

Transparent Film Sensor for Strain Measurement Using Carbon Nanotube Networks

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ABSTRACT

Recently, experimental results show that sing-wall carbon nanotubes (SWCNTs) change their electronic properties when subjected to strain. In this study, the strain sensing characteristics of SWCNTs networks were investigated to develop a transparent film sensor for strain sensing. The SWCNTs film are formed on flexible substrates of poly(ethylene terephthalate) (PET) using spray process. In this manner we could control the transparency and obtain excellent uniformity of the networked SWCNT film. The carbon nanotube film is isotropic due to randomly oriented bundles of SWCNTs. Using experimental results it is shown that there is a nearly linear change in resistance across the film when it is subjected to tensile stress. The results presented in this study indicate the potential of such films for high sensitive transparent strain sensors on macro scale.

Keywords: SWCNT film, Strain sensor, Spray deposition, Electromechanical properties, Gage factor

1 INTRODUCTION

Since their discovery, carbon nanotubes (CNTs) have been proposed for numerous potential application because of their remarkable mechanical and electrical properties. Many promising applications, including reinforcements for composites,¹ electron field emission source,² atomic force microscopy probe tips,³ nanotweezers,⁴ nanoactuators,⁵ nanobalances,⁶ nanowires,⁷ etc, have been reported. More recently, one of the potentially important applications is motivated by the fact that CNTs can be used as component of nano-electromechanical systems.⁸ The experimental investigations⁹ on the change in conductance of metallic and semiconducting carbon nanotubes due to mechanical deformations suggest that carbon nanotubes are potentially useful as high-sensitivity electromechanical sensors. Most studies focused on the change in electrical properties on a nano scale as mechanical deformation is induced. Several experiments¹⁰⁻¹² have demonstrated the potential of single-walled carbon nanotubes (SWCNTs) as strain/stress sensors by relating the strain/stress of the nanotube to the Raman band shift. The electronic bandgap changes have been computed as a function of axial compression, tension stretch, torsion, and bending strain.¹³ However, Raman spectroscopy is not a practical sensing technique in the field of engineering because of its complexity. Dharap et al¹⁴ investigated the strain characteristics of carbon nanotube

films, also called bucky papers fabricated by vacuum filtration of SWCNTs solution and showed the potential of measuring multidirectional strain. In this study, the strain sensing capability of SWCNT film on the macro scale is investigated experimentally. The spray method with purified SWCNTs is applied to fabricate SWCNT film. In this manner we could control the transparency and obtain excellent uniformity of the networked SWCNT film in large area with fast processing time. We proposed the use of transparent carbon nanotube films with isotropic properties due to the random orientation of SWCNTs as strain film sensor and investigated its strain sensitivity performance.

2 EXPERIMENT

2.1 SWCNT Film Fabrication

Purified SWCNTs were grown by using the arc discharge technique. We choose the spray deposition method to fabricate the transparent SWCNT films on a poly(ethylene terephthalate) (PET) substrate. First, the SWCNT samples were purified using standard processes, such as centrifugation, acid treatment, and membrane filtration. The SWCNTs were then dispersed in deionized water with a 1 wt % sodium dodecyl sulfate (SDS) solution and sonicated for several hours. The film transparency was modulated by adjusting the volume of the SWCNT solution between 0.5 and 4.0 mL. This resulted in SWCNT films with a transparency of 75-95% and a sheet resistance of 230-3500 Ω m⁻². The CNT film was sprayed on the front of the PET substrate pre-coated with adhesive layer and Pt electrode layer were deposited to the specimen end by sputtering for resistance measurement as shown in Fig. 1.

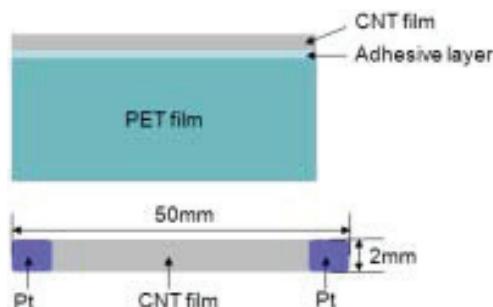


Figure 1: Schematic diagram of a SWCNT film on a PET substrate with an Pt electrode pair

To increase the adhesive strength between SWCNT film and substrate, samples are heated using two methods. One is microwave (MW) oven heating with condition of power of 800 W and time of 5 min and the other one is rapid thermal processing (RCP) in nitrogen atmosphere for 10 min in temperature of 110 °C, which is reactive temperature of the pre-coated adhesive layer. Optical and scanning electron microscopy (SEM) images of the fabricated SWCNT film on PET substrate are shown in Fig. 2 and 3.

