Carbon nanotube Four-Terminal Devices for Pressure Sensing Applications

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Abstract. Carbon nanotubes (CNTs) are of high interest for sensing applications, owing to their superior mechanical strength, high Young's modulus and low density. In this work, we report on a facile approach for the fabrication of carbon nanotube devices using a four terminal configuration. Oriented carbon nanotube films were pulled out from a CNT forest wafer and then twisted into a yarn. Both the CNT film and yarn were arranged on elastomer membranes/diaphragms which were arranged on a laser cut acrylic frame to form pressure sensors. The sensors were calibrated using a precisely controlled pressure system, showing a large change of the output voltage of approximately 50 mV at a constant supply current of 100µA and under a low applied pressure of 15 mbar. The results indicate the high potential of using CNT films and yarns for pressure sensing applications.

Keywords: Carbon Nanotube, Pressure Sensor, Flexible/Stretchable Devices.

1 Introduction

Since its discovery in 1991, carbon nanotubes (CNTs) have been well known as an unprecedented material for a wide range of applications [1-5], owing to its high strength, high Young's modulus, and low mass densities. Intensive research on fundamental properties of individual carbon nanotubes has been conducted for years [6,7]. However, the difficulty in fabrication and implementation has created great challenge for the commercialization of sensors employing individual CNTs. Therefore, recent research has focused on the application of CNT macrostructures such as membranes/films, yarns and nanocomposites for sensing electronic devices [8-10].

The excellent electrical conductivity of such CNT-based macrostructures has been employed to develop mechanical sensors, including strain and pressure sensors [11,12]. For example, the large strain and thermal sensing effects in CNT films and yarns have been recently reported [13,14]. Based on the large piezoresistance and thermoresistance, nanocomposites with CNTs embedded into rubbers have been recently demonstrated for wearable sensing applications including human motion monitoring and electronic skin [9,15]. As such, a gauge factor of above 1000 and a temperature coefficient of resistance of 800 ppm/K have been measured for the CNT nanocomposites and CNT yarns [8,16].

In addition, the development of CNT pressure sensing devices is of interest for a numerous sensing applications, including weather instrumentation, automotive industries, aircrafts, satellites and so on. The recent development of soft robotics and flexible/stretchable actuators has motivated the research on the design and fabrication of soft CNT pressure sensors. For example, CNT pressure sensors with a sensitivity in the range of 2.5×10^{-4} to 1.6×10^{-2} kPa^{-1}, have been reported for CNT-based films [17,18].

In this work, we fabricated soft pressure sensors using CNT web/film and yarn as a sensing element. A four terminal configuration was utilised for the implementation of these pressure sensors. A large output voltage of up to 50 mV was measured for the CNT film at a constant applied current of 100μA. The considerable resistance change of the CNT yarn-based pressure sensors was also monitored, showing the potential use of CNT devices for pressure sensing.

2 Material, design and fabrication

2.1 Oriented carbon nanotube

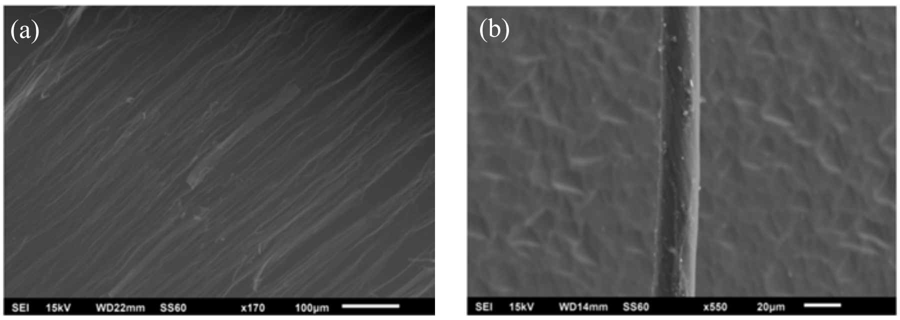

Fig.1. Oriented carbon nanotube. (a) Carbon nanotube web/film. (b) Carbon nanotube yarn.

For the synthesis of carbon nanotube (CNT), chemical vapour deposition (CVD) method was used to grown CNT forest on silica using ferrocene as a catalyst precursor and cyclohexane as a carbon source [19,20]. Oriented carbon nanotubes (OCNTs) were then fabricated from the as-grown CNT wafer with the following steps. First, the spinnable CNT forest was pulled out from the wafer to make oriented webs or films. These webs/films can be subsequently transferred to a stretchable membrane to fabricate pressure sensors, or twisted into CNT yarn using a rod and twisting system [21]. Figure 1(a) shows the scanning electron microscopy (SEM) image of the CNT forest and CNT film. In addition, Figure 1(b) illustrates the as-fabricated CNT yarn with a diameter of approximately 12 µm. In this study, both CNT highly oriented film and yarn were used to fabricate pressure sensors.

