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Double-wall carbon nanotube field-effect transistors: Ambipolar transport characteristics

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Double-wall carbon nanotubes (DWNTs) have been used as channels of field-effect transistors (FETs) to obtain information on their transport characteristics. DWNTs-FETs show metallic or semiconducting behavior depending on the tube diameters. All the semiconducting DWNTs have exhibited both *p*- and *n*-type characteristics, the so-called ambipolar behavior which is absent in normal SWNTs-FETs. Comparisons between the subthreshold swing (S) factor of DWNTs and that of SWNTs indicate that DWNTs are better FET channels than SWNTs. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1689404]

Double-wall carbon nanotubes (DWNTs) have attracted much attention during the past couple of years because of their novel structural and electronic properties compared to those of multiwall (MWNTs) and single-wall carbon nanotubes (SWNTs). DWNTs are the thinnest MWNTs in terms of the number of tube layers composed and can be considered as an ideal carbon nanotube (CNT) system for investigating the interlayer interaction and its influence on the electronic transport and mechanical properties of CNTs. Furthermore, the recent synthesis of high-quality DWNTs[1] enables us to prepare samples suited for such measurements. Furthermore, studies on DWNTs may provide important information on the growth mechanism of SWNTs and MWNTs, since DWNTs are the simplest MWNTs and are similar to SWNTs in layer structure.

Electronic transport measurements of CNTs by using field effect transistors (FET) have been reported since 1998[2,3] and are not only important for actual device applications, but also for providing one of the most useful techniques for elucidating the electronic properties of CNTs. The FET characteristics of SWNTs with about 1 nm diameter have been studied extensively in the past and have shown *p*-type transport behaviors,[3] whereas some of the MWNTs or larger-diameter SWNTs have exhibited *p*- and *n*-type (ambipolar) characteristics originated in small band gaps.[4,5]

DWNTs may provide us with crucial information on the origin of carrier transport for both SWNTs and MWNTs because of their characteristic double-layer structure. In an attempt to study structural, electronic, and solid state properties of DWNTs, we have already developed a new synthetic method to produce DWNTs, the so-called pulsed-arc discharge method,[1] which enables us to prepare high quality DWNTs having an average outer diameter of 1.8 nm.

Here, we report transport properties of DWNTs, synthesized by pulsed-arc discharge, as studied by the FET. We have found that DWNTs-FETs exhibit both *p*- and *n*-type behavior (the so-called ambipolar characteristics) in contrast with *p*-type behavior of SWNTs-FETs. The results are explained by the difference of the bandgap between DWNTs and SWNTs originated from the tube diameter and from the presence of inner tubes in DWNTs.

DWNTs were produced by the high-temperature pulsed-arc discharge method. The experimental set up of the system and details of DWNTs preparation have been described elsewhere.[6–8] Briefly, we used metal/graphite composite rods (Ni/Y 4.2/1.0 at. %: Toyo Tanso Co. Ltd.) as discharge electrodes. The pulsed-arc discharge (600 μs, 40–60 A, and 50 Hz) was generated between the electrodes at 1250 °C under a 100 ml/min flow of Ar at 760 Torr. DWNTs were characterized by a field emission scanning electron microscope (FE-SEM: JEOL-JSM-6340F), a high resolution transmission electron microscope (HRTEM: JEOL JEM-2010F), and Raman spectroscopy (Jobin Yvon, LabRam HR-800).

HRTEM observations show that DWNTs have inner and outer diameters of 0.8–1.2 nm and 1.6–2.0 nm, respectively. Figures 1(a) and 1(b) show a typical micrograph of individual DWNT and the schematic of DWNT synthesized, respectively. Raman spectra of DWNTs at 632.8 nm excitation show two salient peaks in the radial breathing mode (RBM) region at $\omega_R = 214$ and 136 cm^{-1} which corresponds to the inner and the outer diameters of 1.15 and 1.83 nm, respectively. For an isolated SWNT, the calculated diameter dependence of RBM has been fitted to $\omega_R\ (cm^{-1}) = 248/d\ (nm)$,[9] and we also employed this relationship in the diameter evaluation.

