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Tunable double quantum dots in InAs nanowires

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Abstract

Semiconductor nanowires offer a very versatile approach to create tunable quantum dots. Of the different semiconductor materials that can be grown as nanowires, InAs is particularly interesting due to the large spin–orbit coupling and furthermore promising for devices due to the comparably easy processing for Ohmic contacts. Here we study the electronic transport through gateable InAs nanowire devices at low temperatures. The nanowires are grown by MOVPE, and horizontal devices are individually fabricated using electron-beam lithography. We use local top gates to create barriers that can be used to define tunable quantum dots. Towards our final goal of spin manipulation of single electrons, we focus on tunable double dots. We measure the electronic transport through double quantum dots for the different accessible regimes: we present stability diagrams that demonstrate the tunability from two independent dots to one combined dot, including the particularly interesting region of two interacting quantum dots.

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1. Motivation

Quantum dots are a convenient tool to confine and control electrons in a solid-state environment. Recently, the spin of such trapped electrons has gained interest because it constitutes a natural qubit for scalable schemes of quantum computation. Basic steps for quantum operations on electron spins in electrically tunable quantum dots have already been achieved experimentally, but these experiments were limited to quantum dots created in two-dimensional electron gases in the GaAs material system [1,2]. Consequently, to overcome materials limitations of GaAs, new approaches to define tunable quantum dots are desired. Here semiconducting nanowires are particularly promising: electrical operation of quantum dots has already been demonstrated for different approaches and materials [3–8], and the barrier design for tunable quantum dots can be conceptually simple. Here InAs nanowires are particularly interesting because the strong spin–orbit coupling should allow spin manipulation using high-frequency electric fields instead of magnetic fields. Furthermore, achieving Ohmic contacts to InAs nanowires is simpler than for other semiconducting materials due to surface Fermi level pinning in the conduction band.

We have fabricated InAs nanowire devices that can be used as tunable quantum dots. Towards our final goal of spin manipulation, a double quantum dot is particularly helpful (compared to a single dot) because spin blockade in a double dot can be a detection scheme for the spin state of the trapped electrons [2]. Therefore, we will focus our discussion on tunable double dots, although each of these devices can as well be operated as a single dot.

2. Experiment

The InAs nanowires were grown with typical diameter of 50 nm and length of 3 μm using MOVPE. Here the epitaxial nanowire growth on InP (1 0 0) substrates was

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initiated using Au nanoparticles. The wires are not doped intentionally, but are n-type conductive due to impurities (e.g. carbon from the organic precursors) and the Fermi level pinning at the surface. The wires are broken off from the growth substrate and transferred with a tip cut from cleanroom tissue. The wires are deposited onto heavily p-doped Si wafers (which can act as a backgate) covered with 285 nm thermal oxide. Individual nanowires are then located with respect to predefined markers. Device patterning consists of two lithography steps, both defined using electron-beam lithography (two-layer PMMA resist and lift-off procedure). For the Ohmic contacts, we deposit 10 nm Ti and 100 nm Al after a plasma descum and a 5 s etch in buffered HF (to remove the native oxide on the InAs nanowires). For the top gates, we deposit 100 nm of Al after a plasma descum. The measurements presented here were performed in a ^{3}He cryostat with base temperature 330 mK.

3. Results

The Ohmic contacts result in a typical two-point resistance of 5–10 kΩ without applying any gate voltage. Wires can be depleted either with the backgate (typically around 1–5 V) or with the individual topgates (typically around 0.5–2.0 V). We have studied the low-temperature transport of several devices where we apply negative voltages to three topgates to create the barriers that define the double quantum dot. The voltage V_M of the middle gate is tuned to adjust the coupling between left and right dot, whereas the voltages V_L and V_R of the left and right topgates control the tunnel barriers to the source and drain leads and are also used to tune the energies of the quantum dot states. The state of the double quantum dot can then be determined from stability diagrams, where the current trough the double quantum dot is plotted versus the gate voltages of the left and right dots [9].

