Development of Aligned Carbon Nanotubes (CNTs) for Pressure Sensing Application

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ABSTRACT

Besides the unique advantages of high sensitivity, small size, low power consumption, and strong mechanical stability, the driving factor for developing CNTs-based pressure sensor is the thermal stability. Unlike the conventional Si-based pressure sensors which have maximum operating temperature of 120°C, CNT based pressure sensor can be operated up to 250°C. Based on the piezoresistive effect, when the aligned multi-walled carbon nanotube (CNT) array is compressed, individual carbon nanotubes start to buckle, which in turn decreases the array's electrical resistance. This behavior was found to be almost fully recoverable for the loading of up to 500 g. The change in the resistance increases linearly when 100 g and 500 g load were applied at a temperature of 20°C to 180°C. Thus MWCNTs array promises to be a very effective sensing element for pressure and strain sensor operating at elevated temperature.

Keywords: multi-walled carbon nanotubes, piezoresistive, pressure, resistance, sensor

1 INTRODUCTION

As one class of nanostructure materials, carbon nanotubes have been sought after for various applications in devices due to their remarkable mechanical properties and unique electronic properties as well as the high thermal and chemical stability. A very useful relationship when developing extremely small sensors that are sensitive to physical environment is the electronic property of CNTs which is a strong function of their atomic structure and mechanical deformations. Some pressure sensors operate using the principle of piezoresistance of a material. Piezoresistance describes the change in electrical resistance of a material due to applied mechanical stress. At present, such pressure sensors are mostly made of Si. One major disadvantage of using Si sensors is that their electrical resistance is sensitive to temperature due to current leakage at the P-N junction. The current leakage of Si doubles every 8°C meaning that at 120°C, the leakage is almost 4000 times larger than those at room temperature thus rendering it useless when the operating temperature exceeds 120°C [1]. By using the same principle for CNTs, which is more resistant towards temperature, the operating temperature could be increased further. It has been reported that the electrical resistance of CNTs remains almost unchanged at 250°C over an extended period of time [2]. Other advantages include high sensitivity to strain compared to Si and lower temperature coefficient of resistivity [3, 4].

1.1 Electromechanical Properties

Driven by high compressive strength [5] and large elastic modulus of CNTs [6, 7], electromechanical properties have started to be investigated for possible application as electromechanical sensor. Electromechanical properties of CNTs were found to be better than the traditional materials because of their high elastic modulus coupled with their unique electrical properties that can be metallic, semiconducting and semi-metallic depending on the orientation of the atomic lattice with respect to the axis of the tube and the diameter.

1.2 Piezoresistive Effect

In the piezoresistive theory, the gauge factor, K can be defined as [8]

$$K = \frac{dR}{R\varepsilon} = 1 + 2\nu + \frac{d\rho}{\rho_0 d\varepsilon} \tag{1}$$

where dR is the change in resistance due to deformation, R is the undeformed resistance and ε is the strain. K can be further defined into two terms; $(1 + 2\nu)$ and $(d\rho/\rho_0 d\varepsilon)$ where ν is Poisson's ratio of the films, ρ and ρ_0 are resistivities for strain ε and 0, respectively. The first term expressed as $(1 + 2\nu)$ is due to geometrical deformation, and the second term $(d\rho/\rho_0 d\varepsilon)$ is due to the change in the electrical resistivity of the material. If the resistance change resulting from strain is due to only geometrical changes, K derived from the first term would be a small value. Thus the geometrical changes cannot account for the large gauge factor observed in some materials [9].

The piezoresistive effect of semiconductor materials such as germanium, polycrystalline silicon, amorphous silicon, silicon carbide, and single crystal silicon was found to be several orders of magnitudes larger than the geometrical

piezoresistive effect in metals. This is because the resistance of silicon changes not only due to the stress dependent change of geometry, but also due to the stress dependent resistivity of the material, resulting in gauge factors of the orders of magnitudes larger than those observed in metals [9]. Jien *et al* [10] had reported that the mechanical properties of CNTs are the most superior amongst the materials with the highest gauge factor for narrow-gap semiconducting type CNT.