The heavily doped Si substrate (525 μm) was used as a back gate with a Ti/Au gate electrode (100/400 nm). An SiO_2 insulating layer (100 nm) was grown on top of the substrate by thermal oxidation. We used electron beam lithography and photolithography for the fabrication of the source and

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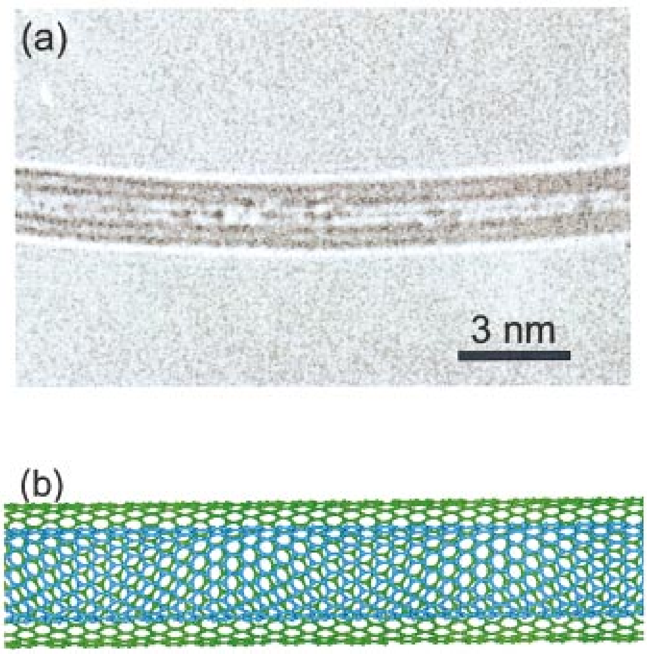

FIG. 1. (Color) DWNT generated by the high temperature pulsed arc discharge method. (a) HRTEM image of individual DWNT; (b) schematic image of DWNT.

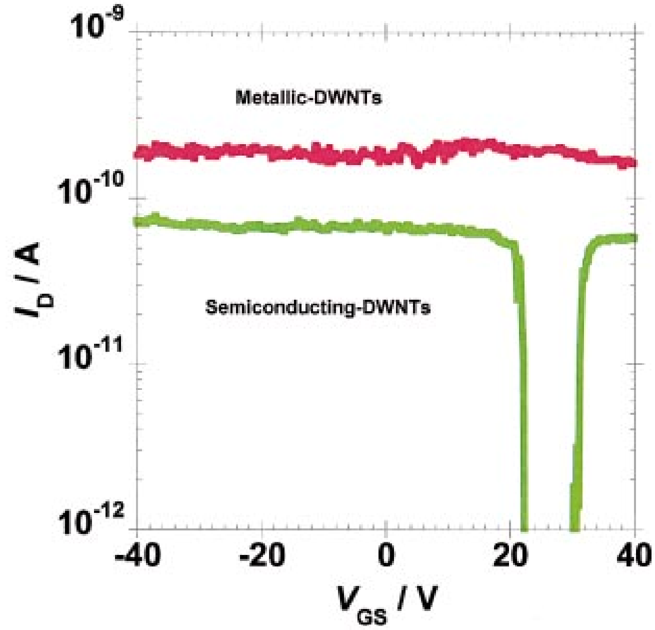

FIG. 2. (Color) Typical FET transfer characteristics of metallic (red) and semiconducting (green) DWNTs. DWNT channels here consist of a rope of ≤10 nm height, which was confirmed by AFM observation of the device (not shown).

drain electrodes (Ti/Au; 3/15 nm). The source-drain gap was 400 nm. DWNTs were dispersed in N,N-dimethylformamide solutions and dropped onto the substrate. This method provides us with a suitable tube density on the substrate. We have obtained over 80 DWNTs-FETs devices. A semiconductor parameter analyzer (Agilent, 4156C) and a low-temperature probe station (Nagase, BCT-21MRF) were used to measure drain current (I_D) as a function of gate bias (V_{GS}) or drain bias (V_{DS}) voltages. After the FET measurements, we have visualized and determined the height of nanotubes by using an atomic force microscope (AFM; Digital Instruments Dimension3100/Nano Scope IV).

Transport and conductivity measurements of DWNTs were performed by varying V_{GS} from positive to negative at $V_{DS}=1$ mV and $T=23$ K. All the devices measured showed metallic or semiconducting behaviors and, in particular, the semiconducting devices exhibited both p- and n-type action, the so-called ambipolar characteristics. Figure 2 shows typical I_D-V_{GS} (transfer) characteristics of metallic and semiconducting DWNT devices. The order of the saturated conductance (G) was about 10^{-6} S. All the ambipolar DWNTs have the voltage widths of off-state region (ΔV_{off}) depending on gate bias. The observed threshold gate biases (V_{th}) vary from $V_{GS}=12$ to 24 V and from 28 to 32 V for p- and n-type channels, respectively. The widths of the off-state region were from 8 to 17 V (13 V in average). It is noted that Fig. 3 shows that the drain currents of both p- and n-type action are almost the same with each other for semiconducting DWNTs, exhibiting a highly symmetric I_D-V_{GS} curve. This strongly suggests that the Fermi level of the FET electrode used is located in the midgap ($E_g/2$) of the current DWNTs investigated.

