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Ballistic Transport of Hole in p type Semiconductive Carbon nanotube

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We have succeeded in observing the coexistence of the Coulomb charging effect and the coherent transport of the holes in the carbon nanotube of the length of 4.5μm at 8.6K.

The sample was prepared as follows. A p-type silicon wafer with a thermally grown oxide of 200nm is used as a substrate. The layered catalysts of Fe/Mo/Si (3/10/10nm) are patterned on the substrate using the conventional photo-lithography process. The distance between two catalysts for the source and drain was 4.5μm and 1.4μm. Single-walled carbon nanotube is grown between two catalysts by chemical vapor deposition using mixed gas with ethanol, hydrogen and argon. Finally, Pt/Au electrodes are deposited on the patterned catalysts for the source and drain and the back side of Si substrate for the gate. Thus, back gate type carbon nanotube field effect transistor was fabricated as shown in Fig. 1.

In the drain current-gate voltage characteristics at 8.6K, the drain current of both sample monotonously decreases with increasing the gate voltage from -10V to 10V (not shown), which indicates that the measured carbon nanotube has the p type semiconductive property.

In the smaller range of the gate voltage from 0V to 1V, the periodic drain current peaks are observed on the 4.5μm CNT sample suggesting the Coulomb oscillation peaks as shown in Fig. 2. The period of the Coulomb oscillation peaks is 150mV, from which the gate capacitance is estimated to be 1.1aF. The origin of the Coulomb charging effect is considered to be the carrier confinement in a single island because of the high periodicity of the Coulomb oscillation peaks. As carbon nanotube has the p type semiconductive property, the Coulomb charging effect occurs by the confinement of holes in the carbon nanotube. On the 1.4μm CNT sample, the similar results with the 4.5μm CNT sample are obtained (not shown). The period of the Coulomb oscillation peaks and the gate capacitance is 1V and 0.16aF, respectively.

In the Coulomb diamond characteristics at 8.6K on the 4.5μm CNT sample as shown in Fig. 3, a Coulomb gap of ~7mV is observed around zero bias voltage. The total device capacitance and the Coulomb charging energy are estimated to be 25.8aF and 3.1meV, respectively. From the Coulomb charging energy, the length of the island L_{island} is estimated to be 5.0μm, which is in good agreement with the entire length of the carbon nanotube at the channel. Hence the Coulomb charging effects occurred by the hole confinement in the whole channel of the carbon nanotube.

The periodic negative differential conductance (NDC) is observed at the outside of the Coulomb gap for higher drain voltages on both 4.5μm and 1.4μm CNT sample as shown in Fig. 4 and Fig. 5. The period of NDC: ΔV_D is ~0.4meV for the 4.5μm CNT sample and ~1.2meV for the 1.4μm CNT sample, respectively. The NDC is attributed to the resonant tunneling of hole through the quantum confinement discrete energy levels of carbon nanotube as shown in Fig. 6. From the period of NDC of ~0.4mV for the 4.5μm CNT sample, the quantum confinement discrete energy levels for hole were found to form through such a long distance of 4.5μm in p type semiconductive carbon nanotube. This fact suggests the existence of the ballistic transport of the holes in the semiconductive carbon nanotube, and its phase coherent length extends over a distance of at least 4.5μm.

We first succeeded in observing the coexistence of the Coulomb charging effect and the ballistic transport of the holes in semiconductive carbon nanotube. We also CNT length dependence of the separation of the quantum confinement discrete energies

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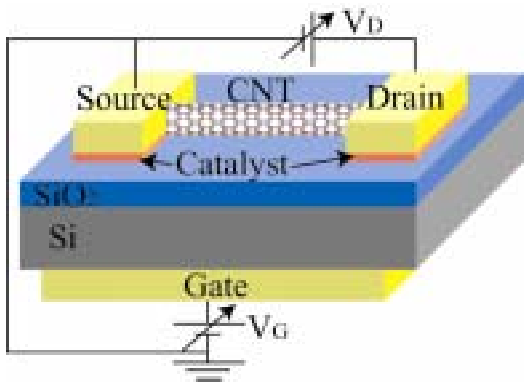