In order to establish the principle for pressure sensing application, the study focused on temperature dependent piezoresistive of well-aligned, pristine MWCNT array when the mechanical load is being applied. Similar work had been reported by Cao *et al* [11] but on different type of sensing element that involved MWCNT film with random alignment. Here, MWCNTs array was grown by catalytic CVD method [12]. The two equal size wafer substrates with MWCNTs array are placed on top of each other in a sandwich configuration in order to obtain the double layer. The sandwich configuration of CNTs offers better compressibility with its thicker height and easy handling for making contacts.

2 METHODOLOGY

Two equal size substrates of Si wafers were deposited with 300 nm SiO_2, followed by Al_2O_3 buffer layer and final coating of Fe catalyst. These coated substrates were then annealed at 400°C for 2 hours before being subjected to NH_3 etching at 850°C for 10 mins and cooling to room temperature. MWCNTs array was grown using CVD system maintained at 700°C with ethylene flowed in at 700 sccm for 10 mins [12]. Then hydrogen was purged in at 500 sccm until the system cooled down to 300°C and then to the room temperature with the flow of argon. The as-produced nanotubes array was then analyzed by scanning (SEM) and transmission electron microscopy (TEM).

The product as shown in Fig. 1 is in the form of well-aligned MWCNTs array with typical height of 28 µm. As depicted in Fig. 2, the two equal size substrates are placed on top of each other with MWCNTs array in between forming double layer with typical height of 59 µm. Contacts were made on the conductive base at the sides of CNTs array as shown in the schematic diagram of the test unit in Fig. 2. The resistance of CNTs array was determined by applying a voltage at the two contacts and measuring the current and voltage. All connections were made to the Compact Fieldpoint (National Instrument) for the purpose of converting all input/output signals, namely the voltage and current, from the test unit to the relevant computerized data and display using LabView software.

Mechanical stress in the form of loading was applied parallel to the axis of CNTs. Weight added was in an increment of 50 g to a maximum of 500 g at different time interval (10 s, 50 s and 100 s) between additions of weights. Electrical resistance was then measured against time for the loading time interval of 10 s, 50 s and 100 s.

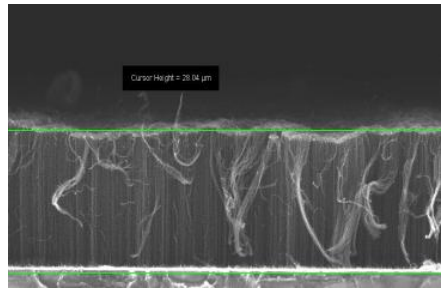


Figure 1: SEM image of MWCNTs array on the substrate

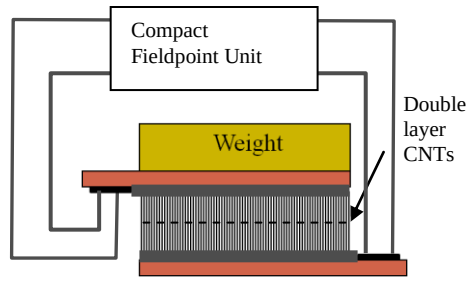


Figure 2: Schematic diagram of the measurement unit.

3 RESULT AND ANALYSIS

Figure 3 shows the SEM image of well-aligned CNTs array. The part which is not covered by nanotubes forest is obtained by omitting the deposition of catalyst film prior to the growth process. This part is designated for the electrical contact required for the measurement of the electrical behavior. TEM analysis shown in Fig. 4 described the multiwalled type with diameter in the range of 30 to 50 nm.

