substrate (~2 μm)





Transient noncontinuum flows are modeled using individual molecules with probabilistic framework

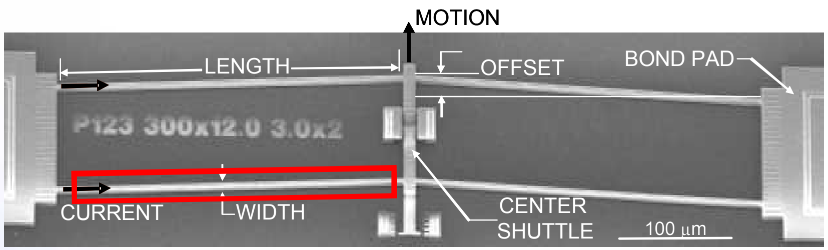


Time snap-shots using 2-D Direct Simulation Monte Carlo 24-hours on 8,000 processors!

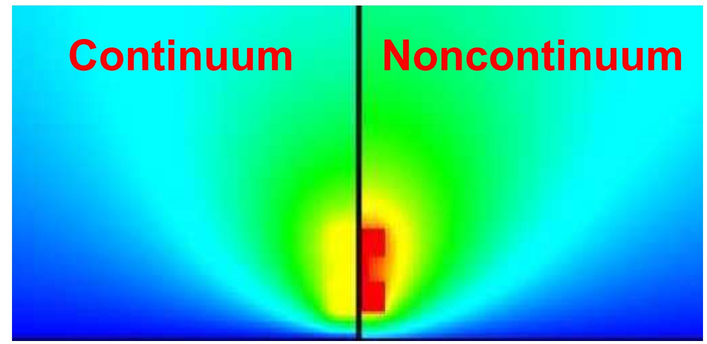
Think Discretely…

Microscale heat transfer involves discrete “particles”

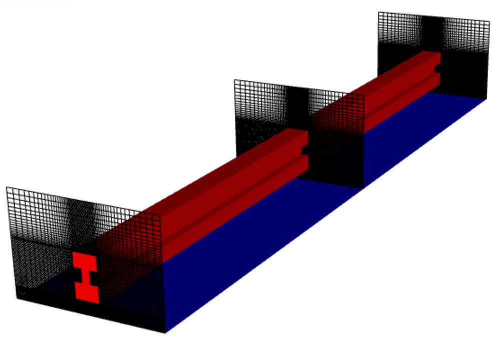
- Molecules in gases and phonons in solids travel ballistically
- Noncontinuum behavior, qualitatively different from macroscale



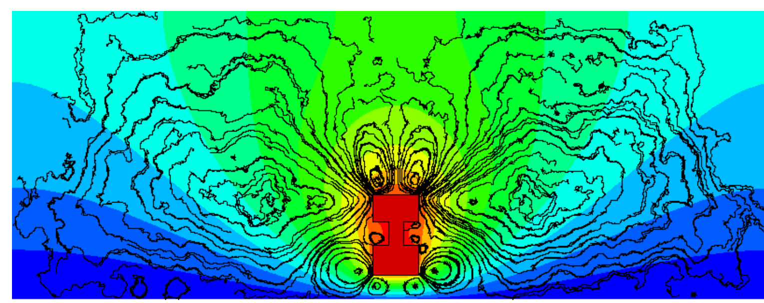
Microscale Thermal Actuator
Beams move shuttle under resistive heating



Beam Temperature Predictions Continuum = 750 K, Noncontinuum = 900 K



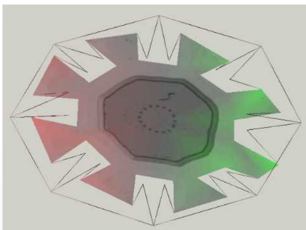
Model of Heated Beam and Gas



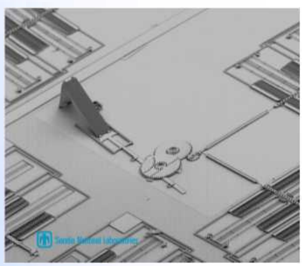
Gas Motion – Noncontinuum
Continuum models predict no flow!

