Nanotechnology **15** (2004) 379–382 PII: S0957-4484(04)70449-3

Nanotube film based on single-wall carbon nanotubes for strain sensing

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Received 15 October 2003, in final form 5 December 2003
Published 13 January 2004
Online at stacks.iop.org/Nano/15/379 (DOI: 10.1088/0957-4484/15/3/026)

Abstract
Carbon nanotubes change their electronic properties when subjected to strains. In this study, the strain sensing characteristic of carbon nanotubes is used to develop a carbon nanotube film sensor that can be used for strain sensing on the macro scale. The carbon nanotube film is isotropic due to randomly oriented bundles of single-wall carbon nanotubes (SWCNTs). Using experimental results it is shown that there is a nearly linear change in voltage across the film when it is subjected to tensile and compressive stresses. The change in voltage is measured by a movable four-point probe in contact with the film. Multidirectional and multiple location strains can be measured by the isotropic carbon nanotube film.

(Some figures in this article are in colour only in the electronic version)

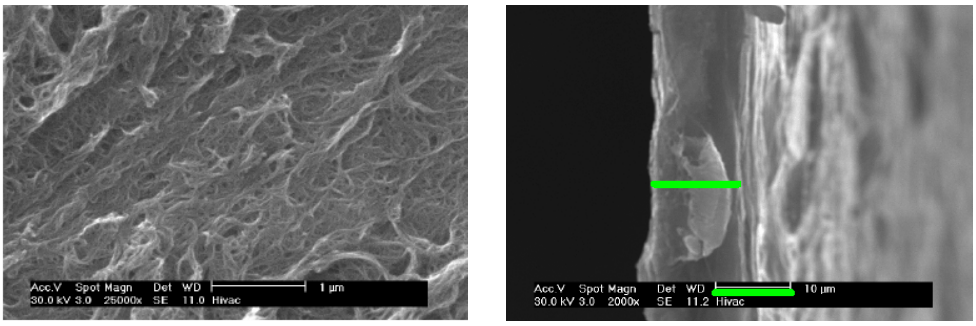
List of symbols:

ρ_s	sheet resistivity of the carbon nanotube film
V	voltage across the inner two probes
I	constant current across the outer two probes
$C\left(\frac{a}{d}, \frac{d}{s}\right)$	constant depending on the dimension of the carbon nanotube film
a	length of the carbon nanotube film
d	width of the carbon nanotube film
s	distance between two probes in the four-point probes
V_1	voltage across the inner two probes at 0% strain
V_2	voltage across the inner two probes at 0.04% strain
C_1	constant depending on the dimension of the carbon nanotube film at 0% strain
C_2	constant depending on the dimension of the carbon nanotube film at 0.04% strain
ΔV	change in voltage across the inner two probes due to change in the dimension of the carbon nanotube film as strain increases from 0% to 0.04%

1. Introduction

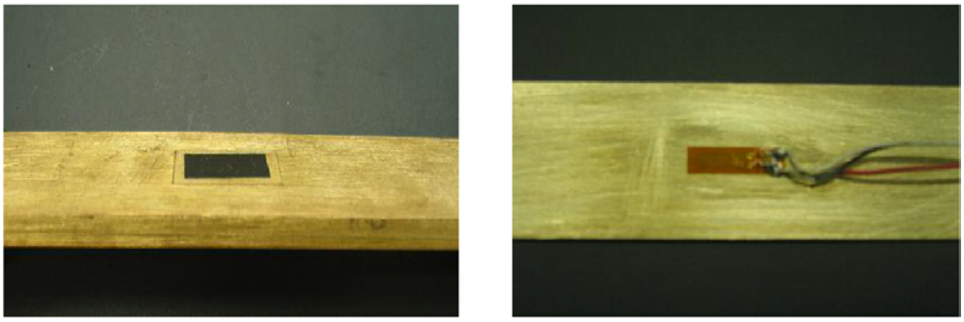
Strain sensors are important in many fields of science and engineering. One of the main limitations of existing conventional sensors such as strain gauges is that they are discrete point and fixed directional sensors, and are separate from the material or structure that is being monitored; hence, not embedded at the material level. There is a need to develop new sensors that can be embedded into the material and can be used for multidirectional and multiple location sensing.

Single-wall carbon nanotubes offer attractive alternatives for developing new sensors because of their superior mechanical and electrical properties. In addition, they can be used as fibres in composites for producing a high strength material capable of strain sensing. To date, several experiments [2, 10, 11, 14] have studied the effect of mechanical strains on the electronic properties of SWCNTs on the nanoscale. Peng *et al* [11] have reported that carbon nanotubes have mechanical deformations such as bending, twisting or flattening and these influence the electronic properties. Tombler *et al* [14] have concluded that the voltage across a SWCNT can be reduced by two orders of magnitude when it is deformed by an AFM tip. Baughman *et al* [1] used carbon nanotube films, also called buckypapers, as actuators. Results showed that large actuator strains can be achieved by smaller operating voltages compared with ferroelectric and electrostrictive materials. SWCNTs are Raman active and many researchers have studied the effect of stress or strain on the Raman-active modes. Recently, researchers have presented results about the Raman shift at $\sim$1590 cm^{-1} [6, 9], called the G band shift, due to the tensile strain in nanotubes. Similar



(a) (b)

Figure 1. SEM image of the carbon nanotube film: (a) carbon nanotube film made up of entangled bundles of SWCNTs; (b) thickness of the carbon nanotube film.



