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Time-resolved single-electron tunnelling between Landau states in a quantum dot

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Abstract

In a quantum dot with two confined Landau levels the Coulomb blockade oscillations develop a distinct structure at zero bias, showing peak splitting and conductance switching in time. It is shown that both phenomena result from single-electron tunnelling between the two confined Landau levels within the dot. The typical dwell time between switching events is found to depend very strongly on the magnetic field, reaching values of the order of 100 s at large fields.

Keywords: Electrical transport; Heterojunctions; Many body and quasi-particle theories; Quantum dots

1. Introduction

In a two-dimensional electron gas (2DEG) subjected to a large magnetic field, the transport in the integer quantum Hall (QH) regime takes place via extended edge states which develop from Landau levels at the boundary of the system. In this regime the scattering probability of electrons is strongly suppressed, allowing electrons in a particular edge state to travel over large distances (up to mms) before being scattered into an adjacent edge state [1–3]. Although the existence of edge states can be visualised in the simple independent particle picture, their properties are largely determined by the self-consistent arrangement of the charge near the edge [4–6]. This results in strips of compressible (i.e. metallic) states at the Fermi energy, spatially separated by incompressible states. The scattering of an electron between adjacent edge states will be determined by the quantum properties of the compressible initial and final states, as well as the incompressible state acting as the barrier.

Confining the 2DEG to a small area or quantum dot will not fundamentally affect this picture, provided the number of electrons enclosed in the dot is not too small. The strips will develop into closed-orbit states. However, in addition the Coulomb interaction leads to a finite energy required to add

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a single-electron to the dot, i.e. the charging energy [6]. If the dot is weakly coupled to two leads, this finite energy in general results in a Coulomb blockade (CB) for the exchange of particles between the dot and the leads, suppressing the conductance through the lead–dot–lead structure. Only whenever the total energy of the system does not change upon the addition of the single electron (i.e. the two states are degenerate in energy), the CB is suppressed. Note that this condition is equivalent to the alignment of the electrochemical potentials of the 2DEG reservoirs and of the electron system in the dot. This results in the well-known Coulomb blockade oscillations.

In this paper we will present experiments to study the tunnelling between edge states confined inside a quantum dot. We will employ the sensitivity of the Coulomb blockade on the total electrostatic energy of the system via the specific distribution of the charge within the dot.

2. Experimental

The experiments were performed in quantum dots (Fig. 1) defined by metallic gates on top of a GaAs/AlGaAs heterostructure with the 2DEG 100 nm below the surface, with an electron density of $\sim 1.9 \times 10^{15}$ m^2 and a mobility of $\sim 2 \times 10^6$ $cm^2/V \cdot s$. A dot is formed at the application of negative voltages to the four gates 1, 2, F and C. Two dots are investigated, with typical dimensions of 600 nm (dot I) and 400 nm (dot II). The weak coupling to the leads is obtained via the tunnel barriers induced by gates 1-F and 2-F, respectively. The number of electrons is varied by the potential V_C of gate C. Experiments were performed in a dilution refrigerator with 10 mK base temperature. The leads connecting to the sample were carefully filtered at room temperature, as well as at the temperature of the mixing chamber. The magnetic field is taken such that only the lowest Landau level (LL) is occupied, forming the two spin-split states LL1 and LL2. The two resulting edge states are represented in Fig. 1 by the black areas labelled 1 and 2.

3. Results and discussion

On application of a magnetic field to dot I (and II as well) the regular CB oscillation pattern in dependence of V_C [6] becomes modified, with some of the CB peaks developing a split shape (Fig. 2). The split peaks show a well-defined behaviour versus the magnetic field. On increasing the magnetic field, the nature of the splitting becomes more clear. Fig. 3 was obtained from dot I at $B = 5.2$ T, with Fig. 3a showing the conductance versus the gate voltage. One regular and two split peaks can be clearly seen. More specifically, with each black dot representing one individual measurement, the split structure is seen to be composed of two regular CB peaks, with one peak being displaced relative to the other in gate voltage. With the measurements progressing in time at a typical rate of one measurement per s, the conductance

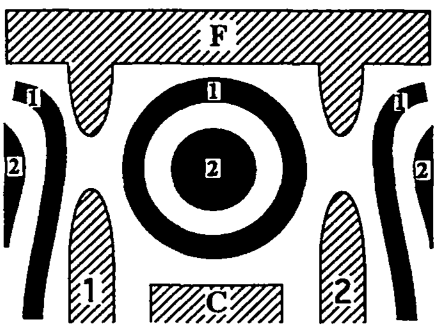

Fig. 1. Schematic diagram of the gate geometry (hatched areas) and the edge states.

