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Counting Single Electrons Using a Carbon Nanotube Field-Effect Transistor

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Adrian Bachtold

CIN2 (CSIC-ICN)
Campus UABarcelona, Bellaterra, Spain

A novel scheme based on a carbon nanotube field-effect transistor allows the detection of single-electron events at relatively high temperature in a reliable way, demonstrating the ultimate capabilities of the carbon nanotubes as single charge sensors.

The detection and manipulation of individual electron charges are one of the hot topics in nanoscale electronics due to the promising applications in ultra low dissipative devices and information processing in molecular circuits. Single-electron detectors consisting off microfabricated devices in metal or semiconducting material have been already reported in literature but with the drawback of being operable at milliKelvin temperatures [1]. On the other hand, single electron detection carbon nanotubes has been resolved for electrons hopping onto defects randomly trapped in a silicon oxide layer [2]. However, these single-electron processes are poorly controlled and the controlled detection by a nanotube transistor of single electrons on a nearby nanosystem still needed to be demonstrated.

The present work shows for the first time a real-time detection of the transfer of single electrons between a gold nanoparticle and the carbon nanotube with an operation temperature close to 150 K, three orders of magnitude higher than the one of previous detectors. This work also demonstrates that nanotube transistors can probe electrons on other molecular systems, which cannot do the other microfabricated detectors. Moreover, the single-electron detection measurements allow for the full electron characterization of the system circuit (Fig. 1 b).

The carbon nanotube transistors were fabricated by means of standard nanofabrication techniques with nanotubes grown under chemical vapor deposition on a Si/SiO_2 substrate. Gold nanoparticles were deposited onto the wafer from an aqueous suspension and positioned on top of the nanotube by atomic force microscopy (AFM) manipulation (Fig. 1 a).

The transfer of single electrons into the Au nanoparticle can be detected by measuring the conductance G_{tube} of the nanotube while sweeping the gate voltage V_G (Fig. 2 a), as the tube conductance is extremely sensitive to the presence of electric charges. As V_G is swept, the conductance is turned off as for typical *p*-doped semiconducting SWNTs. However, we additionally observe abrupt conductance jumps (vertical blue bars) that indi-

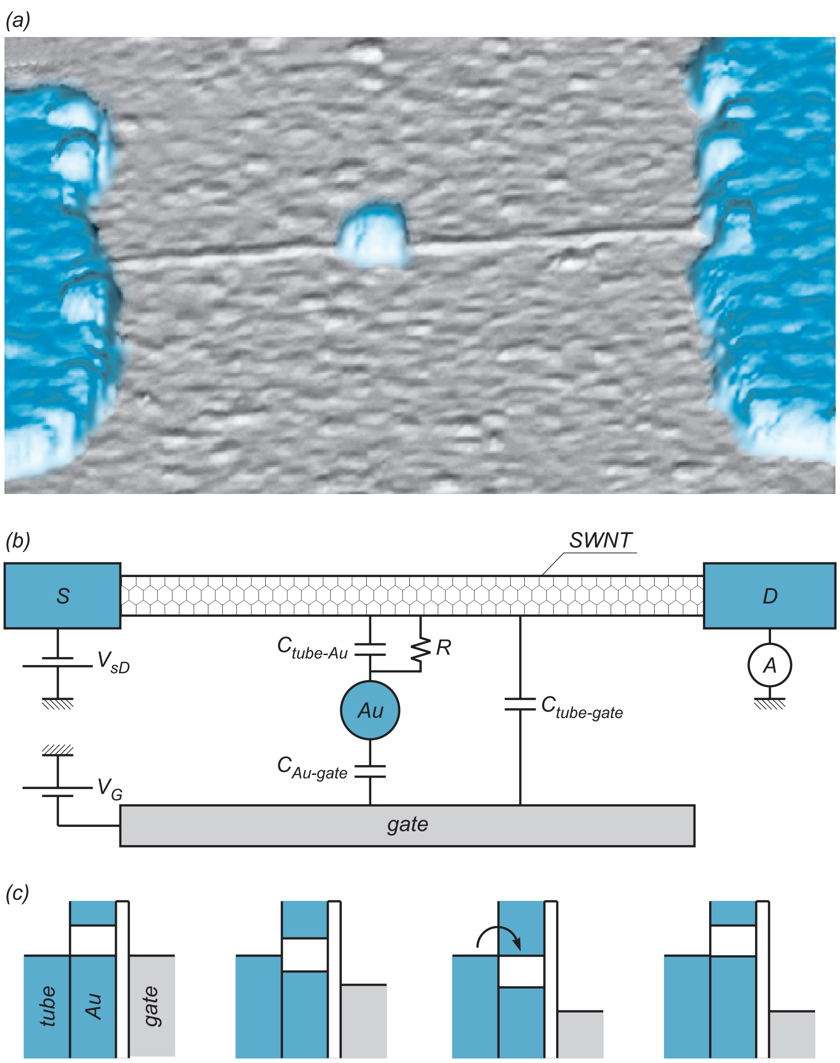

Figure 1. (a) Atomic force microscopy image of the device geometry. **(b)** Schematic of the measurement setup. **(c)** Schematics of the potentials in the nanotube and the particle as the gate potential is swept down. Each time an empty energy level of the particle matches the electrochemical potential of the tube, an electron is transferred onto the particle, which is detected by the nanotube transistor.