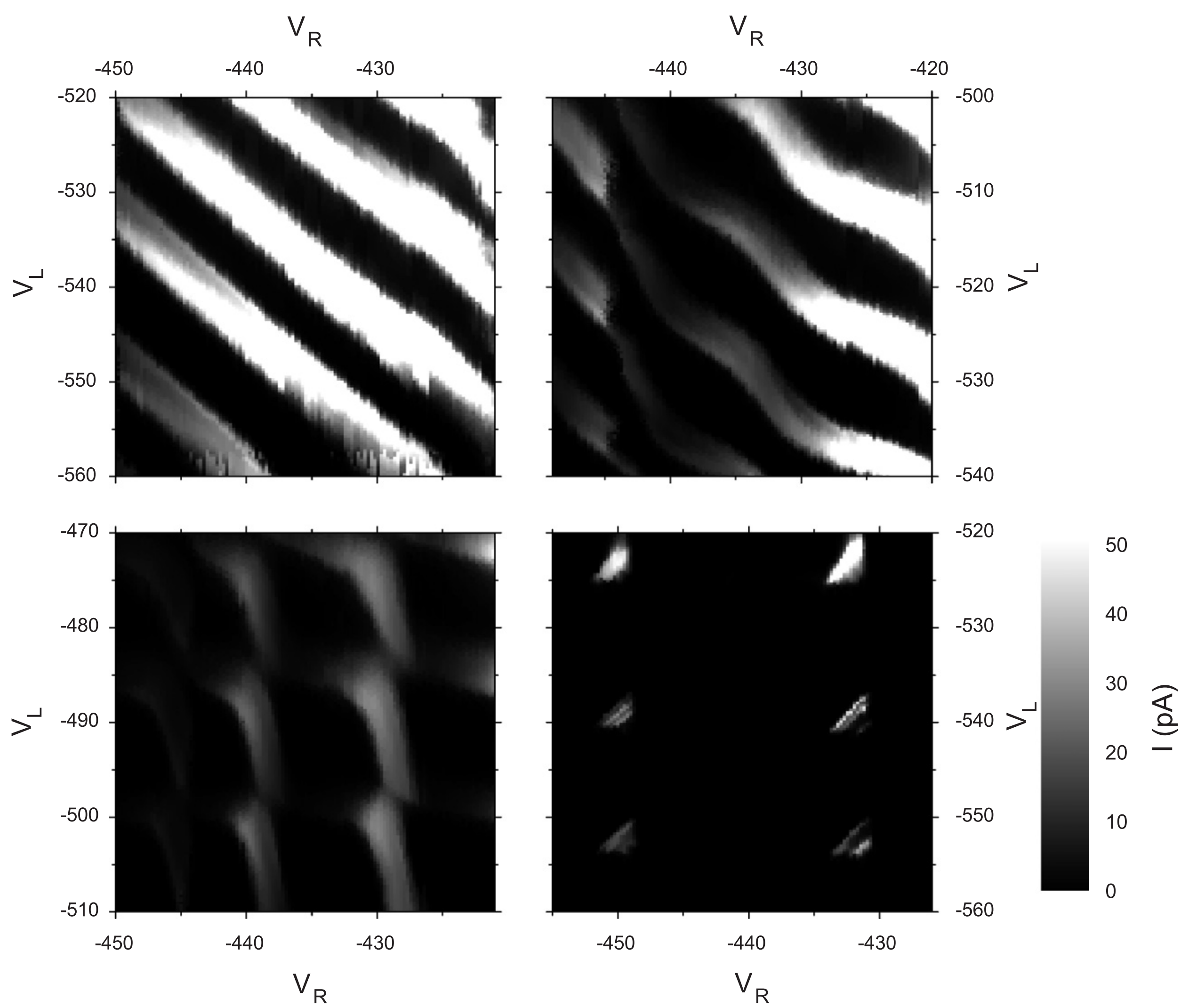

Fig. 1. Stability diagrams of a double quantum dot in an InAs nanowire: current through the device as a function of the voltages V_L and V_R (in mV) applied to the left and right topgates. Applied bias 1 mV; backgate voltage 1.5 V. The four plots with varying voltage V_M of the middle gate ((a) −126 mV, (b) −352 mV, (c) −367 mV, (d) −402 mV) indicate the transition from one big dot via an interacting double dot to two almost decoupled dots.

Fig. 1 shows stability diagrams obtained on a double quantum dot where the top gates have designed width of 40 nm and spacing of 70 nm between adjacent topgates. The data of the four diagrams in Fig. 1 are taken for different coupling between the two dots, as tuned by the middle-gate voltage V_M. For positive and weakly negative V_M, the middle gate does not act as barrier and the system can be considered one big quantum dot. As a result, the energy levels of this single dot can be tuned by V_L as well as V_R, and resonant electron transport (when the quantum dot level is aligned with the leads) occurs at combinations of V_L and V_R that show up as parallel diagonals in the stability diagram, as seen in Fig. 1a. With decreasing coupling between the dots (decreasing V_M), the diagonals first become wavy (Fig. 1b) and then turn into a hexagonal pattern, the characteristic of an interacting double quantum dot (Fig. 1c). By further decreasing V_M, the two dots can be effectively decoupled and electron transport is only possible if energy levels of both dots are aligned with the leads. As a result, the stability diagram shows a rectangular pattern of triangles (Fig. 1d). Only within these triangular regions, considerable current flows through the device; the size of the triangles is given by the source-drain voltage ('bias triangles').

By tuning the three topgates, we can achieve the different double dot regimes. The global backgate gives an additional degree of freedom that we employ to optimize the transport through the double dot. In particular, a positive backgate voltage can help to reduce the influence of intrinsic barriers (e.g. due to defects in the nanowire) which can lead to quantum-dot behavior that is not tuned by the local gates. Although we can operate quantum dots by tuning the top gate voltages without any voltage applied to the backgate, we typically perform measurements at a positive backgate voltage; the data presented in Fig. 1 was measured with a backgate voltage of 1.5 V.

4. Discussion and conclusions

The stability diagrams show that our present design of quantum dots—top gates covering an InAs nanowire—allows tunability of a double dot system from two decoupled dots to strong coupling with effectively one big dot. By adjusting the gate voltages, we can change the number of electrons in each dot individually. However, so far we were not able to reach the state with only a single electron left in a dot (the easiest starting point for spin manipulation) [8]. Here we are limited by the combined use of the outer topgates to tune the electron states as well as to act as barriers. Successive removal of the electrons on the dots by decreasing the topgate voltage leads to a simultaneous increase of the barrier height and strong suppression of the current through the dot. With the current suppressed, we cannot detect the number of electrons any more, as the current is the only signal that we measure within the present setup. Here independent charge detection could establish the electron number in the dots. To avoid the problem of increasing the barriers while tuning the electron states, additional plunger gates help. During measurements with additional topgates that act as plunger we have not reached the single-electron regime yet, but expect to solve this problem with a modified gate design.

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