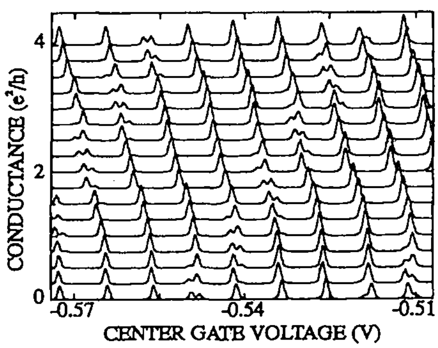

Fig. 2. Coulomb blockade oscillations versus V_C of dot I from $B = 4.600$ T (bottom) to 4.632 T (top) in increments of 2 mT.

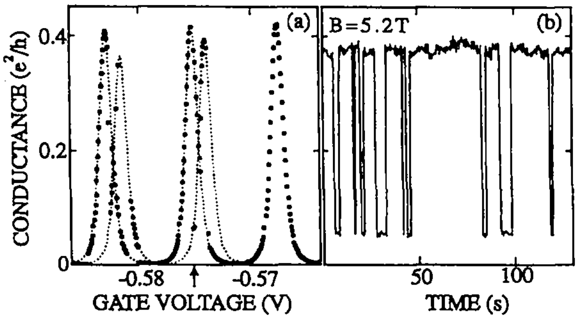

Fig. 3. Conductance of dot I in dependence of (a) the gate voltage V_C at a fixed field ($B=5.2$ T) measured with a time constant of 150 ms, and (b) versus time at fixed B and V_C (arrow in (a)).

follows either one of the two branches, randomly switching between the two. This switching is shown in Fig. 3b. At fixed V_C (indicated by the arrow in Fig. 3a) the conductance versus time is measured, showing a switching behaviour between two discrete levels, with a typical dwell time between switching events of ~10 s. Increasing the magnetic field increases this time, and a value of ~200 s is found at ~6 T [7]. By the same token, a smaller field increases the rate strongly. This is exactly what is seen in Fig. 2, where the rate is so large that individual switching events can no longer be resolved due to the rather long averaging time (~150 ms) in the measurement. This results in a smearing between the two individual branches, yielding a continuous split-peak trace.

As discussed before, the Coulomb blockade is controlled by the electrostatic energy of the system. Any rearrangement of the charge, either near to or inside the dot, leads to a change in this energy, and so will affect the CB [4]. We attribute the switching of the conductance to the tunnelling of a single electron between states in Landau levels 1 and 2 shown in Fig. 1. Inside the dot, the two compressible strips develop into a ring-shaped strip (RI) of states associated with LL1, and a disc-shaped core (CO) of states derived from LL2, separated by a ring-shaped tunnel barrier of incompressible states. Given the small scattering rate between CO and RI, and the large distance of CO from the entrance and exit tunnel barriers induced by the gates 1-F and 2-F, we assume that electron transport from entrance to exit only occurs via the ring states. Note, however, that the transport through RI is affected by the charge residing on CO.

With the decomposition of the electron system in the dot into two "isolated" areas (RI or 1, and CO or 2) containing N_1 and N_2 electrons, respectively, three charging energies become important. In addition, the weak coupling implies the assignment of individual electrochemical potentials to the ring (μ_1) and the core (μ_2), each depending on N_1 and N_2, and on the external parameters V_C and B. Now two tunnelling processes have to be distinguished. First, the intradot tunnelling of the exchange of one electron between RI and CO, governed by internal charging with $N=N_1+N_2$ constant, depends on the difference $\delta=\mu_1(N_1,N_2-1)-\mu_2(N_1-1,N_2)$. The actual tunnel rate depends on the properties of the RI and CO states, and on the barrier. At non-zero temperatures, the rate may become thermally assisted to overcome the energy difference δ. Secondly, the transport through (the ring states of) the dot depends on the alignment of the electrochemical potentials of the ring (μ_1) and the reservoirs (μ_{res}). As μ_1 depends directly on N_1 and N_2, it will shift upon the exchange of a particle between RI and CO. More specifically, if the external parameters are chosen such that initially $\mu_{res}=\mu_1(N_1-1,N_2)$ (yielding a maximum in the conductance), the tunnelling of an electron from core to ring will shift the electrochemical potential of RI to $\mu_1(N_1,N_2-1)$, i.e. away from the resonance condition with respect to μ_{res}. This will result in a switch of the conductance from "high" to "low". In this way, the conductance through the ring states of Landau level 1 can be used as a probe to detect a tunnel event between the two confined Landau levels [8]. Note that the system actually forms a fully controllable two-level fluctuator.

