Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp1126-1127

Multi-walled Carbon Nanotube-Dispersed Resin Films for Remote Strain Measurement

Katsuya Ohsaki[1], Hideki Fuji[1], Masato Ohnishi[1], Ken Suzuki[2], and Hideo Miura[2],
[1]Department of Nanomechanics, 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: Katsuya.oosaki@rift.mech.tohoku.ac.jp
[2] Fracture and Reliability Research Institute, Graduate School of Engineering, Tohoku University
6-6-11-712, Aoba, Aramaki, Aobaku, Sendai Miyagi 980-8579, Japan

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.

Thus, the authors have proposed a new highly sensitive strain sensor using a popular resin in which CNTs are dispersed uniformly. It is easy to make a cheap, flexible and stable sensor by using the CNT-dispersed resin. In this study, the change of resistivity of multi-walled carbon nanotube (MWCNT) under an uni-axial strain was analyzed by applying the abinitio calculation (Density functional theory). In addition, the change of the resistivity of the CNT-dispersed resin was measured by applying a four point bending test. The measured change rate was about a hundred times higher than that of metals. In order to validate the possibility of remote strain sensing, microwave of 99.5 GHz was irradiated to the carbon nanotube-dispersed resin. The change of the intensity of the reflected wave was also measured under the application of uni-axial strain.

2. Strain dependence of the band gap of MWCNT analyzed by the abititio calculation

It is reported that most multi-walled carbon nanotubes (MWCNTs) show metallic conductivity and they are rather cheap comparing with single-walled carbon nanotubes (SWCNTs). The effect of the longitudinal axial strain on the band structures of electrons in CNTs was analyzed by applying the abinitio calculation (Density functional theory). It was found that the electric conductivity of MWCNTs changes significantly because of the drastic change of their band gap. Therefore, the authors have focused on the possibility of the application of MWCNTs to a noncontact strain sensor. The change of the band structure of MWCNT under an uni-axial strain was analyzed.

In this study, various combinations of double-walled carbon nanotube structures were modeled for the analysis. An example of a (14,0)-(6,0) MWCNT is shown in Fig. 1. The outer tube is semiconductive and the inner tube is metallic. The length of the tube was varied by considering the uni-axial longitudinal strain. An example of the calculated result of band structure (in the vicinity of Fermi level) is also shown in this figure. Since the band cuts across the Fermi level (dotted line in the figure), this MWCNT is metallic. We calculated again the band structure under the uni-axial tensile strain of 3%. It was found that the band structure changes drastically, and this result clearly indicates that the electronic conductivity of this MWCNT decreases significantly under tensile strain. It was found that further application of the strain made a band gap in the band structure. This result indicates that the metallic CNT changes a semiconductive CNT due to the applied strain.

The effect of the diameter of the zigzag type CNT on the critical strain of buckling deformation was analyzed under compressive strain. In this analysis, the aspect ratio of each structure was fixed at 10. It was found that the critical strain decreased monotonically with the increase of the diameter. This was because that the flexural rigidity of a cylinder decreases with the increase of its diameter when the thickness of the wall of the cylinder is fixed. It was found that the critical strain decreases drastically from about 5% to 0.5% when the aspect ratio was changed from 10 to 30. Since the typical aspect ratio of CNTs often exceeds 1000, most CNTs show buckling deformation when an axial compressive strain is applied to the CNTs.

Figure 2 shows the estimated change of the electronic band structure of the MWCNT. The MWCNT showed metallic conductivity when the amplitude of the applied strain was less than 0.4%. However, it changed to semiconductive conductivity when the amplitude of the applied strain exceeded the critical value of about 0.4%. Thus, the resistivity

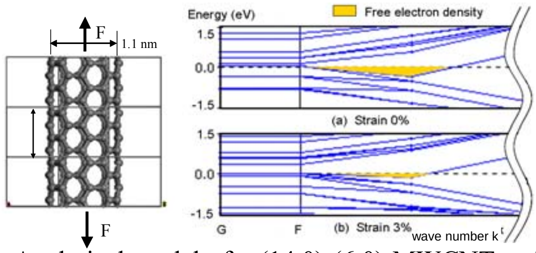

Fig. 1 Analytical model of a (14,0)-(6,0) MWCNT and the change of its band structure under an uni-axial strain

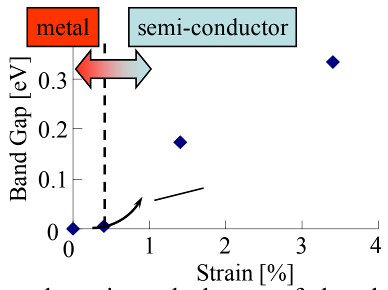

Fig. 2 Example estimated change of the electronic band structure of MWCNT under the applied strain

of the MWCNT should change drastically around this critical strain, and thus, the very high strain sensitivity is expected around this strain range.

3. Strain sensitivity of the resistance of the MWCNT-dispersed resin

Multi-walled CNTs were dispersed in various kinds of resins to form a thin film which can be attached rounded surfaces. The length of the CNTs was about a few µm. One of the base materials of resin employed was polycarbonate and the volumetric concentration of CNT dispersed was also varied from about 0.5% to about 11.5%. The thickness of the film was about 500 µm.

