

## Time-Resolved Tunneling of Single Electrons between Landau Levels in a Quantum Dot

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We have investigated Coulomb blockade oscillations in a quantum dot with two confined Landau levels. Some oscillations show switching between two discrete conductance values as a function of time. We show that these switches are due to single electron tunnel events between the two Landau levels. Upon increasing the magnetic field, we find that the time between two tunnel events reaches macroscopic values on the order of 100 s.

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The quantum Hall regime is known for its small scattering probabilities. Experiments [1,2] have shown that electrons can travel over distances as long as a millimeter with only a small chance of being scattered into an adjacent edge channel. Only recently, it has become appreciated that the self-consistent arrangement of charge is important for understanding the properties of the electron states at the sample edge [3–7]. The emerging picture is that near the sample edge the quantum Hall states separate in alternating strips of incompressible and compressible states. This picture is still valid when the quantum Hall states are confined in a quantum dot [4]. Scattering between the confined quantum Hall states involves the movement of a single electron in space. At present, little is known about the dynamics of such a scattering event. In this Letter we present a method, based on the Coulomb blockade of tunneling [8], that enables us to control and measure single electron scattering events. We find that the time between two tunnel events can be tuned from less than 10 ms to more than 200 s, which allows a time-resolved measurement of single electron tunneling between confined quantum Hall states.

Figure 1 shows the geometry of our quantum dot [9]. The hatched parts are metallic gates fabricated on top of a GaAs/AlGaAs heterostructure with a two dimensional electron gas (2DEG) 100 nm below the surface. The ungated 2DEG has a mobility of  $2.3 \times 10^6$  cm<sup>2</sup>/Vs and an electron density of  $1.8 \times 10^{15}$  m<sup>-2</sup> at 4.2 K. Applying a negative voltage to gates *F*, *C*, 1, and 2 depletes the electron gas underneath them, and forms a quantum dot with a diameter of about 600 nm containing roughly 300 electrons. Electron transport occurs via the tunnel barriers induced by gates 1-*F* and 2-*F*, which couple the dot to the two wide 2DEG reservoirs. We set the conductances of the tunnel barriers at about  $0.1e^2/h$ . The number of electrons in the dot can be varied with the voltage  $V_C$  applied to the center gate *C*. The experiments are performed in a dilution refrigerator with a base

temperature of 10 mK using a small dc-bias voltage of  $6 \mu\text{V}$ . We work in the magnetic field regime where only the two spin-resolved states ( $LL_1$  and  $LL_2$ ) of the lowest Landau level are occupied.

At zero magnetic field, we observed equally spaced Coulomb oscillations as a function of gate voltage, where each period corresponds to a change of one electron in the dot [9]. Figure 2 shows the conductance through the dot versus center gate voltage for different magnetic fields from 4.600 T (bottom curve) to 4.632 T (top curve). A striking feature is that each trace shows one or two *split* oscillations alternated by a few regular Coulomb oscillations. When we follow the split peak in the bottom curve marked by an asterisk, we see that upon increasing the magnetic field the left maximum decreases and the right maximum increases. The split peak then evolves into a regular peak and starts to split again when the field is increased by 26 mT. In the top curve the field is increased by 32 mT and again the peak is symmetrically split, as it was in the bottom curve.

The origin of the split peaks becomes clear at higher fields. Figure 3(a) shows two split peaks and a regular

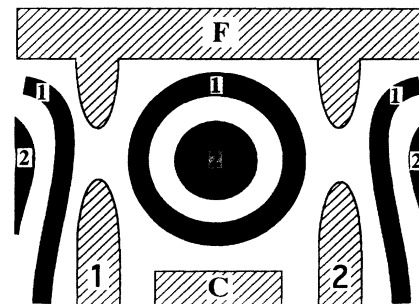


FIG. 1. Schematic of the gate geometry defining a dot with lithographic dimensions of  $0.8 \mu\text{m}$  by  $1 \mu\text{m}$ : *F* denotes the finger gate, 1 and 2 the quantum point contact gates, and *C* the center gate. The location of the compressible parts of  $LL_1$  and  $LL_2$  are denoted by the dark parts.

