Transactions of the Materials Research Society of Japan 31[1] 215-217 (2006)

Electrical properties of carbon nanotube sheets with Ni and Mg electrode metals

Hideyuki Maki, Testuya Sato and Koji Ishibashi *
Department of Applied Physics and Physico-Informatics, Faculty of Science and Technology, Keio University, Hiyoshi, Yokohama 223-8522, Japan
Fax: 81-45-566-1587, e-mail: maki@appi.keio.ac.jp
* Advanced Device Laboratory, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-0198, Japan
Fax: 81-48-462-4659, e-mail: kishiba@riken.jp

We have fabricated SWNT-FETs using large (Ni) and small (Mg) work-function metals as source and drain electrodes. For the device with Ni electrodes, p-type characteristic is obtained due to small Schottky barrier for holes. On the other hand, for the device with Mg electrodes, n-type characteristic is obtained due to small Schottky barrier for electrons. These results indicate that conduction type of p-type or n-type can be controlled by choosing of metal work function.
Key words: carbon nanotube, field effect transistor, work function, Schottky barrier, ambipolar

1. INTRODUCTION

Single-walled carbon nanotubes (SWNTs) are extensively investigated for the basic studies of low dimensional transport and the applications of electronic devices, e.g. field effect transistors (FETs), one-dimensional conductor, single electron transistors and quantum dots. In addition, SWNTs are expected to be applied to optical and optoelectronic devices, because optical properties, e.g. fluorescence[1,2] and photoluminescence[3], are clearly observed due to direct band gap. In addition, it was recently reported that optical emission from SWNT-FETs due to the recombination of electrons and holes that are injected at the opposite contacts into a SWNT is observed[4-6]. The simultaneous injection of electrons and holes is due to small Schottky barriers for holes and electrons at the appropriate drain and gate voltage. Furthermore, simultaneous injection of electrons and holes was reported using FET by biasing the split gates with opposite potentials. In this case, rectification property was observed[7,8]. In order to realize simultaneous injection of electrons and holes without chemical doping, it is necessary to prepare SWNT-FETs that exhibit ambipolar behavior[4,5,7]. However, SWNTs with large band gap, i.e., small diameter are easy to exhibit p-type behavior[5,7,9-11]. To realize functional devices, e.g. light emitters and rectification devices, using SWNTs with various band gaps, new fabrication methods for obtaining n-type or ambipolar characteristic must be developed.

Recently, it was reported that n-type FETs with an individual SWNT are fabricated by using Ca with small work functrion as the contact electrodes[12]. In this case, the Fermi energy (E_F) of the source electrode is located close to the conduction-band edge of the SWNT due to small work function of Ca, and the Schottky barrier height for electron is low; therefore, electrons are injected into the SWNT. This study is noteworthy because conduction type of SWNT-FETs can be chosen by the electrode metal without chemical doping.

In this study, we have fabricated SWNT-FETs by using metals with large (Ni: 5.2 eV) and small (Mg: 3.7 eV) work function as source and drain electrodes. In this experiment, a large number of SWNTs prepared by spin coating (SWNT sheet) are used as channel of the FET. If an individual SWNT is used for channel of FET, electric properties of the samples are easy to change by

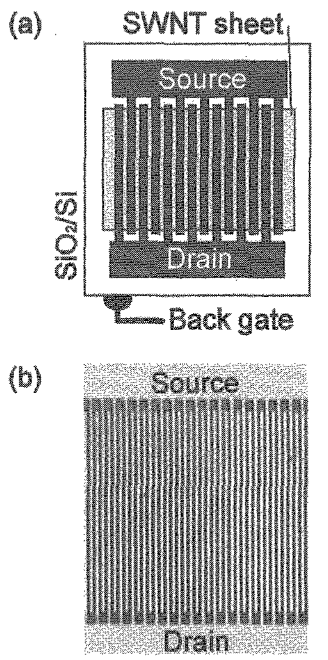

Fig. 1. (a) A schematic top view of SWNT-FET. A large number of SWNTs prepared by spin coating (SWNT sheet) are used as channel of FET. The size of SWNT sheet is 40×30 μm^2. On the SWNT sheets, two comb-shape electrodes are formed as source and drain. Width and gap of the electrodes are 600 nm and 400 nm, respectively. (b) Optical microscope image of fabricated comb-shape electrodes.

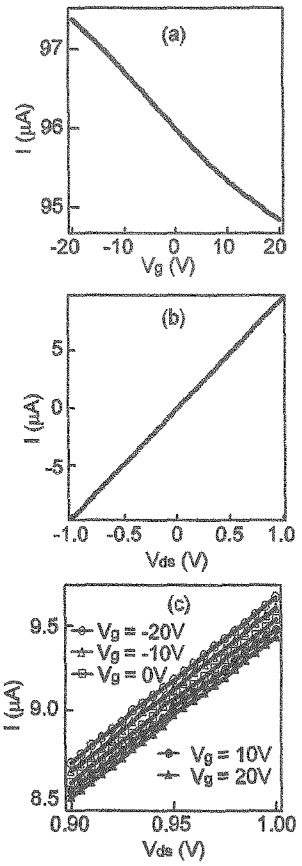

Fig. 2. (a) The V_g dependence of the current for the FETs with Ni metals as source and drain electrodes at V_{ds} = 10 mV. (b) I-V_{ds} curve at V_g = 0V. (c) Magnified I-V_{ds} curve from V_{ds} = 0.9 to 1.0 V at V_g = -20, -10, 0, 10 and 20 V.

