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Quantum-dot transport in carbon nanotubes

T. IDA, K. ISHIBASHI†, K. TSUKAGOSHI‡, Y. AOYAGI†
The Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan

B. W. ALPHENAAR
Hitachi Cambridge Laboratory, Madingley Road, Cambridge CB3 0HE, U.K.

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Transport measurements on a bundle of single-walled carbon nanotubes have been made below 4.2 K as a function of side gate and source–drain bias voltage. The transport of an individual nanotube is described by the Coulomb blockade effect. The zero-dimensional quantum states of the nanotube become clear for measurements of large bias voltage. In addition, we present preliminary results of microwave application to the SWNT dot, and the results can be qualitatively explained by classical coupling to the dot.
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Since the discovery of the graphite needles which are called carbon nanotubes [1] with cylindrical diameter of the order of 1 nm, much investigation has been done owing to their unique electronic and geometric properties. In particular, single-walled carbon nanotubes (SWNTs) are quasi one-dimensional quantum wires, and could be a building block of quantum nanostructures, showing quantum effects at higher temperatures. Recently, electrical transport of an individual carbon nanotube has been measured with attention paid to unique quantum effects [2–5].

For future quantum devices, in which quantum states would be manipulated, these effects have to be clearly resolved at reasonably high temperatures. However, in quantum dots made in semiconductor material with standard electron-beam lithography, the size is limited to several tens of nanometers. As a result, the Coulomb blockade effect and the zero-dimensional (0D) effect are observable typically below liquid-helium temperatures [6]. SWNTs could be interesting, in this respect, because they could be used for the element of very small quantum dots. In this report, we study basic transport characteristics of SWNTs and characterize them as quantum dots. The interaction between high-frequency fields and quantum dots is important for the coherent control of quantum states in future devices. As a first step, we present preliminary experimental results on microwave irradiation of SWNT quantum dots.

Figure 1A shows a schematic circuit of the quantum dot in a SWNT rope. The SWNTs had a diameter

† Also at: CREST, Japan Science and Technology (JST), Japan

‡ Also at: Hitachi Cambridge Laboratory, Madingley Road, Cambridge CB3 0HE, U.K.

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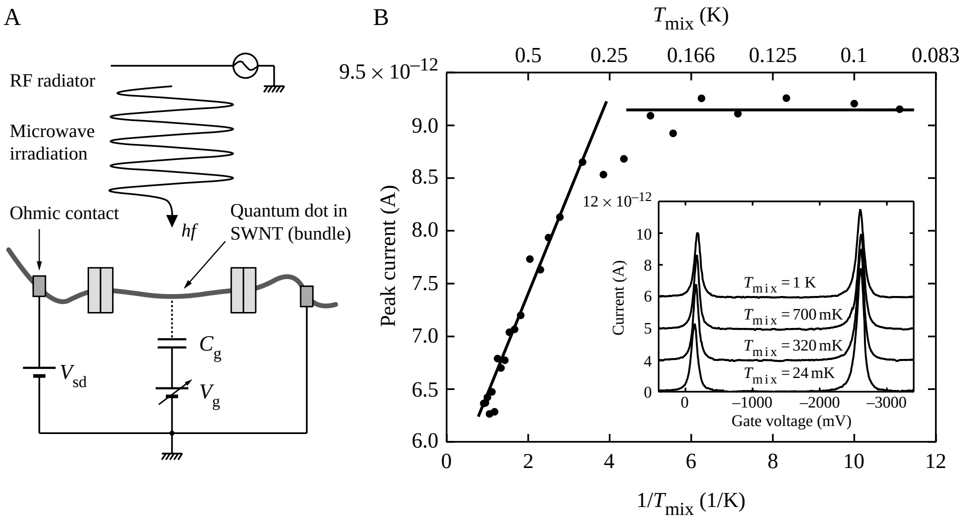

Fig. 1. A, Schematic measurement set-up of a quantum dot in SWNT. A constant bias voltage V_{sd} is applied to the SWNT. The tunnel barrier may exist at the junction of the electrode and SWNT. There is one side gate pad near the SWNT electrostatically coupled to the dot with capacitance C_g. The other side gate is used for the microwave irradiation. B, Temperature dependence of the Coulomb peak current. Inset: Coulomb blockade oscillations of SWNT at increasing temperatures.

