A new approach to materials design

Mechanical Properties of Materials under Extreme Environments

Julia R. Greer

But really it's the work of Andrew T. Jennings,
Ju-Young Kim, Dongchan Jang, Shelby Hutchens, and Mingyuan Huang

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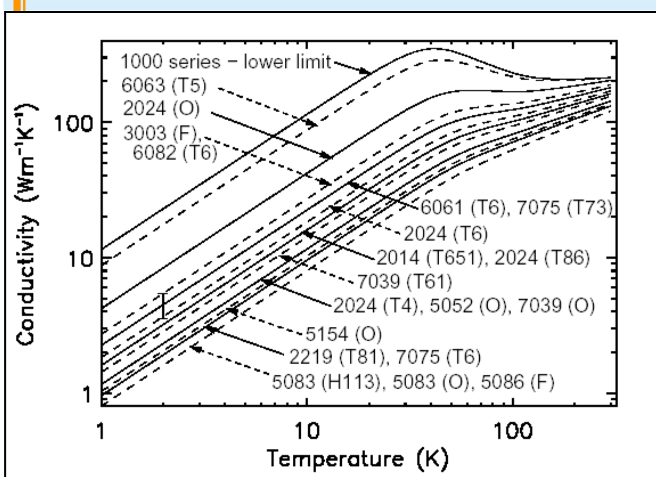
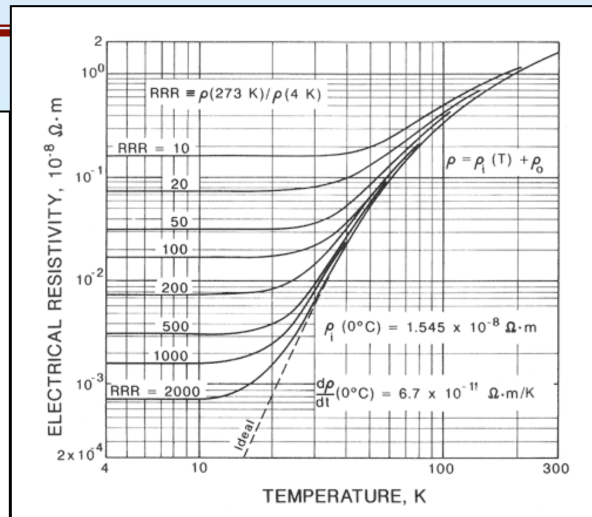
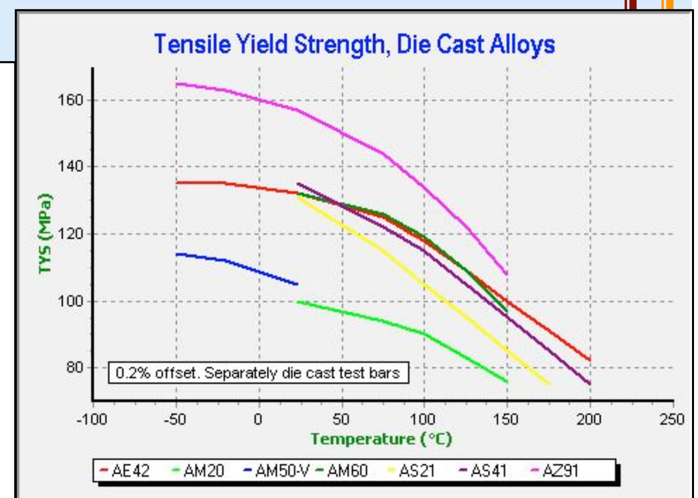
Why do materials matter for Titan?

- Material properties change significantly with temperature
- Variation can be very non linear
- Many materials are unsuitable for low temperature use
- Large amounts of contraction can occur at cryogenic temperatures.
- Successful design requires attention to property variation
- Extensive literature on low-temperature material properties
- **Important**: When it doubt - TEST







Some points to consider:

=> Impact on alignment => Development of interferences between dissimilar materials => Increased strain and possible failure => Impact on wiring

Conventional materials for low-T

Acceptable

- Austenitic stainless steels (304, 316, 321)
- Al alloys (6061, 6063, 1100)
- Cu (OFHC, ETP)
- Brass
- Fiber reinforced plastics (G –10, 11)
- Nb and Ti (used in superconducting RF systems)
- Invar (Ni /Fe alloy) (low α)
- In (used as an O ring material)
- Kapton and Mylar (insulation)
- Quartz (used in windows)

Unacceptable

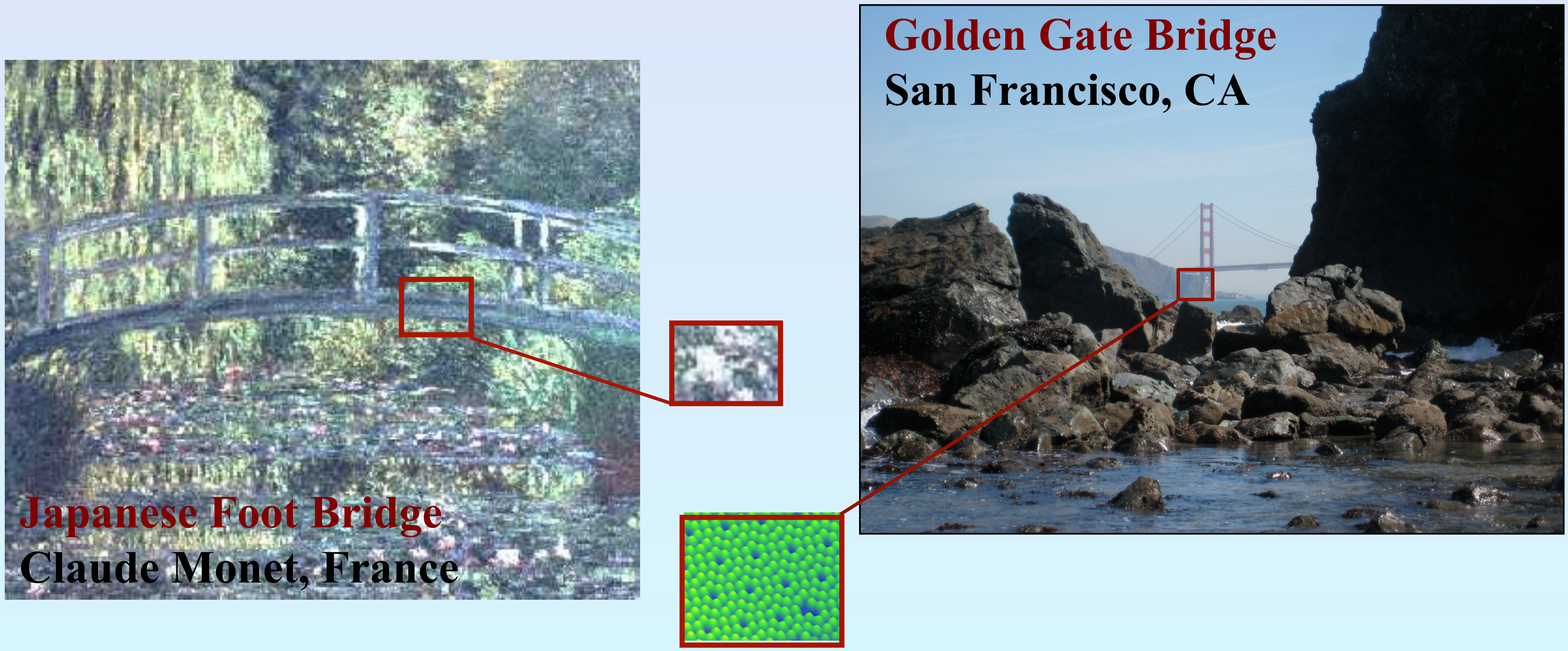
Martensitic stainless steels - Undergoes
ductile to brittle transition when cooled
down.
Carbon steels – also becomes brittle.
Rubber, Teflon and most plastics

Conventional bulk materials may pose limitations need to develop new paradigm of material design => META-MATERIALS

Materials and Length Scales

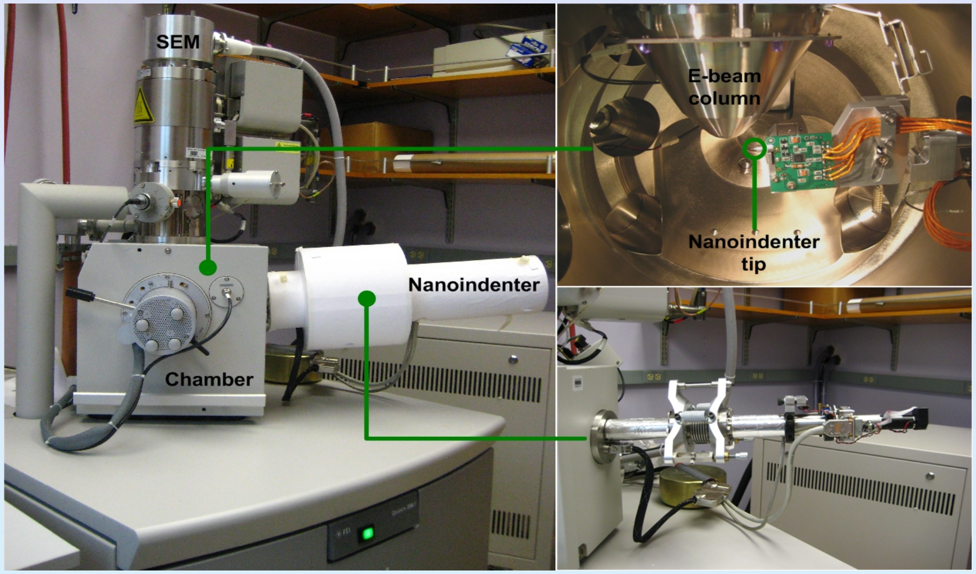
"We are leaving the age of reductionism and entering the age of emergence... "

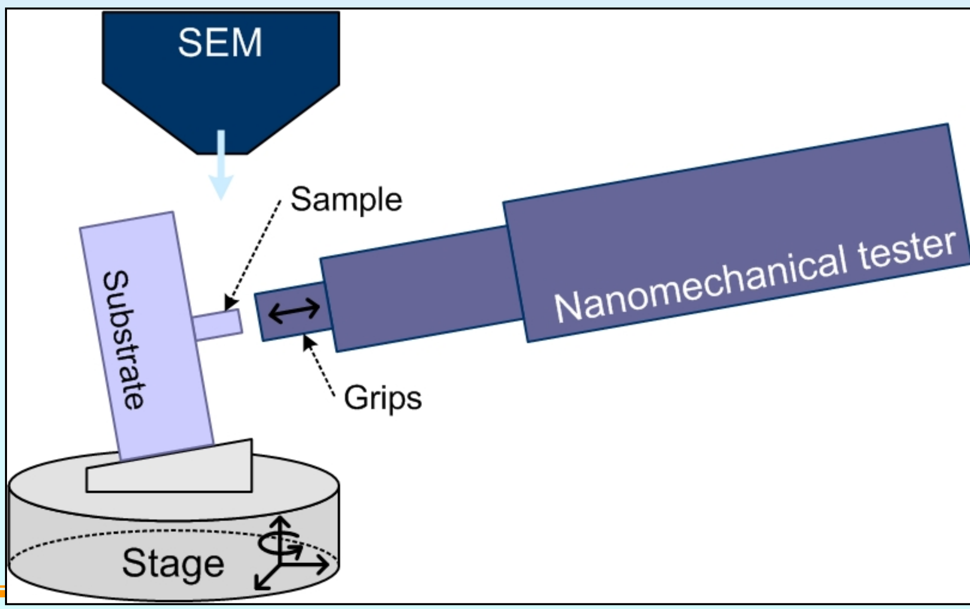
-from "A Different Universe" R. B. Laughlin (Nobel Laureate, Physics 2005)

