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New Measurement Method of Carbon Nanotube Energy Band Gap

M. Maeda[1,4], T. Kamimura[2,4], S. Iwasaki[2,4], K. Matumoto[2,3,4]
University of Tsukuba[1], 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8568, Japan
Osaka University[2], 8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
AIST[3], 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
CREST/JST[4], 4-1-8, Motomachi, Kawaguchi, Saitama 332-0012, Japan

1. Introduction

Carbon nanotube (CNT) is the useful element for the future nano devices such as a CNT FET, biological sensors with high sensitivity, etc. For these applications, the determination of the energy gap (E_{gap}) of CNT is quite important because E_{gap} influences the device performances. An E_{gap} of semi-conducting nanotube is so far, mainly measured using a photo-luminescence (PL). In this measuring method, however, it is necessary to set CNT isolated from the substrate. Therefore, PL technology cannot be applied to the CNT devices for the measurement of the E_{gap} in which CNT directly contacts on the substrate. Another method to determine the E_{gap} is to measure a diameter of CNT by atomic force microscope (AFM). The diameter of CNT is directly related to the E_{gap} by the simple formation. In the present paper, we have established new approach for the determination of the E_{gap} of individual CNT by measuring the temperature dependence of the CNT current from room temperature to 900°C.

2. Experiments

The sample for the measurement of E_{gap} was prepared as follows; Al_2O_3 was used as the substrate. The layered electrodes of Ti / Pt and catalyst of Mo / Fe were patterned on the substrate using the photo-lithography and lift-off process. The CNT was grown between two electrodes by the thermal chemical vapor deposition using bubbled ethanol and hydrogen. After the growth of CNT, the sample was then, set in an electric furnace, and two electrodes were connected to the bias source as shown in Fig.1. The furnace is heat up from room temperature to 900°C in Ar gas atmosphere. DC bias of 100 mV was applied between two electrodes and the CNT current was monitored.

3. Results and Discussions

During the heat-up process, the CNT current starts to increase drastically around 700°C. The CNT current in logarithm scale is almost linearly proportional to the inverse of the temperature as shown in Fig.2. This is owing to electrons directly excited by the thermal energy from the valence band to the conduction band. The E_{gap} was then obtained from the slope of the CNT current in Fig.2, and it was found to be E_{gap} = 0.57 eV. After the measurement of CNT current, the diameter of CNT was confirmed by atomic force microscope (AFM) and shown in Fig.3. The diameter of the CNT is d = 1.41 nm. Therefore, the energy band gap of the CNT can be calculated from the CNT diameter using the simple relation, $E_{gap} = 2 \gamma_0 a_{c\text{-}c} / d$ [1], where γ_0 is the C-C tight-binding overlap energy, $a_{c\text{-}c}$ the nearest-neighbour C-C distance (0.142nm) and d is the diameter. γ_0 and $a_{c\text{-}c}$ are the constant, and E_{gap} was calculated to be E_{gap} = 0.563 eV which almost coincide with that obtained from the temperature dependence. Fig. 4 shows the comparison of measured data from the temperature dependence of the current with the calculated one from the CNT diameter. The E_{gap} obtained from the temperature dependence of CNT current and from the diameter are well coincided. Therefore, it was confirmed that the E_{gap} of CNT can be determined from the temperature dependence of CNT current.

4. Conclusion

We have succeeded in establishing the new technology to determine the energy gap of individual carbon nanotube.

Reference

[1] J. W. G. Wildoer, L. C. Venema, A. G. Rinzler, R. E. Smalley and C. Dekker, Nature 391, 59 (1998).

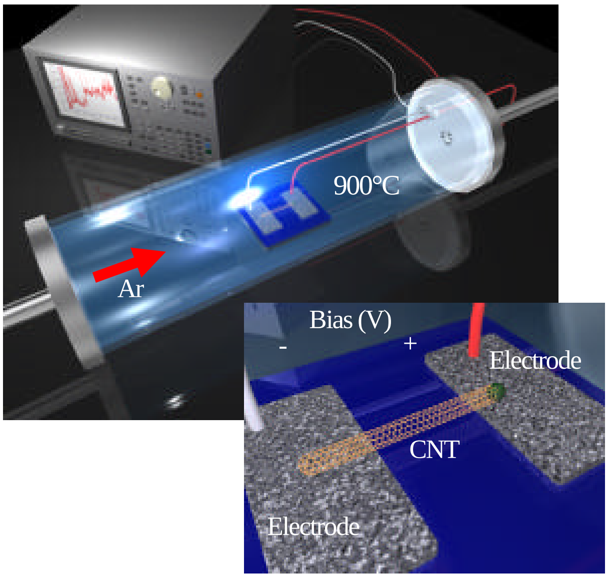


Fig. 1. Schematic diagram for the measurement of CNT current at high temperature. The sample was set in an electric furnace and two electrodes are connected to bias source.

