Electric Transport Properties of Single-Walled Carbon Nanotubes Functionalized by Plasma Ion Irradiation Method

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***Abstract* — We report experimental results of the electric transport properties of single-walled carbon nanotubes (SWNTs) functionalized by plasma ion irradiation method, where purified SWNTs and Cs-encasulating SWNTs are used. SWNTs bundles are well dropped between source and drain electrodes of the filed effect transistor (FET) configuration. Voltage-current characteristics, gate bias dependence, and measuring temperature dependence are investigated. It is found that purified SWNTs exibit p-type semiconducting behavior. Transport measurements for Cs encapsulating individual SWNTs have also been performed, the result of which is discussed.**

***Index Terms* — Carbon, encapsulation, FETs, nanotechnology, plasma applications, semiconductor devices.**

I. INTRODUCTION

One of the most attractive candidates for next-generation electronics field is single-walled carbon nanotubes (SWNTs) because flowing current along the tubes can be controlled by an external electric field. Therefore, extensive researches concerning the application to electronic devices such as field effect transistor (FET), logic circuits, and various sensors have been reported [1-5]. Because pristine SWNTs have been found to behave as a p-type FET, which means no electron current flows even at large positive gate biases, n-type FET formation method becomes a key factor for further development of this field. Up to date, several methods such as doping or annealing have been developed in order to realize n-type FET. Among those efforts, alkali-metal doping has been utilized as a prevailing method to obtain n-type FET [6-8]. However, usual vapor deposition method used for the alkali-metal intercalation has the inherent problem of air-stability. Therefore, filling of alkali-metal into the inner space of SWNTs has been thought to be of great importance. For this reason, we have carried out an interdisciplinary experimental approach using plasma ion irradiation to make novel-structured SWNTs and recently reported for the first time on the alkali-metal encapsulation inside the SWNTs [9-11].

In this study, we present our recent experimental results concerning electric transport of not only purified SWNTs bundles but also Cs-encapsulated individual SWNT using the FET configuration.

II. EXPERIMENTAL DETAILS

SWNTs bundles produced by electric-arc discharge and Cs-filled SWNTs synthesized by plasma ion irradiation method are used in this study. The details of plasma treatment are well described in the literatures [9-11]. At first, we made SWNTs suspension in N,N-di-methylformamide (DMF) with a SWNTs density of 1.13×10^{-2} wt %. After then, supersonic treatment for 6 hrs

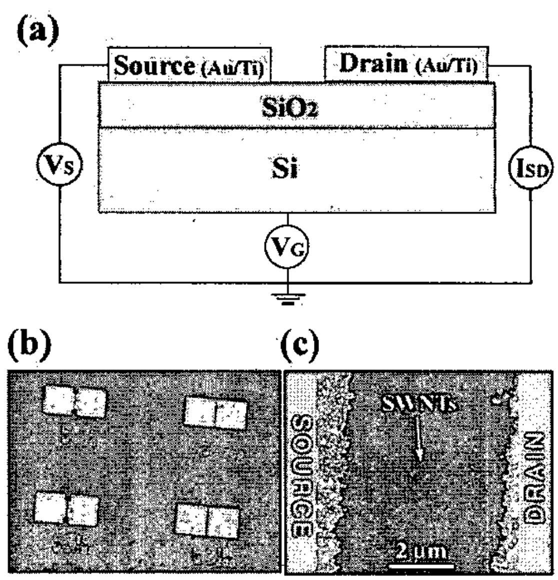

Fig. 1. (a) Schematic presentation of experimental setup, (b) SEM image of the FET configuration used in this study, and (c) SWNTs bundles dropped by spin-coater are located between source-drain electrodes (channel length 5 μm).

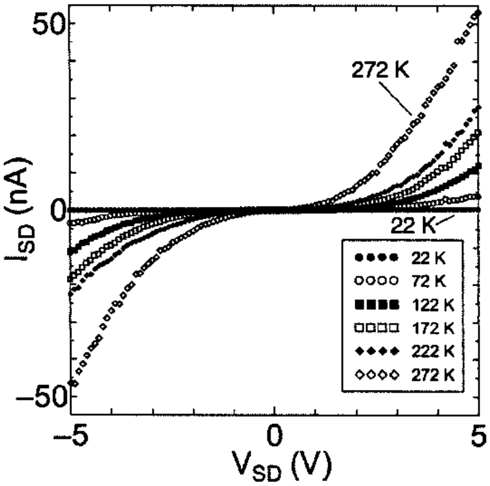

Fig. 2. Variations of I-V curves of the purified SWNT bundles with the various measuring temperatures ($V_G = 0$ V).

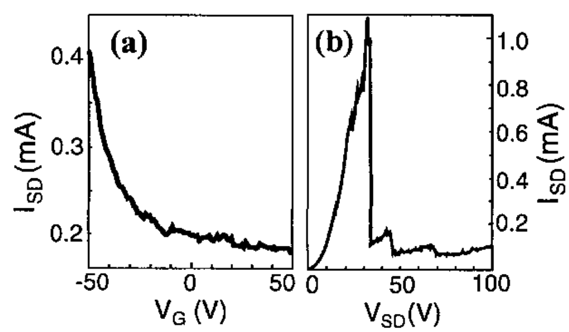

Fig. 3. (a) Source-drain current profile with the gate biases ranging from -50 to 50 V. (b) Electrical breakdown in the SWNTs bundles takes place around V_{SD} = 32 V.

was carried out in order to disperse heavily tangled SWNTs bundles. Electric transport measurements are performed using a four-point microprobe system and measuring temperatures can be down to 22 K for SWNTs bundles. Figure 1(a) shows the schematic side-view of back-gate configuration of the FET used. A scanning electron microscope image of FET structure is shown in Fig. 1(b). Sonicated SWNTs are spin-coated (2000 rpm) on the FET substrate and one of their results is given in Fig. 1(c). The SWNTs bundles are found to be bridged between source-drain electrodes made of Au by vacuum deposition.