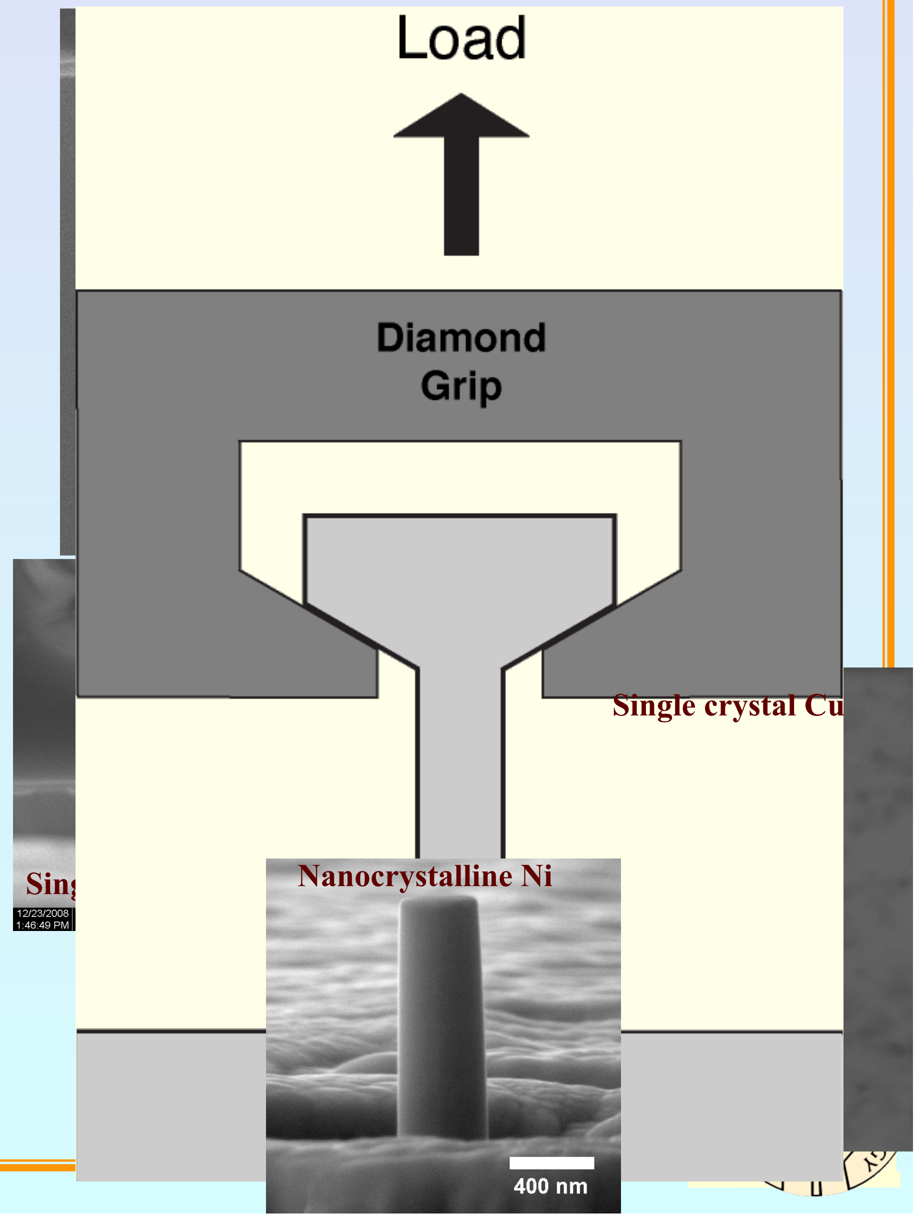


In nanocrystals (quantum dots, nanowires, nanotubes, etc.)
size modification tunes a variety of properties: optical, electronic, plasmonic, thermal, acoustic, etc. which
brings into question **material structural integrity**

In-situ tension and compression
SEMentor: SEM + Nanoindenter

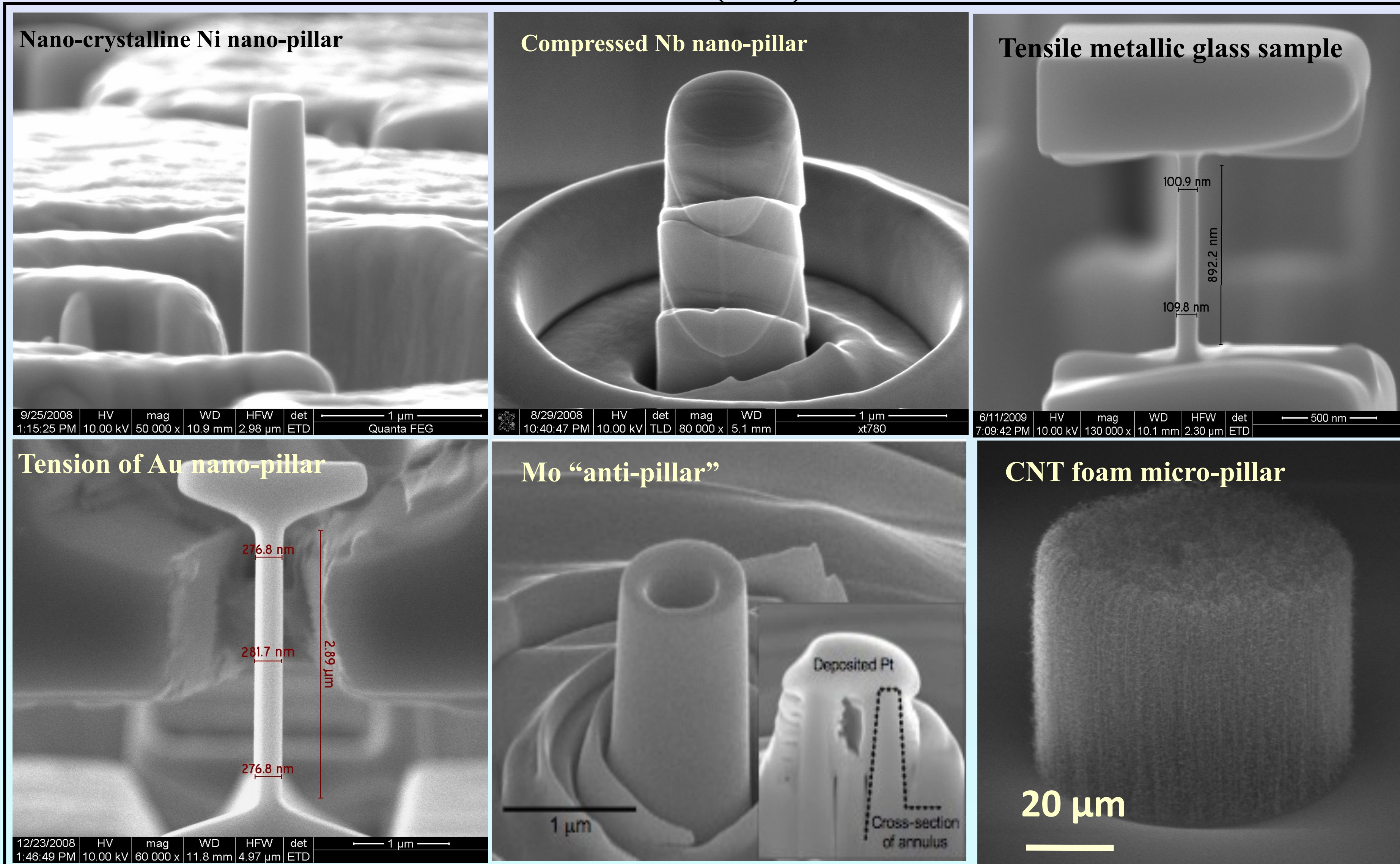






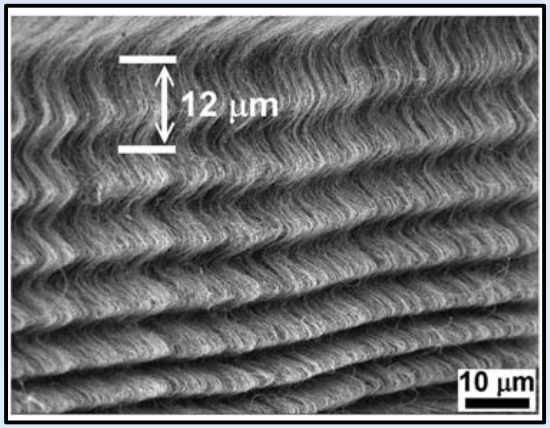
I. Fundamental Mechanical Properties of Materials:
Variety of materials, mainly metals…

Fabrication Method: Focused Ion Beam (FIB)



Protective Applications: Carbon Nanotube Foams

Energy Absorbing Protective Layers



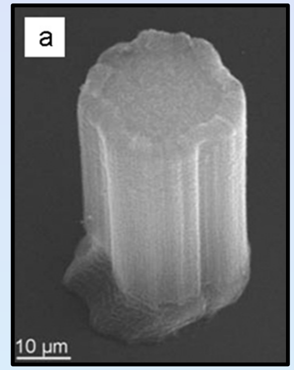
Cao, A., et al. *Science* (2005)
Pathak, S., et al. *Carbon* (2009)

CNT foam characteristics

=> CNTs appear vertically aligned at lower magnification

=> Individual tubes are intertwined at higher magnification

MEMS devices

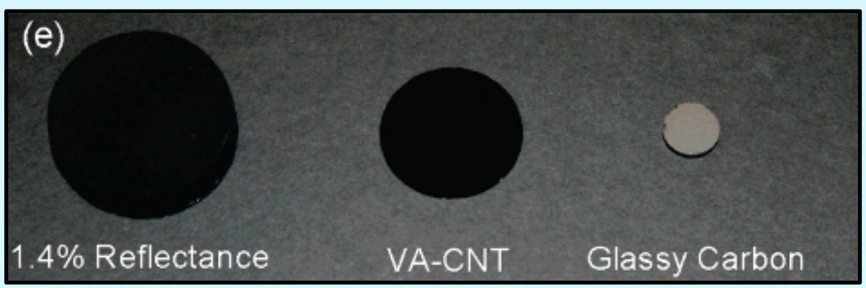


e.g. contact thermal switch materials

Cho, J., et al. *J Mcrmech Mcreng* (2008)

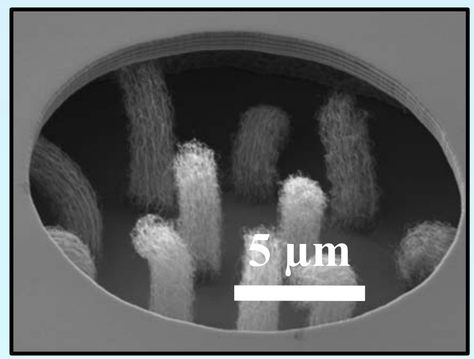
Light Absorbing Coatings

Darkest Man-Made Material, 0.045% reflectance



Yang, Z.-P., et al. Nano. Lett. (2008)

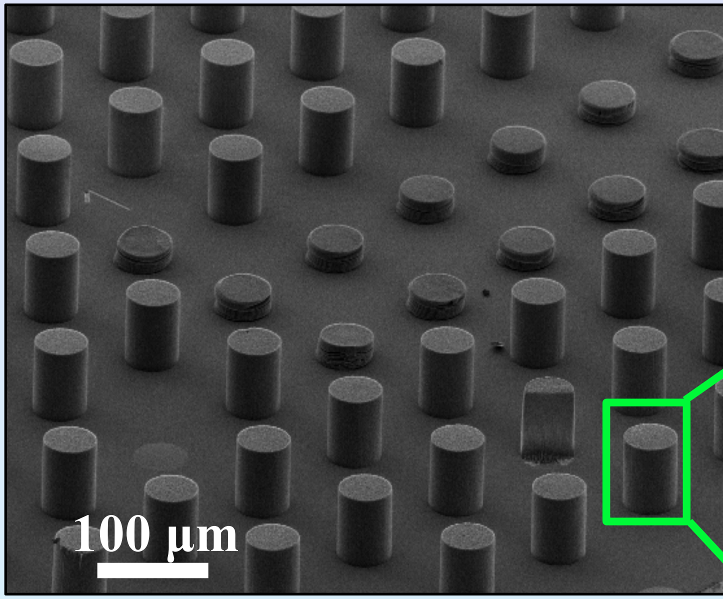
Low Vacuum Field Emission Sources



e.g. cold cathode array

Manohara, H. M., et al. J Infrared Milli TeraHz Waves (2009)

CNT Bundle Morphology



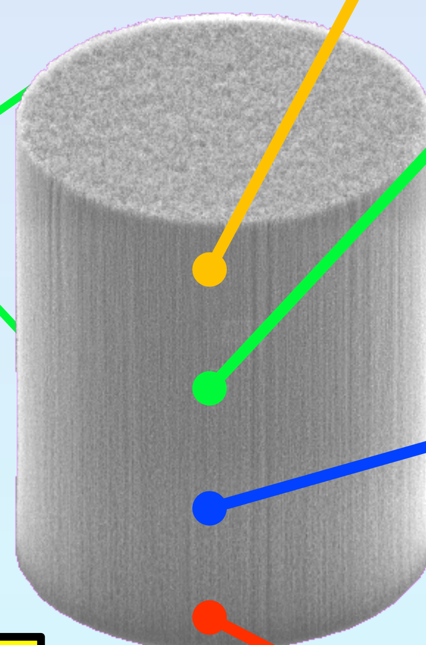
Growth Conditions:

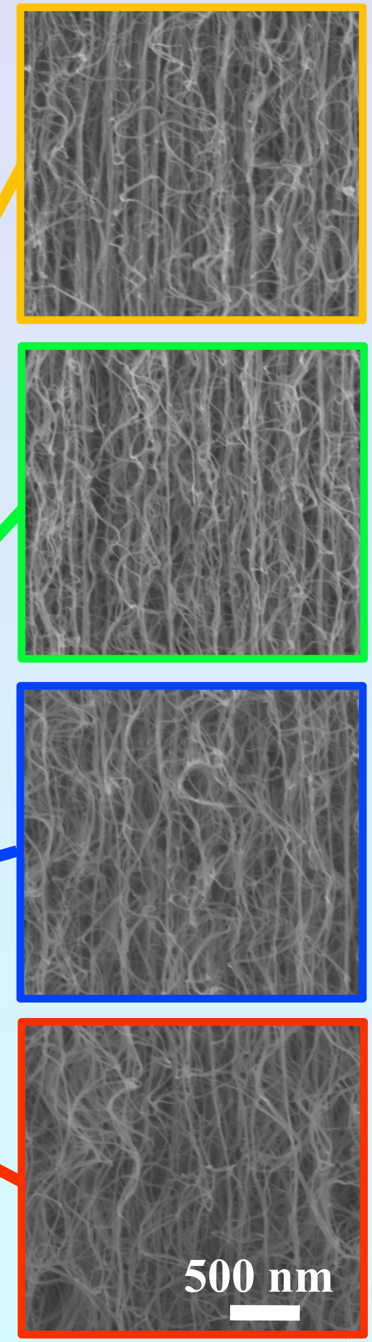
200 Torr 675 °C 15-20 min.

