BULK CARBON NANOTUBES AS SENSING ELEMENT FOR TEMPERATURE AND ANEMOMETRY MICRO SENSING

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ABSTRACT

Bulk multi-walled carbon nanotubes (MWNT) were successfully and repeatably manipulated by AC electrophoresis to form resistive elements between Au microelectrodes and were demonstrated to potentially serve as novel temperature and anemometry sensors. We have measured the temperature coefficient of resistance (TCR) of these MWNT bundles and also integrated them into hot-film anemometry constant current configuration for dynamic characterization. It was discovered that the resulting device could be operated in μW range, which is three orders of magnitude lower than conventional MEMS polysilicon based shear stress sensors. For example, to achieve a resistance overheat ratio in the magnitude of 0.1, only 10 μA of current is needed to heat these MWNT bundle elements compare to mA current range for polysilicon-based sensors. Moreover, the device exhibited very fast frequency response (> 100 kHz) in constant current mode, which is higher than its reported MEMS polysilicon counterparts in this mode of operation. Our current processing technology is scalable in producing these MWNT sensing elements ranging from 5 μm to 15 μm in length.

I. INTRODUCTION

Carbon nanotubes (CNT), since its discovery in 1991 [1], has been widely studied in both the mechanical [2] and electrical properties [3]. Recent breakthroughs [4, 5] in carbon nanotube based nanoelectronic devices have marked a new milestone for further miniaturization of circuit elements in the integrated circuit industry. While efforts have been placed in exploring the applications of individual carbon nanotubes, bulk or bundled carbon nanotubes have been explored for mechanical actuator [6] and field emission display [7]. Our recent experimental findings also show bulk MWNT to be promising for use as thermal and anemometrical sensors. In the field of aerodynamics, the ability to sense the minute fluidic movement is crucial to the fundamental understanding of fluid motion. Ho's group at UCLA and Tai's group at Caltech [8] have pioneered the usage of MEMS technology to build miniature shear stress sensors to sense fluidic movement. However, conventional polysilicon sensors suffer from relative high power dissipation (in the range of mW) [9]. The heat generation may affect the minute fluidic motion through thermal convection, crippling their abilities to sense the true fluidic flow parameters. Our experimental findings show that bulk MWNT devices are capable to operate in μW range, which can minimize the thermal disturbance to the fluid motion. We believe the introduction of carbon nanotubes as sensing element in thermal and anemometrical sensors will make a significant impact on future fluid dynamic applications.

II. AC ELECTROPHORETIC MANIPULATION OF BULK CARBON NANOTUBES

AC electrokinetics technology has been widely used to manipulate micro and nano entities such as virus and latex spheres in the past few years [10]. The technique was first exploited by K. Yamamoto et al. [11, 12] to manipulate and align carbon nanotubes. AC electrophoresis (or dielectrophoresis) is a phenomenon where neutral particles undergoing mechanical motion inside a non-uniform AC electric field [13]. The dielectrophoretic force imparted on the particles can be described by the following equation:

$$\vec{F}_{DEP} = \frac{1}{2}\vec{\alpha} V \nabla \left|\vec{E}\right|^2 \qquad (1)$$

where $\vec{\alpha}$ is the polarizability of the particles, which is a frequency dependent term. V is the volume of the particles and $\nabla = \vec{i}\frac{\partial}{\partial x} + \vec{j}\frac{\partial}{\partial y} + \vec{k}\frac{\partial}{\partial z}$ is the gradient operator. $\left|\vec{E}\right|$ is the magnitude of the electric field strength. Equation (1) reveals that the force generated is dependent of the gradient of the electric field rather than the direction of electric field. Besides, the polarizability function also determines whether the force generated is attractive (positive dielectrophoresis) or repulsive (negative dielectrophoresis).

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In our experiments, Au microelectrodes were fabricated on a glass substrate with standard photolithography techniques and the general procedures to form MWNT across the microelectrodes were reported previously in [14].

