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Response of Carbon Nanotube Field Effect Transistors to Vibrating Gate

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1. Introduction

Combination of carbon nanotube field effect transistor (CNT-FET) and nano-mechanical sensors based on CNTs[1] is expected to be a novel functional force sensing device. Scanning gate microscopy (SGM) is a powerful technique for measuring local electronic properties of these devices because an applied voltage cantilever tip acts as a nanoscale local gate.[2] In this study, we have investigated the response of CNT-FET to vibrating gate using a modified SGM technique.

2. Experiments

The single wall nanotube (SWNT) that is used as a channel of CNT-FET was synthesized by low pressure alcohol chemical vapor deposition (ACCVD) method on a SiO_2 (100nm)/Si substrate, which acts as a back-gate electrode. We fabricated CNT-FET through conventional photolithography process. We used Ti/Pt (5nm/30nm) as source and drain electrodes which gap is 2um.

Figure 1 shows a schematic diagram of the measurement system for the SGM with a vibrating gate, where a Pt coated probe was used as the vibrating gate. We performed the vibrating gate SGM measurement with non-contact mode at room temperature in air. It is noted that only modulated current signal induced by the cantilever vibration was measured using a lock-in-amplifier (LIA), where the vibration amplitude and frequency were less than 50 nm and ~80 kHz, respectively. The current signal was mapped respective to the probe position. Thus, we could take AFM images and modulated current images simultaneously, where the AFM images include the topographic and electro-static force information between the gate and the CNT channel.

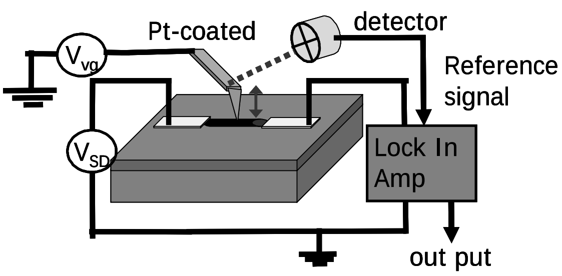

Fig.1 Measurement system of SGM

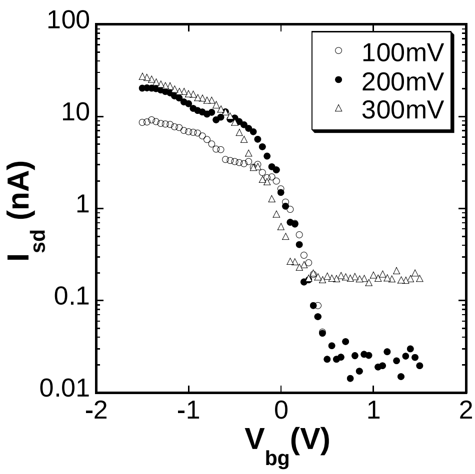

Fig.2 Transfer characteristics of CNT-FET measured using the back-gate with various V_{sd}.

3. Results and Discussions

First, we examined the FET property using the back gate. Figure 2 shows transfer characteristics (the back gate voltage, V_{bg}, dependence of the source current, I_{sd}) of the CNT-FET with the source-drain voltage, V_{sd}, of 100, 200, and 300mV, respectively. The characteristics show the p-type property and transconductance: g_m and on/off ratio are obtained to be 75nS and 10^3, respectively.

Figure 3(a) shows an AFM image of channel part on CNT-FET with 0V of vibrating gate voltage, V_{vg} and V_{sd} = 0 V with floating back gate voltage, where top and bottom of the image corresponds to the source and drain electrodes, respectively. We can clearly confirm that only one CNT channel makes a bridge with a height of 1.6nm. On the other hand, in the case of V_{vg} = -1 V and V_{sd} = 0 V, the CNT channel is scanned thicker as shown in Fig. 3(b). This originates from the electrostatic attraction between a CNT channel and a tip of cantilever, which corresponds to so-called electrostatic force microscopy (EFM) image. Using the non-contact mode AFM, the gap between the probe tip and sample is controlled by the resonant frequency shift of the probe. Thus, in this mode, we can take not only the EFM image but also the SGM image, simultaneously.

