DNA-FET using carbon nanotube electrodes

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Abstract. We demonstrate DNA field effect transistor (DNA-FET) using multiwalled carbon nanotube (MWNT) as nano-structural source and drain electrodes. The MWNT electrodes have been fabricated by focused ion-beam bombardment (FIBB). A very short channel, approximately 50 nm, was easily formed between the severed MWNT. The current-voltage (I-V) characteristics of DNA molecules between the MWNT electrodes showed hopping transport property. We have also measured the gate-voltage dependence in the I-V characteristics and found that poly DNA molecules exhibits p-type conduction. The transport of DNA-FET can be explained by two hopping lengths which depend on the range of the source-drain bias voltages.

1. Introduction
At present, the application of DNA in electronic nano-devices is attracted attention in the nanotechnology research. Many research groups are studying the electrical properties of DNA molecules and artificial nanostructures as nano-gap electrodes [1-4]. DNA is one of the most promising molecules for use in molecular nanotechnology and nano-electronics. Moreover, electronic nano-devices can serve as a major part of chemical and biological sensors in which detection can be monitored electrically [5-9]. On the other hand, carbon nanotubes (CNTs) are also proposed as a candidate transducer material for application of biosensors [10, 11]. For one of the implementations of CNT arrays, an ultrahigh sensitivity biosensor is created to have a selective sensitivity based on chemical properties [12].

Here, we propose DNA field effect transistor (DNA-FET) using metallic multiwalled CNT (MWNT) electrodes as nano-scale source and drain electrodes as shown in Fig. 1(a). This proposition is one of industrial interests from the point of view of fabrication strategies for the application of flexible and electronic nano-organic devices based on CNTs. In this study, we have fabricated and measured DNA-FET using MWNT electrodes by use of a standard semiconductor nano-fabrication technique. Since the FET performance can obtain an interesting result, we will report herein.

2. DNA-FET fabrication

2.1. MWNT electrodes fabrication
The MWNTs studied here were provided by Vacuum Metallurgical Co., Ltd. (diameter of about 50 nm), which was obtained by the arc discharge method, and dispersed in a solvent. Firstly, the solution containing MWNT was dispersed on a Si wafer having a SiO₂ surface layer (500 nm) using the spinner. The electrical contacts were fabricated using Ti/Au pads (15 nm / 65 nm) and a lift-off process that used a high alignment photolithography system. The distance between the Ti/Au pads was 7-8 μm. Secondly, MWNT were processed by focused ion-beam bombardment (FIBB), as shown in Fig. 1(b). The FIBB has been carried out at the central part of the MWNT. It was performed with FIB system (JFIB-2300, JEOL) using a Ga ion beam. After the FIBB, very short channel, approximately 50 nm, was easily formed, as shown in Fig. 1(c). This structure corresponds to two closely spaced nano-scale source and drain electrodes. No conductivity was observed between the source and the drain electrodes before placing DNA molecules. We prepared two samples (sample A and B) by the same method described above.

![Figure 1](image1)

**Figure 1.** (a) The schematic illustration of a DNA-FET using metallic MWNT lead-wires as source and drain electrodes. (b) A schematic shows the fabrication of MWNT electrode by use of FIBB. (c) SEM image of the MWNT electrodes whose spacing is about 50 nm.

### 2.2. Placing DNA molecules as p-channel material

The employed DNA was poly (dG)-(dC) DNA molecules containing identical base pairs produced by Amersham Pharmacia Biotech. The electrical transport properties of the DNA molecules are relatively well explained by the polaron hopping model [3, 13, 14]. Moreover, the poly (dG)-(dC) DNA molecules behaves as a p-type semiconductor [3]. It has been assumed that the contribution of the charge transport is arisen from a G radical cation to a G-rich sequence. The DNA molecules have been placed between the MWNT electrodes by electro-magnetic trapping method [26] in the case of Sample A. We soaked sample A in a dilute DNA solution about 1mg/ml and applied radio frequency waves between source and drain electrodes at 2 MHz radiation (see Fig. 2(a)). In this way, several DNA molecules were trapped between the MWNT electrodes as shown in SEM image of Fig. 2(b). On the other hands, sample B were soaked in a dilute DNA solution without supplying radio waves (see Fig. 2(a)). In the result of SEM observation of sample B, however, we could find almost no DNA molecules. After soaking these two samples, they were dried in vacuum by pumping and were measured the transport properties using a high-resolution electrometer (Keithley 6517).

