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Electronic Transport Properties of C_{60}, C_{90} and Gd@C_{82} Fullerene-Carbon Nanotube Peapods

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1. Introduction

Single wall carbon nanotubes (SWNTs) encaging fullerenes [1], the so-called peapods, have attracted much interests due to their structural and electronic properties. By varying the encapsulated fullerene molecules, tunable electronic properties of the material have been achieved. Recently, low-temperature scanning tunneling microscopy (LT-STS) studies have such electronic properties [2]. The bandgap of a semiconductor SWNT is dramatically reduced from 0.5 to 0.1 eV at the site of the inserted Gd@C_{82} metallofullerenes. This founding has important implications for the fabrication of SWNTs-based molecular devices such as diodes and transistors.

In this study, we report electron transport properties of fullerene and metallofullerene peapods by using them as channels of the field-effect transistors (FETs). C_{60}-peapods-FETs and C_{90}-peapods-FETs show *p*-type behavior, which is the same behavior as the semiconducting SWNTs-FETs, whereas Gd@C_{82}-peapods-FETs show ambipolar (both *p*-type and *n*-type) behavior by tuning gate bias voltages.

2. Experiment

SWNTs were generated by the pulsed laser ablation of carbon target containing Co-Ni metal catalyst at 1250 °C. The diameter of the SWNTs produced under this condition is mainly in the region of 1.4-1.5 nm. The fullerenes were generated by DC-arc discharge of carbon rod containing metal, and were separated by the multistage high performance liquid chromatography (HPLC) [3]. The method for producing peapods was reported previously [4, 5]. The doping of C_{60}, C_{90} and Gd@C_{82} into the SWNTs was carried out at 450-500 °C for 48 hours. The structure of the produced peapods were examined with a high resolution transmission electron microscope (HRTEM) operated at 120 kV (JEOL JEM-2010F). Fig. 1 shows a typical image of C_{90}-peapod. According to the HRTEM observation, yields of C_{60}-, C_{90}- and Gd@C_{82}- peapods were estimated to be >70, ~10 and >70%, respectively.

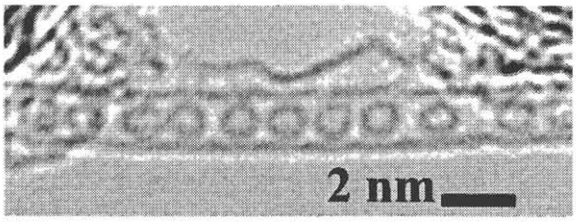

Fig. 1 Room temperature HRTEM image of a C_{90}-peapod, showing the SWNT and encaged C_{90} molecules.

The FETs were fabricated on an SiO_2 insulating layer (100 nm) on top of heavily doped silicon substrate. Source and drain electrodes were formed by electron beam lithography, metal evaporation (Ti/Au 3/15 nm) and lift-off process. Heavily doped silicon substrate was used as a back gate. The back-gate electrode was formed by metal evaporation (Ti/Au 100/300 nm). The peapods were dispersed in 1, 2-dichloroethane or dry *N*, *N*-dimethylformamide solutions and dropped on the substrate.

All measurements were carried out at 23 K. After these measurements, we used scanning electron microscope (SEM, JEOL JSM-6340F) and atomic force microscope (AFM, SII SPI-3700) for imaging these peapods devices.

3. Results & Discussion

Fig. 2 shows drain current versus gate voltage (I_D-V_{GS}) characteristics of a C_{60}-peapods-FET and C_{90}-peapods-FET. As is the case for the SWNTs-FETs [6], the conductance increases as V_{GS} decreases, implying that hole transport occurs through the valence band (*p*-type). In contrast to C_{60}-peapods-FETs, C_{90}-peapods-FETs are not pinch-off. This suggests the coexistence of unfilled metallic SWNTs and metallic C_{90}-peapods.

