Electromechanical Characterization of One-Dimensional Solids

Nakul Reddy, Electrical Engineering, Georgia Institute of Technology
NNIN REU Site: The Penn State Nanofabrication Facility, The Pennsylvania State University

NNIN REU Principal Investigator: Prof. Amanul Haque, Mechanical & Nuclear Engr, Pennsylvania State University
NNIN REU Mentor: Amit Desai, Mechanical & Nuclear Engineering, The Pennsylvania State University
Contact: gtg621q@mail.gatech.edu, mah37@psu.edu, avd112@psu.edu

Abstract:

Materials exhibit unique electrical and mechanical properties at the nanoscale such as quantized conductance and high elastic modulus, which make them ideal for next-generation sensors, actuators and nano-electronics. To study these properties, we have developed MEMS-based nano-Newton force and nanometer displacement resolution sensors. The design philosophy exploits the amplification of displacement and attenuation of structural stiffness in the post-buckling deformation of slender columns. The research experience aims to: (a) explore reliable methods for placing a nanowire or nanotube on the device or co-fabrication, and (b) study the electromechanical coupling in ZnO nanowires. The devices have been patterned on silicon-on-insulator (SOI) wafers using UV photolithography and DRIE. The movable silicon beams were made freestanding using vapor-phase HF etching. Dispersion for ZnO nanowires has been characterized and a focused ion beam (FIB) with a tungsten probe (capable of nanometer level positioning) was used to place the nanowires on the device. An upper bound of 5 GPa for the Young's modulus of ZnO nanowires has been observed. Stress-strain curves for these nanowires have been computed. The experimental setup has also been extended to include electromechanical characterization, and experiments are being conducted to determine strain-conductance relations.

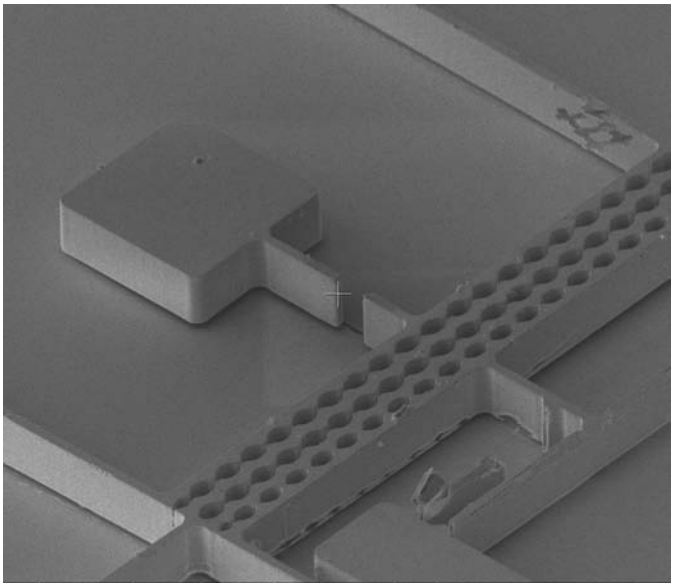

Figure 1: SEM image of the buckling beam device.

Introduction:

Nanotubes and nanowires are expected to have superior thermal, electrical, and mechanical properties that promise breakthroughs in the development of super-strong composite materials and ultra-high resolution sensors. There has been extensive research on the mechanical, electrical and thermal properties but very little effort is evident on determining these properties under coupled (and not individual) domains. This is mainly due to the high measurement resolution requirements and challenges in experimentation at the nanoscale. Existing technologies for obtaining nanostructure stress-strain and strain-conductance data, such as nanoindentation and mechanically-controllable break junction (MCBJ) do not provide for *in situ* experimentation and do not work for nanowires and nanotubes with large variations in structure and chemistry.

We therefore have designed and fabricated a MEMS-based tensilometer based on post-buckling deformation of thin silicon cantilevers, for studying the mechanical and electro-mechanical coupling of nanowires and nanostructures.

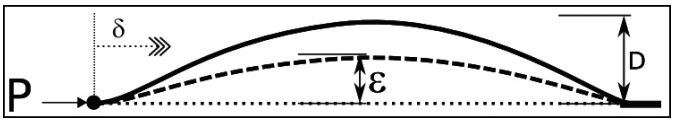

Figure 2. Buckling beam with labeled axial load (P), axial displacement (δ), lateral displacement (D), and initial imperfection (ε).

Buckling Beam Theory:

Buckling of a beam can be used to amplify the axial displacement (δ in Figure 2) into lateral displacement (D in Figure 2), by as much as a factor of 250. The

axial force (P in Figure 2) can also be computed as a function of lateral displacement. The post-buckling deformation mechanics results in reduction of stiffness with increasing lateral displacement and hence the force resolution increases.

