CNT-Based Structural Health Monitor

Prototype single-walled carbon nanotube strain gage sensors were constructed and tested using a load frame. The resistance change of dielectrophoretically aligned carbon nanotubes was monitored as the load was sinusoidally modulated at 0.1Hz from 0-3 kN. A representative set of data is shown in Figure 1 showing all three sets of variation. It is readily apparent that even though there is some overall drift of the sensor (positive in this case), the overall magnitude of the change from one cycle to another is essentially constant. Additionally, as seen in Figure 2, there is still a phase lag apparent between the measured resistance values and the load.

![Figure 1: Representative data showing resistance change with load.](image)

Additional samples of the structural health monitor were also prepared on silicon wafers. These samples were tested for pressure response using a modified chamber. The pressure chamber consists of a sealed steel chamber attached to a Mensor PCS400 Pressure Calibration System. The Mensor PCS400 is capable of controlling pressure from vacuum to 150 psia with a resolution of 0.1%, through a solenoid valve that continuously alternates between a mechanical vacuum pump and a source of air (or nitrogen). The internal pressure of the calibration chamber is further monitored using a Mensor Digital Pressure Gauge. Sample mounting is accomplished on a hollow copper slug mounted to the chamber wall. The temperature of this slug is controlled by a combination of resistive
**Figure 2:** Expansion of 0-2 kN load cycle showing phase lag between sensor and applied load.

Heaters and liquid nitrogen, and overall control is accomplished using a West 5010 Temperature Controller. The temperature controller employs fuzzy logic to iterate between applying heat and liquid nitrogen to control the temperature within 0.1 °C, which is measured using a thermocouple attached to the face of the sample.

Characterization of material samples using this cell requires samples to be mounted to a 3-inch diameter disk (made of aluminum or stainless steel). Electrical contact to the samples is performed through a vacuum feedthrough mounted to the rear of the chamber. Currently, there are 16 available connections.

A typical experiment involves measuring the series resistance by applying a voltage using a Xitron 2000 Voltage Source and measuring the resulting current using a Keithley 6485 Picoammeter. For one of the samples shown in Figure 3A, the resistance was monitored as the pressure was increased from vacuum to 30 psia and back (Figure 4). The resistance increases as the pressure increases, however, it does not recover as the pressure is decreased back to near vacuum. With this sensor, the applied voltage was 0.2V. The second sensor was then tested with an applied voltage of only 0.002V, and no change was observed in the resistance as the pressure was cycled up to 50 psia. This was to be expected as there should be no change in the conducting pathways under these conditions. The change in the resistance in the first sample was thought to be due to Joule heating of the sample from the larger applied voltage. To test this concept, the second sensor was kept at 14.7 psia, and the resistance monitored over time at 0.002V and 0.2 V (as seen in Figure 5). When the smaller voltage is applied, there is no change.
in resistance over time; however, when more voltage is applied, the resistance steadily increases, possibly due to temperature effects between the electrodes (the overall temperature of the disk did not change, but currently there is no way to measure the temperature between the electrodes).

**Figure 4:** Resistance as a function of pressure for sensor with 0.2V applied. The arrows designate the direction of pressure change.

**Figure 5:** Resistance monitored over time at 0.002V and 0.2V.
**SWNT Dispersion and Chirality Characterization**

- Dispersed in ethanol and characterized via AFM three samples synthesized at GMA Industries, Inc. containing:
  1.) alcohol-functionalized SWNTs
  2.) fluorine-functionalized SWNTs
  3.) by-product during formation of alcohol-functionalized SWNTs

Sample 2 showed bundles of SWNTs as deposited on oxidized Si substrates (see image below). Also, performed preliminary demonstration of dielectrophoretic deposition of the fluorine-functionalized SWNTs between metal electrodes.

![AFM Image](image.png)

**Electrical and Magnetic Characterization of SWNT composites**

Magnetic properties of pure polyimide characterized to enable baseline correction for SWNT polyimide composite characterizations.

Temperature dependence of magnetization of SWNT/polyimide composites with weight fractions of 0.1 – 20% analyzed over range from 10 – 300 Kelvin. Saturation magnetization as a function of temperature shows saturation magnetization and critical temperature is dependent upon SWNT volume concentration.

Surface resistance of MWNT and carbon fiber composite measured and analyzed as a function of carbon weight percent. Angular dependence of resistance measured and analyzed to determine anisotropy associated with flow direction. No correlation was found.

Surface resistance of SWNT, MWNT, and carbon fiber composite coupons measured.