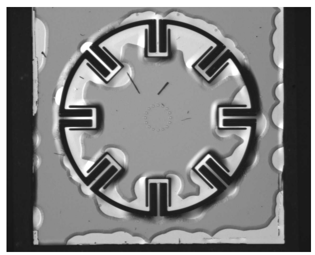
A Growing Reliance on Simulation and Science in Engineering

Silicon Switch

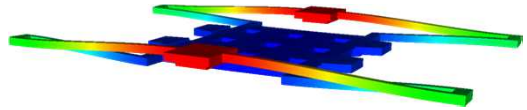


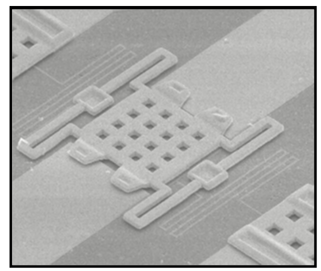
Micro-Mirror



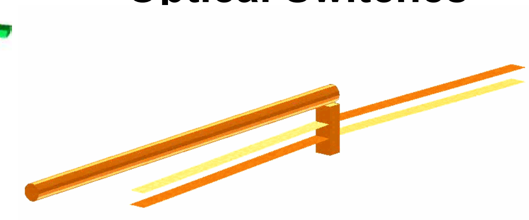


RF Switches





Optical Switches



Innovative Solutions

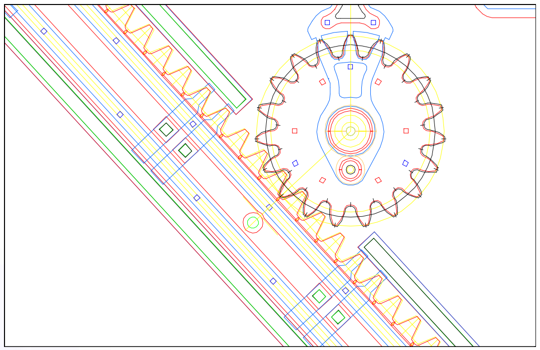
Improved Performance

Exploration

Forensics

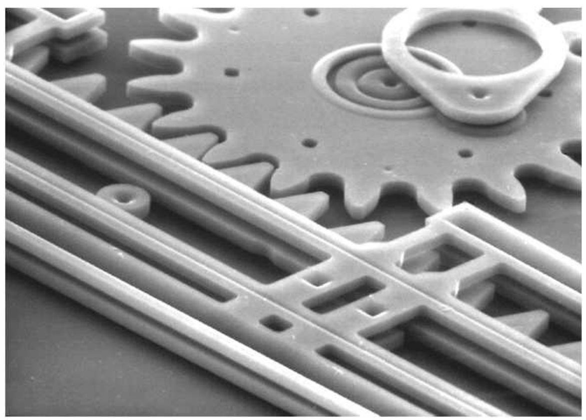
GOAL: Transform component design with micro-scale enabled modeling and simulation and collective innovation

