SURFACE MICRO-STRUCTURED, STRETCHABLE STRAIN SENSOR TOWARDS BIAXIAL SENSITIVITY AND PERFORMANCE ENHANCEMENT

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ABSTRACT

In this work, we developed micro-crack based stretchable strain sensors consist of polydimethylsiloxane (PDMS) with micro-dome structure arrays and carbon nanotube (CNT) film coated on its surface. Due to a stress concentration caused by micro-dome structure under a certain strain, micro-cracks of CNT film are generated and propagated more easily as compared with the case of a CNT film on the plane surface. In addition, because the micro-cracks are only positioned at designed region which is between micro-domes, electrical resistances in elongated and perpendicular directions are clearly different thanks to the novel mechanism. As results of these phenomena, strain decoupling is achieved and a sensitivity of the sensor can be modulated by adjusting the dimension of micro-dome arrays. We also conducted the numerical simulation based on finite element method (FEM) to verify the designed sensing mechanism and predict the performance of the sensor. This kind of work is important for the motion detecting sensor for acquiring decoupled information from complex signal. Finally, we fabricated a smart glove that could detect a biaxial strain applied on the back of a hand skin to demonstrate that this sensor could be used as wearable device.

INTRODUCTION

As interests in personal healthcare are increased, collecting and analyzing the information of a daily motion become important issues. Many studies about various types of flexible physical sensors have been reported to utilize as wearable devices that can accurately detect the signals from a human body [1-3].

Strain is one of the most important information to analyze human motion. Previously, conventional metal strain gauges were widely used to detect infinitesimal range of strain in the industry field. Although they are quite sensitive, robust and compatible to mass production, they cannot cover wide range of strain due to intrinsic properties of the materials which is crucial limitation. However, to utilize for human motion detection by applying to the joints, sensors should maintain their mechanical and electrical property in large deformation caused by a bending motion.

In the last few years, by adopting rubber-like polymer and elastomer materials as a substrate, strain sensors with high stretchability have been developed and mounted to the human joints to demonstrate the sensors [4-6]. These kinds of sensors showed good sensitivity and durability thanks to their structure embedding nano-scale conductive materials. Recently, multi-modal sensors which could detect various types of forces with a single sensor have been reported [7-8]. However, these sensors are not able to distinguish each stimulus, which is an important issue for accurate human motion tracking. Here, we introduce a novel stretchable strain sensor which shows clearly different responses to the strain in elongated and perpendicular directions. We also achieved the improvement of the performance thanks to its operation mechanism.

STRUCTURE AND MECHANISM

Structure and Simulation

This sensor has micro-dome arrays on its surface and applied stress is concentrated on gaps between the surface structures. FEM based numerical simulation was conducted to verify the phenomenon and expect a geometric effects for the sensor performance. Figure 1(a) shows stress and strain distributions on the surface of the 3D sensor model under a certain displacement. The graphical results show stress is concentrated between the micro-domes and the local strain reaches up to 3 times higher than that applied to the overall sensor while the stress on the surface of micro-dome is negligible.

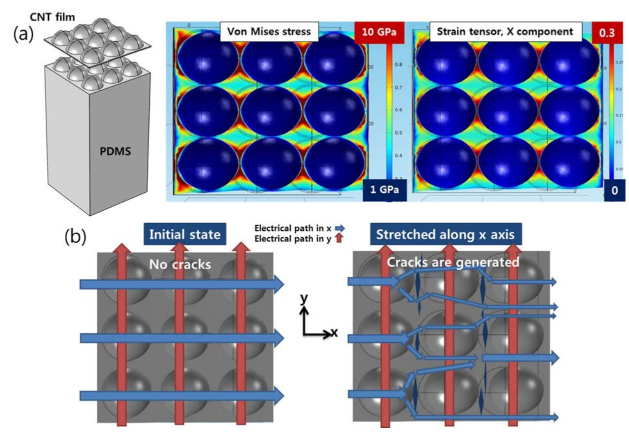

Figure 1: (a) Results of the numerical simulation with a 3D sensor model and the (b) biaxial sensing mechanism of the sensor.

