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Multi-backgate control of carbon nanotube double quantum dot

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1. Introduction

Single walled carbon nanotubes (SWNTs) are attractive materials for the ideal one-dimensional conductors for the physics and quantum-dot studies because of their extremely small diameter of the order of 1 nm. The additional energy E_{add} of SWNTs which is determined by the energy for adding an additional electron to the dot are several tens meV. Therefore, SWNT works as the single electron transistor (SET) at high temperature.

SWNT double quantum dot devices, in which a defect of SWNT is used as the tunnel barriers to split a single SWNT into two dots, have also been demonstrated [1-4]. In these reports, the devices with multi-topgate structure were fabricated. However, SWNTs in the topgate devices are surrounded by the insulator. Therefore, it is difficult to position-selectively create defects, which act as the tunnel barriers, after device fabrication [5]. In this study, we have fabricated the multi-gate device with the backgate structure, in which SWNTs are not surrounded by the insulator. From the electric measurement of this device, double quantum dot properties are observed.

2. Experimental Procedure

A heavily doped p-type Si wafer with a thermally oxidized SiO_2 layer of 500 nm thickness was used as a substrate. Figure 1 shows (a) a schematic side view and (b) a scanning electron microscope image of the SWNT multi-backgate device. The devices are fabricated by electron beam lithography and lift-off processes. Two Mo backgate electrodes and SiO_2 insulator are deposited on the substrate by rf magnetron sputtering. The width and gap of the backgate electrodes are 300 nm. Over the gate electrodes, a SWNT is grown by chemical vapor deposition using ethanol from the Co catalyst, which is formed beside the gate electrodes. On both ends of the SWNT, source and drain electrodes of Pd metal are contacted. The gap of the electrodes is 1.2 μm. The electric properties are measured as a function of the drain-source (V_{ds}) and gate voltages at room temperature or low temperature of 1.7 K. Gate voltages are applied through the backgates of the Mo electrodes (V_{g1}, V_{g2}) and the substrate (V_{bg}). The Mo gates can modify the local charge along the length of the SWNT. The electric properties of the coupled quantum dots are measured by applying multi-backgate voltages.

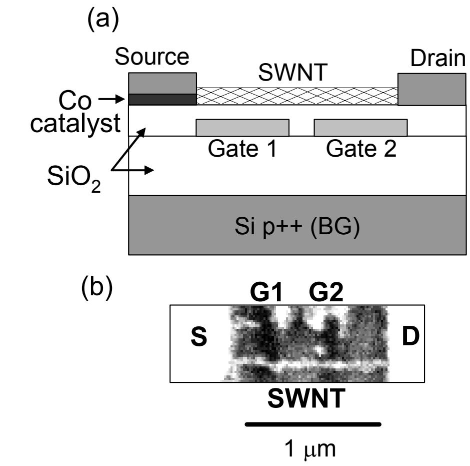

Fig. 1. (a) a schematic side view and (b) a scanning electron microscope image of the SWNT multi-backgate device.

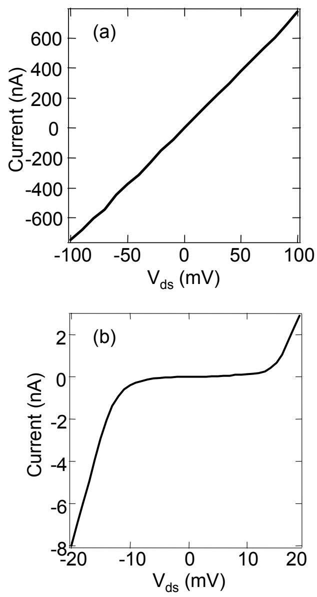

Fig. 2. I_{ds} dependence of V_{ds} at (a) room temperature and (b) 1.7 K.

3. Results and discussions

Figure 2(a) shows the current (I_{ds}) dependence of V_{ds} at room temperature. The I_{ds}-V_{ds} exhibits ohmic characteristic with resistance of 130 kΩ. On the other hand, at lower temperature of 1.7 K, nonlinear characteristic is obtained due to the Coulomb blockade (Fig. 2(b)).

Figure 3(a) shows the gate voltage V_{bg} dependence of I_{ds}. Clear peaks due to the Coulomb oscillation are observed; however, the peak positions are irregular. A gray scale plot of the differential conductance as a function of V_{ds} and V_{bg} is shown in Fig. 3(b). The Coulomb diamonds, where the current is suppressed is observed. However, around the contact points of the diamonds around $V_{ds} = 0$ V, the diamonds are hardly closed. In addition, no periodic pattern of the diamonds is observed. In general, the Coulomb diamonds of single quantum dot exhibit clearly closed and periodic pattern. Therefore, the observed result suggests the formation of multi-quantum dots[6,7].