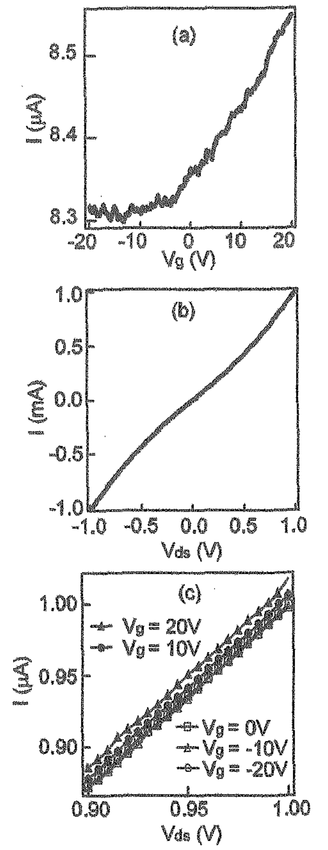

Fig. 3. (a) The V_g dependence of the current for the FETs with Mg metals as source and drain electrodes at V_{ds} = 10 mV. (b) I-V_{ds} curve at V_g = 0V. (c) Magnified I-V_{ds} curve from V_{ds} = 0.9 to 1.0 V at V_g = -20, -10, 0, 10 and 20 V.

difference of SWNT characteristics, e.g. bandgap and electronic state of metal or semiconductor, and by difference of SWNT-electrode contacts at source and drain, e.g. symmetry of source and drain contact barriers[13]. Therefore, many samples must be statistically investigated to understand the effect of work function of the electrode metals. On the other hand, when a large number of SWNTs are formed into the FET, average properties of SWNTs can be measured; therefore, fundamental properties of SWNT-FETs hardly differ from sample to sample. Hence this method is efficient to understand the relationship between electric properties of SWNT-FETs and work function of the electrode metals. The conduction type of n-type or p-type is investigated by current measurement as a function of gate voltage.

2. SAMPLE PREPARATION AND EXPERIMENTAL PROCEDURE

A schematic top view of the device structure used in this study is shown in Fig. 1(a). On a heavily doped *p*-type Si substrate with a thermally grown SiO_2 layer (200 nm), SWNT sheet was prepared by electron beam (EB) lithography, spin coating of SWNT and lift off. The size of SWNT sheets was 40×30 μm^2. On the SWNT sheets, two comb-shape electrodes are formed as source and drain with EB lithography and metal deposition techniques. Optical microscope image of the fabricated comb-shape electrodes are shown in Fig. 1(b). Width and gap of the electrodes are 600 nm and 400 nm, respectively. The electrode gap is very narrow compared with the length of SWNTs (several μm); therefore, source and drain electrodes are directly contacted to one SWNT: carrier transport through more than one SWNT hardly occurs. Mg and Ni are used for electrode metals of source and drain. Gate voltage (V_g) is applied through the back gate. Electrical measurements on the device were carried out at room temperature in vacuum (~ 10^{-6} Torr).

3. RESULTS AND DISCUSSION

The V_g dependence of the current (I) for the FETs with Ni electrode metals as source and drain electrodes is shown in Fig. 2(a). In this measurement, the drain-source voltage (V_{ds}) was fixed at 10 mV. The current monotonically decreases with increasing V_g, that is, *p*-type transfer characteristic is obtained. I-V_{ds} characteristic of the device at V_g = 0 V is shown in Fig. 2(b). A highly linear curve with symmetry for positive and negative V_{ds} is exhibited. Magnified I-V_{ds} curves from V_{ds} = 0.9 to 1.0 V at different V_g of -20, -10, 0, 10 and 20 V are shown in Fig. 2(c). The slope of the curves

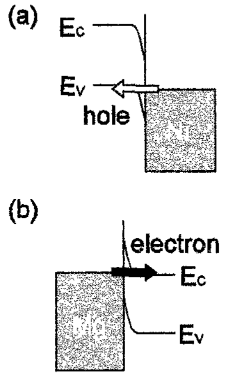

Fig. 4. Schematic band diagrams at the electrode-SWNT interface for the device with the electrode metal of (a) large (Ni) and (b) small (Mg) work function.

decreases as the V_g increases.

The V_g dependence of I for the FETs with Mg electrode metals as source and drain electrodes at V_{ds} = 10mV is shown in Fig. 3(a). The current remains almost constant below around V_g = -10 V, and increases rapidly as the V_g is further increased, that is, n-type transfer characteristic is obtained. The current does not become zero at V_g < -10 V, because the channel of this device consists of the semiconducting and metallic SWNTs. I-V_{ds} characteristic of the device with Mg electrodes at V_g = 0 V is shown in Fig. 3(b). A nonlinear curve with symmetry for positive and negative V_{ds} is observed. Magnified I-V_{ds} curves from V_{ds} = 0.9 to 1.0 V at different V_g of -20, -10, 0, 10 and 20 V are shown in Fig. 3(c). At $V_g \leqq 0$ V, the slope of the curves hardly changed, and increases as the V_g is further increased. This result agrees the I-V_g result of Fig. 3(a).

