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Local Transport Study of Quantum Dots Formed in SWNT Network FET by Scanning Gate Microscopy

Masahiro Matsunaga[1], Xiaojun Wei[1], Tatsurou Yahagi[1], Kenji Maeda[1],Jonathan P. Bird[2], Koji Ishibashi[3], Yuichi Ochiai[1] and Nobuyuki Aoki[1]

[1] Graduate School of Advanced Integration Science, Chiba University
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
Phone: +81-43-290-3430 E-mail: n-aoki@faculty.chiba-u.jp
[2] Department of Electrical Engineering, University at Buffalo,
SUNY, Buffalo, New York 14260-1920, USA
[3] Advanced Device Laboratory, RIKEN, Wako, Saitama 351-0198, Japan

Abstract

A cause of current fluctuations in field-effect transistors composed of a network of single wall carbon nanotubes (SWNTs) has been revealed via scanning gate microscopy (SGM). Concentric-multiple rings were observed in the SGM images within the network at room temperature. The position of the SGM response situate not at the junction of the tubes but on SWNTs. Such SGM responses suggest a transport through discreet energy levels at quantum dots formed due to defects within the SWNT. A clear diamond-shape characteristic has been depicted from the change of the height of SGM response by sweeping the source-drain bias voltage at different back-gate voltages.

1. Introduction

Carbon nanotubes (CNTs) have been regarded as one of the most fascinating materials for scientific research and industrial applications because of their potential for high-speed electronics due to the high electron velocity in CNTs and for flexible electronics due to their elasticity [1]. Field effect transistors (FETs) whose channel is composed of a network of single wall carbon nanotubes (SWNTs) have also been studied for the practical applications as flexible FETs. However, the mechanism of device operation has not been well evaluated yet. For example, the Schottky barrier at the metal/SWNT interface, the SWNT channel itself, defects, and the junction between the SWNTs can all give rise to FET response, and occasionally contribute simultaneously to the gate operation. Especially, it is important for a high-performance FET operation that elimination of metallic-type SWNT by purification process. However, during the process, defects are easily introduced and then such SWNTs cause degradation of FET performance. Current fluctuations are one of the problems typically observed in purified SWNTs. Therefore, we believe it is important to establish a spatially resolved local gate with nano-scale resolution. Scanning gate microscopy (SGM) is one of such techniques that can be used for the local study of semiconductor nano-structures [2, 3]. By using the technique, electrostatic characteristics of each SGM-active regions can be evaluated individually. In this paper, we demonstrated observation of local current-voltage characteristics within the channel region and a depiction of diamond-shape characteristics from the SGM response.

2. Sample preparation and experimental setup

In this study, we use semiconductor enriched SWNTs prepared by the density gradient ultracentrifugation (DGU) process provided from NanoIntegris Inc. (IsoNanotubes S™ 90%). The SWNTs solution was dispersed onto a SiO_2 layer of 300nm thick on an n^{++}-Si substrate using spin coating method. The sample was rinsed with methanol to remove the surfactant. The source-drain electrodes were patterned by photolithography and Pd of 20 nm thick was deposited on the SWNTs. Finally, O_2 plasma was used to remove the unwanted SWNTs to restrict the channel width (6μm). After attaching the electrodes, the sample was installed into an SGM system based on Molecular Imaging, PicoPlus™. A PrIr coated cantilever for tapping-mode atomic force microscopy (AFM) was then approached to the FET channel. The tip was used as “a mobile-point gate electrode” to apply a local electric field. The details of setup for the SGM observation are shown in Ref. 4. All experiments were performed under atmospheric conditions.

3. Results and discussion

Figure 1(a) shows AFM image of a SWNTs network FET and corresponding SGM image. Although huge numbers of SWNTs exist in the channel region, the SGM responses were observed at just some particular positions within the channel region as shown in the bright spots in the image. Any SGM responses were not observed near the electrodes (Pd)/SWNTs contact regions, indicating that ohmic contact was achieved in this sample. These SGM responses show the concentric rings and the center of the ring corresponds to intra SWNTs. The diameter of the rings depends on the back gate voltage and show recurrences with a period of ~6 V. These responses are different from the previous results observed in a high-quality SWNTs [4], where all of the responses corresponded to positions of cross junctions of SWNTs.

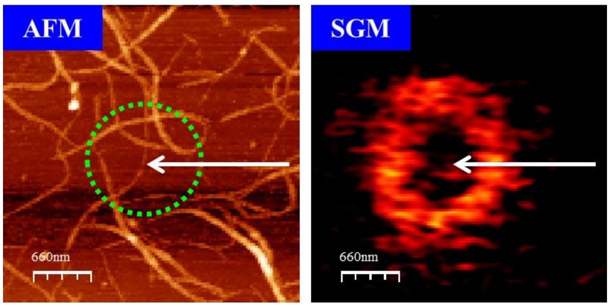

Figure 1 (left) AFM image in a magnified channel region of the SWNT network FET. (right) The corresponding SGM image.

