Nanomechanics Research at NIST

Douglas Smith,

Leader, Nanomechanical Properties Group

Materials Science and Engineering Laboratory

NIST (Gaithersburg)

Workshop on Reliability Issues in Nanomaterials

August 19, 2004

NIST United States Department of Commerce
National Institute of Standards and Technology

Outline

- Applications and assessment of needs
- Test method development
  - AFAM
  - Small-scale structures
  - Nanoparticle/CNT dispersion
- Calibration
  - Traceable force
- Standard methods and materials
- Plans/Proposed Work

Nanomechanics

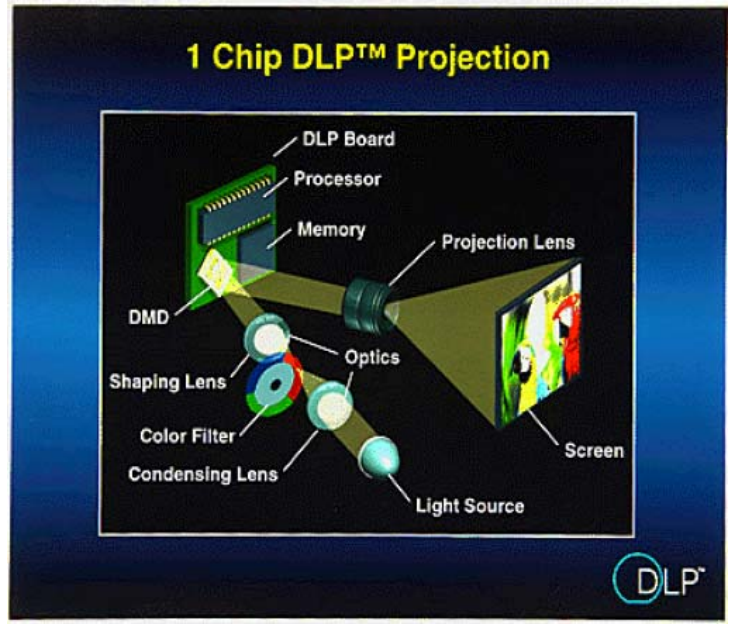
Examples of nano-scale mechanical devices and applications:

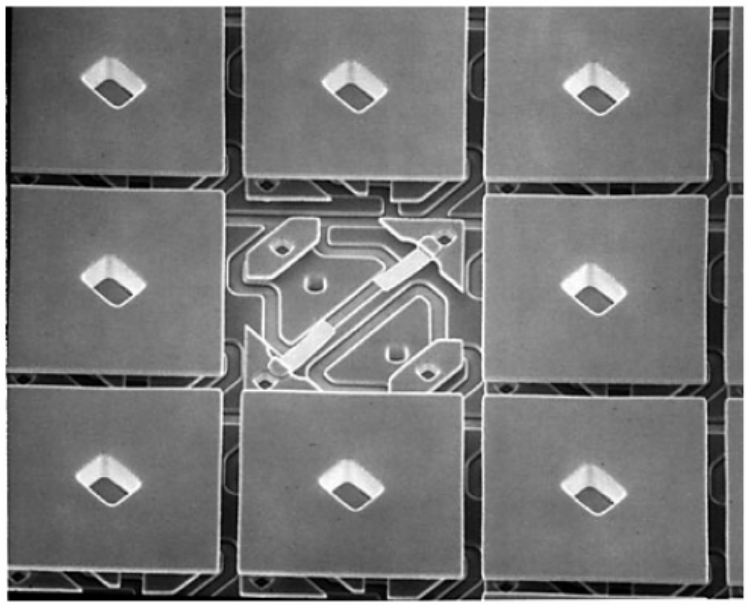
- **Actuators**
- **High-frequency Filters**
- **Sensors/detectors – static deflection or resonance**
  - **Ultrahigh sensitivity – single molecule feasible**
  - **Approaching quantum limit**
    - **100x10x10 nm resonating beam**
    - **at 100 mK has 20 vibrational quanta**
  - **Fascinating "mesoscale" regime:**
    - **Too large for full *ab initio* modeling**
    - **Too small for continuum theory**

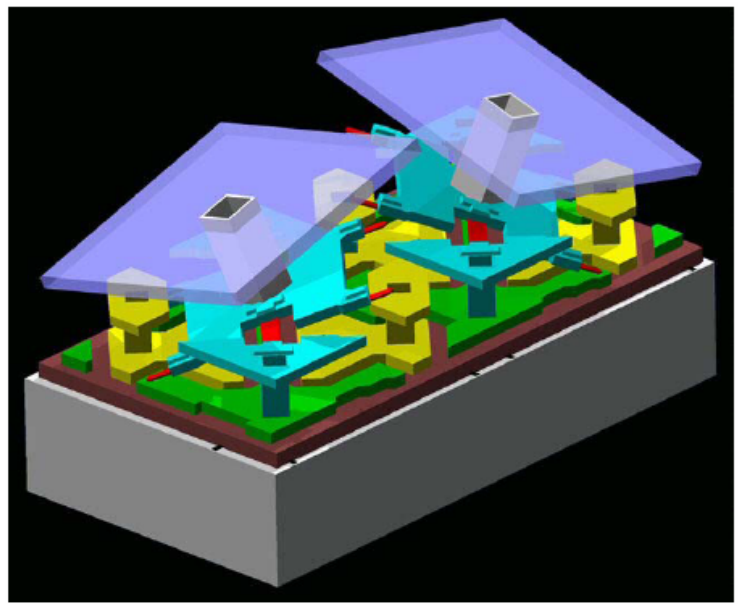
Actuators:

Texas Instruments Micro-mirror Projection – Digital Light Processing (DLP)

Mirrors tilt ± 12º at 20 µm switching time – 10,000 to 40,000 frames/second (1024x768)

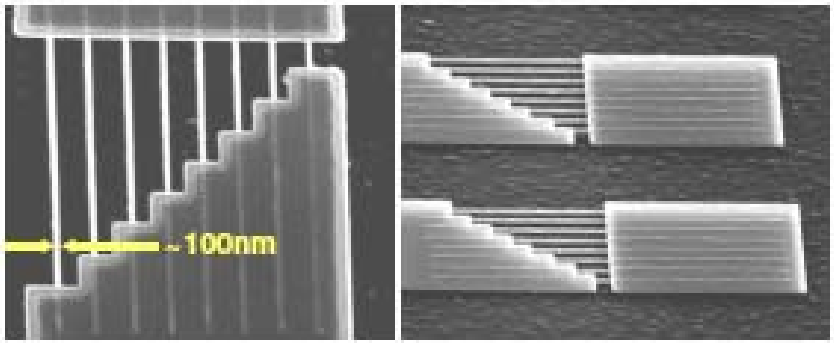


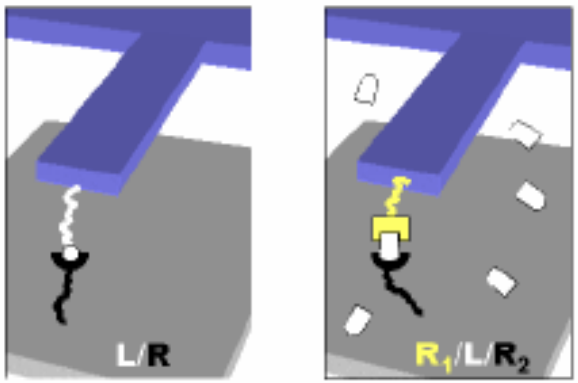




Resonating Beams and Cantilevers

SiC doubly-clamped beams,
f_0 2 – 134 MHz





Bio-NEMS

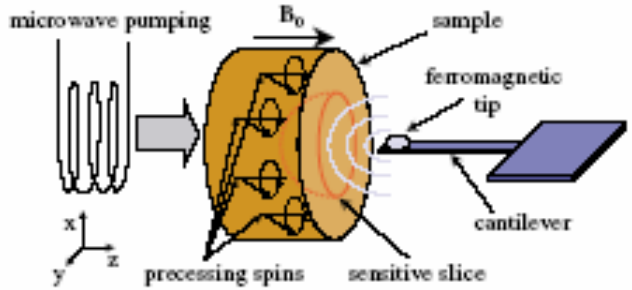


FIG. 1 (color online). Schematic of a mechanical laser device.

Nanomechanical Analog of a Laser: Amplification of Mechanical Oscillations by Stimulated Zeeman Transitions

Bargatin and Roukes, PRL, Sept. 2003

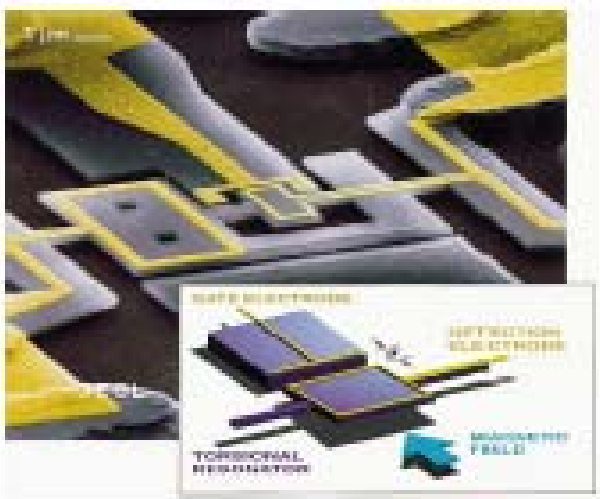
Michael Roukes et al., CalTech

Sensors –
Charge, Mass …

A Nanometre-scale Mechanical Electrometer

Cleland and Roukes, CalTech

Nature 392 (1998)



Femtogram Mass Detection Using Photothermally Actuated Nanomechanical Resonators

Lavrik and Datskos, ORNL, UTK

Applied Physics Letters 82 (2003)

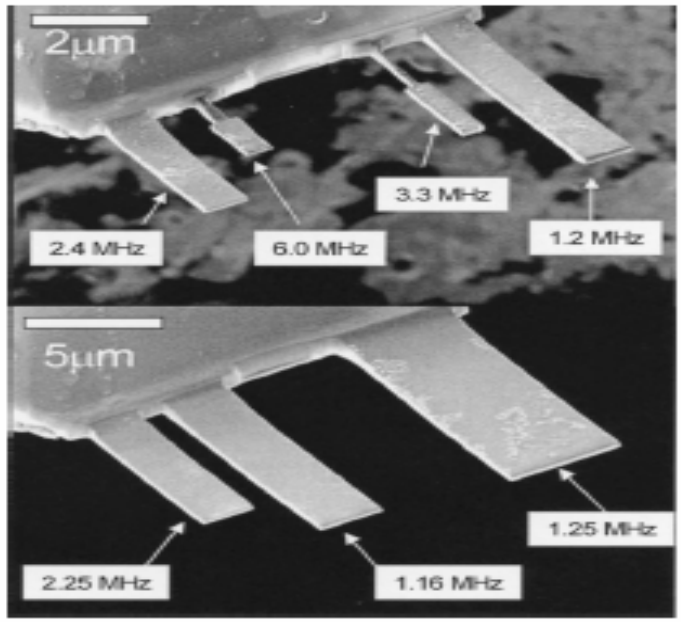


FIG. 1. Ion scanning micrograph obtained using an FIB instrument. Conventional Si microcantilevers were used in these studies as a starting material for FIB milling in order to create much smaller cantilevers with resonance frequencies in the range of 1 to 10 MHz. Approximate values of the resonance frequencies are indicated for each cantilever.

Nanoscale Arrays as High-frequency Filters

High-Q Mechanical Resonator Arrays Based on Carbon Nanotubes

Waveguide-embedded RF-Filters

Davis et al., JPL, Northrop Grumman, Brown, UN Reno

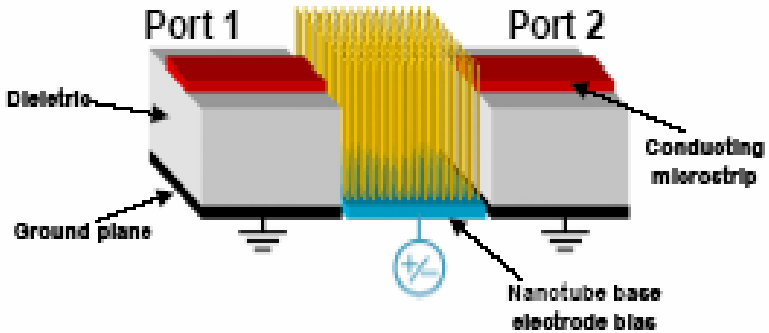


Figure 1. Schematic of the waveguide-embedded nanotube array RF filter

As-grown Carbon Nanotube Arrays

Z.L. Wang, Georgia Tech

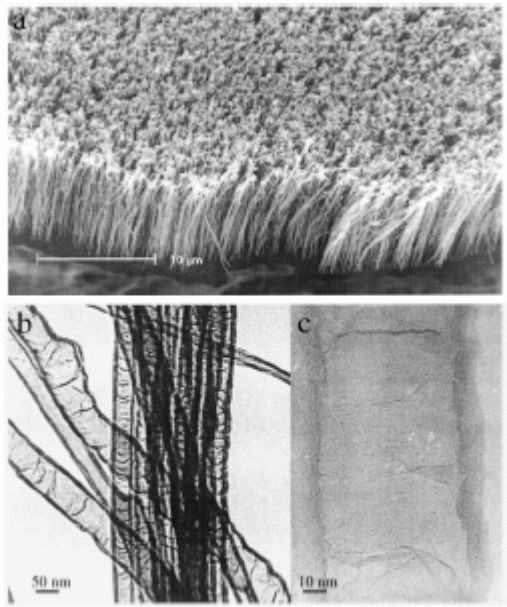


FIG. 1. (a) SEM image of the as-grown aligned carbon nanotube arrays on a quartz substrate. (b) Low-magnification TEM image showing the bamboolike structure of the carbon nanotubes. (c) A high-magnification TEM image showing the graphitic layered structures in the wall of a nanotube.

NNI Grand Challenge Workshop on Instrumentation and Metrology for Nanotechnology January 27-29, 2004, NIST

- Purpose: Roadmap development
- Five Parallel Tracks
  - Nanocharacterization
  - **Nanomechanics**
  - Nanoelectronics, photonics, magnetics
  - Nanofabrication
  - Nanomanufacturing
- Workshop Participants
  - 200 total
  - In Nanomechanics Track:
    - 1/3 each: Industry, Academia, (non-NIST) National Labs
    - Industry: ½ instrument manufacturers, ½ users
      - MTS, Hysitron, Veeco, Pacific Nanotechnology
      - Lucent (2), Honeywell, Seagate, Dow

Assessing Needs and Priorities in Nanomechanics: Grand Challenges

- Facilitated Discussion (Energetics, Inc.) of State of the Art, Long-term Objectives, Barriers, etc.
  - Six areas identified
    - Standardization and Calibration
    - Modeling of Nanomechanical Experiments
    - Instrument Development for Nanomechanics
    - Integration of Multiple Techniques
    - High-Throughput, Automated Nanomechanics Measurements
    - Testing under Real Application Conditions
  - Top two voted most important (with or w/o NIST votes)

I. Standardization and Calibration

- **Vision:**

  Science-based standards with international acceptance that include:

  – primary calibration
  – use of artifacts, and
  – standard methods for testing and analyzing data

  in order to establish quantitative measurement of mechanical properties at the nanometer scale.

I. Standardization and Calibration

- **Barriers:**
  - Need for international collaboration/cooperation
  - Lack of machine-independent standards
  - Poor understanding of contact mechanics and surface forces at the nanoscale
- **Impacts:**
  - Improved quality of scientific results
  - Product/regulatory standards
- **Implementation:**
  - NMI's take the lead
  - International workshops and round robins
  - Standards development roadmaps

II. Modeling of Nanomechanical Experiments

- **Vision:**

  Develop a quantitative connection between mechanical experiments at the nanoscale and relevant material properties using:

  – Accurate, high precision, traceable experiments
  – Close coordination of theory, computation and experiments
  – Multiscale modeling
  – Modeling compatible with experiment

II. Modeling of Nanomechanical Experiments

- **Barriers:**
  - Modeling
    - Computational power
    - Capturing the physics
    - Data storage and mining
  - Experiment
    - Manufacture, characterization and manipulation of specimens (and fixtures)
    - Accuracy and traceability for all experiments
  - Close coordination of experiment and modeling
- **Impacts:**
  - Critical to understanding the meaning of mechanical properties at the nanoscale
  - Critical to any quantitative mechanical property determination at the nanoscale

Assessing Needs and Priorities in Nanomechanics: Grand Challenges

- Six areas identified
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  - Integration of Multiple Techniques
  - High-Throughput, Automated Nanomechanics Measurements
  - Testing under Real Application Conditions
- Others four areas (and other tracks) also cited need for standards and traceable calibration

Nanomechanics Track: Workshop Outcomes

- Reinforced need for calibration and standards
- Supported the need for stronger experiment/modeling/theory collaboration
- Invited to participate in MRS Fall Meeting
  - Other reporting/follow-up opportunities forthcoming
- Specific follow-on activities
  - More focused workshops
  - Sandia National Labs – collaboration on interfacial force microscopy, specimen fabrication
  - Seagate – examine need for thin film mechanical standards

Nanoscale Elastic-Property Imaging

Donna Hurley,
Roy Geiss, Bob Keller,
Gosia Kopycinska-Müller,
Paul Rice, Joyce Wright

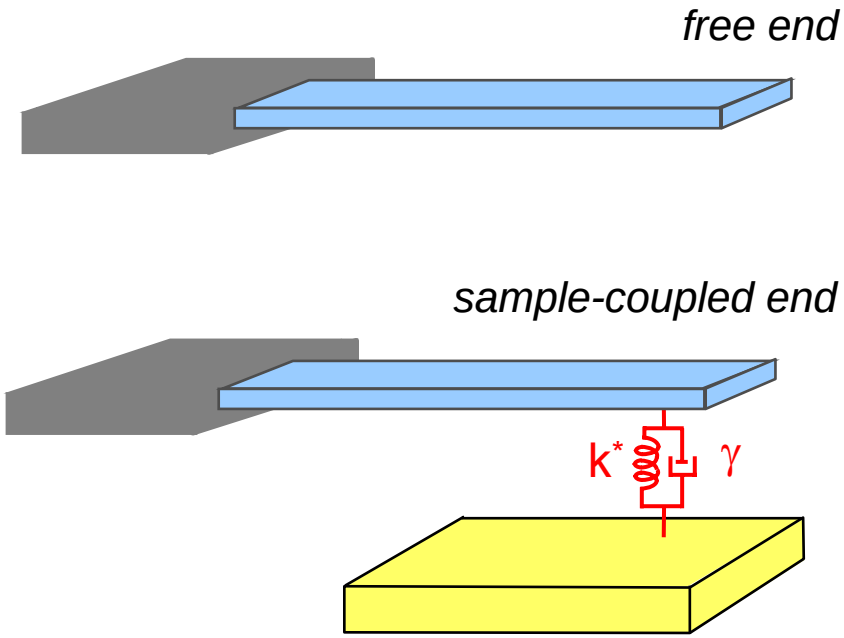
Materials Reliability Division
Boulder, Colorado USA

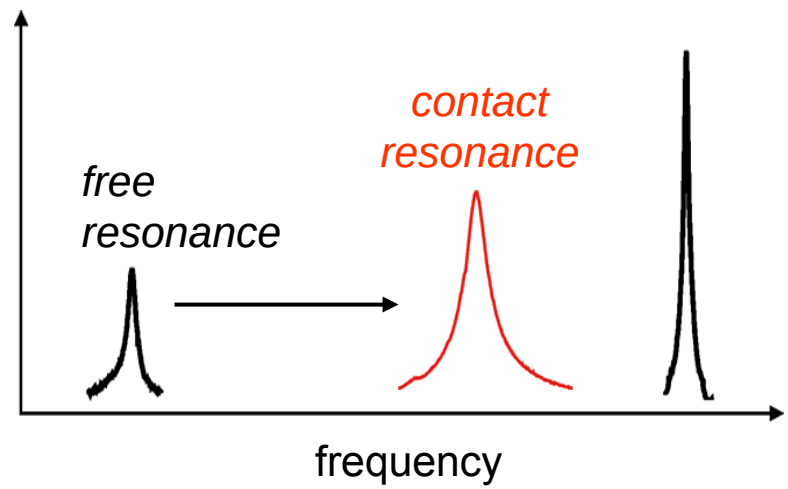
Collaborators: *W. Arnold, IZFP*
M. Fasolka, NIST
D. Smith, NIST
C. Su, DI-Veeco
J. Turner, U. Nebraska

