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Development of Two-dimensional Tactile Sensor Using Carbon Nanotubes

Masato Ohnishi[1], Meng Yang[1], Takuya Nozaki[1], Ken Suzuki[1] and Hideo Miura[1]

[1] Tohoku University, Graduate School of Engineering, Fracture and Reliability Research Institute
6-6-11-716, Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8579, Japan
Phone: +81-22-795-4830, E-mail: masato.ohnishi@rift.mech.tohoku.ac.jp

Abstract

A highly-sensitive two-dimensional tactile sensor has been developed by applying micro electro mechanical systems (MEMS) technology. Area-arrayed bundles of vertically aligned multi-wall CNTs (MWCNTs) were grown on the patterned titanium electrodes on a silicon wafer. The load sensitivity of the sensor was 10 mN, and its spatial resolution of the developed sensor was 500 μm, which is superior to that of human finger, 1 mm. The mechanism of the change in the resistance of CNTs was investigated theoretically by using first principles approach.

1. Introduction

Strain sensitivity of the band gap is one of the unique electronic properties of CNTs. The band gap of CNTs changes drastically under uniaxial tensile strain depending on their chirality [1, 2]. Stampfer *et al.* demonstrated that the gauge factor, the ratio of relative change in electrical resistance to the mechanical strain, exceeds 2900[3], which is approximately 1500 times higher than that of conventional metal gauges. In spite of such electronic sensitivity of CNTs, however, few CNTs-based strain or piezo sensors using their strain sensitivity have been demonstrated in commercial base. In previous studies, CNTs-dispersed resin or area-arrayed CNTs are mainly applied to the strain sensors [4-6]. Since the change in the resistance of the sample used in these studies was dominated by the change in the contact condition between the dispersed CNTs in the sample, gauge factor was rather low, i.e., less than 30. On the other hand, Cullinan *et al.* fabricated a piezo sensor in which CNTs are suspended between movable electrodes and succeeded to increase the gauge factor to near 80 [7]. While the position of suspended CNTs was not well controlled in their sensor, their study showed that a highly sensitive strain sensor can be developed by using CNTs. In this study, a tactile sensor consisting of area-arrayed bundles of vertically aligned CNTs was developed by using MEMS technology. In this sensor, CNT bundles of 20 μm in diameter were area-arrayed at 500-μm period, which can be controlled by changing the size and position of the catalysts used for the growth of CNTs [8]. In addition, the mechanism of the change in the resistance of this sensor was analyzed by using first principles calculation.

2. Development of CNTs-based Tactile Sensor

Titanium (Ti) electrodes of 200 μm-width were patterned on a thermally oxidized silicon wafer at period of 300 μm. Iron-nickel catalysts of 5-nm-thick and 20-μm in diameter were deposited on the patterned Ti electrodes, and then the MWCNT-bundles of 6.1-μm-height were grown on the catalysts by using thermal chemical vapor deposition (CVD) at 750˚C for 1 min. The CNT bundles were electrically isolated and mechanically supported by polyimide resin. After mechano-chemical polishing (Fig. 1(a)), upper electrodes and protective polyimide resin were deposited, respectively. Each MWCNT bundle acted as a sensor element and thus, the achieved spatial resolution of the developing sensor was 500 μm, which was higher than that of human finger, 1 mm (Fig. 1(b)).

An example change in the resistance of a bundle under compressive strain is shown in Fig.1 (c). The initial resistance R_0 of a bundle was approximately 95 Ω. The resistance of the bundle changes almost linearly as the increase in the applied compressive strain. Thus, a two-dimensional strain-distribution sensor using MWCNTs has been developed successfully. However, the measured gauge factor was varied from 0.7 to 100. Therefore, it is indispensable for clarifying the variation mechanism to assure the stable operation of this sensor.

3. Analysis of Electronic Properties of CNTs under strain

The deformation behavior of the developed CNT bundles without support of the polyimide coating was observed by SEM under the application of a coaxial compressive load as shown in Fig. 2. Figure 2 (a) clearly shows that CNT bundles were buckled when a compressive strain was applied and the deformation of the individual CNTs corresponded well to the distribution of the applied load. Figure 2(b) shows the change in the average bond length of (17,0) CNT under uniaxial strain and Fig. 2(c) indicates the outlook of the deformed CNT under 10% compressive strain calculated by molecular dynamics (MD) simulation. Color contour in this figure shows the distribution of dihedral angle, which is the relative angle between π-orbitals of adjacent carbon atoms. This dihedral angle is effective for estimating the local deformation of the electronic band structure of the deformed CNT. Theses structural changes cause the change of electronic properties of the deformed CNTs.

