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To cite this article: Yuji Miyato et al 2005 Jpn. J. Appl. Phys. 44 1633

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Local Surface Potential Measurements of Carbon Nanotube FETs by Kelvin Probe Force Microscopy

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(Received October 12, 2004; accepted January 12, 2005; published April 8, 2005)

We fabricated carbon nanotube FETs (CN-FETs) by dielectrophoresis method. Two types of CN-FETs with either Au or Ti electrodes were prepared for the study of electrical junctions between metal electrodes and nanotubes. Local surface potential of the CN-FETs in working condition was mapped by Kelvin probe force microscopy (KFM). A large surface potential drop occurred at the interface between the Ti electrodes and the bundle of SWNTs, and this potential drop was changed by the applied gate voltage. This result suggests that the Schottky barrier at the drain edge is modulated by the gate bias.

[DOI: 10.1143/JJAP.44.1633]

KEYWORDS: single wall carbon nanotube, dielectrophoresis, Kelvin probe force microscopy, surface potential, Schottky barrier

1. Introduction

Single wall carbon nanotubes (SWNTs) as quantum wires are promising candidates for building blocks of next-generation electronic devices because of their unique electrical and mechanical properties.1) Recently, carbon nanotube field effect transistors (CN-FETs) using semiconducting SWNTs have been intensively studied.2–5) Although these studies indicate that the Schottky barriers at the interfaces between SWNTs and metal electrodes play important roles in the CN-FET operating mechanism, only a small number of studies have included local electrical measurements at the interfaces.6)

In the fabrication of CN-FETs,7,8) it is essential to position SWNTs at a specific location and to extend them in a specific direction. Recently, the chemical vapor deposition (CVD) method has often been used to fabricate CN-FETs.8) With this method, the growth of individual SWNTs can be directly controlled, but the direction of SWNT growth tends to be random. Another promising method is alternating current (ac) dielectrophoresis.9–11) With this method, SWNTs can be controlled such that they connect a specific pair of electrodes. When an ac electric field is applied to SWNTs in suspension, they are aligned along the field. Therefore, if SWNTs are longer than the distance between electrode gaps, SWNTs can bridge the electrodes applying an ac electric field.

On the other hand, atomic force microscopy (AFM) is a powerful tool not only for imaging surface structures but also for investigating material properties with nanometer-scale resolution.12,13) In particular, Kelvin probe force microscopy (KFM), which is capable of mapping local surface potential distribution, is a method for evaluating nanoscale electrical devices.6,14–16)

In this work, we demonstrated that dielectrophoresis is useful for the fabrication of CN-FETs where a small number of SWNTs connect source and drain electrodes. Local surface potential distribution along the SWNT channel between two electrodes in an FET device was investigated by KFM. Furthermore, the variation in surface potential distribution was studied when the drain and gate bias voltages were changed.

2. Experimental

We fabricated CN-FETs by dielectrophoresis in the following procedure. First, we made several pairs of electrodes on a highly-doped Si substrate with a thermally grown oxide layer (thickness: 300 nm) by photolithography. Two electrode materials, Ti and Au, were used. The total thickness of these electrodes was 20 nm and the gap distance was approximately 5 μm. The Au electrodes contained 5 nm Cr layers as adhesion layers. The SWNTs, which were fabricated by the arc-discharge method, were commercially obtained from Bucky USA. The SWNTs were ultrasonically dispersed in ethanol. This suspension having an estimated concentration of 10 ng/ml was dropped onto the electrode gaps while an ac electrical field at a frequency of 1 MHz and a magnitude of 2 V peak to peak was applied between the gaps. The volume of the droplet was 1 μl. After the solution was evaporated in a short time, some SWNTs successfully bridged the electrodes. We checked FET behavior by applying a back gate voltage to the samples. As a result, we obtained CN-FETs which consisted of a single SWNT bundle by adjusting the suspension concentration and estimated the number of SWNTs in these bundles at less than 10 from their height information in AFM.

In this study, we used a commercially available AFM instrument (JEOL: JSPM-4200) for KFM measurements. Since surface potential is very sensitive to humidity in air,17) KFM measurements were carried out in a vacuum at a pressure of 1.0×10−3 Pa. For this reason, we used a frequency modulation (FM) detection method.18) Figure 1 shows a schematic diagram of the KFM setup. The original frequency shift detector was replaced with a newly developed one (Kyoto Instruments: KI-2000XEL).19) The typical frequency shift used in this experiment ranged from −10 to −15 Hz. Si cantilevers coated with a Pt film were used (Olympus: AC240TM-B2). The resonant frequency was about 78 kHz and the spring constant was 2 N/m. A modulation bias voltage (2 kHz, 0.8 V rms) for KFM measurements was applied to the sample. The upper left inset in Fig. 1 shows the electrical connections to measure the...
surface potential during FET operation. A source electrode was electrically connected to the KFM bias feedback electronics. The gate voltage and the drain voltage were added from the source potential.