Figure 1. Schematic of carbon nanotube FET

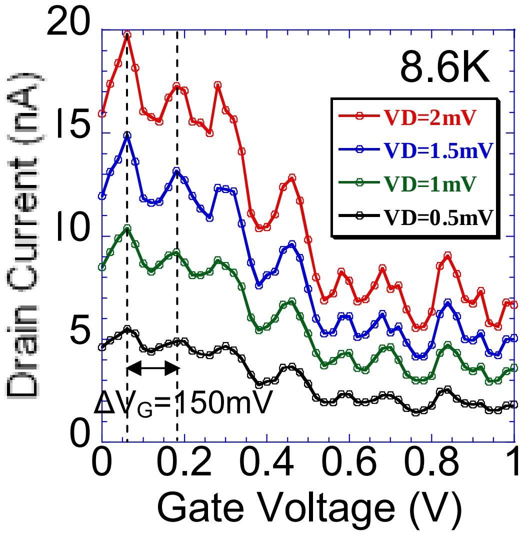

Figure 2. Coulomb Oscillation Characteristic of 4.5μm CNT

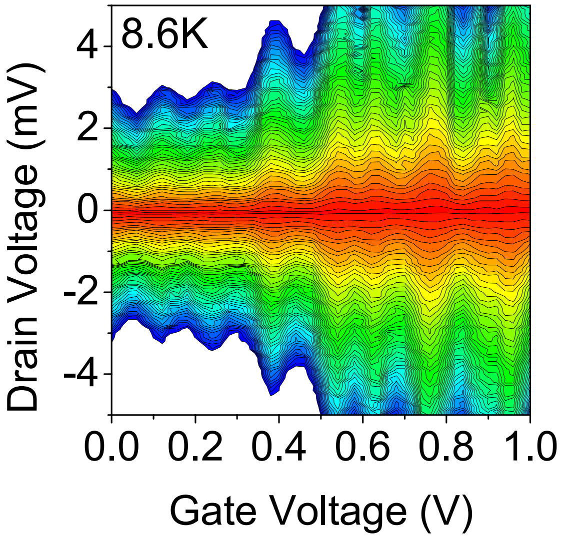

Figure 3. Coulomb Diamond Characteristic of 4.5μm CNT

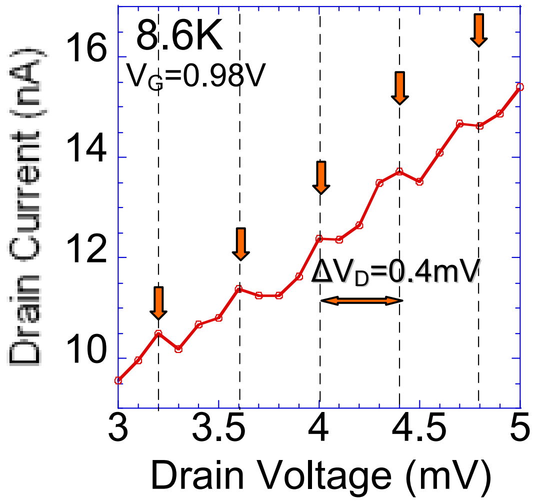

Figure 4. NDC Characteristic of 4.5μm CNT

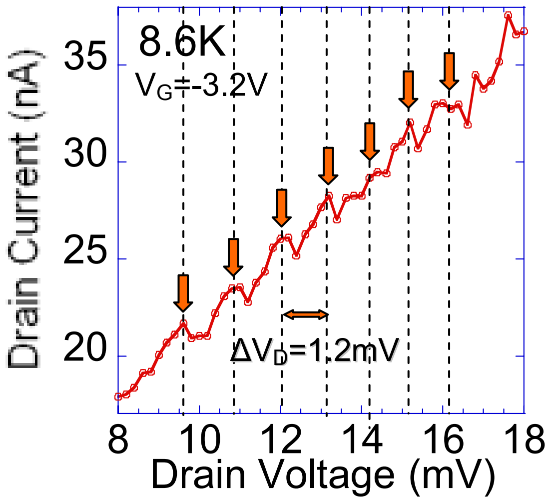

Figure 5. NDC Characteristic of 1.4μm CNT

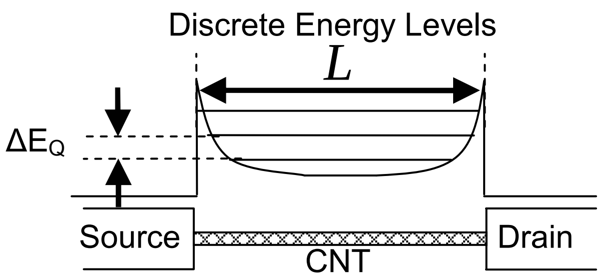

Figure 6. Quantum Energy Levels of CNT