Sensing Mechanism

Schematic illustration of an expected sensing mechanism of this sensor is shown in Figure 1(b). Micro-cracks of the CNT film will be positioned only between the micro-domes according to the simulation results. Because the CNTs on the micro-dome structures maintain their connections, electrical paths in the perpendicular direction to the stretching axis is opened along the surface of the dome arrays. On the contrary, electrical paths in the stretched direction are blocked by the cracks leading dramatic decrease of the electrical resistance. As a result, changes of resistance in two directions are clearly different which means characteristic of biaxial sensing for strain decoupling can be realized.

SENSOR FABRICATION

Master Mold Preparation

Sensors with micro-dome arrays can be fabricated by replica molding process to transfer the engraved dome patterns from silicon master mold to the PDMS substrate. Conventional micro-fabrication processes such as photolithography, metal deposition and reactive ion etching (RIE) were used to make silicon master mold as shown in the Figure 2. First, patterned photoresist was formed on the silicon wafer using photolithography and a metal mask layer for the following RIE process was patterned by lift-off. The RIE process is commonly used for anisotropic etching but here, we controlled the composition and flow rates of the reactive gases (O_2 and SF_6) to enable the silicon wafer to be engraved in the isotropic shape for the dome structuring. Afterwards, the metal layer was removed and C_4F_8 layer for anti-adhesion was conformally coated for easy detachment of the PDMS from the silicon wafer [9].

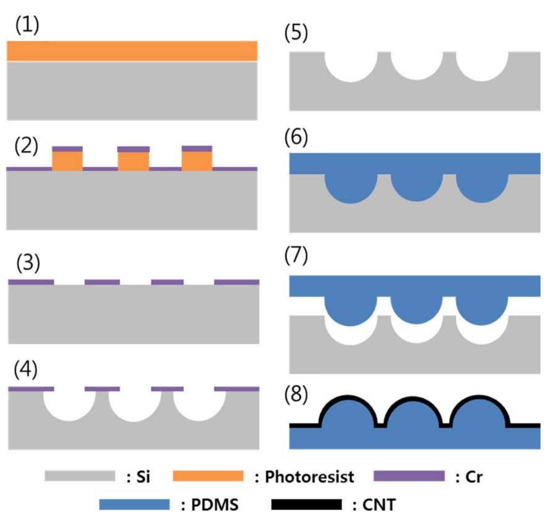

Figure 2: Schematic illustration of the fabrication processes of the CNT coated micro-dome structured sensor

Sensor Fabrication and Cracking Behavior

The micro-dome patterns could be transferred repeatedly from the prepared silicon master mold to the PDMS by the replica molding process. Because the CNTs as the sensing materials have to be coated uniformly, spray coating was used which is a suitable method for the uniform coating of nano-materials dispersed in liquid solvent. Additionally, rough surface of the micro-dome caused by long operating time of the RIE improved an adhesion between CNT and the PDMS. Deposited CNT layer showed 1.2 kΩ/sq of a sheet resistance with 2.5 μm of the film thickness. Photograph and SEM images in the Figure 3 represent uniform and conformal coating of the CNTs by the results of the spray coating. In the SEM images, cracking behavior of the CNT film could be observed. As expecting in the results of the simulation, micro-cracks were only positioned between the micro-dome structures under the stretching. Otherwise, connections of the CNTs coated on the surface of the domes were maintained.

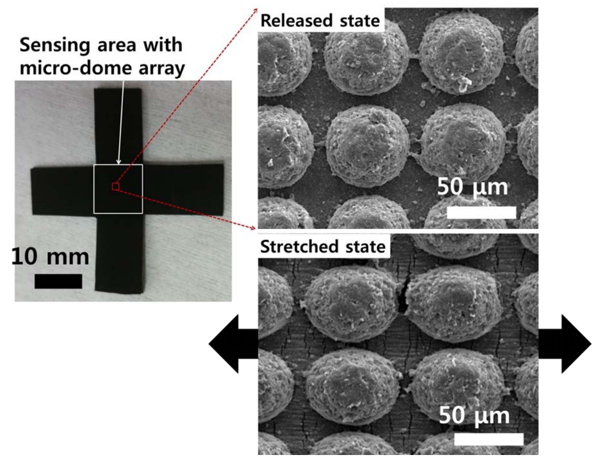

Figure 3: Photograph and the surface SEM images of the fabricated sensor in the released and stretched state

