Multi-walled Carbon Nanotube Film as Strain Sensors for Structural Vibration Control

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ABSTRACT

We have studied the possibility of using multi-walled carbon nanotube (MWCNT) film as strain sensors for structural vibration control. The MWCNT films were prepared by solution/filtration method and were bonded directly onto specimens by nonconductive adhesive, conventional strain gages were also bonded to the structure on the opposite side for comparison. The specimens then underwent uniaxial tensile load-unload cycle to evaluate them as strain sensors. To assure good electrical contact between carbon nanotube film and the wires, a thin layer of copper was thermal deposited on both ends of the film as electrodes, the wires were connected to the electrodes by silver ink. A Wheatstone bridge was used to convert the resistance changes of MWCNT to voltage output. Results indicated the output voltages were proportional to the strain readings from the stain indicator. The temperature effect on the resistance was measured and the MWCNT film resistance was found to be temperature-independent over the range 273 K-363 K. Optimal film dimension for strain sensing was evaluated as well. Our results indicated that MWCNT film is potentially useful for structural health monitoring and vibration control application.

Keywords: multiwalled carbon nanotube, resistance, strain sensor, vibration control

1 INTRODUCTION

Mechanical strain sensors are widely used for the structural health monitoring and vibration control. Traditional strain sensors such as strain gauge are sensitive, stable, low cost and easy to use. However, stain gauges can only measure the strains on the structural surface in designated directions and locations; also strain sensing is usually the only function they can offer. Hence, there is a need for developing new type of strain sensors, which can function on both the micro- and macro-scale, either on the surface or embedded in the structure, and be able to make extra contributions like strengthening or dampening the structures served as well, i.e., behave as multifunctional materials/components.

Since their discovery by Iijima [1] in 1991, carbon nanotubes (CNTs) have been intensively investigated. Their amazing properties make them potential candidates for numerous applications. Both individual SWCNT (single-walled carbon nanotube) and MWCNT were found to exhibit a repeatable load-unload relationship between their mechanical deformation and the electrical conductance [2, 3, 4 and 5], which implies the potential of using CNTs as strain/stress sensors. Recently, CNTs were reported be able to serve as stress sensors by measuring the Raman D* band shift after been embedded into the polymer matrix [6]. A more recent study by Dharap et al [7] showed that pure SWCNT films ("bulky paper") can also serve as strain sensors if they were bonded to the structural surface as conventional strain gauges. A nearly linear relationship between the applied strain and the film resistance change was observed. Besides pure SWCNT films, CNT composite films function as strain sensors were also reported by several research groups: Pham et al [8] fabricated Poly (methyl methacrylate) (PMMA)/MWCNT composites films with different concentrations of MWCNT for strain sensing. Knite and co-works [9] reported a new type of polyisoprene/MWCNT composite strain sensors. Kang et al [10] and Loh et al [11] reported the using of CNT/polymer composites as strain sensors for structural health monitoring. In a similar application, Ramaratnam and Jalili [12] successfully employed the poly-vinylidene floride (PVDF)/CNT composites as dynamic sensors for structural vibration control.

Although some progress has been made on using CNTs for strain sensing, there are still many problems unsolved, like the temperature effect, chemical effect, size effect, stability [11] and linearity [8]. On the other hand, all the research previously mentioned were focused either on pure SWCNT or CNT/polymer composite while pure MWCNT film for strain sensing has yet been explored. Thus, a study on the pure MWCNT film as strain sensors is needed, as to provide comparisons for both pure SWCNT film sensors and the CNT/polymer composite sensors. We report herein the observation of pure MWCNT film resistance changing with applied strain, the temperature effect measured and the optimal sensor dimension, as well.

2 EXPERIMENTAL SETUP

The freestanding MWCNT films (bulky paper) were purchased from Nano-Lab Inc. (Newton, MA) and used "as is". Detailed information about preparation of the MWCNT film can be found from the company website. The film was made of hollow-structured MWCNTs with 15±5 nm in outer diameters, about 5-20 microns in length and purity