Uni-axial strain was applied to the CNT-dispersed resin by applying a 4 point bending method. The film was attached to a vinyl chloride plastic (0.7 mm thick) and adhered on a four-point bending jig with adhesive. After the adhesion, it was dried for 12 hours in the air. In addition, strain gauges were adhered on the back surface of the jig to calibrate the applied strain. The change of the electronic resistance of the film was measured by applying a 4 point bending test. During the experiment, the symmetry of the loading condition was controlled by balancing the output of the adhered conventional metallic gauges. The initial resistance of the resin in this experiment was in the range from 10 to 450 Ω. Measurement temperature was fixed at a constant of 25°C. The change of the resistivity of the film was measured under continuously increased or decreased strain. During the measurement of the electronic resistance, the constant current of 10 mA was applied. And the range of the applied strain was from -0.025% to 0.025%.

Figure 3 shows the measured result of the change of the electric resistance of the film with the MWCNT of about 11.5 vol.%. The electric resistance changed almost linearly with the applied strain. The ratio of resistance change under the tensile strain was about 40%/1000-µstrain and that under the compressive strain was about 15%/1000-µstrain. Thus, the maximum gauge factor obtained from this sample was 400. This value was about 200 times higher than the gauge factor of conventional metal strain gauges. However, this gauge factor dropped down drastically to about 10 when the volumetric percentage of the MWCNT was decreased to 6%. This decrease can be attributed to the difference in the shape of the dispersed MWCNT in resin. When the dispersed-MWCNT is separated one after another in resin, the MWCNT does not deform under the applied strain, while the resin is mainly deformed. Thus, the electronic conductivity of the MWCNT is almost constant even under the applied strain. It can be concluded, therefore, that the control of the volumetric percentage of the MWCNT dispersed in resin is very important to obtain the highly strain sensitive resin.

In this study, the micro wave of 99.5 GHz was irradiated to the CNT-dispersed polycarbonate film through the 1 mm□ metallic prove as shown in Fig. 4. The change of the intensity of the beam reflected from the film was measured by changing the amplitude of the uni-axial in-plane strain applied to the film. During the measurement, the distance between the probe edge and the film surface was fixed at 5 mm. The gauge factor of the test sample was about 90.

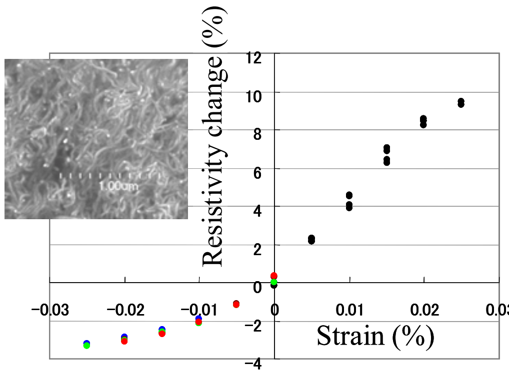

Fig. 3 Change of the resistivity of the CNT-dispersed thin films under the applied uni-axial strain

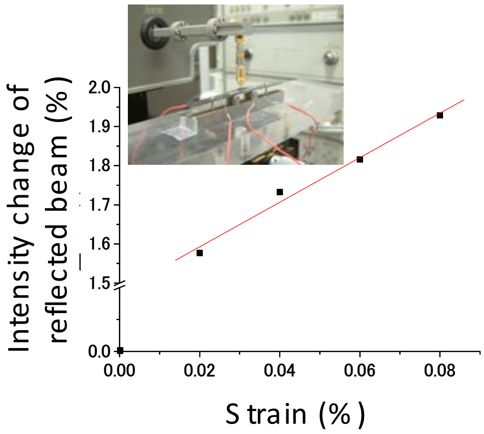

Fig. 4 Measured change of the intensity of the micro wave reflected from the strained CNT-dispersed film

Figure 4 shows the measured change of the intensity. The intensity of the reflected beam increases almost linearly with the increase of the applied tensile strain and the change rate of the intensity was about 0.5%/1000-µstrain. This value corresponded to the gauge factor of 0.5. The reason for this decrease of the gauge factor can be explained as follows. The intensity of the reflected microwave is determined by the dielectric constant, conductivity and permeability of material's surface. Since the maximum absolute value of the reflectance is one and the reflectance is determine by the function of square root of the conductivity of the material's surface, the change of the reflectance caused by the change of the resistance of the CNT-dispersed resin becomes rather small.

4. Conclusions

The maximum strain sensitivity obtained was about 40%/1000-mstrain (gauge factor: 400), when the CNT was dispersed in polycarbonate thin film by about 11.5 vol.%. The resistivity change was detected remotely by the measurement of the change of the intensity of a micro wave of 99.5 GHz reflected from the strained film. This result clearly indicates that the surface dynamic strain can be detected by micro wave nondestructively and remotely.

This research was partly supported by the grants-in-aids for scientific research.