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Operation Mechanism of Single-Wall Carbon Nanotube Network FET Studied by Scanning Gate Microscopy

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1. Introduction

Thin-film field effect transistor (FET) is one of the realistic applications of carbon nanotube (CNT) due to superior characteristics such as high mobility, high current density, transparent, flexible and so on [1]. However, the mechanism of the device operation has not been well evaluated yet. For example, Schottky barrier at the metal/CNT interface, the CNT channel itself, defects, and the junction between the CNTs; all of these mechanisms can show an FET response and they occasionally contribute simultaneously in the gate operation. However, they have not been distinguished in the characterization so far. Especially, the back gate, which is commonly used in a proto-type device, covers the device entirely, therefore it is impossible to understand the characterization of the device mechanism. Moreover, some famous equations used in Si-MOS-FET device are still diverted in a calculation of such mobility also in a CNT network device, in spite of different mechanisms from Si-MOS. However, in order to improve the characteristic for the practical application of SWNT, it must be important to determine which mechanism or the combinations are the most effective in the device operation. Therefore, we believe an impotence to establish a spatially resolved local gate study in nano-scale. Scanning gate microscopy (SGM) is one of such techniques for local study in semiconductor nano-structures. It has been applied also for FETs consisting of a single-wall carbon nanotube (SWNT) [2]. In the SGM, a tip of scanning probe microscope (SPM) is used as “a mobile gate” and a change of the source-drain current is stored as the SGM image during a luster-scan of the tip on the device. We have used the SGM for studies of transports in semiconductor quantum structures at low temperature [3] and also organic FETs at room temperature [4]. In this paper, we have applied the technique for the study of SWNT thin-film FET to determine the mechanism of the FET operation.

2. Sample preparation and SGM observation

The SWNTs synthesized by CoMoCAT® process (SWeNT® SG 65, Sigma-Aldrich) were dispersed in a 2 % surfactant (SDS) solution with ultrasonication for one hour to disentangle the bundles. The solution was spanned on palladium electrodes having a gap of 5 µm fabricated in advance on SiO_2 layer of a thick of 600 nm on an n^{++}-Si substrate. The sample was rinsed in methanol to remove the surfactant. In order to make sure to connect the two electrodes, the process was repeated three times. The FET showed *p*-type and normally on as shown in Fig.1.

The sample was installed into an ambient SPM system and a PrIr coated cantilever was then approached on the FET channel as schematically shown in Fig. 2. Dc voltage ($V_{tip\text{-}dc}$) and ac modulation voltage ($V_{tip\text{-}ac}$) were coupled and applied to the tip during interleave-mode operation with lifting up the tip 40 nm high above the surface.

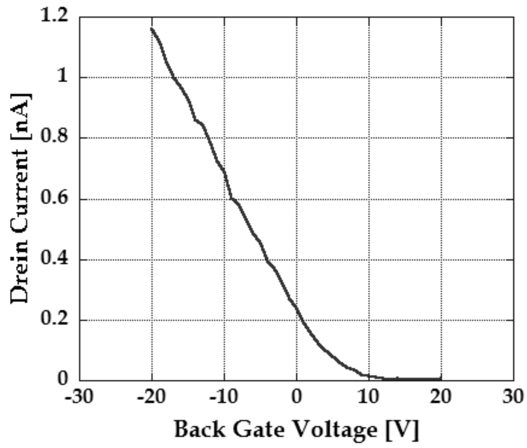

Fig. 1. V_{bg} dependence of I_{sd} of the SWNT network FET. The FET shows *p*-type and normally-on.

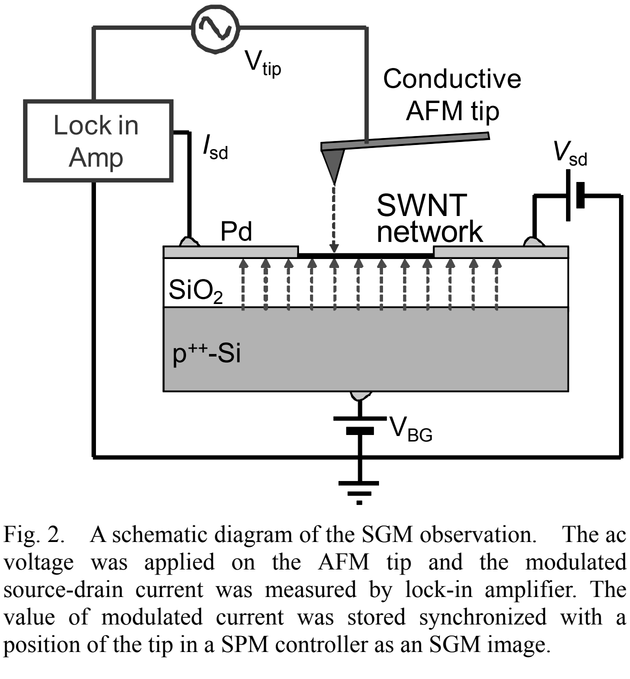

Fig. 2. A schematic diagram of the SGM observation. The ac voltage was applied on the AFM tip and the modulated source-drain current was measured by lock-in amplifier. The value of modulated current was stored synchronized with a position of the tip in a SPM controller as an SGM image.

