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Sensitive and Stable Strain Sensors Based on the Wavy Structured Electrodes

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Abstract—**Herein, we develop capacitive type strain sensors composed of the CNTs-PDMS nanocomposite thin films as electrodes and PDMS dielectric layer. The strain sensing performances of the strain sensors made of the flat and wavy structured electrodes are compared. Both types of strain sensors can measure strains up to 100%. We found that wavy structured based strain sensors possess higher sensitivity with quite stable and reliable responses due to the resistance stability and very low resistance standard deviation of the wavy structured electrodes. To illustrate the applicability of our strain sensors as flexible and wearable devices, we conducted the human motion detection by attaching the wavy structured strain sensors to the human body.**

I. INTRODUCTION

Demands for the flexible, stretchable and sensitive strain sensors are increasing due to their potential applications such as rehabilitation/personal health monitoring [1-3], sport performance monitoring [4, 5], and entertainment fields (e.g. motion capture for games and animation) [6, 7]. Two types of flexible and stretchable strain sensors were developed by several research groups using advanced functional nanomaterials including resistive type strain sensors in which the sensors respond to the mechanical deformations by the change of resistance and capacitive type strain sensors where transduce external strains to the change of capacitance. Piezoresistivity of the resistive type strain sensors are mainly caused by geometrical changes [8], crack propagation in the sensing materials [9, 10] and tunneling and disconnection between sensing elements [8, 11] by the applied strain. However, hysteresis and nonlinear response are among main drawbacks of these type sensors [12].

Capacitive type strain sensors are composed of a dielectric layer laminated between two stretchable electrodes [13]. The capacitance of such a device is given by:

$$C = \varepsilon_0 \varepsilon_t \frac{A}{d}$$

where ε_0 and ε_t are the electric and dielectric constants for the dielectric layer, respectively. A is the capacitive area between two opposing electrodes and d is thickness of the dielectric layer. When strain sensors are subjected to the strain, the capacitance of sensors changes by the change of geometry according to Poisson's effect. The sensitivity or gauge factor (GF) of the capacitive type strain sensors is:

$$GF = \frac{\Delta C}{C_0}$$

where ΔC is the relative change of the capacitance, C_0 is the initial capacitance of the sensor and ε is the applied strain. Main disadvantage of the capacitive type strain sensors is very low sensitivities (GFs<1). For instance, strain sensors with sprayed carbon nanotube (CNT) thin film as electrodes and silicone rubber (Ecoflex) as dielectric layer possess GFs of 0.4 (with stretchability of 30%) and those made of CNT thin film electrodes with silicone elastomer (Dragon skin) dielectric layer had GFs of around 1 (with high stretchability of 300%) [14, 15]. Moreover, Ag nanowire/PDMS composite electrodes (with PDMS dielectric layer) based strain sensors show GFs of 0.7 and 1 with stretchability of 50% and 30% respectively [12, 16]. Besides of low GFs, the capacitive type strain sensors might have unpredicted response and capacitance interaction with the human body [12, 15]. Moreover, micrometer-sized void growth in the network thin film of the stretchable electrodes under stretching can lead to unstable overlap between the opposing electrodes inducing noise in the response of the strain sensors [15]. Therefore, reduction of the void growth, resistance stability and very low standard deviation of resistance for the stretchable electrodes can remarkably improve the performances of the capacitive type strain sensors.

We report highly flexible and stretchable capacitive type strain sensors based on the CNTs-PDMS nanocomposite thin film as stretchable electrodes and PDMS dielectric layer. The strain sensing performances of the strain sensors made of wavy structured electrodes are compared with those of the flat structured strain sensors. The strain sensors can measure strains up to 100% with a reversible manner. We found that wavy structured strain sensors have higher GFs than those of flat structured strain sensors (0.62>0.47) with better stability and reliability. Wavy structured electrodes show much better electromechanical performance in terms of resistance stability and deviation upon stretching. To illustrate the applicability of our strain sensors as flexible and wearable devices, we conducted the human motion detection by attaching the wavy structured strain sensors to the human body for motion sensing.

II. MATERIALS AND SAMPLE FABRICATION

Multi-walled carbon nanotubes (MWCNTs) with an average length and diameter of 5~20 μm and 16 ± 3.6 nm were purchased from Hyosung Co., South Korea. CNTs were functionalized by well-known acid treatment method

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according to Yu et al. [17]. 100 mg of CNTs where added acid with a ratio of 3:1). The solution was stirred on a hot plat for 45 min under 110 °C. The suspension was diluted to 200 ml with deionized (DI) water and washed three times by centrifuging the solution at 5000 rpm for 10 min. Then, DI water was replaced with 125 g of isopropyl alcohol (IPA) and stirred for an hour to obtain 0.8 wt.% suspended CNT solution.

