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Noninvasive detection of charge rearrangement in a quantum dot

C. Fricke[*], M. C. Rogge[*], B. Harke[*], M. Reinwald[†], W. Wegscheider[†], F. Hohls[**,*]
and R. J. Haug[*]

[*]*Institut für Festkörperphysik, Leibniz Universität Hannover, Appelstraße 2, D-30167 Hannover, Germany*
[†]*Angewandte und Experimentelle Physik, Universität Regensburg, D-93040 Regensburg, Germany*
[**]*Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB20HE, U, Great Britain*

Abstract. We demonstrate new results on electron redistribution on a single quantum dot caused by magnetic field. A quantum point contact is used to detect changes in the quantum dot charge. We are able to measure both the change of the quantum dot charge and also changes of the electron configuration at constant number of electrons on the quantum dot. These features are used to exploit the quantum dot in a high magnetic field where transport through the quantum dot displays the effects of Landau shells and spin blockade.

Keywords: quantum dot, quantum point contact, magnetic field, landau shells
PACS: 73.63.Kv, 73.23.Hk, 72.20.My

Recent interest in quantum dots arises from the goal to create quantum bits (qubits) in a semiconductor structure. Non-invasive methods of charge and spin detection are required to realize readout schemes for these qubits[1]. Quantum point contacts (QPC) can be used to detect individual tunneling events of electrons out of the quantum dot (QD) or between the dots of a double dot system [2, 3, 4, 5, 6].

In previous work we demonstrated that the QPC can also be used to detect changes of the electron configuration of a QD without changing the number of electrons [7]. Our interest focuses on a QD in a high magnetic field. Here we will present new result on the redistribution of charge on the QD within the Coulomb blockade regime.

Our device is based on a GaAs/AlGaAs heterostructure providing a two-dimensional electron system (2DES) 34 nm below the surface. The electron density is $n = 4.59 \cdot 10^{15}\ \mathrm{m}^{-2}$, the mobility is $\mu = 64.3\ \mathrm{m}^2/\mathrm{Vs}$. We use an atomic force microscope (AFM) to define the QD and the QPC structure by local anodic oxidation (LAO) [8, 9, 10]. The 2DES below the oxidized surface is depleted and by this insulating areas can be written.

An AFM image of our device is presented in the inset of Fig. 1. The yellow walls depict the insulating lines written by the AFM. The QPC (green area) is separated from the QD structure (red area) by an insulating line. The QPC can be tuned using the in-plane gate G3. The QD is coupled to source and drain via two tunnelling barriers, which can be separately controlled with gates G1 and G2. These gates are also used to control the number of electrons in the QD. We use two electrically separated circuits to perform independent conductance measurements through the QPC and the QD at the same time. All measurements are done in a ^{3}He/^{4}He dilution refrigerator at a base temperature of 40 mK. In Fig. 1 the conductance of the QD and the QPC is shown as a function of the gate voltage applied to gate G2. The conductivity of the QD (red line) displays typical Coulomb blockade peaks: Whenever a state in the QD comes into resonance with the leads, a nonzero conductance through the QD occurs. Simultaneously a step appears in the QPC conductance as the charge of the additional electron on the QD changes. The steps are superimposed on a gradual

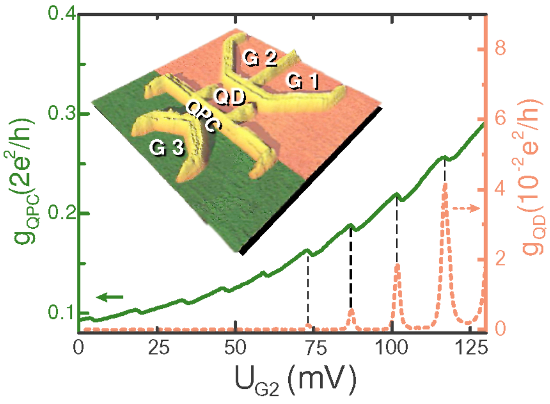

FIGURE 1. Operating principle of the device containing a QD and a QPC. Conductivity of QD (red, right axis) and QPC (green, left axis) are shown as a function of gate voltage applied to G2. The inset shows a three-dimensional AFM image of the device.