Precursor: Ethylene

Catalyst: Fe

Unambiguous calculation of macroscopic stresses and strains under uniaxial compression

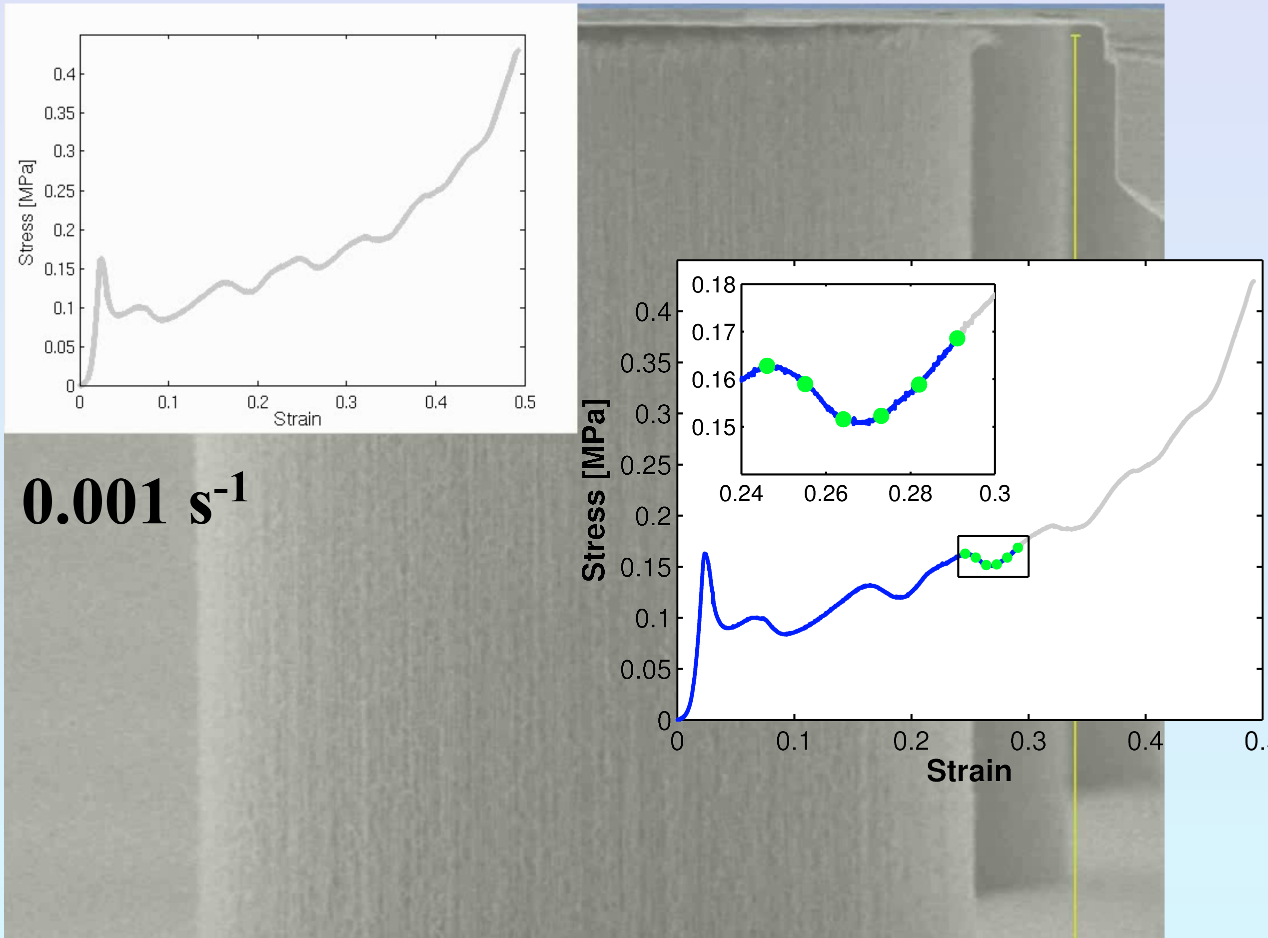


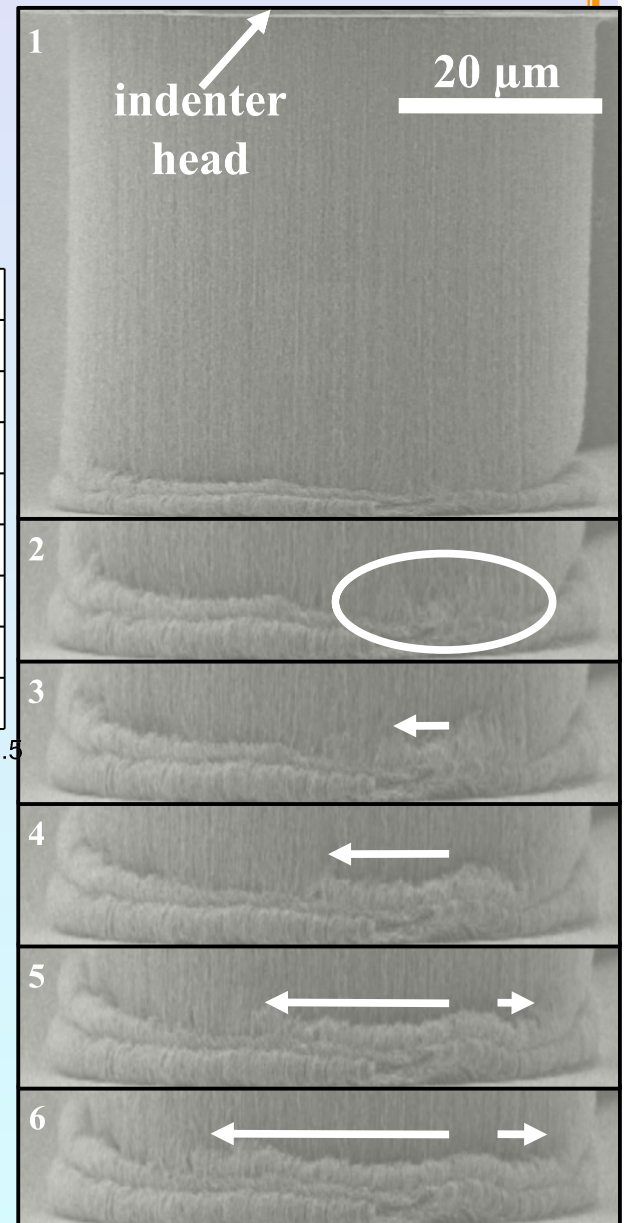


Increasing Density, Alignment, and Stiffness

CNT bundles grown by Lee Hall (JPL)

In situ Micro-Compression





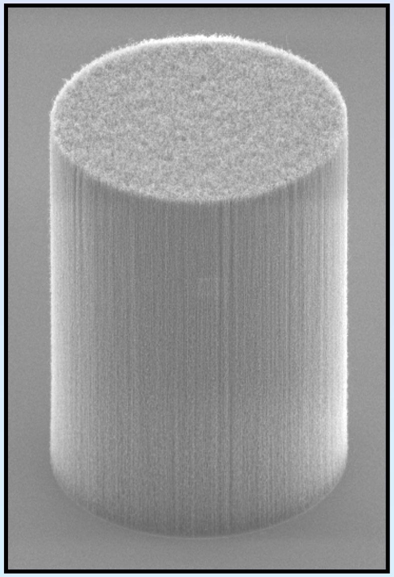
6 µm of undeformed pillar collapses to approximately 2 µm of buckle

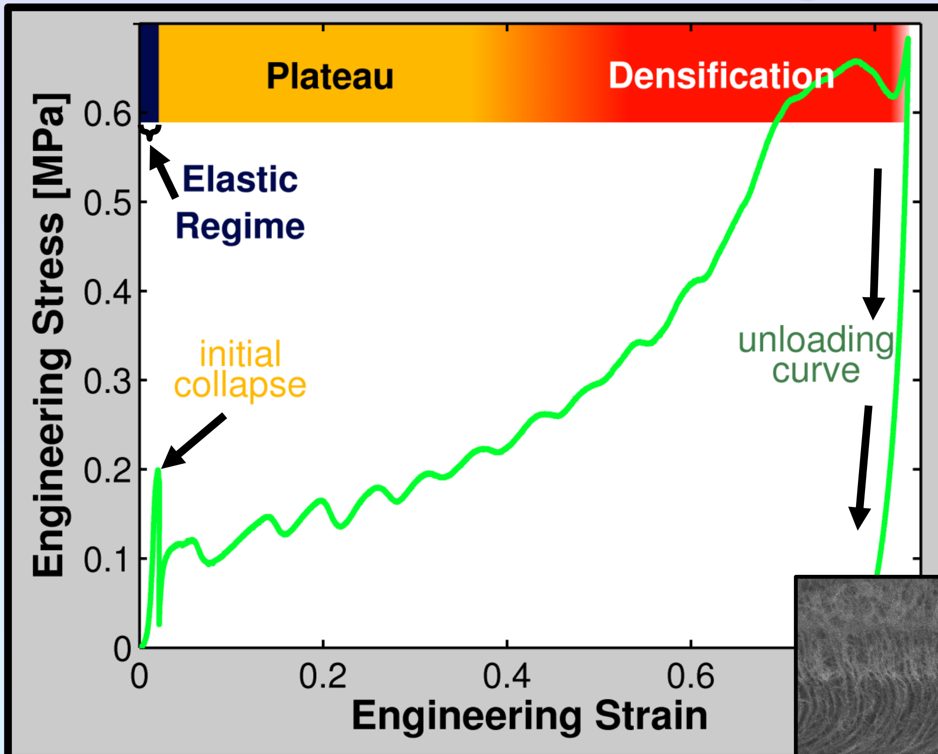
=> Buckles at pillar bottom same size as those at top

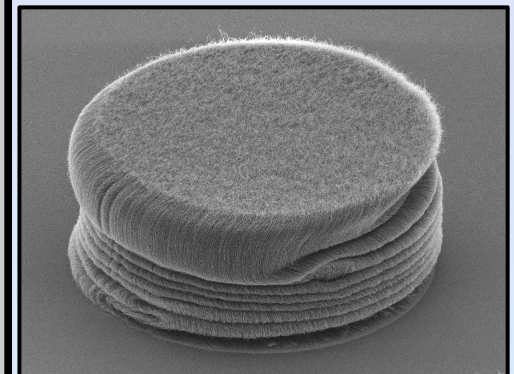
=> Buckle size is independent of strain rate

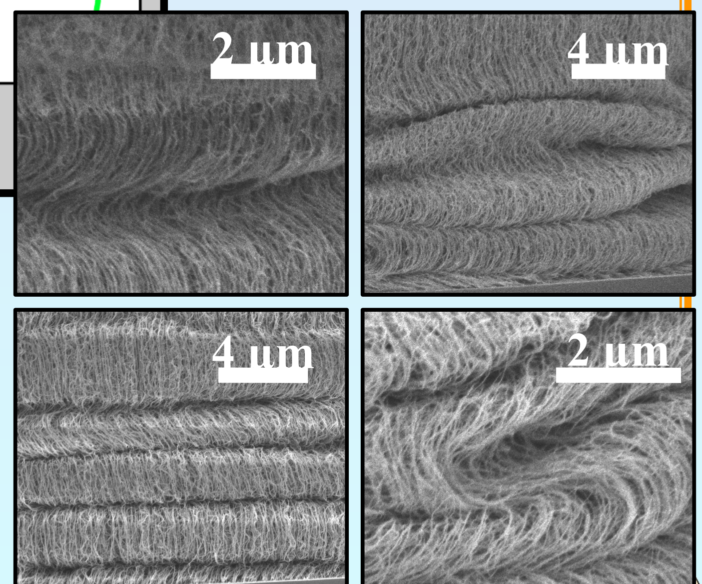
S.B. Hutchens, et al *Adv. Funct. Mater.*, 20, 1-9 (2010)

Stress-Strain Response









=> Repeated folding in compressed structures

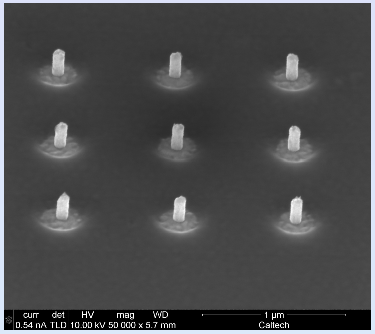
=> Overall foam-like behavior

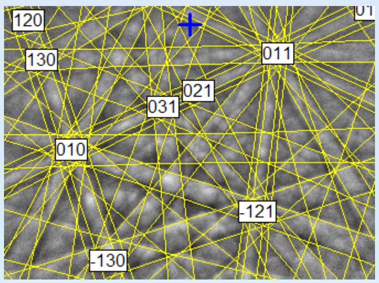
=> Plateau undulations indicate collective buckling

Buckled tubes do not appear to fracture or break, only bend

S.B. Hutchens, et al *Adv. Funct. Mater.*, 20, 1-9 (2010)

