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Mapping potential landscapes of semiconducting carbon nanotubes with scanning gate microscopy

Yongsun Kim¹, Young Mu Oh¹, Ji-Yong Park¹ and Se-Jong Kahng²

¹ Division of Energy Systems Research, Ajou University, Suwon 443-749, Korea
² Department of Physics, Korea University, Seoul 136-713, Korea

E-mail: jiyong@ajou.ac.kr

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Abstract

Inhomogeneities in the energy bands of semiconducting carbon nanotubes (CNTs) are investigated with scanning gate microscopy (SGM). Non-uniform responses of a semiconducting CNT to a local electric field are found in SGM images which are obtained at the different depletion states of the CNT. The results indicate that local potential perturbations affect the transport characteristics of semiconducting CNTs significantly, especially near the off-state of the device.

1. Introduction

Carbon nanotubes (CNTs) have shown exceptional mechanical, electrical and chemical properties, which have made them objects of active research in recent years [1, 2]. CNTs have attracted much interest as a promising electronic material with superior electrical properties such as high conductance, large current-carrying capacity and high mobility [2]. For the investigation of their electrical properties and applications as electronic devices, CNTs are typically studied with macroscopic electrodes attached, and the electronic transport characteristics are obtained through measurements of their current–voltage (IV) characteristics. Measured IV characteristics of the devices result not only from the intrinsic electrical properties of CNTs but also from the combinations of various local electronic characteristics of the system, such as metal–CNT contacts, CNT–CNT junctions, scattering centers due to defects or impurities and electron–phonon interactions in CNTs. As the size and dimension of systems are reduced, as in (quasi) one-dimensional systems like CNTs, local potential perturbations start to play an important role and can even dominate the transport characteristics of the system as only a small number of channels are available for charge transport [3]. Therefore, characterization and control of inhomogeneities resulting from local perturbations in the system are essential for better understanding and reproducible implementation of CNT-based electronic devices.

The characterization of local electrical properties has been made possible with the introduction of the atomic force microscope (AFM), using such techniques as electrostatic force microscopy (EFM) [4, 5], Kelvin force microscopy [6], scanning conductance microscopy [7, 8] and scanning gate microscopy (SGM) [4, 9–11]. Voltage distributions [4], the roles of defects [9, 11], visualization of scattering centers [4, 9–11] in active CNT devices and local density of states [5] and conductivities [7] of CNTs have been investigated with these techniques. With SGM, there is mounting evidence that inhomogeneities exist in the energy band of CNTs due to local perturbations [4, 9–11], which can affect device characteristics profoundly, as recently reported [13]. Despite the importance of local potential perturbations, detailed experimental investigations are still limited.

In this paper the potential landscapes of semiconducting single-walled CNTs (SWNTs) have been investigated with SGM. SGM images of semiconducting CNTs under various back gate voltages, which control the overall band structure of CNTs, were obtained. The results clearly show inhomogeneities in the energy band structure of some semiconducting CNTs and shed light on their possible roles in the transport characteristics of devices based on semiconducting CNTs.

2. Experimental details

The SWNT devices used for this experiment were fabricated in the form of a field effect transistor (FET) with a back
gate as previously reported [14]. Either patterned or non-patterned catalysts of Fe(NO₃)₃ were prepared by depositing a substrate in the catalyst solution with an additional step of photolithography for the patterning of catalysts. SWNTs were then grown from the catalysts with thermal chemical vapor deposition for 10 min at 800 °C with 6 sccm of ethylene (C₂H₄) as a feedstock gas along with 150 sccm of Ar and 100 sccm of H₂ flow. After the CNT growth, source and drain metal electrodes were formed by patterning of electrodes with photolithography, e-beam evaporation of metals and a lift-off process. Pd electrodes without adhesion layers (or a thin adhesion layer of 2 nm-thick Cr) which are formed by e-beam evaporation were used for this experiment. A highly doped (<0.005 Ω cm) Si substrate with a 200 nm-thick SiO₂ layer also acted as a global back gate for all the devices. A commercial AFM system modified to enable simultaneous AFM and transport measurements was used for SGM measurements of the active CNT devices [15].