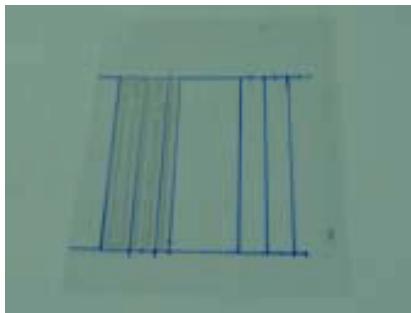


Figure 2: Optical image of specimen

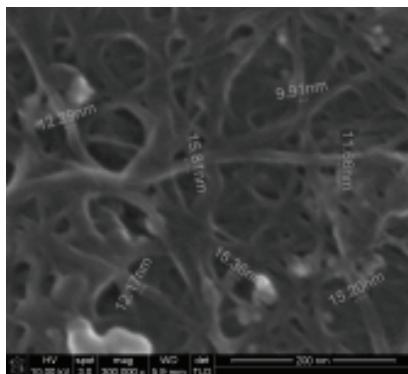


Figure 3: SEM images of the surface morphology observed in SWCNT films

It was observed that highly entangled SWCNT bundles held together by van der Waals forces on PET surface.

2.2 SWCNT Film Characterization

In order to test the macro-scale strain sensing characteristics, tensile test is performed with PET substrate with CNT films using tensile-fatigue machine (Tytron 250, MTS Co.). The specimen is fixed with grippers and loading is induced using load cell with force of 250 N. The gage length is defined as a distance from each grip. The specimen displacement and change of resistance of the film were simultaneously measured to find the sensitivity of the sensor. A constant source current was applied to the specimens during testing and the voltage was measured to calculate the resistance changes. Specimen resistance was measured using a voltage-current meter which has

extremely low voltage sensitivity (Keithley 6400) and resistance, load, strain data were integrated using a customized computer interface written in Lab View. All experiments were done after being conditioned in the laboratory environment (23 °C and 35% relative humidity). The schematics and photography of experimental setup to test the tensile response of the film is shown in Fig. 4.

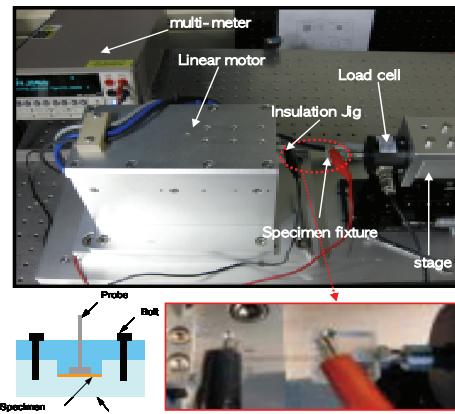


Figure 4: Experimental setup for micro tensile test and measurement of electromechanical properties of SWCNT film

3 RESULTS AND DISCUSSION

The PET/SWCNT film specimens are subjected to tension in a micro-tensile machine and a current is passed through the grips. Proper contact between the grips and the film is ensured so that the voltage across the grips is stable. Load is applied in increments and held constant for several seconds until stable readings are obtained. The measured load-strain curves for specimens are plotted in Fig. 5.