ranging from 1 to 15 nm and a length of about 20 μm. These bundles were dispersed on an oxidized silicon surface. Then, two platinum/gold leads with 6 nm/50 nm thickness were patterned on one of the nanotubes by using the mark alignment technique in conventional electron-beam lithography. The distance between lead contacts was 250 nm. Two side gate pads near the nanotube between two contacts were also formed. One gate was used for varying the potential in the SWNT, while the other was used to apply the microwave field. The sample was mounted on the mixing chamber of the dilution refrigerator with a base temperature of 25 mK, and two-terminal dc measurements were performed. The I–V_{sd} characteristic of the bundle was linear at room temperature with the resistance from 50 k to 100 kΩ, but became nonlinear at low temperature.

The inset in Fig. 1B shows the measured current as a function of the applied gate voltage V_g at various temperatures. The curves are offset for clarity. Two Coulomb blockade peaks are observable in the swept gate voltage range from 0 to -4 V. The basic behavior of Coulomb blockade oscillations is similar for all temperatures. The oscillations were very stable for each measurement, suggesting that no unstable charge states was around the dot. In Fig. 1B, we show the peak current as a function of the inverse of mixing chamber temperature, $1/T_{mix}$. At high temperatures, the peak current monotonically increases as T_{mix} is decreased, and the peak current saturation is observed at temperatures below T_{mix} = 250 mK. This indicates that the electron temperature stays constant even through the mixing chamber temperature further decreases.

Figure 2A shows the I–V_{sd} characteristics for varying gate voltages from -1 to -6 V at $T_{mix} = 4.2$ K. The corresponding differential conductance is shown in Fig. 2B. In the figure, the Coulomb gap with a diamond shape is clearly observed. As seen in these figures, the measured device shows the typical characteristics of a single quantum dot. The lines seen outside of the diamond region in the gray-scale plot are due to the effect of 0D excited states, first observed in a GaAs quantum dot [7]. This effect becomes more pronounced at the lowest temperatures. We do not know how the tunneling barriers are formed in the device. Actually, we have measured a few other devices made in the same way, and all devices have shown similar behavior. This fact means that the tunneling barrier may not be due to some defects in nanotube but may be formed at the junction between the edge of the electrode and the nanotube.

The self-capacitance and the corresponding charging energy obtained from Fig. 2 are $C_\Sigma = 18.6$ aF and $E_C = 8.6$ meV, respectively, which are not easy to realize in a conventionally made GaAs dot. We estimate

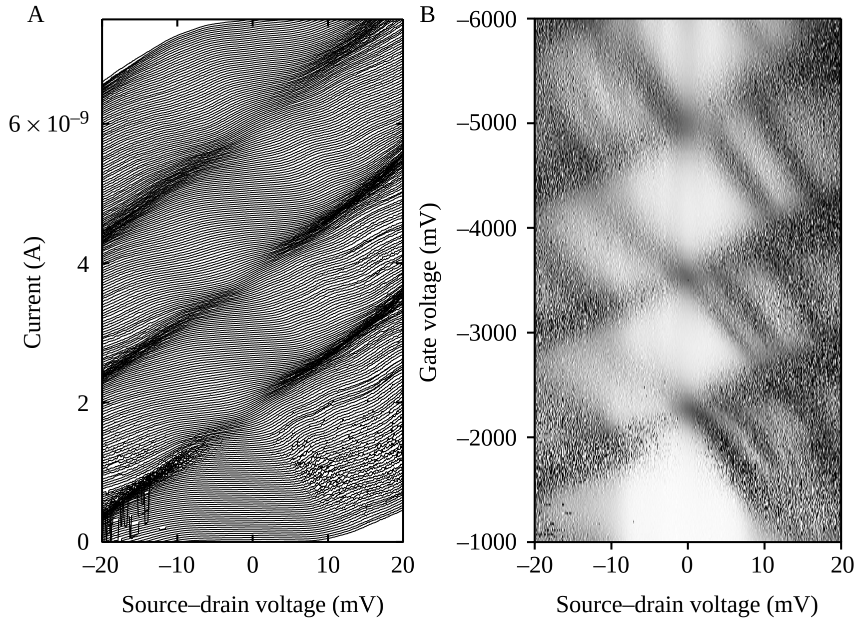

Fig. 2. A, I–V_{sd} characteristics at 4.2 K for gate voltage V_g ranging from -1 to -6 V with an increment of 20 mV. The curves are offset for clarity. B, Gray-scale plot of the differential conductance.

the energy level spacing $\Delta E = 2.3$ meV, which happens to be the similar value to E_C, from the measurements of Coulomb blockade oscillation for large source–drain bias voltages. The charging energy corresponds to a temperature of about 100 K. By narrowing the distance between the two contacts, we may be able to achieve the Coulomb blockade effect at room temperature in the future.

