A PMMA-BASED MICRO PRESSURE SENSOR CHIP USING CARBON NANOTUBES AS SENSING ELEMENTS

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ABSTRACT

A novel polymer-based MEMS pressure sensor was fabricated using bulk multi-walled carbon nanotube (MWNT) as piezoresistive sensing elements. The development of the pressure sensor includes fabrication of 300μm thick Polymethylmethacrylate (PMMA) diaphragms using SU8 molding/hot-embossing technique and AC electrophoretic manipulation of MWNT bundles on the diaphragms. We have measured the pressure-resistance dependency of these MWNT-based micro sensors and preliminary results indicated that the MWNT sensors were capable of sensing input pressure variations. Moreover, the I-V measurements of the resulting devices revealed that the nominal resistance of the sensing elements can be adjusted by annealing the MWNTs through electrical current heating, which offers a potential method for resistance-off set calibration. Based on these experimental evidences, we propose that carbon nanotubes (CNTs) is a novel material for fabricating micro pressure sensors on polymer substrates – which may serve as alternative sensors for silicon based pressure sensors when bio-compatibility and low-cost applications are required.

1. INTRODUCTION

Polysilicon is a well-known piezoresistive material for MEMS sensors because of its much higher sensitivity to strain changes than metals [1]. However, the response of polysilicon sensors is highly temperature dependent, which affect their abilities to sense true strain parameters. Also, they must be fabricated in a high temperature environment, which excludes the possibility of integrating them onto polymer MEMS devices, i.e., low-cost microfluidic devices. On the other hand, single-strand CNTs have recently been shown to exhibit a piezoresistive effect [2]. Based on an order of estimate calculation, we project the gauge factor of carbon nanotubes to be about ~1000, which is 5 to 10 times higher than conventional polysilicon based strain sensors. Moreover, CNTs stand out as a strong candidate for use as a sensing material due to their inherent properties like small size (diameter ~ 1-100nm), and good electrical and mechanical properties. Hence, our motivation is to formulate experimental techniques to conclusively test the piezoresistive effects of CNTs and develop fabrication processes to integrate CNTs into MEMS sensing devices. We have already demonstrated simple CNT thermal and flow sensors in MEMS 2003 [3], and underwater polymer embedded CNT thermal sensors in NANO 2004 [4].

In this paper, we present our latest successful development of a MEMS-compatible process to fabricate functional CNT pressure sensors on PMMA substrates. To utilize carbon nanotubes for pressure sensing application, the electrical performance such as its resistance dependency with pressure and I-V characteristics were investigated. Our preliminary results showed the resistance of these polymer-based CNT sensors varied linearly with change in applied pressure. Moreover, the mechanical characteristic of the PMMA diaphragm will be presented, which showed our experimental results agree with computer simulations that modeled the deflection of the PMMA diaphragm under different applied pressure.

2. SENSOR FABRICATION

A conceptual illustration of the MWNT pressure sensor chip built in our lab is shown in Figure 1. Basically, MWNT bundles can be formed across electrodes on top of the pressure diaphragms to serve as sensing elements using the dielectrophoretic manipulation technique reported in [3]. As a diaphragm deflects due to an applied pressure, the MWNT piezoresistor will be strained, causing a change of resistance across the electrodes.

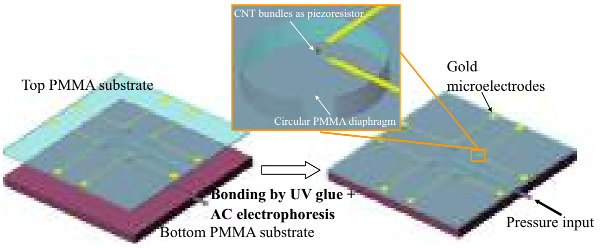

Figure 1: Conceptual illustration of the PMMA pressure sensing chip with MWNT sensing elements.

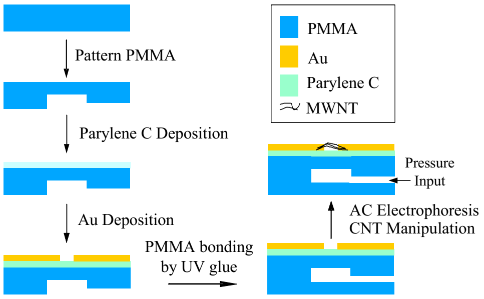

Figure 2: Fabrication process flow for the CNT based MEMS pressure sensor chip.

