Surface potential imaging of CNT-FET devices by scanning Kelvin probe microscopy

H Hosoi¹, M Nakamura¹, Y Yamada¹, K Sueoka², K Mukasa¹
¹Creative Research Initiative “Sousei”, Hokkaido University, Kita 21, Nishi 10, Kita-ku, Sapporo, 001-0021, Japan
²Graduate School of Information Science and Technology, Hokkaido University, Kita 14, Nishi 9, Kita-ku, Sapporo, 060-0814, Japan
E-mail: hosoi@cris.hokudai.ac.jp

Abstract. We investigated the surface potential around nanotube channel during CNT-FET operation by scanning Kelvin probe microscopy (SKPM). The results demonstrate that the local surface potential distribution depends on the fabrication process of FET devices. We also measured the transfer characteristic of CNT-FET and compared with the surface potential image. In addition, we investigate the specific FET device with the closed CNT loops into which channel CNT penetrates. The surface potential distribution is completely different with that of a simple single CNT channel. We find that the closed loop of CNT has a capability of trapping the charge inside the loop.

1. Introduction

There are a large number of basic and applied researches on carbon nanotube field effect transistor (CNT-FET) device. Still, a few ambiguous issues related to the transfer characteristics exit. One of these problems is that many CNT-FETs exhibit hysteresis behavior upon sweeping the back gate voltage due to the rearrangement of charges in the substrate and/or in surrounding dielectric material such as water [1, 2]. This hysteresis can be utilized in memory device [3], but reproducible operation is inhibited by the hysteresis behavior. Especially, the stable operation is required for CNT-FET based chemical and bio-sensors [4] due to detecting the difference in the conductance modulated by chemical species. Although this hysteresis can be partially and fully removed by annealing [2, 5] or by surface passivation [6], thermal treatment of the device coincidentally modifies hysteresis behavior and contact properties between CNT channel and electrodes. The transfer characteristics of the device are accordingly changed. It is an essential to evaluate the hysteresis properties without additional device processing in order to understand the factors responsible for hysteresis.

On the other hand, atomic force microscope is a powerful tool not only for imaging surface topography but also for mapping the material properties on nanometer scale. Scanning Kelvin probe microscope (SKPM) especially is capable of imaging local surface potential and is employed to investigate CNT on SiO₂ substrate [7, 8].

In this work, we observed the surface potential around nanotube channel during CNT-FET operation by SKPM. We investigated FET devices fabricated by different process and compared their surface potential distributions. Furthermore, we demonstrated that the location of CNTs affects the potential distribution and the transfer characteristics.
2. Experimental

We fabricated FETs by position-controlled CNT growth technique. A p-doped silicon wafer with thermally oxidized SiO$_2$ (135nm) was used as the substrate. The CNT was synthesized via chemical vapor deposition. In this work, we evaluated two types of devices fabricated by the different processes. One is that the catalysts are the particles composed of Fe and Mo. In this case, the catalytic particles were dispersed after the supporting layer composed of Fe, AlO, and Si films were patterned on the silicon wafer. Although the catalytic particles covered all over the surface of device, CNTs grow only from the particles on the supporting layer because alumina plays a key role in catalytic action. The other is that the patterned thin film consisting of multi layers of Mo/Fe/Al/Si is catalyst. The position of the catalyst was controlled in the both fabrication processes. In the patterned film catalyst, the two layer light-sensitive films are used with lift-off process in order to smooth the edge of electrodes. The light-sensitive films coated over CNT also differs from that with the dispersed catalysts.

In this study, we used a commercially available AFM instrument (SII: SPI3800, SPA340) for SKPM measurement. Si cantilevers coated with Au film were used as force sensors (SII: DFM-3A). The electrical connections to image surface potential during FET operation is same as Ref. [5], but the AC voltage for bias voltage feedback can be applied to either CNT-FET or tip in our SKPM system. We cannot find the significant difference of the spatial and the potential resolution in both cases. In this works, we have measured surface potential with both modes.

3. Results and Discussions

The all fabricated CNT-FETs exhibit the hysteresis in drain current ($I_{ds}$) versus gate voltage ($V_g$) characteristics. Figure 1(a) is $I_{ds}$-$V_g$ characteristics of FET fabricated with the dispersed catalysts. We recognized a large hysteresis in the $I_{ds}$-$V_g$ curves as $V_g$ is swept forth and back between -10 and +10 V. The threshold gate voltage ($V_{th}$) at which the nanotube begin to conduct is shifted by more than 6 V ($\Delta V_{th}$). Fig. 1(b) shows a topographic and surface potential images of this device. A CNT expands to two electrodes and forms a gate channel as shown in AFM image. The SKPM images of the FET under operative conditions show that the potential of CNT continuously changes between the source and drain electrodes. This result supports the fact that the imaged CNT properly acts as channel of FET. Now, we should pay attention to the area surrounding CNT channel. When $V_g$ ($\pm 5$ V) is applied to device, the surface potential distribution drastically changes. The surface potential around CNT is higher (lower) at almost

![Figure 1](image-url)
Figure 2. (a) $I_{ds}$-$V_g$ characteristics of FET at $V_{ds} = -1.0V$. (b) The AFM image size is 5 µm×5 µm. SKPM images show the magnified area surrounding the gray broken line in AFM image. (c) Line profiles of white broken lines indicated in SKPM images.