Physical Concepts

- atomic force acoustic microscopy (AFAM)
- dynamic AFM method
- nondestructive

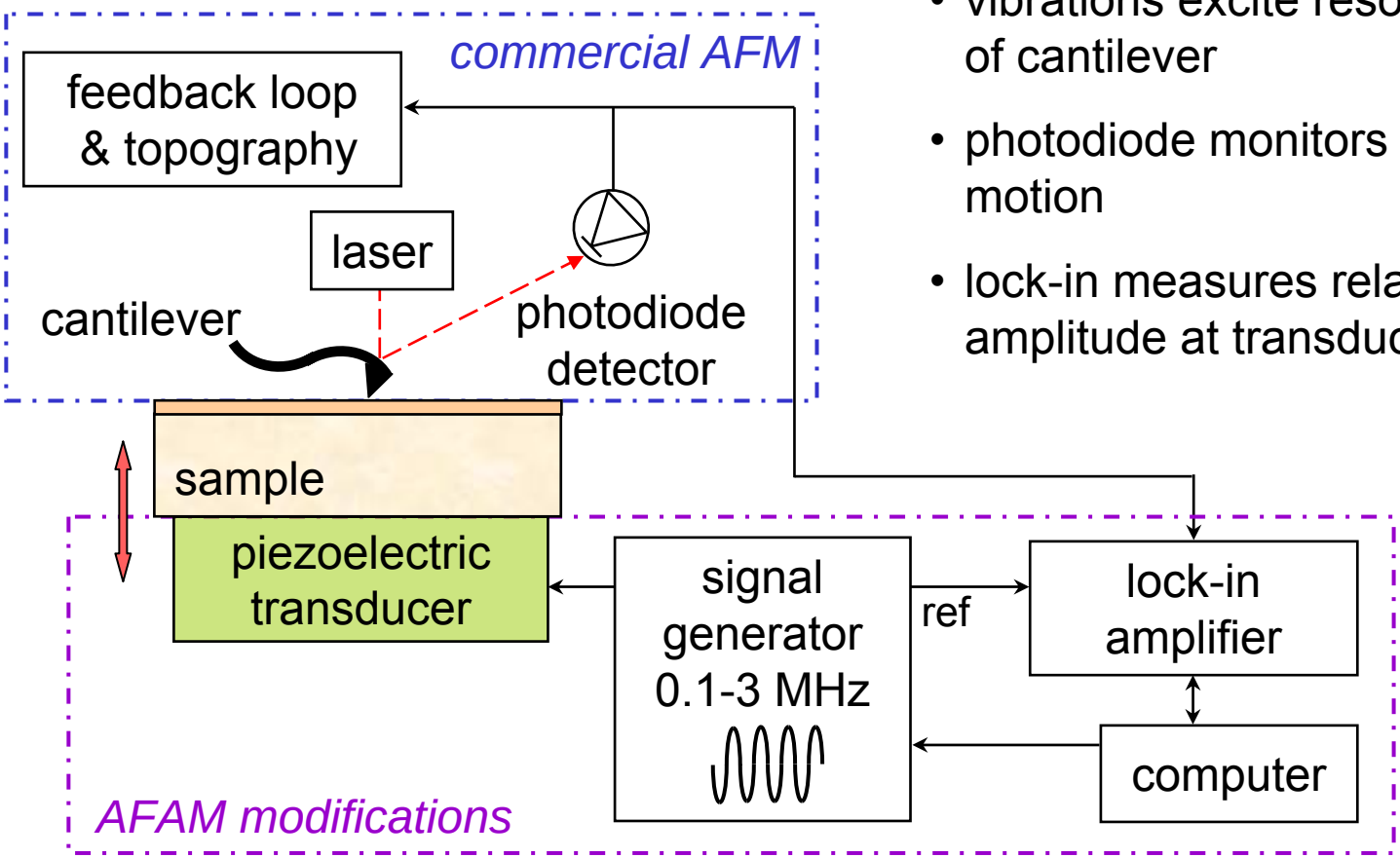
- tip in contact with sample
- spatial resolution determined by contact radius (10-50 nm)
- applied forces ~0.4-3 μN





Resonant frequencies of cantilever provide information about sample's mechanical properties

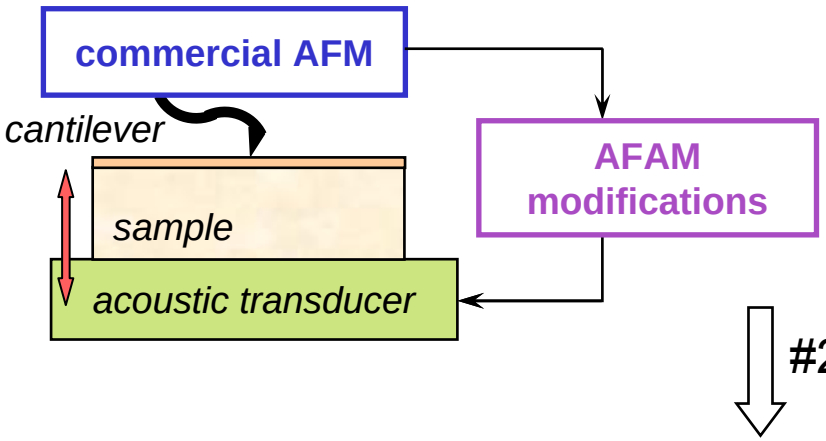
Experimental Apparatus



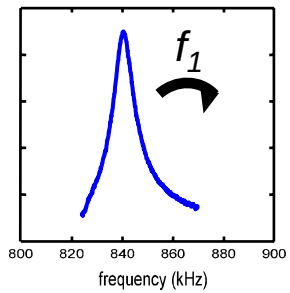
- transducer couples to cantilever through tip-sample contact
- vibrations excite resonant modes of cantilever
- photodiode monitors cantilever motion
- lock-in measures relative amplitude at transducer frequency

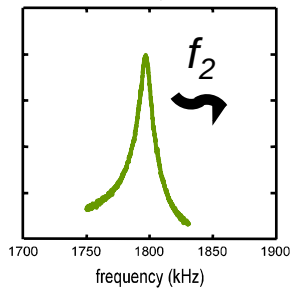
Nanoscale Measurements with AFAM

1. sweep frequency at fixed position → <u>quantitative point measurement</u>
2. OR scan position at fixed frequency → <u>qualitative image</u>



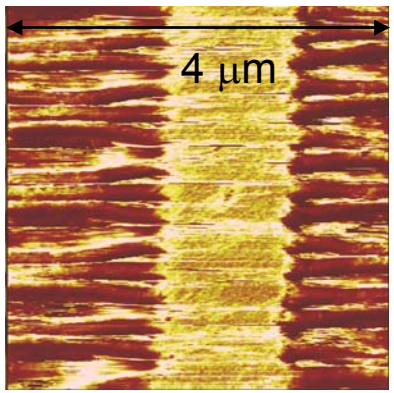
#1



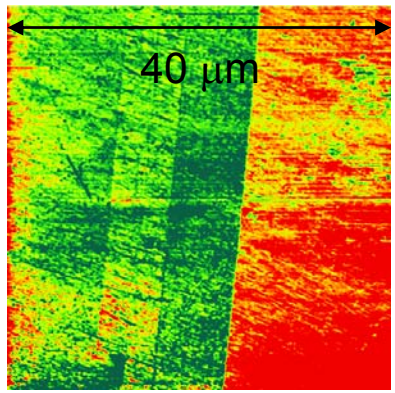


$$M = \frac{E}{(1-\nu^2)}$$

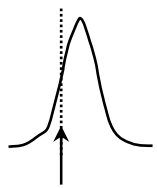
#2



nanopatterned polymer film

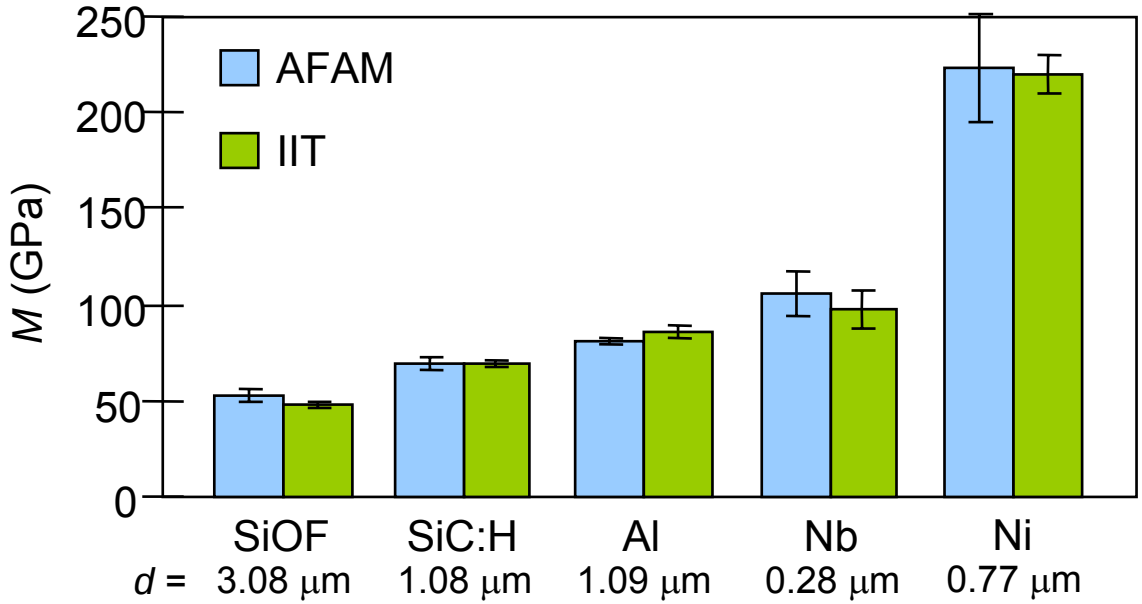


disk drive recording head



Single-Point Measurements of Thin Films

- typically average 20-30 measurements
- films as thin as 50 nm successfully measured
- effect of substrate properties negligible
- excellent agreement with instrumented (nano-) indentation



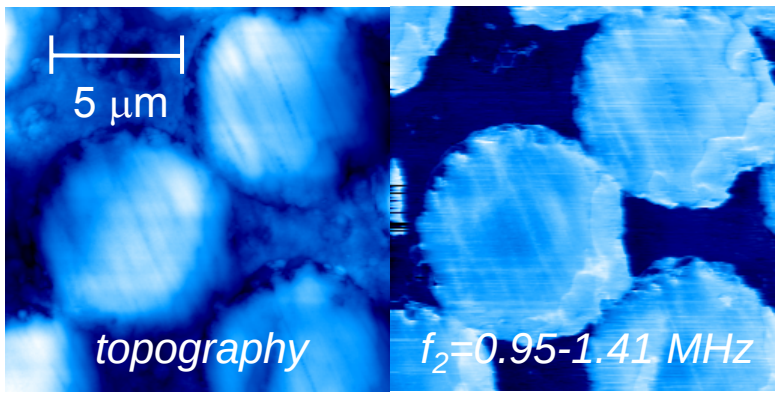
d **(nm)**	***M*** **(GPa)**
772 ± 5	223 ± 28
204 ± 4	220 ± 19
53 ± 2	210 ± 26

AFAM measurements of nanocrystalline Ni films

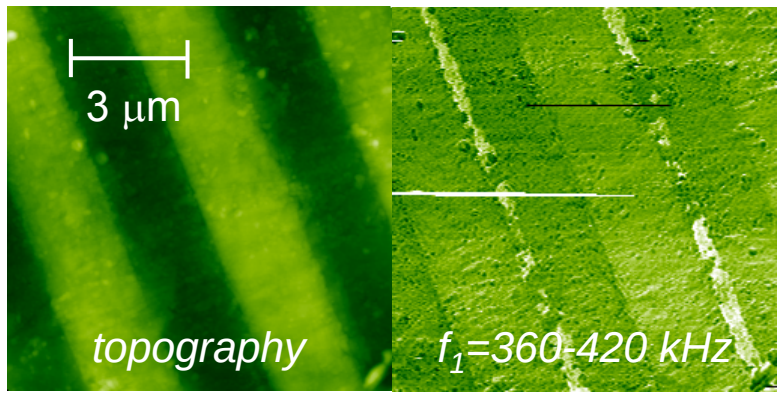
Quantitative Elastic-Property Mapping

- goal: combine quantitative methods with 2D scanning
- fixed-point approach too slow for imaging
- developed frequency-tracking circuit (Tony Kos, EEEL)
- ~30 min. to acquire resonance-frequency image
- final step: convert frequency information to modulus maps

Resonance-Frequency Images



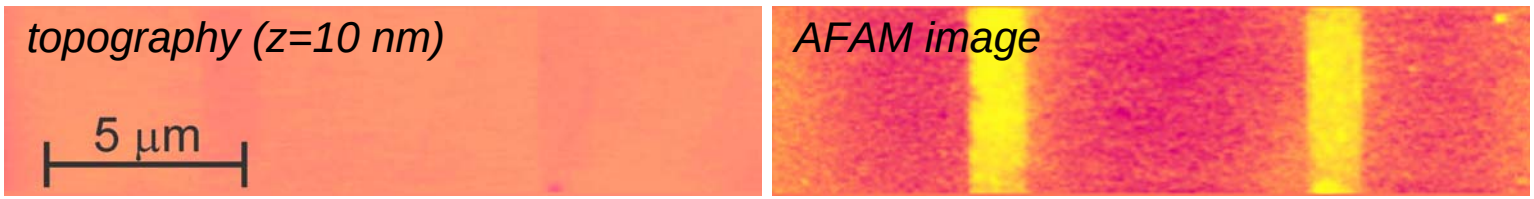
polymer/glass composite



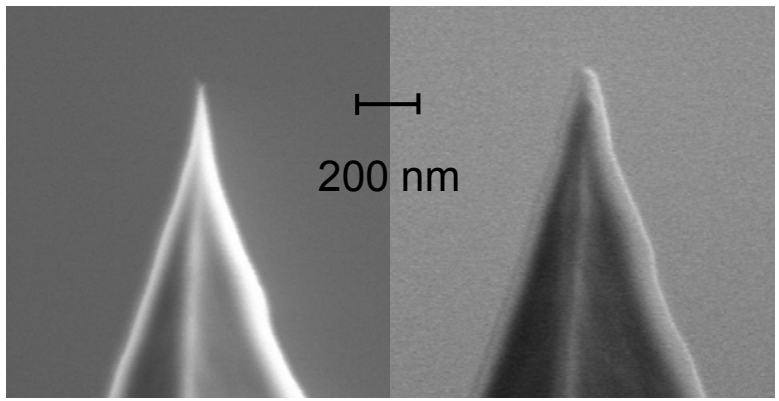
Cu/SiO_2 stripes

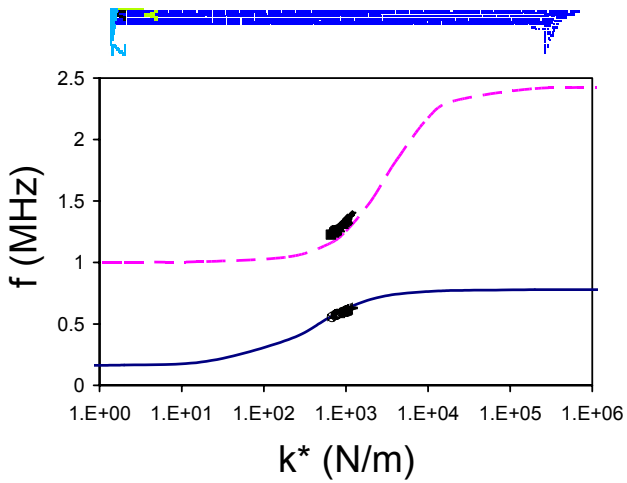
Related Metrology Issues

- SEM + AFAM tip wear and tip shape studies
- effects of tip-sample adhesion
- finite-element modeling for improved analysis methods
- additional property information using torsional modes



hydrophobic n-octyldimethylchlorosilane SAM stripes on Si





Mechanical Property Measurements via Small-Scale Structures

Ajit Jillavenkatesa,* Dan Xiang,†
Renato Machado,‡ George D. Quinn,
Douglas T. Smith, and Edwin R. Fuller, Jr.

Nanomechanical Properties Group, MSEL

* now in Standards Services Division (210)
† guest scientist
‡ INMETRO, Brazil

National Institute of Standards and Technology

INMETRO

Materials Science & Engineering Laboratory

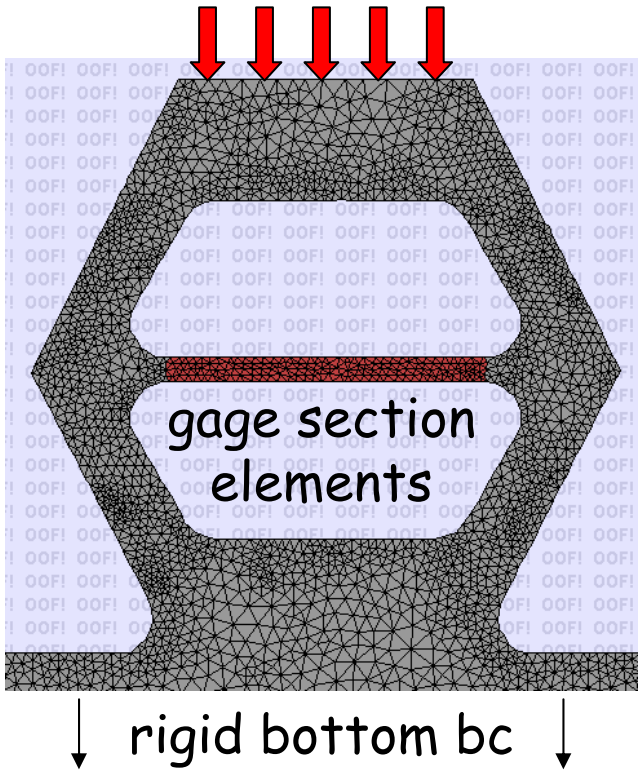
Needs:

- to measure mechanical properties of microstructures that cannot be fabricated in bulk samples
- to study small-scale phenomena that may be controlled by surface effects and surface stresses
- to obtain quantitative mechanical property data of materials and interfaces for designing small-scale structures and components and for assessing their mechanical reliability

Why NIST?

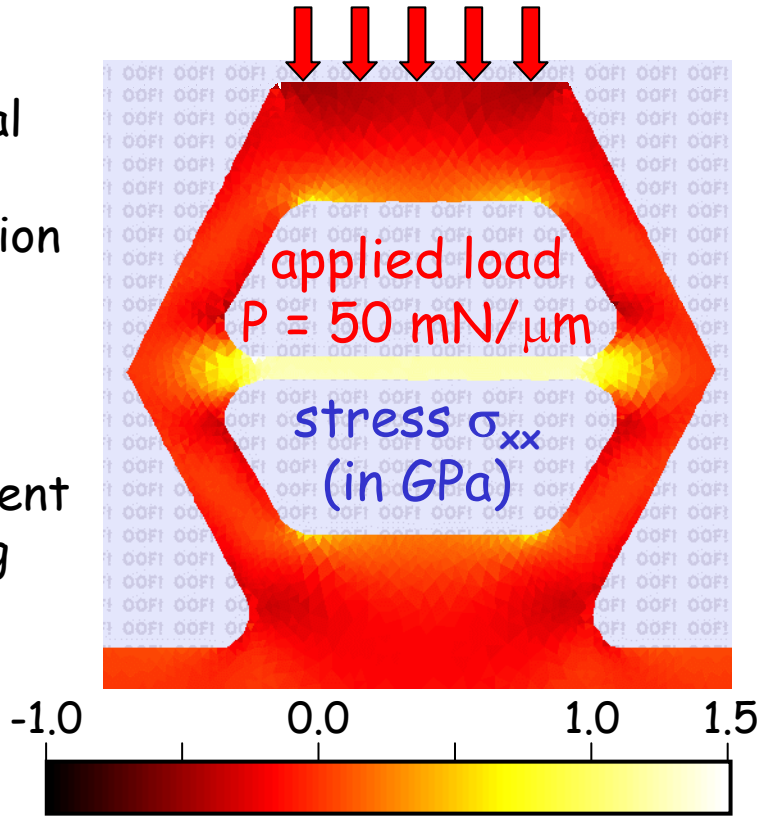
- unique expertise in mechanical & fracture testing — not in just test methods, but in accurate and precise measurements
- unique experience in development of mechanical test standards
- unique expertise in fractography and reliability methodologies
- unique combination of research groups

Design Objective:
to develop a compressively-loaded test configuration with a well-defined, tensile gage-section. Use depth-sensing indenter as a universal testing machine.