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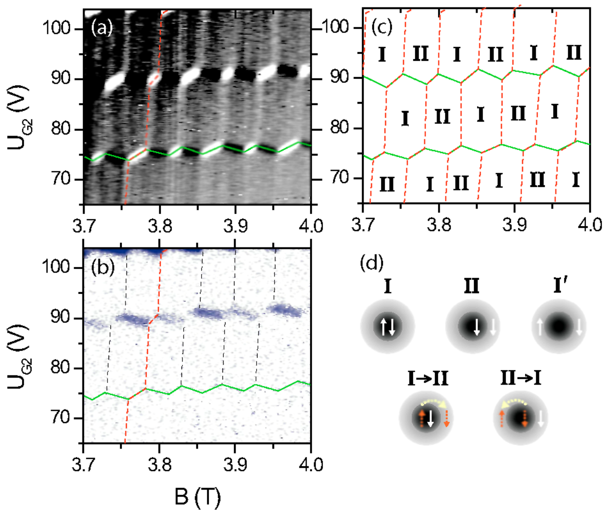

FIGURE 2. (a) dg_{QPC}/dB as a function of magnetic field and gate voltage. Between Coulomb lines additional relocation lines appear in the blockade region. (b) QD Conductance for the same parameters. The last two detectable coulomb peaks can be seen. (c) Schematic view of the QD configuration identified using the model (d) taken from [7].

rise of the conductance due to the direct influence of G2 on the QPC potential. Because of its high sensitivity the QPC is an excellent probe for charge redistributions on the QD. Not only a changing number of electrons on the QD can be detected but changes in the electron distribution for a fixed number of electrons.

This can be seen in Fig. 2(a). It shows dg_{QPC}/dB as a function of magnetic field and gate voltage applied to gate G2. White regions correspond to a decreasing charge detected by the QPC, black regions depict an increasing charge. The three horizontal Coulomb lines are divided in black and white segments due to typical zigzag pattern that occurs in high magnetic fields. In Fig. 2(b) the QD conductance is shown for the same region. Due to the high sensitivity of the QPC there are three well developed Coulomb lines in the QPC signal, while the QD conductance only shows two Coulomb lines (green line is added as a guide to the eye).

While in the QD conductance no changes can be seen in the Coulomb blockade region between two Coulomb lines, in the QPC signal additional vertical relocation lines appear. In this regions, where the total number of electrons on the QD is constant, the QPC detects small changes in the effective charge on the QD for changing magnetic field. This results from the Landau shells on the QD. For rising magnetic field electrons are redistributed from the center to the outer shell. Due to this slight change in the effective potential the QPC conductance changes whenever an electron is relocated [7, 11]. These lines are called relocation lines in the following.

In the presented results these lines are resolved for the first time in a larger region. As the red trace in Fig. 2(a,b) indicates, the full area is divided by the Coulomb lines and the relocation lines into hexagonal regions of fixed electron configuration. This is depicted in Fig. 2(c). The green lines show the position of the Coulomb blockade lines and the red lines mark the positions of the relocation lines. In this range of the magnetic field there are two different electron configuration shown in 2(c). One configuration is *I* where the electrons occupying the two highest energy states are in the same shell. For the second configuration *II* one electron occupies the inner shell and the other electron is located in the center. The relocation lines identify transitions form one configuration to the other.

Taking into account the spin blockade behavior in the QD transport (alternating conductance along the Coulomb blockade line visible in Fig. 2(b)) we can identify in detail the electron spin and charge configuration for each hexagon, using the model presented in [7].

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