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Development of Two-Dimensional Strain-Distribution Sensor Using Carbon Nanotube-Dispersed Resin

Ken Suzuki, Yusuke Suzuki, Yusuke Ohashi, Masato Ohnishi and Hideo Miura,
[1]Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University
6-6-11-716, Aoba, Aramaki, Aobaku, Sendai Miyagi 980-8579, Japan
Phone: +81-22-795-4830 E-mail: kn@rift.mech.tohoku.ac.jp

1. Introduction

To maintain and improve the secure and reliable society of human beings is one of the key issues in the 21st century. In particular, on-line monitoring of the operating conditions of basic infrastructures such as energy plants and transportation systems is demanded strongly because the system has become complicated and aged. To assure the mechanical reliability of those systems, it is very important to measure the stress or strain field in them. Recently, physical and chemical properties of CNTs have been investigated by quite a few researchers all over the world in detail, and their superior characteristics have been made clear theoretically and experimentally. Both the electronic and mechanical properties of CNTs are much better than those of metals used in a strain sensor. In addition, they are deformed easily and stable chemically. Therefore, if the resistivity of CNTs changes drastically depending on applied external strain, it is possible to develop a highly sensitive strain sensor using CNTs [1, 2].

Thus, the authors have proposed a new highly sensitive strain sensor using a multi-walled CNTs (MWCNTs) dispersed resin [3]. In this study, in order to discuss the possibility of the two-dimensional strain distribution measurement by the MWCNTs-dispersed resin, the anisotropy of the strain-induced change of the resistance of the MWCNTs-dispersed resin was measured using 4-probe method. Moreover, two dimensional strain fields were evaluated by using finely area-arrayed MWCNTs-dispersed resin made by MEMS technology with spatial resolution of 50 μm.

2. Strain sensitivity of resistance of MWCNTs-dispersed resin film

The MWCNTs-dispersed (11.5 vol.%) polyisoprene film whose thickness was about 1 mm was used for the measurement. Tensile strain was applied to the MWCNTs-dispersed resin film as shown in Fig. 1. The change of the resistance of the resin film was measured parallel and perpendicular to the direction of elongation, respectively. The amplitude of the applied uni-axial tensile strain was varied from 0% to 70%. An example of the changes of the resistance of the MWCNTs-dispersed resin both parallel and perpendicular to the strain direction is shown in Fig. 2. As shown in this figure, both the resistance change along the directions parallel to the applied strain and perpendicular to the applied strain increased monotonically with the increase of the amplitude of the applied strain. In this study, obtained maximum gauge factor along the direction parallel to the applied strain was about 25.

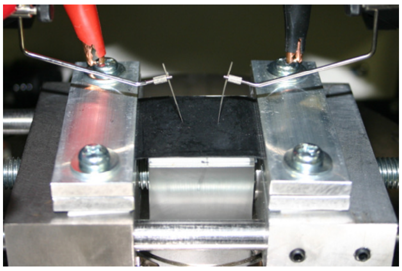

Fig. 1 Measurement of the change of resistance of a MWCNTs-dispersed resin under tensile strain

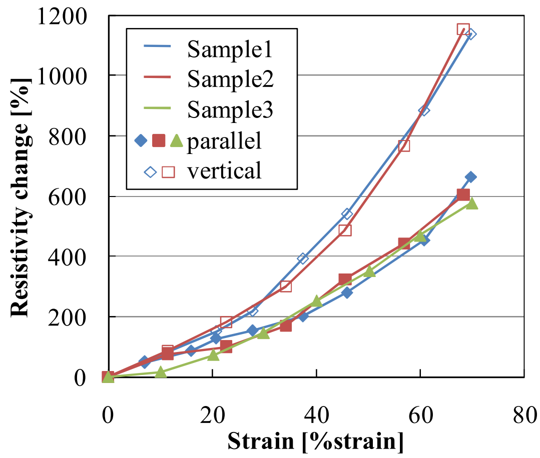

Fig.2 Changes of the resistance of the MWCNT-dispersed resin both parallel and perpendicular to the direction of the applied uni-axial strain

This sensitivity was about 12 times higher than that of conventional metallic strain gauges. When MWCNTs were dispersed separately from each other in a resin, it is well-known that the resistance of the resin can be explained by tunneling current through the resin. Thus, the resistance should be changed when the distance between the MWCNTs is changed by the applied external mechanical stress. Fig. 2 also shows that the gauge factor perpendicular to the direction of the applied strain was higher than that parallel to the direction by about twice. The observed anisotropic change of the resistance clearly indicates that two-dimensional strain field can be detected by applying this MWCNTs-dispersed resin. When CNTs are dispersed in a resin, however, the shape of the dispersed CNTs is not always straight and there should be large distribution of the residual strain in each CNT. Thus, even when uni-axial strain is applied to the CNTs-dispersed resin, the deformation of each CNT should be varied significantly. Thus, it is not easy to estimate the change of electronic conductivity of the deformed CNTs quantitatively. Further analyses are indispensable for explicating the strain-induced change of the electronic conductivity of the deformed CNTs.

