Local current density detection of individual single-wall carbon nanotubes in a bundle

Akihiko Fujiwara,[a)] Ryosuke Iijima,[b)] Kenji Ishii,[c)] and Hiroyoshi Suematsu[d)]
Department of Physics, School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

Hiromichi Kataura and Yutaka Maniwa
Department of Physics, School of Science, Tokyo Metropolitan University, 1-1 Minami-osawa, Hachi-oji, Tokyo 192-0397, Japan

Shinzo Suzuki and Yohji Achiba
Department of Chemistry, School of Science, Tokyo Metropolitan University, 1-1 Minami-osawa, Hachi-oji, Tokyo 192-0397, Japan

(Received 1 October 2001; accepted for publication 21 January 2002)

We have measured the local current density on individual single-wall carbon nanotubes (SWNTs) with the conducting tip of an atomic force microscope; the SWNTs make up a nanometer-scale electronic circuit on an insulating substrate. Scanning tunneling spectroscopy measurements at certain positions on a SWNT bundle show that both metallic and semiconducting nanotubes can coexist in a bundle. The approach applied in this experiment appears as a powerful technique for the investigation of the spatial variation of current density and electronic states of nanometer-scale electronic devices. [DOI: 10.1063/1.1461901]

Since the discovery of carbon nanotubes (NTs),[1] they have attracted great attention as a potential electronic material because of the one-dimensional tubular network structure on a nanometer scale.[2,3] Actually, the findings of many properties of NTs, such as single electron transport,[4,5] spin transport,[6] rectification,[7,8] switching function,[9] and tunable electronic structure by magnetic fields,[10,11] have opened up a route towards the nanometer-scale electronic devices. Measurement techniques with nanometer resolution have also been developed under the progress of nanotechnology.[12–16] However, research in evaluating the nanometer-scale functions, namely, spatial variations of current density and electronic states on a nanometer scale are yet to be explored although they are important for the basic studies of nanoscience, and for designing and developing of nano-order devices. In this letter, we report investigations of structure, local electronic transport, and local electronic structure of single-wall carbon nanotube (SWNT) bundles which form a nanometer-scale electronic circuit on an insulating substrate determined by means of an atomic-force-microscopy (AFM)/scanning-tunneling-spectroscopy (STS) dual-probe method (DPM).

The soot containing SWNTs was prepared by laser ablation of a carbon rod containing Ni–Co catalyst. The obtained soot was purified by oxidation in a H_2O_2 solution for 2 h.[17] The diameter of the SWNTs was determined to be about 1.4 nm by the Raman frequency of a breathing mode. Circuits consisting of the SWNT bundles and tungsten (W) electrodes on an insulating substrate were prepared by the electron lithography.[10,11] The principle of the AFM/STS-DPM is illustrated in Fig. 1 where a metal-coated conducting AFM tip monitors the tunneling current from electrically connected nanometer-sized circuits while a bias voltage V_B is applied during a conventional AFM measurement. In this method, we can simultaneously measure the topographic AFM image and the local current density [topographic current image (TCI)] of the circuit. The main advantages of this method are (i) adaptability of the insulating substrate, (ii) nanometer-scale resolution in the measurement of local transport properties, and (iii) emancipation from the influence of electronic states of the substrate on that of sample. From these points, it is clear that the technique is very effective for evaluating electronic circuits on an insulating substrate. Neither the AFM nor the scanning tunneling microscopy (STM) can perform individually.

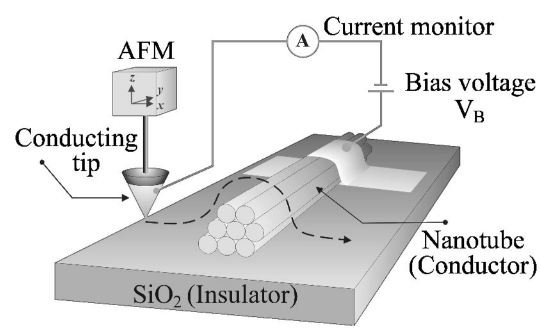

FIG. 1. Schematic illustration of the AFM/STS dual-probe method.