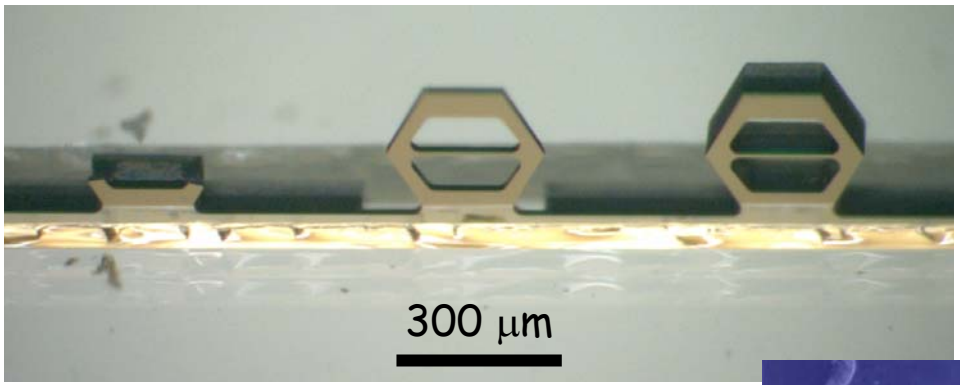


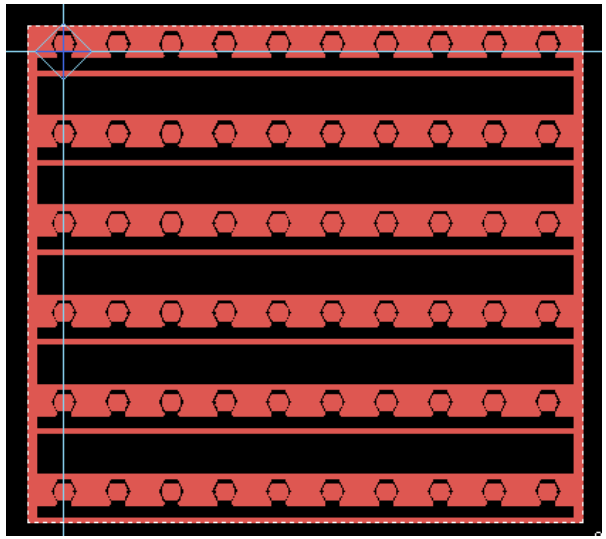
hexagonal theta configuration

finite element modeling

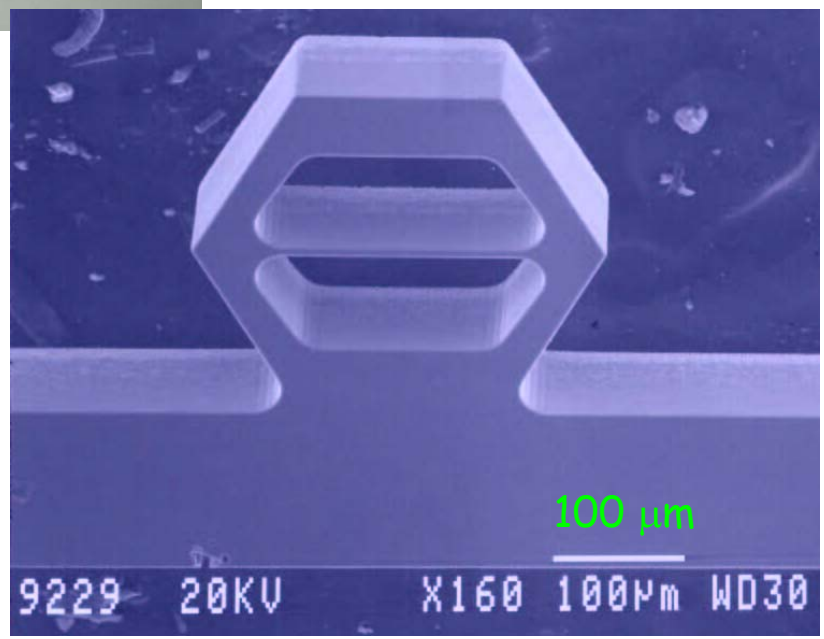


Specimen Fabrication

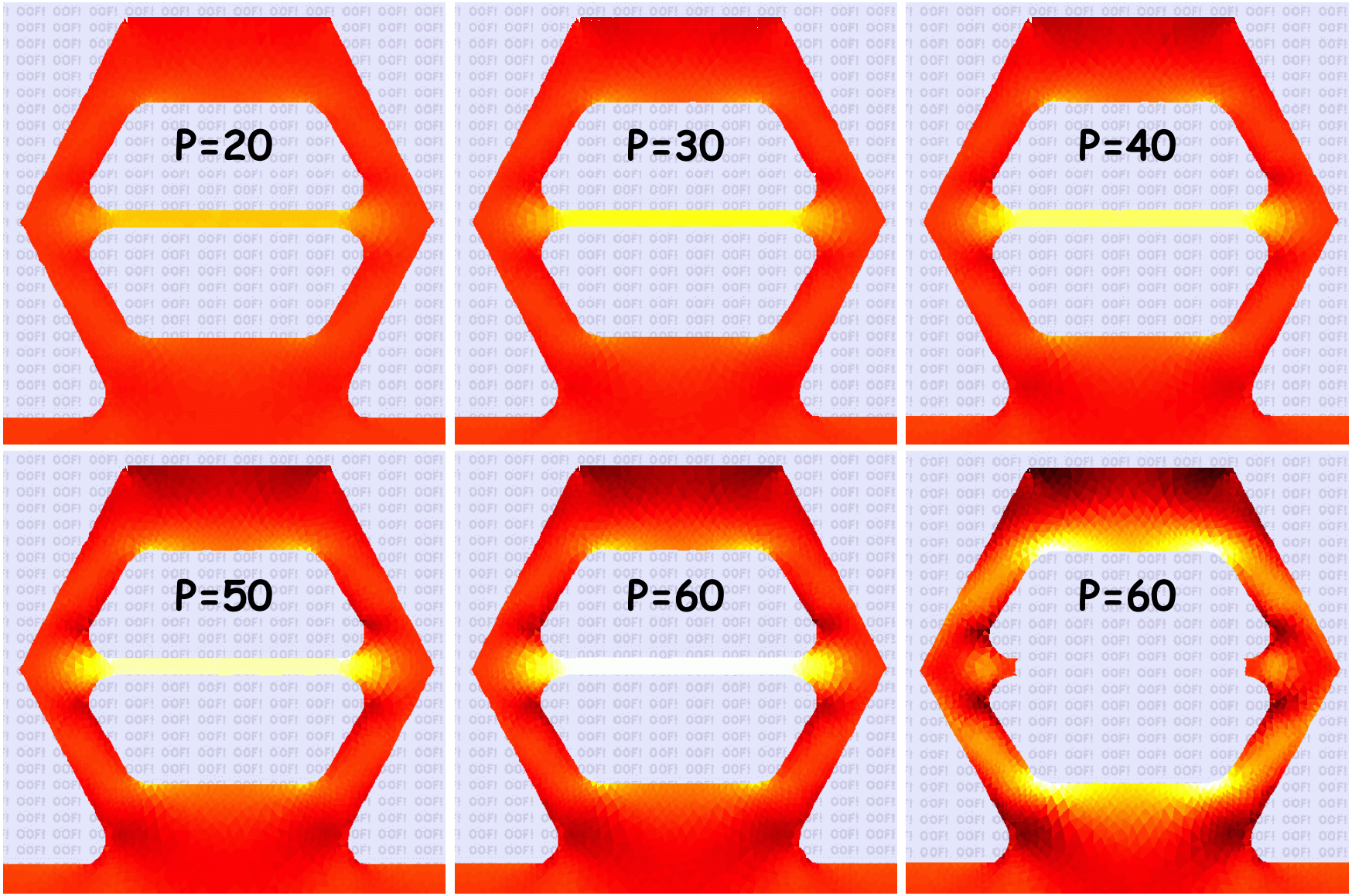




courtesy of James A. Beall
Quantum Electrical
Metrology Division (817)
NIST Boulder

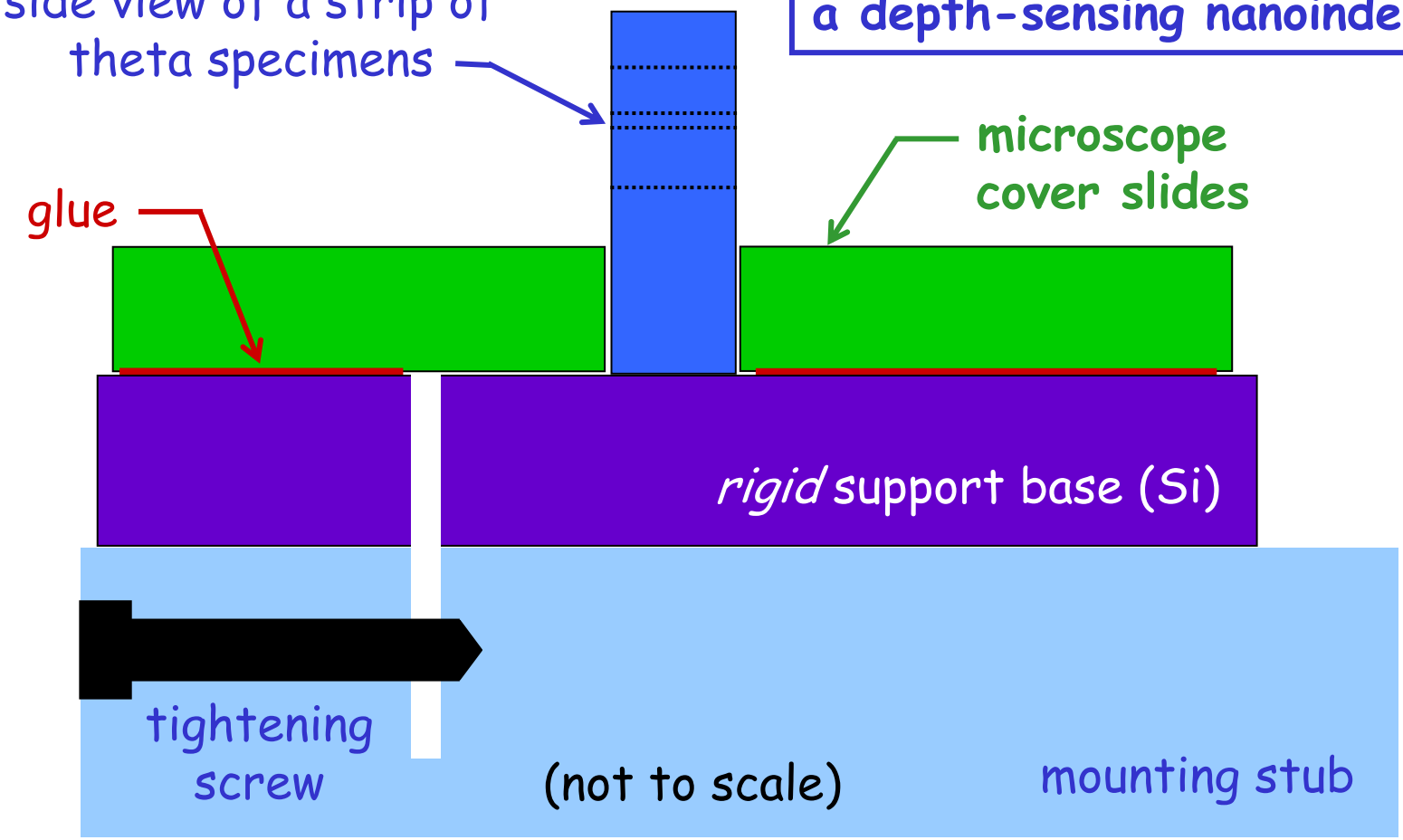


stress σ_{xx} for applied load P (mN/μm)

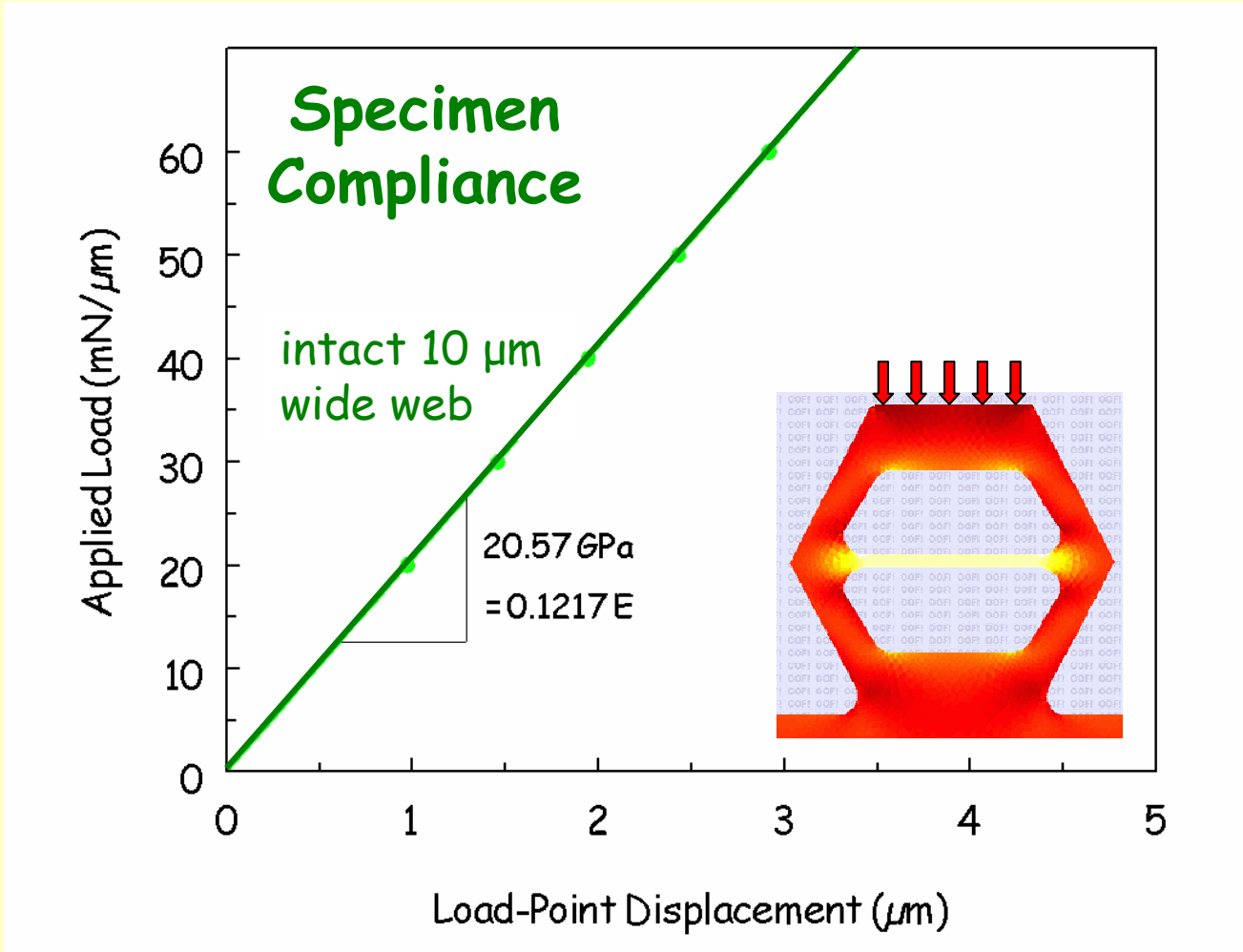


Mechanical Testing Arrangement

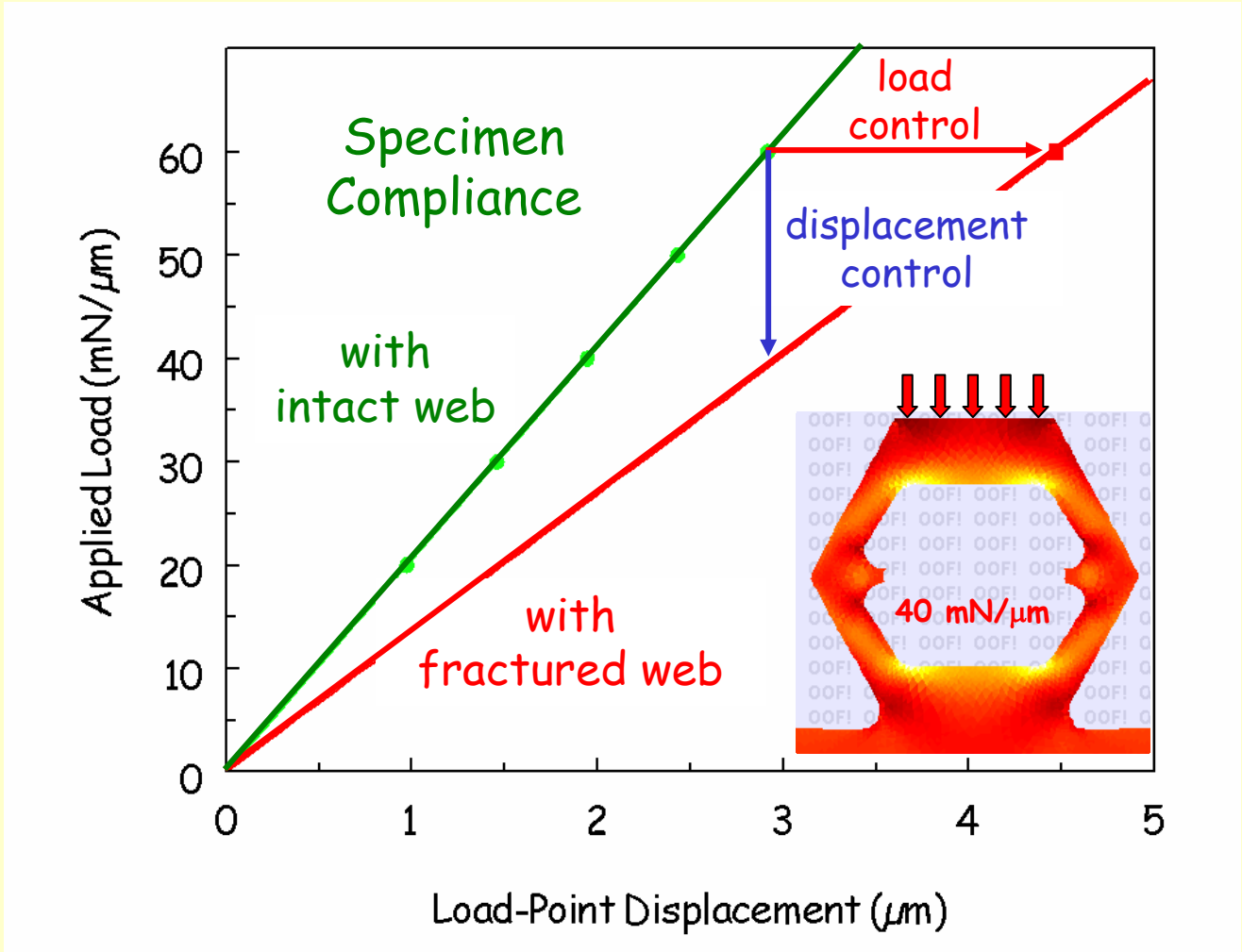
universal testing machine:
a depth-sensing nanoindenter



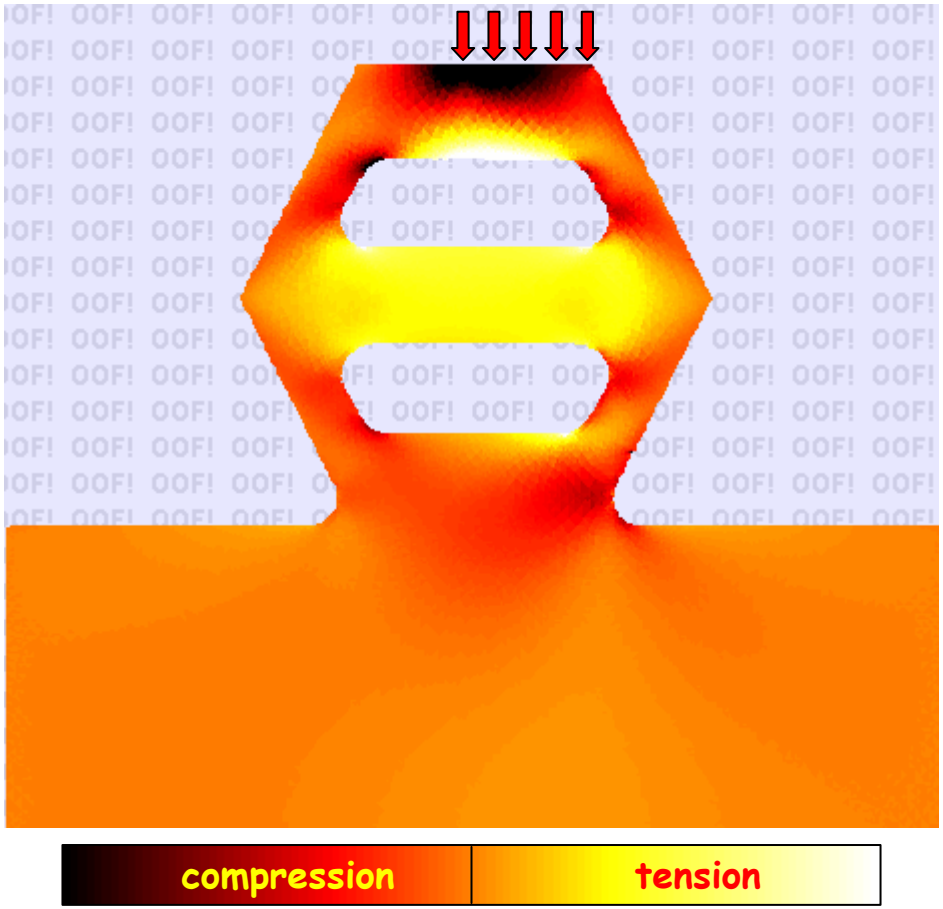
Mechanical Testing



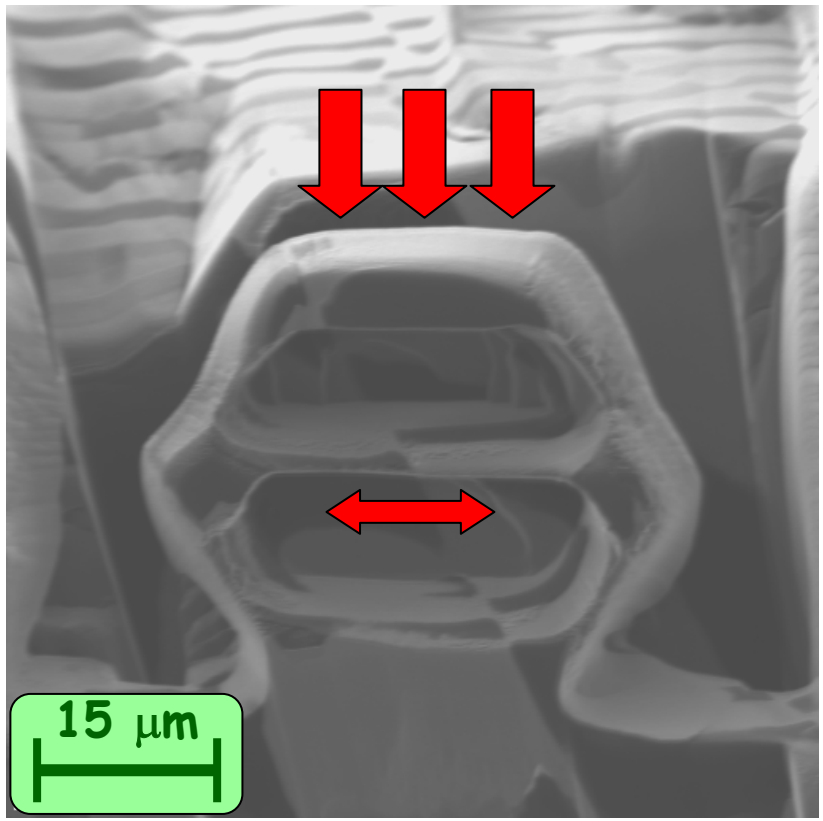
Mechanical Stability



Influence of Off-Center Loading

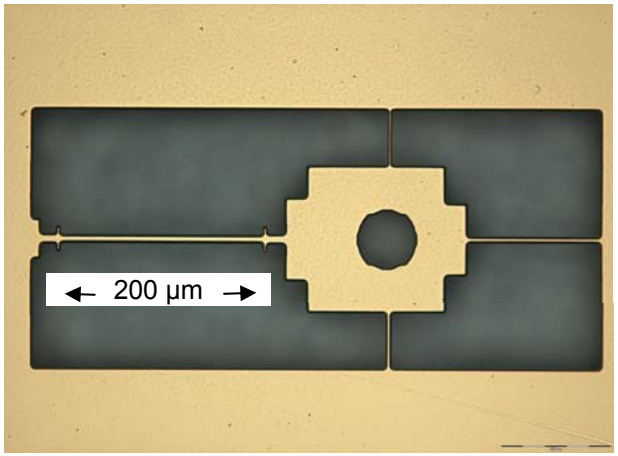


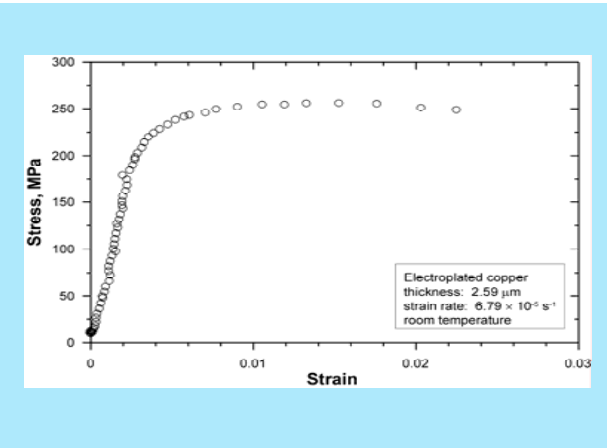
Tensile Strength and Mechanical Properties of $Ni_{0.5}Co_{0.5}O-ZrO_2$ Directionally Solidified Eutectics