2.2 Sensor design and fabrication process

Sensor design/structure: Figure 2 shows the structure of CNT pressure sensors with its four terminal configuration. A circular diaphragm of elastomer is employed for pressure sensing. The sensing element includes two rectangular CNT films/yarns crossing each other. A constant current is applied to two terminals while voltage measurement is performed at the two others.

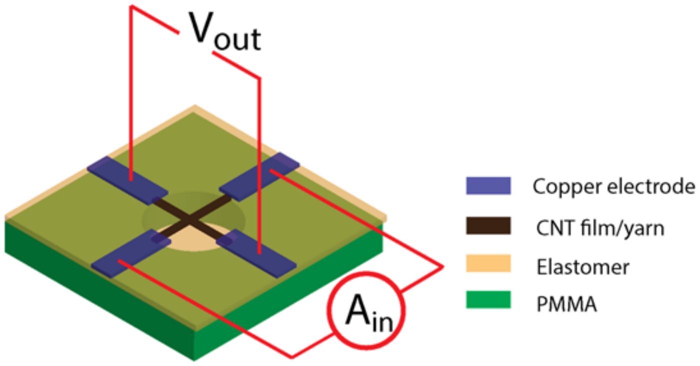

Fig.2. Structure and four terminal configuration of the pressure sensor

Fabrication process: Figure 3 shows the fabrication process of CNT pressure sensors with the following steps. First, a PMMA (poly methyl methacrylate) square frame and an elastomer membrane (3M VHB Acrylic Foam Tape) were formed using a laser cutter (Trotec Speedy 300, Figure 1(a)). The thicknesses of the frame and the elastomer layer are 30 mm and 0.5 mm, respectively. The rectangular diaphragm has a diameter of 10 mm. The membrane was then aligned and assembled on the frame thanks to the strong adhesion of the 3M tape. In the next step, the CNT films and yarns were handled on the membrane (Figure 1(b)). Finally, the copper electrodes were formed and highly conductive silver epoxy was used for making interconnection between the CNT films/yarns and the copper electrodes. Figure 1(d) shows an as-fabricated CNT device.

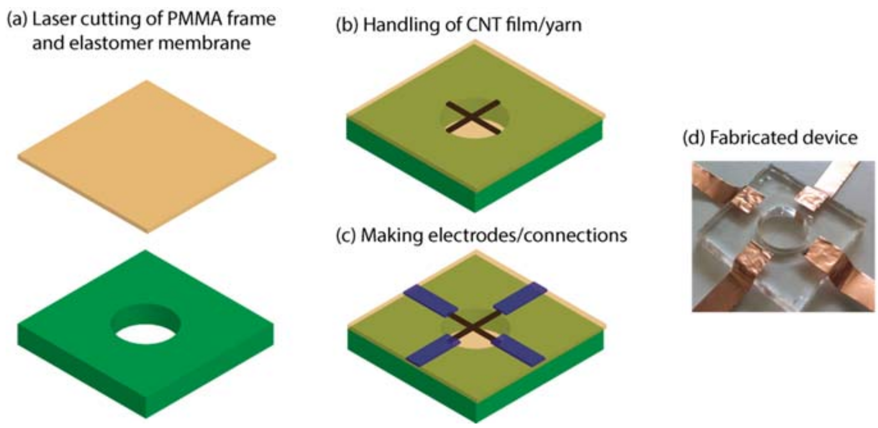

Fig.3. Fabrication process.

3 Experimental

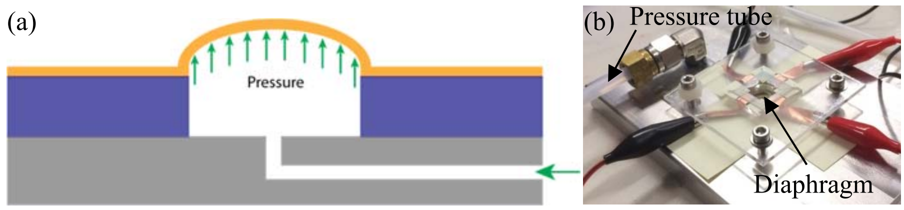

Fig.4. Experimental setup. (a) Schematic sketch of pressure characterization system. (b) A photo of the experimental setup with a four terminal configuration for measurement.

Figure 4(a) shows the schematic diagram of the CNT pressure sensor in the pressure calibrating system. The CNT sensors were clamped on a pressure calibration base connecting with a pressure controller through a pressure tube. The positive pressure from 0 to 15 mbar was supplied from a precise pressure controller (MK3 OB1 Pressure Controller, Elveflow). This low pressure regime was used because of the very high deformability of the elastomer diaphragm under higher pressure ranges. Four point measurements were performed under different applied pressured with a constant applied current of 100 μA. Figure 4(b) shows a photo of the experimental setup.