MEMS Design Challenges



Conventional Production Process Relies on Cast, Cut, Shape, Assemble in 3-D

MEMS Production Based on Deposit, Polish, Pattern, Etch, Repeat…in 2.5-D



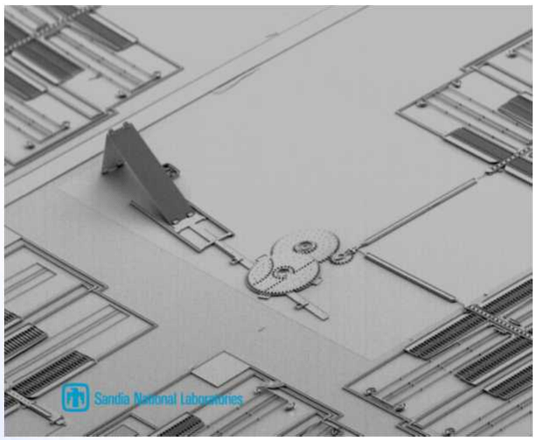
Process Resolution

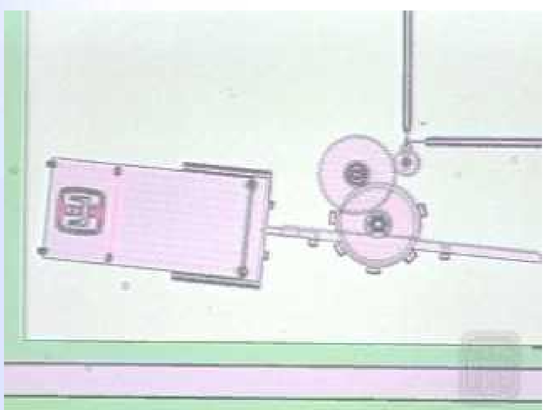
- **Line Width 1μm +/- 5%**
- **Film thickness 1.5-2.25 μm +/-15%**
- **Surface Roughness 3-7nm rms**
- **Sidewalls Roughness 10-20 nm:**

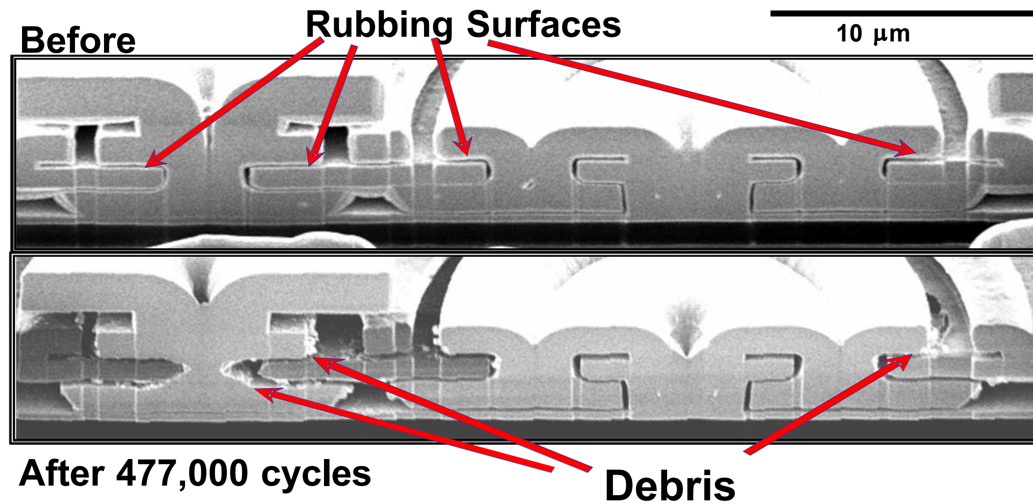
MEMS production is an automated 2 month process, so model-based design verification is essential prior to initiating fabrication.

Early MEMs Used Iterative Development Cycle

Hardware-intensive test cycle used to optimize the micro-engine – an early MEMS product







