Abs. 2599, 206th Meeting, © 2004 The Electrochemical Society, Inc.

High Resolution Force and Displacement Sensing with MEMS

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We present design and fabrication of a novel MEMS device for nano to pico Newton force and nanometer displacement measurements. The device design is based on the structural mechanics (buckling) of microfabricated slender silicon beams. Mechanical and geometrical amplification of displacement and attenuation of structural stiffness (spring constant) ensues buckling, which is commonly known as failure of beam-columns; whereas we exploit this failure phenomenon constructively. Using deep reactive ion etching (DRIE) on a silicon-on-insulator (SOI) wafer and subsequent hydro-fluoric (HF) acid etch release, we have fabricated a device with overall dimension 2 mm x 2 mm. The small device size allows in-situ testing in scanning, transmission and tunneling electron microcopy (SEM, TEM and STM), where the small chamber size makes it challenging to integrate conventional force-displacement sensors. Very high degree of customization is possible to allow coupled electrical, mechanical, thermal and chemical characterization of nanoscale structures (including biological materials).

After a critical load is applied, a slender beam buckles and its spring constant reduces drastically reduced and becomes a function of the lateral displacement of the beam. For example, the spring constant of a 2 microns wide, 10 microns deep and 500 microns long silicon beam can be as low as $0.1\text{x}10^{-3}$ N/m. This is shown in figure 1. Assuming one can measure nanometer scale displacement, this stiffness results in less than a sub-picoNewton force resolution. The buckling phenomenon also allows precision displacement measurement since the axial displacement is magnified by the lateral displacement (square relationship), and we have been able to measure 50 nm even with optical microscope. The stiffness attenuation and displacement amplification phenomena are utilized in form of two sets of buckled beams (with very close but different buckling loads) joined by rigid frame for specimen (fabricated separately) attachment. Schematic of the device is shown in figure 2.

The MEMS device, shown in figure 3 is a passive type and requires only externally applied displacement. For the present work, we use a resonant electrical circuit to detect sub-femtofarad capacitance change (which translates to nanometer scale displacement resolution before any signal amplification. The device consists of two sets on slender silicon beams, each 2 microns wide, 10 microns deep. The lengths of the beams at the moving and fixed ends are 510 and 500 microns respectively. A piezo-motor is used to buckle the set of beams at the moving end of the device (with lower buckling load). Further displacement of application will continue to buckle these beams and at some point, the second set will start to buckle. At this point, the specimen starts to be loaded. Both the load and displacement on the specimen are obtained from the buckled configurations of the beams using beam mechanics theory validated by device calibration. This is measured from their lateral displacements.

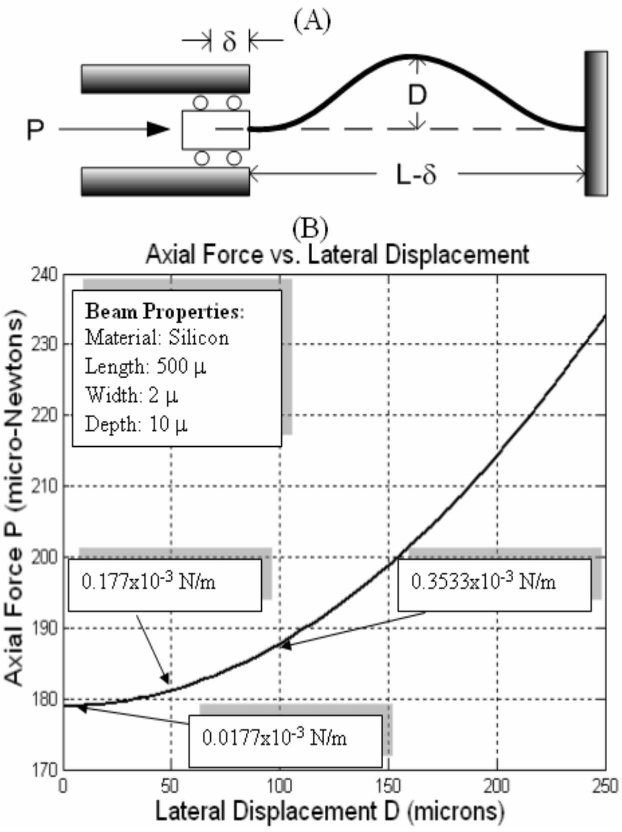

Figure 1. (a) Post buckling geometry and (b) force-displacement relationship (slopes shown inset).

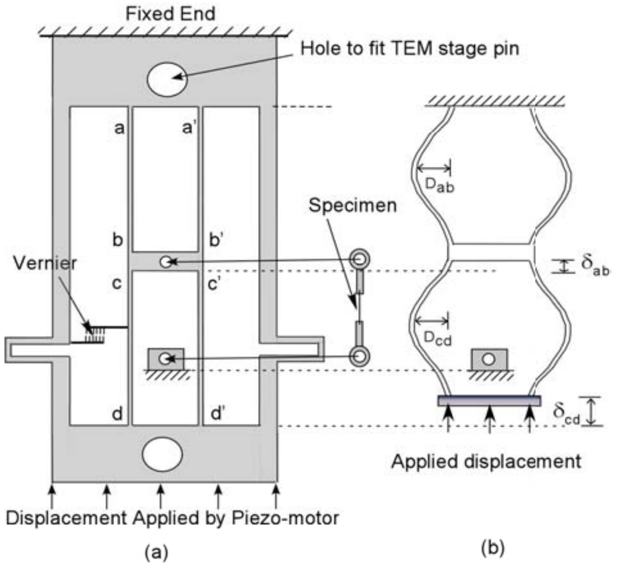

Figure 2. (a) Proposed device design for coupled electro-mechanical characterization of nanotubes, (b) Buckled device (shown without the specimen).

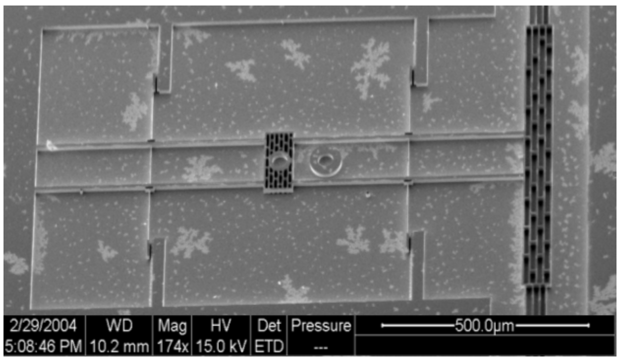

Figure 3. Scanning electron micro-graphs of the device that exploit buckling beam mechanics.