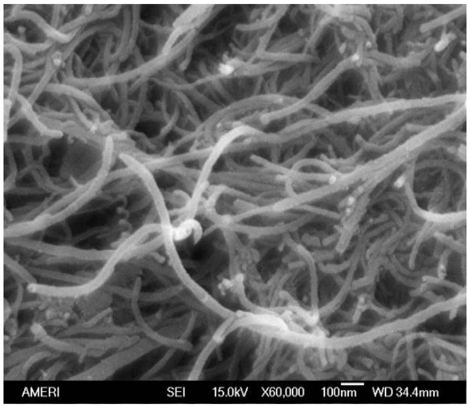

Figure 1: SEM image of the MWCNT film

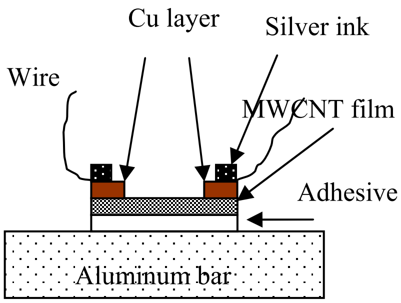

Figure 2: contact treatment of MWCNT film

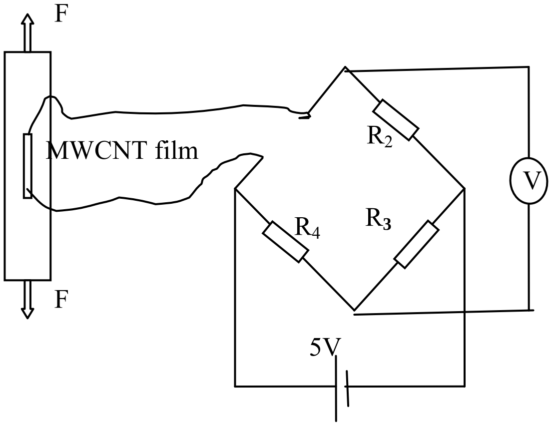

Figure 3: Wheatstone bridge setup for tensile test

label	Size		before sealing		after sealing		source
	L	W	R_0 (Ω)	R_{sheet}	R' (Ω)	R_{sheet}	
1	1"	1"	12.92	12.92	36.60	36.60	A
2	1"	0.5"	20.46	10.23	30.93	15.46	B
3	1"	0.5"	25.19	12.60	40.72	20.36	C
4	1"	0.25"	38.77	9.69	52.52	13.13	C
5	1"	0.125"	72.66	9.08	185.90	23.24	C
6	0.5"	0.5"	37.35	37.35	68.38	68.38	D
7	0.5"	0.25"	35.26	17.63	130.12	65.06	D
8	1"	0.08"	169.77	13.58	312.50	25.00	E
9	1"	0.2"	73.16	14.63	140.01	28.00	E
10	2"	0.3"	94.18	14.12	178.88	26.83	E

Table 1: sample resistance

higher than 95%. The thickness of the film is around 0.13mm and relative density is about 50%. In order to increase the flexibility of the MWCNT film, a few drops of latex rubber cement (in decane) were sprayed on the surface of the film and then air dried. A scanning electron microscopy (SEM) image of the film is shown in Figure 1. We conclude that the film is composed of randomly tangled, 3D networks of MWCNTs, due to which we consider the film electrical property to be isotropic.

Good electrical contacts were achieved by first depositing a thin layer (1μm) of copper on both ends of the film as electrodes by vacuum thermal deposition method, then connecting the wires to electrodes by silver ink, as showed schematically in Figure 2. In order to determine the optimal MWCNT film dimension for strain sensing, we also sized the films into variable dimensions. The sample resistances were typically between 30 to 300 **Ω**. Table 1 listed the detailed parameters of all the samples. The sheet resistance is defined as:

$$R_{sheet} = R_{measured} \frac{W}{L} \tag{1}$$

$$R_{measured} = R_{contact} + R_{MWCNT} \tag{2}$$

with *W* and *L* being the width and length of the film, respectively. The measured resistance included the contact resistance and the intrinsic resistance of the MWCNT film. If the MWCNT resistance dominates the contact resistance, and represents $R_{measured}$, the sheet resistances with different dimensions, but cut from the same source, should have close values. From Table 1's results for the same source we can deduce that this is the case, and we can conclude that good contacts had been achieved by the thermal coating treatment. Sample #4 is an outlier due to possible damage.

The strain sensing tests were carried out by direct tension with load and unload cycles on MTS 858 MimiBionix test machine. The test scheme is shown in Figure 3. The MWCNT films were bonded to the center of the specimen by nonconductive 3M CA100 liquid adhesive. A strain gauge was also bonded to the specimen on the other side for comparison. The MWCNT film and three resistor substitutes with the resolution of 1 ohm were used to construct a Wheatstone bridge, which will convert the resistance changes of MWCNT to voltage output. Load speed was controlled to be 0.01 inch per minute. The power source was maintained at 5 volt by BK precision multi-meter.