3. Results and discussion

An SGM image was obtained by plotting measured currents between source and drain (I_DS) at each AFM tip position with bias voltage (V_t) as it scanned over an active CNT device as schematically shown in figure 1(a) [4, 9–11]. The biased AFM tip acts as a local gate electrode on top of a CNT device during scanning and locally modifies the electrochemical potentials of the CNT [16]. This can result in the modulation of the current through the CNT if the CNT is responsive to the electric field from a globally biased AFM tip. But as the CNT device is depleted further local potentials perturbations. By taking alternate line scans of topography and SGM at a predetermined height from a device, topographic and SGM data can be drawn, as in figure 1(b). Darker areas in SGM images correspond to regions with reduced current when the AFM tip is over the area. The SGM image in figure 1(b) shows non-uniform current drops along the CNT. The current drop is small (∆I_DS ~ 20–30 nA, compared to the overall current level of ~1 μA) since the shift in the electrochemical potential of the CNT due to the biased AFM tip is only a fraction of the bias due to the small tip–CNT capacitance and the large spacing between the tip and the CNT, compared to the radius of the CNT [11, 16]. One thing to note is that strong SGM signals at the metal–CNT contacts area which are believed to be due to the Schottky barriers at the contacts are seldom seen in our devices [17]. This indicates that contacts with negligible or no Schottky barriers are formed in our devices and CNT FETs are believed to operate in a channel-controlled regime not a contact-controlled one [18].

In this case, the potential profiles of the CNT energy bands are mainly responsible for the charge transport characteristics. Some of the devices we measured show rather uniform SGM responses, especially when the device is near the on-state. However, it was found that many devices show irregularities in SGM images as in figure 1(b), which also depends on the back gate voltages.

In order to have a better look at the potential profiles of semiconducting CNTs, we took SGM images of the same semiconducting CNT at different back gate voltages. The electric field from the global back gate shifts the energy bands of the whole CNT with respect to the Fermi level of the metal electrode, putting the CNT in different depletion states. When a back gate voltage is applied during a whole SGM measurement, which typically takes about 10 min, the current (I_DS) drifts by about 10% due to the hysteresis effect. In order to minimize the current drift during scanning, the back gate voltage is applied to the device only during the SGM line scans by synchronization with the line scan signal of the AFM. A series of SGM images taken in this way is shown in figures 2(c)–(e) for a semiconducting CNT (length = 18 μm, diameter = 2.1 nm, see figure 2(a)), corresponding to three different depletion states of the semiconducting CNT as marked by arrows in its transfer characteristics in figure 2(b). The transfer characteristic shown in figure 2(b) indicates that this semiconducting CNT is a p-type one, typical for semiconducting CNTs in ambient conditions. The same tip bias voltage (V_t = 5 V) and tip–CNT distance (lift height of 30 nm) were used for all the SGM images in figures 2(c)–(e). At V_BG = −5 V (corresponding I_DS ~ 120 nA) in figure 2(c), the SGM signal is almost uniform with current changes of 3–4 nA along the whole CNT due to local gating effects of the biased AFM tip. But as the CNT device is depleted further with V_BG = 0 V (corresponding I_DS ~ 80 nA) in figure 2(d), several dark spots showing larger current drops start to appear (the spot with the largest current drop indicated by an arrow in figure 2(d) corresponds to a current change of ~20 nA). The trend becomes more obvious as the device is near the off-state with V_BG = 2 V (corresponding I_DS ~ 40 nA) as shown in figure 2(e). On this image, the spot showing the largest SGM response (indicated by an arrow) corresponds to a current change of ~32 nA, while other parts of the CNT (between strong spots) show rather small and homogeneous current drops of 4–5 nA. The presence of several dark spots in the SGM images implies an inhomogeneous potential profile in the CNT, as schematically shown in figure 3. For the schematic band diagrams in figure 3, only the valence band of the CNT is drawn since it is relevant for the hole transport in the p-type semiconducting CNT as in this case, and the contacts between Pd electrodes and the CNT are assumed to be ohmic. The applied source–drain bias voltage (10 mV) is assumed to be small enough not to affect the energy band significantly. The dark spots in SGM images are believed to originate from local potential perturbations in the form of potential wells along
Figure 2. (a) An AFM topographic image of the CNT FET. (b) Transfer characteristics of the CNT FET in (a) with bias voltage of 10 mV. SGM images simultaneously obtained with (a) at different back gate voltages \( V_{BG} \) of (c) \( V_{BG} = 5 \) V, (d) \( V_{BG} = -5 \) V, (d) \( V_{BG} = 0 \) V, and (e) \( V_{BG} = 2 \) V. Corresponding device states for each SGM image is marked in (b) by arrows. Arrows in (d) and (e) point at the same spot with the largest current drop in each image. Defects 1–3 are marked in (e) (see text). The scale bars are 2 \( \mu m \).