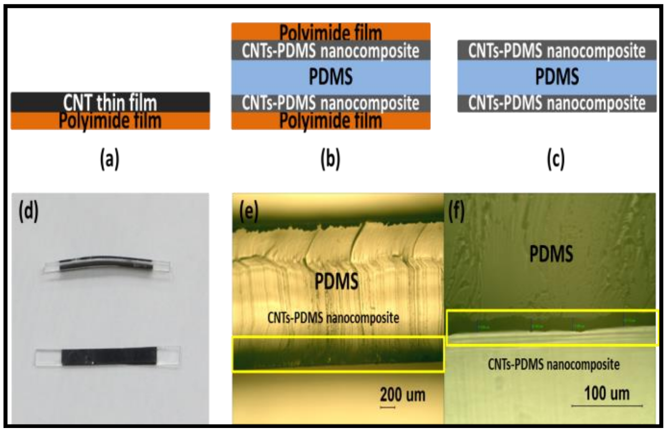

Figure 1. a-c) Fabrication processes of the flat structured strain sensors. a) Deposition of CNTs on the polyimide film and drying the solution under light heating. b) Casting the liquid PDMS between two face to face CNT deposited thin films. c) Transferring all CNTs to the surface of PDMS by penetration of the liquid PDMS into the network of CNT thin film. d) Photographs of the fabricated strain sensors. e, f) Cross-sectional optical images of a flat structured sample.

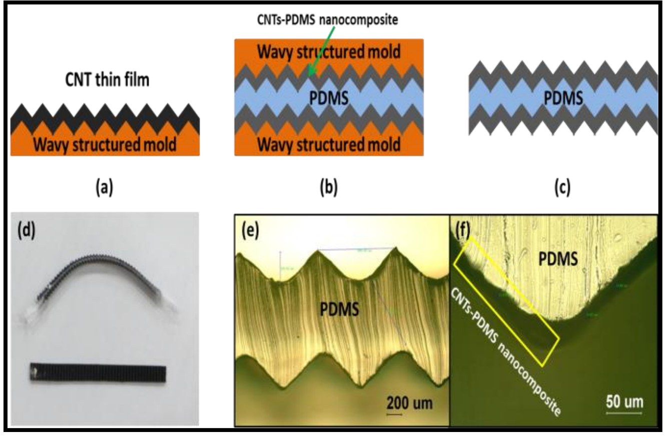

Figure 2. a-c) Fabrication processes of the wavy structured strain sensors. a) Deposition of CNTs on the wavy structured mold. b) Casting the liquid PDMS between two opposing CNT deposited thin film and curing it at °C for 2 hours. c) Transferring all CNTs to the surface of PDMS. d) Photographs of the fabricated samples e, f) Cross-sectional views of a wavy structured sample.

Figure 1 depicts fabrication processes for the strain sensors made of the flat structured electrodes. First, CNT solution was deposited on the patterned polyimide film by simple drop casting. The CNT thin film with approximate thickness of ~ 11 µm on the patterned polyimide film was into the 40 ml of mixed acids (i.e. sulfuric acid and nitric obtained by drying the CNT solution under light heating. Then, the liquid PDMS (with thickness of ~1 mm) was cast into the gaps between two face to face CNT thin films. The liquid PDMS penetrated into the CNT network and formed a robust nanocomposite of CNTs-PDMS. After curing the liquid PDMS at 70 °C for 2 hours, all CNTs were transferred to the surface of the PDMS layer formed flat structured strain sensors, see Figure 1f.

Wavy structured electrodes have been fabricated by transferring the CNT thin film (with thickness of ~ 11 µm) from a wavy structured mold to the surface of PDMS, as shown in Figure 2. The CNT solution was drop casted onto the wavy structured molds with teeth width and height of 1085 µm and 320 µm, respectively. Then, the liquid PDMS was poured into the two opposing wavy structured molds. All CNTs were transferred from molds to the surface of PDMS by curing the liquid PDMS at 70 °C for 2 hours.

III. RESULTS AND DISCUSSION

Figure 1d and Figure 2d show photographs of the fabricated strain sensors based on the flat and wavy structured electrodes. Both types of sensors are highly flexible and stretchable so that they can be utilized for wearable motion detection applications. Figure panels 1e and 2e illustrate the cross sectional optical images for the flat and wavy structured electrodes based strain sensors, respectively. As the figures show, the CNT nanocomposite thin films are highly cross-linked with the PDMS dielectric layer on the top and bottom forming highly flexible and stretchable capacitors. Figures 1f and 2f show the CNTs-PDMS nanocomposite layers. The penetration of the liquid PDMS made the sparse network of the CNT thin film highly robust.

