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Electrical Properties of the Graphitic Carbon Contacts on Carbon Nanotube Field Effect Transistors

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1. Introduction

Carbon nanotubes (CNTs) are a promising semiconducting material for nanoscale electron devices such as carbon nanotube field-effect transistors (CNT-FETs), because of their potential for high-speed operations due to the large carrier velocity [1,2] in the CNT channel and high current density [3] . Recently, a clever method to use graphitic carbon (G-C) layer between the contact metal and the CNTs to improve the wettability was proposal and good results were obtained where the contact resistance (R_C) of the p-channel CNT-FETs with G-C interlayer contacts was decreased [4]. However, in spite of that the work function of the G-C is expected to be almost same as that of the CNTs, the CNT-FETs with G-C interlayer contacts exhibited p-channel behavior. The origin of the p-channel behavior is not clear at present. It is important to fully understand the electrical property of the G-C contacts for improving the device performance. In this study, we fabricated CNT-FETs with G-C interlayer contacts and studied the effect of air atmosphere on the electrical properties of the devices. The Fermi level position of the G-C contacts was also studied by estimating the barrier heights at the contact based on the temperature dependence of the drain current.

2. Results and Discussions

A schematic cross section of a fabricated CNT-FET with G-C interlayer contacts is shown in Fig. 1(a). A heavily-doped p^+-Si substrate with thermally-oxidized SiO_2 (100 nm) was used as a backgate. CNTs were grown by thermal chemical vapor deposition (CVD) at 800°C for 30 min using C_2H_5OH as a source gas and patterned Co (0.1 nm) as a catalyst. The radial breathing mode in the Raman scattering

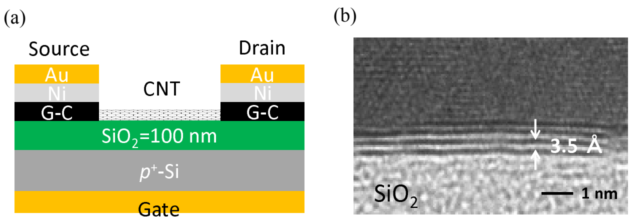

Fig. 1 (a) Schematic cross section of a CNT-FET with G-C interlayer contacts. (b) Cross-sectional TEM image of the G-C layer.

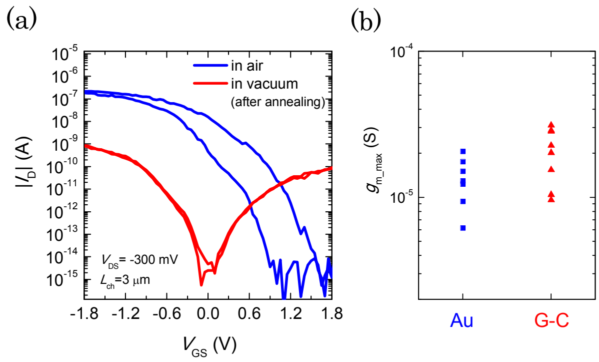

Fig. 2 (a) Typical I_D-V_{GS} characteristics of the fabricated CNT-FETs with G-C interlayer contacts in ambient air (blue line) and in a vacuum after annealing (red line). (b) Measured transconductance of the CNT-FETs with G-C contacts (red triangles) and Au contacts (blue rectangles).

spectrum indicates that the tube diameter was 1.1~1.8 nm. Amorphous carbon (2 nm) /Ni (5 nm)/Au (30 nm) tri-layer structures (listed in the order from the bottom layer upward) were formed at the source and drain electrode regions by electron-beam evaporation, which was followed by graphitization annealing at 800°C for 15 min in a vacuum. Graphitization was confirmed by TEM observation and also by Raman scattering spectrum. From the cross-sectional TEM image of the electrode/SiO_2 interface, it is confirmed that three layers of graphene were formed between the SiO_2 and Ni layers, as shown in Fig. 1(b). The spacing between graphene layers was 0.35 nm.

Fig. 2(a) shows the typical I_D-V_{GS} characteristics of the fabricated CNT-FET at a drain voltage of -300 mV. The device showed p-channel behavior with good pinch-off characteristics with an ON/OFF current ratio of about 10^5, as shown by the blue solid line. Fig. 2(b) shows the transconductance (g_m) of many devices with G-C contacts and Au contacts. The devices with G-C contacts exhibited a larger transconductance than the devices with Au contacts. By considering the formula of $g_m = g_{m0}/(1+g_{m0}R_C)$ where g_{m0} is an intrinsic transconductance, we can conclude that a smaller R_C was achieved by employing G-C contacts.

In order to study the reason for the p-type conduction, the devices were annealed at 200°C for 90 h in a vacuum. The I_D-V_{GS} characteristics of the devices are shown in Fig.