From our experimental results, MWNT showed positive dielectrophoretic effect under non-uniform AC electric fields (with applied frequency of 1 MHz) as bulk MWNT was attracted towards the Au microelectrodes (see Figure 1.) and connected across the microelectrodes (see Figure 2.). By appropriate microelectrodes designs, it is possible to align the MWNT linkage in different directions (see Figure 3.).

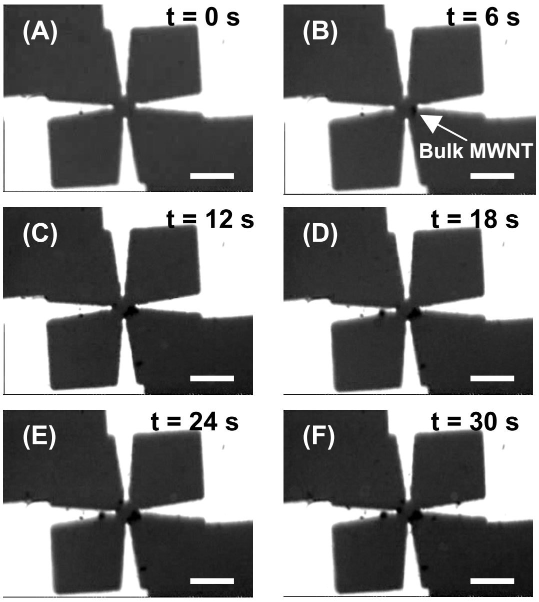

Figure 1. Optical microscopic images (A – F) showing the process of AC electrophoretic manipulation of bulk MWNT which was suspended in ethanol medium (concentration of MWNT/Ethanol = 0.01 mg/ml). Consecutive pictures were captured with 6 seconds intervals. AC voltage of 16 V peak-to-peak at 1 MHz was applied across the microelectrodes. (Scale Bar = 20 μm)

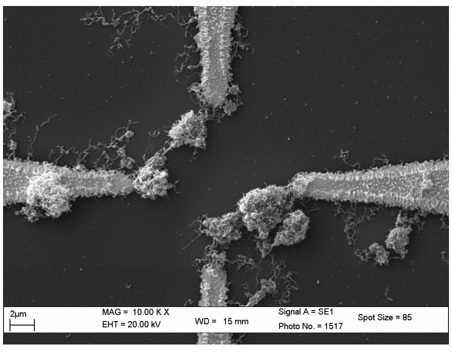

Figure 2. Scanning Electron Microscopic (SEM) image showing the formation of bulk MWNT between the gold microelectrodes. This is the corresponding image of (F) in Figure 1.

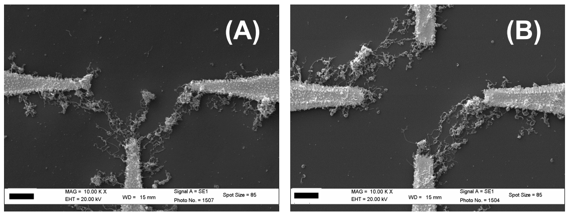

Figure 3. SEM images showing different alignments of MWNT linkages formation. (A) Right angle alignment (B) Parallel alignment. (Scale Bar = 3 μm)

III. CARBON NANOTUBES AS SENSING ELEMENT FOR THERMAL AND ANEMOMETRICAL SENSING

With the ability to manipulate the bulk MWNT on Au microelectrodes, we have successfully utilized the bulk MWNT as resistive elements and integrated them into hot film anemometry constant current mode (see Figure 4.) for dynamic characterization.

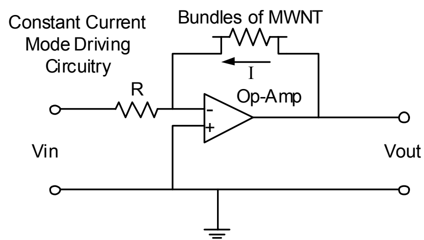

Figure 4. Schematic diagram showing the constant current mode configuration.

