Resistive Pressure Sensor with Carbon Nanotube Electrodes towards Flexible Electronics Applications

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ABSTRACT

Here, we present a flexible and stretchable pressure sensor composed of vertically aligned CNTs (VACNTs) partially embedded in a polydimethylsiloxane (PDMS) substrate. VACNTs were grown via chemical vapor deposition and transferred onto PDMS as a stretchable electrode. Two such electrodes were placed face-to-face. Increased orthogonal pressure is directly proportional to a detectable change in resistance, enabled by increased contact between the opposing electrode surfaces. The measured resistance was maintained at stretching, demonstrating its ability to accommodate various mechanical disturbances such as large bending, twisting and stretching, while retaining its performance. This work will directly impact the development of pressure sensing devices toward medical and wearable electronics applications.

Keywords: carbon nanotubes, pressure sensor, flexible electronics, polydimethylsiloxane (PDMS), electronic skins

1 INTRODUCTION

Flexible electronics has directed development and research of unique instrumentation and measurement techniques to achieve conformable sensors for a wide range of applications [1]–[3]. Conventional high-performance electronic materials such as silicon are not flexible, whereas many flexible materials, such as conducting polymers, are often characterized by poor electric properties [4]–[6]. Thus, high mobility materials in a flexible configuration are desirable, and carbon nanotubes (CNTs) are promising materials owing to their excellent electronic properties and flexibility owing to their small diameter [7]–[10].

Carbon nanotubes have been demonstrated in various potential applications, including conductive and high-strength composites, energy storage, sensors, semiconductor devices, filtration, and electronics [11]–[13]. In combination with polydimethylsiloxane (PDMS), flexible platforms have been realized that combine the inherent stretchability of PDMS with the superior electronic properties of CNTs. CNTs have been incorporated with PDMS in various configurations and composites to achieve diverse flexible electronics applications including gas separation [14], energy storage [15], [16], electrocardiogram monitoring [17], and strain sensing [18].

For skin-attachable electronic devices, pressure sensors in those platforms can be subjected to various lateral strains via stretching, bending and distortion, while the sensor must provide a reliable pressure sensing under pressure orthogonally applied to the surface. Flexible/stretchable electrodes need to be capable of accommodating various mechanical disturbances such as large bending, twisting and stretching, while retaining their performance

Here, we utilize vertically aligned carbon nanotubes (VACNTs) embedded in a polydimethylsiloxane (PDMS) substrate. VACNTs were grown via chemical vapor deposition and transferred onto partially cured PDMS as a stretchable electrode. Two such electrodes were placed face-to-face to create a resistive-based pressure sensor. As orthogonal pressure is increased, greater contact between the opposing electrode surfaces results in a directly proportional detectable change in resistance. The pressure sensor's ability to accommodate various mechanical disturbances such as large bending, twisting and stretching, while retaining its performance will impact the developing field of flexible electronics.

2 METHODS

2.1 CNT Growth

CNTs were grown via atmospheric pressure chemical vapor deposition (APCVD). For the growth substrate, a silicon (Si) chip with a 500 nm oxide layer (SiO_2) was deposited with layers of 5 nm of aluminum (Al) and 3 nm of iron (Fe) via physical vapor deposition (PVD) as the catalyst layer for CNT growth. The substrate was placed in a quartz tube fixed to a furnace to allow application of heat and gas flow. The furnace was heated to 750ºC for the growth temperature, in which the temperature is maintained for 15 min with application of 60 sccm H_2 and 100 sccm C_2H_4. Ar gas was flowed throughout the entire process at a gas flow rate of 500 sccm. Following the growth, the quartz tube was rapidly cooled to room temperature by removal of the thermal blocks insulating the tube within the furnace, while maintaining the Ar flow. The resulting CNT were vertically aligned (VACNT), composed of individual nanotubes mechanically cross-linked with each other.