SENSING RESULTS AND DISCUSSION

Sensitivity Enhancement

Characterization of the fabricated sensor was carried out by the electromechanical testing setup. Because local strain is much higher than overall applied strain, cracks are much easily generated than the case of CNT film deposited on a plane substrate. It means sensitivity of the sensor can be tuned by changing a dimension of the micro-dome arrays. In the Figure 4, responses of the four sensors with different gap size between micro-domes are shown when 20 % to 50 % ranges of strain are applied. Sensitivity defined by $\Delta R/R_0$ is clearly different between with and without micro-dome structures on the surface of the substrate. Furthermore, sensitivity is increased as the gap sizes are decreased which is reflecting the applied stress is much concentrated in the case of the narrow gap of the micro-domes. There are slight drift of the signals caused by disparate behavior of connection and disconnection of contacts among CNTs in network and intrinsic hysteresis and stress relaxation property of the elastomeric materials [10].

In the other view, concentrated and localized stress could affect not only to the sensitivity but also to the long-term reliability of the sensors. Stability is also important issue for the stretchable sensors used to the wearable devices and many factors affect to the reliability like a restoration of the micro-structure of the sensor, thickness of the CNT film, environment conditions and electrode connection problems. To achieve both high sensitivity and good long-term stability, we need optimization of these various factors by conducting further intensive researches.

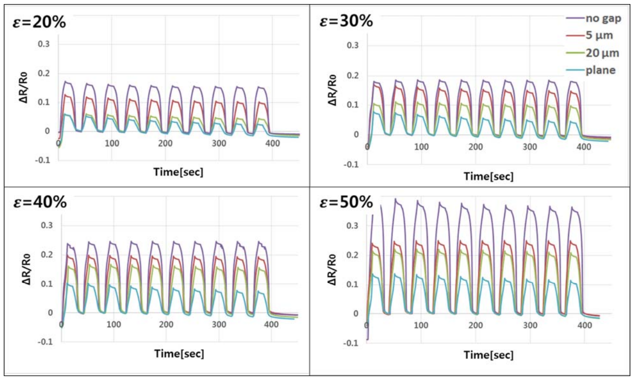

Figure 4: Sensitivity comparison between four sensors with different gap sizes of micro-domes under 20 % to 50 % of strain

Biaxial Sensitivity

In the Figure 5, there is response comparison between the sensors with and without micro-dome structures on their surface with respect to biaxial sensitivity. The results show the resistance change of two axes while the sensor is stretched to a certain axis, so-called x-axis. In the case of the sensor without micro-domes, changes of the resistance in both x and y direction are similar because the cracks are generated randomly and electrical path in y direction also interrupted by the cracks. On the contrary, in the case of the sensor with the micro-domes, the resistance in y direction is changed with tiny amount and even decreased over the certain strain due to the Poisson's effect. The Poisson's effect becomes much dominant in this case since compressive strain applied to the perpendicular direction is also concentrated and localized between the domes. Over about 2% of strain, the total resistance of the y-axis is affected by the Poisson's effect which is leading decrease of the resistance rather than the cracks causing increase of the resistance.

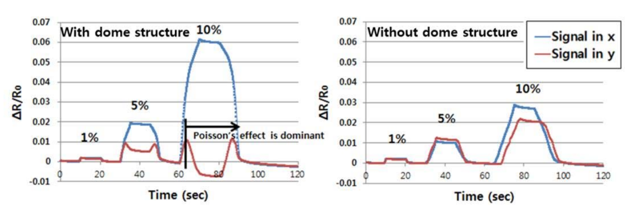

Figure 5: Biaxial responses of the sensors with and without the micro-dome structures under the uniaxial strain

Figure 6 shows resistance changes of the each direction under the strain applied simultaneously along the two axes. When seeing the signals in x direction, resistance is dominantly changed by the strain applied along the x axis while the resistance is almost maintained or negligibly changed by the y directional strain. Strain decoupling can be realized if the change of the signals is reflected just by elongated axis. Because the resistance of this sensor mainly changed only by the elongated axis, although there are some experimental errors occurred by its measurement manner which is a static analysis, expected characteristics of biaxial sensitivity and strain decoupling are successfully achieved.