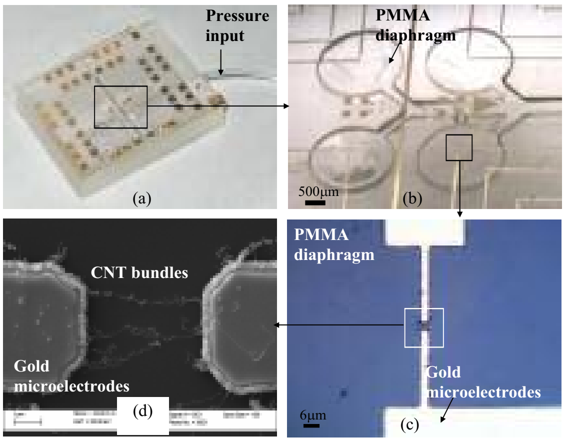

Figure 3: (a) Photograph of a PMMA pressure sensor chip with MWNT sensing element; (b) optical microscope image showing an array of MWNT sensors on top of PMMA diaphragms; (c) optical microscope image showing a pair of microelectrodes with CNT bundles; (d) SEM image showing the formations of MWNTs (~5µm in length) between gold microelectrodes.

The simplified fabrication process of the pressure sensor is shown in Figure 2. An array of circular diaphragms (300µm thick, 2mm diameter) was fabricated using a customized SU8 molding/hot-embossing process. PMMA was chosen as the diaphragm material because it is electrically insulating, optically transparent, bio-compatible, and low-cost. As seen in the fabrication process, a parylene C layer was first deposited on the PMMA diaphragm to protect the PMMA substrate and improve the adhesion of gold to the substrate. Then an array of gold (Au) microelectrodes was patterned on the substrate. The gap distance between the electrodes is between 3µm and 10µm, which would be used for the dielectrophoretic CNT manipulation in the later process. After that, a channel (~1mm width) as a pressure inlet was patterned on the PMMA substrate by using the same SU8 molding/hot-embossing process. The two PMMA substrates were then bonded by UV glue to form a sealed diaphragm. By using the dielectrophoretic technique, the MWNT bundles were successfully formed across the Au electrodes on the diaphragm. A prototype MWNT pressure sensor array is shown in Figure 3 .

3. MECHANICAL CHARACTERIZATION OF PMMA DIAPHRAGM

Experimental results

As described before, the piezoresistive CNT sensing elements rest on top of the elastic diaphragm, which may be used as a piezoresistive pressure sensor. The deflection change in the diaphragm causes the resistance change of the pressure sensitive CNT resistor. Therefore, in order to characterize the piezoresistivity of CNTs, it is very important to calculate the relationship between the deflection distribution in the diaphragm and the applied pressure. We investigated the mechanical characteristics of the diaphragm by measuring the deflection of PMMA diaphragms using a WYKO Interferometer with input pressure variations. Figure 4 shows the deflection profile and contour of a diaphragm at room temperature. On the other hand, the behavior of a circular diaphragm under uniform pressure was simulated by both Finite Element Method (FEM) modeling (see Figure 5) and the analytical solution of a thin plate with small deflection model. Since the diaphragm is free of support at the pressure inlet near to the y axis, the deflection along y axis is not symmetric as shown in the FEM modeling (see Figure 5). However, FE analysis matches the fact that behavior along x-axis is still symmetric as shown in Figure 5.

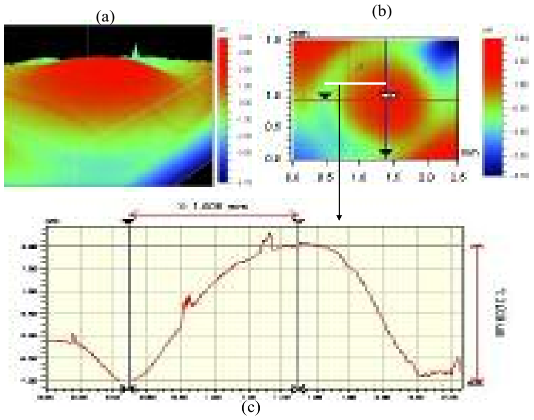

Figure 4: WYKO interferometer measurement of a PMMA diaphragm (diameter is 2mm and thickness is ~300µm). (a) 3-D deflection profile; (b)-(c) deflection contour and profile (the initial deflection at the center of the diaphragm is ~3µm at 0kPa).

