Extended Abstracts of the 2006 International Conference on Solid State Devices and Materials, Yokohama, 2006, pp. 246-247

A-6-3

Electric properties of single-walled carbon nanotube film field effect transistors with various work function electrodes: a comparison between pristine and potassium-encapsulated nanotubes

Hideyuki Maki[1], Satoru Suzuki[2], Tetsuya Sato[1], and Koji Ishibashi[3]

[1]Department of Applied Physics and Physico-Informatics, Faculty of Science and Technology, Keio University, Hiyoshi, Yokohama 223-8522, Japan
Phone: 048-462-1111 ext. E-mail: hmaki@postman.riken.go.jp
[2]NTT Basic Research Laboratories, NTT Corporation,
3-1 Morinosato- Wakamiya, Atsugi, Kanagawa 243-0198, Japan
[3]Advanced Device Laboratory, The Institute of Physical and Chemical Research (RIKEN)
2-1, Hirosawa, Wako, Saitama 351-0198, Japan

1. Introduction

Single-walled carbon nanotubes (SWNTs) are attractive materials 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, optical properties of semiconducting SWNTs have received considerable attention, because they are direct band-gap materials. Recently, it was reported that electrically induced optical emission from SWNT-FETs due to the recombination of electrons and holes that are injected at the opposite contacts into a SWNT is demonstrated[1-3]. In order to realize simultaneous injection of electrons and holes without chemical doping, it is necessary to prepare SWNT-FETs that exhibit ambipolar behavior[1]. Ambipolar behavior is easy to be obtained for SWNTs with small band gap, i.e., large diameter. Meanwhile, SWNTs with large band gap, i.e., small diameter are easy to exhibit unipolar p-type behavior. To realize functional devices, e.g. light emitters and rectification devices, new fabrication methods of ambipolar FET must be developed. Recently, it was reported that *n*-type SWNT-FETs are fabricated by using Ca with small work functrion as the contact electrodes[4]. 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. In this study, we have fabricated SWNT-FETs by using metals with small (Mg) and large (Ni) work function as source and drain electrodes to control transfer characteristic. Moreover, pristine and potassium-encapsulated SWNTs are used for the channel of the FETs, and electric properties of them are compared.

2. Experimental Procedure

Figure 1 shows (a) a schematic top view of SWNT-FET and (b) magnified scanning electron microscope image of the device. SWNT films with the size of 40×30 μm^2 are prepared by electron beam (EB) lithography, spin coating of SWNT and lift off on a heavily doped p-type Si substrate covered with a thermally grown SiO_2 layer (200nm). On the SWNT sheets, two comb-shape electrodes are formed as source and drain with EB lithography and metal deposition techniques. 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 (as shown in Fig. 1(b)): carrier transport through more than one SWNT hardly occurs. 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). In this study, we have fabricated SWNT film FETs by using metals with small (Mg) and large (Ni) work function as source and drain electrodes to control transfer characteristic. The conduction type of *n*-type or *p*-type is investigated by current measurement as a function of gate voltage. In this experiment, a large number of SWNTs prepared by spin coating (SWNT films) 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 difference of SWNT characteristics, e.g. bandgap, 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. Moreover, pristine and potassium-encapsulated SWNTs are used, and electric properties of them are compared. Preparation method of potassium-encapsulated SWNTs is indicated in Ref. [5].

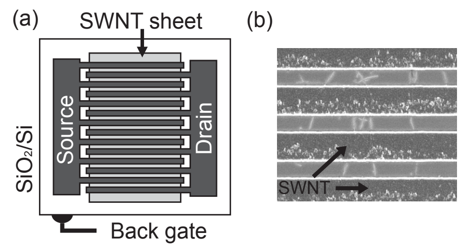

Fig. 1. (a) A schematic top view of SWNT-FET and (b) scanning electron microscope image of the device.

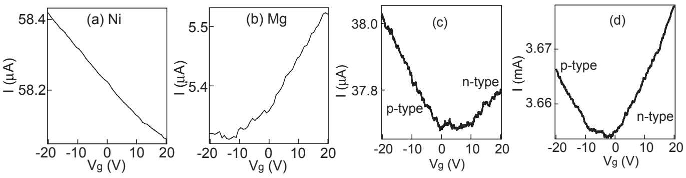

Fig. 2. The V_g dependence of I_{ds} for the pristine SWNT film FETs with (a) Ni, (b) Mg, (c) Mg-Ni at V_{ds} = -10 mV and (d) Mg-Ni at V_{ds} = -1 V.

The FETs with individual single SWNT encapsulating potassium and Ti electrodes are also fabricated.