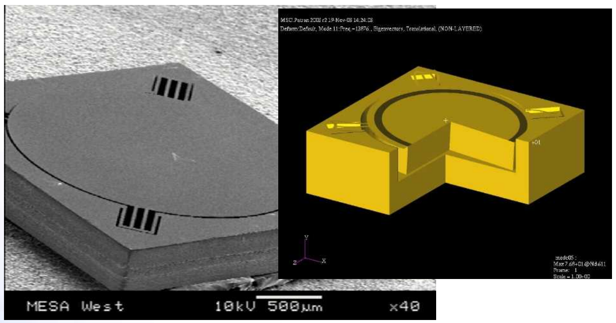
Debris caused poor reliability

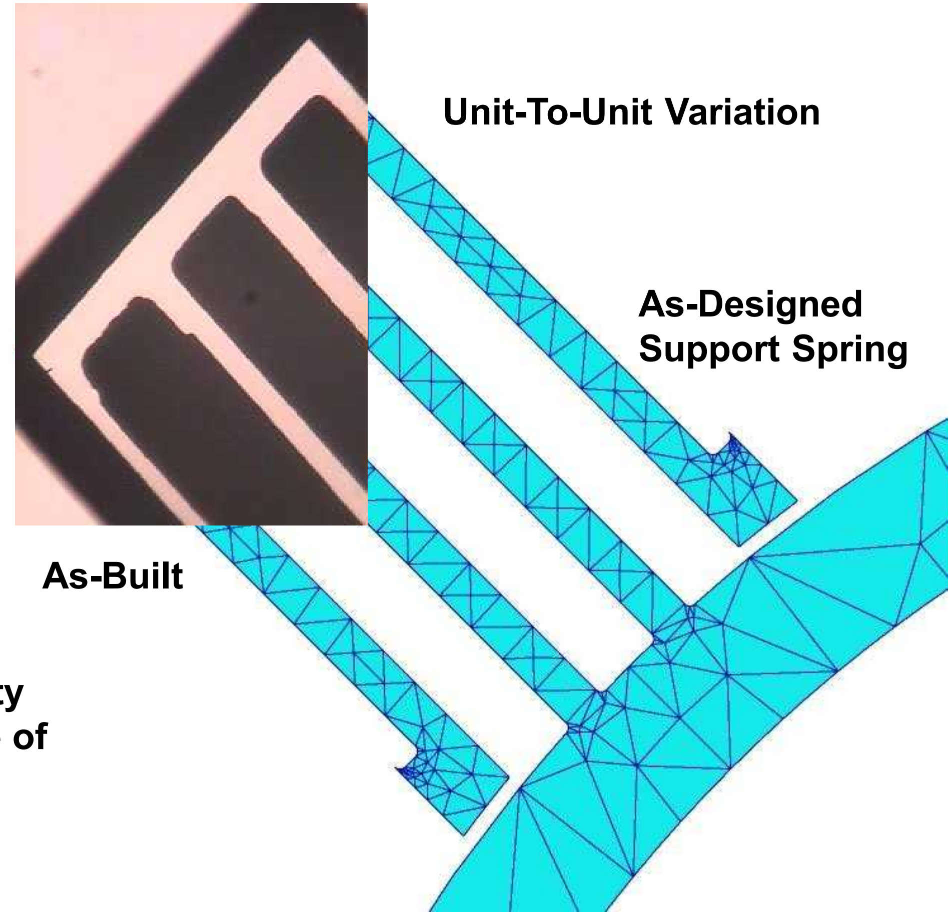
Little understanding of wear mechanisms

Drove research into micro-scale science and engineering!

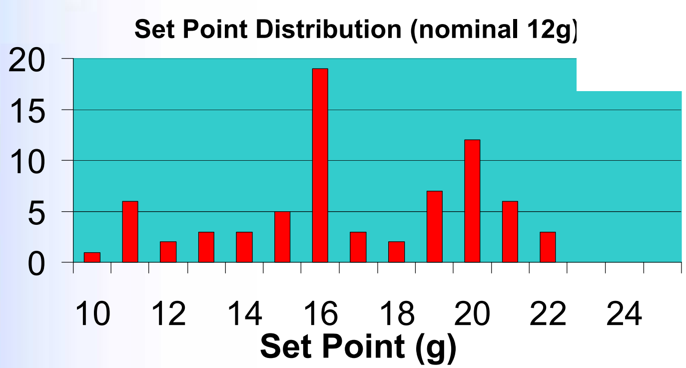
SiRES – Silicon Reentry Switch

Late-cycle use of modeling and simulation to optimize g-switch design (still top-down)