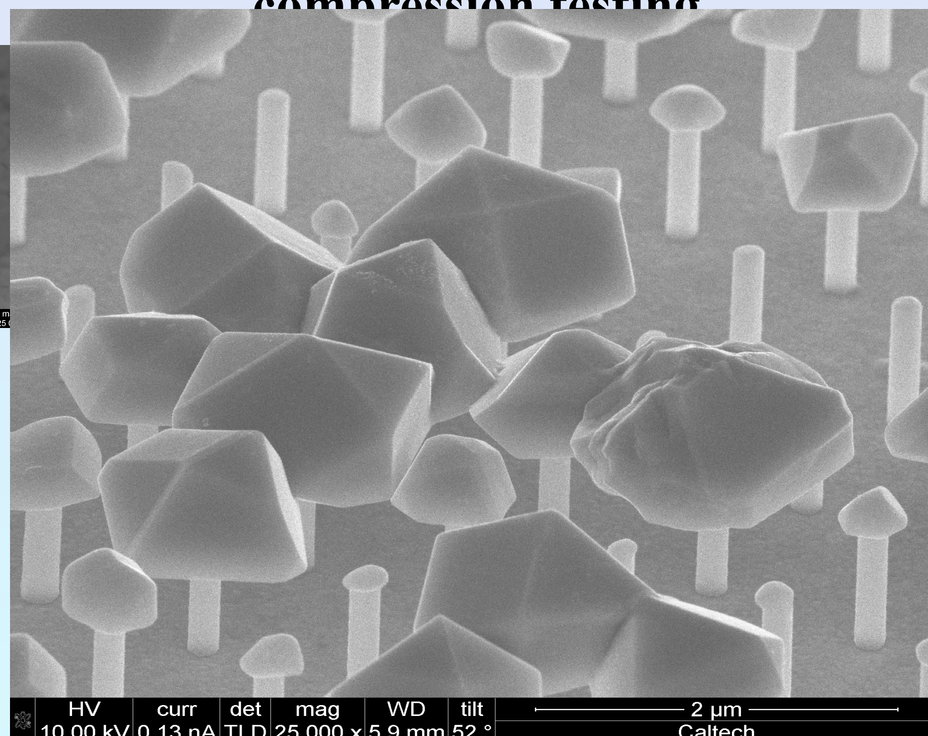
Metals: Microstructure Control through Novel Synthesis





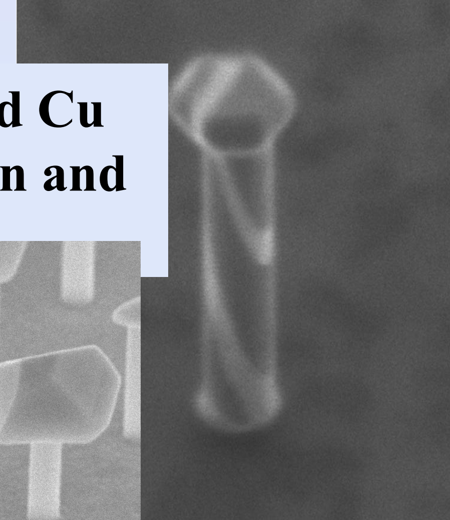
Nanocrystalline Au

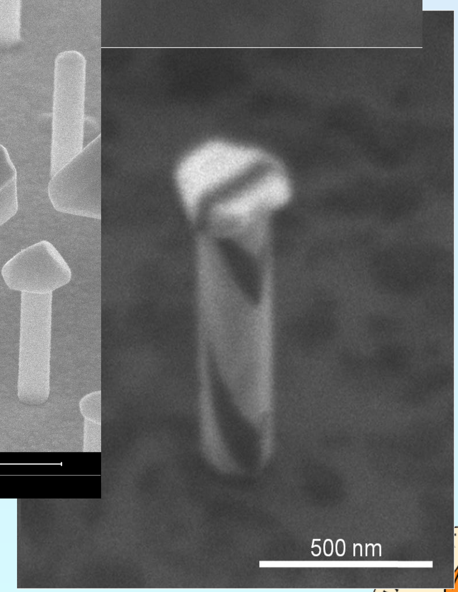
Array of intentionally over-plated Cu single crystalline pillars for tension and compression testing



Nanotwinned Cu

Nano candy canes!

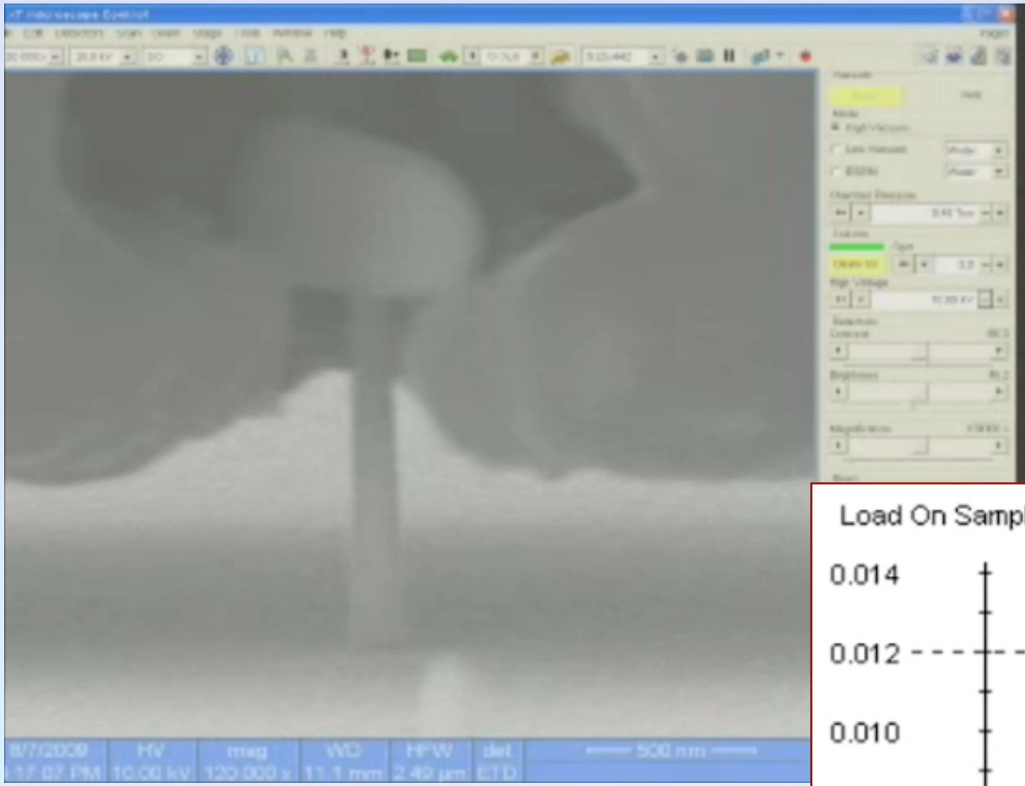


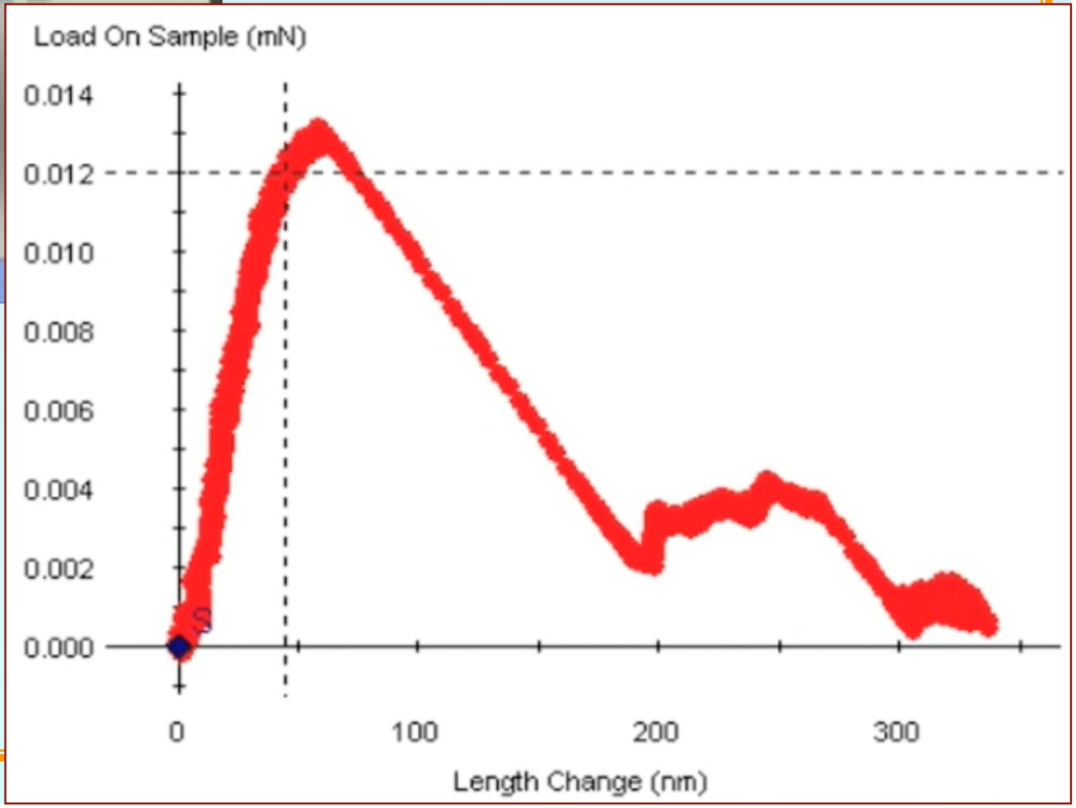


Cu with occasional twin boundaries

M.J. Burek and J.R. Greer *Nano Lett* 10, 69-76 (2009).

Tensile deformation of Cu at nano-scale

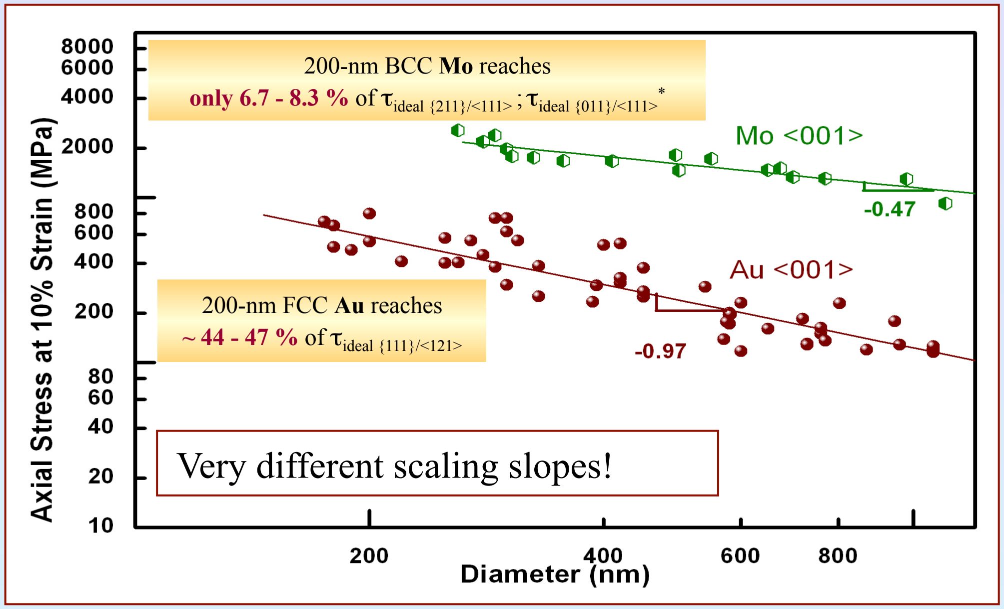




A.T. Jennings and J.R. Greer *Phil Mag* (submitted, 2010)

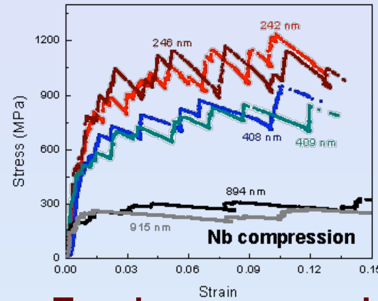
Scaling Laws Single Crystals

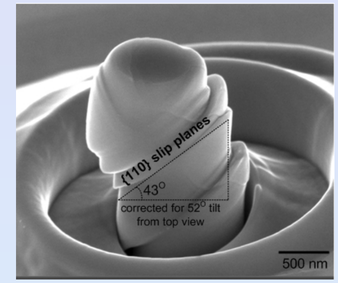
*W. Cai (recent calculations)
*S. Ogata, et al *Phys. Rev. B* 70, 104104 (2004)
*W. Luo, et al *Phys. Rev. B* 66, 094110 (2002)



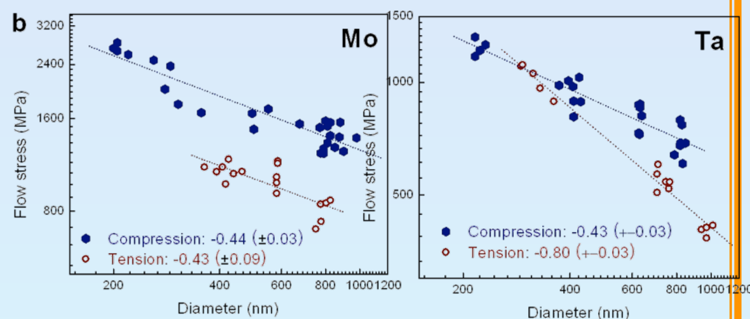
Brinckmann, Kim, Greer, *Phys Rev Lett* (2008)

Stochastic discrete strain bursts

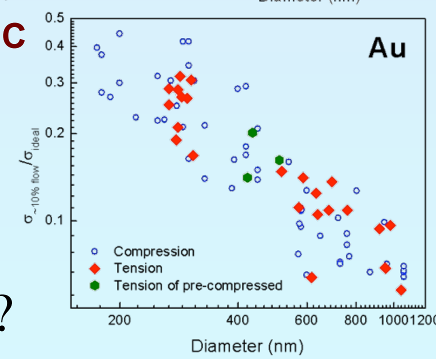




Tension-compression asymmetry in BCC

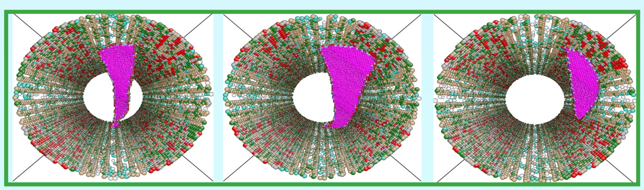


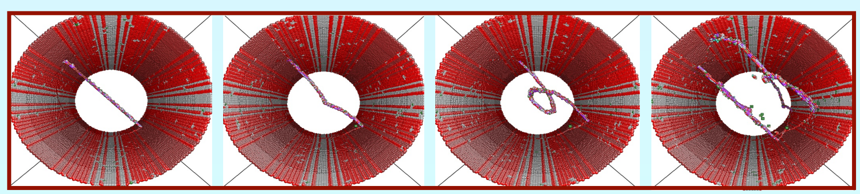
But not in FCC



Smaller is Stronger

Perhaps fundamentally different plasticity mechanisms:
Dislocation starvation in FCC while Junction formation in BCC?