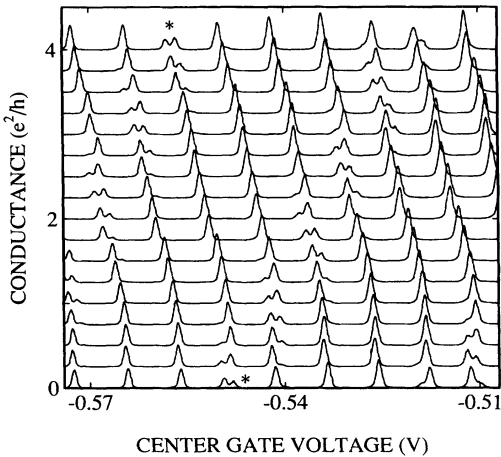


FIG. 2. Coulomb oscillations versus center gate voltage for different magnetic fields from 4.6 T (bottom) to 4.632 T (top) in increments of 2 mT using a time constant of 500 ms. The curves are offset for clarity.

Coulomb peak versus gate voltage at 5.2 T. A split peak consists of two regular Coulomb peaks. We have added two dashed lines to each split peak as a guide for the eye [10]. At some gate voltages, the conductance switches discontinuously between the two branches of a split peak. This behavior is further illustrated by Fig. 3(b) where we have fixed the gate voltage at the value denoted by the arrow in Fig. 3(a). Here, the conductance is measured versus time and shows switching between two discrete levels. The high value corresponds to the left branch and the low value to the right branch of the split peak in Fig. 3(a). The typical time between two switches is on the order of 10 s. We found that at 6 T this time increases to about 200 s. On the other hand, in the lower magnetic field range of Fig. 2 the typical time between two switches is too short to be resolved by our measurement setup.

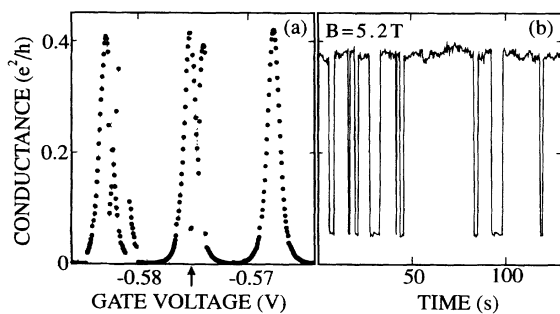


FIG. 3. (a) Conductance through the dot as a function of center gate voltage at a field of 5.2 T using a time constant of 150 ms. We have scaled the amplitude of the regular peak at the right hand side to fit the left and right branches of a split peak as a guide for the eye (dashed lines). (b) Conductance versus time with the gate voltage fixed at the value is denoted by the arrow in (a).

This smears out the switching between the two branches and gives rise to a continuous split peak.

We will now discuss that a switch in the conductance in Fig. 3(b) is a time-resolved measurement of a tunnel event by a single electron between the two Landau levels in the dot. McEuen *et al.* [4] have pointed out that the phase separation of quantum Hall states in a quantum dot leads to the picture of Fig. 1. Self-consistent arrangement of the charge in a high magnetic field causes  $LL_2$  to form a compressible core in the center of the dot.  $LL_1$  is compressible only in the ring region around the core. The ring and the core are spatially separated by an incompressible quantum Hall fluid which acts as a tunnel barrier. Transport from one 2DEG reservoir via the dot to the other reservoir primarily occurs via the ring, since the core is separated from the reservoirs over a much larger distance [11].

Adding an electron to a small isolated region costs a finite charging energy. At zero magnetic field, only one charging energy is important. However, in a high magnetic field with only  $LL_1$  and  $LL_2$  occupied, three charging energies are relevant. The total number of electrons  $N = N_1 + N_2$  is divided between  $N_1$  electrons in  $LL_1$  and  $N_2$  electrons in  $LL_2$ . Adding an electron to  $LL_1$  increases the electrochemical potential  $\mu_1$  of  $LL_1$  with an amount  $E_1$  and also increases the electrochemical potential  $\mu_2$  with an interaction energy  $E_{12}$ . Similarly, adding an electron to  $LL_2$  increases  $\mu_2$  with  $E_2$  and  $\mu_1$  by  $E_{12}$ . Single electron tunneling *within* the dot keeps the total number  $N$  constant. However, removing an electron from  $LL_2$  and putting it in  $LL_1$  increases  $\mu_1$  by  $E_1 - E_{12}$  and decreases  $\mu_2$  by  $E_2 - E_{12}$ . The same energies accompany the opposite process. We call these processes *internal charging*.

The concept of internal charging provides a qualitative understanding of the observed two-level switching. A peak in the conductance occurs when  $\mu_1$  is on resonance with the reservoirs:  $\mu_1 = \mu_{res}$ . However, a tunnel event of a single electron between the Landau levels changes  $\mu_1$  which switches the conductance from *on to off resonance*. The conductance through  $LL_1$  can therefore be used as a time-resolved probe to detect a tunnel event between two quantum Hall states. This type of time-resolved experiment resembles the electrometer-box configuration employed by Fulton, Gammel, and Dunkleberger [12] and Lafarge *et al.* [13] to measure single electron hopping events in the superconducting and normal states of aluminum tunnel junctions.

