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Barrier Formation in Carbon Nanotubes for Quantum Dot Application

Masaki SUZUKI[1, 2], Koji ISHIBASHI[1, 3], Tetsuya IDA[1] and Yoshinobu AOYAGI[1, 3]

[1] Semiconductors Laboratory, The Institute of Physical and Chemical Research (RIKEN)
2-1, Hirosawa, Wako, Saitama 351-0198, Japan
Fax:81-48-462-4659, e-mail: masuzuki@postman.riken.go.jp
[2] Department of Electrical and Electronics, Toyo University
2100, Kujirai, Kawagoe, Saitama 350-8585, Japan
[3] CREST, Japan Science and Technology (JST)

We present our experimental results on the quantum dot formation in single-wall carbon nanotubes, and make a phenomenological discussion on the barrer formation mechanism. For the controlled barrier formation, an effect of the SiO_2 deposition has been investigated, and discussed in terms of the resistance change.

Key words : quantum dot, carbon nanotubes, Coulomb blockade, coupled dots

1. INTRODUCTION

Single-wall carbon nanotubes (SWNTs) have an extremely small diameter, and could be expected for a building block of quantum-dot based nanodevices[1], [2] which could operate at higher temperatures. Recently, high quality SWNTs are available. In combination with microfabrication technology, it is now possible to fabricate electrical contacts to individual SWNTs to measure transport properties[3-5]. In this report, we present our experimental effort to fabricate the quantum dots. First, we show a result on the single quantum dot formation by depositing a metal on each side of nanotubes, then the preliminary results will be presented on the SiO_2 deposition effect on the barrier formation.

2. DEVICE FABRICATION

To measure the electrical transport of individual SWNTs, we have developed the following device fabrication process. Electrical pads (Ni/Au) for wire bonding were formed by photolithography on Si wafer with a surface SiO_2 layer. SWNTs dissolved in a solvent were dispersed on the surface by the spin coating. The position of individual SWNTs was recorded using scanning electron microscope (SEM). Source and drain electrodes (Ti/Pt) were formed on top of the nanotubes using an alignment technique in e-beam lithography and lift-off. Gate electrodes were formed near the source-drain electrodes. Figure 1 shows an example of the fabricated device. The distance between two electrodes is defined as a "gap", which has been ranging from 0.2μm to 1.3μm for our samples. The SWNTs we used in the present study seemed to be a bundle (rope) of several nanotubes from the observed width in a SEM image.

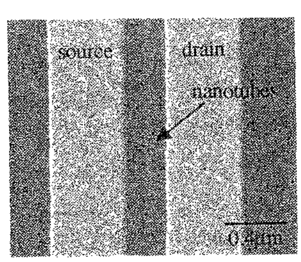

Fig.1 SEM image of the fabricated device.

To develop a controlled technique of the tunnel barrier formation, we have studied an effect of SiO_2 deposition on the nanotubes in between two metallic contacts (0.5μm gap). The thickness and the width of SiO_2 are 25nm and 100nm respectively. The change of the resistance and the current-voltage (I-V) characteristics was investigated before and after the deposition.

3. ELECTRICAL PROPERTIES AND DISCUSSION

Samples we have studied until now seem to be divided into two groups. Figure 2 shows the I-V characteristics at three different temperatures for two extreme examples of these groups. In the table, the resistance values of some samples are listed together with the resistance change by the SiO_2 deposition which will be discussed later.

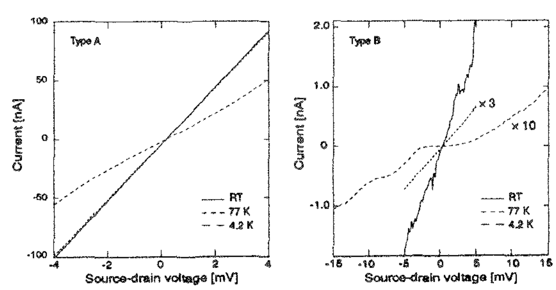

Fig.2 Temperature dependent of I-V characteristics. TypeA : sample#1, TypeB : sample#3.