III. Results and Discussion

Figure 2 shows the measuring temperature dependence of current (I_{SD})-voltage (V_{SD}) characteristics between the

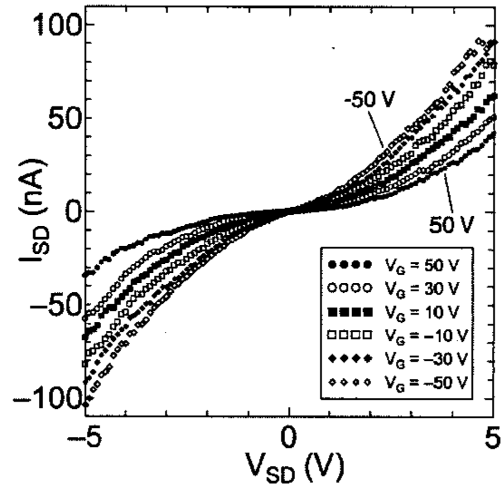

Fig. 4. Variations of I-V curves of the purified SWNT bundles undergoing electrical breakdown treatment with the various gate bias (293 K in air).

source-drain electrodes in vacuum surrounding. It is found that I_{SD} increases with increasing measuring temperatures. That is SWNTs bundles present semiconducting behavior.

After this, we have checked the relationships between gate bias (V_G) and I_{SD} at 293 K in order to investigate the polarity of semiconductor. We can clearly see the V_G dependence that I_{SD} increases with decreasing V_G as given in Fig. 3(a). From these results, we can understand that SWNTs bundles observed have the p-type semiconducting property. However, it is found that SWNTs bundles have some leak currents, which means SWNTs bundles may contain some metallic tubes. Here, we have applied electrical breakdown method [12] to preferentially burn out only metallic tubes in the bundles. The result is given in Fig. 3(b). We can clearly confirm I_{SD} drastically drops around V_{SD} = 32 V. Based on these, we can conjecture metallic tubes in the bundles are selectively destroyed by this electrical treatment. After these serial procedures, we have measured the V_G dependence of I_{SD}-V_{SD} at 293 K in air and the result is presented in Fig. 4. We have confirmed the clear gate-bias dependence and increased I_{SD} compared to the I_{SD} measured in vacuum surrounding. This increase of I_{SD} has been explained by oxygen effect [13].

Concerning the transport properties of Cs encapsulating SWNTs, their characteristics of V_G versus I_{SD} are investigated both in vacuum and air as presented in Fig. 5, where the measurements are performed at 293 K. According to the result in vacuum [(a) in Fig.5], it is found that the FET made of Cs encapsulating SWNTs has the ambipolar semi-conductor characteristic. Since the

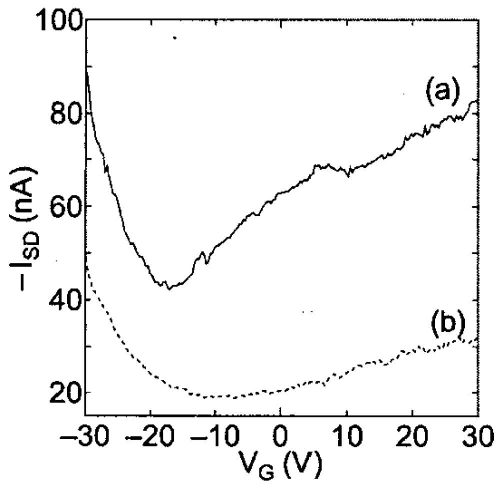

Fig. 5. V_G-I_{SD} characteristics of Cs-encapsulating SWNTs with V_{SD} = -2 V; (a) in vacuum, (b) in air.

channel region of our FET is electrically connected in parallel by both Cs encapsulating and pure SWNTs, it is conjectured that the ambipolar feature measured is caused by this structure bridged by both n-type (Cs filled) and p-type (pure) SWNTs. In the case of measuring the electrical transport property in air, on the other hand, our notice is to investigate whether the FET operates well or not. The result [(b) in Fig. 5] indicates that the value of source-drain current is quite decreased in contrast to the vacuum case. The ambipolar transport property, however, is not lost even in air. Based on this result, we can finally confirm the stability of Cs incorporated SWNTs' FET in air although the reason for current decrease is now under investigation.

IV. Conclusion

We have successfully measured the purified and Cs encapsulated SWNTs transport property under the FET configuration. It is found that the currents between the source-drain electrodes can be controlled by changing the gate bias and the charge carrier in the purified samples is hole, showing p-type semiconductor. After electrical breakdown treatments, the gate dependence of SWNTs bundles and current increase are clearly observed at ambient conditions. On the other hand the Cs encapsulating samples have the ambipolar electrical transport caused by bridging both purified and Cs filled SWNTs electrically in parallel.

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