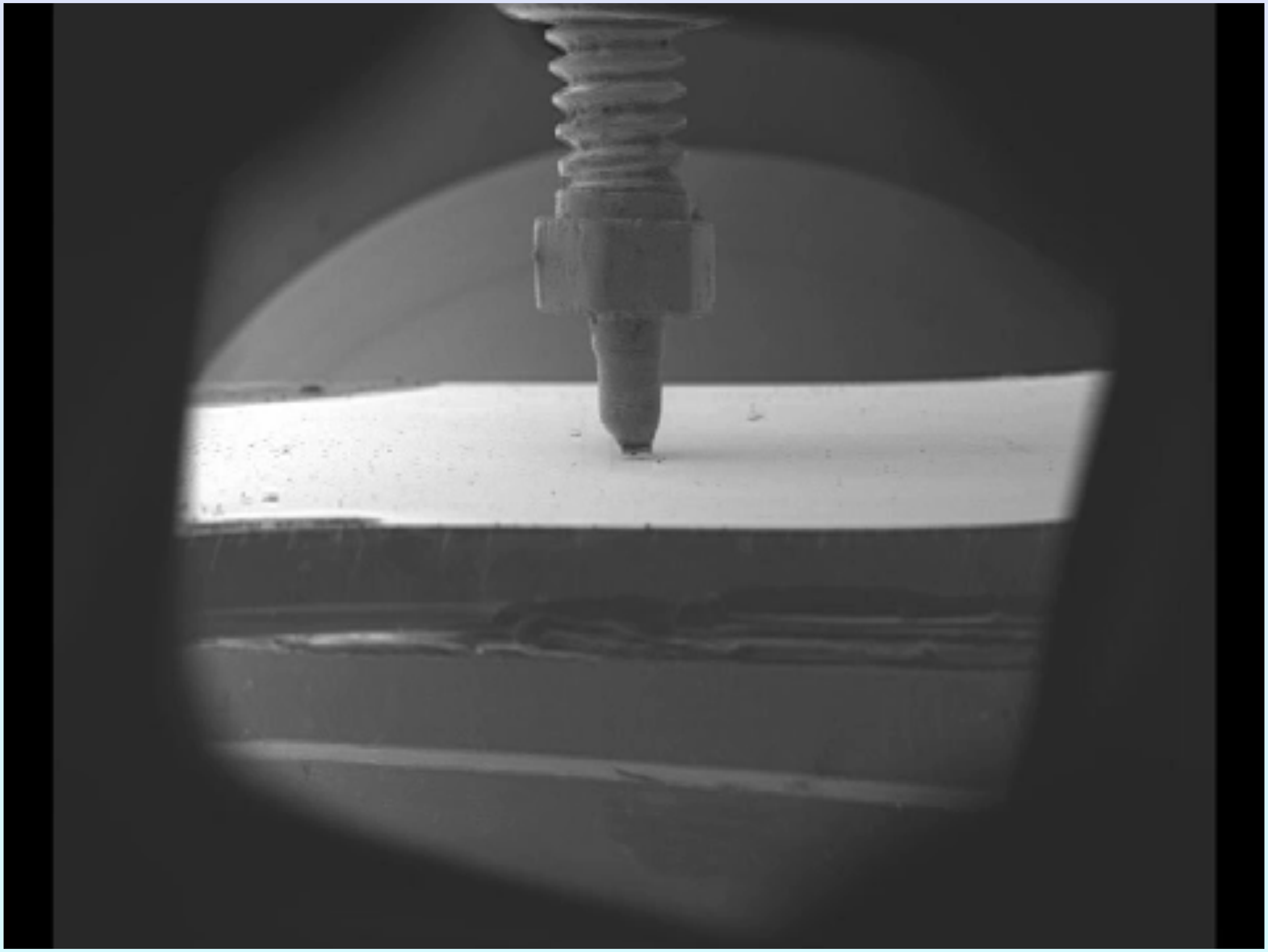




Weinberger, C.R., Cai, W. *PNAS* (2008)   Kim, J.-Y., Greer, J.R. *Acta Mater.*, 57 (2009)   Kim, J.-Y., et al. *Acta Mater.*, 58 (2010)

Insights into deformation mechanisms: TEM

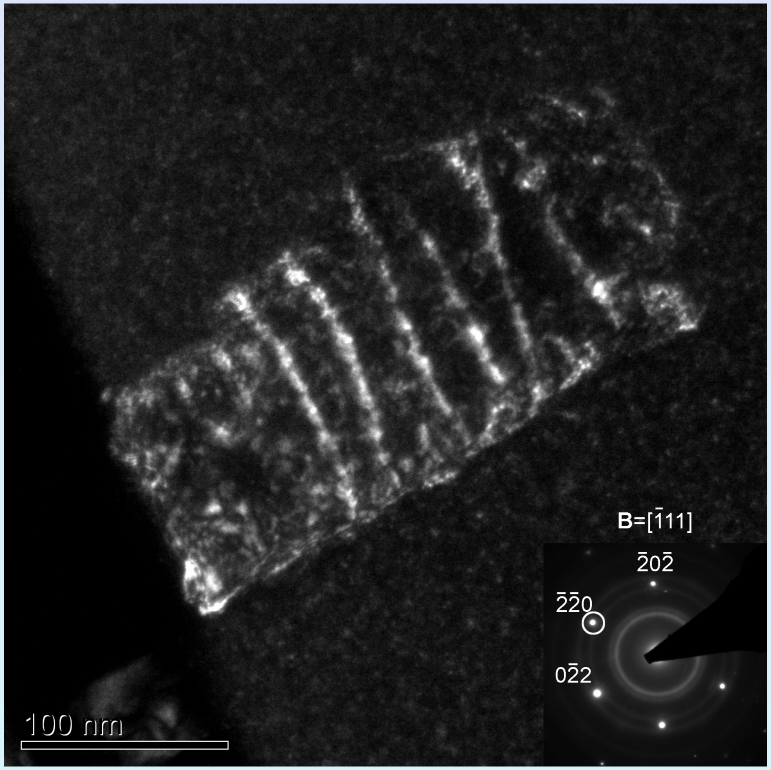
Wait, but how do we TEM the same nano-pillars before and after deformation???



We test them directly on TEM grid!

TEM Analysis of Deformed Pillars

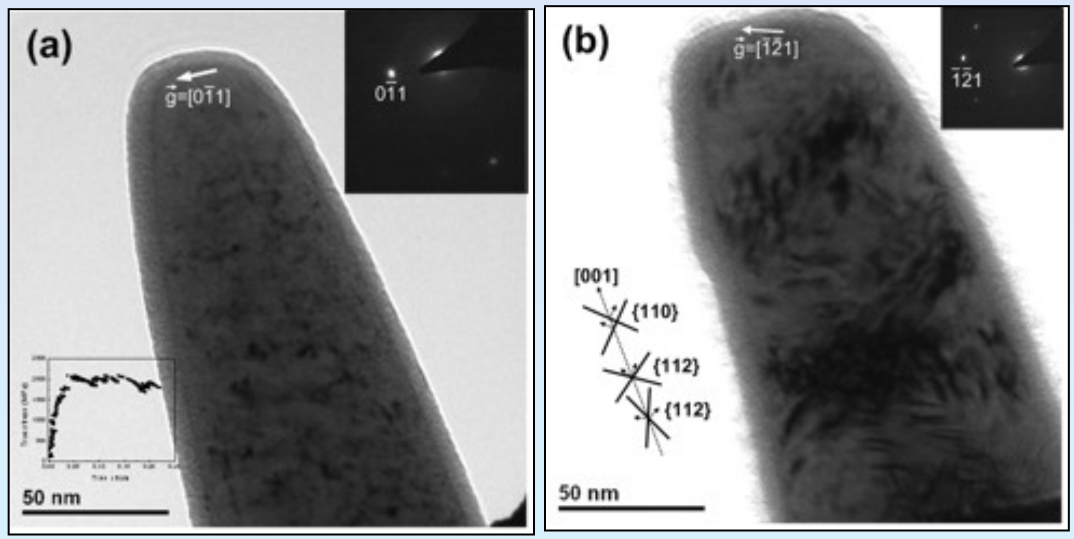
Post-compression Copper



g•b condition =>
Burgers vector = [1-21]

Dislocations observed only in planes with no resolved shear stress!

Niobium



Complex dislocation network, junctions, straight parallel segments

Jennings, A. T., et al *Phys Rev Lett* 104, 135503 (2010) (2010)

Kim, J.-Y., Jang, D., Greer, J.R. *Scripta Mater*. 61, 3 (2009)

II. Fundamental Mechanical Properties of Materials: Amorphous Metallic Glasses

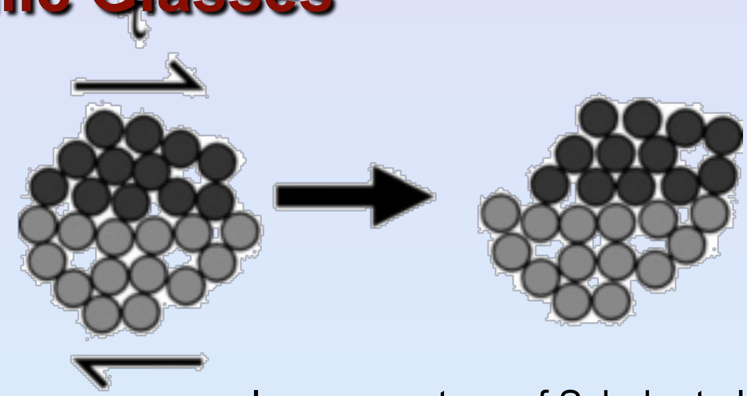
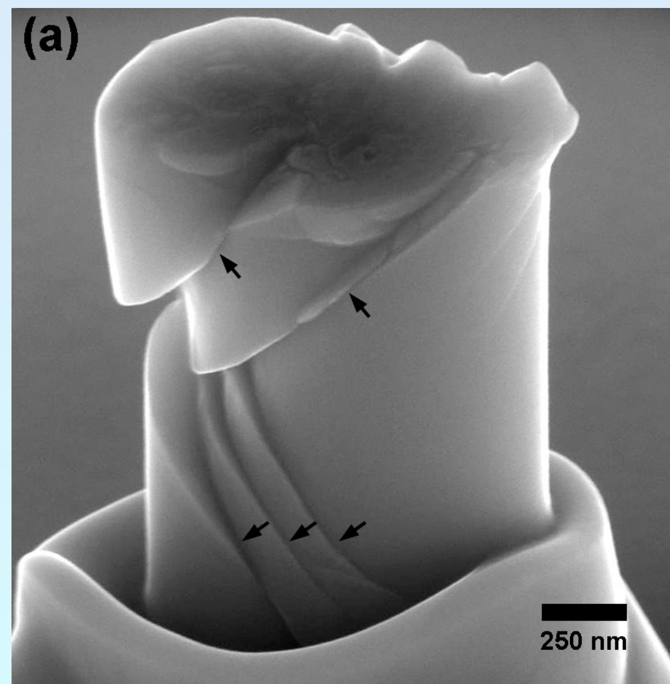


Image courtesy of Schuh et al.