4 Results and discussion

4.1 Current-voltage (IV) characteristics

To confirm the Ohmic behavior of the fabricated devices, IV measurements were performed on both film-based and yarn-based CNT pressure sensors. The maximum applied voltage of 1 V was used in the IV measurement to avoid Joule heating effect. Figure 5(a) shows the linear IV characteristics of the CNT film four terminal devices. Figure 5(b) also confirms the Ohmic contact of the CNT yarn with electrodes. The maximum current of 0.8 mA was measured at 0.5 V for CNT device which is at least 40 times higher than that recorded for the CNT film. This is attributed to the fact that the CNT yarn is more compact and higher density of CNTs; hence it has a much lower resistance.

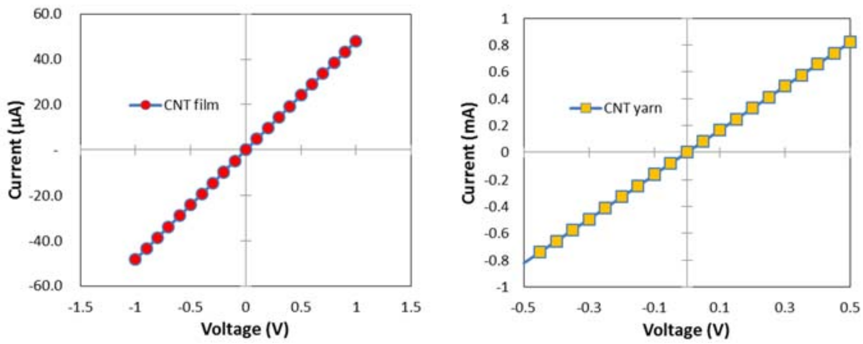

Fig. 5. Current-voltage (IV) characteristics of the pressure sensors. (a) Carbon nanotube web/film. (b) Carbon nanotube yarn.

4.2 Deformation analysis

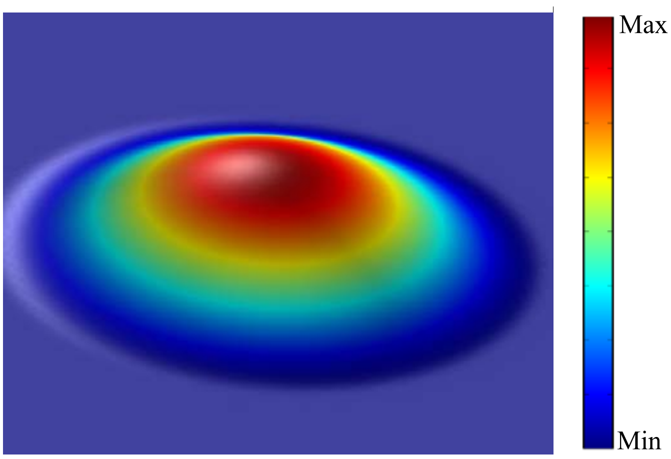

Fig.6. Deformation of the diagram (simulated using COMSOL software)

For the circular diaphragm, the loading pressure p causes the displacement w(x,y) with the following relationship [22]:

$$D\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)w(x,y)=p \tag{1}$$

where D is the flexure rigidity of the diaphragm. Let a and r the radius of the circular diaphragm and distance from the point on the diaphragm to its centre. Using the boundary conditions of w(a)=0, w′(a)=0 and w″(a)=0, the displacement w(r) is found to be:

$$w(r)=\frac{pa^4}{64D}\left(1-\frac{r^2}{a^2}\right)^2 \tag{2}$$

where $w(0)=\frac{pa^4}{64D}$ is the maximum displacement observed at the centre of the diaphragm. In addition, the stress induced in the radial direction (along the film/yarn axis) is calculated as:

$$\sigma=\frac{3a^2}{8h^2}p\left[(3+\nu)\frac{r^2}{a^2}-(1+\nu)\right] \tag{3}$$

where ν is the Poisson ratio and h is the thickness of the diaphragm. The COMSOL simulation was also performed to obtain the deformation of the diaphragm under applied pressure (Figure 6).

4.3 Pressure sensing

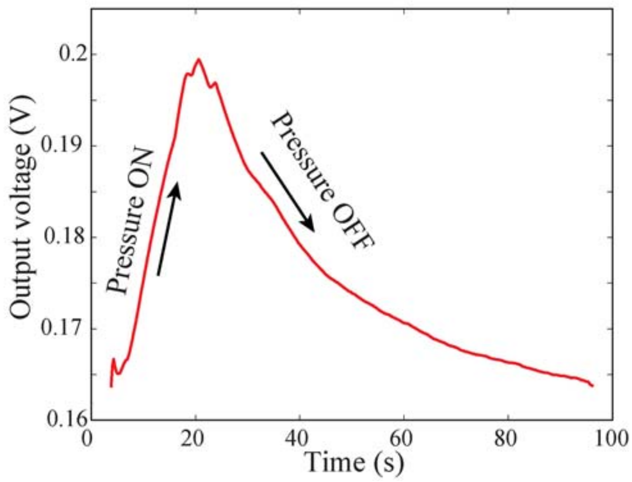

Fig. 7. Response of the CNT film pressure sensor to a pressure of 12 mbar.