Figure 3 shows the changes in the band gap of CNTs with different chirality calculated by π-orbital tight-binding approximation. This result shows that the direction of the change of the band gap under compressive strain is a strong function of the chirality of each CNT [9]. This result indi-

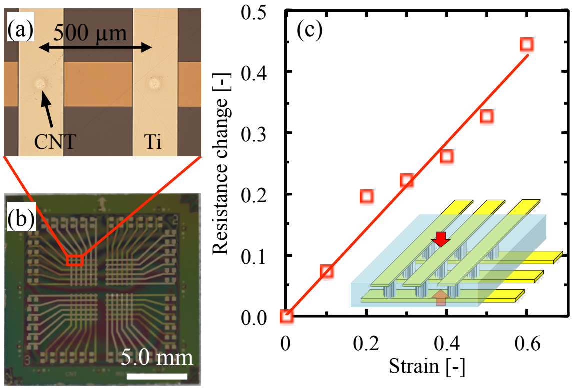

Fig. 1 Two-dimensional tactile sensor using multi-walled carbon nanotubes [8]: (a, b) Microscopic images of the sensor. (c) Example strain sensitivity.

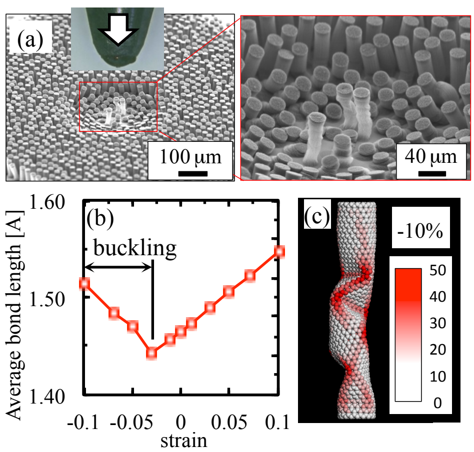

Fig. 2 Compressive test of MWCNT-bundles: (a) MWCNT-bundles after the application of the compressive strain. (b) Change in average bond length under uniaxial strain and (c) outlook of a CNT under 10% compressive strain.

cates that the strain sensitivity of MWCNTs should vary widely depending on the combination of the chirality of the consisted SWCNT. Figure 4 shows the change in electronic properties of CNTs under homogeneous radial strain analyzed by using SIESTA package [9], first principles calculation. The current is calculated under 1.0 V through 3-nm-long region. Because the current through the semiconducting SWCNT increases under the radial strain, the radial strain should increase the current in a buckled bundle. These analyses indicate that buckling deformation is one of the important structural factors for obtaining the strain sensitivity of CNTs. In addition, the combination of the chirality of consisting SWCNT in a MWCNTNT is the dominant factor of the sensitivity. Further analysis is necessary to clarify the resistance change of CNT-bundles under compressive strain.

4. Conclusion

A highly-sensitive two-dimensional tactile sensor has been developed by using MEMS technology. The spatial resolution of the developed sensor was 500 μm, which is superior to that of human finger. The measured gauge factor of the sensor was varied from 0.7 to 100. The mechanism of the change in the electronic properties of CNTs under strain was analyzed by using first principles approach. It was found that it is very important to control both the structure of a MWCNT and its buckling deformation to assure the stable operation of the sensor.

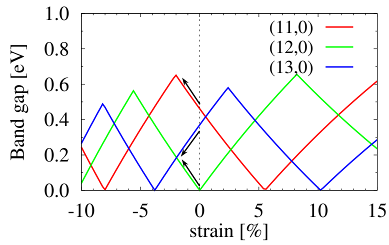

Fig. 3 Change in the band gap of CNTs under uniaxial strain

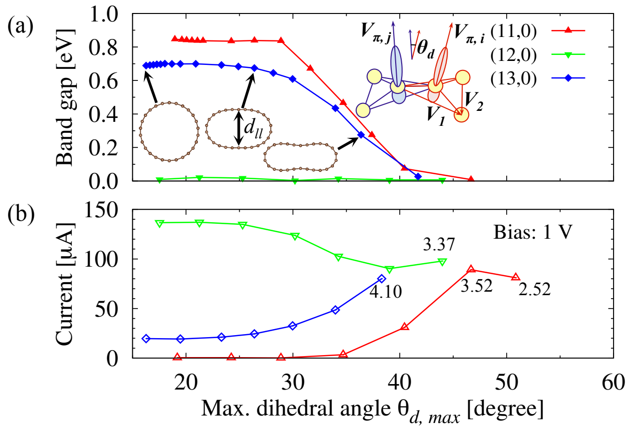

Fig. 4 Effect of radial strain on electronic property of CNTs: Change in (a) the band gap and (b) current through 3 nm-length region of CNTs as a function of the dihedral angle of π-orbit between nearby carbon atoms.

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