We also calculated plane fitting of these 3D plot and obtained quite linear relationship (R^2=0.989). Total change of the resistance could be expressed by the formula like Equation 1 and we could find the values of the k_{11} and k_{12} from the fitting. This analysis allows converting the total resistance changes into each strain components by an inverse calculation.

$$\left(\frac{\Delta R}{R_0}\right)_x = k_{11}\varepsilon_x + k_{12}\varepsilon_y \quad (1)$$

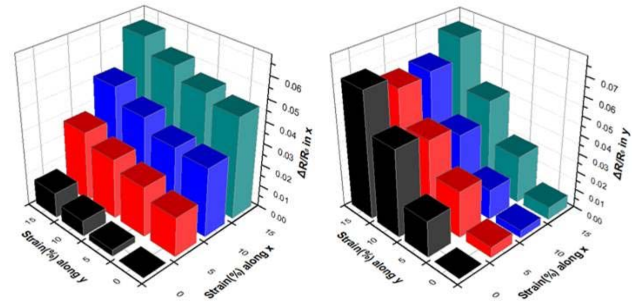

Figure 6: 3D plot of the biaxial responses under the simultaneously applied strain along the two axes.

Smart Glove Setup and Measurement

A prototype of smart glove which could detect a strain applied on a skin of a back of the hand was simply fabricated to demonstrate that the sensor can be applied as wearable device. Pre-fabricated sensor is mounted and fixed on the commercial latex glove as shown in the figure 7(a). Due to CNT layer is coated overall surface of the sensor, the electrical paths are opened each other. In order to avoid an electrical coupling happened between the two axes, signals from each axis are collected alternately by using switching module and Arduino Uno.

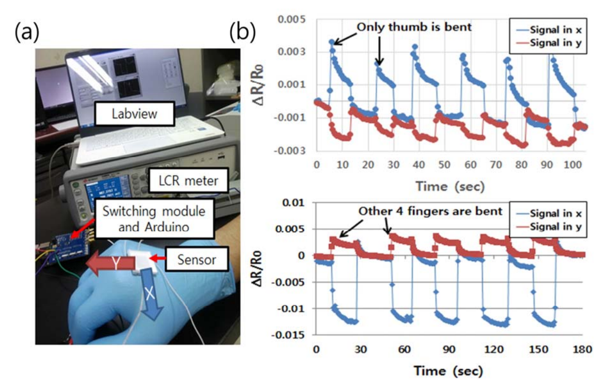

Figure 7: (a) A prototype smart glove setup and (b) responses from the glove detecting strain applied on the skin of the back of the hand with different motions of fingers

We carried out measuring biaxial signals to check the performance of the sensor when used as the wearable applications. The resistance changes of two axes show totally different trends when fingers have some motions. As shown in figure 7, under grasping motion like bending of 4 fingers, the resistance in the y direction is increased while negative sensitivity is shown in the x direction. When bending only thumb, response tendency is opposite to the previous grasping motion.

This prototype has many issues such as sensor mounting methods, position of sensor, slip between the glove and the skin, effects of the vein and bending of the back of the hand. Thus, it is difficult to calculate a real applied strain of skin by applying the Equation 1 because signals of the glove come from many variables like previously mentioned factors as well as deformation of the skin. In these senses, further study to overcome those issues must be conducted to utilize this sensor to the real application.

CONCLUSION

Decoupling the multi-directional forces is the one of the most important issues for the real applications of the wearable sensors. In order to solve this issue, we developed the surface micro-dome structured stretchable strain sensor by using conventional micro-fabrication processes and nano-scale materials

Thanks to the novel sensing mechanism induced by the stress concentration behavior, the sensors have a biaxial characteristic which is leading the strain decoupling. In addition, sensitivity of the sensor can be modulated by varying the dimension of the surface structures which is proved from the results of the simulation and experiments.

Finally we carried out detecting biaxial strain applied on the skin of the hand under different finger motions by using the sensor-mounted smart glove to demonstrate that our sensor has a potential to be utilized as wearable devices.

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