Microtensile Testing

D. T. Read, J. D. McColskey, Y.-W. Cheng





Specimens:

- 10 x 200 x 1 µm

Measurements:

- Displacements: 1/10 to 1/50 pixel
- Engineering strain: ± ~50 microstrain
- Forces: ± ~ 40 µN

Results:

- Stress-strain curves
- Young's modulus (often low)

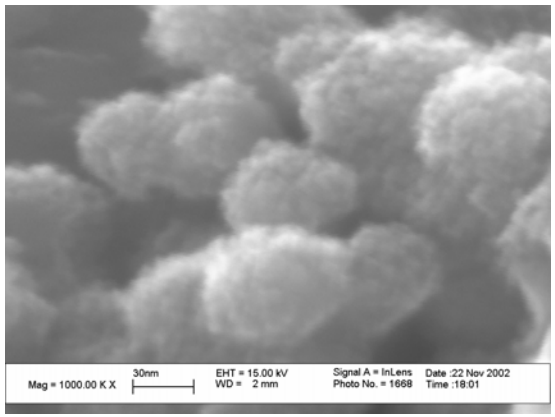
Issues:

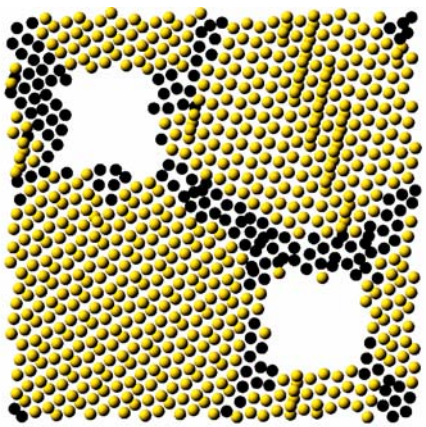
- Do we want to try to take this into the nanoscale?
- What industry or technology would benefit?
- What specimens could we get, from whom?

Mechanisms for phenomena observed in microtensile testing:

Low Young's modulus in electrodeposited copper:

Morphology effect?



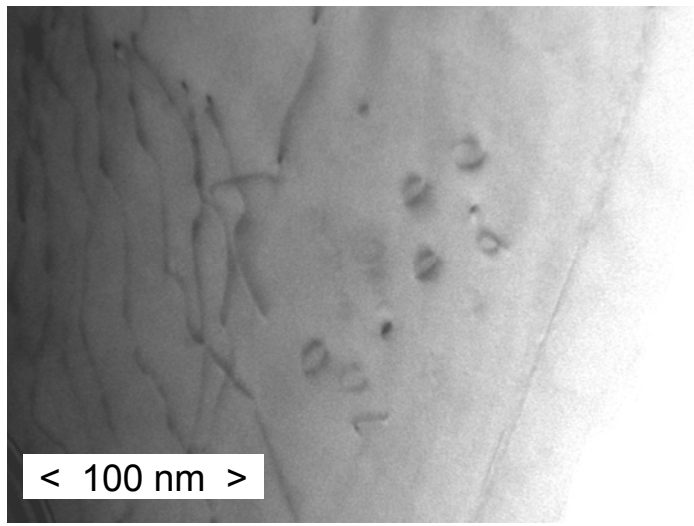


MD simulation of morphology (scaled down) produces low modulus

Plastic deformation in the neck of tensile specimens:

Too thin for dislocations?

Thick neck: dislocations



Thin broken edge: no dislocations

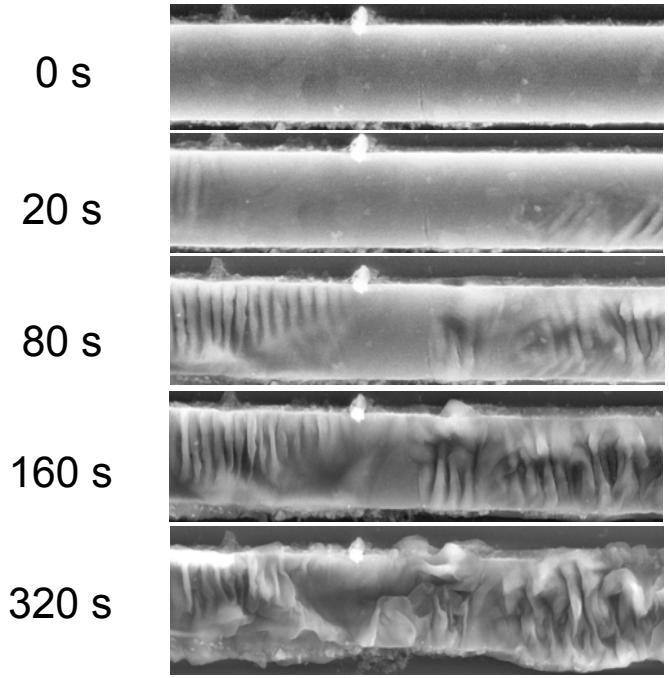
EBSD Analysis of AC-Induced Thermomechanical Fatigue

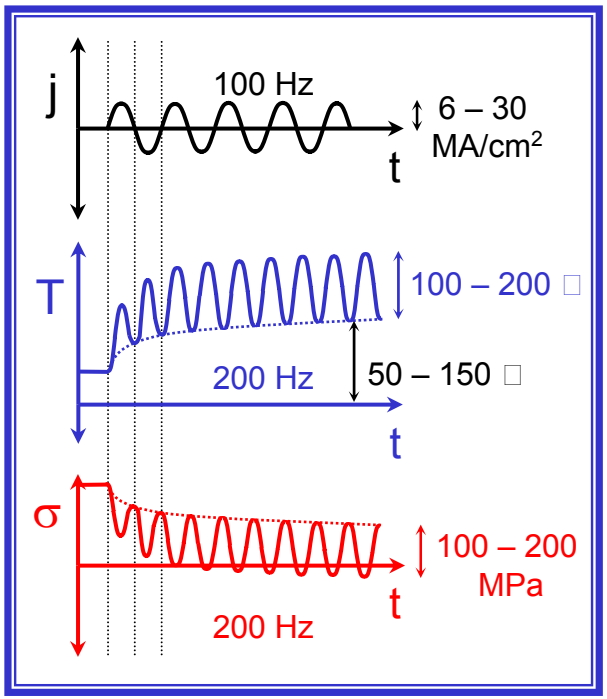
Roy Geiss, Yi-wen Cheng, Bob Keller, NIST Materials Reliability Division

Problem:

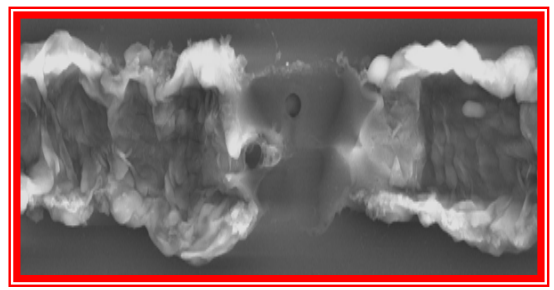
Thermomechanical fatigue of interconnect structures due to power cycling, energy-saving, application-specific thermal fluctuations. Al-1Si/SiO_2/Si in this example (unpassivated); Cu/Ta/SiO_2/Si shows similar damage. High strain, thousands of cycles. Simulated using low frequency, high density AC.

$$\varepsilon_{thermal} = \Delta\alpha\ \Delta T \text{ (between Al and Si)}$$



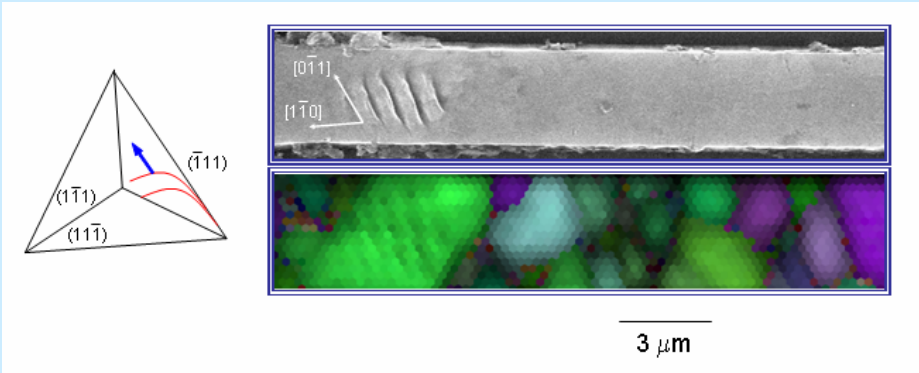


$\Delta\sigma$ ~ 100 – 200 MPa is approx. same magnitude as thin film yield strengths in Al and Cu



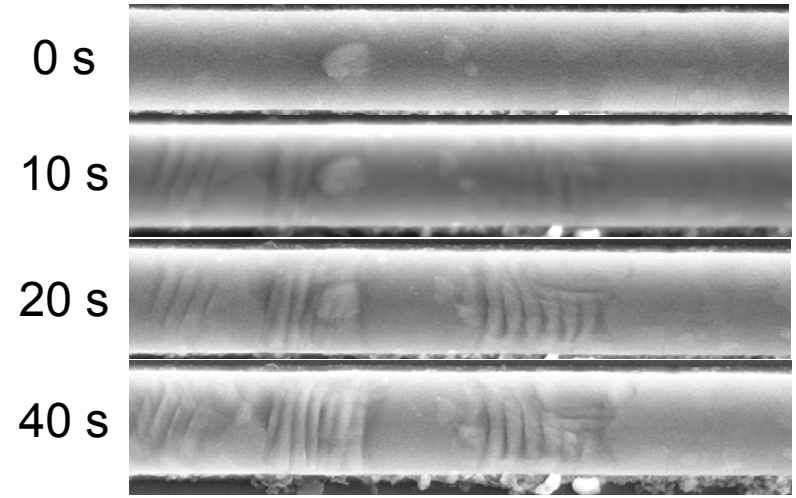
Ultimately, open circuit!

Orientation Mapping Reveals Role of Microstructure on Damage Progression



Damage extent varies from grain to grain and is due to plasticity via dislocation motion.

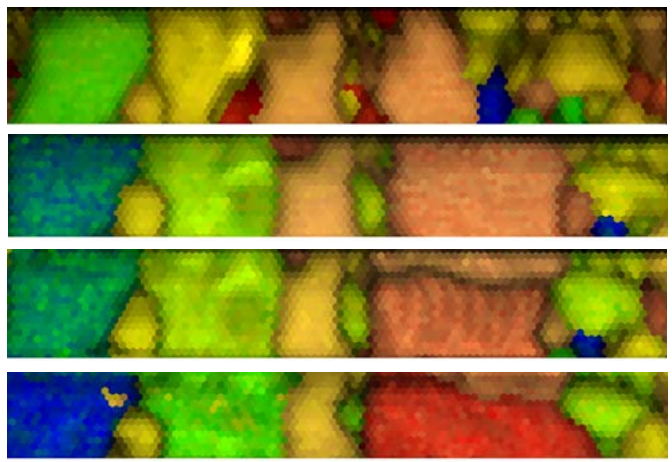
Quasi *in-situ* test (observe, test, observe, test…)



Damage also takes the form of grain growth/consumption and orientation changes, as revealed in orientation map sequence. Orientation changes affect subsequent deformation, revealed by Schmid factor contrast.

Lifetime prediction model under development, incorporating grain size, orientation, grain boundary structure, mechanical constraint of overlayer.

"Real-world" testing underway to measure CPU temperature variations.



5 μm

EBSD: 200 nm steps
Schmid factor contrast

Dispersion Studies:

USAXS Capillary Flow Cell

V. Hackley, A. Allen, A. Jillavenkatesa

Developed for in-situ, real-time USAXS studies of nanoparticulate fluid dispersions.

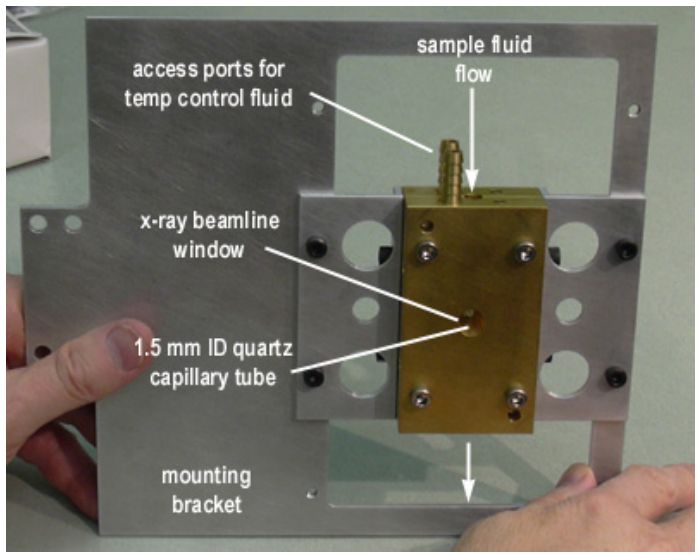
Capillary quartz cell has uniform flow field with a well-defined geometry for scattering experiments. Capillary shear-rate variation from 0.5 to 122 s^{-1}.

New cell will permit studies of:

- unstable & reactive dispersions as conditions are varied by changing pH, temperature, or chemical composition.
- flow-induced alignment/disentanglement of high aspect ratio particles

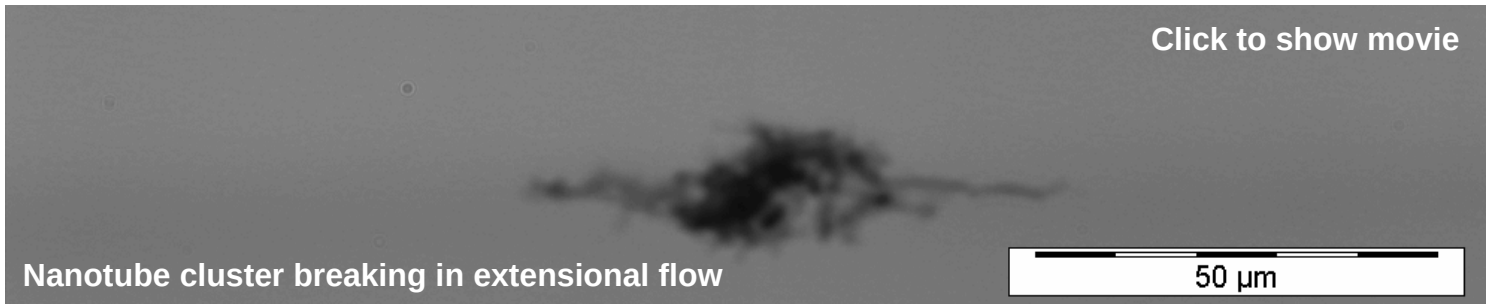
Some possible applications :

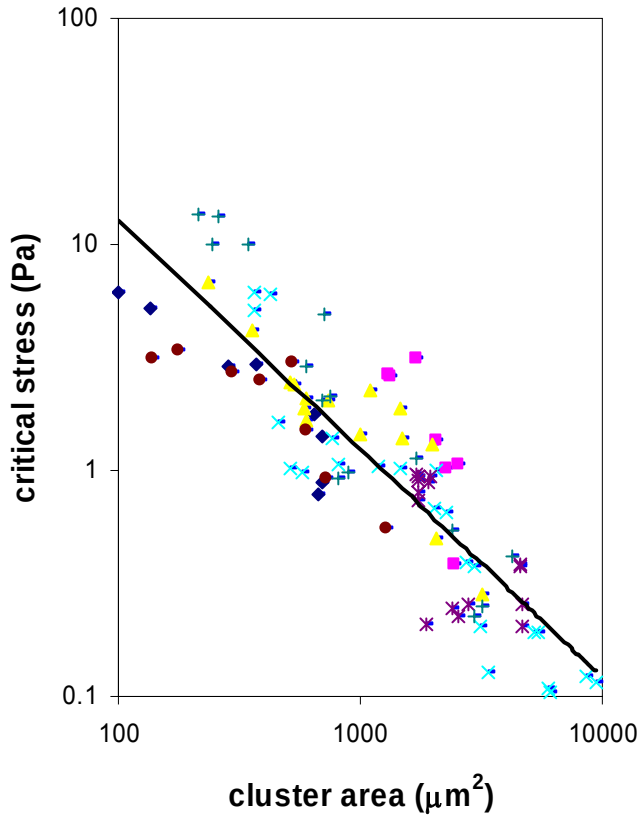
- Control of nanocluster assembly for deposition of thin films in solid oxide fuel cells
- Early-stage aggregation in unstable nanoparticle fluids
- Chemically assisted self-assembly
- In situ heterogeneous association processes (e.g., nanocomposite formation)
- Alignment and dispersion of CNTs in liquid media –current collaboration with Rick Smalley, Rice



Measuring the critical stress to breakup clusters of carbon nanotubes using microfluidic traps

P. R. Start, S. D. Hudson, K. B. Migler, E. K. Hobbie





- Critical stress depends on cluster size and aspect ratio.
  In extensional flow, we find that the number of nanotubes in a cluster is proportional to $(\text{stress})^{-0.66}$.

- *"Elastic flow instability in nanotube suspensions," Lin-Gibson,S., Pathak,J.A., Grulke,E.A., Wang,H. & Hobbie,E.K., Physical Review Letters **92**, (2004).*
- *"Microfluidic Analog of the Four-Roll Mill," S. D. Hudson, F. R. Phelan Jr., M. D. Handler, J. T. Cabral, K. B. Migler, E. J. Amis, Applied Physics Letters **85**, 335-337 (2004).*

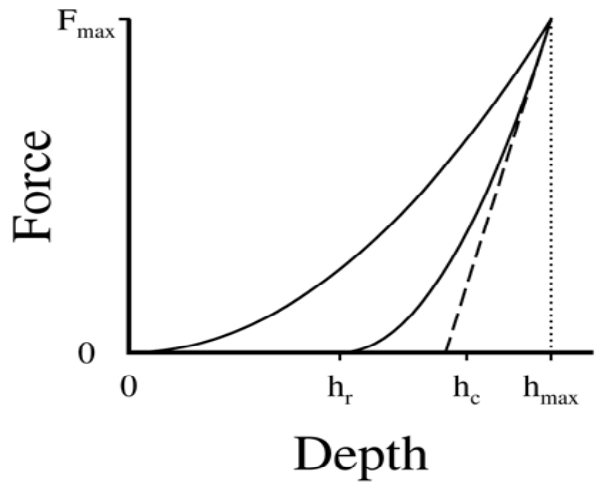
Also measuring the stress to uncoil polymer micelles: flexible threads whose diameter is 14 nm and length is approximately 10,000 nm.