300 mV than that of SiO$_2$ in corresponding to the negative (positive) $V_g$. The brighter (darker) image contrast extends over the distance of 1µm from the CNT. In Fig. 1(b), there is a CNT fragment isolated from two electrodes as shown in dots circle. We cannot recognize the local potential variation around the isolated CNT without electrical contact to electrodes. Therefore, we think that the change of surface potential originates in the charges injected from CNT channel into the surrounding dielectric such as adsorbed water, residual photo-sensitive film, and SiO$_2$.

We also measured the device fabricated with using multi layer film as catalyst in order to compare that with dispersed catalysts. The transfer characteristics differs with a previous device as shown in Fig. 2(a). The $I_{ds}$ slightly flows at positive $V_g$ and this device shows a behavior like as ambipolar type. Figure 2(b) shows AFM and SKPM images. The CNT acting as channel stretches obliquely across the two electrodes as shown in AFM image and there is no significant difference with the previous devices. SKPM images however represent the distinctive feature in the surface potential around CNT. The potential difference between CNT and SiO$_2$ surface is about 30 mV and the width of surface potential broadening is 300 nm. These values are fairly smaller than that of the previous results. This result indicates that a number of charges injected to dielectric material are small. One of this reason is that the saturation current of $I_{ds}$ is low and that the carriers injected to CNT through the junction with source electrodes is few. In the case of the isolated CNT electrified by the AFM, it is reported that the width of the local potential change around the isolated CNT is about 200 nm [9]. Furthermore, we think that the difference in the fabrication process of devices affects the surface potential distributions. We use the different two types of photo-sensitive films and there is a possibility that the circumstance surrounding CNT differs between devices if the photo-sensitive film is not sufficiently removed on lift-off process. The residual materials may influence amount of adsorbed water and dielectric constant around CNT and may induce the lowering of $V_g$ actually applied to CNT channel. It is think that the degree of the local potential variation around CNT reflects on the hysteresys behavior of device. However, there is no significant difference in the $\Delta V_{th}$ of both devices. We think that this fact is due to that the device fabricated with film catalyst is ambipolar type, because the holes are injected from CNT on applying positive $V_g$. Therefore, it is a difficult to simply compare with hysteresis characteristics from the $\Delta V_{th}$. In order to quantitatively evaluate the hysteresis, the time-decay measurement [10] which can determine the device parameter such as threshold voltage may be required.

Finally, we provide an example demonstrating the effects of location of CNT cannel. The AFM and SKPM images are shown in Fig. 3(b). In this device, the two CNTs form the closed loops and a CNT channel penetrates into these loops. In the previous devices, the surface potential of SiO$_2$ along channel changes gradually. However, this device has a stepwise potential
variation along CNT channel and the surface potential is almost same inside the closed loops as shown in Fig. 3(b). We think that the specific potential variation is induced by the trapping charges inside CNT loops. Actually, it is reported that the CNT loops can trap charges which stem form ions introduced during sample preparation [7]. We speculate that the charges injected from CNT and/or the electrode are accumulated inside the loops. $I_d$-$V_g$ curves of this device also has a specific property. The $V_{th}$ and the saturation current of $I_d$ depend on the sign of the $V_g$ as shown in Fig. 3(a). We conclude that this asymmetric property originates in the charge trapped inside the closed loops.

4. Summary
We measured the transfer characteristics and imaged the surface potential distribution of CNT-FET devices. We demonstrated that the local potential around the CNT channel depends on the circumstance surrounding the channel. Especially, the closed CNT loop has a capability of trapping the charge inside and the transfer characteristic shows an asymmetry with the sign of $V_{ds}$. However, we cannot find the unambiguous relationship between $\Delta V_{th}$ and the local surface potential distribution. To clarify this issue, we need the further investigation such as the time decay measurement of $I_d$ and the imaging of the time evolution of the surface potential.

Acknowledgments
We thank Y. Watanabe, A. Konya and T. Itoh for the fabrication of CNT-FET devices. This work was supported by Special Coordination Funds for promoting science, by New Energy and Industrial Technology Development Organization (NEDO) and by Japan Science and Technology Agency (JST).

References
[1] Tersoff J, Freitag M, Tsang J C and Avouris P 2005 Appl. Phys. Lett. 86 263108
[2] Kim W, Javey A, Vermesh O, Wang Q, Li Y and Dai H 2003 Nano. Lett. 3 193
[3] Fuhrer M S, Kim B M, Dürkop T and Brintlinger T 2002 Nano Lett. 2 755
[4] Balasubramanian K and Burghard M 2006 Anal. Bioanal. Chem. 385 452
[5] Cui J B, Sordan R, Burghard M and Kern K 2002 Appl. Phys. Lett. 81 3260
[6] Shimauchi H, Ohno Y, Kishimoto S and Mizutani T 2006 Jpn. J. Appl. Phys. 45 5501
[7] Jespersen T S and Nygö 2005 Nano Lett. 5 1838
[8] Miyamoto Y, Kobayashi K, Matsushige K and Yamada H Jpn. J. Appl. Phys. 44 1633
[9] Zdrojek M, Mélín T, Boyabal C, Stiévenard D, Jouault B, Wozniak M, Huczko A, Gebicki W and Adamowicz L 2005 Appl. Phys. Lett. 86 213114
[10] Kar S, Vijayaraghavan A, Soldano C, Talapatra S, Vajtai R, Nalamasu O and Ajayan P M 2006 Appl. Phys. Lett. 89 132118