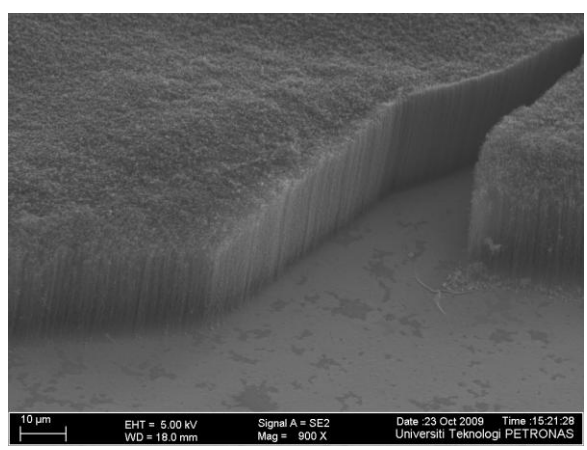


Figure 3: SEM image of large area of MWCNTs array with the uncovered part reserved for the electrical contact.

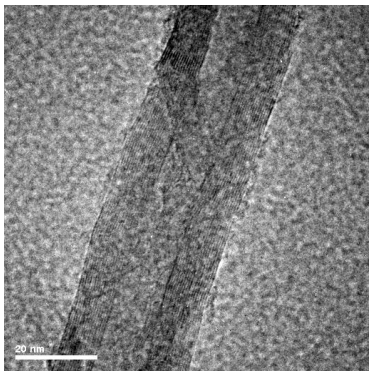
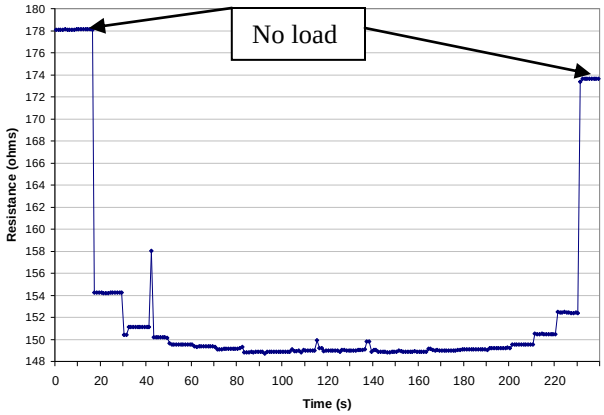


Figure 4: TEM image of carbon nanotube

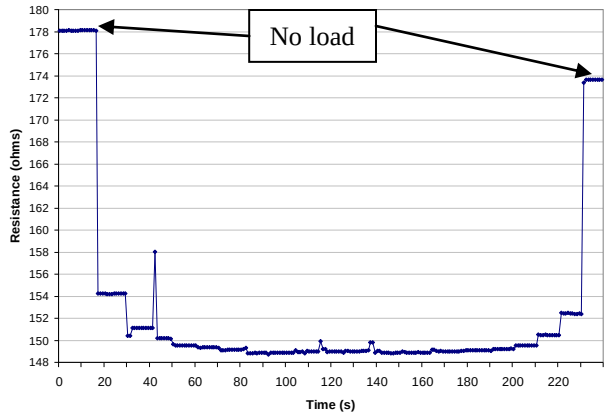
In the above measurement, the load was applied to nanotubes array by continuously added with 50 g weight at a time until 500 g and then released with the removal of 50 g at a time until completely free of the load. It is observed from Fig. 5a and 5b that almost full recovery of the initial resistance value is obtained for the loading interval of 10 s (99%) and 50 s (93%). However for the longer loading interval of 100 s (Fig. 5c), no recovery was recorded indicating the occurrence of creep phenomenon [13].

As shown in Fig. 6, when the change of resistance is plotted against weight applied, the curve describes the initial drastic increase in resistance followed by gradual decrease in the change of resistance and finally tapers off when it reaches 350 g. Hysteresis effect [14] is observed where there is a slight difference between the values with increasing weights and decreasing weights with the latter recording a change of resistance of 5 ohm upon total removal of the load.

