Electronic Transport Characteristics of a Single Wall Carbon Nanotube Field Effect Transistor Wrapped with Deoxyribonucleic Acid Molecules

J S Hwang, H T Kim, H K Kim, M H Son, J H Oh, S W Hwang and D Ahn

1Center for Quantum Information Processing and School of Electronics and Computer Engineering, University of Seoul, Seoul 130-743, Korea
2Research Center for Time Domain Nano-functional Device and School of Electronic Engineering, Korea University, Seoul 136-701, Korea

E-mail: swhwang@korea.ac.kr; dahn@uos.ac.kr

Abstract. A SWCNT-FET device wrapped with DNA molecules was fabricated and the electronic transport properties were investigated. The gate modulated current-voltage characteristics of a bare SWCNT-FET device showed a p-type conduction behavior, which was consistent with generally characteristics in previous studies. However, the characteristics of the DNA-wrapped SWCNT-FET showed clear staircase structures. In addition, the conduction type was changed from p-type to n-type and the transconductance of the DNA-wrapped SWCNT-FET became smaller than that of the bare SWCNT-FET. All these observations provided the evidences of DNA wrapping on the surface of SWCNTs. Especially, the observed type conversion was interpreted as a result of oxygen transport from the surface of SWCNT to DNA molecules across the SWCNT-DNA interface.

Introduction

Combined systems of single-walled carbon nanotubes (SWCNTs) and deoxyribo nucleic acid (DNA) molecules have attracted much attention recently, in view of practical nano device/sensor applications as well as fundamental scientific research interests [1, 2]. Both SWCNTs and DNAs have the same one-dimensional, nanometer-diameter wire structures, and the surface electrical charge of these two materials makes it easy for them to interact with each other [3, 4].

Recently, Zheng et al. demonstrated that wrapping single stranded DNA molecules around SWCNTs produces stable aqueous suspensions with high concentration of individual nanotube [5]. These authors also demonstrated that a specific DNA molecular sequence allowed preferential separation of metallic and semiconducting nanotubes. Meng et al. investigated the interaction of individual DNA nucleosides with a SWCNT in the presence of external gate voltage, to obtain electrical identification of DNA sequences [6]. Furthermore, optical characterization of SWCNTs wrapped by DNA molecules was studied to investigate the effects of DNA and SWCNT molecular interactions [7-9].

However, so far, the effects of DNA molecules on the electronic transport characteristics of SWCNTs have remained unexplored. In this work, we fabricated a SWCNT field effect transistor.
(FET) where the SWCNT was wrapped with single stranded DNA molecules and investigated the electronic transport properties of the fabricated DNA wrapped SWCNT-FET.

Experiments
We used DNA molecules consisting of 60 base pairs of poly(dG) (Cosmo Genetech) [10] and HiPco SWCNTs (Carbon Nanotechnologies). The length and diameter of DNA were around 20 and 1 nm respectively. DNA molecules were diluted with deionized water to the concentration of 25 μM. Purified SWCNTs with the weight of 0.1 mg were suspended in 0.3 ml of the DNA solution and this ratio is equivalent to approximately one hundred DNAs for one SWCNT. Because the maximum length and diameter of SWCNT are around 1 μm and 1 nm respectively, the number of DNA is enough to wrap the SWCNTs in the solution. The mixture was sonicated for 1 hour at room temperature for complete hybridization (and wrapping) of SWCNTs with DNAs [5].

The SWCNT-FET devices were fabricated by using conventional e-beam lithography and lift-off processes. A 200-nm-thick Al gate layer was sandwiched in between 100-nm-thick top and bottom SiO₂ insulating layers on a Si wafer. Synthesized DNA-wrapped SWCNT solution was coated on the top insulating layer. Parallel Ti/Au electrode patterns with the gap of 1 μm were fabricated on the DNA-wrapped SWCNTs to form source and drain electrode contacts. Finally, the surface was rinsed with deionized water and dried to remove residual DNA wrapped SWCNTs.

Electronic transport properties of the fabricated DNA-wrapped SWCNT-FET were measured by a semiconductor characterization system (Keithley 4200-SCS) at room temperature. A monitor SWCNT-FET without DNAs was fabricated on the same substrate and simultaneously measured.

Discussion
Figure 1 shows typical electronic transport properties of the SWCNT-FET without DNA wrapping. The source-drain bias (V_{sd}) were in the range from -3 to +3 V and the gate bias (V_{g}) was in the range from -10 to +10 V with 5 V steps. The gate leakage current of SWCNT-FET devices was less than 100 pA.

![Figure 1](image-url)
The source-drain current ($I_{sd}$) is almost linear and is decreased by the increase of $V_g$. This corresponds to the p-type conduction behavior, which is normally observed in previous SWCNT-FETs [1,11-13]. The observed change of $I_{sd}$ by $V_g$ at 3V of $V_{sd}$ was approximately one order, and it is also consistent with the previous study [11]. The $I_{sd}$-$V_{sd}$ curves show almost linear characteristics. It suggests that the quality of the ohmic contact between the SWCNT and the metal electrodes is acceptable. The inset in Fig. 1 shows a schematic diagram of the SWCNT-FET.

The electronic transport properties of the DNA-wrapped SWCNT-FET are shown in Fig. 2. The inset in Fig. 2 also shows a schematic diagram of the DNA-wrapped SWCNT-FET. There are three major differences between the $I_{sd}$-$V_{sd}$ curves of the SWCNT-FET with DNA and those of the SWCNT-FET without DNA wrapping. First of all, from the shape of $I_{sd}$-$V_{sd}$ curves, we observe clear staircase structures which are usually obtained from direct electrical transport through DNA molecules [2, 14]. The transport properties of the SWCNT-FET without DNA wrapping exhibit an almost linear $I_{sd}$-$V_{sd}$ curve as shown in Fig. 1. The observed staircase structure in the $I_{sd}$-$V_{sd}$ curves strongly suggests that the charge transport occurs simultaneously through SWCNT and DNA in the DNA-wrapped SWCNT-FET.