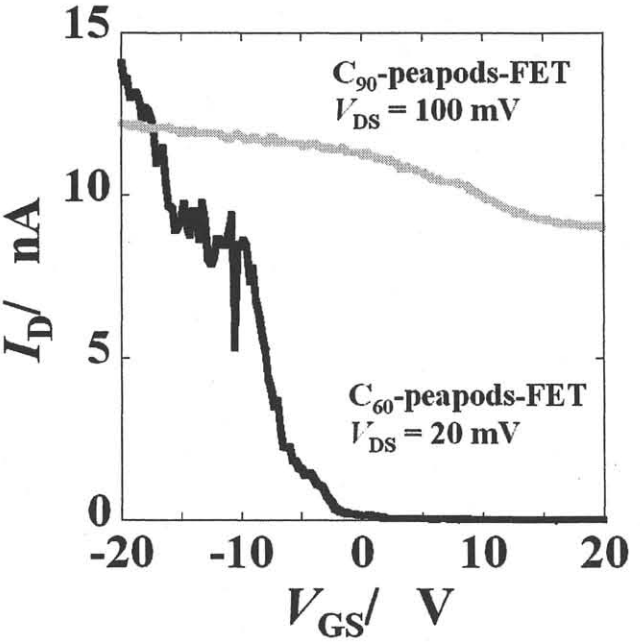

Fig.2 I_D-V_{GS} curves of C_{60}-peapods-FET (black line, V_{DS} = 20 mV) and C_{90}-peapods-FET (gray line, V_{DS} = 100 mV) at T = 23 K.

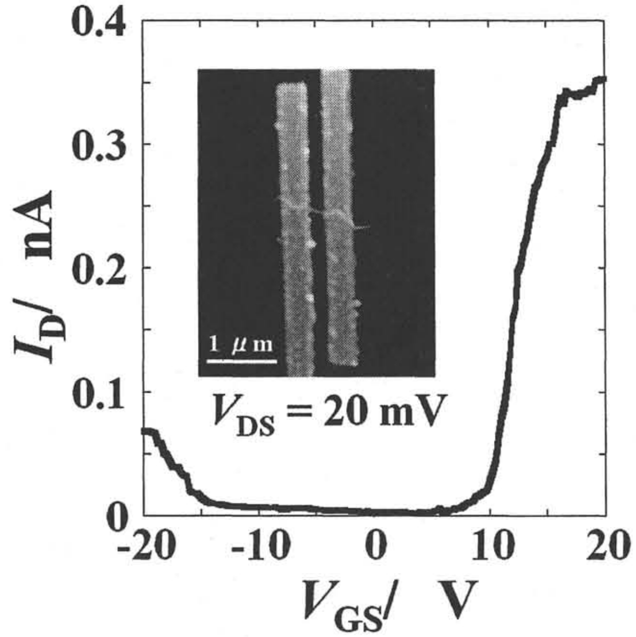

Fig.3 I_D-V_{GS} curve of Gd@C_{82}-peapods-FET at V_{DS} = 20 mV, 23 K. Inset: AFM image of the Gd@C_{82}-peapods-FET used in this measurement. The bundle rope of Gd@C_{82}-peapods consists of about 10 of individual peapod. The distance of between electrodes is 200 nm and width is 400 nm

Fig. 3 shows I_D-V_{GS} characteristics for a Gd@C_{82} -peapods-FET. Starting from a positive gate voltage, I_D decreases first, then becomes three orders of magnitudes smaller, and finally increases again. This indicates that Gd@C_{82} peapods exhibit ambipolar FET behavior with both n- and p-channels easily accessible by electrostatic gates. Such ambipolar behavior has not been so far observed in C_{60}- and C_{90}-peapods-FET.

In Gd@C_{82}, the endohedral Gd atom is in +3 valence state as revealed by electron energy loss spectroscopy (EELS) [7]. Hence, C_{82} fullerene cage have -3 valence state. This negatively charged C_{82} cage significantly alters the electronic state of the SWNTs. This effect has been confirmed as the bandgap narrowing by LT-STS [2]. For example, a bandgap of 0.5 eV is reduced to 0.1 eV at sites where Gd@C_{82} are encaged. In Gd@C_{82}-peapods-FETs, such a small bandgap can induce both hole and electron carrier transport by tuning gate voltages.

4. Conclusions

We have investigated the electric characteristics of C_{60}- and C_{90} -peapods and Gd@C_{82}-peapods. These fullerene-peapods show p-type conduction, while the metallofullerene-peapods show ambipolar both p- and n-type conduction behaviors depending on gate bias. The difference in these transport properties stems from the bandgap narrowing by insertion of metallofullerene to SWNTs.

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