Force Metrology for Nano-Mechanical Testing

NIST United States Department of Commerce
National Institute of Standards and Technology

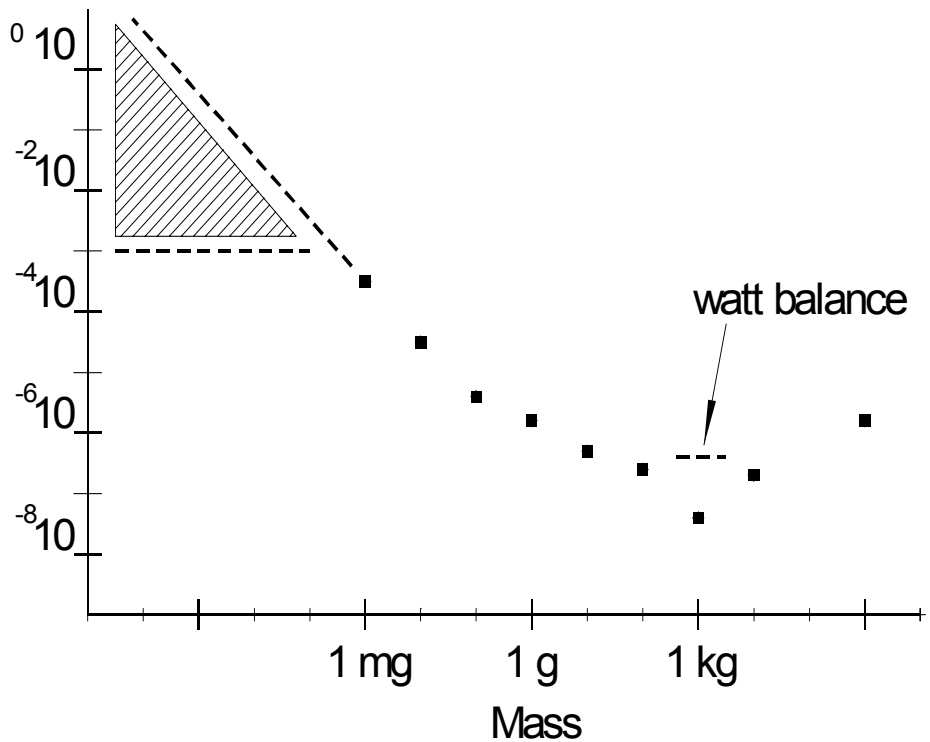
Force Calibration Issues

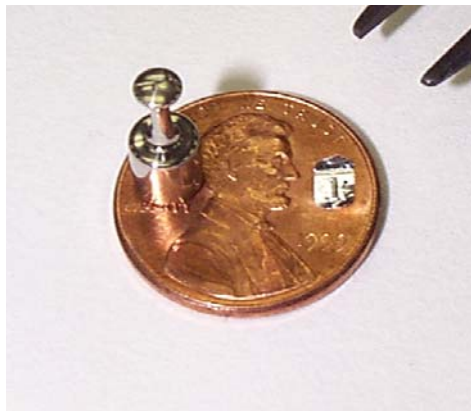
- Current standards being written for 1% force and displacement calibration
- Verified with traceable devices to 0.25% - 0.5%
- “As available”!

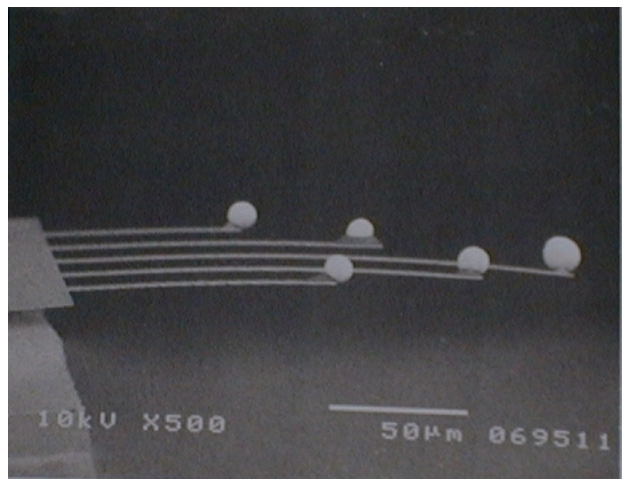


How about small deadweights?

- Smaller mass artifacts can be obtained, but their uncertainty may be a limiting factor...







www.asylumresearch.com/springconstant.asp

The World's Kilogram Standard

- Platinum-iridium artifact
- "Copies" at NMI's around the world
- Their average mass is, by definition, the kilogram

More fundamental definitions

- Link to atomic mass units with Avogadro's number, N_A: count atoms in a silicon crystal.
- Equate electrical and mechanical force:

$$1 \text{ Newton} = 1 \text{ kg*m/s}^2$$
$$= \text{electronic force units}$$

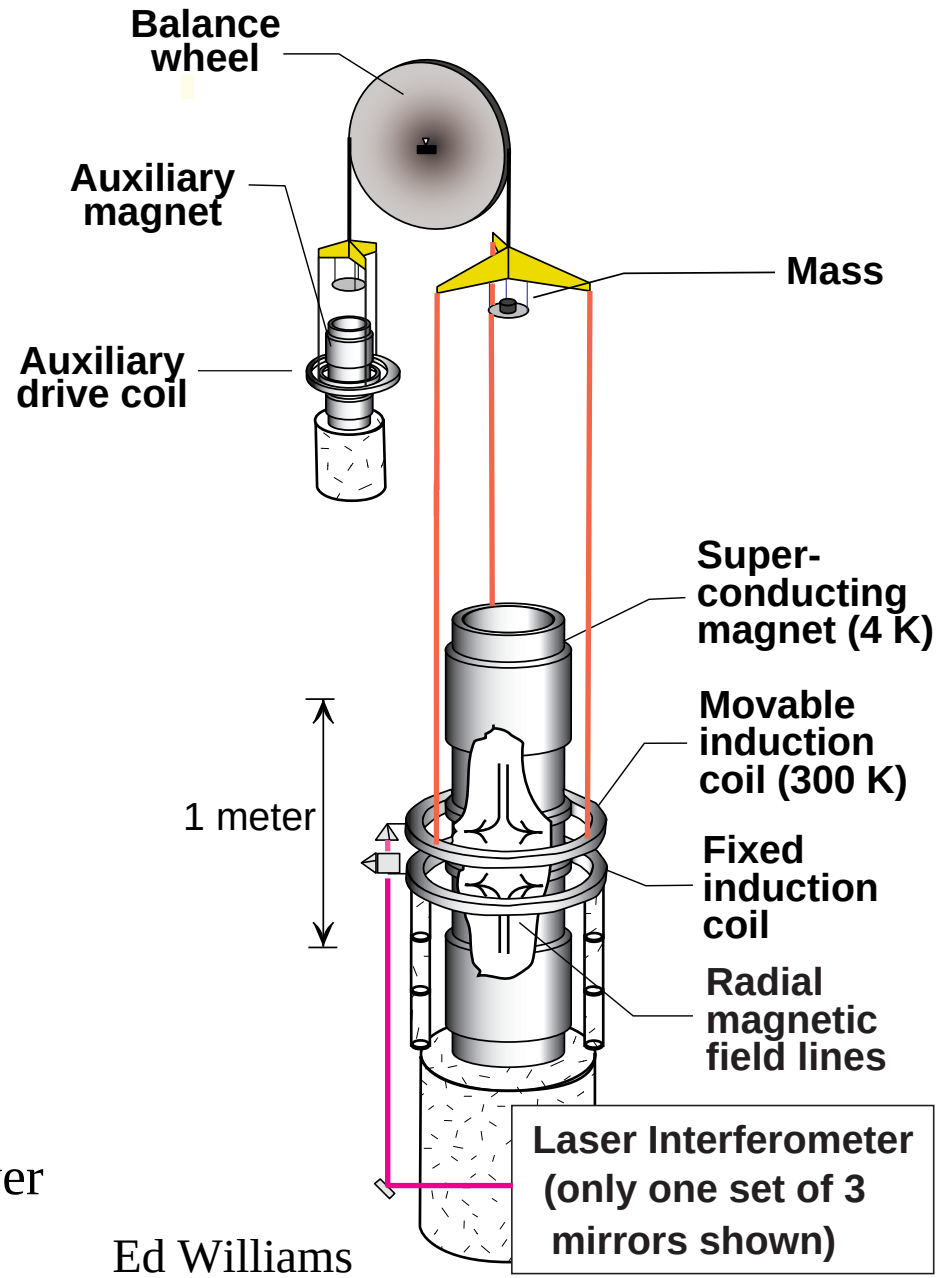
Electrostatic or electromagnetic force

NIST Watt Balance

Generate EM force:

$$F_z = 1\ \text{kg} \times g$$

- Force mode:
  - $(F_z/I) = (\text{Geom.factor}) \times \text{field}$
- Velocity mode:
  - $(E/V_z) = (\text{Geom.factor}) \times \text{field}$
- Eliminate (Geom.factor) × field
  - $F_z \times V_z = E \times I$
- Mechanical power = Electrical power
  - Hence, the '**Watt**' balance

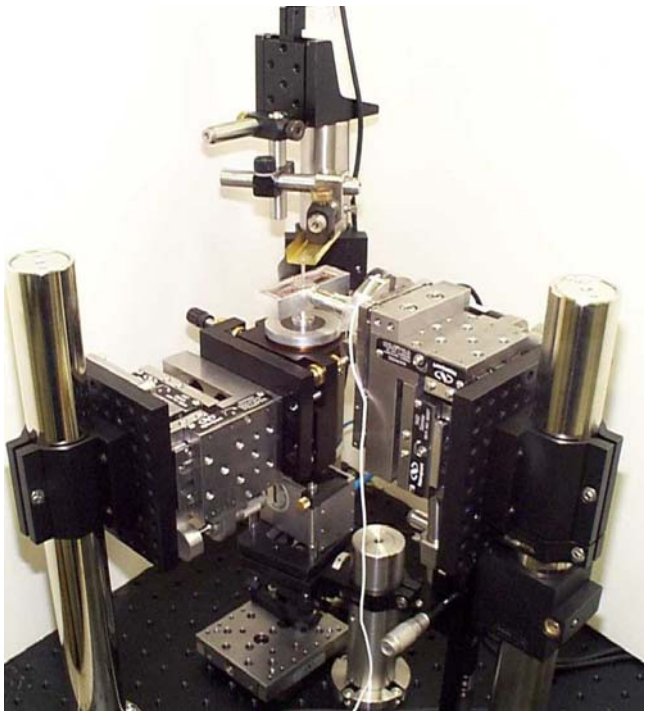


Ed Williams (NIST)

Microforce Realization and Measurement Project

5-year Director's Competence

Goal is to realize and disseminate SI-traceable force
at the μN and nN level



Champion:
Jon R. Pratt, MEL/822

Co-Investigators:
John Kramar, MEL/821
David Newell, EEEL/811
(Ed Williams, EEEL/811)
Douglas Smith, MSEL/852
Eric Whitenton, /MEL822
Shane Woody, SURF
Jonathan Mulholland, SURF

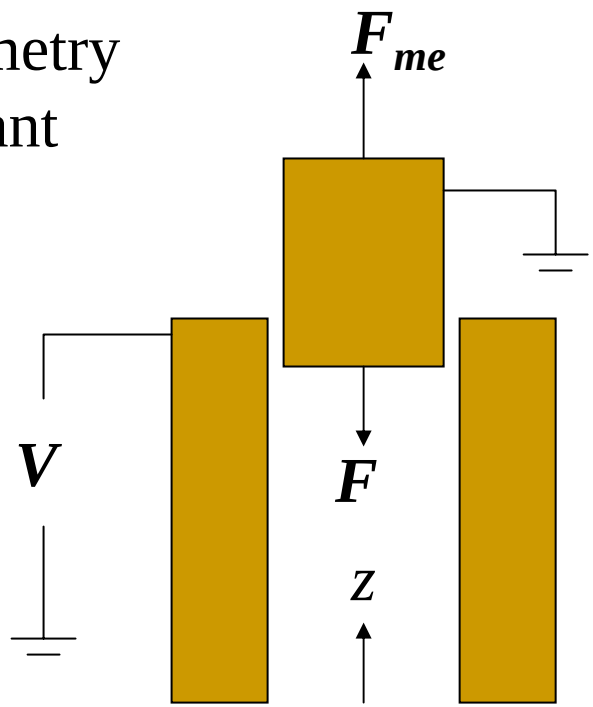
Force from electrostatic energy

Mechanical work required to change the geometry of a capacitor while holding its voltage constant

$$dW = F_{me} dz = -\frac{1}{2} V^2 (dC)$$

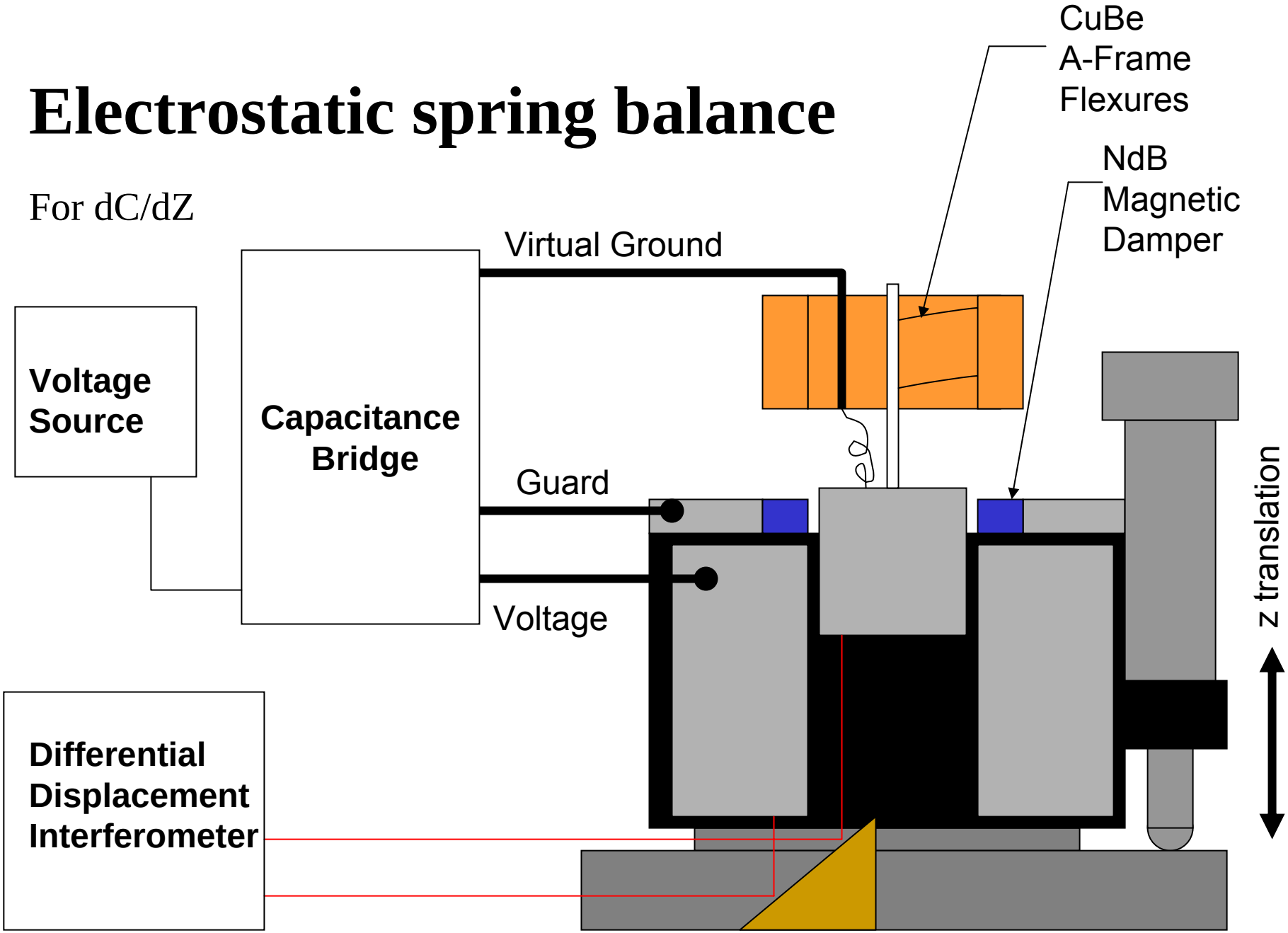
The force exerted by the fixed electrode on the moving electrode

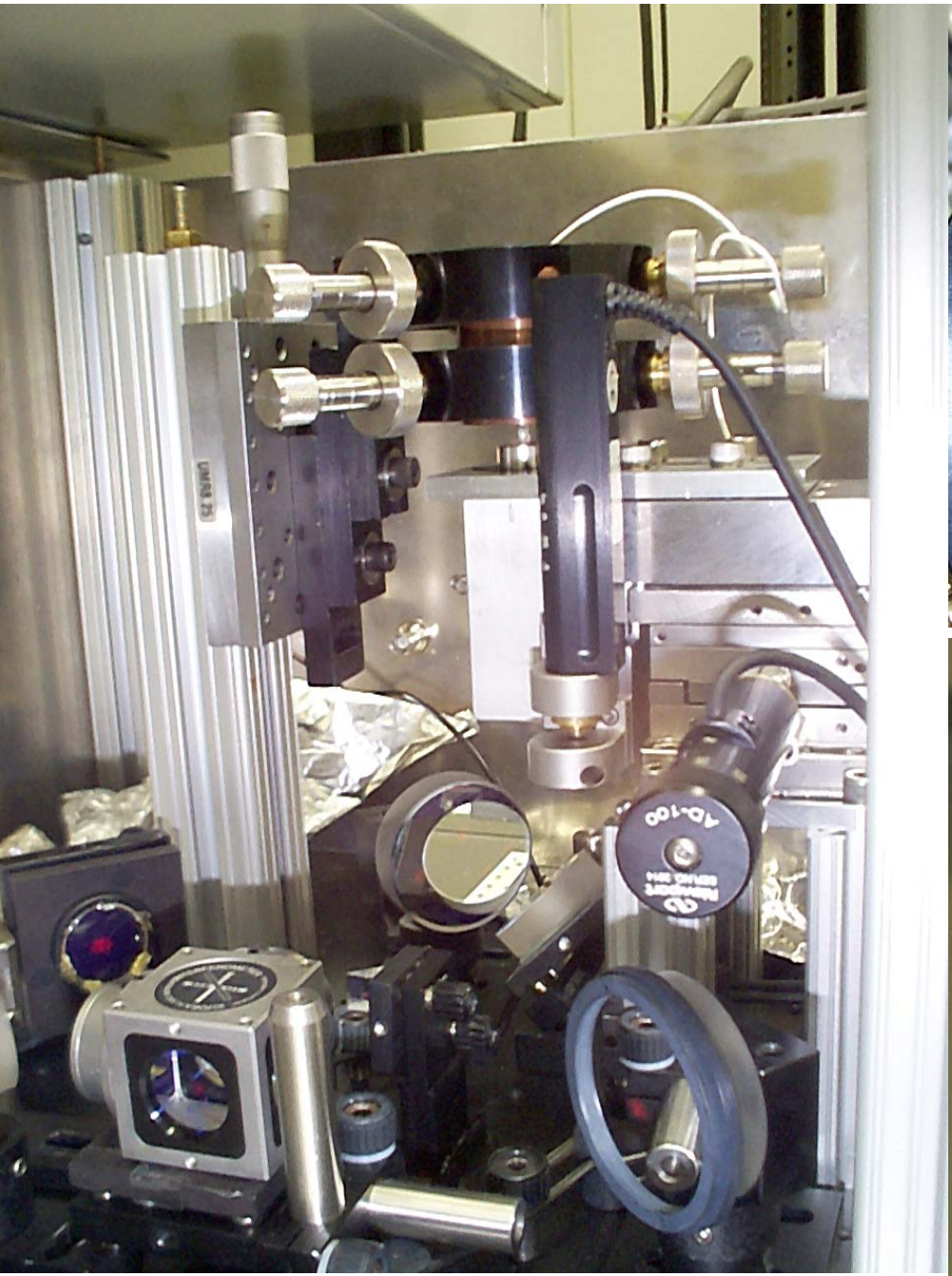
$$F = -F_{me} = \frac{1}{2} V^2 \frac{dC}{dz}$$