The values of the internal charging energies can be determined from the spacings of the Coulomb oscillations in gate voltage. A closer examination of Fig. 2 reveals that there are three distinct peak spacings: 1.5 (between the two maxima of a split peak), 6.5, and 8 mV. These spacings are proportional to  $E_1 - E_{12}$ ,  $E_{12}$ , and  $E_1$ , respectively. Using a factor of 10 for this sample to convert the gate voltage scale to energy [9] we find  $E_1 - E_{12} =$

150  $\mu\text{eV}$ ,  $E_1 = 800 \mu\text{eV}$ , and  $E_{12} = 650 \mu\text{eV}$ . From the average peak spacing we obtain  $E_2 = 1175 \mu\text{eV}$  [14]. We found that the splitting of the peaks smears out for bias voltages above 150  $\mu\text{V}$ . This is in good agreement with the estimated energy separation associated with the split peaks  $E_1 - E_{12} = 150 \mu\text{eV}$ .

Figure 4 shows an energy diagram which illustrates the role of the internal charging energies. The electrochemical potentials  $\mu_1$  and  $\mu_2$  denote the minimum energy for having a certain number of electrons in the ring (LL<sub>1</sub>) and the core (LL<sub>2</sub>). The left hand side shows schematically the conductance through the dot versus the center gate voltage  $V_C$ . The topmost conductance peak occurs when  $\mu_{\text{res}}$  lines up with  $\mu_1(N_1, N_2)$  (solid arrows). By decreasing  $V_C$ , one electron is permanently removed from LL<sub>1</sub>. This lowers  $\mu_1$  by  $E_1$  and  $\mu_2$  by the interaction energy  $E_{12}$ , and blocks transport; the dot is now in the charge state  $(N_1 - 1, N_2)$ . When  $V_C$  is decreased further  $\mu_{\text{res}}$  lines up with  $\mu_1(N_1, N_2 - 1)$  (dashed line). Transport via this state is possible only after an electron has tunneled from LL<sub>2</sub> to LL<sub>1</sub> (dashed arrow) which switches the conductance from *off to on resonance*. The conductance is switched back from on to off resonance when an electron tunnels back to LL<sub>2</sub>. Depending on the energy difference  $\delta$  of the initial and final states of the tunneling electron, these processes may require thermal assistance. Another change in gate voltage aligns  $\mu_{\text{res}}$  with  $\mu_1(N_1 - 1, N_2)$ . Similar arguments show that in this case a tunnel event from LL<sub>2</sub> to LL<sub>1</sub> switches the conductance from *on to off resonance*. When the switching is too fast to be resolved, the conductance shows a continuous split peak.

Switching does not occur in the topmost Coulomb oscillation. For this peak the energy difference  $\delta$  is too large. This explains the observed pattern of regular and split peaks in Fig. 2. Each time when a regular peak occurs,  $\mu_1$  drops by  $E_1$  and  $\mu_2$  by  $E_{12}$ . Since  $E_1 > E_{12}$ , this continues until  $\mu_2 > \mu_1$  and  $\delta$  becomes on the order

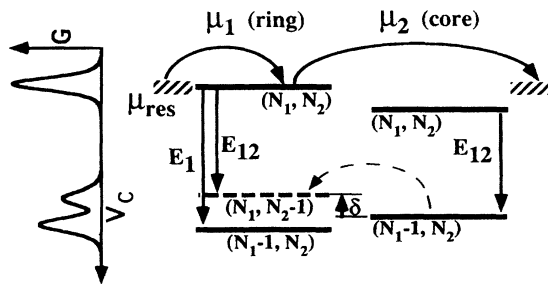


FIG. 4. Energy diagram showing the electrochemical potentials  $\mu_{\text{res}}$  of the reservoirs,  $\mu_1$  of LL<sub>1</sub> and  $\mu_2$  of LL<sub>2</sub> for different numbers of electrons  $N_i$  in LL<sub>1</sub>. The width of the thick dashed line represents the applied bias voltage across the dot.  $E_{12}$  and  $E_1$  denote the energy changes when  $N_i$  is changed. The left hand side shows schematically the conductance  $G$  when the gate voltage  $V_C$  is varied.

of the thermal energy, which results in a split peak (see Fig. 4). As we will show below,  $\delta$  can also be changed with the magnetic field. This mechanism is responsible for the evolution of a regular peak into a split peak in Fig. 2.