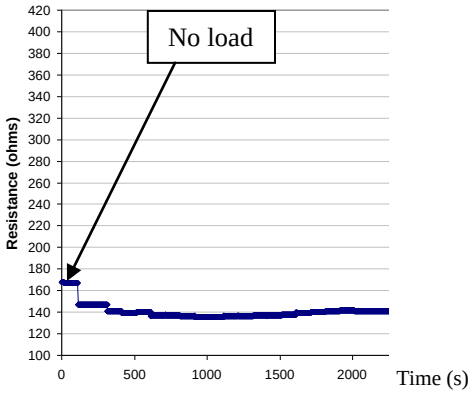
In order to understand the effect of temperature on the resistance as the load is been applied to the nanotubes array, measurement were also carried out by varying the temperature from room temperature, 20°C to 180°C.



(a)



(b)



(c)

Figure 5: A plot of resistance against time on applying the load with an increment of 50 g for the loading time interval of (a) 10 s, (b) 20 s and (c) 100 s.

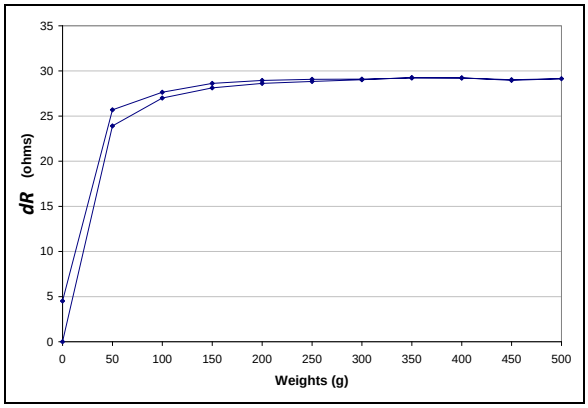


Figure 6: A change in resistance, *dR* (Ω) as a function of the weight applied, w (g).

When the weights of 100 g and 500 g were applied to CNTs array, linear decrease in resistance values were registered as described in Fig. 7. From equation (1), an increase in the change of resistance, *dR* would result in an increase in the gauge factor. This finding of an increased

dR with temperature is agreeable with Cao *et al* [11] who discovered a rapid increase in the gauge factor with an increase in temperature of up to 50°C.

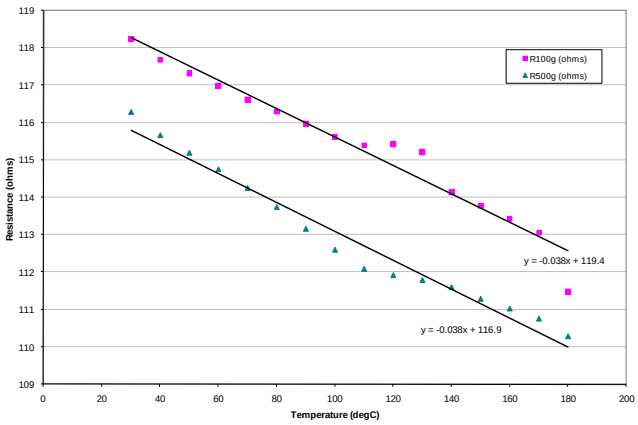


Figure 7. Plot of resistance (ohms) against temperature (deg C) for 100g (■) and 500g (▲) load.

4 CONCLUSION

The resistance was found to decrease on the application of the load and upon removal of the applied load; the resistance value almost retains its original value for the 10 s loading interval (99%) and 50 s loading interval (93%). The decrease in resistance is attributed to the bending of CNTs that lead to overlapping of electron states in adjacent nanotube walls resulting in an increase in the accessible number of conduction channels [15]. The study on the temperature dependent piezoresistive effect has shown that MWCNTs array exhibits a significant increase in the change of resistance with increasing temperature of 20°C to 180°C. Physically, applying load causes the array structure to become denser, allowing more contact between nanotubes and resulting in higher conduction. On removing the load from the CNT array, the electrical resistance almost regained its original no-load value. The high elasticity of the covalent carbon-carbon bonds is responsible for the return to its original state even from a strong deformation. This property combined with the remarkable electrical response to the mechanical load makes CNT array a suitable and effective sensing element for pressure or strain sensor operating at elevated temperature.

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