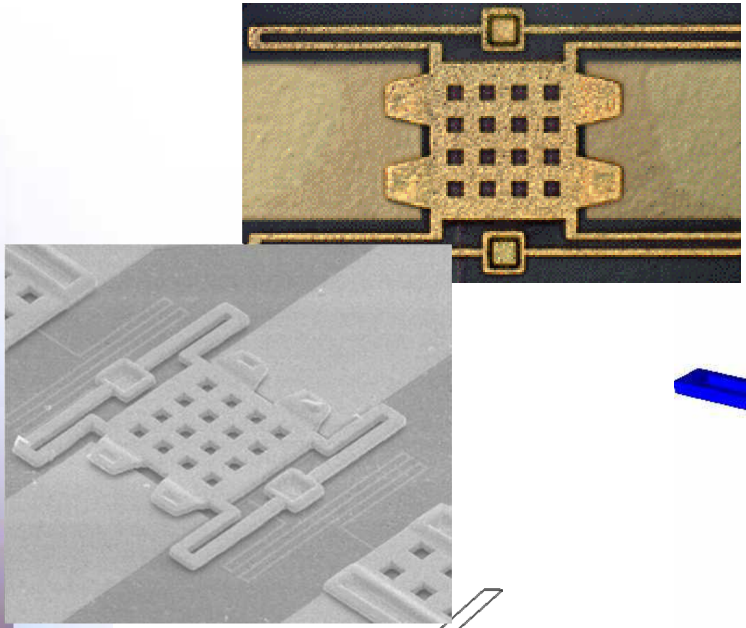
Low damping and process uncertainty led to poor performance – earlier use of modeling would have helped!



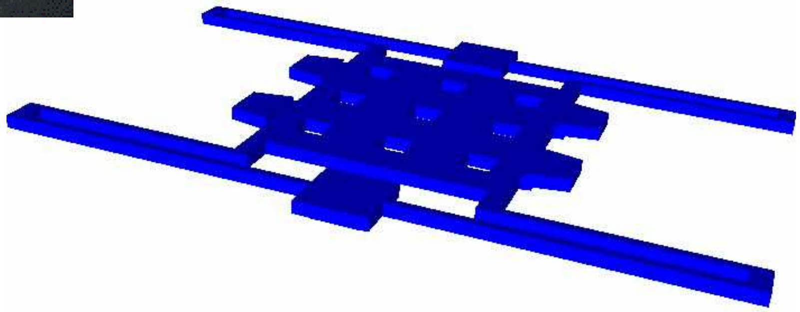
First demonstration of micro-scale enabled modeling and simulation for late-cycle design optimization

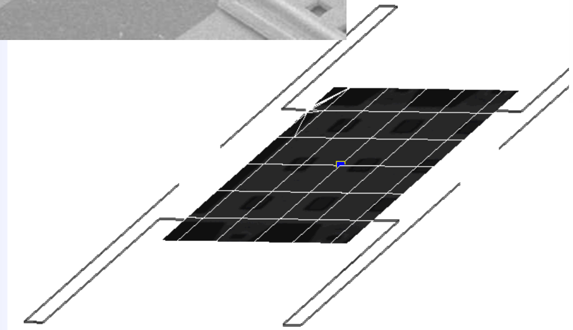
RF Switch for Long-Life and Low-Loss Band Shifting