Table : Resistance at room temperature and 77K. The resistance change has been observed by a factor of 2 to 30 before and after the SiO_2 deposition.

sample#	room temperature		77K	
	before	after	before	after
1	41.5 kΩ	55.9 kΩ	42.3 kΩ	60.6 kΩ
2	312.5 kΩ	10.9 MΩ	666.7kΩ	22.8 MΩ
3	3.2 MΩ	20.9 MΩ	21.7MΩ	38. 1MΩ
4	54.1 MΩ	375.6 MΩ	64.5MΩ	544.2 MΩ

The I-V curves at room temperature (RT) and 77K are linear for all samples. The resistance at RT varies very much from sample to sample ranging from several tens of kΩ to several tens of MΩ, and is difficult to control at the moment. Type "A" samples have relatively low resistance at RT, while type "B" samples have relatively high resistance. In general, the resistance increases as the temperature is decreased. The resistance change with temperature is small for type "A" samples and is large for type "B" samples. The resistance of some type "B" samples became too high to be measured. At 4.2K, the I-V curve becomes nonlinear, the degree of which is small for type "A" samples and is large for type "B" samples. Some of the type "B" samples showed Coulomb blockade characteristics with a current suppression near zero bias (Coulomb gap) as seen in Fig.2 (type"B"). These variation may arise from the uncontrolled factors such as the microscopic structure of the contact between the metal and the nanotubes, and the electronic structure of the nanotube itself which depends on the chirality and the diameter[6]. Figure 3 shows an example of the gray scale plot of the differential conductance at 4.2K for the 0.25μm contact gap device as a function of the gate voltage (V_g) and the source-drain voltage (V_{sd}). This shows the Coulomb diamond with a periodic appearance of the diamond shaped Coulomb blockade region. The estimated charging energy and the zero-dimensional level spacing are $E_c = e^2/2C_\Sigma = 8.6$meV and $\Delta E = 2.3$meV, respectively, where E_c is the charging energy for single electron, and ΔE is the mean level spacing of 0D states. These parameters depend on the length of the gap between two contacts[7].

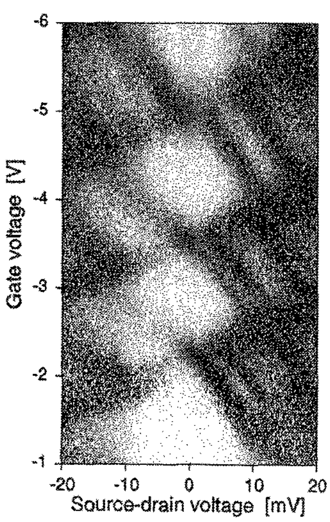

Fig.3 Gray scale plot of the differential conductance at 4.2K.

The whole nanotubes between metallic contacts seem to form quantum dots. Although the detailed mechanism of the barrier formation is not clear, the deposition of the metal on nanotubes seems to play an essential role. For some samples, the tunnel barrier formation inside nanotubes as well as at the contacts has been indicated[7]. The importance of the metal deposition is also suggested by the deposition of multi-metallic contacts on the nanotubes[5].

These results suggest that the tunnel barrier may be formed by the metal deposition on nanotubes. But, to realize the quantum mechanically coupled-dot formation, the use of metals may not be a correct choice, since an electron may tunnel into the metal where the coherence should be destroyed. With these in mind, we have tried the barrier formation by depositing an insulating material, SiO_2. As seen in the table, the resistance increase by the SiO_2 deposition was observed for most of the samples we have tested. The I-V curves were linear at RT and 77K, and became nonlinear at 4.2K. The details of the low temperature transport will be presented elsewhere. The effect of the deposition seems to be similar to that of the metal. But, again, further study is necessary to control the resistance change.

4. CONCLUTIONS

We have developed a technique to fabricate metallic contacts on individual carbon nanotubes. The low temperature transport has shown the single quantum dot formation. The results suggest that the tunnel barrier could be formed by the metal deposition. We also deposited SiO_2 on nanotubes to form the tunnel barrier, and observed the resistance increase. Although we do not understand the detailed mechanism of the tunnel barrier formation, the controlled way to do it would be possible by optimizing this technique.

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