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# Quantum dot transport of semiconducting single-wall carbon nanotubes

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## 1. Introduction

Carbon nanotubes are attractive materials as a building block of quantum dot-based nanodevices, because of their extremely small diameter [1]. Semiconducting and metallic nanotubes are possible, depending on how they are rolled up from the graphene sheet, but to grow them in a distinguished manner is not possible with present growth techniques. As a result, devices, fabricated by dispersing single-wall nanotubes (SWNTs) on a substrate, usually contain both nanotubes. Therefore, to study the quantum dot transport in semiconducting SWNTs (s-SWNTs) is important, and should be compared with that in metallic nanotubes.

This paper reports the electrical transport properties of s-SWNTs. It is shown that the quantum dot transport with positive carriers (p-type) in a limited gate voltage range is similar to that of metallic nanotubes, but the number of electrons can go to zero by applying the sufficient positive gate bias. In the intermediate gate range, the multi-dot behavior has been observed. We discuss the possible origin of the gate-dependent quantum dot behavior. The tunnel barrier height is also estimated from the observed activation behavior.

## 2. Device structure and procedure

SWNTs were dispersed on the thermally oxidized silicon wafer and were observed by the atomic force microscopy (AFM). An individual SWNT was contacted by 50 nm-thick Au-Ag alloy electrodes. The length of the SWNT between metallic contacts was ~500 nm. The heavily doped silicon wafer was used for the back gate (lower inset of Fig.1). Electrical measurements were carried out at various temperatures from 1.5 K to room temperature in a $^4$He cryostat.

## 3. Results and discussions

Fig. 1 shows the transfer characteristics, taken at source-drain voltages ($V_{sd}$) from 0.2 to 1.0 V with 0.2 V steps at room temperature. A linear *I-V* curve is obtained at zero gate voltage ($V_g$) as shown in the upper inset of Fig. 1. As the positive $V_g$ is applied, the current is gradually reduced and is finally suppressed. These characteristics are indications of p-type s-SWNTs.

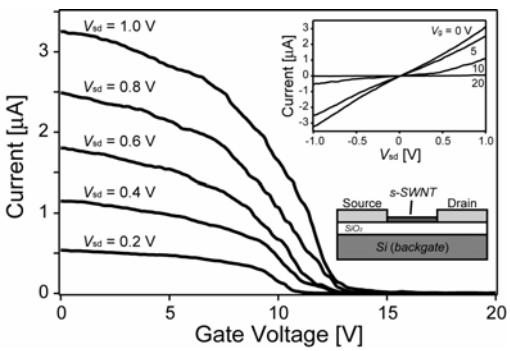


Fig. 1. Transfer characteristics taken at $V_{sd}$ from 0.2 to 1.0 V in 0.2 V steps. Upper inset: *I-V* curves at various $V_g$. Lower inset: Schematic cross section of the sample.

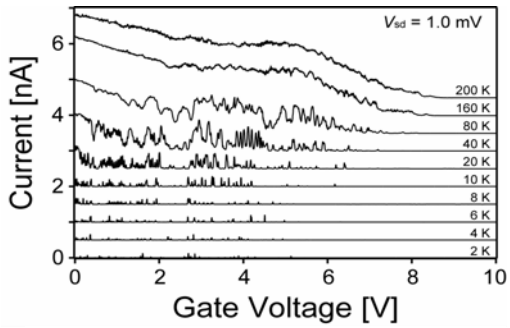


Fig. 2. Temperature dependence of Coulomb oscillations at $V_{sd}$ = 1 mV. The curves are shifted along the current axis by 0.5 nA.

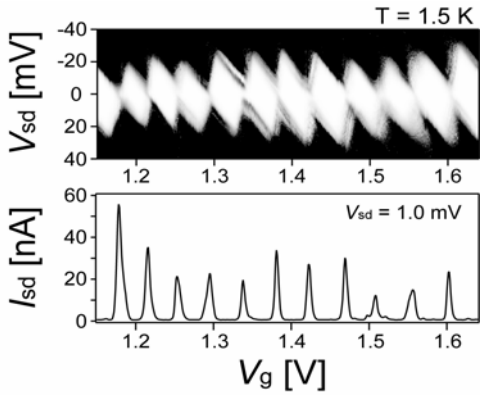


Fig. 3. Upper: Gray scale plots of differential conductance as a function of $V_{sd}$ and $V_g$. Lower: Coulomb oscillations at $V_{sd}$ = 1mV.

Fig. 2 shows temperature dependence of Coulomb oscillations at $V_{sd}$ = 1 mV. We should note three different gate voltage ranges. In the first range, $V_g$ < 3 V, the regular Coulomb oscillations have been observed at low temperatures, suggesting the single quantum dots (See Fig. 3). In the second range, 3 V < $V_g$ < ~8 V, the number of Coulomb peaks increases as the temperature is raised, a typical behavior for multiple dots. In the third range of sufficiently large gate voltage, no peaks are observed, suggesting the complete depletion of the carriers. These results may be attributed to the fluctuating valence band. In the first range, the Fermi level is far below the fluctuating valence band, forming the single dot. In the intermediate range, some peaks of the valence band could get lower than the Fermi level, which works as tunnel barriers and may divide the single dot into the smaller multiple dots. Finally, the carriers can be completely depleted when the Fermi level comes in the band gap. The temperature dependence of the *I-V* curves, measured at the top of the Coulomb peak, shows the activation behavior at temperatures larger than around 10 K. The estimated barrier height ~10 meV is consistent to the reported value in the needle-like metal-nanotube junction [2], which may indicate that the junction in a similar geometry is also realized in our devices.

## 4. Conclusions

We measured electrical transport properties of s-SWNTs at various temperatures. A single quantum dot and multiple dots behaviors were observed in different $V_g$ regimes. The phenomena arise from the Fermi level position relative to the fluctuating valence band.

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**References**

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