3. Results and discussions

Figure 2 shows the dependence of the current (I_{ds}) on V_g for the pristine SWNT FETs with same kinds of metals as source and drain electrodes at the drain-source voltage (V_{ds}) of 10 mV in vacuum. The result for the device with Ni electrodes is shown in Fig. 2(a). The current monotonically decreases with increasing V_g, that is, *p*-type transfer characteristic is obtained. The V_g dependence of I_{ds} for the device with Mg electrodes is shown in Fig. 2(b). In contrast to the device with Mg electrodes, 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. 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; therefore, holes are injected into the SWNT. 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; 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 an individual SWNT[4].

The pristine SWNT-FETs with small work-function metal (Mg) as drain electrode and large work-function metal (Ni) as source electrode were also fabricated in this study. The dependence of I_{ds} on V_g for the Mg-Ni device at V_{ds} = -10 mV is shown in Fig. 2(c). Transfer characteristics of *p*-type and *n*-type are obtained at V_g < 0 V and V_g > 0 V, respectively: ambipolar characteristic can be obtained by using Mg-Ni electrodes. At V_g < 0, holes are injected from Ni electrode to SWNT due to low Schottky barrier height for holes. On the other hand, at V_g > 0 V, electrons are injected from Mg electrode due to low Schottky barrier height for electrons. Also, at higher drain-source bias of V_{ds} = -1 V, ambipolar characteristic is observed as shown in Fig. 2(d).

The FETs with potassium-encapsulated SWNTs are also fabricated in this study. Figure 3 shows the dependence of I_{ds} on V_g for potassium-encapsulated SWNT film devices with (a) Ni and (b) Mg electrodes at V_{ds} = -10 mV. From these measurements, electrical properties of potassium-encapsulated SWNT-FETs show the ambipolar characteristic and have small dependence on work function of electrode metals. This is quite different from the results for pristine SWNT (as shown in Fig. 2(a) and (b)): that is, pristine SWNT-FETs show the unipolar characteristic of

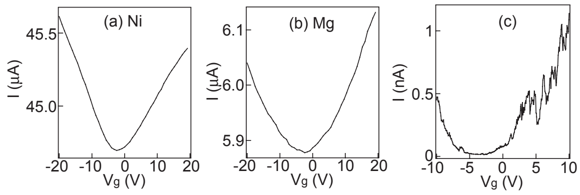

Fig. 3. The V_g dependence of I_{ds} for the potassium-encapsulated SWNT film FETs with (a) Ni, (b) Mg. (c) The V_g dependence of I_{ds} for the FETs with individual single SWNT encapsulating potassium.

p-type or n-type depending on work function of electrode metals. This result indicates that the Schottky barrier height for electrons and holes is low due to small band gap of potassium-encapsulated SWNT and the FETs exhibit ambipolar characteristic. Meanwhile, the FETs with individual single SWNT encapsulating potassium and Ti electrodes are also fabricated, and I_{ds}-V_g property is shown in Fig. 3(c). Transfer characteristics of *p*-type and *n*-type are obtained at V_g < -3 V and V_g > -3 V, respectively: ambipolar characteristic is observed for individual SWNT-FET. Electronic structure of potassium-encapsulated SWNTs was calculated in previous report of Ref. [6]. This shows that the nearly free electron state of nanotubes couples with the K 4*s* orbital and the state comes downward toward the bottom of the conduction band. There is a possibility that this state is the one of the reasons of band-gap narrowing.

4. Conclusion

We have fabricated pristine and potassium-encapsulated SWNT film FETs using small (Mg) and large (Ni) work-function metals as source and drain electrodes. For the pristine SWNT film-FETs with Ni electrodes, *p*-type characteristic is obtained. For the device with Mg electrodes, *n*-type characteristic is obtained. The devices with small work-function metal (Mg) as drain electrode and large work-function metal (Ni) as source electrode exhibit ambipolar characteristic at small and large drain-source voltage. On the other hand, the FETs with potassium-encapsulated SWNT film show the ambipolar characteristic and have small dependence on work function of electrode metals. This result indicates that the Schottky barrier height for electrons and holes is low due to small band gap of potassium-encapsulated SWNT. The FETs with individual SWNT encapsulating potassium also exhibit ambipolar characteristic.

References

[1] J. A. Misewich, R. Martel, Ph. Avouris, J. C. Tsang, S. Heinze, and J. Tersoff, Science **300**, 783 (2003).

[2] M. Freitag, V. Perebeinos, J. Chen, A. Stein, J. C. Tsang, J. A. Misewich, R. Martel, and Ph Avouris, Nano Lett. **5**, 1063 (2004).

[3] M. Freitag, J. Chen, J. Tersoff, J. C. Tsang, Q. Fu, J. Liu, and Ph Avouris, Phys. Rev. Lett. **93**, 07803 (2004).

[4] Y. Nosho, Y. Ohno, S. Kishimoto, and T. Mizutani, Appl. Phys. Lett **86**, 073105 (2005).

[5] S. Suzuki, F. Maeda, Y. Watanabe, and T. Ogino, Phys. Rev. B **67**, 115418 (2003).

[6] T. Miyake, and S. Saito, Phys. Rev. B **65** 165419 (2002).