a)Author to whom correspondence should be addressed; present address: Japan Advanced Institute of Science and Technology, 1-1 Asahidai, Tatsunokuchi, Ishikawa 923-1292, Japan and CREST, JST (Japan Science and Technology Corporation); electronic mail: fujiwara@jaist.ac.jp
b)Present address: Advanced LSI Technology Laboratory, Corporate Research and Development Center, Toshiba Corporation, 8 Shinsugita-cho, Isogo-ku, Yokohama 235-8522, Japan.
c)Present address: Synchrotron Radiation Research Center, Kansai Research Establishment, Japan Atomic Energy Research Institute, 1-1-1 Kouto Mikazuki-cho Sayo-gun, Hyogo 679-5148, Japan.
d)Present address: Materials Science Division, SR Research Laboratory, Japan Synchrotron Radiation Research Institute, 1-1-1 Kouto Mikazuki-cho Sayo-gun, Hyogo 679-5198, Japan.

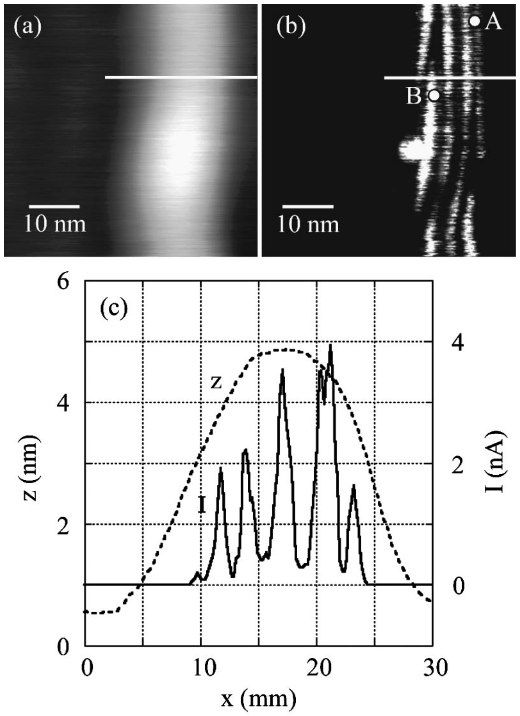

FIG. 2. (a) Topographic AFM image and (b) topographic current image with a V_B of 0.6 V of sample No. 1, (c) cross sections along lines in images (a) and (b).

A high-resolution topographic AFM image of a SWNT bundle (sample No. 1) is shown in Fig. 2(a) and a simultaneously measured TCI is shown in Fig. 2(b). From the AFM image, a single bundle is observed but not the components, for instance individual SWNTs cannot be identified. On the other hand, from the TCI with a V_B of 0.6 V, the current paths with a width less than 2 nm are clearly observed in a bundle and can be attributed to the current flowing on the individual SWNTs. This difference can be clearly seen by comparing cross sections in both the AFM image and the TCI as shown in Fig. 2(c).

At both positions A and B in Fig. 2(b), the current actually flows on SWNTs under a V_B of 0.6 V. However, it is clear that the electronic structures at positions A and B are different by comparing the data from the tunneling spectroscopy as shown in Fig. 3. First, the zero bias tunneling conductance ($dI/dV_{B\ V_B=0}$) data are different: at position B $dI/dV_{B\ V_B=0}$ shows a finite value and much larger than that of position A which is almost zero. This result suggests that the SWNTs at positions A and B are semiconducting and metallic, respectively. In addition, the van Hove singularity (VHS) characteristics support this conclusion: the spectra at positions A and B show relatively large peaks corresponding to the VHS of semiconducting and metallic NTs,[12,13] respectively. Each spectrum contains peaks due to another kind of SWNT. This is because of the observed tunnel current coming from the circuit containing many SWNTs in a bundle. Therefore, it is expected that the spectra are influenced mainly by the electronic structure of the SWNT at the measured position, and also by the various electronic structures of the SWNTs in the current path. In any case, we can conclude from this result that the metallic and semiconducting NTs coexist in sample No. 1.