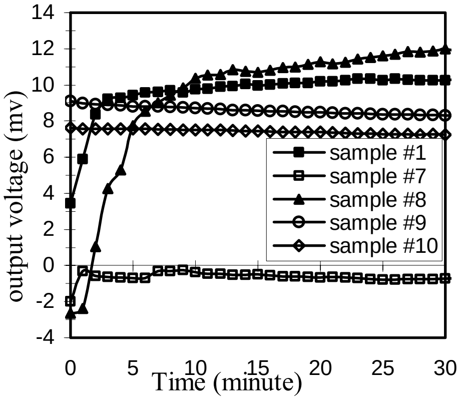

Figure 4: zero load drift test

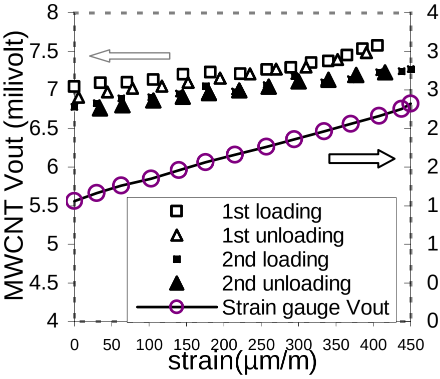

Figure 6: loading and unloading circle

In order to eliminate those possible chemical effects, the films were separated from environment by sealing the MWCNT films with three layers of adhesive, which was brushed onto the top of the film successively when the previous layer was air dried. The sheet resistance of the film after sealing typically doubled. Considering that the relative density of the MWCNT film is 50%, this increment is reasonable.

3 RESULTS AND DISCUSSION

The resistances of MWCNT film were first measured under zero-load condition to evaluate the sensor stability. Figure 4 plots the test results of some samples. The drift test indicated that the samples can be classified into three groups: the unstable group, which included sample #2, #3, #4, #5and #6 (not plotted in Figure 4), the resistance of those samples kept increasing during the entire period of drift testing, which means they were not suitable for sensing test; the unstable-stable group included sample #1, #7 and #8; resistance increased rapidly in the beginning and then gradually became stable; and the stable group, which included sample # 9 and # 10, the desired group for sensing application. Their resistances were kept as constants.

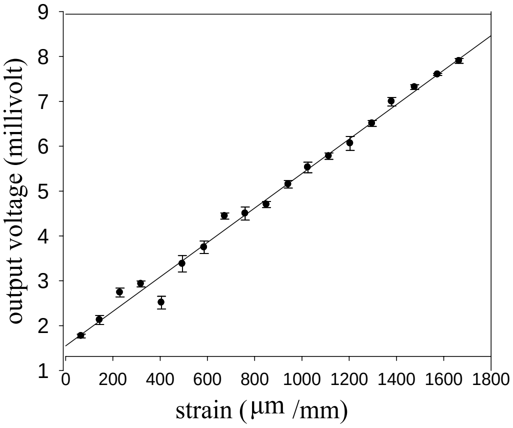

Figure 5: output voltage vs. strain

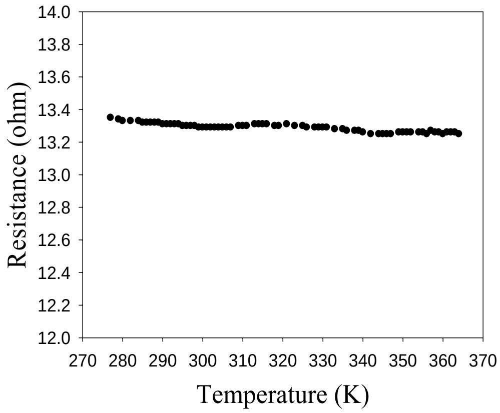

Figure 7 MWCNT resistance vs. temperature

Ours is not the only group which has had this zero-load unstable signal problem; other research groups confronted the same situation [8, 10, and 11]. We think this may result from CNT shell structure defects and breakdown. According to the simulation work by Son et al [13], the defects in the CNTs can dramatically change the resistance of SWCNT under electrical field (up to three orders). Dohn et al [5] observed the MWCNT resistance increased sharply when the applied current across the MWCNT reached 600 μA to 1000 μA, which indicates a breakdown of the shell structure. However, Wei [14] reported an opposite case where the resistance of a single MWCNT was measured by applying high current (10 mA) at high temperature (250 C) for a long time (two weeks continuously) in the air. The resistance was reported to be fluctuating yet no observable defects were found after the test. The cause for the unstable signal needs further investigation.

Figures 5 and 6, show the Wheatstone voltage output as the function of strain. Clearly a linear correlation between the film output and the strain gage reading can be seen. The test results of strain sensing are repeatable as shown in Figure 6.

