Conduction-Type Control of Carbon Nanotube Field-Effect Transistors by Pd and Ti Overlayer Doping

Satoshi Ishii[1,2], Masato Tamaoki[1], Shigeru Kishimoto[1,2], and Takashi Mizutani[1]

[1] Dept. of Quantum Eng., Naogya Univ.
Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan
Phone: +81-52-789-5455 E-mail: ishii@nuee.nagoya-u.ac.jp
[2] Venture Business Lab., Nagoya Univ.
Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan

1. Introduction

Carbon nanotube field-effect transistors (CNTFETs) have been expected to be applied for integrated circuits, because carbon nantotubes (CNTs) have high current density and high mobility in addition to their small size. In order to fabricate such integrated circuits by using CNTFETs, both p- and n-type CNTFETs are needed. Among various methods [1-4], the conduction-type controls of the CNTFETs through work function of the contact metals is often employed.   The p-type CNTFETs using large-work-function metal such as Pd (ϕ=5.1 eV) as contacts were reported [5].   In addition, the n-type CNTFETs using small-work-function metals such as Ca (ϕ=2.8 eV) [6] and Al (ϕ=4.2 eV) [7] as contacts were reported. However, the characteristics of the n-type CNTFETs change in ambient air due to high chemical activity of contact metals or adsorbed molecules on the device surface. Meanwhile, the n-type CNTFETs were reported [8], where Al overlayer was deposited onto the CNT channel.   This is expected to be due to the doping effect of the Al overlayer.

In this study, we propose the conduction-type control of the CNTFETs by charge transfer using metal overlayer with different work functions (Pd and Ti (ϕ=4.4 eV)) onto the side surface of the CNT channel.

2. Results and discussion

Figure 1 shows the schematic of the fabricated back-gate type CNTFET with metal overlayer. The graphitic carbon (G-C) contacts were used to study the doping effects, since it was confirmed that the CNTFETs with G-C contacts showed ambipolar behaviors [9].   After the amorphous carbon/Ni/Au trilayer was patterned at the both ends of the CNTs, the amorphous carbon were graphitized to form graphene layers by annealing the substrate in vacuum at 800 ℃ for 30 min.   The Pd and Ti overlayers (=30 nm) were then deposited onto the side surface of the CNT channel for the doping.   The channel lengths and width of the fabricated devices were 9 and 100 μm, respectively, and the length of the overlayers was 5.5 μm.

In order to evaluate the conduction properties of the device eliminating the effects of adsorbed molecules on the device surface, the devices were baked at 250 ℃ for 5 hours in vacuum, and then transferred into a nitrogen-gas-filled glove box, which was followed by the measurements of the electrical properties.
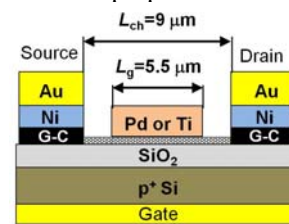

Fig. 1 Schematic of the fabricated CNTFETs with metal overlayer. The SiO$_2$/p$^+$Si substrate is used as the back-gate electrode.   The CNTs were grown by alcohol catalytic chemical vapor deposition using Co metal catalysts.
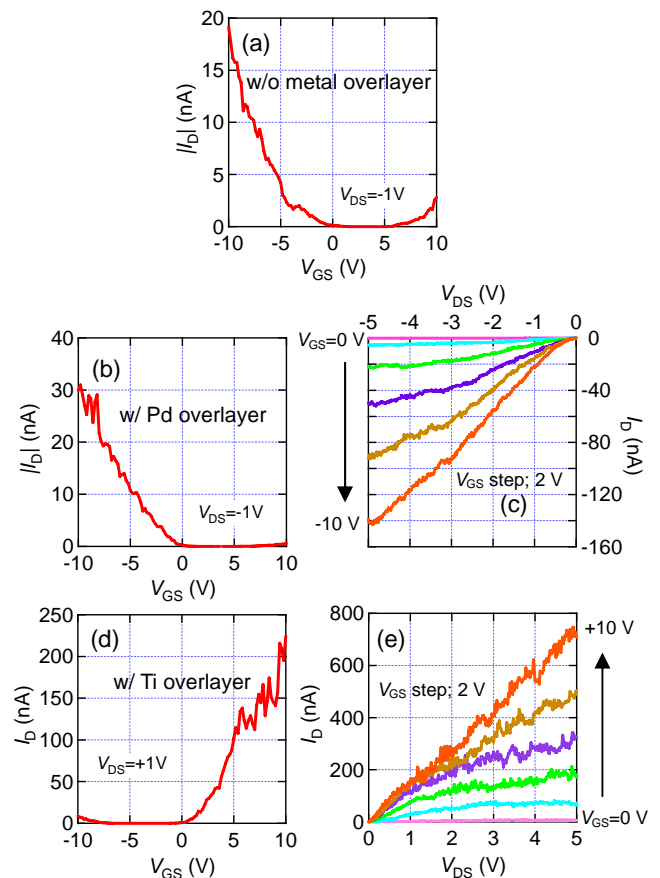

Fig. 2 (a) I_D-V_{GS} characteristics of the device without metal overlayer.   (b) I_D-V_{GS} and (c) I_D-V_{DS} characteristics of the device with Pd overlayer.   (e) I_D-V_{GS} and (f) I_D-V_{DS} characteristics of the device with Ti overlayer.