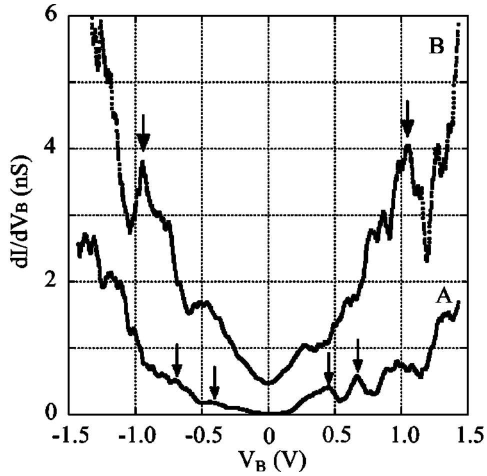

FIG. 3. Tunneling conductance dI/dV_B spectra at positions A and B in Fig. 2(b). Big and small arrows show the van Hove singularity corresponding to the metallic and the semiconducting SWNTs, respectively.

Figures 4(a)–4(d) show TCIs for a SWNT bundle (sample No. 2) with various V_B. The clear spatial variation in TCIs as observed in sample No. 1 cannot be detected in this sample, showing only one kind of electronic structure may exist in a SWNT bundle. Current flowing on a SWNT bundle can be observed and it increases with increasing V_B. However, the value of the current at the SWNT bundle in TCIs is not proportional to V_B, but increases suddenly between 0.3 and 0.4 V of V_B. The current–voltage curve shown in Fig. 4(e) makes it clear that the intensity of TCI is due to the local electronic structure of a SWNT bundle. This result is quite natural but very important. Because, we can

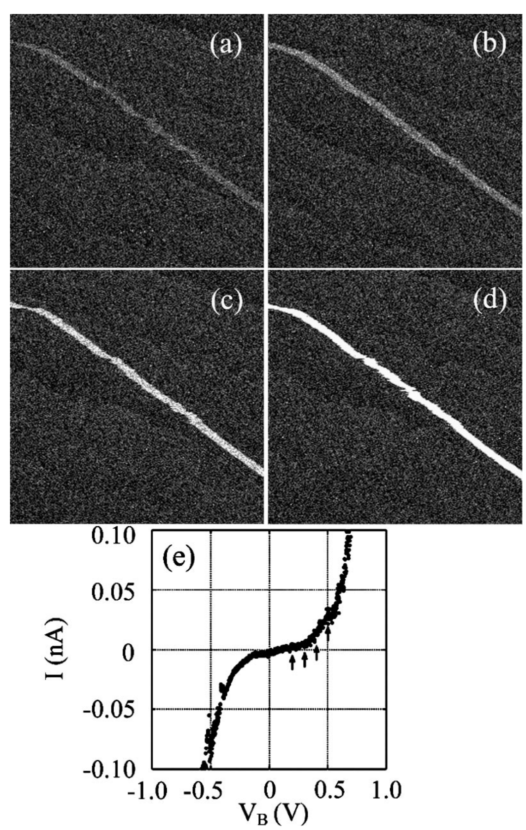

FIG. 4. Topographic current images of sample No. 2 with V_B=(a) 0.2, (b) 0.3, (c) 0.4, and (d) 0.5 V, (e) current–voltage curve.

expect that the TCIs are very sensitive to the local electronic structure and that the changes in TCI will appear where the electronic structure changes in a circuit.

Electronic properties of intramolecular junctions of the NTs, such as transmission/reflection ratio and rectification were investigated theoretically.[18] On the other hand, although very recently the molecular structure and its electronic structure around the intramolecular junctions (IMJ) are measured by STM,[19,20] the spatial variation of current density has not yet been clarified. From the results of this work, TCI, which is influenced mostly by the electronic structure at the tip position and additionally by that of the current path, can provide information about local transport properties and local electronic structure in electronic circuits having nanometer-scale resolution. Therefore, we believe that this method is very effective for the investigation of functions of the IMJ, etc.