We have performed an additional experiment to investigate the magnetic field dependence of the switching. Figure 5 shows the conductance through the dot versus magnetic field in the time-resolved regime of Fig. 3. The conductance changes in a sawtooth way and at slowly increasing intervals [15] of the magnetic field the conductance switches between two sawtooths. Around 5.5 T, the magnetic field interval is 40 mT, which corresponds to adding one flux quantum  $h/e$  to a disk with a diameter of 320 nm.

Threading an extra flux quantum through the dot depopulates LL<sub>2</sub> with one electron and populates LL<sub>1</sub> with one electron. The magnetic field changes the self-consistent charge distribution in the dot. This increases  $\mu_2$  relative to  $\mu_1$  until it is energetically favorable to transfer one electron from LL<sub>2</sub> to LL<sub>1</sub> [4], for example, when the initial and final states of the tunneling electron have the same energy ( $\delta = 0$  in Fig. 4). This internal charging process changes  $\mu_1$  in a discrete way, which results in a switch in the conductance (see Fig. 5) [16]. Each time when one flux quantum is added to the dot, internal charging processes can occur. Note that multiple switching occurs at some magnetic fields and that the switching rate decreases with magnetic fields. This is further illustrated in the inset of Fig. 5 which shows two regular peaks and one split peak versus gate voltage at

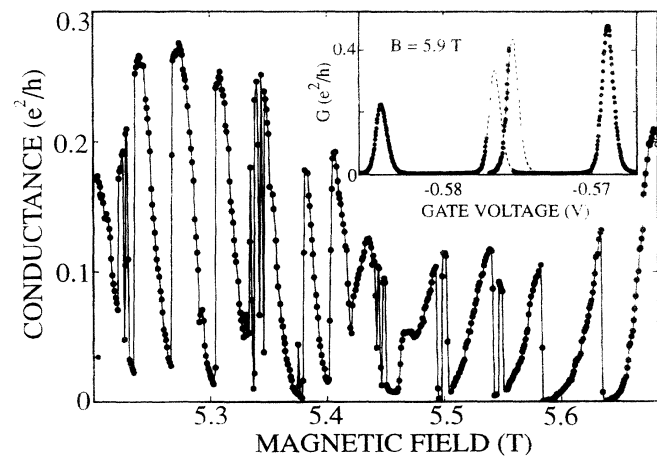


FIG. 5. Conductance through the dot as a function of magnetic field, illustrating that the frequency of switching decreases with field using a time constant of 500 ms. A switch between two sawtooths occurs when one electron tunnels from the ring to the core or vice versa. Inset shows a measurement of the conductance  $G$  versus gate voltage at a field of 5.9 T, showing a split peak and two regular oscillations. The trace is taken in 300 s. We have added dashed lines as a guide for the eye.

a field of 5.9 T. The two branches of the split peak are clearly visible and switching between them occurs only twice now, while in the lower field regime of Fig. 3 more frequent switching was observed.

We have shown that the gate voltage and the magnetic field allow an experimental tuning of the two-level switching. Theoretically it is possible to describe the internal charging energies in terms of a capacitance model [6, 17], with which we have been able to calculate the split peaks and regular pattern of Fig. 2, including the magnetic field dependence [14]. However, the dynamics of scattering between the Landau levels is still unknown. The macroscopic time scale of 100 s has some striking implications. If we assume that the drift velocity of the electrons along the circumference of the dot is about  $10^4$  m/s [1], we obtain an enormous length scale of 1000 km before an electron is scattered to another quantum Hall state. In order to explain the long time scale one needs to consider both the shape of the incompressible strip and the many body interactions in the two Landau levels. For noninteracting electrons the transmission probability through the incompressible strip depends exponentially on the strip width. Since the strip width increases with magnetic field [5], this could lead to a strong suppression of tunneling when the magnetic field is increased, but the exponential dependence makes it difficult to compare our results with the presently available theories. However, we would like to emphasize that scattering between the quantum Hall states involves a rearrangement of the charge distribution in the dot. The macroscopic time scale between two tunnel events is presumably related to such a kind of many body rearrangement [18]. In this respect, our experiment may be related to the observed suppression of tunneling into quantum Hall states in a bulk 2DEG [19]. We expect that a study of the temperature dependence and the characteristics of the switching will further clarify the dynamics of scattering between confined quantum Hall states.

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