(a) (b) (c)

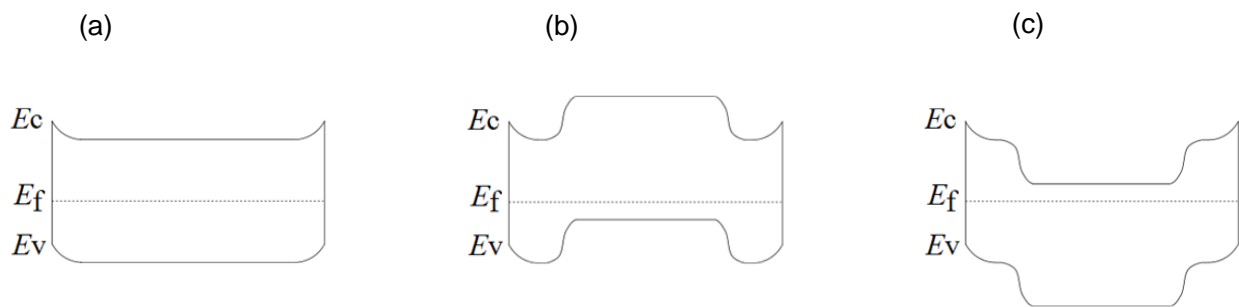E_c E_f E_v E_c E_f E_v E_c E_f E_v

Fig. 3 Schematic energy-band diagrams of the devices (a) without metal overlayer, (b) with Pd overlayer, and (c) with Ti overlayer, taking into account the charge transfer from the metal overlayer to the CNT.

Figure 2(a) is the I_D-V_{GS} characteristic of the CNTFETs without metal overlayer. Here, heavily-doped p$^+$-Si substrate was used as a back gate. The device without metal overlayer showed p-dominant ambipolar behavior. On the other hand, the I_D-V_{GS} and I_D-V_{DS} characteristics of the device with Pd overlayer showed p-channel behavior, as shown in Fig. 2(b) and 2(c). In contrast, the I_D-V_{GS} and I_D-V_{DS} characteristics of the device with Ti overlayer showed n-channel behavior, as shown in Fig. 2(d) and 2(e).

These results can be explained as follows. Figures 3 shows the schematic energy-band diagrams of the CNTFETs (a) without metal overlayer, (b) with Pd overlayer, and (c) with Ti overlayer, taking into account the work function of the metal overlayers. In the case of the device without metal overlayer, energy band can be drawn as shown in Fig. 3(a) taking into account the higher barrier height (~90 meV) for electrons than that for holes measured previously [9] and assuming no doping in the CNT channel. In the case when the Pd overlayer was deposited onto the CNT channel, on the other hand, the holes are expected to transfer from the Pd overlayer to the CNTs due to the larger work function of Pd as compared to the CNT (ϕ=4.8 eV [10]). Then, the energy band of the CNT under the Pd overlayer is thought to be bent upward, resulting in a higher barrier height for electrons than that for holes, as shown in Fig. 3(b). This leads to the p-channel behavior of the CNTFETs. In the case when the Ti overlayer was deposited onto the CNT channel, the electrons are expected to transfer from the Ti overlayer to the CNTs due to the smaller work function of Ti as compared to the CNT. Accordingly, the energy band of the CNT under the Ti overlayer is thought to be bent downward, resulting in a higher barrier height for holes than that for electrons, as shown in Fig. 3(c). Then, n-channel operation is realized.

3. Conclusions

It has been demonstrated that the conduction type of the CNTFETs with ambipolar behavior can be controlled by choosing the metal overlayer deposited onto the side surface of the CNT channel; p channel by Pd and n channel by Ti. The behavior was explained by band bending caused by the charge transfer from the metal overlayer to the CNT channel.

References
[1] V. Derycke *et al.*, Appl. Phys. Lett. **80** (2002) 2773.
[2] Y. Nosho *et al.*, Nanotechnology **18** (2007) 415202.
[3] Z. Zhang *et al.*, Nano Lett. **7** (2007) 3603.
[4] Y. Nosho *et al.*, Nanotechnology **17** (2006) 3412.
[5] A. Javey *et al.*, nature **424** (2003) 654.
[6] Y. Nosho *et al.*, Appl. Phys. Lett. **86** (2005) 073105.
[7] S. Ishii *et al.*, Mater. Express **1** (2011) 285.
[8] H. Oh *et al.*, Appl. Phys. Lett. **88** (2006) 103503.
[9] M. Tamaoki *et al.*, *Abstracts of the 4th Fullerenes-Nanotubes-Graphene General Symposium* (2012) 116.
[10] S. Suzuki *et al.*, Appl. Phys. Lett. **76** (2000) 4007.