- Basic plasticity units: shear transformation zones (STZs)

- collective atomic rearrangement

- ~ 100 atoms (~ 5 atoms in each direction)



Shear bands formation under load

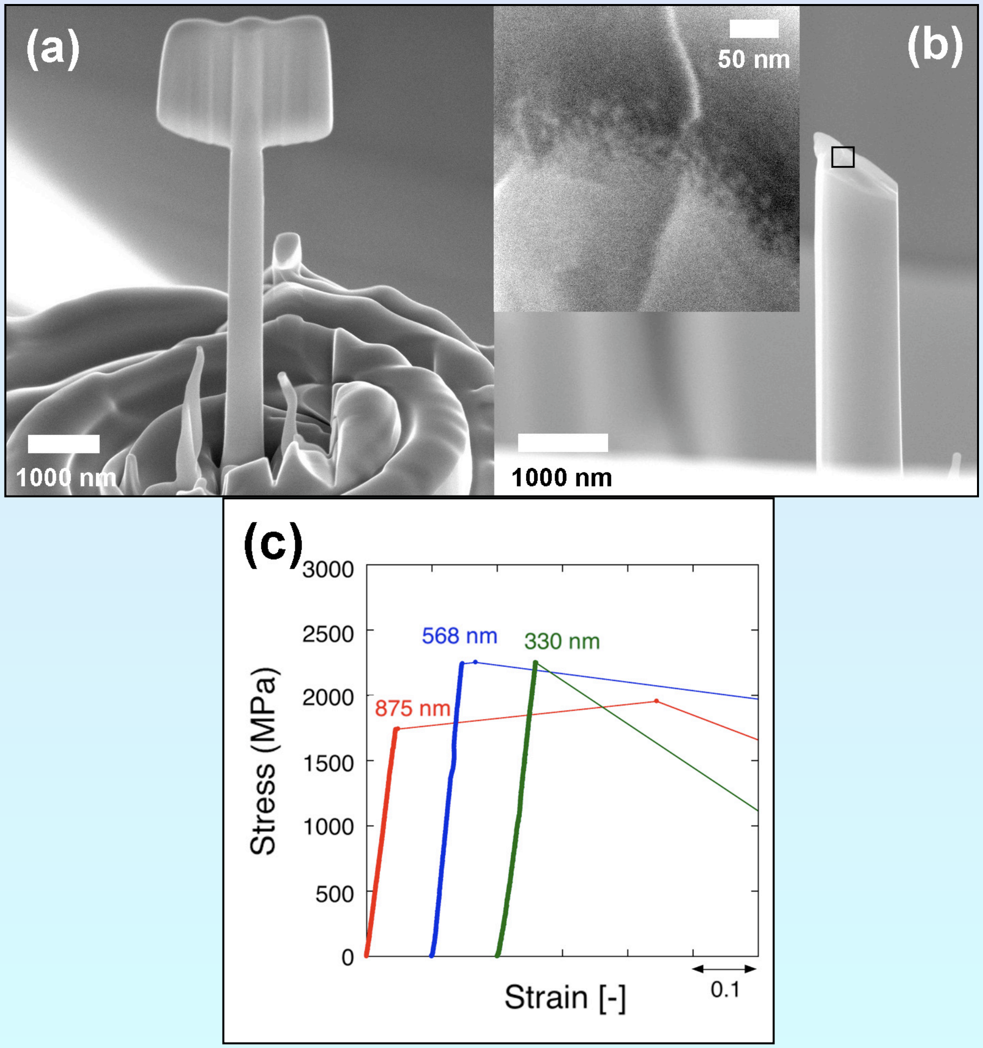
- Macroscopic plastic deformation governed by spatial and temporal distribution of STZs

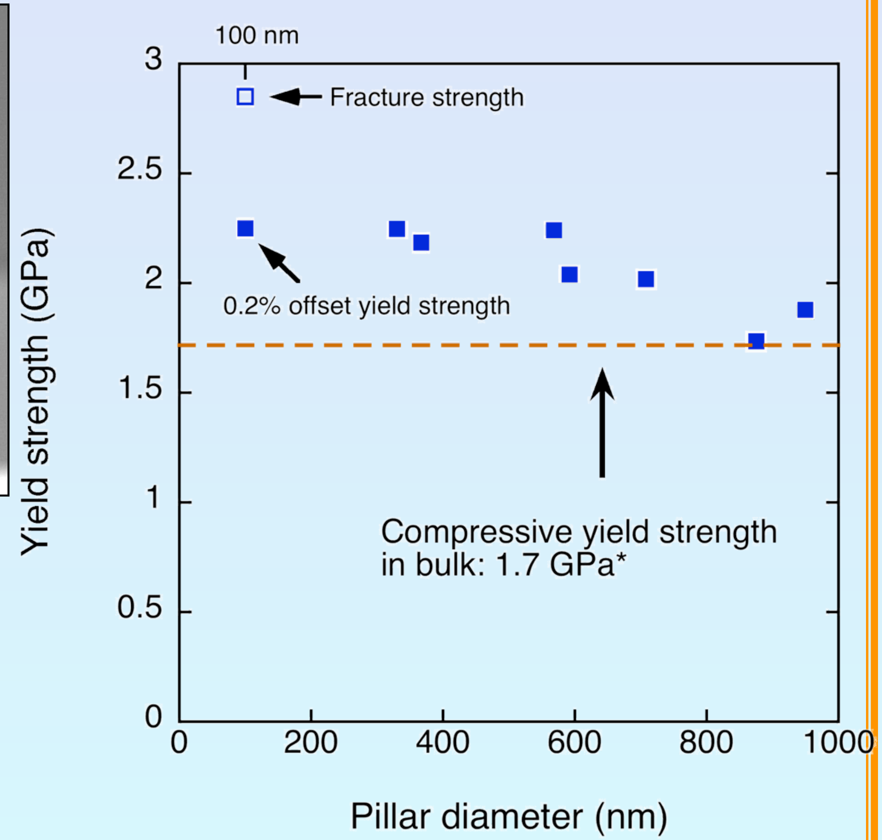
- uniform distribution ⟶ homogeneous deformation (high T & low σ)

- densely populated within narrow region ⟶ shear localization, or shear bands (low T & high σ)

Uniaxial tension of nano-pillars: D=200nm +

Generally fail by catastrophic failure due to shear band formation and propagation

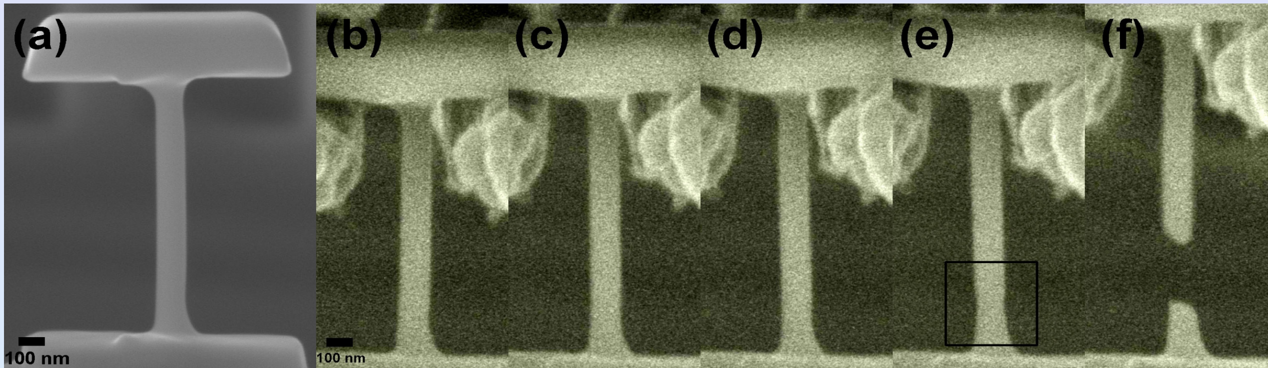


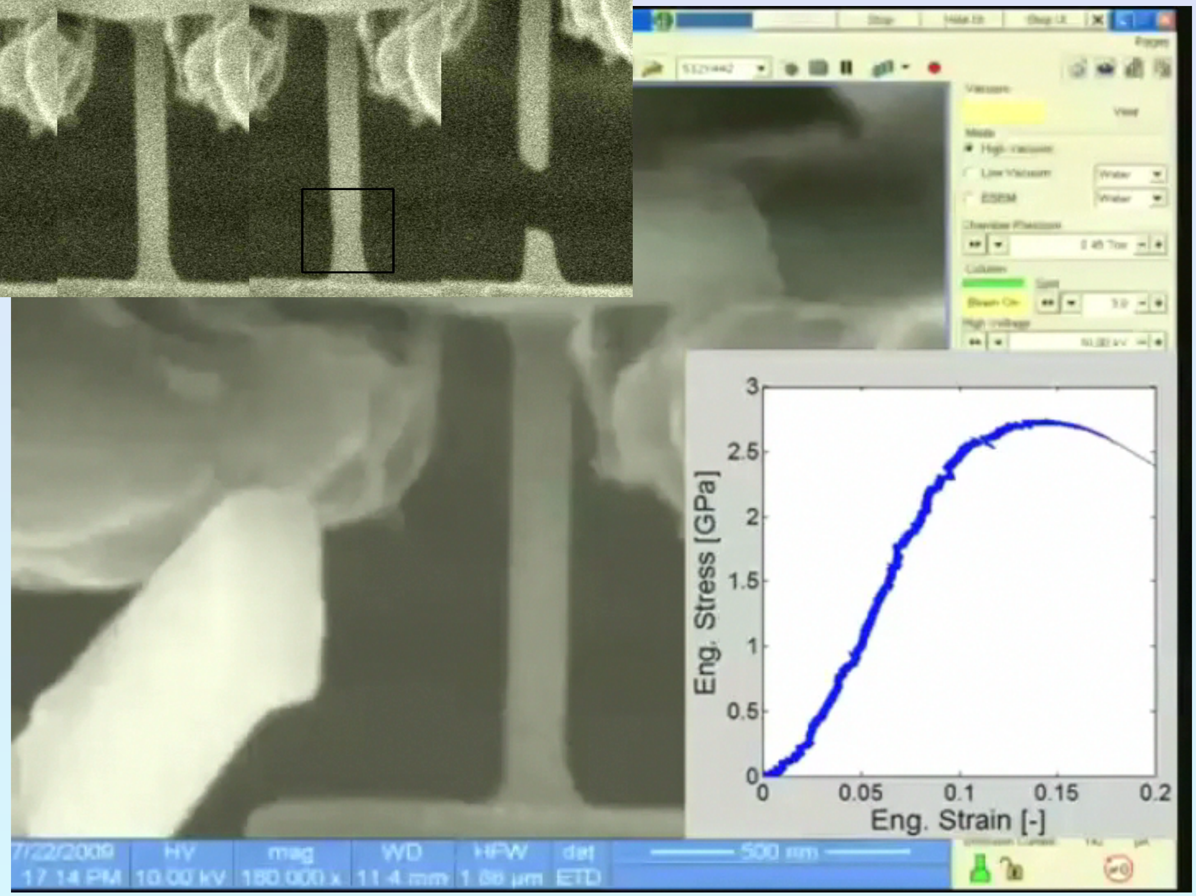


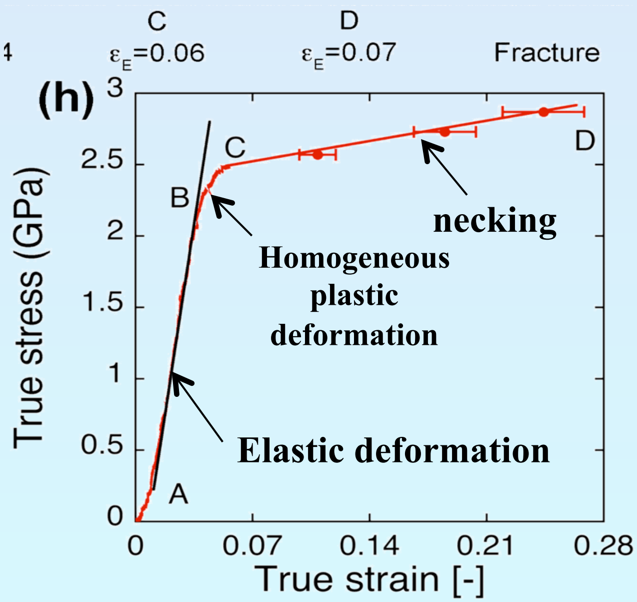
Jang, D., Greer, J.R. *Nature Mater* 9, 215-219 (2010)

Jang, D., et al *Acta Mater* (in review, 2010)

Uniaxial tension at 100nm diameter







❖Homogeneous plastic deformation ❖Necking ❖Work-hardening

Transition to homogeneous deformation mode: stronger and ductile at nano-scale!