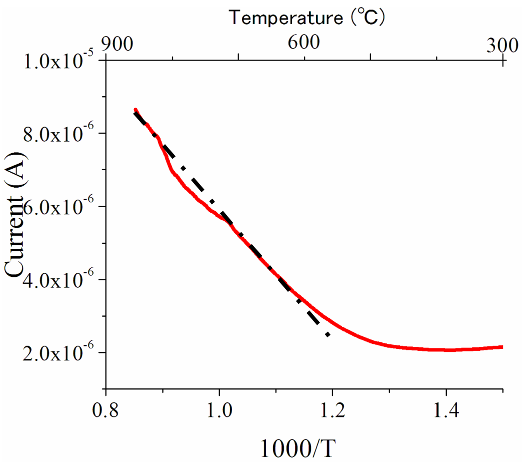
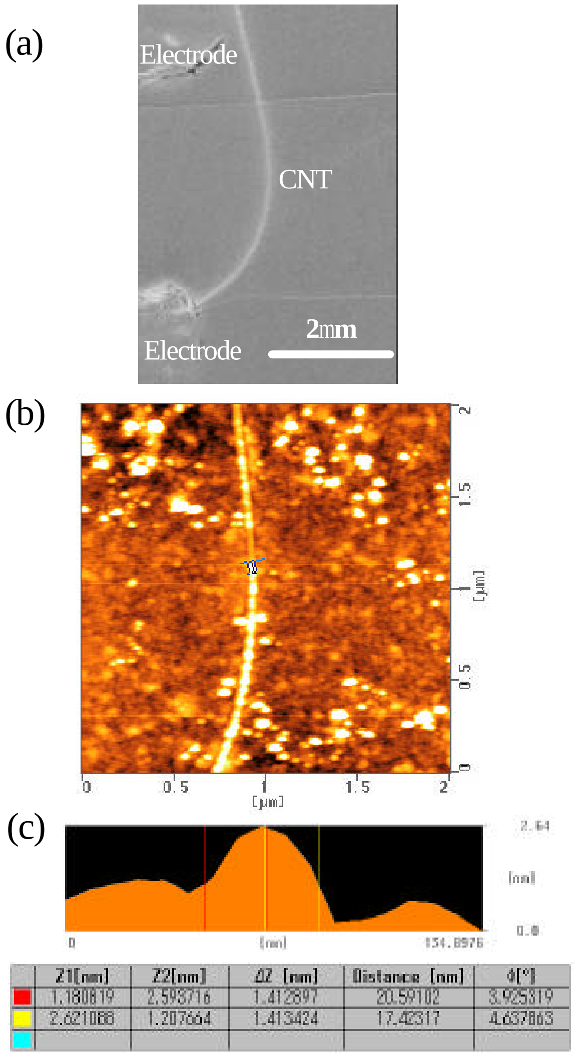


Fig. 2. Dependence of CNT current on inverse of temperature from R.T. to 900°C.



	Z1[nm]	Z2[nm]	ΔZ [nm]	Distance [nm]	ϕ[°]
	1.180819	2.593716	1.412897	20.59102	3.925319
	2.621088	1.207664	1.413424	17.42317	4.637863

Fig. 3. (a) Scanning electron microscope image of measurement sample. The white lines are CNTs between electrodes. (b) The AFM image in square area of SEM image. (c) The line profile on the CNT and Al_2O_3 surface. The diameter of this CNT is 1.41nm.

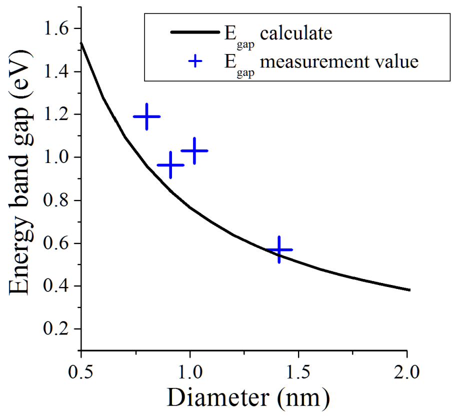


Fig. 4. . The dependence of energy gap of CNT on diameter. The cross points shows the measured values. The solid line shows the calculated one from $E_{gap} = 2\,\gamma_0\, a_{c\text{-}c} / d$ with $\gamma_0 = 2.7$ eV.