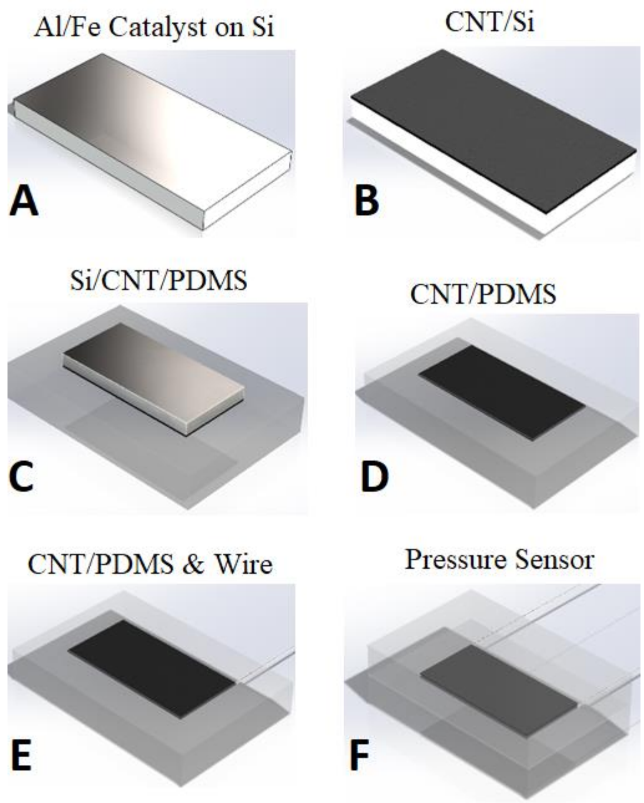

Figure 1: Fabrication sequence of resistive pressure sensor with CNT/PDMS electrodes, according to the following steps in sequence: (a) Al/Fe catalyst deposited on Si substrate with 500 nm oxide layer (SiO_2) as the growth substrate, (b) CVD growth of CNT on the growth substrate to create CNT/Si, (c) CNT transfer onto partially cured PDMS to create Si/CNT/PDMS, (d) removal of Si substrate once PDMS fully cured to create CNT/PDMS, (e) conductive wire connected to CNT/PDMS electrode for electrical characterization, (f) two CNT/PDMS electrodes are placed face-to-face, resulting in a completed pressure sensor.

2.2 CNT Transfer to PDMS

As shown in Figure 1, CNT/PDMS electrodes were fabricated by transferring grown CNT onto partially cured polydimethylsiloxane (PDMS). The curing condition of PDMS was optimized to fully wet the individual roots of CNT in contact. Upon fully curing the PDMS, CNTs were partially embedded into PDMS, resulting in a VACNT/PDMS structure with a high level of integrtiy for flexible and stretchable electronics applications. Due to the mechanical cross-linking of naotubes with neighboring nanotubes, the entire VACNT layer retains mechanical and electrical integrity during stretching, bending, or twisting. To fabricate PDMS, liquid elastomer base was well mixed with a curing agent (Sylgard 184 Silicone Elastomer, Dow Corning) at a ratio of 10:1. To remove bubbles, the mixture was degassed in a dessicator under reduced pressure via vacuum pump. The liquid PDMS was heated on a hot plate at 70ºC for approximately 20 min, until partially cured. The consistency of PDMS was tested with a tweezer to determine the degree of curing. CNT was first grown a silicon (Si) chip with a 500 nm oxide layer (SiO_2) and deposited layers of 5 nm of aluminum (Al) and 3 nm of iron (Fe), as shown in Figure 1a. The grown CNT layer (Figure 1b) was placed face-to-face onto the partially cured PDMS (Figure 1c) to allow the PDMS to wet the individual CNTs, due to the capillary effect and viscoelastic property of PDMS. Thus, CNT tips were embedded into the PDMS and PDMS was allowed to fully cure in an ambient environment for 12 h. Following curing, the CNT/PDMS substrate was removed (Figure 1d) from the Si/SiO_2 substrate, as a result of the stronger adhesion of the CNTs embedded in PDMS than the adhesion between CNTs and the underlying Si/SiO_2 growth substrate.

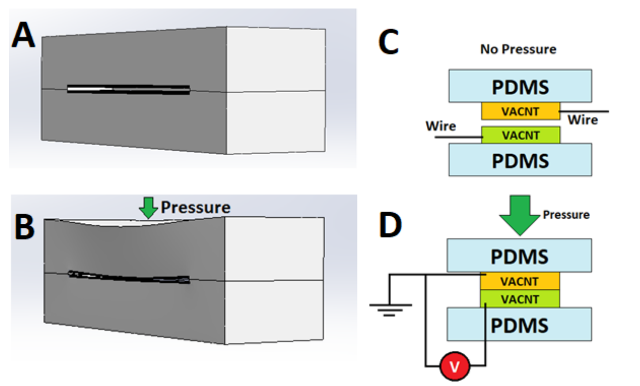

Figure 2: Illustrative model of pressure sensor (a) without pressure and (b) with orthogonally applied pressure. An illustration of the operating principle of the resistive-based pressure sensor is shown (c) without pressure and (d) with orthogonally applied pressure.

2.3 Pressure Sensor Fabrication

Following fabrication of PDMS/CNT electrode, conductive wires were fixed to the CNT portion to allow conductive measurements, as shown in Figure 1e. To fabricate the resistive pressure sensor, two CNT/PDMS electrodes were placed face-to-face with conductive wires fixed to each distinct electrode, as shown in Figure 1f. The fabrication allows for a resistive based pressure sensor, as pressure increases contact between opposing CNT electrodes, as shown in Figure 2. When no pressure is applied (Figure 2a&c), the contact is minimal, resulting in relatively high resistance measurements. As pressure is introduced (Figure 2b&d), the increased contact between opposing CNT/PDMS electrodes results in decreased resistance. The change in resistance is proportional to the amount of pressure applied.