3. Results and Discussion

When SWNTs bridged the electrodes, some samples showed metallic characteristics and others showed semiconducting characteristics. Figure 2(a) shows a topographic image of a CN-FET with Au electrodes. The SWNT extended almost perpendicular to the edge of the electrodes and formed a gate channel. The gate channel in this sample was a single bundle with an average height of 4 nm. Figure 2(b) shows the drain current ($I_D$) vs. drain voltage ($V_{DS}$) curves with various gate voltages ranging from $-15$ to $15$ V. The curve clearly shows nonlinear characteristics, which partly come from the contact resistance between the electrodes and the SWNTs. Note that SWNTs are only in physical contact with the electrodes. The drain current ($I_D$) vs. gate voltage ($V_G$) curve is shown in Fig. 2(c). The gate voltage was changed from $-15$ to $15$ V while the drain bias voltage was held constant. The drain current was drastically changed in the gate bias range between $5$ V and $12$ V, which clearly shows FET characteristics. This result suggests that semiconducting SWNTs were contained in this bundle. These electrical measurements were performed in a vacuum ($1 \times 10^{-4}$ Pa).

Figure 3(a) shows a topographic image of a CN-FET sample with Ti electrodes. The $I_D$--$V_{DS}$ curves at various gate voltages and the $I_D$--$V_G$ curve are shown in Figs. 3(b) and 3(c) respectively. A drain current modulation with respect to the gate voltage change was also observed, but the gate dependence was not large in the case of the Ti electrodes, as shown in Fig. 3(c). This is probably because a bundle of SWNTs are the gate channel.

The surface potential of each sample was measured by KFM when the bias voltage was changed. Figure 4 shows surface potential images of the CN-FET (Au electrodes),
a topographic image of which is shown in Fig. 2(a) at three different drain voltages. Surface potential images of the CN-FET (Ti electrodes: Fig. 5(a)) are also presented in Fig. 5. It is clearly shown that the contrast of the SWNT channel is changed as a function of the drain voltage change in both CN-FET samples. The surface potential profiles along the bundle of SWNTs from the source to the drain were obtained from the surface potential images at different $V_{DS}$. Figure 6 shows the potential profiles of the SWNTs in contact with the Au electrodes, the potential profiles in the case of the Ti electrodes are shown in Fig. 7. The shaded regions on the right and left sides in each figure indicate the source and drain electrodes.

According to the simple interpretation, the surface potential is related to the gaps between the Fermi level and the vacuum level. We paid attention to the potential drops at the interfaces between the electrode and the bundle. As shown in Fig. 6(b), the potential drop at the drain edge in each potential profile is nearly equivalent. This suggests that these potential drops are mainly due to the contact resistance, taking into account that the potential changes in the gate modulation are not so large in this gate voltage range (from $-2$ to $+2$ V) as shown in Fig. 2(c). Although it is better to measure the surface potential in the gate voltage range from 5 V to 12 V where the drain current is strongly modulated, the measurement accuracy in this voltage range is extremely reduced, because the KFM signal is greatly disturbed due to the high electric field at the gate area.

In contrast, the surface potential drops at the drain edge were remarkably modulated by the gate voltages in the Ti electrode, as shown in Fig. 7(b). The potential at a distance of 4 $\mu$m in Fig. 7(b) changed by approximately 1 V when the gate voltage was changed from $-2$ to 2 V. This agrees with the fact that the drain current is decreased as the gate voltage
is increased in this gate voltage range where hole transfer is dominant. These surface potential changes at the interface between the Ti drain electrode and the SWNTs probably originate from the Schottky barrier change caused by gate bias modulation.1–4)

This result suggests that the electrical conduction between the SWNTs and the Ti electrode is dominated by the tunneling of the holes, which strongly depends on the width of barriers. The gate voltage at the drain edge can modulate the tunneling barrier width; specifically, the Schottky barrier can be thinned, which is favorable for tunneling, by applying a gate bias voltage toward the negative side.

The work function of SWNTs is estimated to be approximately 4.8 eV.21) The work function of Au is close to 5 eV, with some variation depending on its environment, while the work function of Ti is about 4.3 eV. A Schottky barrier can be formed at the Ti electrode interface in this gate voltage range, whereas in the case of the Au sample, ohmic contact is likely to be formed rather than a Schottky barrier due to the negligibly small contact potential difference.5) Thus, the potential can be modulated at the Ti drain edge through the Schottky barrier variation induced by the gate voltage change. This explanation is consistent with the result that a large variation in surface potential at the drain edge was seen only in the Ti electrode sample. For further discussion, it is essential to improve the contacts and reduce the contact resistances.

In addition, some potential drops exist in the middle of the SWNT bundle in both electrode cases (indicated by the arrows in Figs. 6 and 7). As the drain bias voltage is increased, these drops become larger. These are probably caused by some structural defects in the nanotubes such as untwisting points, breaking points or connecting points. Figure 8 shows a magnified topographic image corresponding to the shaded region where the potential drops sharply in Fig. 7.

4. Conclusions

We demonstrated a new fabrication method for CN-FETs by ac dielectrophoresis. Local surface potentials of CN-FETs in working conditions were mapped by KFM. In the CN-FET sample with Ti electrodes, the Schottky barrier changes at the drain edge depending on gate voltages were directly observed. The result suggests that the Schottky barrier plays an important role in the operating mechanisms of the CN-FETs. The gate voltage modulation probably affects the Schottky barrier, leading to a large change in the tunneling conduction. We also observed sharp changes in surface potential originating from structural defects in the SWNTs by KFM.

Acknowledgments

This work was supported by a Grant-in-Aid for Scientific Research and Grants for Regional Science and Technology Promotion from the Ministry of Education, Culture, Sports, Science and Technology of Japan, and by Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency (JST). The authors would also like to acknowledge the Kyoto University Venture Business Laboratory Project and the 21st Century COE Program.