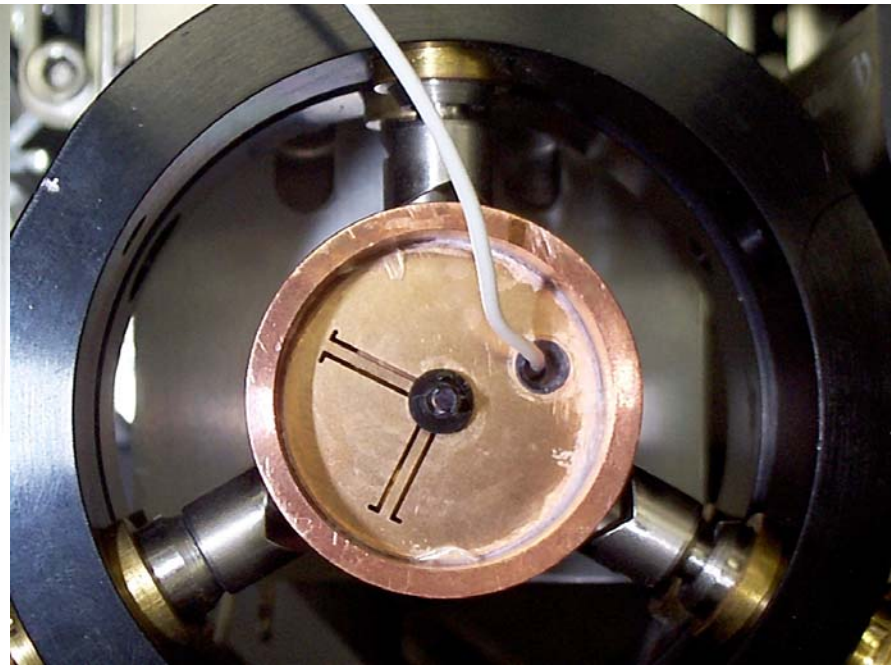


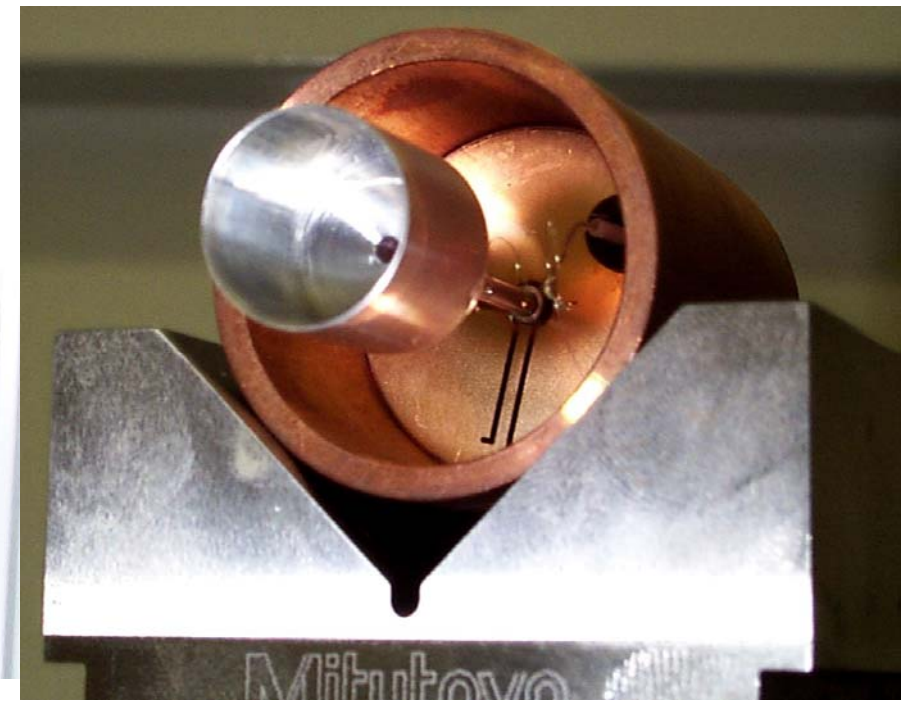
Electrostatic spring balance

For dC/dZ



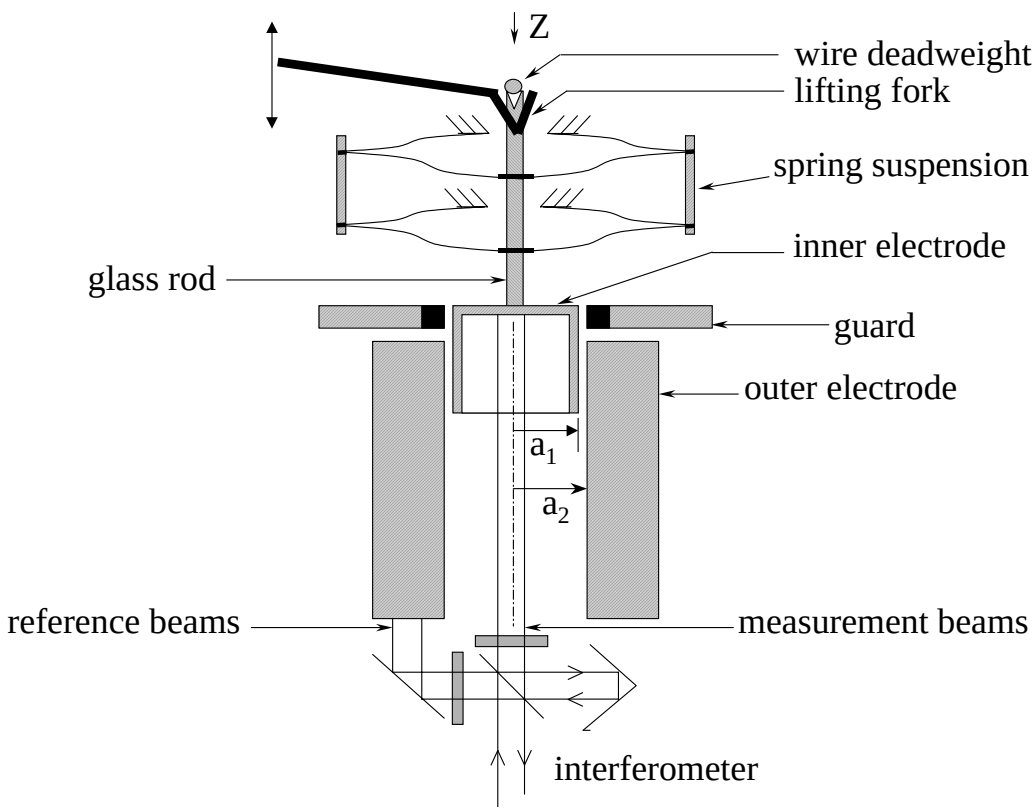

AD-100

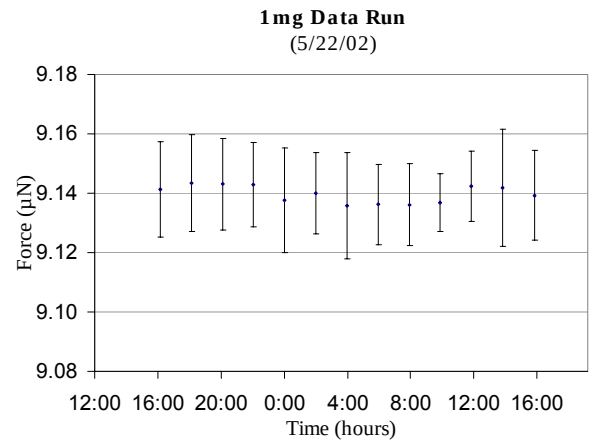


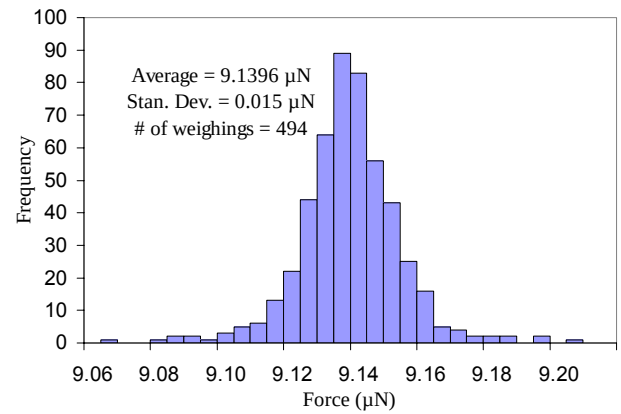

Mitutoyo

An accurate SI electrostatic force

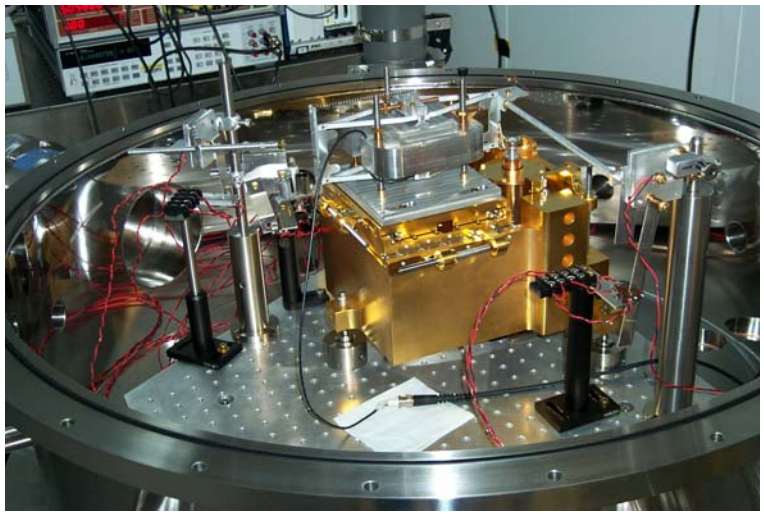
- Prototype EFB #1 achieves comparison of electronic and gravitational force at parts in 10^4

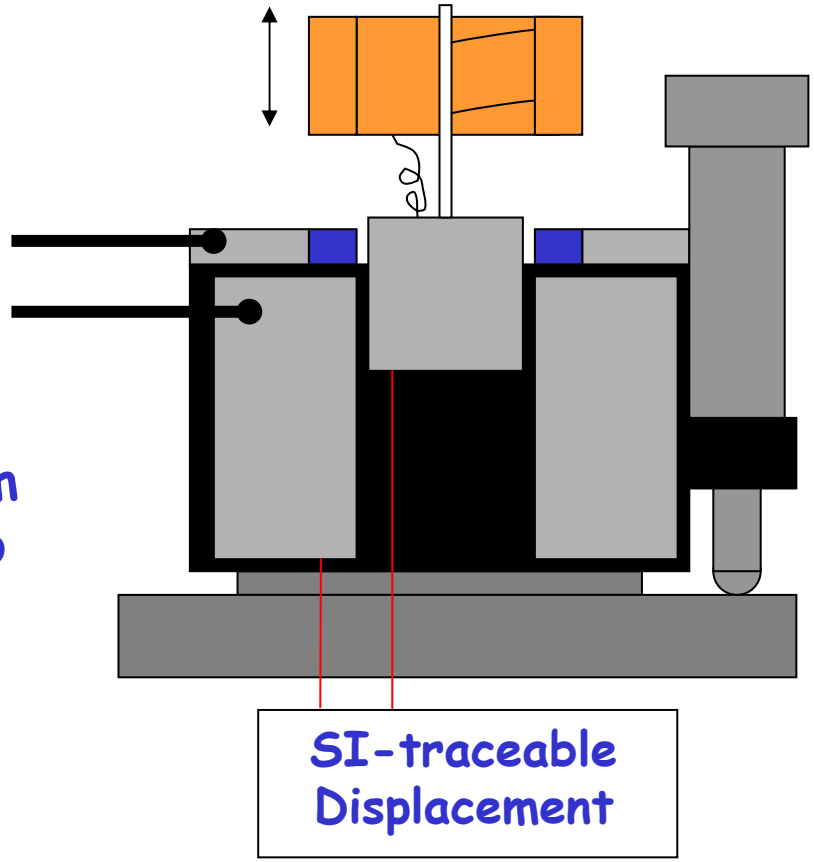






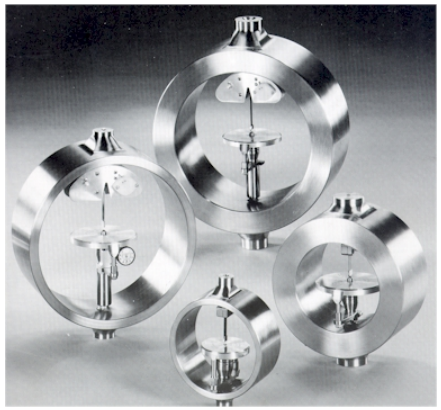
Existing Electrostatic Force Balance (EFB#2)



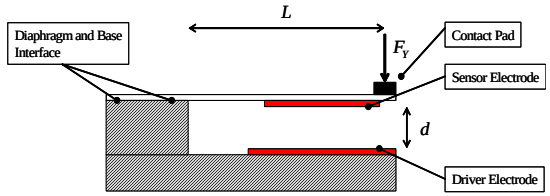


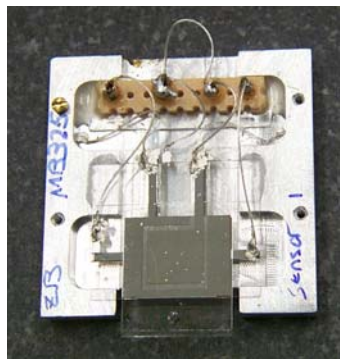
SI-traceable force derived from electrostatic force between two concentric cylinders.

Dissemination



Need simple, stable transfer devices

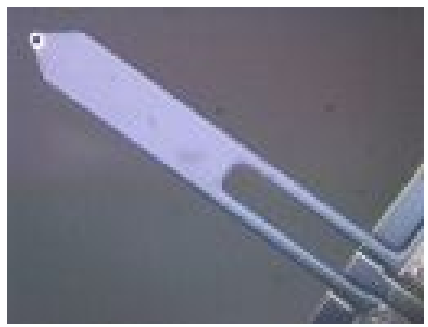




- Capacitance based micro loadcells

  D.T. Smith, S.C. Woody, and J.R. Pratt, “Compact Force Sensors for Low-Force Mechanical Probe Calibration”, *Proceedings of IMEKO*, Celle, Germany, September 23-27, 2002, pp. 309-314.

- Commercial piezoresistive devices



Gradient Reference Specimens for Advanced Scanned Probe Microscopy

Goal: Design, Prototype and Test Reference Specimens for *Next Generation* SPM Techniques

- **Mechanical and Adhesion Properties (w/ Donna Hurley, MSEL)**
  - Atomic Force Acoustic Microscopy (AFAM), colloidal AFM
- **Surface Chemistry, Chemical Properties (w/ Tinh Nguyen, BFRL)**
  - Chemical Force Microscopy (CFM), Phase, Friction AFM
- **Electro-optical and Magnetic Properties…**
  - NSOM, MFM, Scanning Capacitance

Combinatorial Design: Reference substrates that present a multitude of conditions on convenient a single substrate

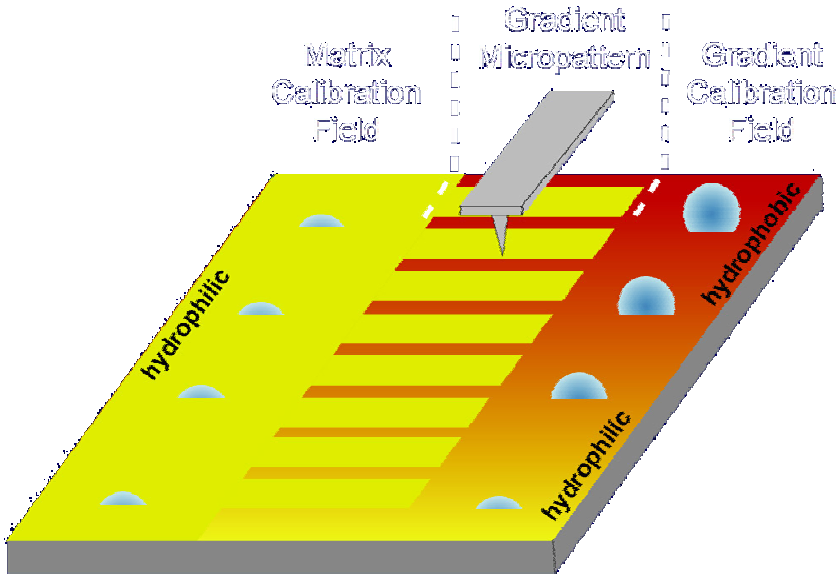
- **Contrast Calibration with respect to traditional measures**
- **Probe Characterization over a range of conditions**

M.J. Fasolka, D. Julthongpiput, E.J. Amis, Polymers Division
NIST Combinatorial Methods Center (NCMC) www.nist.gov/combi

Gradient Reference Specimen Example

For Measuring the Role of Surface Chemistry on AFM Image Contrast

A Hydrophobic ➔ Hydrophilic gradient micropattern with a constant matrix.



Micropattern chemical contrast calibrated with e.g. FTIR, contact angle, XPS…

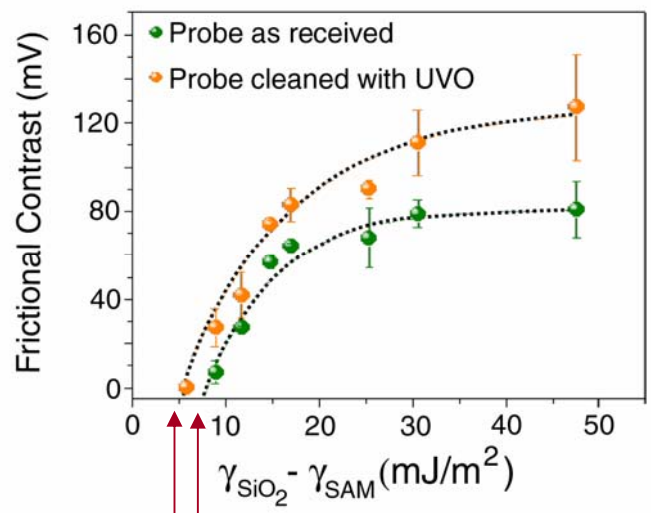
SPM images along micropattern thus related to traditional measures

- Contrast Calibration
- Sensitivity and Probe Characterization

Friction AFM Contrast

$\gamma_{SiO2} - \gamma_{SAM}$

Chemical contrast – surface energy (γ)



Probe sensitivity

Nanomechanics Metrology through Integrated Measurement and Computer Modeling

Doug Smith, Lyle Levine – MSEL

Jon Pratt, John Kramar – MEL

Anne Chaka – CSTL

Mission Statement

We seek to greatly accelerate material and device design by providing experimentally validated modeling tools with quantifiable uncertainties.

Industrial Drivers and Obstacles for Design

Drivers:

- Minimize time and cost of product development.
- Design components close to operational limits (for efficiency, cost and speed).

Obstacles:

- Lack of insight into mechanisms and factors that govern performance. Very difficult to do experiments in this regime.
- Can't measure behavior and limits for everything – modeling required. No experimental data available for novel materials and designs.
- Lack of suitable quantitative, experimentally validated, modeling tools.

Goals

I. Develop best-in-the-world capabilities in nanoscale force-displacement measurement to provide:

- Metrology infrastructure for calibration of all commercial nanomechanical test equipment.

II. Develop validated, predictive modeling methods and data to:

- Delineate the material and application-specific essential physics and provide benchmarks for developers of atomic potentials.
- Enable quantitative error estimates for simulations used by industry to predict material properties, and device behavior and operational limits.

National Nanotechnology Initiative Grand Challenge Workshop:

Instrumentation and Metrology for Nanotechnology

NIST, January 27-29, 2004

Five Tracks, including **Instrumentation and Metrology for Nanomechanics**

Participation 1/3 each: Industry, Academia, National Labs

Discussion generated "need categories," which evolved into

Six Grand Challenges (in priority order):

- **Standardization and Calibration**
- **Modeling of Nanomechanical Experiments**
- **Integration of Multiple Techniques in Nanomechanics**
- **Instrument Development for Nanomechanics**
- High Throughput Automated Nanomechanics Measurement
- Experimenting/Testing under Real Application Conditions

We directly address the four highest priority challenges.

NSF-Sponsored Multi-Agency Study: Industrial Applications of Molecular and Materials Modeling

- Detailed reports on 91 institutions (75+ companies)
- Additional data from 55 US companies who have used molecular/materials modeling, 256 world-wide institutions

Good News: When modeling is mature, it is regarded as a requirement to stay in business

Conclusion for Materials Modeling in NSF Report

"….One of the major drawbacks of U.S. funding methods is that there is no concerted effort to develop interaction potentials for materials simulations. This is not considered an exciting area of research. However, *without high-quality interaction potentials, it is not possible to carry out realistic materials simulations….*"

The Problem in Materials Design

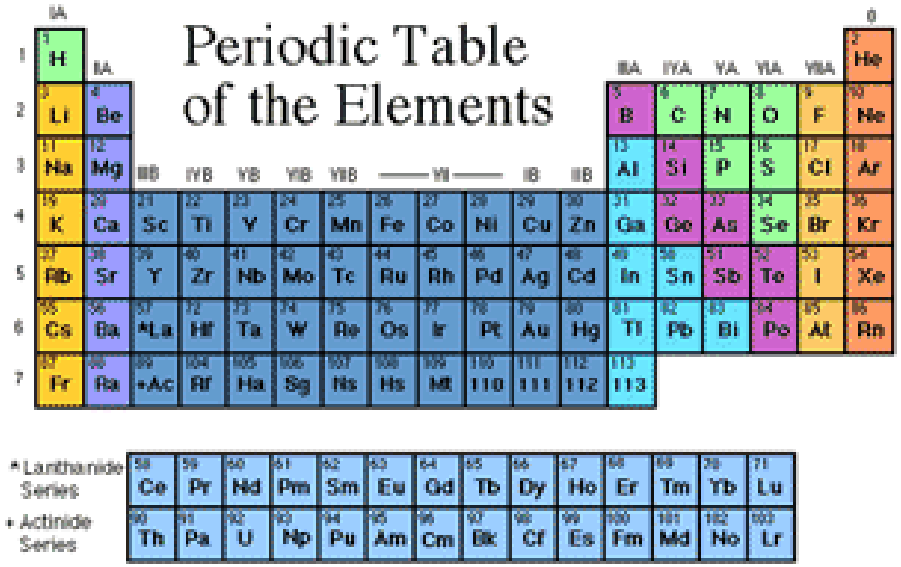
If we are interested in perhaps 50 elements on the periodic table, there are:

2,500 binary combinations, 125,000 ternary combinations, etc. . . .