Of all the specimens, sample #10 gave us the best results for the loading-unloading test. We consider the shape of sample # 10 to be the optimal sensor shape. This is reasonable due to its dimension, and since it has the longest sensing strip along the tensile direction and a moderate resistance. We can calculate the gauge factors, which are the criterions for sensitivity by

$$GF = \frac{\Delta R}{R\varepsilon} \tag{3}$$

The calculated gage factor for specimen #1, non-seal treated specimen #10 and the seal-treated specimen #10 are: 3.09, 3.76 and 2, all are close to the gage factor of strain gages. However, we believe, a high purity MWCNT film and well aligned MWCNT film may provide better results and this is our next step and the ongoing research.

Mendoza [15] reported a remarkable resistance decrease of pure MWCNT mat with the increase of temperature between the ranges of 100 K to 430 K, which suggested a semi-conductive property. Koratkar et al [16] reported a similar semi-conductive behavior for well-aligned MWCNT films. A detailed measurement of resistance vs. temperature was carried out. The measurement was achieved by sealing the samples in waterproof plastic bag and soaked in the water tank. The temperature increment of the water was one degree per step. Our results are shown in Fig 7. The resistance only dropped 0.1 ohm over the range of 273 K to 363 K, for which we can consider the MWCNT resistance is virtually temperature independent in that temperature range. This behavior was similar to that of the properties of amorphous carbon [17] and agreed with the results in [15] and [16]. Our result clarified the temperature effect on the resistance change as questioned by [7, 8 and 11].

4 CONCLUSION

We have studied the possibility of using Multi-walled carbon nanotube (MWCNT) film for strain sensing. Reliable electrical contact was achieved by thermal deposition of a thin layer of copper electrodes. Uniaxial load-unload tensile test to was carried out. Results indicated that the MWCNT film resistance change was proportional to the applied stain. The temperature effect on the resistance was measured as well and the resistance was found to be temperature-independent over the range 237 K-363 K. Our results indicated that MWCNT film is potentially useful for structural health monitoring and vibration control application.

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REFERENCES

[1] S. Iijima, Nature 354, 56-58, 1991.
[2] T.W. Tombler, C. Zhou, L. Alexseyev, J. Kong, H. Dai, L. Liu, C.S Jayanthi, M. Tang and S.Y. Wu, Nature, 405, 6788, 769-772, 2000.
[3] E.D. Minot, Y. Yaish, V. Sazonova, J. Y. Park, M. Brink and P. L. McEuen, Physics review letter, 90, 15, 156401, 2003.
[4] V. Semet, V. T. Binh, D. Guillot, K.B.K Teo, M. Chhowalla, G. A. J. Amaratunga, W.I. Milne, P. Legagneux and D. Prilbat, Applied physics letters, 87, 223103, 2005.
[5] S. Dohn, K. Molhava and P. Boggild, Sensor letters, 3, 4, 1-4, 2005.
[6] Q. Zhao, M. D. Frogley, D. H. Wagner, Composites Science and Technology, 62, 1, 147-150, 2002.
[7] P. Dharap, Z. Li, S. Nagarajaiah and E.V Barrera, Nanotechnology, 15, 379-382, 2004.
[8] G. T. Pham, Y. B. Park and B. Wang, Manufacturing Engineering Division, 16-2, 987-993, 2005.
[9] M. Knite, V.Tupureina, A. Fuith, J. Zavickis and V. Teteris, Materials science and engineering C, (article in press) 2006
[10] I. Kang, M. J. Schulz, J. H. Kim, V. Shanov and D. Shi, Smart materials and structures, 15, 737-748, 2006.
[11] K. J. Loh, J. P. Lynch, and N. A. Kotov, Proc SPIE Int Soc Opt Eng, 6174 I, 61741Z, 2006.
[12] A. Ramaratnam and N. Jalili, Proceedings of the ASME Dynamic Systems and Control Division, 73, 1 part A, 533-539, 2004.
[13] Y. W. Son, J. Ihm, M. L. Cohen, S. G. Louie and H. J. Choi, Physical review letters, 95, 21, 216602, 2005.
[14] B. Q. Wei, R. Vajtai and P.M. Ajayan, Applied Physics Letters, 79, 8, 1172, 2001.
[15] D. Mendoza, Optical materials, 29, 122-125, 2006.
[16] N. Koratkar, A. Modi, E. Lass and P. Ajayan, Journal of nanoscience and nanotechnology, 4 7,744-748, 2004.
[17] L. J. Collier, W. S. Stiles, and W. G. A. Taylor Proceedings of the Physical Society, 51, 1, 147-152, 1939.