Multi-backgate voltage dependence of I_{ds} is shown in Fig. 4(a). In this measurement, applied V_{g1} and V_{bg} were same voltage. Both of V_{g1} and V_{bg} can modulate the Coulomb oscillation. This indicates that the charge states of the multi-quantum dots in a single SWNT can be independently controlled by applying V_{g1} and V_{g2}. In Fig. 4(b), a gray scale plot of I_{ds} as a function of V_{g1} and V_{g2} is shown. Regular Coulomb peaks are observed. Moreover, the honeycomb-shaped array is observed as indicated by the white solid lines in Fig. 4(b). This honeycomb structure resembles the charge stability diagram obtained from the coupled double quantum dot [1]. Each honeycomb cell corresponds to well-defined charge configuration of the double dots. From the size of honeycomb cell (ΔV_{g1} and ΔV_{g2}), estimated gate capacitances of C_{g1} and C_{g2} are 8.9 and 1.1 aF, respectively.

4. Conclusions

We have fabricated the multi-gate device with the backgate structure, in which SWNTs are not surrounded by the insulator. From the electric measurement of this device, the double quantum dot properties are observed.

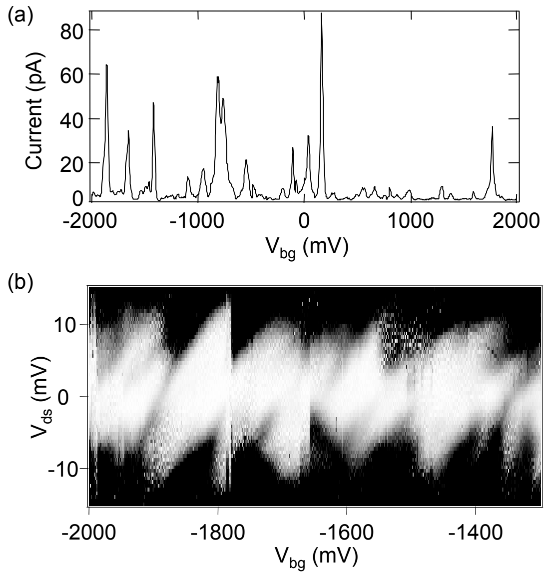

Fig. 3. (a) the gate voltage V_{bg} dependence of I_{ds} at $V_{ds} = 1$ mV. (b) A gray scale plot of the differential conductance as a function of V_{ds} and V_{bg}

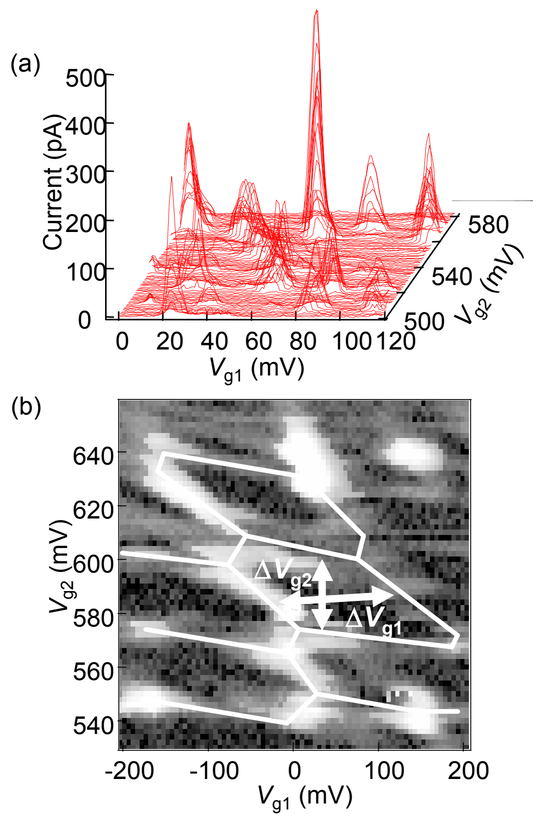

Fig. 4. (a) 3D plot of V_{g1} and V_{g2} dependence of I_{ds} at $V_{ds} = 1$ mV. (b) a gray scale plot of I_{ds} as a function of V_{g1} and V_{g2} at $V_{ds} = 1$ mV.

References

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