The occupation of the core and ring Landau states is determined by the gate voltage as well as the magnetic field. Increasing the magnetic field increases the Landau-level degeneracy. As a result, each time approximately one flux quantum is added to the dot, LL1 can accommodate one additional electron which is gained from the core region of LL2. In terms of energy this can be understood to result from the increase of the electrostatic energy accompanying the increased Landau-level degeneracy [4]. This will increase μ_2 relative to μ_1, a process which continues until it becomes energetically more favourable to transfer one electron from LL2 to LL1, i.e. whenever $\delta = 0$. Once the electron has tunnelled to LL1 μ_2 drops relative to μ_1. The addition of successive flux quanta results in an approximately periodic saw-tooth shaped behaviour of μ_1 and μ_2. Note that during this process the total number of electrons N in the dot is constant, and so only internal charging occurs.

If the gate voltage is adjusted such that μ_1 approximately lines up with μ_{res}, the conductance will be non-zero with a value determined by the difference between μ_{res} and μ_1. Fig. 4a shows the conductance of dot II in dependence of the magnetic field, showing a strong asymmetry in the peak shape which demonstrates the saw-tooth behaviour of μ_1. In addition, strong switching is seen in all peaks. The detailed field-dependent behaviour of the two-level switching can be seen more clearly by expanding one of these peaks (Fig. 4b). From $B \approx 4.15$ T to ≈ 4.20 T a gradual transition occurs from preferentially "low" to "high" conductance. At $B \approx 4.17$ T the up–down and down–up rates are equal, marking the condition $\delta = 0$. From Fig. 4a, two important observations can be made. First, the occurrence of switching is indeed found to be approximately periodic in a single-flux quantum threading the dot, as anticipated from the behaviour of μ_2 relative to μ_1. Second, from the "raggedness" of the low-field side of each peak, we clearly see a strong increase of the typical dwell time (at $\delta = 0$) at increasing magnetic field, rising from ~ 0.1 s at $B \approx 4.10$ T (Fig. 4a, second peak) to ~ 3 s at $B \approx 4.42$ T (Fig. 4a, sixth peak). As mentioned before, values of > 100 s are found in dot I at $B \approx 6$ T.

To explain this tunnelling rate behaviour, one needs to consider the properties of the incompressible strip and the density of states of the two Landau levels, including the effect of many-body interactions. In the simple single-particle approximation the transmission probability depends exponentially on the width of the incompressible strip. Since this width increases linearly with magnetic field [5] this may lead to an exponentially strong

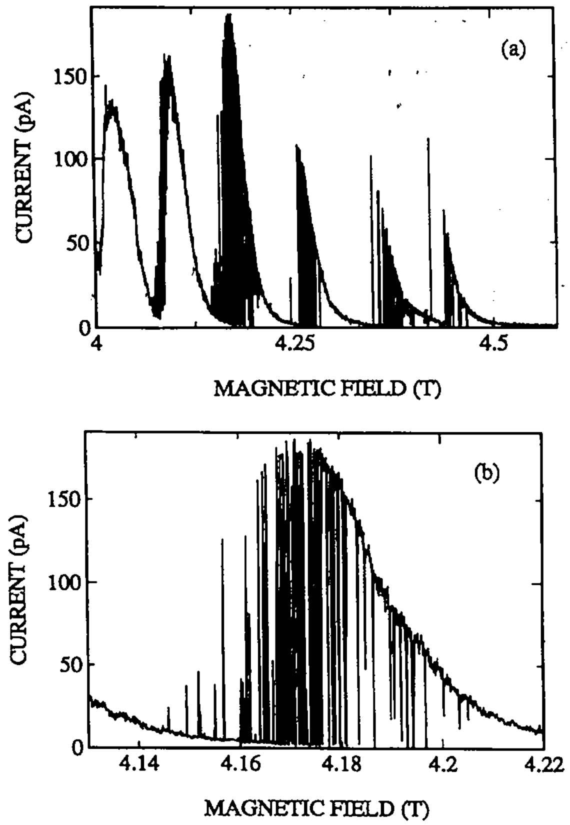

Fig. 4. Conductance through dot II in dependence of magnetic field ((a) and (b)). Peaks occur periodic in one flux quantum added to the dot. Switching is seen at the low-field side of each peak. Note the increase of the switching rate with B. (b) Expansion of a part of (a).

suppression of the tunnelling with the field, which is not incompatible with our experimental results. Further work, including the temperature dependence of the switching, is in progress to obtain a more quantitative description.

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