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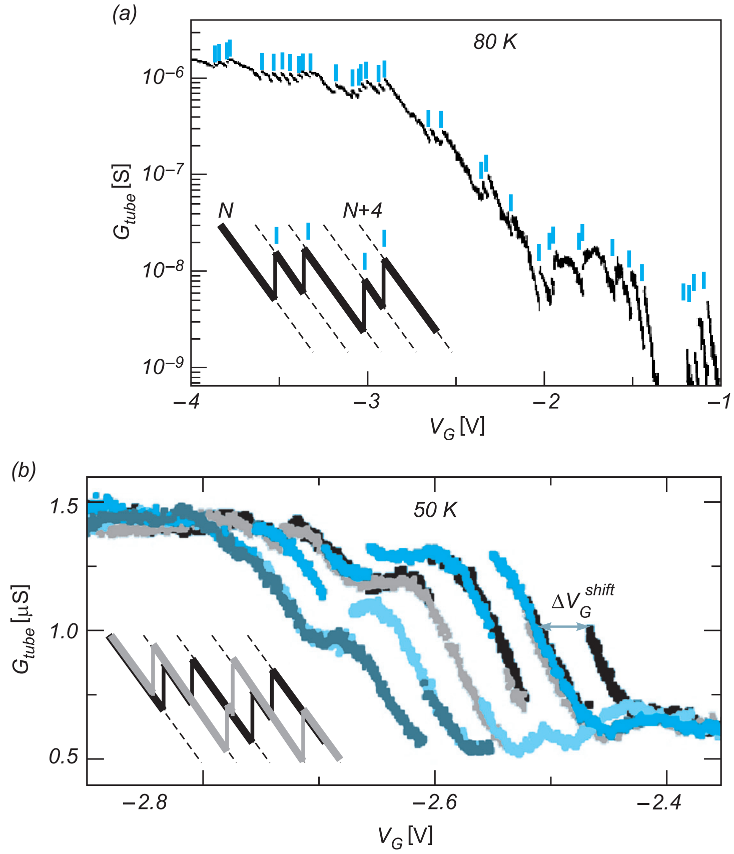
cate discrete electron transfers from the nanotube into the particle. Each extra electron in the particle changes the electrostatic potential in the particle and, in turn, the charge density in the nanotube, which shifts the conductance G_{tube} tube horizontally in V_G.

In order to unequivocally confirm that these discrete jumps correspond to single electron events, we have performed repetitive scans in V_G (Fig. 2 b). A collection of curves is obtained which are periodically spaced in gate voltage with a period of about ΔV_G^{shift} = 60 mV. This periodicity suggests that adjacent curves differ by one electron in the Au particle and in turn that the observed jumps correspond to transfers of single electrons.

The detection of single electrons allows the characterization of Au nanoparticle electrical properties by looking at the time dependence of the electron transfer versus temperature. For instance, if the gate voltage is set at a fixed value while measuring the tube conductance at 50 K (Fig. 3), the tube conductance fluctuates between two values on a time scale of several hundred seconds corresponding to an electron going back and forth into the Au particle due to thermal excitation and changing the number of electrons between N and $N + 1$. This kind of measurements are very useful since the fluctuations of N due to thermal excitation can provide information on the energy separation between electron states of the Au particle. For further informations, see reference [3].

In conclusion we have demonstrated well-controlled single electron detection in a simple, well-defined highly resistive molecular circuit consisting of a carbon nanotube transistor and a gold nanoparticle. The nanotube transistors are shown to be excellent detectors of single electrons at high operation temperatures. We have exploited such single electron counting and its low transfer rate to electrically characterize the Au particle. Single electron counting with nanotubes offers great promise for future studies on organic molecules, biomolecules, or semiconducting particles, which most often are highly resistive and it is not possible to pass a current measurable with conventional electronics. For example, single electron photoelectric effects can be investigated in CdSe particles as well as charge transfer in biomolecules involved in photosynthesis and respiration activities.

Figure 2. Detection of single electrons. **(a)** Tube conductance as the gate voltage is swept from –4 to –1 V. Vertical blue bars indicate conductance jumps. The inset shows the relation between G_{tube} (V_G) and the number of electrons in the Au particle. **(b)** Tube conductance as a function of V_G in a smaller range. Each color corresponds to a different scan. The inset shows two traces of G_{tube} (V_G) in black and gray; jumps appear at different V_G values as a result of the stochastic nature of the electron transfer.



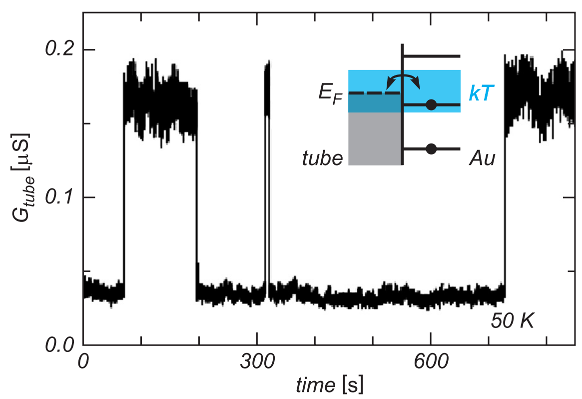


Figure 3. Fluctuations of the electron number due to thermal excitation. Tube conductance as a function of time at 50 K for V_G = –1.35 V. The conductance experiences two levels at 50 K. We attribute the extra level at 50 K to the electrochemical potential of the tube that matches the center of the Coulomb gap. The insets show the energy levels in the tube and in the Au particle for different numbers *N* of electrons. The thermal energy is shown in blue.

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Opracowanie edytorskie: Danuta Czudek-Puchalska, Oficyna Wydawnicza Politechniki Warszawskiej, ul. Polna 50, 00-644 Warszawa, tel. 0-22 234-75-03