Electrical properties of individual carbon nanotubes have been studied [3, 15] by many research groups in the past few years and the I-V characteristics reported by the groups showed the μW power characteristics of individual carbon nanotubes. We have determined the I-V characteristics of the bulk MWNT after hybridly integrating the bulk MWNT into the constant circuit configuration. Similar to those of individual carbon nanotubes, the bulk MWNT also showed μW power characteristics (see Figure 5.), though bulk MWNT can be regarded as a complex network of individual carbon nanotubes. This experimental finding suggested that bulk carbon nanotubes could be used as resistive element for ultra low power consumption devices. Typically, the two-probe room temperature resistance of the bulk MWNT ranged from several kOhm to several hundred kOhm, and these variations were mainly contributed by the random connections between MWNT bundles during the AC electrophoresis. Despite the random variations in room temperature resistance of different MWNT bundles, we found that all of our samples have similar I-V characteristics to that of Figure 5. In our sample circuit, the current required to induce the non-linearity of bulk

MWNT is about 3.6 μA at 0.6 V, which implies the operation power range of the device is in μW .

A proof-of-concept experiment was performed to validate its flow sensing capability in μW operating power. The CNT sensor was placed perpendicular to a flow source with constant outlet velocity (see Figure 6.). The distance between the source and the sensor was then varied to induce different impinging velocities on the sensor (similar to Hiemenz flow). Although the flow environment was not well-controlled, results do clearly indicate the response of the sensor to different impinging velocities (see Figure 7.).

Besides, the MWNT-based device exhibited very fast frequency response (about 177 kHz) in constant current mode configuration (see Figure 8.) which out-performed the traditional polysilicon MEMS shear stress sensors used in this mode of operation reported thus far.

Apart from this, we have measured the TCR of the CNT sensors. The bulk MWNT was sensitive to the change of temperature and its resistance dropped with increasing temperature. Interestingly, the TCR of all of our testing devices did not converge to a certain value, but the ranges were generally around -0.1 %/°C to -0.2 %/°C (see Figure 9). The negative TCR of the MWNT has been reported previously in [3], though the measurements were based on individual MWNT. Currently, we suspect the variations in TCR were mainly contributed by the mismatch in thermal coefficient of expansion between the bulk MWNT and Au electrodes, i.e. some of the bulk MWNT detached from the Au electrodes during thermal expansion and contraction cycles. Other possible reason was due to contaminations such as moisture to the sample during measurements.

Based on our hypothesis, we are currently developing a novel process to embed the bulk MWNT inside parylene C diaphragms (see Figure 10.). The reasons for using parylene C as the diaphragm layer are because it can be conformally deposited at room temperature and will protect the bulk MWNT inside. Besides the protection against the contamination, the bulk MWNT will not detach from the Au electrodes easily during thermal expansion cycles since they are embedded inside the parylene C diaphragms. The devices are currently under testing to determine the effectiveness of the proposed technique and the results will be published elsewhere later.

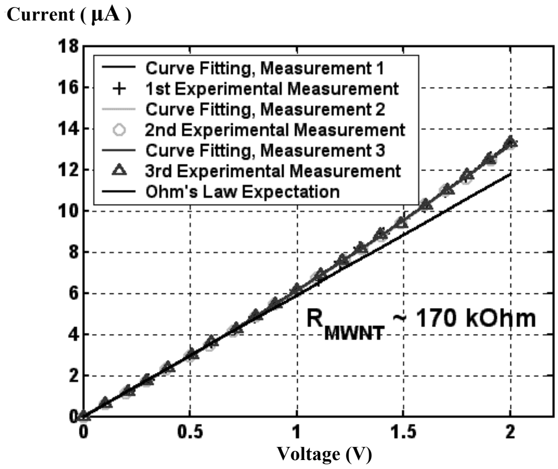

Figure 5. I-V characteristics of the MWNT bundles. Three repeated measurements were performed to validate the repeatability. Experimental measurements were fitted into second order curves by least square method. The straight line is the theoretical expectation by Ohm’s Law and the room temperature resistance of the MWNT bundles in the testing sample was about 170 kΩ .