Jang, D., Greer, J.R. *Nature Mater* 9, 215-219 (2010)

Summary and Acknowledgements

- Single metallic crystals at nano-scale exhibit strong size effects in uniaxial compression and tension: SMALLER IS STRONGER
- 100nm metallic glasses exhibit enhanced strength and ductility at nano-scale
- Carbon nanotube (CNT) foams can be used in protective application due to their superior energy absorption
- Band gap in graphene might be induced by mechanical perturbation

For details/publications: http://www.jrgreer.caltech.edu/

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Columbia U: Jim Hone

Award No: N000140910883

Army Research Office
Institute for Collaborative Biotechnologies (ICB)

DMR-0520565

Cryogenic module construction

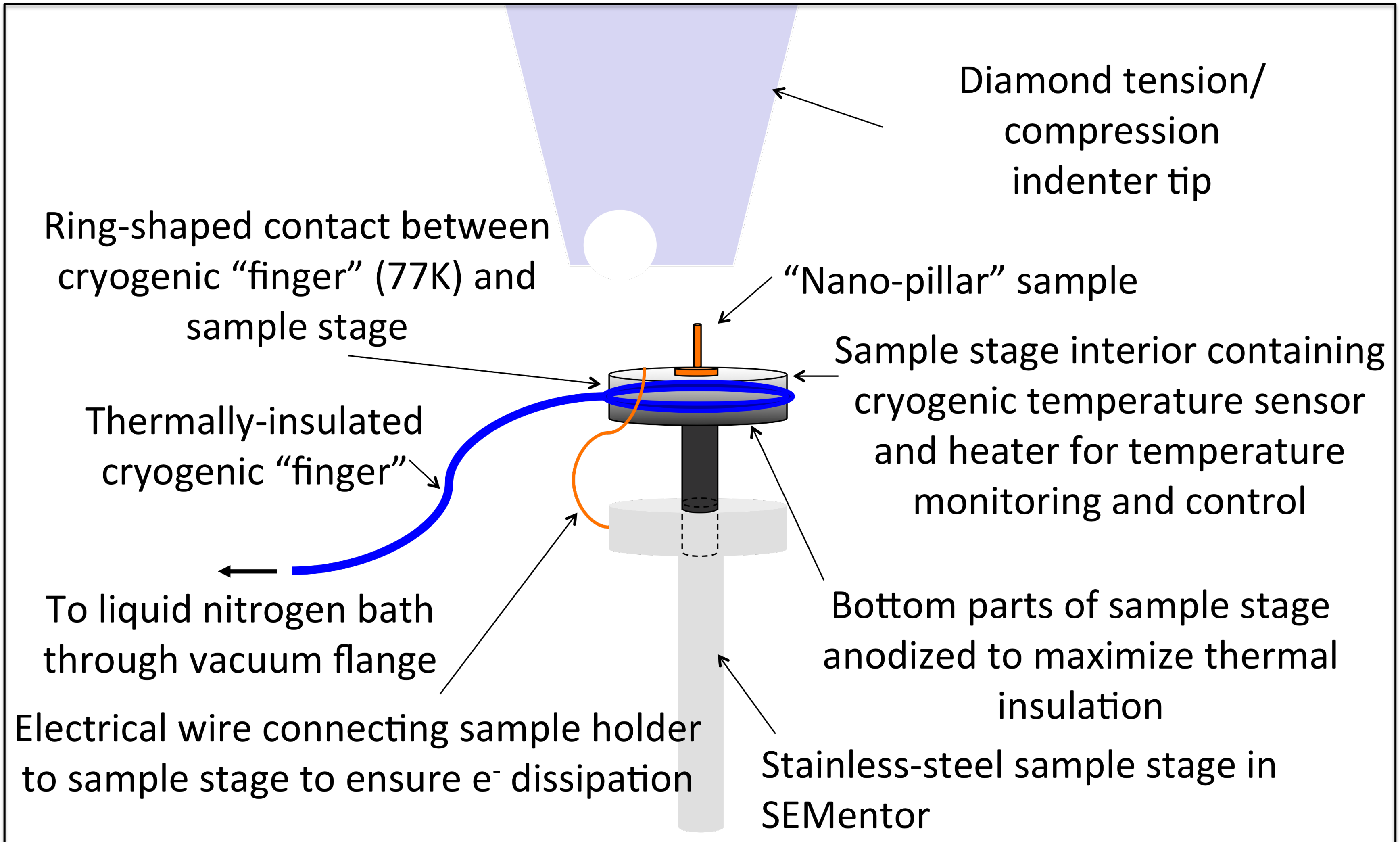
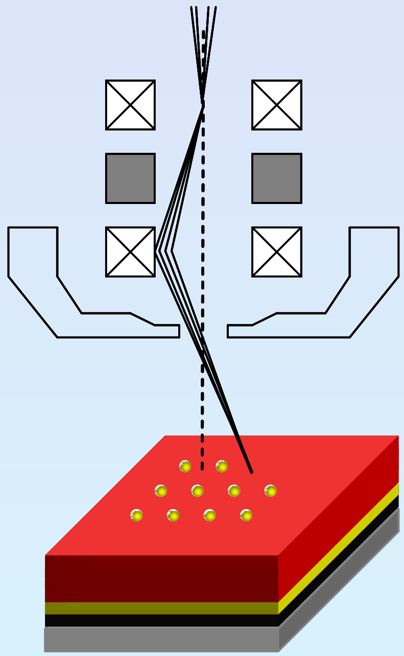


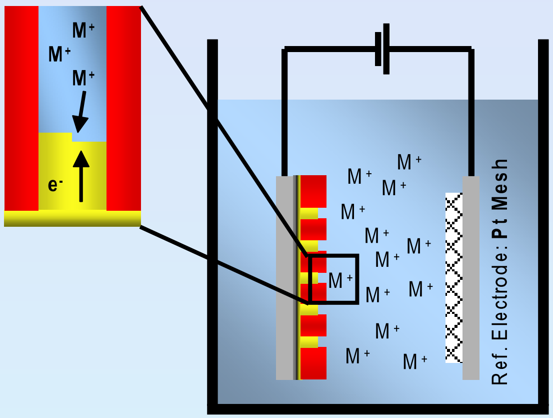
Figure 13. (not to scale) Schematic of cryogenic cooling configuration showing sample stage, sample holder (sample on top), ring-shaped contact between cryogenic finger and sample, conducting wire to dissipate electrons from e-beam, and indenter tip.

FIB-less fabrication: E-beam Litho => Electroplating

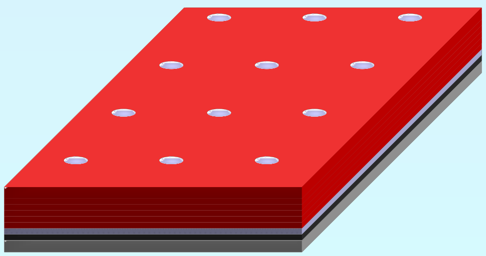
1. E-beam patterning



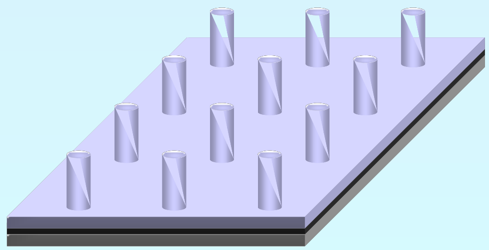
2. Electroplating



3. Pillars in PMMA Matrix

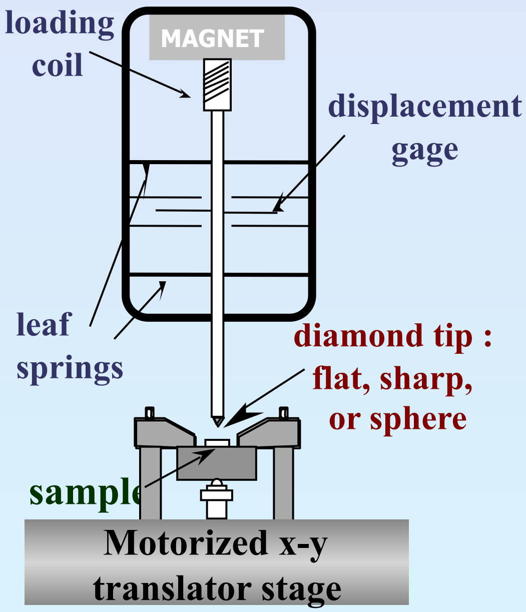


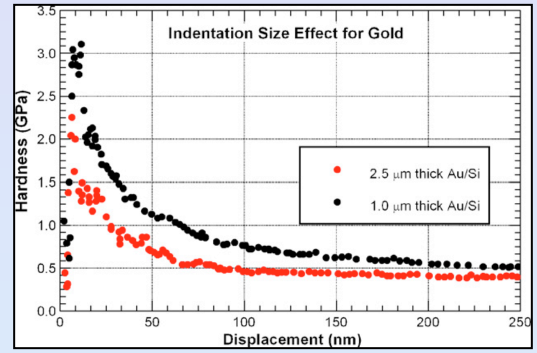
4. Free-standing pillar array



M.J. Burek and J.R. Greer *Nano Lett* 10, 69-76 (2009)

Mechanical Properties via Nanoindentation

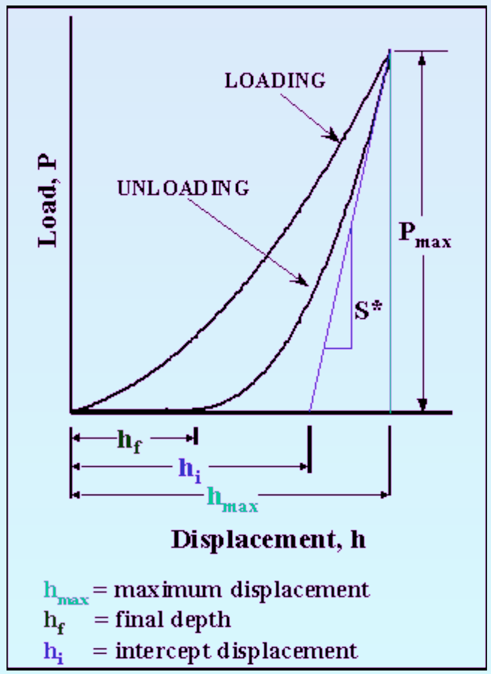


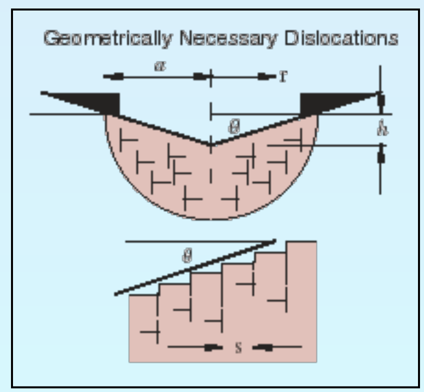


Nix, Feng, Greer, et al Thin Solid Films (2007)

$$\therefore \left(\frac{H(h)}{H_0}\right)^2 = 1 + h^* \times \frac{1}{h}$$

strain gradients drive hardness increase





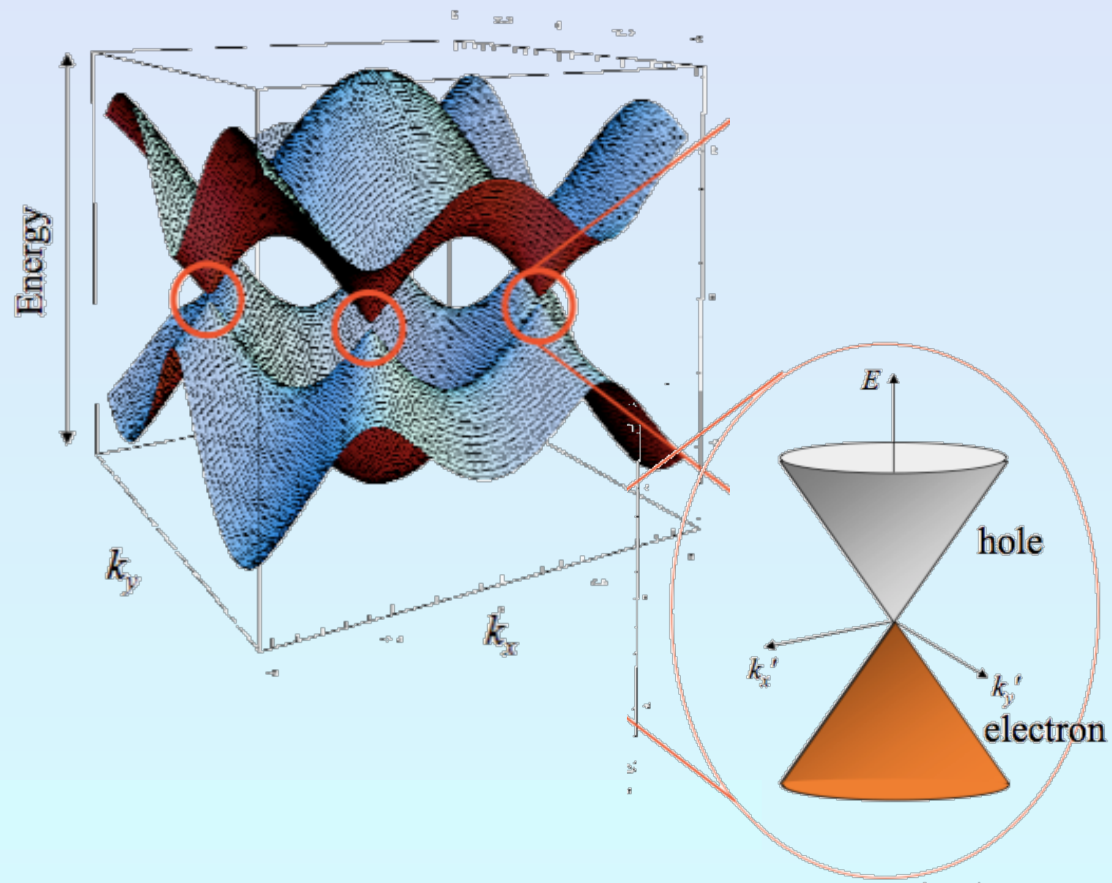
$$\rho_{GND} = \frac{3\tan^2\theta}{2bh}$$

Great need for experimental techniques testing mechanical deformation at nano-scale *without* strain gradients!

