Pulse-Excited Current Measurements in Carbon Nanotube Quantum Dots

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Abstract We present experimental results on the electrical pulse-excited transport measurements of an individual single-wall carbon nanotube (SWNT) quantum dots. By applying a square pulse signal, the pulse-excited Coulomb peaks are observed in Coulomb oscillation measurements. In the SWNT quantum dot, the even-odd effect is confirmed by the alternate change of the Coulomb diamond size in the standard dc measurement. Magnetic fields perpendicular to the tube axis have revealed the simple Zeeman splitting of single particle states, this splitting is directly observed in the pulse-excited current in even-odd regime. We find the spin relaxation time at least longer than 1 μs.

1. Introduction

Electrical pulse measurements in quantum dots are useful not only to investigate an energy relaxation time of single electron states, but also to realize the future spin qubit operation. Recent electrical transport measurements in GaAs/AlGaAs semiconductor quantum dots have observed very long electron-spin relaxation time between spin-triplet and singlet states of two electrons [1], and between Zeeman sublevels of single electron [2]. On the other hand, single-wall carbon nanotube (SWNT) forms one-dimensional quantum dots because of their extremely small diameter, and may be used as a building block of extremely small quantum-dot based nanodevices [3]. The energy scales of a larger charging energy ($E_c = e^2/C_Σ$: $C_Σ$ is a self-capacitance) and a larger level spacing ($ΔE$) of zero-dimensional confined states make it possible to realize the simple one-dimensional shell structures [4], an artificial atom behavior. An important implication of these results is that the single spin-1/2 system can be easily formed in the SWNT quantum dot with the odd number of electrons, regardless of the number of electrons in the dot [5]. Therefore, to measure the electrical pulse transport in SWNT quantum dots and to determine the relaxation time of single-electron spin is important step toward the realization of the spin-qubit.

In this report, we present results on the electrical pulse-excited transport measurements of an individual (SWNT) quantum dot. Square pulse signal is applied to the gate voltage to modulate the electrostatic potential of the dot. Zeeman splitting is directly observed by the pulse-excited current in
the even-odd regime in magnetic fields. The spin relaxation between Zeeman splitting sublevels may not occur in our experimental time window, suggesting that the relaxation time be longer than 1 μs.

2. Experimental procedure

Single quantum dots were realized just by depositing metallic source and drain contacts on top of an individual SWNT [6]. The atomic force microscope was used to find position of the specific individual SWNT. The height of the measured SWNT was about 0.8 nm. The distance between the contacts was designed to be 300 nm, and a heavily p-doped Si substrate was used for application of the gate voltage. Fig.1(a) shows the schematic picture of the fabricated device and an experimental setup for the square pulse measurement. The square pulse signal was applied to the gate voltage with a low-loss coaxial cable, and all the electrical transport measurements were carried out in a dilution refrigerator at a electron temperature of $T_{\text{mix}} = 40$ mK and under magnetic fields ($B$) up to 10 T. DC current ($I$) was measured as a function of the gate voltage ($V_g$) with a small fixed source drain bias ($V_{sd}$) (Coulomb oscillation measurement), and was measured as a function of both $V_{sd}$ and $V_g$ (Coulomb diamond measurement).