Figure 5: FEM [side and 3D view] using Algor to simulate the deflection of the whole diaphragm. The scale of the deformed shape is 5 percent of the model size. The maximum deflection under varying pressure is plotted in Figure 6.

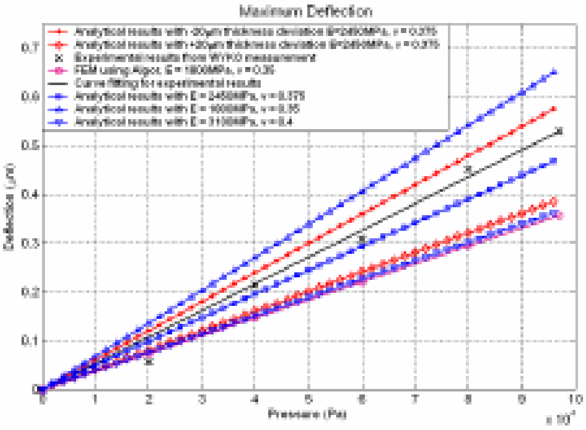

Figure 6: Plot of the maximum deflection at the center of the diaphragm from FEM, the analytical solution and WKYO experimental results from x profile due to different applied pressure.

In order to find the analytical solution, deflection w of a clamped circular plate under a uniform applied pressure P is given by [5]:

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

where r, a are the radial coordinate and diaphragm radius, respectively. D is the measurement of stiffness, and is given by [5]:

$$D = \frac{Eh^3}{12(1-v^2)} \tag{2}$$

where E, h and v are Young's modulus, plate thickness, and Poisson's ratio, respectively. Eq. (1) and (2) implies that the diaphragm will exhibit a maximum strain at the center and would therefore be the ideal place for the nanotubes to lie. A comparison of theoretical results, after modeling, and WYKO experimental measurement of the deflection at the center of the diaphragm due to input pressure variation is shown in Figure 6. Experimental results showed that the deflection increased with applied pressure as theoretically predicted. Since parameters such as E, h and v are not known precisely, the slope of the experimental plot cannot be matched precisely. Hence, we have tried a range of parameters in the analytical solution to prove that the experimental data is within the same order of magnitude of analytical predications. For example, diaphragm thickness ranging from -20μm to 20μm are analyzed, and the range of deflection deviation is also plotted in Figure 6. The curve fit for experimental results lies between the theoretical curves calculated by the range of the thickness variation, maximum and minimum value of young's modulus and poison ratio of PMMA.

4. SENSOR CHARACTERIZATION

Pressure sensing experiment

A pressure sensing experiment was also performed to validate the sensing ability of the MWNT sensor array. The sensor chip was fixed to a PCB circuit board as shown in Figure 7 with an inlet tube for inputting pressure. An air compressor and a regulator were used to input the pressure though the inlet tube to the diaphragm. A pressure sensing instrument was used to monitor the input pressure during the experiment. The pressure applied to the CNT sensors was then varied from 0kPa to 70kPa and the corresponding resistance of a sensor was monitored (see Figure 8).

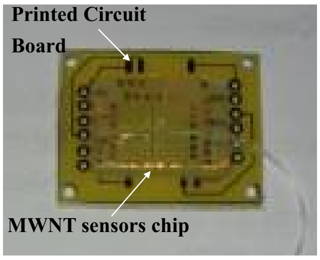

Figure 7: The printed circuit board used to test a PMMA pressure sensor chip.