High velocity closure resulted in long settling time and limited life time



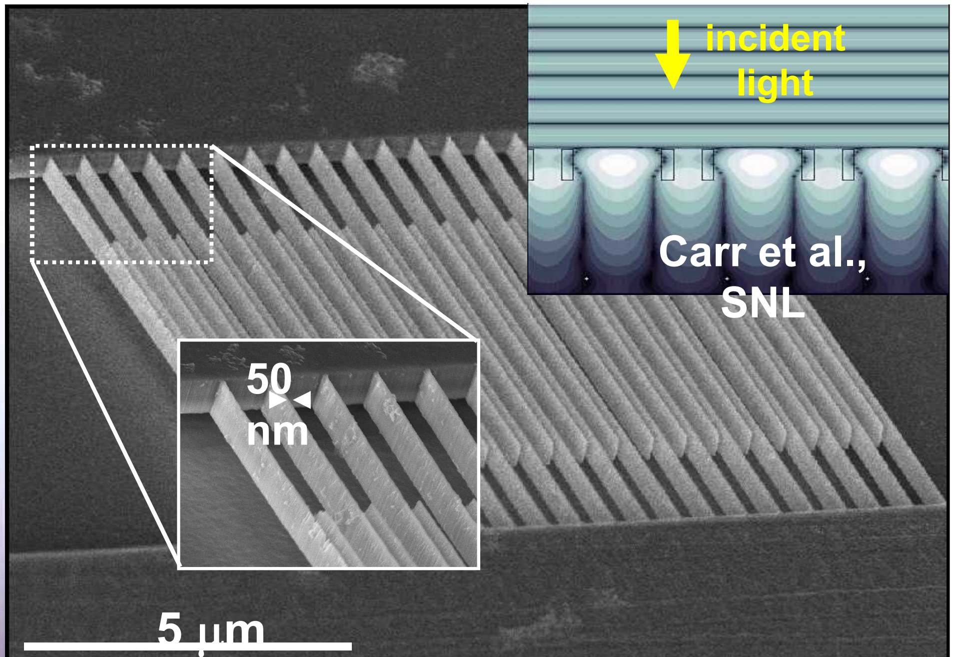
Multi-physics and robust optimization using uncertainty models used to reduce settling time by 85% and increase life time by two orders of magnitude!





Dramatic design improvements – additional gains possible by bottom-up approach to redesign based on coupled fluid-structural dynamics…

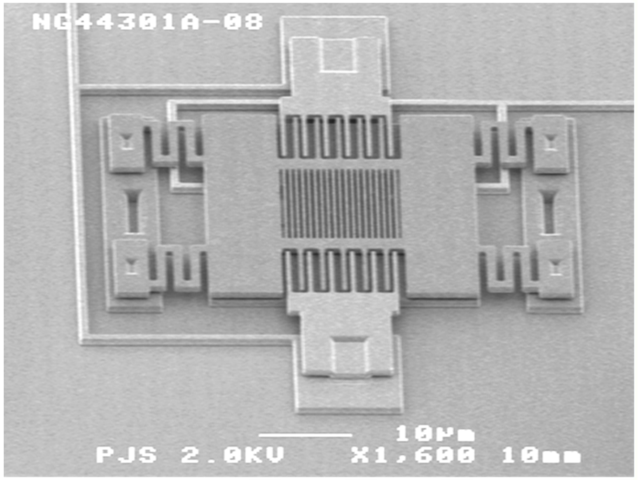
Nanoscale Grating
Enables Nano-G Accelerometer



Light reflected off array is modulated by in-plane motion of grating

Enables extremely sensitive position detection: 160 fm/Hz$^{1/2}$

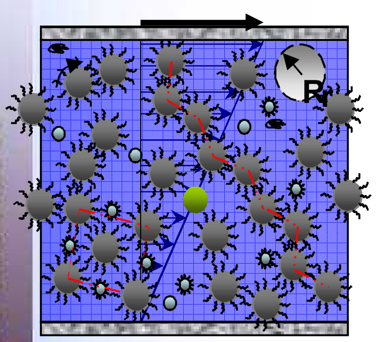
Scientific concept has been turned into a nanoG accelerometer device (with target 40 nG sensitivity)



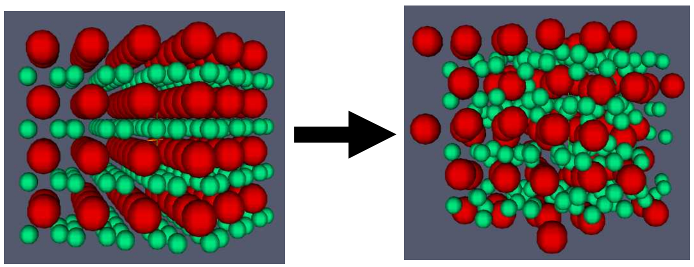
Nano-particle Assembly

- Disperse nanoparticles in films, fibers, monolithic bulk structures for material engineering
- Fluidization in liquid followed by traditional processing techniques (coating, casting, spinning) allows control of nano-building blocks at the macro-scale
- Modeling and simulation of flow of dense suspensions to build process understanding and control