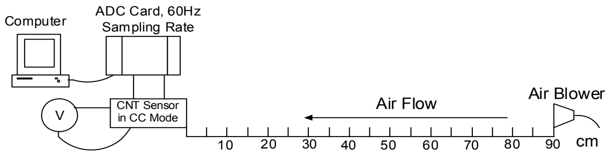

Figure 6. Schematic diagram showing the experimental setup for simple air blowing testing. The CNT sensor was placed normal to the direction of the air flow.

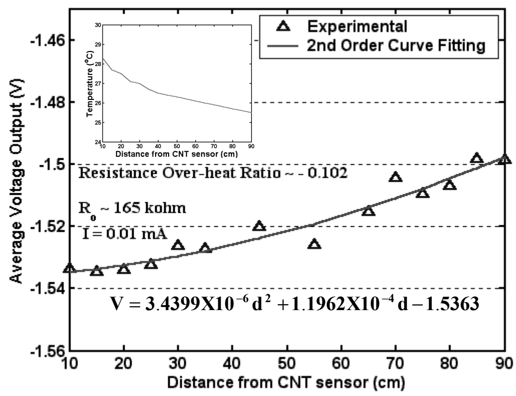

Figure 7. Output voltage variations with the air flow at different locations between the sensor and the air blower. Inset shows the temperature of the air flow at different locations and the range was generally within 2 °C . The operating power of the sensor was about 15 μW .

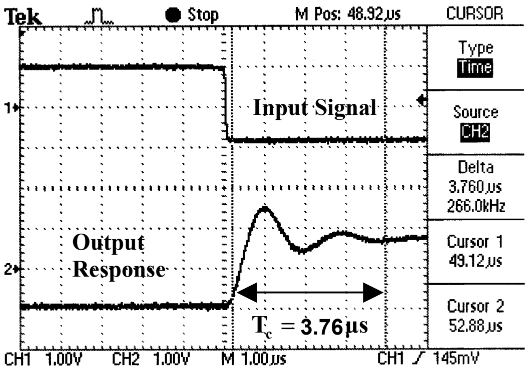

Figure 8. Input square wave of 2V peak-to-peak at 10 kHz was fed into the circuit for the frequency response measurement. The cutoff frequency was estimated by $f_c = 1/(1.5 \cdot T_c)$ [9]. Therefore, the cutoff frequency of the sample circuit was about 177 kHz.

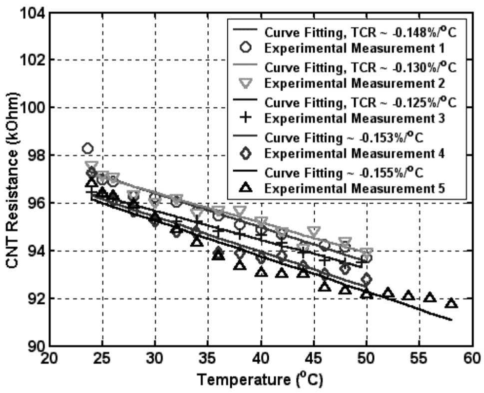

Figure 9. TCR variations of a MWNT sensor in five consecutive measurements. The TCR of the MWNT bundles was generally within the range of -0.1 %/°C to -0.2 %/°C

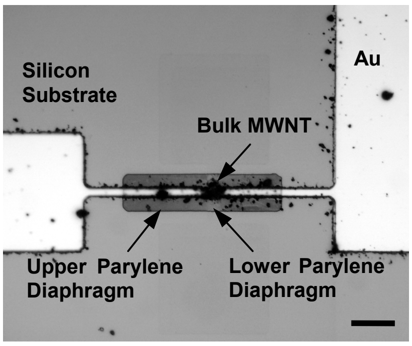

Figure 10. Optical microscopic image showing the top view of the parylene/MWNT/parylene device prototype. (Scale bar = 20 µm).