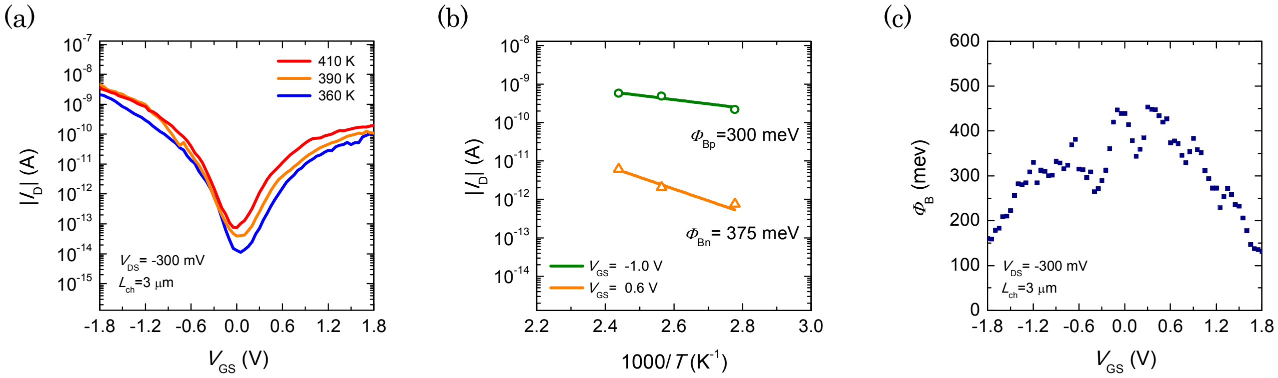

Fig. 3 (a) I_D-V_{GS} characteristics at 360 K, 390 K and 410 K. V_{DS} = -300 mV. (b) Arrhenius plots at V_{GS}= -1.0 (blue open circles) and 0.6 V (red triangles). (c) Dependence of measured barrier height on V_{GS}.

2(a). The conduction type of the devices changed from p-type (blue line) to ambipolar after annealing (red line). This suggests that the p-channel behavior of the CNT-FETs with G-C interlayer in ambient air is attributed to the adsorbed oxygen [5].

In order to study the G-C contacts in more detail, we estimated the barrier height against carriers by measuring the temperature dependence of the drain current in a vacuum. Fig. 3(a) shows the drain current (I_D) versus gate voltage (V_{GS}) characteristics measured in a vacuum at 360 K, 390 K, and 410 K. Fig. 3 (b) shows the Arrhenius plot of the drain current at a drain voltage of -300 mV. The barrier heights ($Φ_B$) were 375 meV at V_{GS}= 0.6 V and 300 meV at V_{GS}= -1.0 V for electrons and holes, respectively. The gate voltage dependence of the barrier height is shown in Fig. 3(c). The dependence is asymmetrical for positive and negative gate voltages. In addition, it seems that there are two plateaus at positive and negative V_{GS} regimes. The gate voltage dependence of the barrier height should be symmetrical if the Fermi level (E_F) of the G-C contact is located at the midgap of the CNT, as shown in Fig. 4(a). The blue and red lines show the qualitative V_{GS} dependence of the barrier height for holes ($Φ_{Bp}$) and electrons ($Φ_{Bn}$), respectively. The decrease in the barrier height at the large gate voltage reflects the occurrence of the thermionic field emission. $Φ_{Bp}$ is equal to $Φ_{Bn}$ at V_{GS} = 0 V and larger than $Φ_{Bn}$ for positive V_{GS}. The experimentally measured barrier height obtained from the Arrhenius plot should be the lower barrier among the barriers for electrons and holes at each V_{GS}. Then, experimentally obtained gate voltage dependence of the barrier height $Φ_B$ should be similar to the solid line. When E_F of G-C is located at slightly below the midgap of the CNTs, on the other hand, the V_{GS} dependence of the barrier height is expected to be asymmetrical and will have the shape as shown Fig. 4(b). The plateaus correspond to the barrier heights for the flat band condition, $Φ_{Bp0}$ for holes and $Φ_{Bn0}$ for electrons, respectively. The experimentally obtained gate voltage dependence of the barrier height shown in Fig. 3(c) is similar to that in Fig. 4(b). Then the barrier heights for holes ($Φ_{Bp0}$) and electrons ($Φ_{Bn0}$) at flat band condition can be estimated to be ~310 and ~400 meV, respectively. These values suggest that the E_F of the G-C contact is located at slightly (~50 meV) below the midgap of the CNTs in a vacuum.

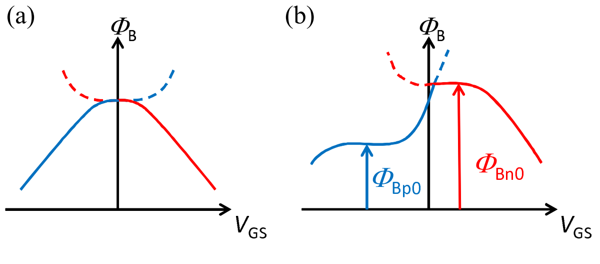

Fig. 4. Qualitative dependence of the barrier height for the various Fermi level positions of the contact (a) at the midgap and (b) below the midgap.

3. Conclusion

We have fabricated CNT-FETs with G-C interlayer contacts and studied the origin of the p-type conduction in ambient air. The contact resistance of the CNT-FETs with graphitic carbon contacts was smaller than that of the devices with Au contacts. The conduction type has changed from p-type in air to ambipolar in a vacuum after annealing at 200 °C for 90 h, which suggests that the p-type conduction in air is due to the adsorbed oxygen. The barrier heights at the G-C/CNT contacts in a vacuum were ~400 meV for electros and ~310 meV for holes. These values suggest that the E_F of G-C is located at slightly below the midgap of the CNTs in a vacuum.

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