Figure 4(a) shows a modulated current image induced by the gate vibration with V_{vg} = -1V and V_{sd} = 0.2 V. We could confirm ~ 2 nA source-drain current modulation. Under this condition, the average DC component of the current was 2 nA. When we changed the phase of the LIA 180 degrees, the contrast of the modulated current image was reversed as shown in Fig. 4(b). In this case, the vibration amplitude of the probe is around 50 nm, so that the sensitivity of the CNT-FET to the vibrating gate of 80 kHz is ~ 0.04 nA/nm. In the cases of the V_{vg} = 0 and 1 V, we could not observe clear modulated current images, although the corresponding EFM images could be observed clearly similar to Fig. 3(b). Thus, the vibrating probe certainly acts as the local vibrating gate.

Assuming the tip shape of the probe is cylinder with a diameter of 0.8 nm, we can estimate the gate capacitance induced by the probe tip to be 1.4 x 10^{-19} F under the condition that the distance between the probe tip and the CNT channel is 33 nm. Using this gate capacitance and the g_m obtained from Fig. 2, we can estimate the static response of I_{sd} to the distance between the scanning gate and the CNT channel, dI_{sd}/dz. As a result, $dI_{sd}/dz = 0.5\varepsilon V_{vg}$ (A/m) was obtained for the FET, where ε is the relative permittivity for the measured environment. Thus, the expected static sensitivity in air is 0.5 nA/nm for this CNT-FET. However, this value is much larger than that of the dynamic response described in Fig. 4. This degradation at the vibration frequency of 80 kHz may be due to the high contact resistance at the source-drain electrodes. Furthermore, these experiments were performed in air, so that the trapped charge and/or induced dipole by the adsorbed water may be also affected to the dynamic response.

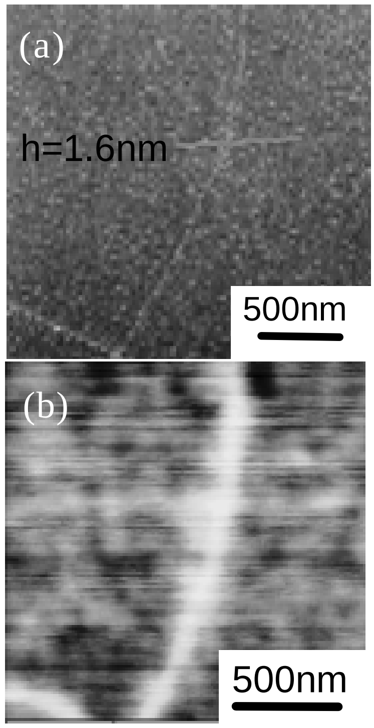

Fig. 3 AFM images of CNT channel with V_{vb} = 0, (a), and V_{vb} = -1 V, (b), where the top and the bottom of these images correspond to the source and drain electrodes, respectively.

4. Conclusions

We have investigated the response of the CNT-FET to the vibrating gate using the modified SGM technique, which can be obtained the vibrating gate response and the EFM image, simultaneously. The CNT-FET was successfully detected the cantilever vibration with the amplitude less than 50 nm and the frequency of 80 kHz with the sensitivity of 0.04 nA/nm.

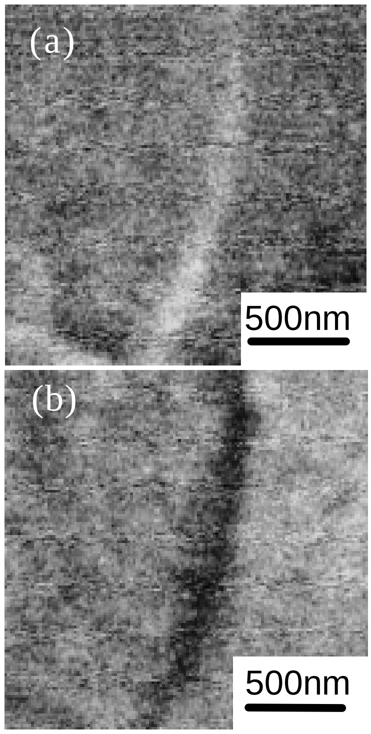

Fig.4 Modulated current images with V_{vb} = -1V taken under the LIA phases of (a) 0 deg. and (b) 180 deg.

References

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