IV. CONCLUSION AND SUMMARY

A technique to form bulk MWNT between Au microelectrodes has been presented and the bulk MWNT were demonstrated to potentially serve as sensing element for thermal and anemometrical sensors. Through the I-V and frequency response measurements, the bulk MWNT devices were shown to operate at µW power range and picked up very fast input changes (generally over 100 kHz) from the environment. Therefore, we believe that bulk MWNT is very promising to be used as ultra low power consumption thermal and anemometrical sensors for future aerodynamic applications.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

[1] S. Iijima, "Helical Microtubules of Graphitic Carbon", Nature, Vol. 354, pp.56 – 58 (1991)

[2] E.W. Wong, P.E. Sheehan, C.M. Lieber, "Nanobeam Mechanics: Elasticity, Strength and Toughness of Nanorods and Nanotubes", Science, Vol. 277, pp. 1971 – 1975 (1997)

[3] T.W. Ebbesen, H.J. Lezec, H. Hiura, J.W. Bennett, H.F. Ghaemi, T. Thio, "Electrical Conductivity of Individual Carbon Nanotubes", Nature, Vol. 382, pp. 54 – 56 (1996)

[4] S. Frank, P. Poncharal, Z.L. Wang, W.A. de Heer, "Carbon Nanotube Quantum Resistors", Science, Vol. 280, pp. 1744 – 1746 (1998)

[5] S.J. Tans, A.R.M. Verschueren, C. Dekker, "Room-Temperature Transistor Based on a Single Carbon Nanotube", Nature, Vol. 393, pp. 49 – 52 (1998)

[6] R.H. Baughman, C. Cui, A.A. Zakhidov, Z. Iqbal, J.N. Barisci, G.M. Spinks, G.G. Wallace, A. Mazzoldi, D.D. Rossi, A.G. Rinzler, O. Jaschinski, S. Roth, M. Kertesz, "Carbon Nanotube Actuators", Science, Vol. 284, pp. 1340 – 1344 (1999)

[7] W.B. Choi, D.S. Chung, J.H. Kang, H.Y. Kim, Y.W. Jin, I.T. Han, Y.H. Lee, J.E. Jung, N.S. Lee, G.S. Park, J.M. Kim, "Fully Sealed, High-Brightness Carbon-Nanotube Field–Emission Display", Applied Physics Letters, Vol. 75, No. 20, pp. 3129 – 3131 (1999)

[8] G.B. Lee, A. Huang, C.M. Ho, F. Jiang, C. Grosjean. Y.C. Tai, "Sensing and Control of Aerodynamic Separation by MEMS", The Chinese Journal of Mechanics, Vol. 16, No. 1, pp. 45 – 52 (2000)

[9] C. Liu, J.B. Huang, Z. Zhu, F. Jiang, S. Tung, Y.C. Tai, C.M. Ho, "A Micromachined Flow Shear-Stress Sensor Based on Thermal Transfer Principle", Journal of Microelectromechanical Systems, Vol. 8, No.1, pp. 90 – 99 (1999)

[10] M.P. Hughes, "AC Electrokinetics: Applications for Nanotechnology", Nanotechnology, Vol. 11, pp.124 – 132 (2000)

[11] K. Yamamoto, S. Akita, Y. Nakayama, "Orientation of Carbon Nanotubes using Electrophoresis", Japanese Journal of Applied Physics, Vol. 35, pp.L917 – L918 (1996)

[12] K. Yamamoto, S. Akita, Y. Nakayama, "Orientation and Purification of Carbon Nanotubes Using AC Electrophoresis", Journal of Physics D: Applied Physics, Vol. 31, pp. L34 – L36 (1998)

[13] H.A. Pohl, "Dielectrophoresis: The Behaviour of Neutral Matter in Nonuniform Electric Fields", Cambridge University Press (1978)

[14] V.T.S. Wong, W.J. Li, "Dependence of AC Electrophoresis Carbon Nanotube Manipulation on Microelectrode Geometry", International Journal of Non-linear Sciences and Numerical Simulation, Vol. 3, Nos 3 - 4, pp.769 – 774 (2002)

[15] P.G. Collins, M.S. Arnold, P. Avouris, "Engineering Carbon Nanotubes and Nanotube Circuits Using Electrical Breakdown", Science, Vol. 292, pp. 706 – 709 (2001)