(a) (b)

Figure 2. (a) Carbon nanotube film with insulating PVC film attached to the brass specimen; (b) metal strain gauge attached on the opposite side.

Raman studies on multiwall carbon nanotubes have also been reported [12, 15].

To date, most studies [2, 4, 10, 11, 14] relate the mechanical deformation to the change in electrical properties on the nanoscale. The main objective of this study is to use the strain sensing capability of SWCNTs on the nanoscale to develop a strain sensor on the macro scale. The use of carbon nanotube films with isotropic properties, due to the random orientation of SWCNTs, is proposed; such films can be applied to structural surfaces such as the skin of an aircraft to measure strains. It is difficult to implement Raman spectroscopy for strain measurements in field applications, due to bulky hardware, such as the measurement of strain in an aircraft wing. The use of external probes to measure strain by contact with carbon nanotube films is proposed: the probes can be easily moved to a different direction or location to sense multidirectional and multiple location strains on the macro scale. Carbon nanotube films can be integrated into the material, for example in composites, and can function as sensors and structural material as well [15]. The ability of such films to measure strains on the macro scale is demonstrated by experimental results.

The carbon nanotube film is produced by mixing unpurified SWCNTs from Carbon Nanotechnologies Incorporated (CNI) with 0.25 mg ml^{-1} N,N-dimethylformamide (DMF). The mixture is filtered by a 0.2 mm Teflon membrane. The film (buckypaper) is peeled from the filter after drying. Then the film is further dried for 24 h under vacuum and heat. Figure 1(a) shows the scanning electron microscope (SEM) image of the carbon nanotube film where it can be seen that the film is composed of mechanically entangled randomly oriented nanotube

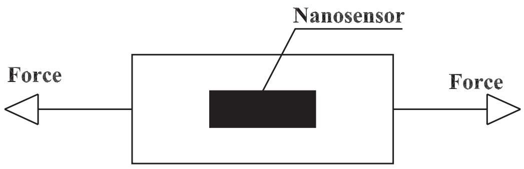


Figure 3. Schematic of the brass specimen under tension and compression.

bundles, due to which it has isotropic electronic properties [5]. Figure 1(b) shows the 10 μm thick carbon nanotube film measured by SEM.

The carbon nanotube film is attached to a 12 × 1.5 × 0.25 inch^3 brass specimen having a Young's modulus of 166 GPa, shown in figure 2(a). A PVC film is attached, between the carbon nanotube film and the conducting brass specimen, by high strength epoxy for perfect strain transfer and for insulation, as shown in figure 2(a). The vacuum bonding method [8] is used to ensure that the epoxy produces a firm, thin and stiff bond such that no slippage occurs between the brass specimen, PVC and the carbon nanotube film. Figure 2(b) shows an electrical resistance strain gauge attached to the brass specimen on the opposite side of the brass specimen for strain measurement comparisons. A schematic of the brass specimen is shown in figure 3.

A four-point probe is used to measure voltage changes in the carbon nanotube film. The brass specimens are subjected to tension as well as compression cycles in a servo hydraulic test frame and a current is passed through the outer two probes. Proper contact between the probes and the film is ensured

