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Observation of the spin-related even-odd effect in single-wall carbon nanotube quantum dots

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1. Introduction

Carbon nanotubes are attractive material for the building block of quantum-dot based nanodevices [1,2], because of their extremely small diameter of the order of a few nm for the single-wall nanotubes (SWNTs). The relatively long length (>1μm) makes an electrical access possible to flow current by using standard electron beam lithography. The small dot size makes the operation temperature higher, compared with sub-micron dot fabricated with standard lithography technique. Another interesting feature of carbon nanotubes is that they might be an ideal one dimensional conductor, which may suppress some kind of scatterings [3,4] and may hopefully result in a longer coherence. These unique features as a quantum dot may be useful for the single electronics, quantum computing devices, and other new functional devices.

In this paper, we present our recent experimental results on the even-odd effects which are related to the shell filling of the single electron states. The electrical measurements of a single rope of SWNTs were carried out in low temperatures above 1.8K. The Coulomb diamond measurement indicated the alternate change of the diamond size, which could be attributed to the even-odd effect. In some gate voltage range, an indication of the four fold degeneracy of the electronic state was also observed. The present experiments suggest the non-interacting electron in the present quantum dots and the presence of S=1/2 state which could be used for the spin-qubit [5].

2. Experimental Procedure

The SWNTs were dispersed on the Si wafer with a thermal oxide layer on the surface. The source-drain contacts were deposited on a single rope of SWNTs for the current flow, and the heavily doped substrate was used for the back gate. Figure 1 shows the scanning electron microscope (SEM) image of the typical device, in which Au-Ag alloy was used for the contact material. The distance between two contacts is about 370nm. From the previous results, the whole nanotubes between two contacts could form a single quantum dot [6]. The two terminal resistance at room temperature usually varies very much form sample to sample in our device fabrication process[6]. In the present device design, we could modify the resistance to some extent, by flowing the current through the metallic leads in vacuum. This may have something to do with the annealing effect, and may result in the microscopic change of the contact between the nanotubes and the metal. The details of the process will be presented elsewhere. The conductance of the nanotubes presented here decreased about 90% at room temperature as the gate bias is changed from -10V to 10V, suggesting the semiconducting tube.

The sample was set in the ^{4}He cryostat, and the current-voltage characteristics at various gate voltages (Coulomb diamond measurement), and the current at a fixed source-drain voltage (V_{sd}) were measured (Coulomb oscillation measurement) in a temperature range from 1.8 to 80K. But, we focus on the lowest temperature result in the present abstract.

3. Results and discussions

One of the samples with a reasonable resistance at room temperature (roughly about ~ 1MΩ after current annealing) was selected, and the result of the Coulomb oscillation measurement at 1.8K and V_{sd}=2mV is shown in Fig.2 (a). The periodic current oscillations due to Coulomb blockade effects are observed. The gray scale plot calculated from the Coulomb diamond measurements are shown in Fig.2 (b). The periodic modulation of the Coulomb gap, where the current is suppressed, indicates the formation of the single electron transistor (SET). The charging energy estimated from Fig.2(b) is roughly $E_c(e^2/C_\Sigma$: is the self capacitance of the dot) ≈30meV. The Coulomb blockade effect was observed up to around 80K for the present sample

We should note that the peak shape in Fig.2(a) cannot be fitted with a standard model for single electron transistor, [7] and rather can be fitted by the Lorenzian form. This fact indicates that the peak width is not determined by the Fermi level smearing at the source and drain contacts, but rather determined by the life time broadening due to the weak confinement at the barrier to the source or the drain (or both). Usually, for the sample with a similar source drain distance indicates the 0-D level spacing of the order of 10meV as lines parallel to the diamonds in the gray scale conductance mapping plot. However, it is not clear in Fig.2(b), which may be consistent with the above

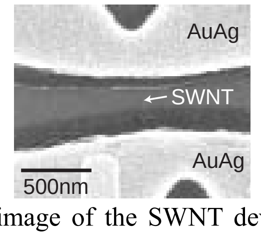

Fig. 1. SEM image of the SWNT device. Au-Ag alloy was used for the contact material. The distance between two contacts is about 370nm.

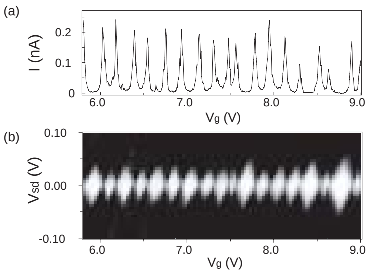

Fig. 2. (a) Coulomb oscillation measurement at 1.8K and V_{sd}=2mV. (b) The gray scale plot calculated from the Coulomb diamond measurements.

observation in Fig.2(a). Because of the fact, the present sample is relatively in the strong coupling regime.

The current of the SET flows at the gate voltages where two adjacent diamonds meet where the number electron is fixed at the single electron level. In the constant interaction (CI) model, E_c is constant, independent on the number of electrons. However, the diamond size in Fig.2(b) is not constant in the measured gate voltage range. Its size changes alternately, and in the range between V_g=7.6V and 8.3V, the diamond size changes with a period of four. These are clearly seen in Fig.3, where the gate voltage distance (ΔV_g) is plotted as a function of the peak position. In the quantum dot where the 0-D level spacing is not ignored, compared with E_c, the addition energy depends on the number of electrons in a dot, known as an even-odd effect which is recently also observed in the nanotube dot[8]. In the non-interacting electron model, the addition energy for the dot with an even number of electrons should be $E_c+\Delta E$, where ΔE is the 0-D level spacing. On the other hand, when the number of electron in the dot is odd, the addition energy is just E_c, because Nth electron can occupy the same level as (N-1)th electron with a different spin. Based on the model, ΔE can be estimated from the size difference between adjacent diamonds, and is roughly estimated in the range of 1~ 35meV. These values might be consistent with ΔE obtained from the excitation energy which appears in the gray scale plot in the sample with a similar length.

Another interesting feature of the period of 4 observed in the range between V_g=7.6V and 8.3V, as mentioned before, is related to the fourfold degeneracy at the Fermi level in the electronic band structure in carbon nanotubes. In the gate voltage range where only the even-odd effect is observed, the so called K-K' degeneracy is somehow lifted, and the gate voltage range where the fourfold degeneracy is observable appears to be limited. The further study is necessary to make clear in what condition it can be observed.

A question comes about that the even-odd effect was observable in the present experiment, even though the indication of the 0-D state was not observable in the gray scale plot of the conductance in Fig.2(b). We do not understand it correctly, but two situations may be different. As for the confinement effect observable in the gray scale plot of the Coulomb diamond, it has to do with the excited state. On the other hand, the ground state may be important for the even-odd effects.

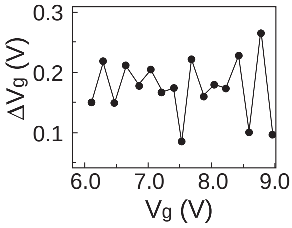

Fig. 3. The gate voltage spacing (ΔV_g) of peak position in Fig. 2(a).

4. Conclusion

The transport measurements have been carried out in a single rope of the SWNTs in the temperature range from 1.8K to 80K. The Coulomb oscillation measurement indicated that the Coulomb peak width is determined by the broadening of the quantum levels. However, the even-odd effect and the effect of the fourfold degeneracy were observed in the Coulomb diamond measurement, suggesting the importance of the ΔE and the alternate electron filling in the single electron state.

The observation of the even-odd effect indicates that the S=1/2 state for a single electron is possible. This fact may be important for the spin qubit in a quantum dot.

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