3. Development of two-dimensional strain sensor using MWCNTs

It is very important to control the shape of MWCNTs for improving the performance of the strain sensor using the MWCNTs-dispersed resin. Thus, the method for controlling the shape of the MWCNTs on a Si substrate was developed by applying a chemical vapor deposition (CVD) method. Acetylene gas (C_2H_2) was applied to the deposition of MWCNTs. The gas was diluted by nitrogen (N_2) gas by about 15%. The pressure during the deposition was fixed at 0.1 MPa and the deposition temperature was fixed at 750^{o}C. Before the deposition of the MWCNTs, iron particles were deposited on a Si wafer as catalysts by sputtering. We found that the shape of the grown MWCNTs can be controlled by changing the average thickness of the deposited iron particles as shown in Fig. 3. When the average thickness of the iron particles was less than 10 nm, the grown MWCNTs were almost straight as shown in Fig. 3 (a). The length of the grown MWCNTs was about 200 µm. On the other hand, the shape of the grown MWCNTs changed from the straight one to the bended and jammed one when the average thickness of the deposited ion particles was about 15 nm, as shown in Fig. 3 (b). When the shape of the MWCNT is straight, the expected gauge factor along the longitudinal direction of the tube should be high and thus, this structure can be applied to the uni-axial strain sensor. On the other hand, the expected gauge factor of the jammed structure may be lower than that of the straight MWCNTs. But this structure should show the isotropic sensitivity regardless of the direction of the applied strain.

These MWCNTs were grown on a Si wafer with the patterned interconnection structure as shown in Fig. 4. In this test sensor, the MWCNTs were grown on a 20-mm long line. The change of the resistance of the grown MWCNTs was measured by 4 probe method using the electrodes shown in the figure. Both the change of the resistance along the longitudinal direction of the line and that perpendicular to the line can be measured by using these electrodes. In addition, the effect of hydrostatic pressure applied to the wafer on the change of the resistance was measured for discussing the possibility of the application of this sensor to a pressure sensor.

4. Conclusions

The possibility of the development of highly sensitive two-dimensional strain sensors was validated by applying the MWCNTs-dispersed resin. When the MWCNTs were dispersed into the polyisoprene film, the obtained maximum gauge factor along the direction parallel to the applied strain was about 25. At the same time, the gauge factor parallel to the applied strain direction was lower than that perpendicular to the strain. This result clearly indicated the possibility of two-dimensional strain measurement by applying MWCNTs-dispersed resin. We also developed the two-dimensional strain sensor by applying thin-film processing on a silicon wafer. The shape of the MWCNTs can be changed from the straight to bended and jammed by changing the thickness of the iron catalyst layer.

References

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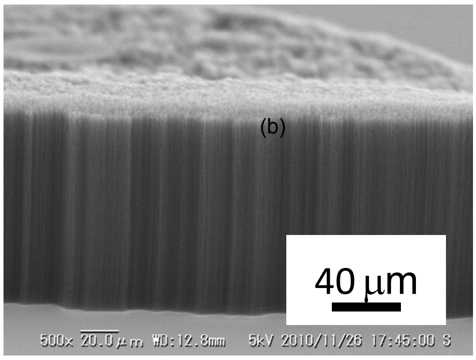
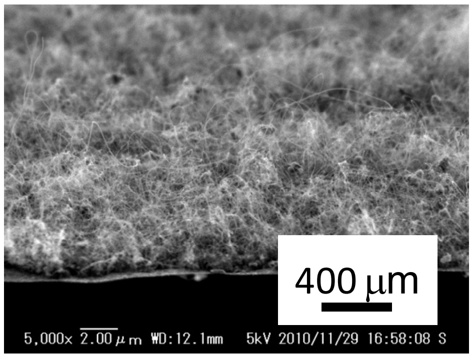


(a) MWCNTs grown on the 10-nm thick iron layer



(b) MWCNTs grown on the 15-nm thick iron layer

Fig. 3 Scanning electron micrograph of MWCNTs grown by a CVD method using acetylene gas

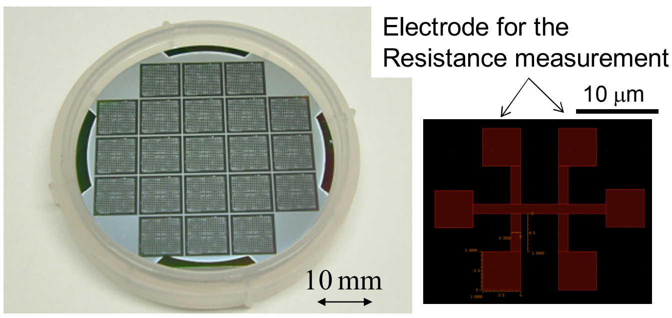


Fig. 4 Outlook of a Si wafer on which two-dimensional strain sensors using MWCNTs was formed