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A Triple Quantum Dot in a Single Wall Carbon Nanotube

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1. Introduction

Carbon nanotubes are predicted to have promising properties as quantum information devices based on quantum dots [1]. The small hyperfine coupling due to zero nuclear spin of the most abundant isotope ^{12}C in natural carbon as well as a small spin-orbit interaction give hope for long spin relaxation times compared to for instance III-V semiconductor quantum dots. One of the interesting pathways in carbon nanotube quantum dots is therefore to scale up the number of quantum dots by defining multiple quantum dots in series along the carbon nanotube. Conventional carbon nanotube single quantum dots are now routinely fabricated by contacting the nanotube by two closely sub-micron spaced metallic electrodes. For appropriate choice of electrode material, the metal-nanotube interfaces form tunnel contacts making the nanotube segment between the electrodes a quantum dot. Two quantum dots in series in a carbon nanotube have also been demonstrated by depositing thin metallic gate fingers on top of the nanotube (top-gates) separated by an insulating layer to avoid electrically contacting the nanotube [2-5]. The top-gates are then used to introduce barriers in the nanotube, thereby defining a carbon nanotube double dot system. In these system the electrostatic and the tunnel coupling (quantum mechanics) are interesting, topics which have already been examined intensively in GaAs quantum dots [6,7]. Extension of this system to three quantum dots in series or a ring shaped geometry lead to more complicated electrostatic and quantum mechanical behavior, which recently have been under examination in GaAs based systems [8-10]. We show that single wall carbon nanotubes in a top-gated geometry also can define a carbon nanotube (serial) triple dot identified by a charge stability diagram resulting from current measurements through the three serially connected quantum dots.

2. Experimental methods

Single wall carbon nanotubes are grown from lithography defined catalyst islands by chemical vapor deposition on a highly doped silicon substrate capped by a silicon dioxide layer. The nanotubes are contacted by two Au/Ti leads defined by electron beam lithography several microns from the catalyst island to increase the probability of only contacting one nanotube. Finally three top-gates (Tg1-3) consisting of an insulating layer (silicon or aluminum oxide) followed by a Ti layer are placed between the two electrodes (see Fig. 1(a)) [5]. An additional processing step to define bonding pads of Au/Cr is done by optical lithography. The samples are cooled to temperatures around 50 mK in a ^3He-^4He dilution refrigerator and probed by DC-measurements.

3. Experiments and results

Figure 1(b) shows current measured from source to drain at constant bias voltage as function of voltages on Tg1 and Tg3. The overall pattern in the diagram consists of three sets of lines with finite current but different slopes as

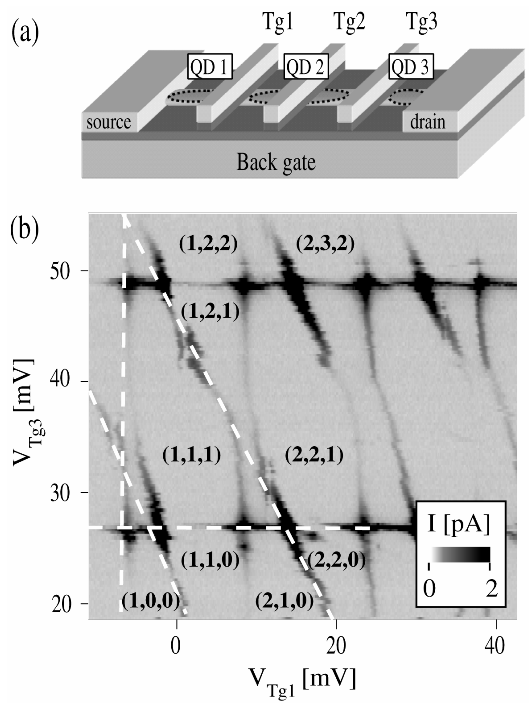

Fig. 1 (a) Schematic figure of the carbon nanotube triple dot device, where the ovals indicate the deduced position of the three quantum dots. (b) Stability diagram of the triple dot sweeping the two outer gates (current versus Tg1 and Tg3, V_{bg}=4V, V_{sd}=50μV, V_{Tg2}=0V). Crossing vertical and horizontal lines correspond to adding an electron in the QD 1 and 3, respectively, while crossing the lines with negative slope adds an additional electron in QD 2. Additional numbers of electrons are written in parenthesis for some charge configuration.

shown in the lower left corner by the white dashed lines, i.e., vertical, horizontal and sloping lines. These lines primarily reflect the charging of each quantum dot in the triple quantum dot by single electrons. Assuming an increasing voltage on Tg3, the vertical lines correspond to a condition, which energetically allows an additional electron to enter QD 1. Despite only having charge degeneracy between two different charge states in QD 1 exactly at a vertical line (i.e. having a level in QD 1 aligned to the chemical potential in source and drain), a finite current can flow through all three quantum dots due to cotunneling (or creation of molecular states). The number of electrons in QD 1 between two vertical lines is thus constant. In similarly way, crossing a horizontal line corresponds to addition of an electron in QD 3 (increasing V_{Tg3}). In the case of crossing a sloping lines, an electron is added to QD 2 due to cross capacitances between Tg1 (Tg3) and QD 2. The vertical and horizontal lines indicate that the crosstalk (cross capacitance) from Tg1 to QD 3 or from Tg3 to QD 1 is negligibly small, which is suitable for independent control of the dot states. For some charge configurations, the number of additional electrons in the triple dot is written by (N_1,N_2,N_3) in Fig. 1(b), where N_i is the number of electron in QD *i*.

The stability diagram also reveals that QD 1 and 2 are better coupled than QD 2 and 3, since clear anti-crossings are seen for intersections between vertical and sloping lines, while this is not the case for horizontal and sloping lines. The anti-crossings stem from a combination of electrostatic and tunnel coupling [6]. This picture is confirmed in double quantum dot stability diagrams, where the electron numbers in only two of the neighboring dots are changed, e.g., QD 1 and 2 form a double quantum dot. Furthermore, each quantum dot is probed by bias spectroscopy keeping the number of electron in the other two quantum dots constant. This yield a Coulomb diamond structure from which the charging energies (and level spacings) of the three dots are found. Finally, an idea of the positions of the quantum dots can be deduced from the capacitive coupling to the top-gates and the charging energies as shown in Fig. 1(a).

3. Conclusions

In conclusion a triple quantum dot stability diagram has been observed by current measurements through a single wall carbon nanotube with three top-gates (Tg1-3). The electron number of each quantum dot can be controlled by applying voltage to the three top-gates. Furthermore, double dot stability diagrams for two neighboring quantum dots as well as Coulomb blockade diamond structures of each individual quantum dot are seen yielding the positions of the quantum dots. A triple quantum dot would allow us to study quantum three-level systems often discussed in quantum optics and transport [11].

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