How to vary concentration and distribution? Materials with identical chemical compositions can have totally different mechanical properties, depending upon processing and dimensions (nano vs. macro)

The ever-increasing pace of science and technology has already outstripped our ability to produce needed data.

Screening classes of materials prior to a synthesis and testing cycle is essential.



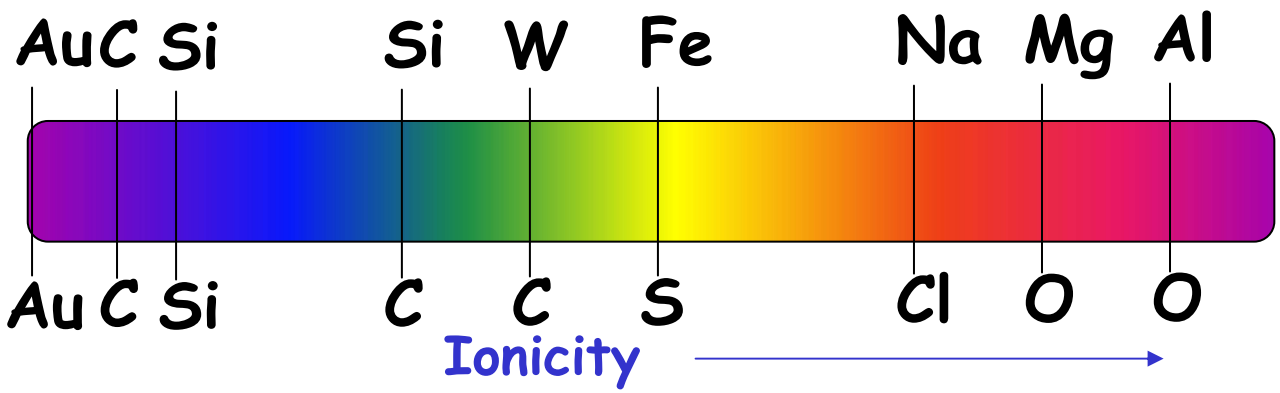
We can't measure everything

We can't calculate everything either…

Aim:

Develop a synergy between experiment, theory, and modeling to delineate the essential physics and develop a rational strategic approach to design.

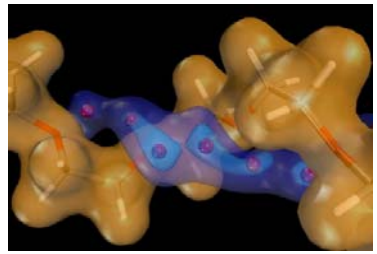
Example:
AB Charge Transfer (EA/IP)



Definitions

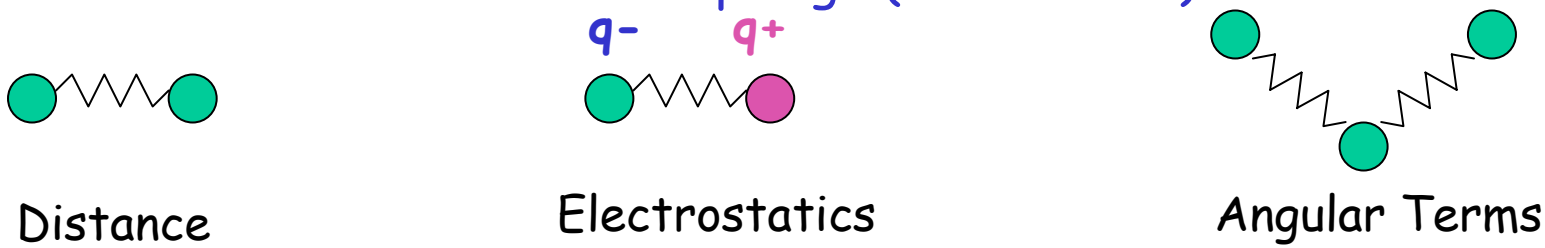
Quantum Mechanics (Electronic Density Functional Theory - DFT)

- No parameters
- Calculate total energy, potential, electronic structure, charge density, and forces *ab initio*



Classical potentials and dynamics simulations (Molecular Dynamics)

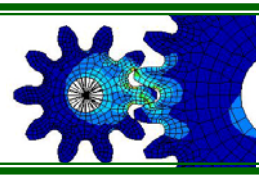
- Atoms modeled as balls and springs (Force field)



- Parameters from quantum mechanics and from experiment
- Dynamics from solving Newton's equations of motion

Continuum (Finite Element Modeling - FEM) :

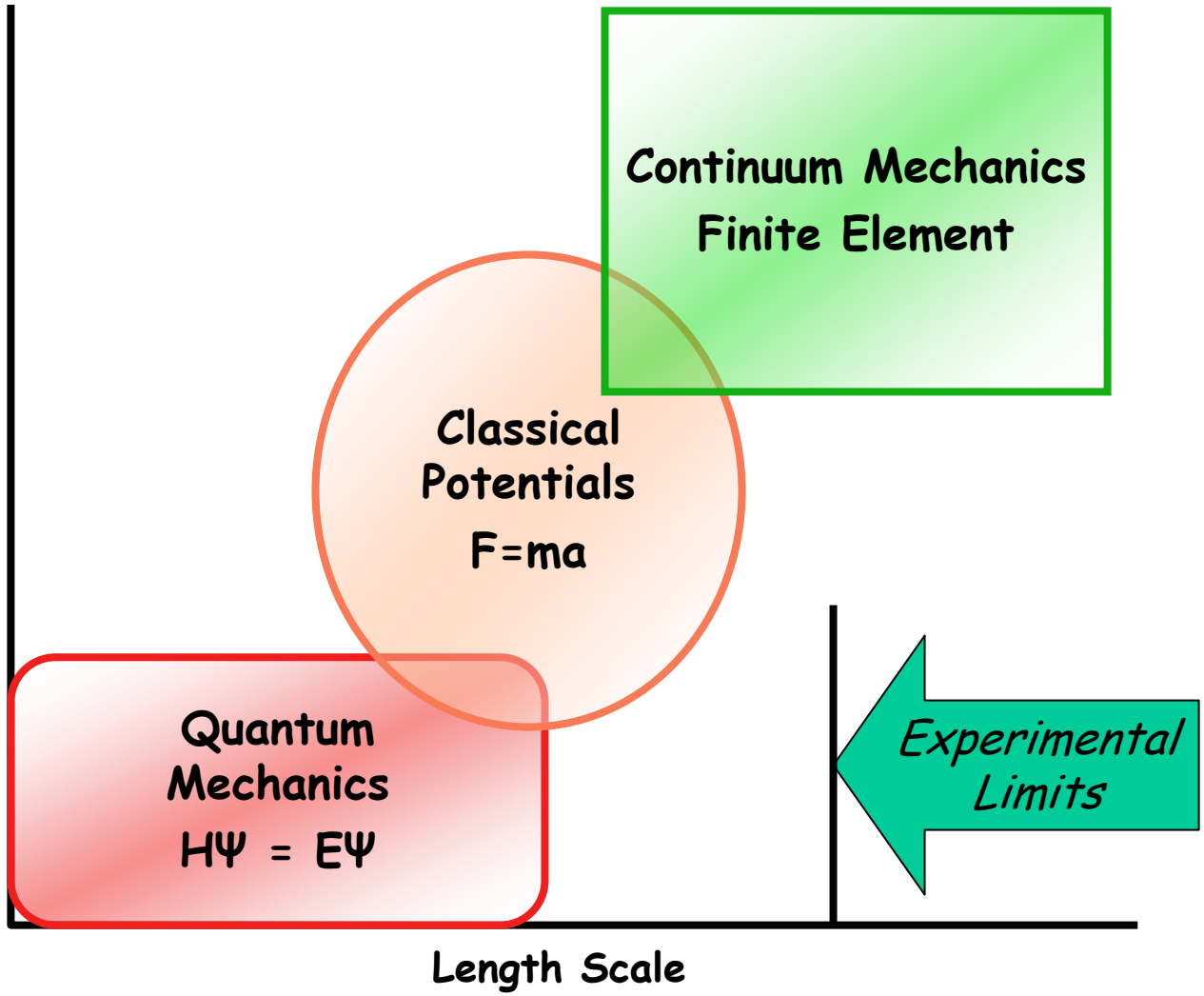
- Fit parameters to experiment for mechanical properties



Modeling: Current Strengths and Limitations

	Quantum Mechanics	Classical Atomistics	Continuum (FEM)
ADVANTAGES	• **Very accurate and predictive for any material** • No parameters • Describes chemistry, vacancies, bond breaking • ***Insight*** ➔ ***What if…?***	• **Millions - billions of atoms** • Very fast • Some chemistry (if parameters from QM) • Some medium range effects (if parameters from bulk properties)	• **Macroscopic devices with complex geometry** • Accurate for macroscopic properties within range of parameters • Long range effects
DISADVANTAGES	• **Hundreds of atoms** •Slow - $O(n^3)$ scaling • No long range effects	• **Fails for large strains and chemical processes** • Parameterization tedious • Potentials not transferable to other compositions or properties	• **No inherent failure criteria** •No chemistry • No reactivity

Challenge: Bridging the Gaps



Usefulness of data depends upon the uncertainty

Calculations and Measurements are the Product of Many Uncertainties

Reference Measurement
First Principles Calculation → Functional Forms and Parameters for Models

Sensitivity and error analyses will determine the impact of parameters on accuracy of predictions

For each model:

Quantum

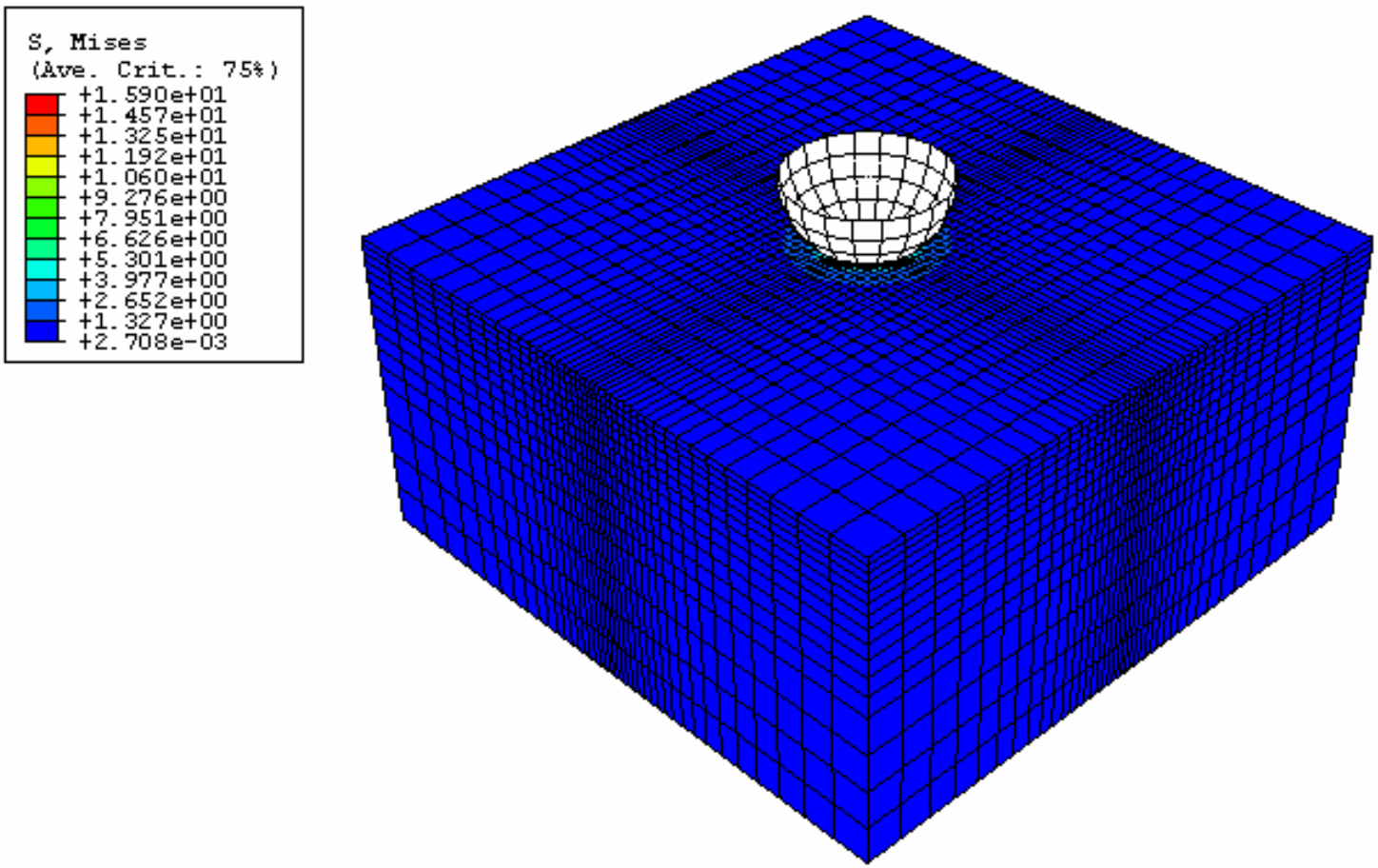
↓

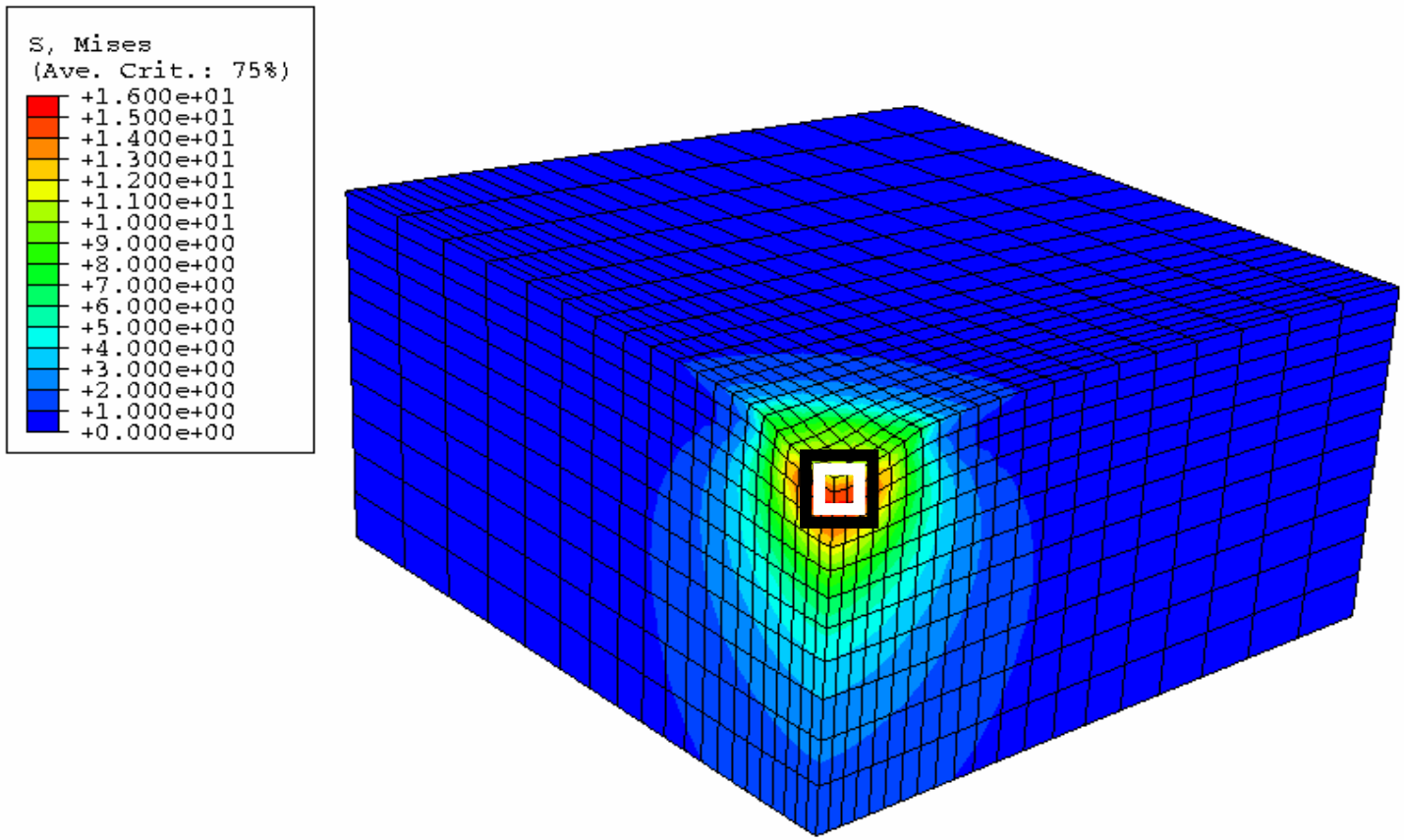
Macroscopic

Assumptions, advantages, limitations, applicability, cost, data quality required for validation?

Indentation simulation using FEM

FEM simulation of rigid, 100 nm diameter sphere indenting an aluminum sample




S, Mises
(Ave. Crit.: 75%)
+1.600e+01
+1.500e+01
+1.400e+01
+1.300e+01
+1.200e+01
+1.100e+01
+1.000e+01
+9.000e+00
+8.000e+00
+7.000e+00
+6.000e+00
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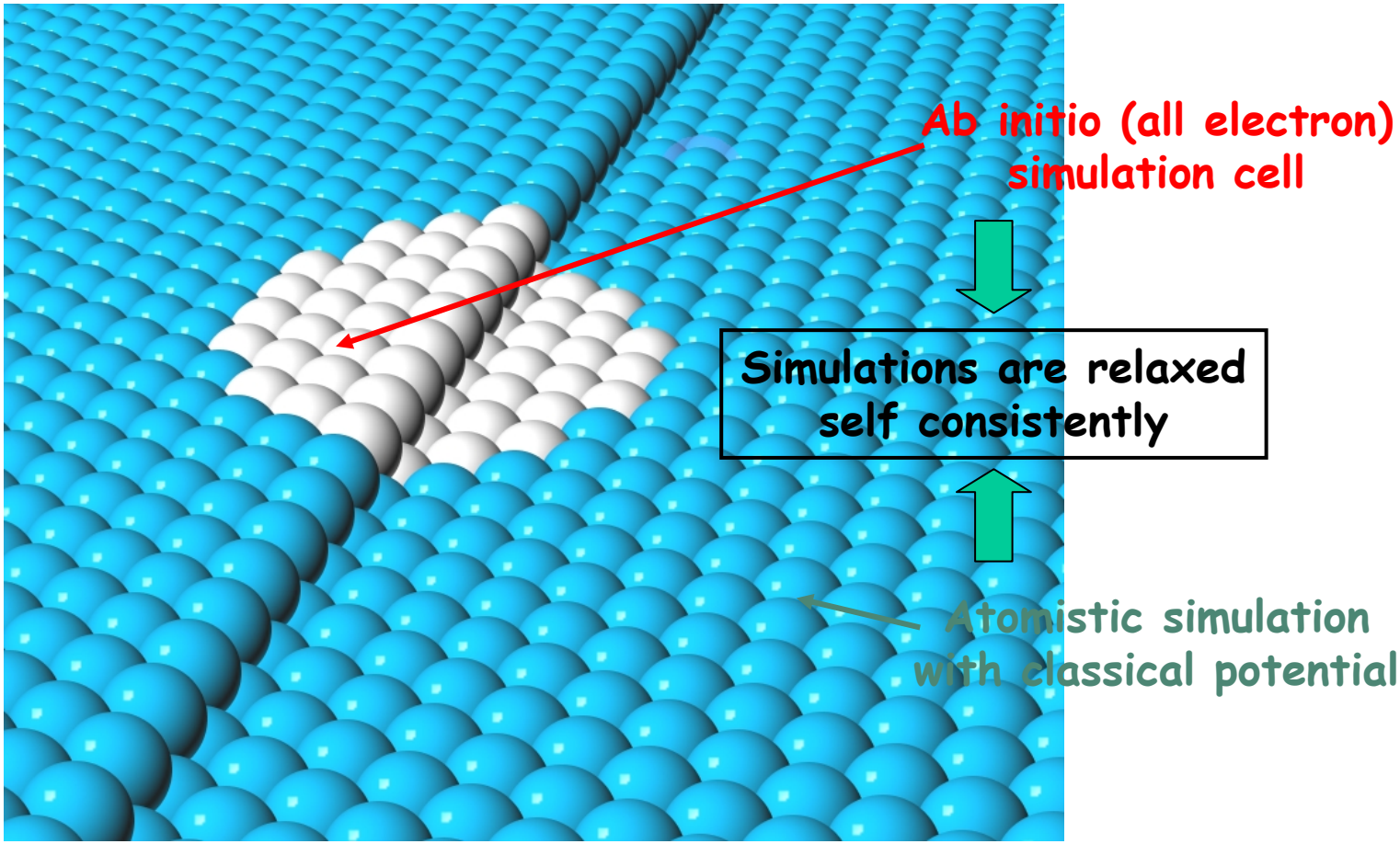
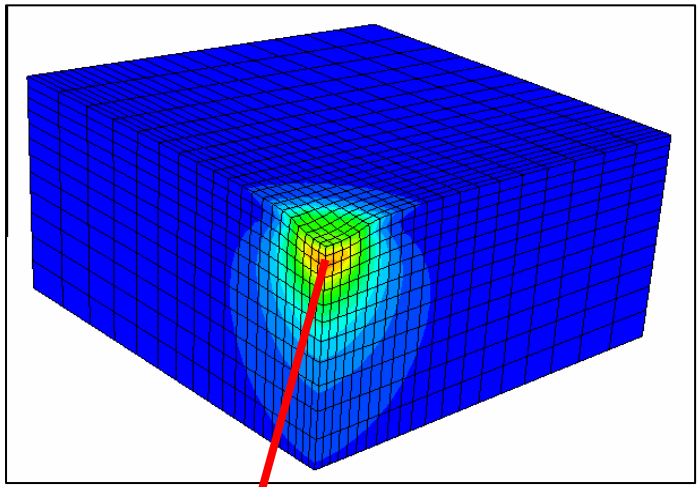
+1.000e+00
+0.000e+00

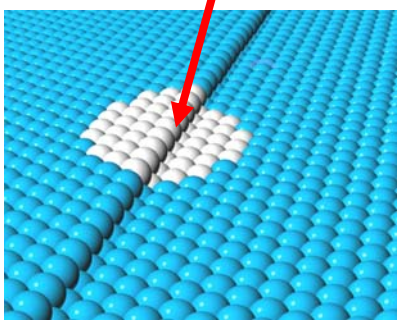


First *ab initio*/classical simulation: Tavazza, Chaka and Levine (2004)

Simulations are Quasi Static

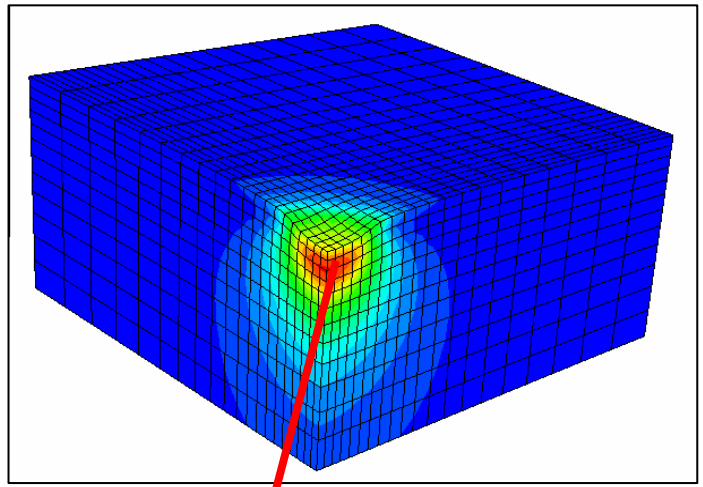
First applied force level

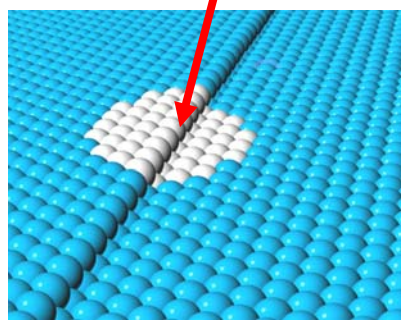




Did a bond break?