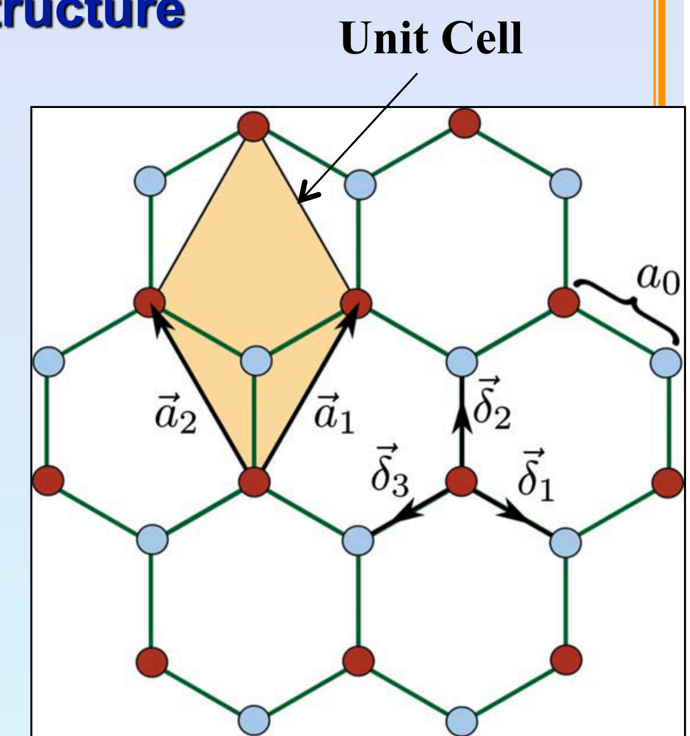
III. Mechanical/Electrical coupling in graphene-based devices

Physical and Electronic Structure

Band structure of graphene (Wallace 1947)



$$E \approx \hbar v_F \left| \vec{k}'_{\perp} \right|$$

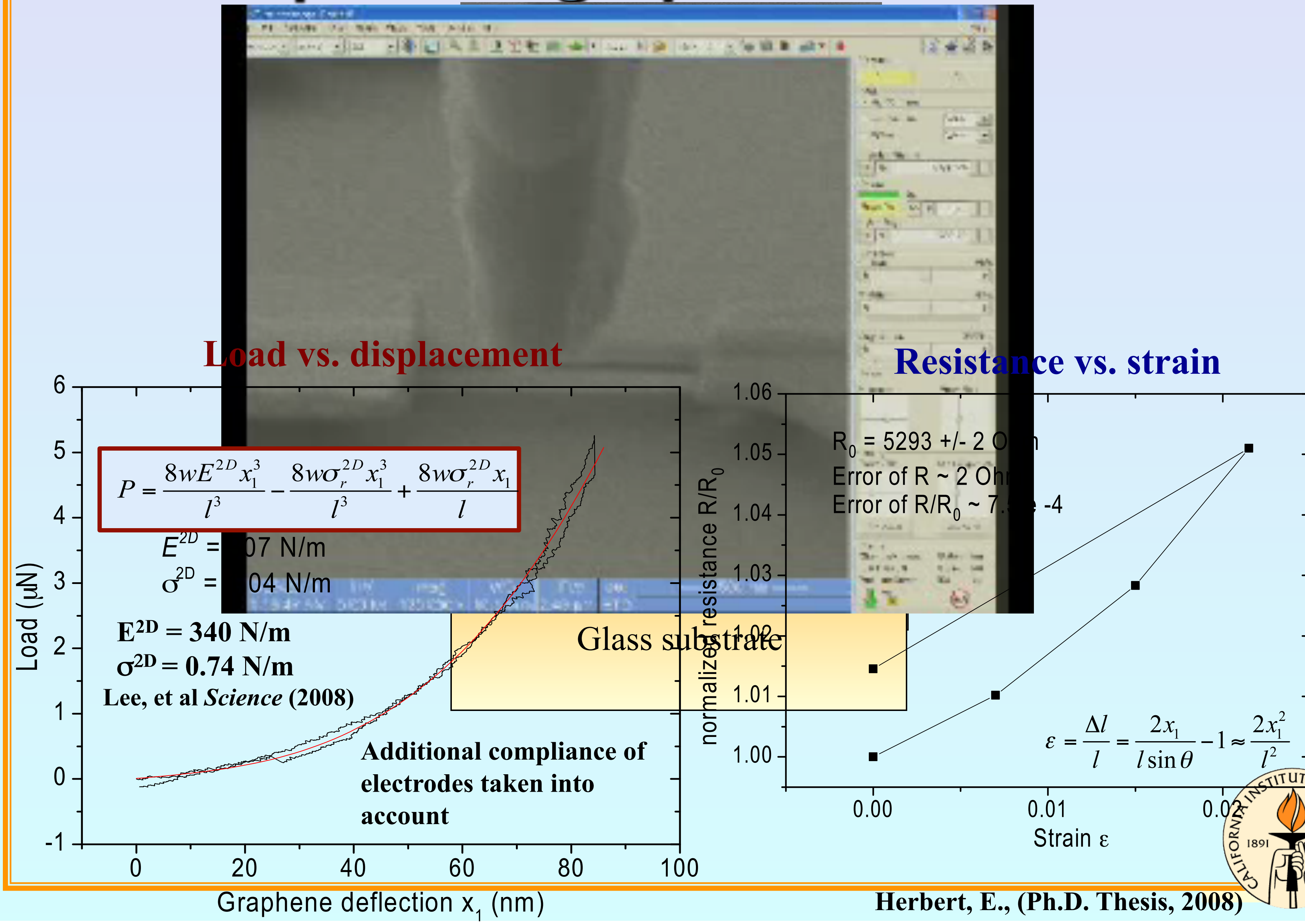


2-D Graphene Lattice

Graphene: Zero band gap "semiconductor"

Novoselov and Geim, *Nature Mater (*2005)

Suspended graphene devices



Herbert, E., (Ph.D. Thesis, 2008)

Mathematical model:

Graphene deflection:

$$P = \frac{8wE^{2D}x_1^3}{l^3} - \frac{8w\sigma_r^{2D}x_1^3}{l^3} + \frac{8w\sigma_r^{2D}x_1}{l} \qquad \textbf{(1)}$$

Electrode deflection: $P = 2Kx_2$

Where K is estimated by beam deflection: $K = \frac{4E_g w_g h_g^{\,3}}{L_g^3} \approx 1\times 10^2$

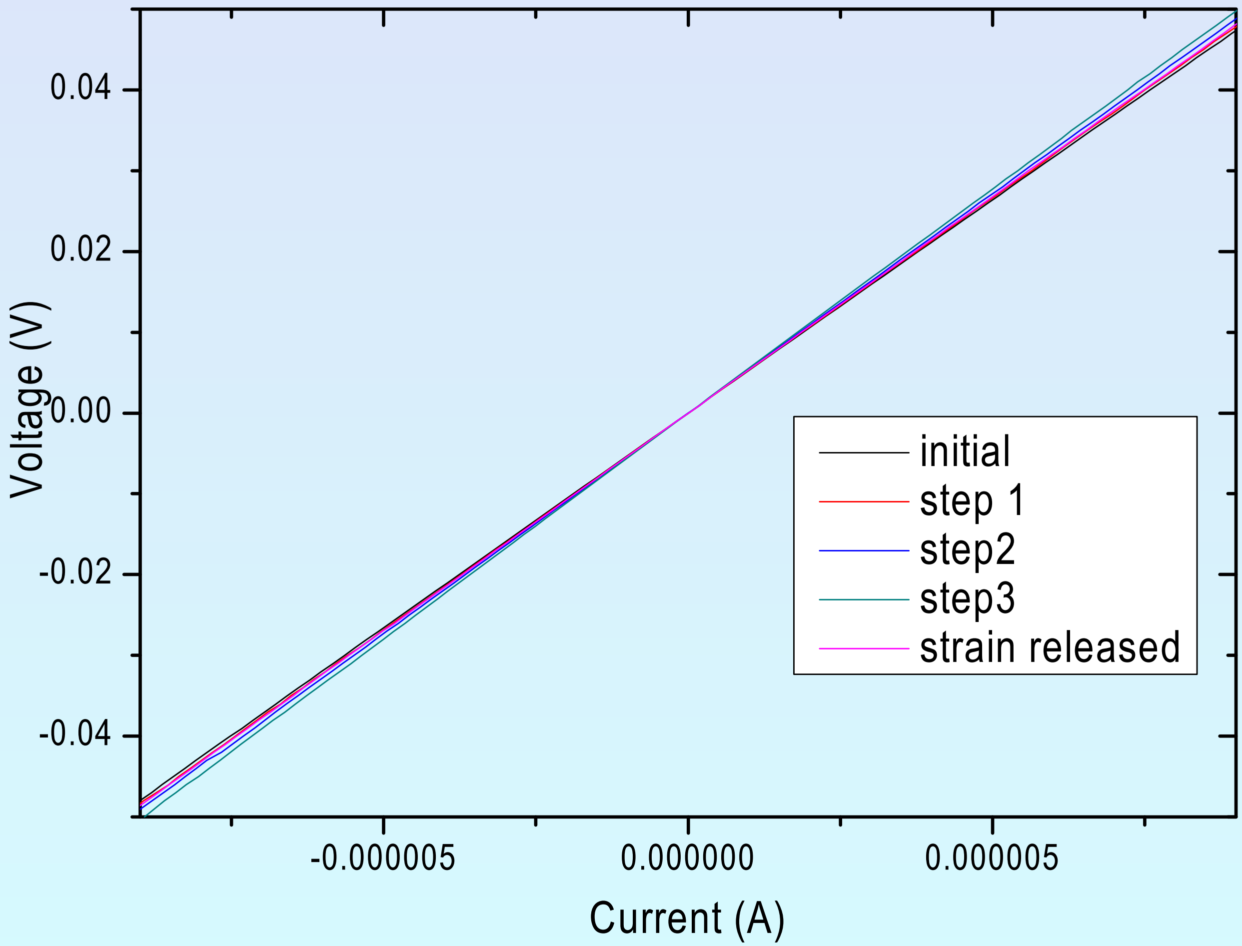
Instrument measures total displ: $\boldsymbol{x = x_1 + x_2}$

To obtain load vs. displacement, the electrode deflection is subtracted from gross displacement: $\boldsymbol{x_1 = x - x_2}$

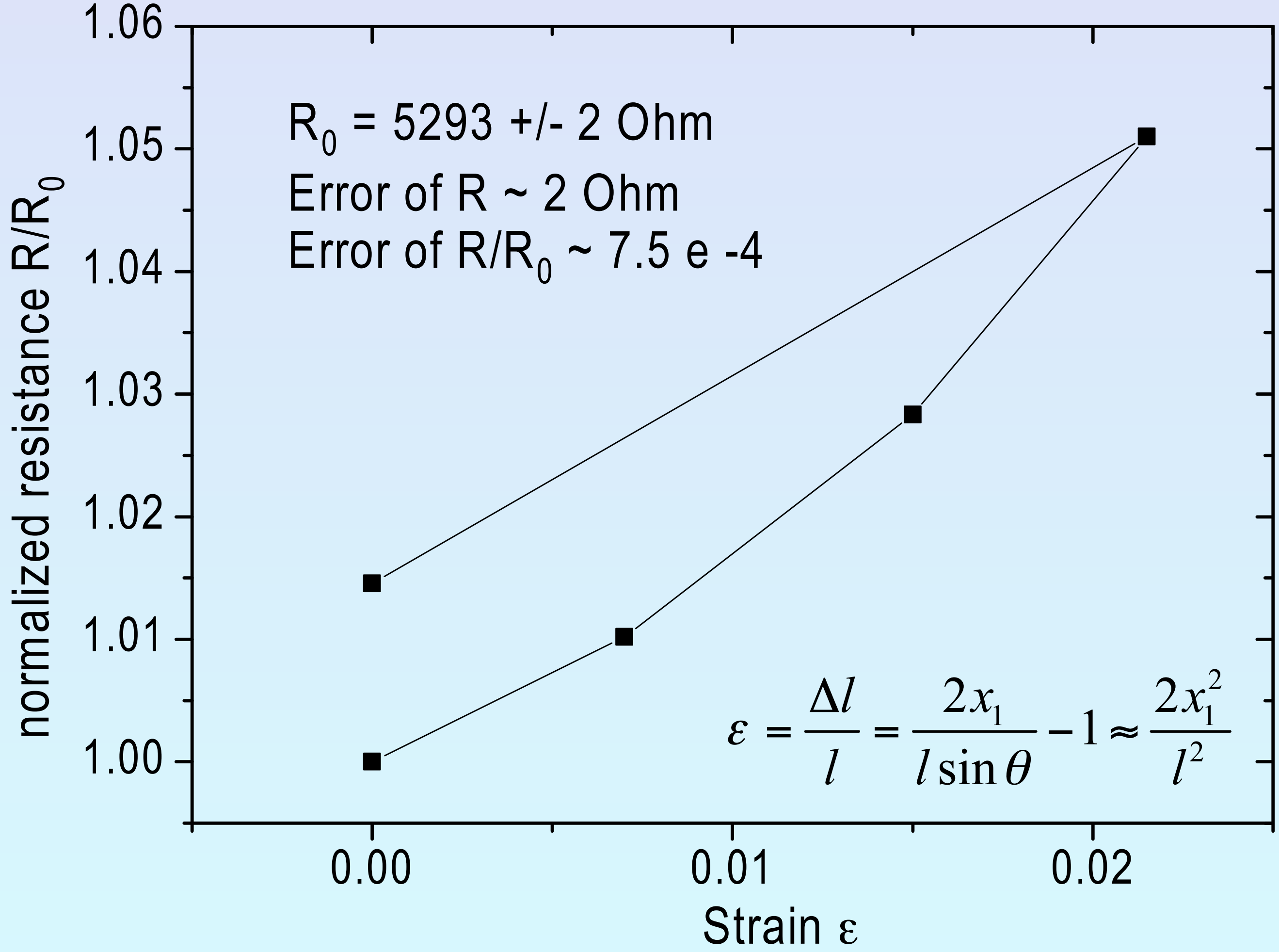
Stiffness:

$$\frac{dP}{dx} = \frac{\frac{dP}{dx_1}\,\frac{dP}{dx_2}}{\frac{dP}{dx_1} + \frac{dP}{dx_2}} = \frac{\left(Ax_1^2 + B\right)2K}{2K + Ax_1^2 + B}$$

Electromechanical results: I-V curve



Resistance Change



Strain: