# Characterization of Carbon Nanotube Thin Film Transistors by Scanning Probe Microscopy

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## 1. Introduction

Carbon nanotube thin film transistors (CNT-TFTs) are expected to be suitable for flexible and high-speed electronics [1,2]. In order to fully develop the potential of the devices, it is important to understand the behavior of the device in detail. Scanning probe microscopy (SPM) is effective in characterizing the behavior of the devices with nanostructure because of its inherent potential of high spatial resolution. However, few studies on the characterization of the CNT-TFTs using SPM have been reported. Recently, we have reported the electrical properties of CNT-FETs measured by Kelvin probe force microscopy (KFM) [3] and scanning gate microscopy (SGM) [4]. In this study, we measured the CNT-TFTs in detail by KFM, SGM, and point-contact current-imaging AFM (PCI-AFM) [5]. Non uniform images of electrical properties of the device were obtained even in the randomly-oriented 2D networks of CNTs.



Fig. 1 (a) Schematic structure of the CNT-TFTs (b) AFM image of the fabricated CNT-TFT.



Fig. 2  $I_{\rm D}$ - $V_{\rm GS}$  characteristics of the CNT-TFT



Fig. 3 (a) and (b) KFM images with  $V_{\rm DS} = 0$  and -2 V, respectively.  $V_{\rm GS} = 0$  V. (c) potential profiles along the channel.

## 2. Results and Discussion

Figure 1 illustrates (a) the schematic structure of the CNT-TFT with a back-gate electrode, and (b) the AFM image of the fabricated CNT-TFT ( $L_{ch} = 5 \ \mu m$ ,  $W_{ch} = 3 \ \mu m$ ). The CNT network channel was directly grown on a SiO<sub>2</sub>/Si substrate by plasma-enhanced chemical vapor deposition [6, 7]. The fabricated CNT-TFTs showed p-type conduction with an on/off current ratio of about 1500, as shown in Fig. 2 [8].

Figure 3 (a) and (b) show potential images measured by KFM. In the case of  $V_{\rm DS} = 0$  V, the uniform potential image was obtained as shown in Fig. 3 (a). In the case of  $V_{\rm DS} = -2$  V, on the other hand, an terrace(island)-like potential image was observed as shown in Fig. 3 (b). The boundary of the terrace is rather parallel to the edge of the source and drain electrodes. In addition, it seems that the potential in each terrace is almost constant. It is interesting to note that such

a unique potential image was obtained even for the randomly-oriented 2D networks of CNTs. Figure 3 (c) shows a potential profile along the line shown by an arrow in Fig. 3 (a) and (b). It is notable that, in addition to the step-like potential profile, the potential of the channel near the source/drain electrodes is almost same as that of the source/drain electrodes.

In order to clarify the origin of these results, we measured the resistance between the arbitrary point on the channel and the source electrode by PCI-AFM using a conductive probe. The low resistance region (bright area at source side) and high resistance region (dark/red area) were clearly distinguished as shown in Fig. 4 (a). Good correlation between the potential image and resistance image is obtained. Low resistance region was observed at the drain side when PCI-AFM was performed for the measurements using drain electrode. If the low resistance regions are in contact with the source/drain electrodes, it is reasonable that the potential near the contact edge is almost equal to that of source/drain electrodes. Figure 4 (b) shows the SGM image in which the current modulation is prominent at the same position as the narrow low resistance region observed by PCI-AFM, indicating that current path is limited in a narrow area even in the randomly-oriented 2D networks of CNTs. This result suggests, in conjunction with KFM and PCI-AFM images, that the CNT network is divided into several islands which are connected with narrow conductive area.



Fig. 4 (a) PCI-AFM image ( $V_{GS} = 0$  V,  $V_{tip} = -0.2$  V) (b) SGM image ( $V_{GS} = 0$  V,  $V_{tip} = 6$  V).

In order to study in more detail, CNTs were randomly distributed on the channel area using Monte Carlo simulation. The length and density of the CNTs used in the simulation are 0.5  $\mu$ m and 24 CNTs/mm<sup>2</sup>. Figure 5 (a) is the simulated result and Fig. 5 (b) is the schematic drawing representing CNT connections of the simulated result in which dark regions correspond to the areas covered by the electrically-connected CNTs. Island-like structure in which each islands are connected by narrow channel is obtained. If this kind of island structure exists in the CNT-TFTs, it is possible to explain above SPM results.



Fig. 5 (a) CNTs distributed by Monte Carlo simulation (b) schematic drawing representing CNT connections.

### 3. Conclusion

Non uniform electrical properties were demonstrated by using SPM even in the CNT random network channel. Correlation between KFM, SGM and PCI-AFM was confirmed.

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