![Figure 2](image2)

**Figure 2.** (a) The DNA molecules were placed between the MWNT electrodes by electro-magnetic trapping method on Sample A. Sample B were soaked in a dilute DNA solution without supplying radio waves. (b) The SEM image of trapped DNA molecules between MWNT electrodes on sample A.
3. Experimental results

$I-V$ characteristics of sample A and B were studied at room temperature (≈297 K). The electron transport measurements have been carried out in vacuum for all cases. The vacuum was about $1.0 \times 10^{-5}$ torr. The black line in Fig. 3(a) shows the $I-V$ curve of sample A. The source-drain voltage was swept from –20V to 20V. The $I-V$ curve clearly shows a nonlinear dependence. In the case of sample B, no conductivity was observed so that it did not trap a number of DNA molecules. Fig. 3(b) indicates the $dI/dV$ characteristic.

In order to discuss the $I-V$ characteristic of sample A, we carried on curve fitting based on small polaron hopping model [3] in the range of –20V to 20V as shown in the doted line of Fig. 3(a). The hopping distance can be estimated to be 3.8 Å at room temperature. It is almost corresponding to the distance between general base pairs (~3.4 Å). In Fig. 3(b), we also carried on same curve fitting in the range of –10V to 10V for the experimental date as shown in Fig. 3(a). In this case, the hopping distance can be estimated to be 9.08 Å. It could be assumed that the hopping transport mechanism is different between high and low bias voltage regions.

![Figure 3](a) The solid curve is $I-V$ characteristic of sample A. Doted curve is the calculated one based on the small polaron hopping model [3] in the range of –20V to 20V. The activation energy was referred from Ref. 3 in this study. (b) Doted curve is the calculated one in the range of –10V to 10V. (c) The $d^2I/dV^2$ characteristic of sample A is plotted and there exist two kinds of differential feature with a boundary around 10V or –10V.

![Figure 4](a) $I-V$ curves of sample A measured for subtracted current using negative or positive back-gate voltage ($V_g$) for sample A. The inset is the schematic diagram of electrode arrangement for gate-dependent transport experiments. The symbol of $I_{V_g(20)}$ in (a) stands for the measured current at $V_g = 20$ V. (b) The net current of $I_{V_g(-20)} - I_{V_g(20)}$ has been plotted as a current $I$ and around 12 V polarity is clearly changed.

Moreover, sample A has been examined the back-gate voltage dependence of the measurement current by subtracting the zero-gate-voltage current from each negative or positive one. At the high bias voltage region (above 12 V), the subtracted current seems to cause a small depletion when a
positive \( V_g \) is applied and a slight enhancement when applying a negative \( V_g \) is applied, so therefore, it implies that poly \((dG)\)-poly \((dC)\) DNA molecules act as a \( p \)-type semiconductor. Fig. 4(b) shows two curves for the subtracted current, \( I \) vs. drain voltage, \( V \), measured at room temperature with a negative or positive back-gate voltage, \( V_g = 20 \) or \(-20 \) V, for sample A. This supports the assumption that there are many positive charge carriers in \( G \)-rich sequences of poly \((dG)\)-poly \((dC)\) DNA molecules. However, there also exists a threshold bias on the source drain voltage near the value of 12 V in Fig. 4(a). In Fig. 4(b), the component of \( I_{V_g(-20)} - I_{V_g(20)} \) below 12 V in Fig. 4(a) is altered. It is converted to absolute values. Considering the threshold bias, the carrier transport mechanism is also different between high and low bias voltage regions.

4. Conclusion

We have proposed DNA-FET using metallic MWNT electrodes as nano-scale source and drain electrodes. 50nm gap between MWNT electrodes was easily fabricated by FIBB process. The poly \((dG)-(dC)\) DNA molecules as \( p \)-channel material have been placed in the gap by electrostatic trapping method. In the electron transport properties of the DNA molecules, the hopping distance can be estimated 3.8 Å at the high bias voltage region (\( > 12 \) V). It is similar to a distance of base pairs in the poly \((dG)-(dC)\) DNA molecules. This confirms that the current seems to actually flow through the employed DNA molecules. However, at the low bias region (\( < 12 \) V), the hopping distance changed as longer (9.08 Å). On the other hands, the results in the gate-voltage dependence of the \( I-V \) characteristics showed that poly \((dG)-(dC)\) DNA molecules have a threshold bias voltage near the value of 12 V but exhibit \( p \)-type conduction as well as previous theoretical mode [13, 13, 14]. Therefore, we may conclude that an intrinsic direct transport measurement of DNA molecules was successfully achieved using MWNT electrodes at the high bias voltage region. From the finding described above, we conclude that the DNA-FET has been successfully achieved by use of metallic MWNT electrodes as nano-structural source and drain electrodes.

For the purpose of implementing DNA-FET using CNT nano-electrodes, further progress of FET properties is needed. The results described above suggest that transport mechanism of the DNA molecules in our DNA-FET is different between high and low bias voltage regions. However, it seems this work to be worthwhile subject to investigate as trigger for the development of new flexible and electronic bio nano-devices based on CNTs and DNA.

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