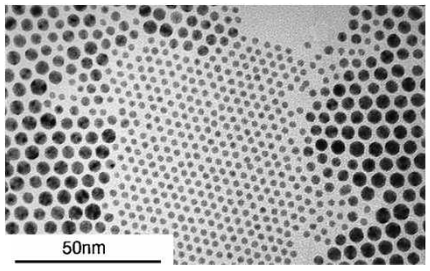
Dispersal and Flow



Dispersion Stability:
melting of a bi-disperse lattice of nanoparticles

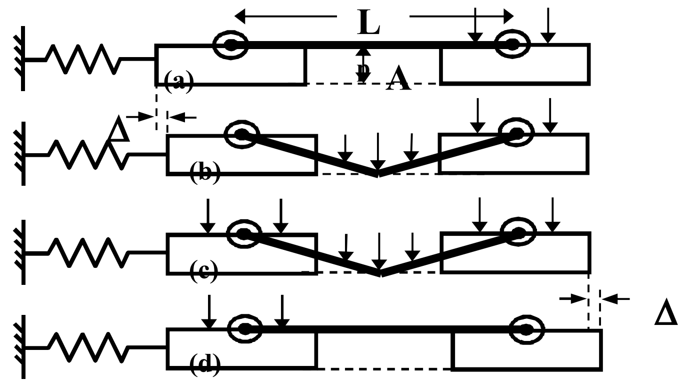


Coating into Functional Films



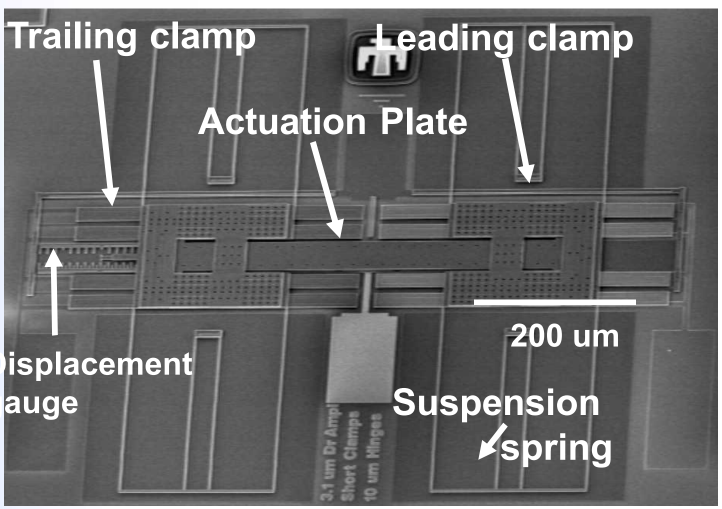
Championed consortium with industry for modeling and simulation R&D