We also measured transfer characteristics of SWNT ($d=1.3$–1.6 nm) devices for reference [cf. Fig. 3(b)] at $V_{DS}=1$ mV and $T=23$ K. The SWNTs devices showed either metallic or p-type semiconducting behaviors, whereas all the semiconducting DWNTs devices so far studied have shown ambipolar behavior. The order of saturation conductance (G) for SWNTs was about 10^{-6} S. The V_{th} value varies from $V_{GS}=5$ to 18 V for p-type channels.

In our previous study, we suggested that the voltage width of the off-state region depends on the bandgap of the nanotubes employed.[10,11] A similar observation was also reported by Dai, Shim, and Javey for the ambipolar characteristics in large diameter SWNTs.[5] Experimental and theoreti-

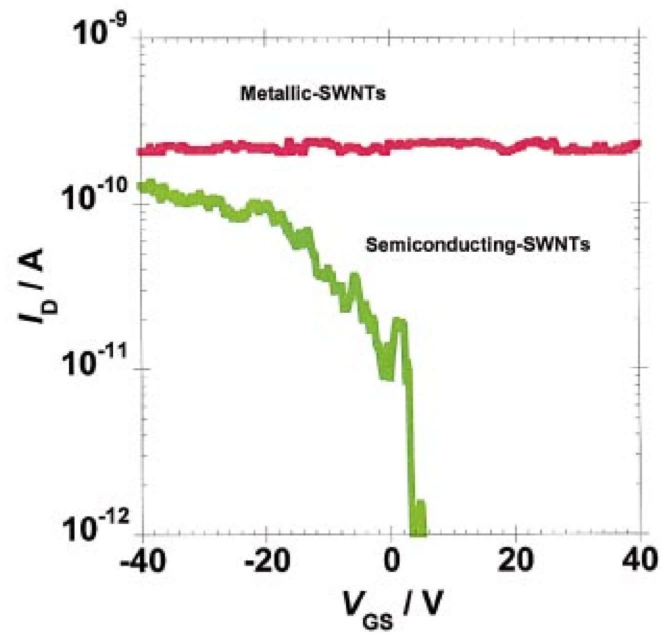

FIG. 3. (Color) Typical FET transfer characteristics of metallic (red) and semiconducting (green) SWNTs. SWNT channels here consist of a rope of ≤2 nm height, which was confirmed by AFM observation of the device (not shown).

cal studies have shown that the bandgap of carbon nanotubes is inversely proportional to their diameters.[12–14] The width of the off-state region of DWNTs can primarily be dominated by the diameters. In fact, the diameter distributions of SWNTs and DWNTs (outer tube) are 1.3–1.6 nm and 1.6–2.0 nm, respectively. The difference in the diameter distributions between SWNTs and MWNTs consistently explains the difference in the ΔV_{off} value between the two types of CNTs. Currently, we presume that the variations of V_{th} and ΔV_{off} values are due to the presence of residual impurity molecules physisorbed on the DWNTs surface or to the contact resistance between DWNTs and the FET electrodes.[15]

To further investigate FET operation of DWNTs and SWNTs, we have compared the subthreshold swing (S) of the two types of CNTs, which is commonly used to characterize metal oxide semiconductor FETs.[16] The S factor is defined by an equation, $S = dV_{\mathrm{GS}}/d\log_{10} I_D$.[17] The obtained S factors are 0.5–2 V per decade and 5–10 V per decade for DWNTs and SWNTs, respectively. DWNTs show much better S factors compared to those of SWNTs. Obviously, FETs employing DWNTs as a channel provide better performance than SWNTs-FETs in terms of the fundamental FET operation. We suggest that DWNT channels are an important candidate for high-performance CNT-FETs and have much potential for fabricating sophisticated future nanoelectronics devices.

In summary, we have investigated the transport properties of DWNTs used as FET channels. DWNTs showed metallic or semiconducting behavior, and all the semiconducting DWNTs exhibited ambipolar behavior. These transport properties can be explained by the bandgap narrowing owing to the larger outer diameters of DWNTs. Comparisons between the S of DWNTs and that of SWNTs indicate that DWNTs are better FET channels than SWNTs and that DWNT channels are an important candidate for high quality CNT-FET devices.

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