3. Results and Discussion

Figure 1(b) shows the Coulomb oscillations at 40 mK without electrical pulse signals. Coulomb blockade oscillations are observed in a wide gate-voltage range without the pulse signals. The effective electron temperature, obtained by the theoretical fitting [7] of the individual Coulomb peak (Fig. 1(b) inset), is estimated to be 120 mK (~10 μeV) in the measurement. Next, pulse-excited current was measured by applying square-shaped voltage pulses to the dc gate voltage, as schematically shown in fig. 2(a). Figure 2(d) shows the pulse-excited current peaks as a function of a dc gate voltage ($V_g$) and the pulse length ($t_p$) of the high phase of the pulse at a fixed repetition time $t_r = 400$ nsec and a pulse amplitude $V_p = V_{h} − V_{l} = 20$ mV without magnetic fields. The repetition time, $t_r$ always sets much longer than the escape time of a tunneling electron from the dot. Without pulse signals, simple Coulomb oscillations are observed, but when the pulse signal is applied each dc peak split into two. Figure 2 (b) and (c) shows the schematic energy diagrams that explain the peak splitting. In fig. 2(b), electrons can flow from source and drain during the high phase of the pulse, which corresponds to the left peak (pulse-excited current). Similarly, fig. 2(c) explains the right peak of the Coulomb peak, where electron transport can occur during the low phase of the pulse.
In the measured SWNT quantum dot, two- or four-electron shell structures have been observed at different gate voltage ranges [8], which are understood by the twofold band degeneracy of a metallic SWNT in addition to the twofold spin degeneracy [9]. Here, we focus on the two-electron shell structure regime, as shown in Fig. 3 (a). The alternate change of the diamond size, which corresponds to the addition energy of the dot, is clearly observed, indicating the even-odd effect [10]. A simple model for explaining the effect is as follows. When the number of electrons in the dot is odd, the next electron can be charged in the same level with an opposite spin, so that the addition energy is only the charging energy ($E_c$). When the number is even, the next electron has to be charged with arbitrary spin in the upper shell. In this case, the addition energy is $E_c + \Delta E$. With this simple model, the addition energy changes alternately, depending on whether the number of electrons in the dot is even or odd. When the number of electrons in a shell changes from zero to one, a simple Zeeman splitting of single particle levels can be observed in the excitation spectrum [4, 5]. Figure 3 (b) shows the magnetic field evolution of typical pulse-excited current peaks when the number of electrons changes from even to odd (zero to one in a shell). Since the pulse amplitude (3 meV) is larger than the Zeeman splitting (1.2 meV at $B = 10$ T), an extra current peak which is the pulse-excited current through the upper level of the Zeeman splitting sublevels during the high phase of the pulse can be observed. The estimated Zeeman energy is equal to $g\mu_B B$ with $g \sim 2.0$, which is consistent with the result from the standard dc measurement. The pulse length dependence of the pulse-excited current peaks was investigated, as shown in Fig. 3(c). Peaks indicated by “P” and “Q” peaks correspond to the pulse-excited peaks, which indicate two Zeeman splitting sublevels. The average number of tunneling electrons per unit pulse can be calculated from $\langle n \rangle = I_l/e$ for each pulse-excited current $I$. For both peaks, $\langle n \rangle$ depends on linearly on pulse length. The peak “P”, $\langle n \rangle$, is increased linearly, as expected for the current of the ground state, however, the peak “Q”, $\langle n \rangle$, is expected to saturate due to the spin relaxation. This experimental result indicates that the spin relaxation between Zeeman splitting sublevels may not occur in our experimental time window, suggesting that the relaxation time be longer than at least 1 $\mu$s.
Figure 3. (a) A gray scale plot of Coulomb diamonds in the even-odd regime, calculated from the $I$-$V_s$ curves for different gate voltages. (b) Magnetic field evolution of the typical pulse-excited Coulomb peak from $B = 6.0$ to $10.0$ T. Each line is shifted for clarity. (c) Pulse-excited current when number of electrons changes from zero to one in a shell at $B = 8.0$ T. The pulse length corresponds to 0.5 (bottom), 0.6, ..., 1.0 μs (top) with a fixed $t_r = 2.0$ μs. Each line is shifted for clarity. Inset: The average number of tunnelling electrons per unit pulse.

The lower bound of the relaxation time may be limited by the measurement scheme. Therefore, this single-square pulse measurement is not appropriate to measure a long spin relaxation time. We need to provide the improved measurement setup to observe the longer relaxation time, i.e., double-step pulse measurement \[1\], which is one of the next targets of the experiment.

4. Conclusion
We have carried out the electrical pulse-excited transport measurements on the individual SWNT quantum dot by applying single-square pulses. Pulse-excited peaks of the single particle states in Coulomb oscillations were observed without magnetic fields, and the Zeeman splitting was directly observed by the pulse-excited current in the even-odd regime in magnetic fields. The spin relaxation time of a single-electron between Zeeman splitting sublevels was found to be longer than 1 μs.

5. Acknowledgement
This work was supported in part by the Special Postdoctoral Researchers Program of RIKEN.

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