Figure 3. Schematic energy band diagrams of the CNT in figure 2 when the device is near (a) the on-state \( (V_{BG} < 0 \) V) and (b) the off-state \( (V_{BG} > 0 \) V). Inhomogeneities in the energy bands are represented as a series of potential wells with different depths, and local depletions by a positively biased AFM tip are represented as dotted lines in both schematic diagrams. \( E_v \) denotes the valence band edge and \( E_F \) denotes the Fermi level.

The significant role of the local potential well on the device characteristics near the off-state can be seen in figure 4. In figure 4(a), an SGM image is taken while the device is almost at the off-state \( (I_{DS} < 1 \) nA) with \( V_{BG} = 4 \) V with a negative tip voltage \( V_t = -5 \) V. The negative tip voltage up-shifts the local potential well as shown in figure 4(b). If the energy band of the whole CNT is responsible for the current modulation (that is a barrier for the hole transport as a whole), increasing a local electrochemical potential would not result in an increase in the current level. The SGM image in figure 4(a) shows a bright spot at the same position where strong SGM
Figure 4. (a) An SGM image of the CNT FET in figure 2 at $V_{BG} = 4$ V with $V_t = -5$ V. The scale bar is 2 μm. (b) A schematic representation of the energy band of the CNT with a negatively biased AFM tip when the back gate voltage is near the threshold voltage ($V_{th}$) of the device. The local lifting of a potential well by a negatively biased AFM tip is represented as a dotted line.

responses were found in figures 2(d) and (e), and they are all marked by arrows in each image. This implies that the device could be got out of the off-state (the brightest spot in figure 4(a) corresponds to $I_{DS} \sim 10$ nA while $I_{DS} < 1$ nA on the background) when a negatively biased tip is over the spot, which indicates that this spot is responsible for the transport characteristics of the device near the off-state. Therefore, it is believed that a local potential well such as in figure 4(b) dominates the transport characteristics near the off-state (linear and subthreshold region). The presence of these potential wells can partially explain the wide variances in device parameters in semiconducting CNT FETs as reported in the literature [13]. The origin of these potential wells is not clear at present. It is believed to be from defects on CNTs [19] or charge traps in nearby oxides, which change the local electrostatic environments of semiconducting CNTs.

4. Conclusions

Inhomogeneities in the potential landscapes of semiconducting CNTs are elucidated with SGM at different back gate voltages. In some semiconducting CNTs, local areas which strongly respond to the gate voltage are found and these are believed to significantly affect the transport characteristics of semiconducting CNTs, especially near the off-state. These results underscore the importance of control and further characterization of these local perturbations for better understanding of nanoscale electronic devices such as CNTFETs.

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References