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Conversion between particle nature and wave nature of hole in single-walled carbon nanotube transistor by gate voltage

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We have succeeded in fabricating the convertible transistor which can operate as a resonant tunneling transistor (RTT) and also as a single hole transistor (SHT) using single-walled carbon nanotube (SWNT) by modulating the strength of the coupling between the electrode and the quantum island using the gate voltage that changes the thickness of Schottky barrier, in which RTT is the device using wave nature of hole and SHT is the device using particle nature of hole.

The schematic sample structure is shown in Fig. 1. SWNT is contacted to the source and the drain electrode by Ti metal. The distance between both electrodes is 73 nm. The gate electrode is in the back side of Si substrate. SWNT is completely purified.

Contour plot of differential conductance characteristic as a function of gate voltage and drain voltage at 7.3 K is shown in Fig. 2. When the gate voltage V_G is relative low as shown in Fig. 2 (a) (V_G=-10 V to -15), the plot clearly shows the Coulomb diamond characteristic. Additionally, line shape quantum levels are appeared at both sides of Coulomb diamonds. The Coulomb diamonds are getting blurred with negatively increasing gate voltage as shown in Fig. 2 (b) (V_G=-15 V to -20 V). The quantum levels are still remaining. Finally, at relative high gate voltage as shown in Fig. 2 (c) (V_G=-20 V to -25 V), Coulomb blockade is lifted and Coulomb diamonds are disappeared. However, quantum levels are still remaining. Differential conductance characteristic as a function of gate voltage at 7.3 K is shown in Fig. 3. Coulomb blockade regions indicated by arrows are observed at relative low gate voltage region. Quantum levels are observed at relative high gate voltage region. Insets show the Coulomb oscillation and the resonant tunneling current oscillation in the liner scale. The transition from Coulomb blockade region to resonant tunneling region is attributed to the Schottky barriers at the contact between SWNT channel and electrodes [(1)]. Thickness of the Schottky barriers can be modulated by gate voltage as shown in schematic figures of inset of Fig. 2. When the thickness of the Schottky barriers is thick enough to confine hole, the device operate as SHT. When the thickness of the Schottky barrier is too thin to confine hole, the device operate as RTT. In the case of thin tunneling barrier, overlap of hole wave functions of pre-tunneling and post-tunneling is very large and inhibition of tunneling dose not occur. Therefore, condition of $R_t >> h/4e^2 \equiv R_Q$, where R_t is the tunnel resistance and R_Q is the quantum resistance, is required to observe the Coulomb blockade.

Full-width at half maximum (FWHM) of quantum oscillation peaks as a function of gate voltage is shown in Fig. 4. Inset is the quantum oscillation peaks V_G=-12.85 V with FWHM of 30 mV. FWHM of quantum oscillation peak is proportional to tunneling probability [(2)] and increases with negatively increasing gate voltage. That means tunneling probability also increases with negatively increasing gate voltage. Therefore, the Coulomb blockade becomes weaker at the high gate voltage region.

The separation of quantum energy levels as a function of gate voltage, estimated from the differential conductance characteristic on gate voltage is shown in Fig. 5, which shows almost constant value. Inset shows the separation of quantum energy levels as a function of drain voltage, which is ΔV_D=26 mV. Separation of quantum energy levels is indicated by $\Delta E_Q = (h\nu_F/2L)\left[1+(2L/3rn)^2\right]^{-1/2}, (n=1,2,3\cdots)$ (1), where the L is length of quantum island and r is the radius of SWNT [(3)]. When n becomes large, the equation becomes $\Delta E_Q = h\nu_F/2L$ (2) and shows constant value independently of n. ΔV_D=26 mV is in good agreement with the estimated value of the separation of quantum energy levels from the eq. (2) of ΔE_Q=24 mV. Almost constant peak separation in Fig. 5 on gate voltage is also coincided with the eq. (2).

The drain current I_D in logarithm scale as a function of inverse of temperature is shown in Fig. 6. At V_G=-38 V, I_D is almost constant independently on temperature. In this region, the Schottky barrier is so thin that the tunneling current becomes dominant. On the contrast at V_G =-10 V, I_D is drastically increases at high temperature region, and the estimated Schottky barrier height from the slope is $\Delta\phi$ =50 mV. In this region, the Schottky barrier is so thick and the thermal emission current becomes dominant. These results mean that tunneling probability at the Schottky barriers is modulated by the applied gate voltage.

We have succeeded in fabricating the convertible transistor between RTT and SHT using SWNT. The device can be converted from SHT to RTT by gate voltage, in which hole express particle nature and wave nature, respectively.

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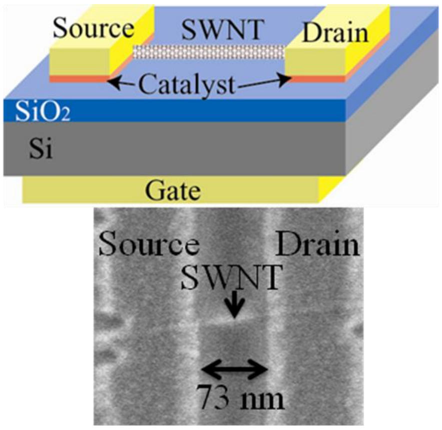

Fig. 1 Schematic sample structure and SEM image around channel.