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2.4 Experimental Setup & Electrical Characterization

The CNT/PDMS resistive pressure sensor was fixed in a setup with clamps that allow introduction of stretching strain through a simple turn-screw mechanism, as shown in Figure 3. Each turn of the device resulted in a proportional change in strain. Pressure was applied on the top surface of the pressure sensor using weights, and pressure values were calculated by the contact area (e.g., 500 Pa, 1000 Pa, and 0 Pa for the control). The conductive wires connecting to the CNT electrodes were wired to a potentiostat and characterized in a two electrode configuration. Cyclic voltammetry was performed at a scan rate of 100 mV/s in the range of 0 to 0.5 V to determine the resistance values for each applied pressure and applied stretching strain.

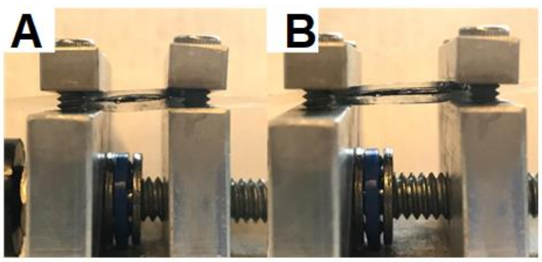

Figure 3: Photographs of pressure sensor fixed to clamps to demonstrate stretchability (a) at initial state without stretching strain and (b) with ~100% stretching strain.

3 RESULTS AND DISCUSSION

A representative graph demonstrating the calculated resistance for the pressure sensor over increasing stretching strains is shown in Figure 4. In addition to the control (i.e., no applied pressure), the orthogonally applied pressure was either 500 Pa or 1000 Pa. The unique resistive pressure sensor utilizing two face-to-face electrodes of CNT partially embedded in PDMS can be used for reliable and stable pressure sensing under both stretching and bending (flexibility).

A proportional change in resistance is demonstrated with respect to the applied pressure. As pressure is applied, the top electrode approaches the bottom electrode. Increasing pressure results in opposing electrodes of PDMS/CNT becoming in greater contact. The increased contact is a result of a greater contact area of individual CNTs with those from the approached opposite electrode. The increased quantity and area of individual CNT tips in contact with those of the opposing electrode allows for enhanced electronic transport. Thus, the increased contact between CNT layers results in a decreased resistance.

Furthermore, it is observed that the resistance remains relatively consistent for each set of pressures, irrespective to the stretching strain. As the electrodes are stretched, the contact between neighboring CNTs within an electrode are maintained. The spacing between individual nanotubes is increased during stretching; however, individual nanotubes are still interconnected when CNT/PDMS structure is stretched. The CNTs are embedded into PDMS and the interwoven CNTs maintain contact with neighboring CNTs despite lateral elongation of PDMS substrate.

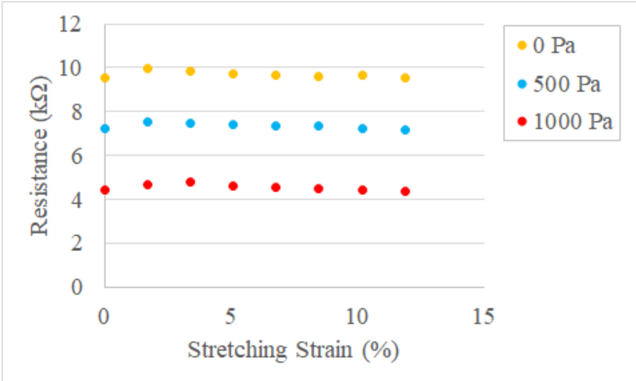

Figure 4: Graph of CNT/PDMS resistive-based pressure sensor with 0 Pa, 500 Pa, and 1000 Pa exerted pressures, maintaining measured resistance under introduced stretching strains.

4 CONCLUSION

We demonstrate stretchable and flexible electrodes composed of vertically aligned CNTs (VACNTs) partially embedded in a polydimethylsiloxane (PDMS) substrate as a platform for fabricating a flexible resistive-based pressure sensor. The fabrication process of the CNT/PDMS platform is facile and simple, and two electrodes are configured face-to-face as a flexible resistive pressure sensor. Pressure sensing is successfully demonstrated with the device, and resistance is maintained at stretching. A proportional change in resistance is demonstrated with respect to the applied pressure, owing to the increased contact area between opposing electrodes proportionally reducing the resistance. Since the devices are reliable and stable under stretching and are insensitive to lateral strain induced by mechanical deformation (such as stretching, bending, twisting, and wrinkling), the electrodes are expected to have potential impact in the developing fields of wearable electronics and flexible sensors.

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