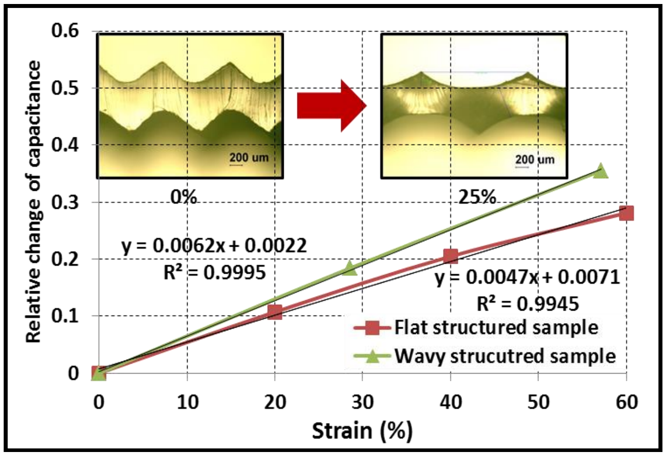

Figure 3. Response of the flat and wavy structured strain sensors to the applied strain; inset, morphology changes of the wavy structured electrodes by the applied strain (gap opening/closing mechanism).

To characterize the strain sensing applicability of our strain sensors, the top and bottom electrodes were attached to copper wires by silver paste. Then, two ends of the sensors were clamped to a moving stage for applying the stretch/releasing cycles. The capacitance changes were measured by an impedance analyzer (4192A LF IMPEDANCE ANALYZER, HP). Both types of the strain sensors can measure strains as large as 100% which are much larger than those of conventional strain gauges (stretchability<5%) [7, 9]. Figure 3 shows the relative change of capacitance against the applied strain for both strain sensors. The wavy structured strain sensors possess higher GFs (0.62>0.47) with an excellent linearity (R^2~1) and stable response. Higher GFs could be due to the gap opening/closing mechanism of the wavy structured electrodes providing more overlapped capacitive area between top and bottom nanocomposite electrodes, as shown in the inset of Figure 3.

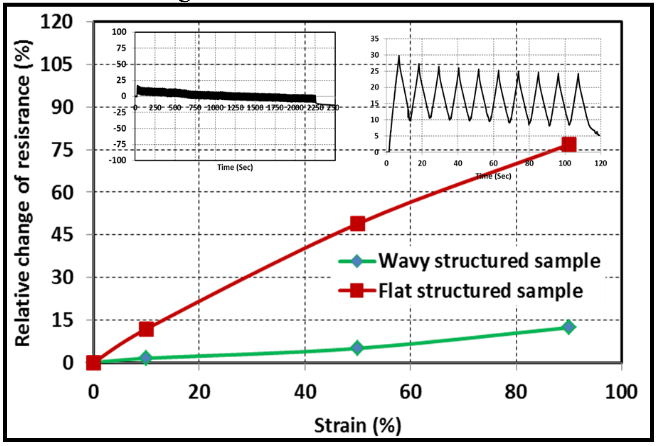

Figure 4. Electromechanical behavior of the flat and wavy structured electrodes; very high resistance deviation in the case of the flat structured electrodes; left inset, relative change of resistance in the case of the wavy structured electrode more than 200 cycles (from Ɛ=0% to Ɛ=50%); right inset, irreversible change of resistance to the cyclic loading for a flat structured electrode.

We further characterized the electromechanical behaviors of the flat and wavy structured electrodes. As Figure 4 depicts, the resistance of a wavy structured electrode is increased gradually by the applied strain (with deviation of less than 15 % under 90% of strain) and recover to its original value after releasing. The resistance changes of the electrode for more 200 cyclic loading/unloading (from ε=0% to ε=50%) is illustrated in the left inset of Figure 4 showing high reliability and resistance stability of the wavy structured electrodes to the applied strain. Moreover, the wavy structured electrode can withstand to large strains by a mechanism where planar strains are absorbed by the nonplanar movements of the wavy-shaped parts while nanocomposite layer itself is subjected to minimum harmful strains [15]. On the other hand, very large resistance deviation with an irreversible manner was observed in a flat structured electrode (deviation of more than 75% by the 90% of strain), as shown in Figure 4. Very large resistance variations in the flat structured electrode is due to the micrometer-sized void growth and buckling of the nanocomposite layer decreasing the number of electrical pathways and thereby increasing the resistance of electrodes. Moreover, high resistance deviation in the flat structured electrodes produces unstable overlapped capacitive area between top and bottom electrodes inducing unpredictable and unstable responses from strain sensors.