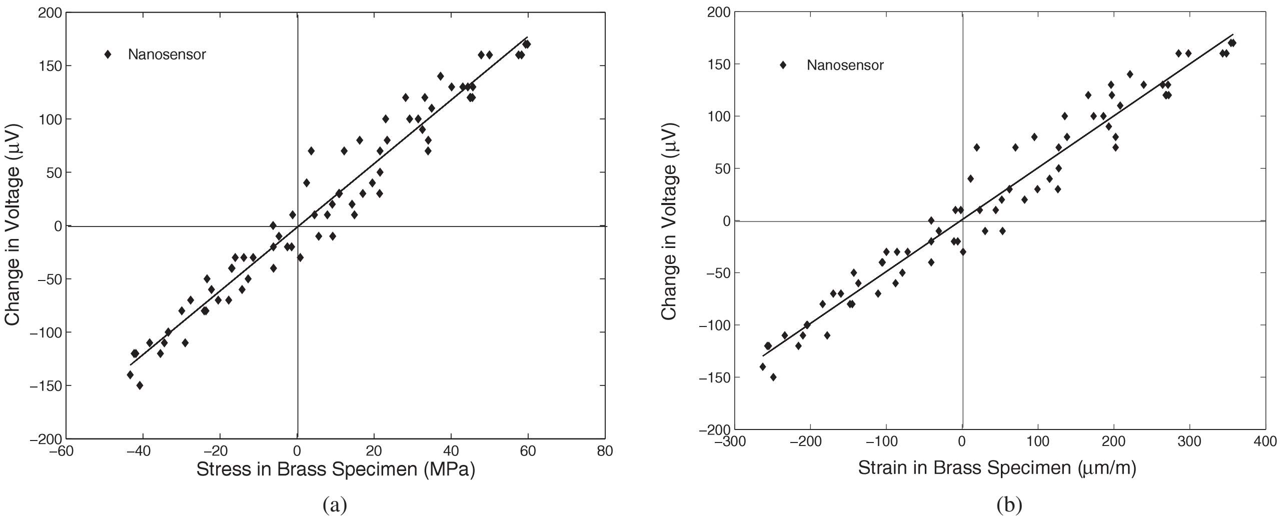


Figure 4. Specimen subjected to tension and compression cycles. (a) Change in voltage in the carbon nanotube film as a function of stress in the brass specimen; (b) change in voltage in the carbon nanotube film as a function of strain in the brass specimen.

so that the voltage across the inner two probes is stable. Load is applied in increments and held constant for several seconds until stable readings are obtained. Input current across two outer probes is kept constant during the measurement and changes in voltage across the two inner probes, as well as the strains from the strain gauge, are measured. The brass specimen is in the elastic range during the tension and compression cycles.

The change in voltage varies nearly linearly for specimens subjected to both tension and compression cycles, as shown in figure 4(a). For comparison, the change in voltage across the inner two probes for the carbon nanotube film is plotted against the strain readings from the conventional strain gauge in figure 4(b). A nearly linear relation exists between the change in voltage measurements obtained from the nanosensor and the strain gauge readings. Additionally the change in voltage is measured using a four-point probe in several parallel (in line with the axial forces) locations on a single carbon nanotube film sensor. Such multilocation sensing also leads to a nearly linear relationship between the change in voltage and strain.

The change in voltage across the inner two probes is partly due to the change in the dimension of the carbon nanotube film and is mainly due to the change in resistivity of the film. Since in the case of brass specimens the measured axial tensile strains are of the order of 0.04%, the changes in the dimensions of the film will be small; their contribution to the change in voltage will also be small, which is shown next. The film (sheet) resistivity measured using a four-point probe is given by [13]

$$\rho_s = \frac{V}{I} C\left(\frac{a}{d}, \frac{d}{s}\right) \tag{1}$$

where V is the voltage across the inner two probes, I is the input current across the outer two probes and $C(\frac{a}{d}, \frac{d}{s})$ is a factor that depends upon the dimension of the film (a is the length of the film, d is the width of the film and s is the distance between the two probes in a four-point probe). Let us assume that the resistivity ρ_s of the carbon nanotube film remains constant as the strain changes from 0% to 0.04%:

$$\rho_s = \frac{V_1}{I} C_1\left(\frac{a}{d}, \frac{d}{s}\right) \qquad \text{at 0.0\% strain} \tag{2}$$

$$\rho_s = \frac{V_2}{I} C_2\left(\frac{a}{d}, \frac{d}{s}\right) \qquad \text{at 0.04\% strain} \tag{3}$$

where V_1 and V_2 are the voltages across the inner two probes at 0% strain and 0.04% strain, respectively. C_1 and C_2 are the corresponding constants depending upon the dimensions of the carbon nanotube film. The current I is kept constant. The corresponding constants [13] $C_1 = 2.190\,560$ at 0% strain and $C_2 = 2.190\,314$ at 0.04% strain are obtained. Subtracting equation (2) from (3) gives

$$\Delta V = \rho_s I\left(\frac{1}{C_2} - \frac{1}{C_1}\right) = 21\ (\mu\text{V}). \tag{4}$$

For the results presented in figure 4, the change in voltage is about 170 μV. It can be seen that the change in voltage due to the change in the dimensions of the carbon nanotube film is small (~12%) and the rest of the change in voltage is due to the change in resistivity (~88%). Hence, it can be concluded that the change in voltage is mainly due to the change in resistivity of the film.

The deviation from the linear trend in the recorded data shown in figure 4(a) needs further investigation. One of the factors could be the temperature around the carbon nanotube film during the experiment. Hone *et al* [7] and Bezryadin *et al* [2] have observed that the resistance of a carbon nanotube changes with temperature. Further study is necessary to quantify the effect of temperature on the change in electronic properties due to strain. Exposure to different gases is also another factor that affects the electronic properties of the carbon nanotubes. Collins *et al* [3] have reported that the electronic properties of a given nanotube are not only specified by the diameter and chirality of the nanotube but also by its gas exposure history.

2. Conclusion

The effectiveness of carbon nanotube films in measuring strain on the macro scale has been investigated experimentally. It can be concluded from the results of this study that there is a nearly linear relationship between the measured change in voltage and the strains in the carbon nanotube films. The results presented in this paper are very encouraging and indicate the potential of such films for multidirectional and multiple location strain sensors on the macro scale.

Acknowledgments

The authors wish to acknowledge the support of the Texas Institute for the Intelligent Bio-Nano Materials and Structure for Aerospace Vehicles, funded by NASA Cooperative Agreement no. NCC-1-02038.

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