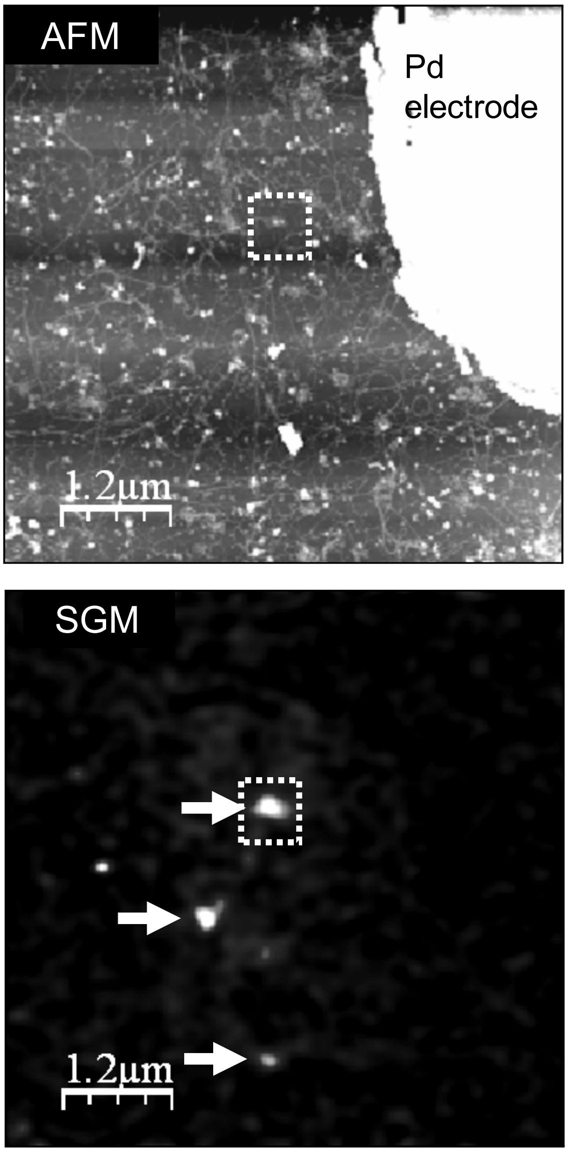

Fig. 3. (a) AFM topographic image of a channel region of the SWNT network FET. The upper-right (bright) region corresponds to the drain electrode (Pd). The SWNTs are almost unbundled however there still exist numbers of nano-particles included the pristine SWNT powder. (b) The right image is the corresponding SGM image. The SGM responses were obtained only at a few restricted regions (indicated by arrows). The other white spots have not been confirmed the reproducibility. No response was observed at the interface between the Pd electrode and the SWNT network. The dotted squares indicate a region which is used for taking magnified images shown in Fig. 4.

The $V_{\text{tip-ac}}$ of -0.2 V was applied and then modulated current ($I_{\text{sd-ac}}$) was measured by a lock-in amplifier, and stored in a SPM controller simultaneously. The use of the lock-in amp. has successfully improved signal/noise ratio of the SGM response. In this configuration, a local gate spectroscopy can be performed by sweeping the $V_{\text{tip-dc}}$ at a specific point or by taking the SGM image with changing the $V_{\text{tip-dc}}$.

3. Results and discussion

The Fig. 3 (a) shows a topographic image of a part of a channel region of the SWNT network FET and the corresponding SGM image is shown in Fig. 3 (b). Although there exist huge number of SWNTs in the channel region, such a resonantly-appeared SGM response was observed at some specific points within the channel region as indicated by arrows in the image. By magnifying one region as shown in Fig. 4, we found that the response is coming from a junction of two SWNTs. Moreover, it is also confirmed that most of the responses appear at junctions of SWNTs but never appear along the whole of the individual SWNT. Such specific junctions would suggestively play an important role in the operation of the SWNT network FET.

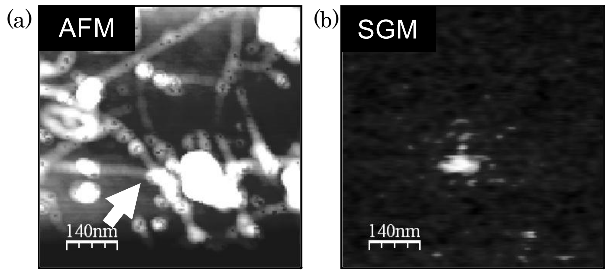

Fig. 4. (a) Magnified topographic image of SWNT network. (b) The corresponding SGM image. The response was coming from a junction of two SWNTs as indicated by arrow.

4. Conclusions

SWNT network FET has been observed by a high resolution SGM. The SGM responses are obtained only at some specific position in the channel region. It is also confirmed that the responses appear at junctions of SWNTs. This fact indicates that such a junction would play an important role for an FET operation of the network device.

Acknowledgements

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