The device design consists of two pairs of beams (as shown in Figure 3). One end of the specimen is fixed and the other end is attached to the movable middle rib, as shown in Figure 3. On loading the device, the middle rib moves to the right and applies very small forces and displacements on the specimen. The tensilometer can achieve much higher resolution than a single set of buckling beams by exploiting the small difference in axial displacement and load for each set of beams (δ_1 - δ_2 and P_2 - P_1). The average lateral displacements, D_1 and D_2 are on the order of microns, and can be measured using a high-power optical microscope.

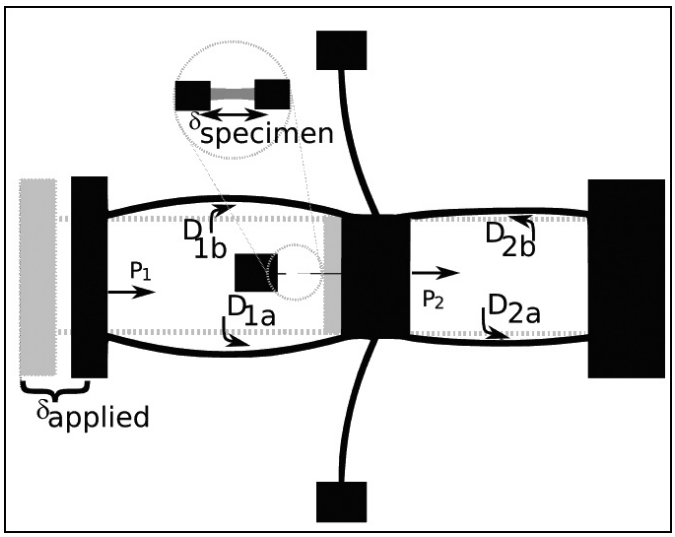

Figure 3: Buckling beam device schematic with labeled displacements.

Fabrication and Preparation:

The devices were fabricated on a silicon-on-insulator wafer with a 20 μm Si layer on a 1 μm oxide layer. The device was patterned using Shipley 3012 resist, and the Si layer was etched using deep reactive ion etching with SF_6. The oxide layer was then etched with a 3 μm undercut using a vapor-phased HF tool. The photoresist was then stripped and the devices were sputtered with 100 nm of gold for improved conductivity and imaging.

Nanowires were dispersed on a thin but stiff oxide grid with a 75 nm gold layer for conductivity. The focused ion beam (FIB) was used to deposit an adhesive Pt compound on the ends of the nanowire. A grid with a freestanding nanowire was then cut using the FIB, and picked up using the OmniProbe® nanomanipulator. The FIB was then used to etch posts onto the jaws of the device, and the nanomanipulator was used to place the grid onto the posts (see Figure 3). The ends of the grid were cut so that the sample was the only conductive path between the two jaws.

Results and Progress-to-Date:

The characterization of dispersion of ZnO nanowires made it possible to successfully prepare samples. Preliminary results for the Young's modulus for ZnO nanowires were estimated to 5 MPa using the aforementioned method. Electrical measurements were not possible due to the lack of a reliable conductive path between the device and the specimen, possibly due to the low conductivity of FIB deposited Pt. Chemical vapor deposited growth of nanotubes directly onto the jaws of the device is also being explored for nanotube measurements.

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References:

[1] "Microscale application of column theory for high resolution force and displacement sensing." Samuel, B.A.; Desai, A.V.; Haque, M.A. Applied Physics Letters, v 87, n 2, 11 July 2005.

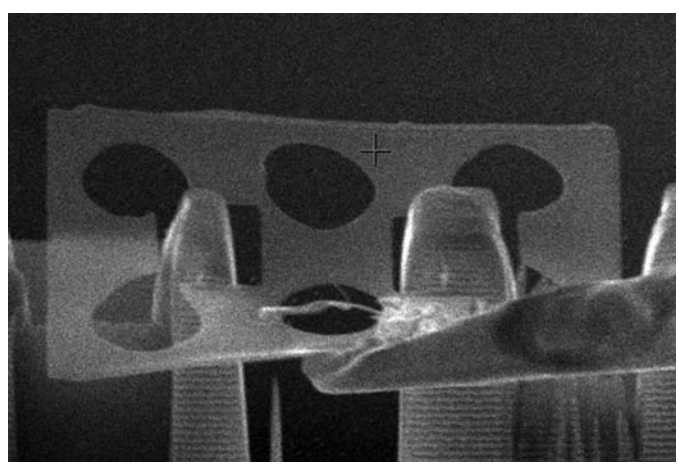

Figure 4: Oxide grid being placed on device jaws using a nanomanipulator.