In conclusion, with a conducting tip of an AFM, we have investigated the structural property, local electronic structure, and local electronic transport properties of the SWNT bundles that form a nanometer-scale electronic circuit on an insulating substrate. We have observed the local current flowing on the individual SWNTs in a bundle, and is found that metallic and semiconducting SWNTs can coexist in a bundle. Our results show that this approach will be a powerful technique for the evaluation of electronic devices in nanometer-scale circuits, and will contribute to the development of nanotechnology.

The authors thank S. A. Haque for critical reading of the manuscript. This work was supported in part by the JSPS Future Program No. RFTF96P00104, Industrial Technology Research Grant in 2001 from New Energy and Industrial Technology Development Organization (NEDO) of Japan and the Grant-in-Aid for Scientific Research (A) No. 13304026 from the Ministry of Education, Culture, Sports, Science and Technology of Japan. One of the authors (A.F.) was supported by a Grant-in-Aid for Encouragement of Young Scientists No. 12740202 from The Ministry of Education, Culture, Sports, Science and Technology of Japan.

[1] S. Iijima, Nature (London) **354**, 56 (1991).
[2] M. S. Dresselhaus, G. Dresselhaus, and P. Eklund, *Science of Fullerenes and Carbon Nanotubes* (Academic, New York, 1996).
[3] R. Saito, G. Dresselhaus, and M. S. Dresselhaus, *Physical Properties of Carbon Nanotubes* (Imperial College Press, London, 1998).
[4] S. J. Tans, M. H. Devoret, H. Dai, A. Thess, R. E. Smalley, L. J. Geerligs, and C. Dekker, Nature (London) **386**, 474 (1997).
[5] M. Bockrath, D. H. Cobden, P. L. McEuen, N. G. Nasreen, G. Chopra, A. Zettl, A. Thess, and R. E. Smalley, Science **275**, 1922 (1997).
[6] K. Tsukagoshi, B. W. Alphenaar, and H. Ago, Nature (London) **401**, 572 (1999).
[7] Z. Yao, H. W. Ch. Postma, L. Balents, and C. Dekker, Nature (London) **402**, 273 (1999).
[8] R. D. Antonov and A. T. Johnson, Phys. Rev. Lett. **83**, 3274 (1999).
[9] S. J. Tans, A. R. M. Verschueren, and C. Dekker, Nature (London) **393**, 49 (1998).
[10] A. Fujiwara, K. Tomiyama, H. Suematsu, M. Yumura, and K. Uchida, Phys. Rev. B **60**, 13492 (1999).
[11] A. Fujiwara, K. Tomiyama, H. Suematsu, M. Yumura, and K. Uchida, Physica B **298**, 541 (2001).
[12] J. W. G. Wildör, L. C. Venema, A. G. Rinzler, R. E. Smalley, and C. Dekker, Nature (London) **391**, 59 (1998).
[13] T. W. Odom, J.-L. Huang, P. Kim, and C. M. Lieber, Nature (London) **391**, 62 (1998).
[14] A. Bachtold, M. S. Fuhrer, S. Plyasunov, M. Forero, E. H. Anderson, A. Zettle, and P. L. McEuen, Phys. Rev. Lett. **84**, 6082 (2000).
[15] M. Freitag, M. Radosavljević, W. Clauss, and A. T. Johnson, Phys. Rev. B **62**, R2307 (2000).
[16] H. Watanabe, C. Manabe, T. Shigematsu, and M. Shimizu, Appl. Phys. Lett. **78**, 2928 (2001).
[17] H. Kataura, Y. Kumazawa, Y. Maniwa, Y. Ohtsuka, R. Sen, S. Suzuki, and Y. Achiba, Carbon **38**, 1691 (2000).
[18] R. Tamura and M. Tsukada, Phys. Rev. B **55**, 4991 (1997); **58**, 8120 (1998); **61**, 8548 (2000).
[19] B. C. Satishkumar, P. J. Thomas, A. Govindaraj, and C. N. R. Rao, Appl. Phys. Lett. **77**, 2530 (2000).
[20] M. Ouyang, J.-L. Huang, C. L. Cheung, and C. M. Lieber, Science **291**, 97 (2001).