Second applied force level

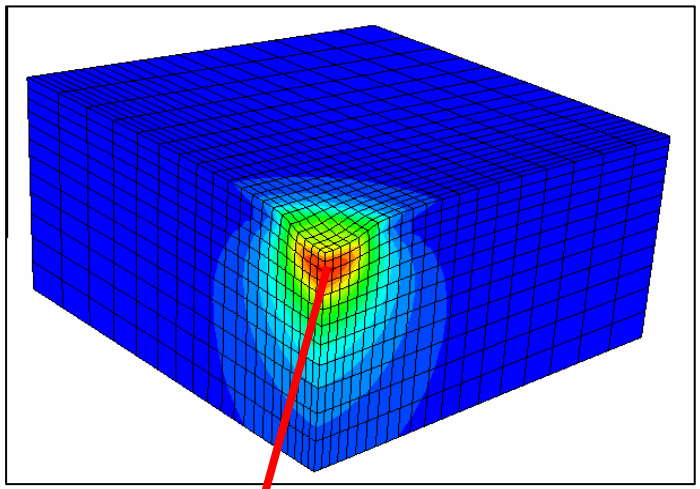


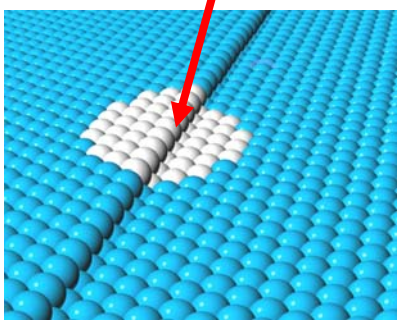


Did a bond break?

Standard Reference Simulation (SRS)

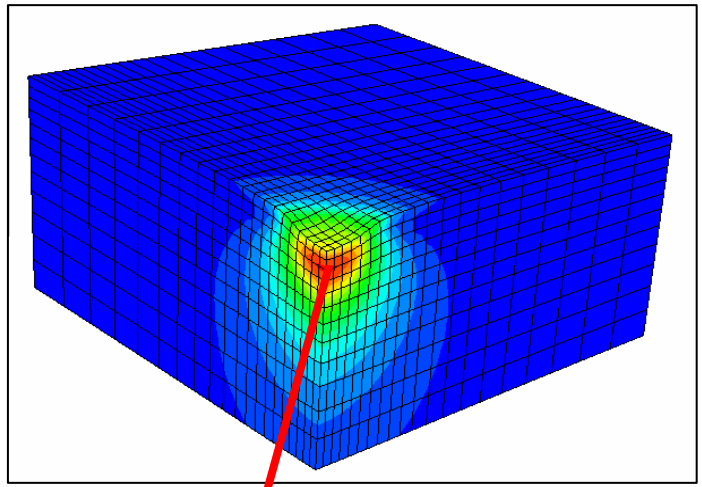
Validated Hybrid Model



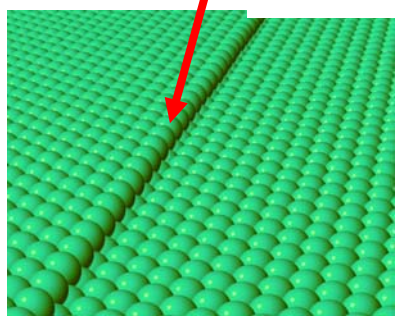


Did a bond break?

Validated Boundary Conditions

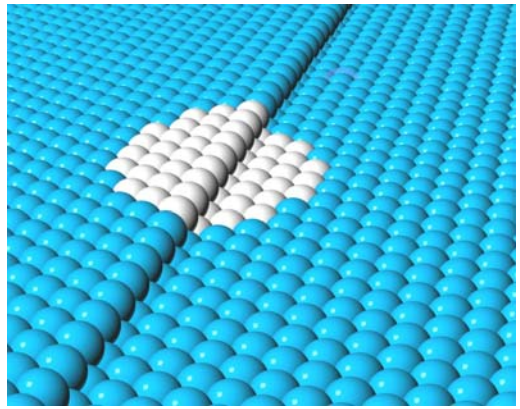


Potential / Technique to Test



Did a bond break?

Experimental Challenge:



UHV for clean surfaces and probes

Surface and probe imaging

Atoms are 0.1 nm – displacement resolution must be better ➔ 10 pm

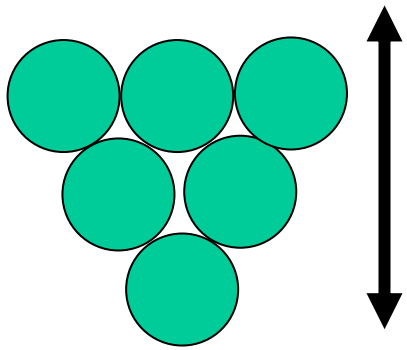
Atomic bond strengths are 1 nN or less – would like 1% resolution ➔ 10 pN

High stability

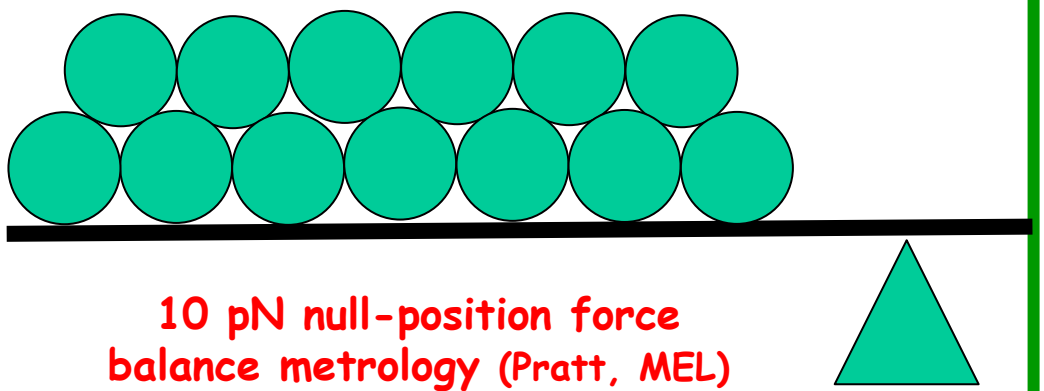
High dynamic range – looking for F-d "hiccups"

Primary Force Experiment

- **Goal:** Direct measurement of the force between a probe and a surface as a function of separation or contact force.
- Investigate macroscopic, microscopic, and nanoscopic probe geometries to move from surface forces to true interatomic forces
- Variety of materials and bonding: metallic, ionic, covalent. Interfaces.
- SI traceability – so that you can believe the numbers!



10 pm interferometric displacement metrology (Kramar, MEL)



10 pN null-position force balance metrology (Pratt, MEL)

NIST Experimental Background

High-resolution dimensional metrology:

- Lawall and Kessler, 2000, "Michelson interferometry with 10 pm accuracy", *Rev Sci Inst* **71**:7, p. 2669. (Atomic Displacement Metrology Competence).
- Silver et al, 2004, "Atomic-resolution measurements with a new tunable diode-based interferometer", *Optical Engineering* **43**:1 p.79.

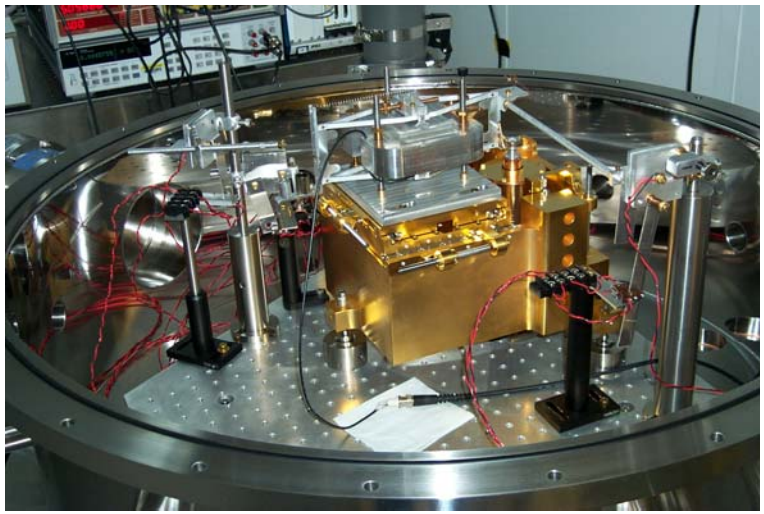
Characterization of tips:

- Villarrubia, 1994, "Morphological estimation of tip geometry for scanned probe microscopy," *Surf. Sci.* **321**, p. 287

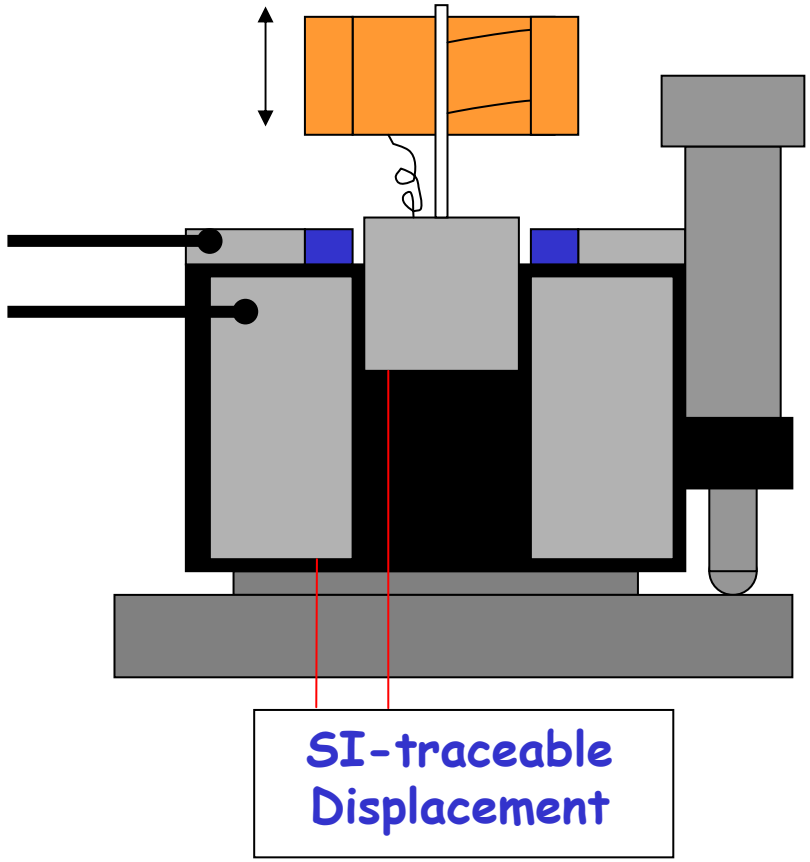
SI traceable small force:

- Pratt et al, 2004, " Progress towards Systeme International d'Unites traceable force metrology for nanomechanics", *J. Mater. Res.* **19**:1, p. 379. (Microforce Realization and Measurement Competence – EFB)

Existing Electrostatic Force Balance (EFB)



SI-traceable force derived from electrostatic force between two concentric cylinders.



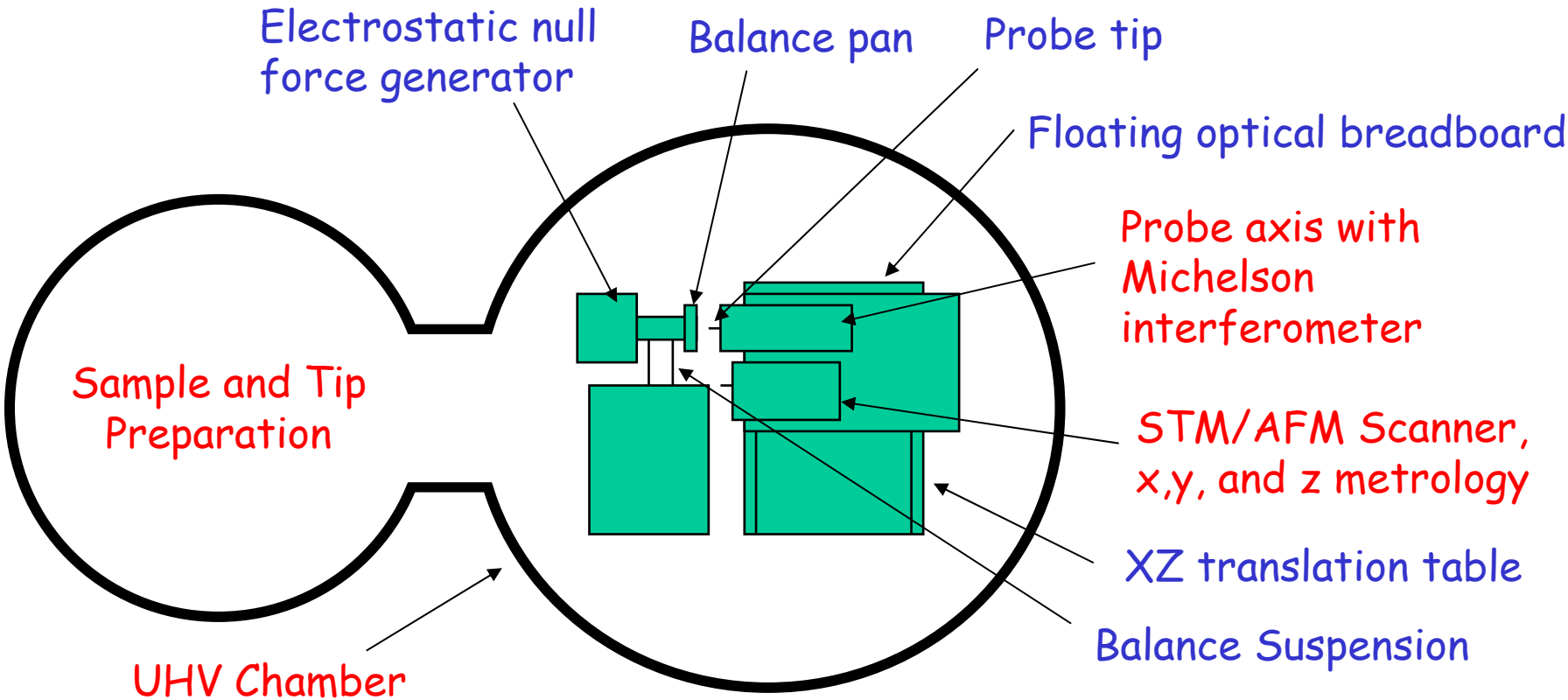
Available part time, gets us started quickly, but:

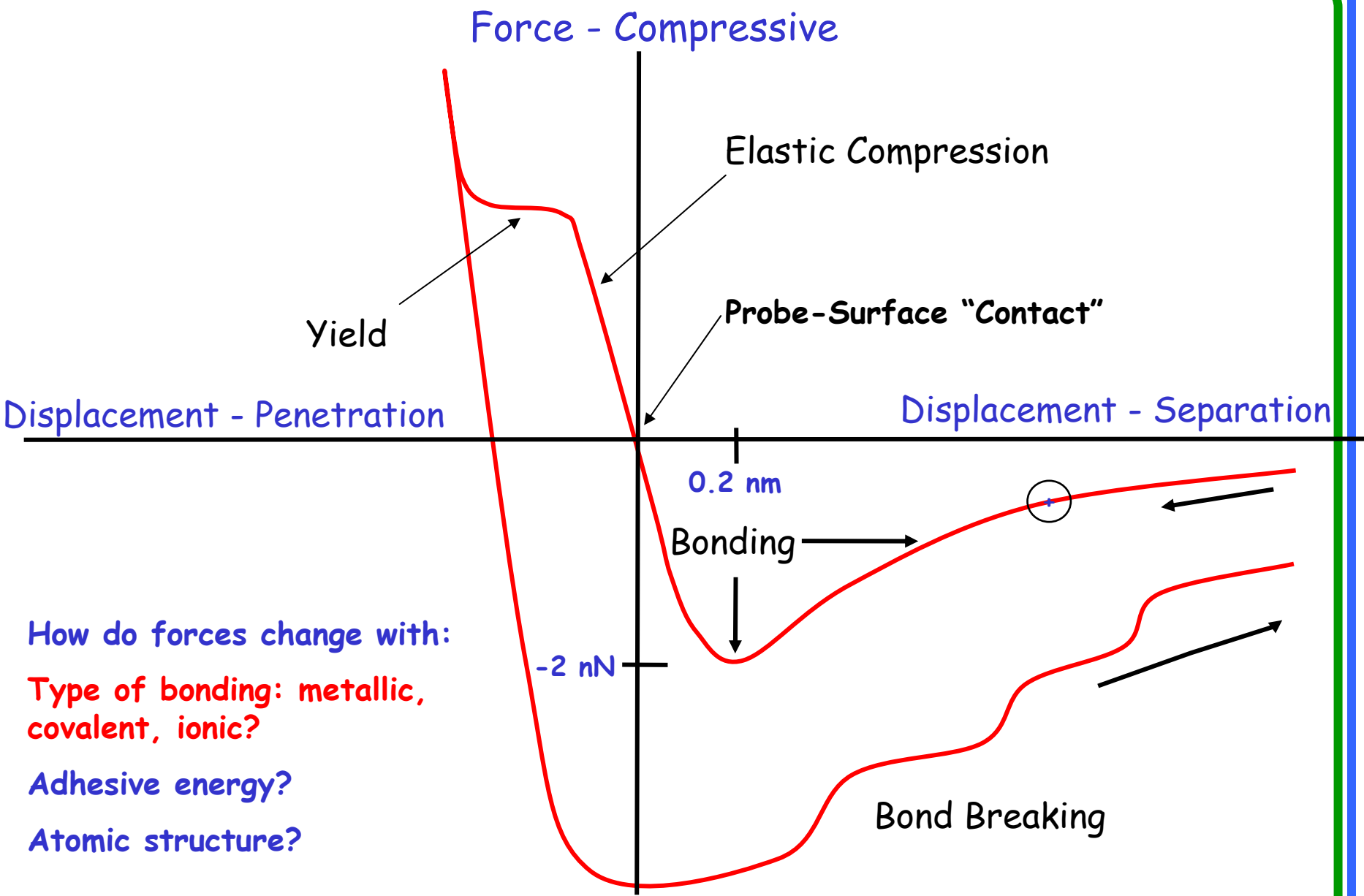
- Other role – the international standard for low force
- No UHV
- No imaging, tip characterization
- Inadequate F, d resolution

Needed: Next Generation Nanomechanics Instrument

"EPPICS" Electrostatic PicoNewton Picometer Calibration System

UHV instrumented contact probe machine of unprecedented absolute accuracy and resolution





How do forces change with:

Type of bonding: metallic, covalent, ionic?

Adhesive energy?

Atomic structure?

Nanomechanics Metrology through Integrated Measurement and Computer Modeling

MSEL / MEL / CSTL