Secondly, the value of $I_{sd}$ is increased by the increase of $V_g$ in the DNA-wrapped SWCNT-FET. This is the n-type behaviour and it indicates that the conduction type of the SWCNT was changed from p-type to n-type after DNA wrapping. In the case of semiconductor nanowires, such type conversion was usually occurred by the doping control [12]. However, in the case of SWCNTs, it is known that the adsorption/desorption of oxygen molecules occurs around SWCNTs. It is reported that the origin of the p-type properties is due to the oxygen molecules adsorbed on the surface of SWCNTs, which shifts the Fermi level towards the valence band edge [13]. Both SWCNTs and DNAs have negative surface charges. It implies that the oxygen molecules may shift from the SWCNT surface to DNAs at the SWCNT-DNA interface during the wrapping process. As a results, oxygen desorption by DNA wrapping process changes the conduction type of SWCNT-FET devices to the n-type. It was reported that the wrapping process created pi-orbitals between the DNA bases and the carbon atoms in the SWCNT [6]. Such binding process will change the amount of charge in the DNA and the electron density in the SWCNT is determined both by the amount of desorbed oxygen and by the amount of
decreased surface charge in the DNA. The observed smaller current level in Fig. 2 directly shows that the electron density is smaller than the original hole density.

Third, the transconductance of the DNA-wrapped SWCNT-FET became smaller than that of the monitor SWCNT-FET without DNAs. The DNA wrapping could provide screening of the electric fields from the gate. There are DNAs underneath the SWCNTs, since the wrapping process was performed before SWCNTs are scattered on the substrate. All these observations are consistent with the scenario of DNA wrapping around SWCNT surfaces.

Recently, we reported the electronic transport properties of a DNA conjugated SWCNT-FET device [15]. In our previous study, the DNA conjugation was performed by poly(dC) DNA solution drop on the already fabricated SWCNT-FET for 1 min. It is contrasting to the present study where DNA conjugation was performed before the fabrication of FET. It was observed that the $I_{sd}$ at the same $V_{sd}$ and $V_{g}$ bias condition was decreased by approximately half of the $I_{sd}$ measured before conjugation [15]. However, the type conversion was not observed in the previous study, suggesting that the level of conjugation was weaker than this work.

Summary
We reported the electronic transport through a SWCNT-FET device wrapped with DNA molecules. The gate modulated $I_{sd}$-$V_{sd}$ characteristics of the DNA-wrapped SWCNT-FET exhibited an n-type behaviour with clear staircase structures. In addition, the transconductance of the DNA-wrapped SWCNT-FET became smaller than that of the bare SWCNT-FET. The type conversion was explained by the movement of oxygen molecules from the SWCNT surface to DNAs. The staircase structures were due to the parallel conduction through the DNAs, and the smaller transconductance was due to the screening by the DNAs wrapping the SWCNTs. All these observations could provide evidences of DNA wrapping on the surface of SWCNTs.

Acknowledgement
This work was supported by BK21 program, and through (KOSEF) grants funded by MOST (No. R16-2007-007-01001-0 and R17-2007-010-01001-0).

References
[1] Tans S J, Verschueren R M and Dekker C 1998 Nature (London) 393 49-52
[2] Hwang J S, Kong K J, Ahn D, Lee G S, Ahn D J and Hwang S W 2002 Appl. Phys. Lett. 81 1134-1136
[3] Ago H, Azumic R, Ohshimab S, Zangheb Y, Katauraib H and Yumurab M 2004 Chem. Phys. Lett. 383 469-474
[4] Heim T, Melin T, Deresmes D and Vuillaume D 2004 Appl. Phys. Lett. 85 2637-2639
[5] Zheng M, Jagota A, Semke E D, Diner B A, Mclean R S, Lustig S R, Richardson R E and Tassino G 2003 Nature Materials 2 338-342
[6] Meng S, Maragakis P, Papaloukas C and Kaxirias E 2006 Nano Lett. 7 45-50
[7] Chou S G, Ribeiro H B, Barros E B, Santos A P, Nezich D, Samsonidze Ge G, Fantini C, Pimenta M A, Jorio A, Plentz Filho F, Dresselhaus M S, Dresselhaus G, Saito R, Zheng M, Onoca G B, Semke E D, Swan A K, Unlu M S and Goldberg B B 2004 Chem. Phys. Lett. 397 296-301
[8] Fantini C, Jorio A, Santos A P, Peressinotto V S T and Pimenta M A 2007 Chem. Phys. Lett. 439 138-142
[9] Wang X, Liu F, Andavan G T S, Jing X, Singh K, Yazdanpanah V R, Brueque N, Pandey R R, Lake R, Ozkan M, Wang K L and Ozkan C S, 2006 small 11 1356-1365
[10] Website: http://www.bioneer.co.kr
[11] Martel R, Schmidt T, Shea H R, Hertel T and Avouris Ph 1998 Appl. Phys. Lett. 73 2447-2449
[12] Derycke V, Martel R, Appenzeller J and Avouris Ph 2002 Appl. Phys. Lett. 80 2773-2775
[13] Kamimura T and Matsumoto K 2005 J. Appl. Phys. Lett. 44 1603-1605
[14] Porath D, Bezryadin A, Vries S de and Dekker C 2000 Nature (London) 403 635-638
[15] Hwang J S, Kim H T, Son M H, Oh J H, Hwang S W and Ahn D Physica E in print