The room temperature resistance at 0kPa of a sensor was typically ranged from several kΩ to several hundred kΩ, which suggested that the connection of MWNT bundles between the Au electrodes as mentioned in [3]. Experimental results showed that resistance across the MWNT-microelectrodes increased linearly with the applied pressure up to ~70kPa. Moreover, the gauge factor of the piezoresistive CNT sensing element can be estimated in the following equation:

$$G = \frac{\Delta R}{R}\left(\frac{1}{\varepsilon}\right) \tag{3}$$

where R, ΔR, ε are the initial resistance of the sensor without applying pressure, resistance change of the CNT under applied pressure, and the strain of the sensor, respectively.

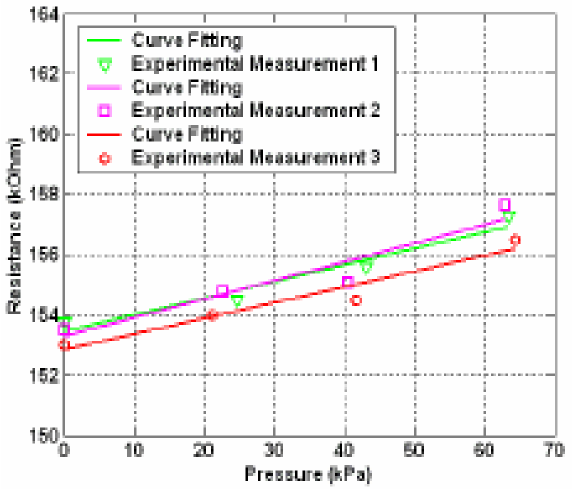

Figure 8: Resistance-pressure dependency of a typical MWNT pressure sensor for 3 different measurements. The drift in the 3rd measurement may be due to the change in contact-resistance of the CNT with an electrical pad.

Based on the theoretical deflection found from Eq. (1), the strain at the center of the diaphragm can be estimated and is calculated in the range from 0 to $8.07691*10^{-5}$ with the applied pressure from 0 to 60kPa (assume that the initial strain is zero due to no deflection at 0kPa). On the other hand, the resistance change due to the applied pressure can be experimentally obtained from three measurements as shown in Figure 8. Based on Eq. (3), the average estimated gauge factor of the piezoresistive CNT sensing element is ~235.

I-V Characteristic

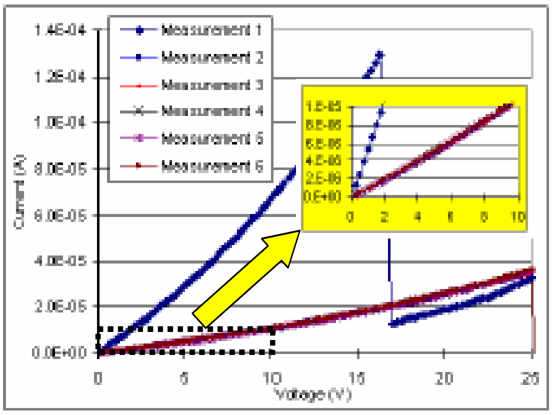

Figure 9: I-V characteristics of a MWNT pressure sensor. As shown, the nominal resistance of a sensor can be stabilized (after measurement 1) by annealing the sensor with a sufficiently high voltage.

The I-V Characteristic of the CNT pressure sensor was also investigated. We have shown that the nominal resistance of the sensing elements can be adjusted by annealing the MWNTs with sufficiently high current-heating (see Figure 9), i.e., if enough current is passed through a MWNT, its wall(s) may be “burned” off, there by causing an increase in nominal resistance of the sensing element. This is a very repeatable phenomenon, and is used to stabilize the resistance value across the sensing electrodes.

5. CONCLUSION

The fabrication process and electrical characterizations of a novel PMMA-based CNT pressure sensor have been presented. The pressure-resistance dependency and I-V characteristics of the CNT sensor were discussed. Experimental results indicated the pressure sensing ability of the device and the nominal resistance of the sensing elements can be adjusted by annealing the MWNTs through electrical current heating. Besides, FEM and analytical modeling were performed to simulate the mechanical characteristic of the diaphragm and the comparison to the experimental and theoretical deflection of PMMA diaphragm was presented. Our fabricated novel polymer-based pressure sensing devices may potentially serve as bio-compatible and low-cost sensors for biological and MEMS/NENS applications.

6. ACKNOWLEDGEMENT

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