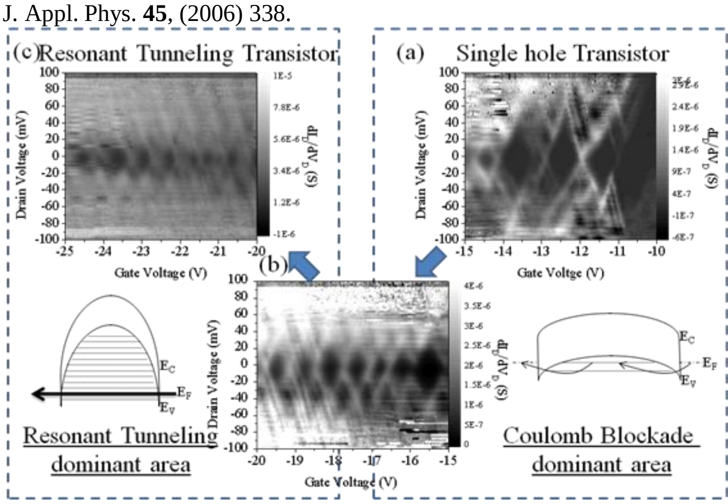

Fig. 2 Contour plot of differential conductance characteristic as a function of gate voltage and drain voltage at 7.3 K.

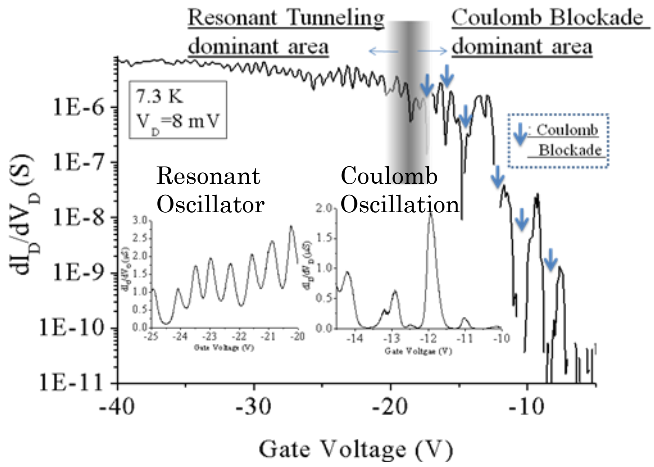

Fig. 3 Differential conductance characteristic as a function of gate voltage at 7.3 K. Insets show the Coulomb oscillation and the resonant tunneling current oscillation in the liner scale.

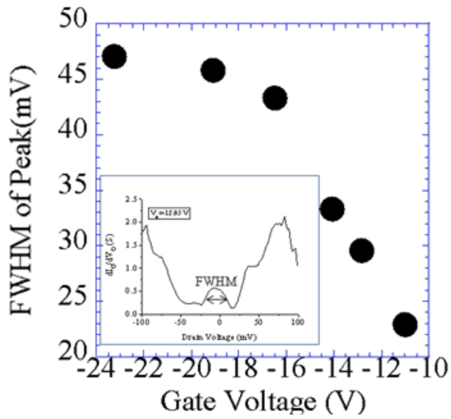

Fig. 4 FWHM of quantum peaks characteristic as a function of gate voltage.

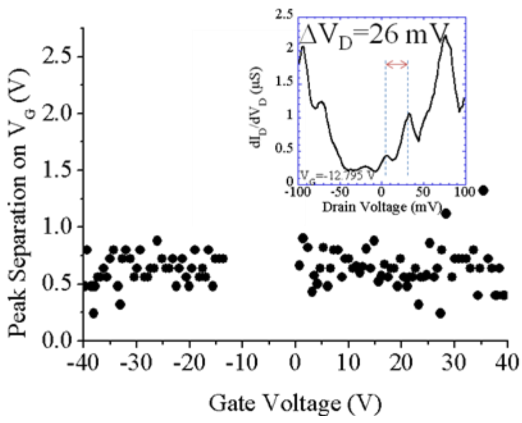

Fig. 5 Peak separation of quantum energy levels as a function of gate voltage estimated from differential conductance characteristic on gate voltage.

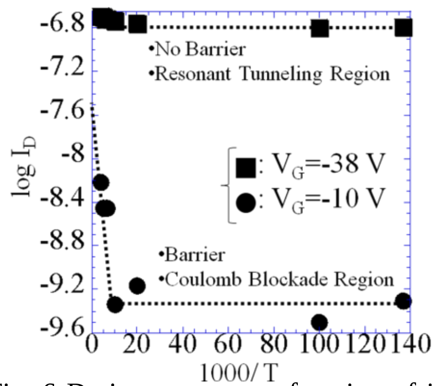

Fig. 6 Drain current as a function of inverse of temperature at V_G=-38 V and -10 V.