Figure 7 shows the output voltage measured for the CNT film pressure sensor under an applied pressure of 12 mbar. The output voltage increased approximately 30 mV when the pressure was applied. It is important to note that the response time of the sensor is in few seconds while the relaxation time is much longer. This is due to the elasticity of the 3M elastomer.

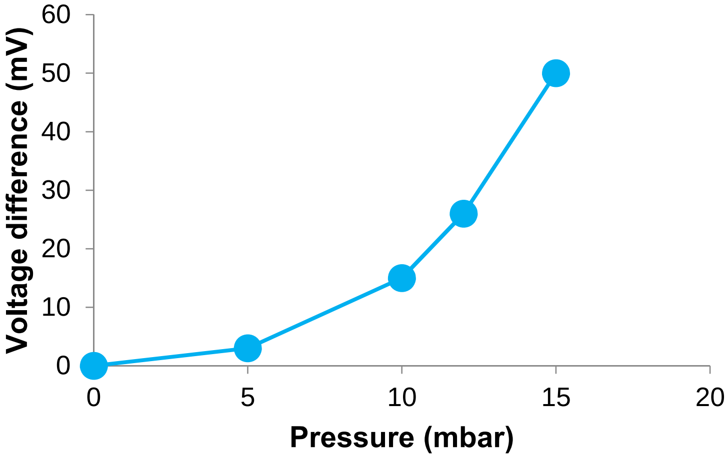

Fig. 8. Pressure sensing characteristics of the CNT film pressure sensors

Figure 8 shows the offset voltage differences (ΔV) of the CNT film pressure sensor under different applied pressure from 0 to 15 mbar. It is evident that, the voltage difference increases with increasing pressure. The maximum ΔV is approximately 50 mV at an applied pressure of 15 mbar, corresponding to a sensitivity of 3.33 V/bar. As the sensor response is non-linear with applied pressure, future work will be conducted to improve the linearity of the sensor.

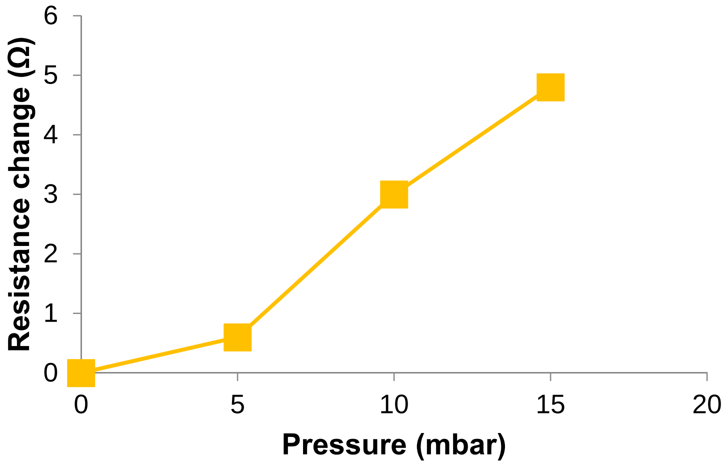

Fig. 9. Pressure sensing characteristics of the CNT yarn-based pressure sensors with two terminal measurements.

Figure 9 shows the resistance change of the CNT yarn pressure sensor. The sensor was fabricated with a four point configuration. However, only two terminals were used to measure the resistance of the pressure sensor. The results show a resistance change of approximately 5 Ω under 15 mbar applied pressure, corresponding to a sensitivity of 8 bar^{-1}. In comparison to CNT film-based pressure sensor, a better linearity of the CNT-based pressure sensor is observed.

5 Conclusion

In conclusion, pressure sensors employing oriented carbon nanotubes were fabricated using a facile method with a four terminal configuration. Carbon nanotube films/yarns were arranged on circular diaphragms using elastomer with their capability of deformation at low pressure regime (e.g. 0 to 15 mbar). The large output voltage of upto 50 mV was measured for the CNT film device while significant resistance change was observed for the CNT yarn pressure sensor. The results indicate the high potential for the development of carbon nanotube four terminal devices for highly sensitive flexible/stretchable pressure sensors. In the future work, the material of the diaphragm will be selected to wider working pressure range and improve the linearity of the pressure; detailed analysis on theoretical and experimental results will be presented.

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