Such concentric rings have been observed in SWNTs by SGM observation at low temperature. They were explained as detection of Coulomb-blockade effect caused by defects in SWNTs [5]. However, most of such experiments have been performed at low temperature since thermal energy must be smaller than the charging energy of the Coulomb island. Although the origin of our ring has not been clarified yet, such a ring-shape response would be related to transport through discreet energy levels of quantum dots due to defects in the SWNT introduced during the DGU process.

In order to investigate these responses precisely, the AFM tip was fixed at the center of the response with applying ac- (V_{tip-ac}) and dc- (V_{tip-dc}) tip voltage. This allows that an observation of the local differential conductance (Δg_m) not only as a function of the back gate voltage (V_{bg}) but also the source-drain voltage (V_{sd}). The SGM response, which is ac component of source current (i_s) modulated from V_{tip-ac}, was detected by a lock-in amplifier. Figure 2 (a) shows clear change of slope of i_s-V_{tip-ac} characteristics at different V_{bg} (V_{bg} = -6 V, 0 V, 3 V and 7 V) and then some of steps can also be confirmed. The slopes of i_{sd} -V_{sd} curves oscillate with increasing V_{bg}. The characteristics as a function of V_{bg} and V_{sd} are shown in the contour plot in Fig. 2(b). Clear diamond-shaped structures are resolved even at room temperature.

If we assume that the characteristics represent Coulomb blockage effect, different Coulomb peaks appeared successively with increasing the back gate voltage. A series of well-pronounced current steps observed in Fig. 2(a) could be explained as Coulomb staircases. The positions of the current steps slightly decreases with increasing source-drain voltage. The observed current steps are similar to single electron tunneling in the nanotubes device, demonstrating that a quantum dot was formed by two tunneling barriers [6]. These results show that quantum dots are formed intra tubes. From these results, we can roughly estimate the charging energy (E_c) and dot size (L) as $E_c \sim$ 70meV (exceeding the thermal energy at room temperature) and $L \sim$ 10 nm, respectively. Thus Coulomb blocked effect could be expected at room temperature. And then, such quantum dots course fluctuations of current in the FET operation.

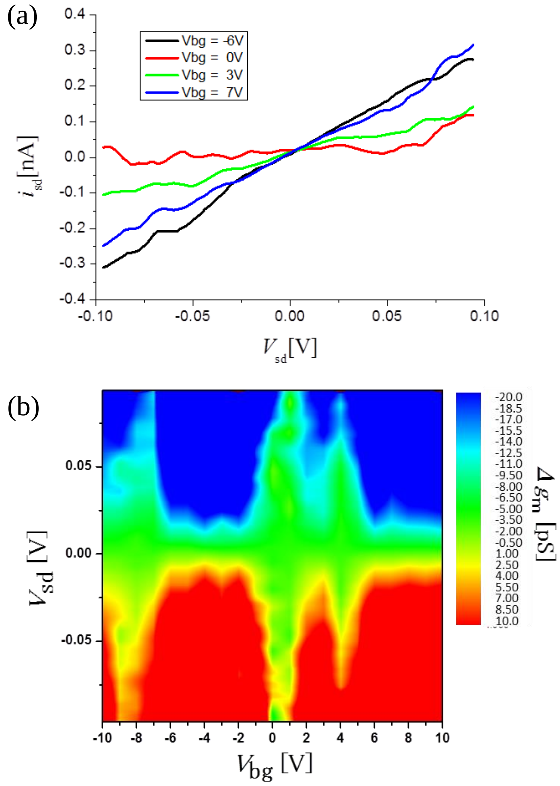

Figure 2 (a) ac component of source-drain current (i_{sd}) versus source-drain voltage (V_{sd}) observed at several fixed back gate voltage of V_{bg} = -6 V, 0 V, 3 V and 7 V at room temperature. (b) Contour plot of i_{sd} as a function of V_{bg} and V_{sd}. The green color corresponds to a region where the conductance is suppressed.

4. Conclusions

We have studied a FET composed of a network of SWNT repaired by DGU process using SGM observation, in which the scanning probe tip is used as a local mobile gate. Some of ring-shape responses are observed in the SGM images of the channel region. Modulating one of the SGM-active regions, the local characteristics are revealed. Step-like current-voltage characteristics and diamond-shaped contour plots are successfully visualized using the local SGM responses. It can be suggested that these responses would be attributed to the presence of Coulomb blockade effect at quantum dots formed in SWNTs and such effects cause current fluctuations during the FET operation.

Acknowledgements

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References

[1] T. Takenobu *et al*., Appl. Phys. Expr. **2** (2009) 025005.
[2] N. Aoki *et al*., AIP Conf. Proc. **1399** (2011) 829-830.
[3] D. Mann *et al*., Nano Lett. **3** (2003) 1541.
[4] X. Wei *et al*., Jpn. J. Appl. Phys. **51** (2012) 04DN05.
[5] M. T. Woodside and P. L. McEuen, Science **296** (2002) 1098.
[6] J. B. Cui *et al*., Nano Lett. **2** (2002) 117.