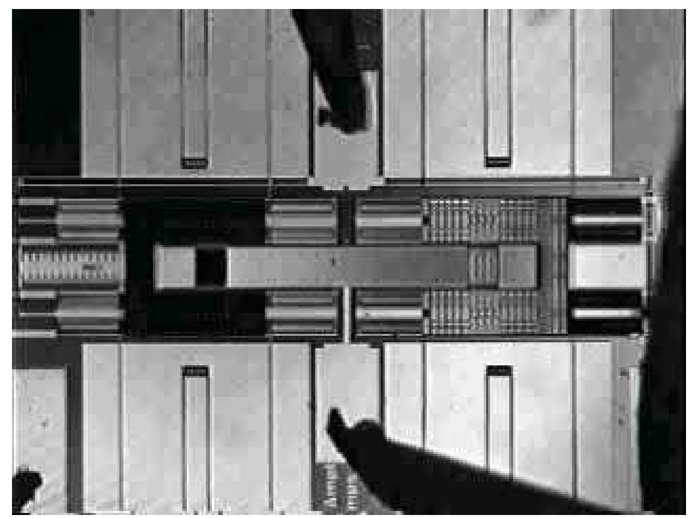
New Micro-scale Motor Designs



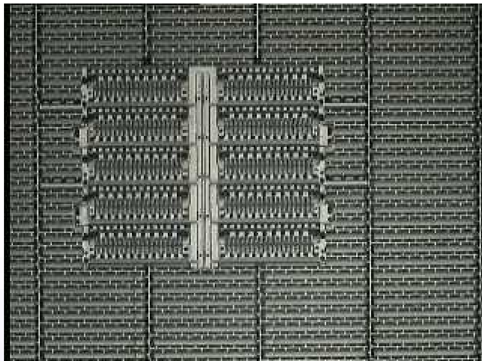
Moving to the microscale increases importance of surfaces, allowing new actuator designs

Nanotractor relies on electro-static attraction between closely separated surfaces

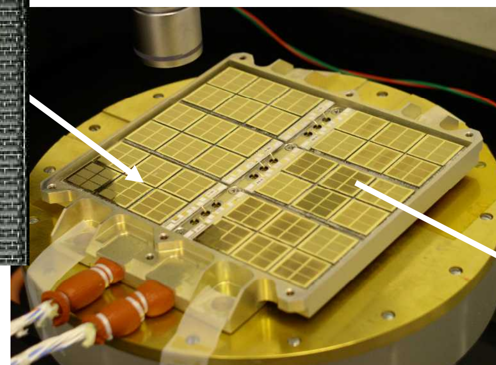




Satellite Component Temperature Control with MEMS Louvers

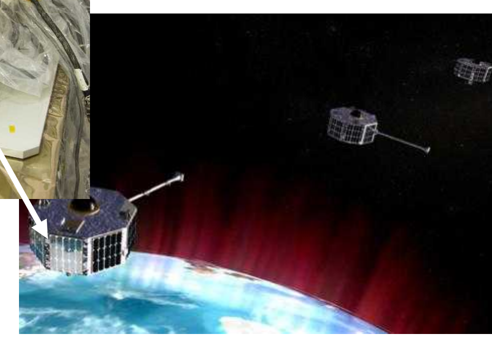


2592 SUMMiT V™ Die
w/ Buried Interconnects



4x4” Johns Hopkins/APL
Thermal Regulator

3 NASA/Goodard
ST5 Microsats
Launced 3/22/06



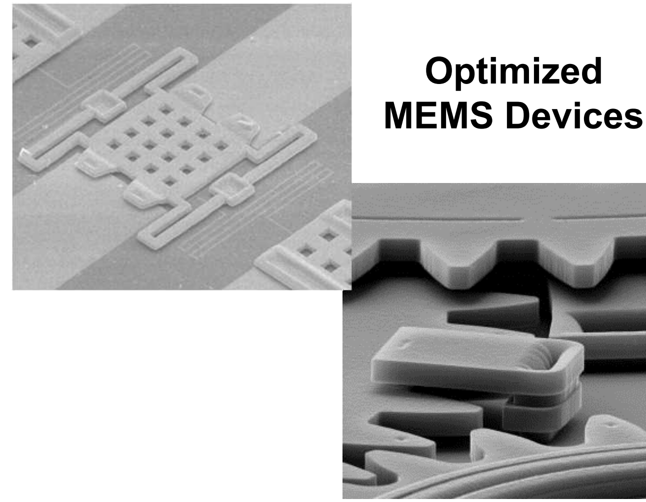
Experimental
satellites monitor
space weather

"This is the first time a fully space-qualified device of this type has ever been flown, and the first to be flown on the outside of a satellite.“

- Ann Darrin
Applied Physics Laboratory Program Manager

Summary

- **Micro- and nano-scales introduce complex physics**
- **Need ground-up approach that takes advantage of micro-scale physics**
- **Provide "micro-enabled solutions"**
- **Need "scale aware" modeling tools**
- **Modeling included as integral part of product realization cycle**
- **A new breed of engineer requires rethinking of engineering education**
  - **Multidisciplinary**
  - **Multiscale**
  - **Collaborative teams**



Optimized MEMS Devices

MESA