In Fig. 3, the effect of the microwave irradiation on I–V_{sd} characteristics is shown. The data were taken at the lowest temperature with the microwave power changing from -40 dBm to -12 dBm, while the lowest one corresponds to the curve without irradiation. We should note that the applied microwave power was kept small such that the temperature would not change during the measurement. Without microwave irradiation, the curve shows the Coulomb gap and structures due to the excited state of the 0D quantum state. As the microwave power is increased, the curve becomes smooth with less structure. The differential conductance, which is calculated from the I–V_{sd} data and shown in the inset of the figure, indicates that the curve become less structured as the microwave power is increased. We have made measurements at different frequencies and at 4.2 K, and observed the similar result. These experimental observations suggest the classical coupling mechanism of high-frequency radiation to the dot. The high-frequency field couples to the source–drain voltage as an ac source in addition to the dc bias voltage. The measured dc current under microwave irradiation is the time-averaged current over the modulating voltage around the fixed dc bias voltage. This may explain the observed I–V_{sd} characteristics under microwave irradiation. At the moment, we do not fully understand the reason of the classical coupling even through hf for 20 GHz ($\sim$1 K) is larger than kT ($\sim$0.25 K) [8–10]. Since special care was not paid to the connection between the coaxial line and the sample gate, the electromagnetic field around the dot could be very much complicated. The microwave signal may couple to various electrodes with macroscopic dimensions, resulting in the effective modulation of V_{sd}.

In summary, we have measured electrical transport of a single bundle of SWNTs at low temperature. The basic characteristics can be understood by that of a single quantum dot separated from the source and drain electrodes with tunneling barriers. The charging energy and the level spacing are larger by an order compared

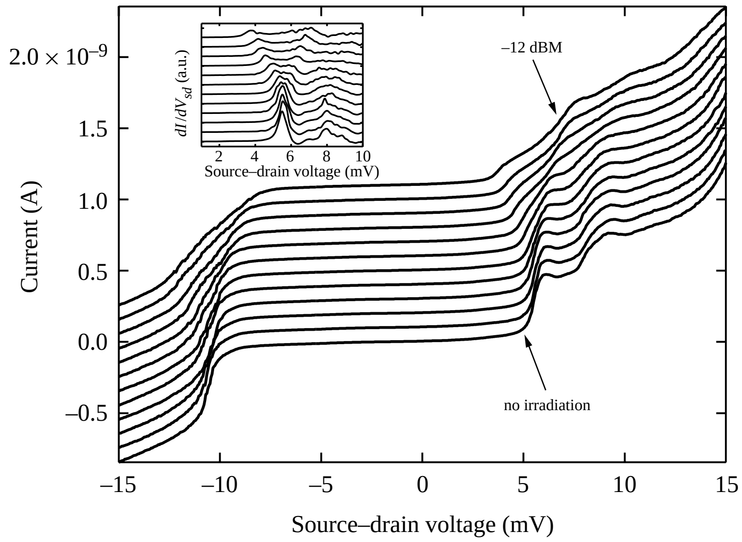

Fig. 3. I–V_{sd} characteristics at $T_{mix} = 25$ mK under 20 GHz irradiation with different microwave powers at a gate voltage of −200 mV. The curves correspond to microwave power levels of no irradiation (bottom), −40, −37, −35, −30, −27, −24.5, −22, −19.5, −17, −14.5 and −12 dBm. Inset: differential conductance calculated from the I–V_{sd} data.

with those for a conventional surface gate GaAs dot. By reducing the separation between the electrodes, the dot could be made smaller and higher-temperature operations could be expected. However, the origin of the tunnel barrier formation has to be investigated in the future study. We also have presented the preliminary result on the microwave irradiation effect on the dc transport of the dot. It is found that the microwave signal effectively modulates the source–drain voltage in a classical manner. Further optimal design of the electrodes is necessary for the efficient coupling of the microwave signal to the dot, which may realize photon assisted tunneling.

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