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Suppression of the unconventional metallic behavior by gate voltage in MWNT device

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Abstract

We observed an ambipolar behavior in multiwalled carbon nanotubes (MWNT) in a back-gate configuration, which allowed us to perform systematic inspection of the low-temperature transport properties against gate voltage. Power-law behaviors in temperature and bias-dependent conductance, disappeared when a high gate voltage was applied, and conductance became temperature- and bias independent. This indicates a gate-induced transformation from the unconventional to the normal metallic states in MWNT.

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1. Introduction

The field effect transistor (FET) is known as a highly affective device for switching electron conduction in semiconductors, but researchers have also used this device to modulate electronic phase transition phenomena, such as ferromagnetism [1] and superconductivity [2,3]. This indicates that, although the effect of the gate field is generally weak, it is possible to tune electronic states of materials in FETs when devices are well prepared in combination with chemical tuning of material properties that will provide novel opportunities for FET devices.

In multiwalled carbon nanotubes (MWNTs), electrical conductance displays a power-law temperature and bias voltage dependence [4–7], which

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is ascribed to a Tomonaga–Luttinger liquid behavior driven by pure exchange Coulomb interaction [8–10] or to a kind of localized behavior induced by disorder combined with the Coulomb interaction [11,12]. In this paper, we demonstrate that this so-called unconventional metallic state is suppressed when a gate voltage is applied, and conductance becomes temperature- and bias independent. The result is understood as a crossover phenomenon from an unconventional metallic state to a normal Fermi liquid state in MWNTs, induced by gate-doped carriers.

2. Experimental

MWNTs produced by an arc-discharge method were used as it is to avoid defects that may be introduced by chemical treatments. The radii of MWNTs, which were several μm in length, were estimated to be 2–5 nm from height profiles in atomic force microscope (AFM) images. MWNTs were sonicated in 1,2-dichloroethane, and deposited on SiO_2/Si substrates with Pt(5 nm)/Au(15 nm) markers. The positions of MWNTs were determined using a scanning electron microscope (SEM). The electrodes of Pt(5 nm)/Au(60 nm) were formed on a MWNT ('end-contact' configuration) by evaporation of metals through a resist mask made by an electron beam lithography system [13]. Fig. 1(a) shows a SEM image of a MWNT device. The drain current (I_D) was measured at the source-drain voltage, applied to a MWNT from the Pt/Au electrodes. The gate voltage V_G was applied from the back-gate through the SiO_2 insulator of thickness, $t_{SiO_2} = 200$ nm. All measurements were performed in vacuum.

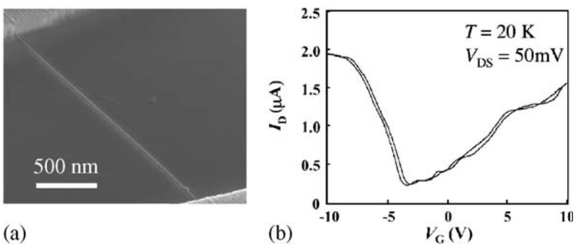

Fig. 1. (a) Scanning electron microscopy image of the device. (b) Transfer characteristics at $T = 20$ K, $V_{DS} = 50$ mV.

3. Results and discussion

We observed an ambipolar behavior with a minimum of drain current in the MWNT device. The on–off ratio (I_{on}/I_{off}) is enhanced with decreasing temperature and reaches approximately 10 at 20 K. In Fig. 1(b), transfer characteristic at 20 K is shown. The ambipolar behavior in MWNT has been observed by Kruger et al.[14] in the electrochemical transistor configuration, since the electrochemical gate is much more effective than the back gate. It is widely known that electronic conduction in MWNTs is dominated by the outermost shell [15], which is regarded to be a graphene sheet. Thus, the minimum drain current should be attributed to the minimum density of states of MWNTs and the increased drain current with the negative and positive V_G is due to the accumulation of holes and electrons, respectively [14]. The large hysteresis was observed and became smaller with decreasing temperature, indicating that they are most likely ascribed to an extrinsic effect, that is, the movement of impurity ions near the surface of SiO_2 insulator [16,17].

The observation of ambipolar behavior of MWNTs in the back-gate configuration can be ascribed firstly to the low density of carriers, which were introduced unintentionally, but more importantly, to the proper choice of the Si substrate. In the present experiment, we used a highly doped p-type Si substrate with a doping level of $10^{19}/cm^3$, which is higher than the $10^{18}/cm^3$ at which a Mott-type metal–insulator transition in doped Si takes place [18]. This high amount of doping ensured the high conductance of the gate electrode, particularly at low temperature.

In order to clarify the transport properties near the current minimum, we measured detailed temperature T and V_{DS} dependence of the transfer characteristics.

Fig. 2(a) shows the V_{DS} dependence of G in a double logarithmic scale. All the data are fitted well by a linear relation, indicating that G shows a power-law behavior proportional to V_{DS}^{α}. The important information gained from Fig. 2(a) is that the slope of the $\log G - \log V_{DS}$ plot shows a systematic V_G dependence. The slope, which is the steepest at $V_G = 0$ V, becomes gentler with