Figure 4 shows schematic band diagram at the electrode-SWNT interface for the devices with (a) Ni and (b) Mg electrodes. Work function of Ni and Mg are larger and smaller than that of SWNT (~ 4.8 eV)[13], respectively. For the electrode metal with large work function (corresponding to Ni in this experiment), the E_F of the electrode is located close to the valence-band edge of the SWNT, and the height of Schottky barrier for holes is small (Fig. 4(a)); therefore, holes are injected into the SWNT. Therefore, I-V_g curve of Fig. 2(a) shows the p-type characteristic. In addition, a highly linear I-V_{ds} curve is obtained for the device with Ni electrodes. In the previous study[14], the contact resistance of SWNT-electrode contact can be reduced by using Pd as electrodes due to large work function of Pd metal. Therefore, FET with Ni metal has very small Schottky barries for holes, hence a linear I-V_{ds} curve is obtained. On the other hand, for the electrode metal with small work function (corresponding to Mg in this experiment), the E_F of the electrode is located close to the conduction-band edge of the SWNT, and the height of Schottky barrier for electron is small (Fig. 4(b)); therefore, electrons are injected into the SWNT. Similar result was previously reported using Ca electrodes, and n-type transfer characteristic was observed from the FET with individual SWNT[12]. Meanwhile, from the result of Fig. 3(b), a nonlinear curve is observed for the device with Mg electrodes. This is because undoped SWNT-FETs usually show p-type conducting characteristics[10,11] and hence the Schottky barrier for electron has a certain heigth.

In conclusion, we have fabricated SWNT-FETs using large (Ni) and small (Mg) work-function metals as source and drain electrodes. For the device with Ni electrodes, p-type characteristic is obtained due to small Schottky barrier for holes. On the other hand, for the device with Mg electrodes, n-type characteristic is obtained due to small Schottky barrier for electrons. These results indicate that conduction type of p-type or n-type can be controlled by choosing of metal work function.

ACKNOWLEDGEMENTS

We would like to thank Prof. Y. Matsumoto of Keio University and Dr. N. Ohashi of National Institute for Material Research for support. This work is supported by the Encouragement of Young Scientists (Grant No. 16760016) from Ministry of Education, Science, Sports, Culture and Technology of Japan.

REFERENCES

[1] M. J. O'Connell, S. M. Bachilo, C. B. Huffman, V. C. Moore, M. S. Strano, E. H. Haroz, K. L. Rialon, P. J. Boul, W. H. Noon, C.Kittrell, J. Ma, R. H. Hauge, R. B. Weisman and R. E. Smalley, Science, **297**, 593-96 (2002).
[2] S. M. Bachilo, M. S. Strano, C.Kittrell, R. H. Hauge, R. E. Smalley and R. B. Weisman, Science, **298**, 2361-66 (2002).
[3] J. Lefebvre, Y. Homma and P. Finniel, Phys. Rev. Lett., **90**, 217401 (2003).
[4] J. A. Misewich, R. Martel, Ph. Avouris, J. C. Tsang, S. Heinze and J. Tersoff, Science, **300**, 783-86 (2003).
[5] M. Freitag, V. Perebeinos, J. Chen, A. Stein, J. C. Tsang, J. A. Misewich, R. Martel and Ph Avouris, Nano Lett., **5**, 1063-66 (2004).
[6] M. Freitag, J. Chen, J. Tersoff, J. C. Tsang, Q. Fu, J. Liu and Ph Avouris, Phys. Rev. Lett., **93**, 07803 (2004).
[7] J. U. Lee, P. P. Gipp and C. M. Heller, Appl. Phys. Lett., **85**, 145-47 (2004).
[8] J. U. Lee, Appl. Phys. Lett., **87**, 073101 (2005).
[9] A. Javey, M. Shim, and H. Dai, Appl. Phys. Lett., **80**, 1064-66 (2002).
[10] S. J. Tans, A. R. M. Verschueren and C. Dekker, Nature, **393**, 49-52 (1998).
[11] R. Martel, T. Schmidt, H. R. Shea, T. Hertel and P. Avouris, Appl. Phys. Let, **73**, 2447-49 (1998).
[12] Y. Nosho, Y. Ohno, S. Kishimoto and T. Mizutani, Appl. Phys. Lett., **86**, 073105 (2005).
[13] S. Suzuki, C. Bower, Y. Watanabe and O. Zhou, Appl. Phys. Lett., **76**, 4007-4009 (2000).
[14] A. Javey, J. Guo, Q. Wang, M. Lundstrom and H. Dai, Nature, **424**, 654-57 (2003).

(Received December 11, 2005; Accepted January 15, 2006)