Figure 5 represents the stability and drift performance of a wavy structured strain sensor. Furthermore, several random strains were applied to the sensor while relative change of the capacitance was continuously monitored (in each strain step, the strain was kept fixed for 2 min while the response of the sensor was measured). As the figure depicts, the sensor responded to the strain with excellent stability, reliability and negligible drift.

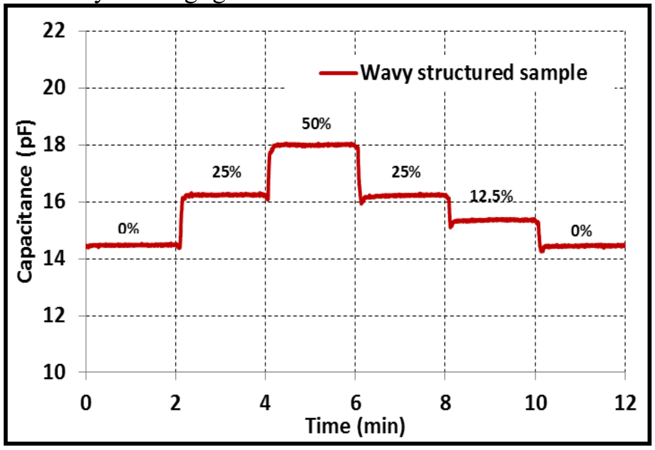

Figure 5. Response of a wavy structured strain sensor to the some random strains (strain was fixed to 2 min per each); excellent stability without any unpredictable response, hysteresis and drift.

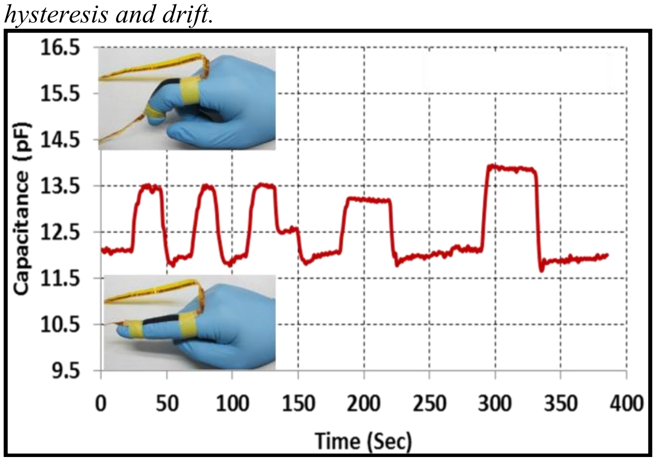

Figure 6: Finger motion detection using a wavy structured strain sensor; stable, sensitive and quite fast response to the bending with an excellent reversible manner.

As our experiments indicate, the wavy structured strain sensors possess good sensitivity, reliability and stability and drift performance. High stretchability (Ɛ~100%) and flexibility of the strain sensors enabled us to apply them for the human motion detection where a large strain level (ε> 50%) should be accommodated by the strain sensor [7]. The strain sensors could easily be attached to the body or clothing as wearable devices. For instance, our strain sensors could be utilized for the joints' angle measurement device by mounting the strain sensors on the body joints (e.g. fingers' joints, wrist joint and *etc.*). Figure 6 shows the motion detection of a finger's joint where a wavy structured strain sensor was attached to the index finger and then the capacitance changes by the downward and upward movements of the finger were measured. When the finger is moved downward, the strain is accommodated by the sensor increasing the capacitance of strain sensor. The capacitance change could be a parameter for the corresponding bending angle calculation. For a normal bending and relaxation of the finger, the capacitance change is ~ 12.5% which corresponds to the ~ 18% of strain.

IV. CONCLUSIONS

In this paper, we report highly flexible and stretchable capacitive type strain sensors based on the CNTs-PDMS nanocomposite electrodes. The performances of the wavy structured strain sensors are compared with those of the flat structured strain sensors showing that wavy structured electrodes have very low resistance deviation upon stretching with very good resistance stability. Wavy structured strain sensors have higher GFs than flat structured strain sensors (0.62>0.47) with stretchability of 100%. As an application of our wavy structured strain sensors as flexible and wearable devices, we conducted the motion detection of fingers' joint by attaching the wavy structured strain sensors to the index finger.

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