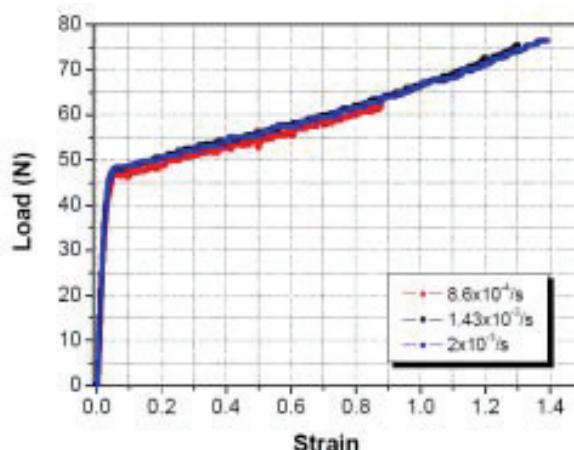


Figure 5 Load-strain curves of SWCNT/PET specimens w/ and w/o post process

For evaluation of carbon nanotube film for tensile stress, specimens were loaded with three strain rates of 8.6×10^{-4} , 1.43×10^{-3} , and 2.0×10^{-3} /s. Stress-strain behavior for varying strain rates was not critically changed and shows a nearly linear response, corresponding to tensile yield strength and elastic modulus (E), 191 MPa and 3.35 GPa, respectively. To investigate the effect of the adhesive force between CNT film and substrate, specimens treated using RTP and microwave process were tested with strain rate of 8.6×10^{-4} /s as shown in Fig. 5. Experimental results show that higher tensile yield strength of the specimen with post processing increases by 8% from 191 to 207 MPa, and the elastic modulus increases by 36% from 3.35 to 4.45 GPa. It is expected that post processing strengthen the plastic substrate itself by thermal hardening of polymer and also interfacial force between nanotube film and PET substrate.

To test the electromechanical properties input current of 0.01 mA across two grips is kept constant during the measurement and changes in voltage across the grips, as well as the strains are measured. The change in the resistance of the nanotube film is converted in a normalized change of resistance (R_N):

$$R_N = \frac{R - R_0}{R_0} \quad (1)$$

where R_0 is the resistance without any displacement or strain and R is the measured film resistance when the specimen is strained. Figure 6 shows the change of resistance of the specimen with respect to the change of strain.

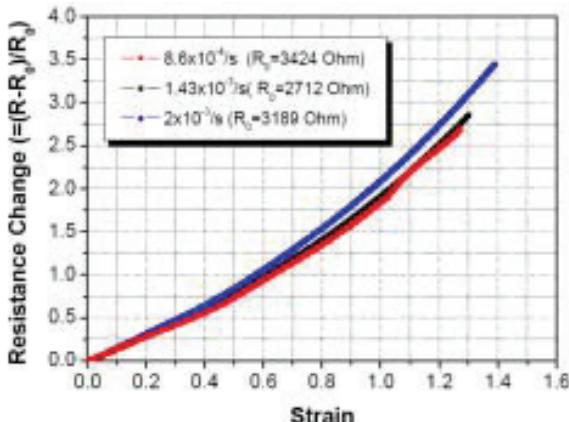


Figure 6: Change of electrical resistance of SWCNT/PET specimens w/ w/o post process as a function of strain in the specimen.

In this experiment, the slope of the curve represents the sensitivity of CNT film. The data shown are the average values of four strain measurements for each specimen. The strain response of CNT film shows a higher sensitivity and

linearity even in structural deformation range. Ideally, strain applied to the specimen is transferred to the nanotube film. However, the CNT film has some slippage among the nanotubes in bundles because there is only weak bonding due to the van der Waals interactions at the junction points of the nanotubes. This may degrade strain measurements as shown in Fig. 5. Thus, a SWCNT film deposited specimen was fabricated to improve strain transfer across the nanotube film by means of better interfacial bonding using pre-coated adhesive and post processing as mentioned above. The sensitivity of the strain sensor is defined as the gage factor (S_g) which relates the change in resistance to the axial strain (ϵ_a)¹⁵. From the definition of gage factor, the gage factors of each film sensor can be found using equation (2) and they are the slope of the curves in figure 5:

$$S_g = \frac{\Delta R_N}{\Delta \epsilon} \quad (2)$$

Compared to specimen without post processing, the gage factor of interfacial bonding enhanced specimen is dramatically improved by 346% from 1.3 to 5.8 in case of micro wave treatment and by 500% from 1.3 to 7.8 in case of thermal heat treatment, respectively. These results show a higher sensitivity than previous results¹³⁻¹⁴ with thick buckypaper of ~10 μm. The results are very encouraging and indicate the potential of such thin film for high sensitivity and multidirectional strain sensors on the macro scale.

4 CONCLUSIONS

Electromechanical properties of carbon nanotube film on plastic substrate were measured using a micro-tensile machine with functionality of simultaneous measurement of displacement, load and electrical resistance. The CNT thin film deposited on PET substrate using spray process formed uniform network and maintained the transparency of 75-95%. The effect of post process conditions on the electromechanical properties was investigated. Based on the experimental results, heat treatment specimen shows dramatic increase of gage factor. It is expected that high sensitivity thin film strain sensor could be fabricated in mass production way.

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