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LETTER TO THE EDITOR

Detecting charge redistribution between edge states in a quantum dot

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Abstract. Coulomb blockade oscillations in a laterally confined quantum dot are modulated in a magnetic field by a larger oscillation whose period is proportional to the number of filled Landau levels in the dot. In this experiment an additional separate higher-frequency oscillation is observed on top of this structure which may be due to the rearrangement of charge within the dot. These effects are still observed when the total conductance exceeds $2e^2/h$, and different Coulomb blockade periods are found when tunnelling into each of the first four Landau levels.

Charge transport through a weakly coupled quantum dot [1] is dominated by the charging energy associated with adding a single electron (e^2/C_Σ, where C_Σ is the total capacitance of the dot) at low temperatures. The conductance oscillates as the voltage on a capacitively coupled gate is varied, an effect known as Coulomb blockade (CB) oscillations [2, 3]. In a magnetic field CB oscillations persist at conductances, G, above e^2/h, and further structure is revealed [4, 5, 6].

Applying a magnetic field produces magnetic quantization of the electron energy levels, which form Landau levels (LL). Charge transport is now by means of edge states [7] and a split-gate constriction reflects consecutive edge states as it is pinched off. The magnetic field strength and the electron sheet carrier concentration fix the number of LLs present, and it is possible to tune a quantum dot to confine any number of these LLs whilst allowing charge transport via the edge states of the unconfined LLs. The edge state of the outer confined LLs may be close enough to the edge states in the leads to allow electrons to tunnel.

A lateral quantum dot is formed using patterned Schottky gates on top of a GaAs/AlGaAs heterostructure with a two-dimensional electron gas (2DEG) 700 Å below the surface. The ungated 2DEG has a mobility of 120 $m^2\ V^{-1}\ s^{-1}$ and a sheet carrier concentration of $n_s = (3.61 \pm 0.16) \times 10^{15}\ m^{-2}$. The Shubnikov–de Haas oscillations indicate that spin splitting of LLs occurs at fields $\geqslant$1.1 T. A diagram of the gate geometry is shown in the inset to figure 1. The lithographically defined dimensions of the dot are $0.75 \times 0.34\ \mu m$, with split-gate widths of 0.2 μm and a separate 'plunger' gate to change the size of the dot. On estimating the depletion width to be half of the split-gate separation (0.1 μm), the dot will be approximately $0.65 \times 0.24\ \mu m$ with $N \approx 400$ electrons. All experiments were performed in a dilution regrigerator with a base temperature $T < 20$ mK using AC biasing of 10 μV and phase-sensitive current detection.

In zero magnetic field, with both constrictions $G \ll e^2/h$, CB oscillations of period $\Delta V^{CB} = 12.3 \pm 0.5$ mV are observed when the plunger gate voltage is swept, allowing

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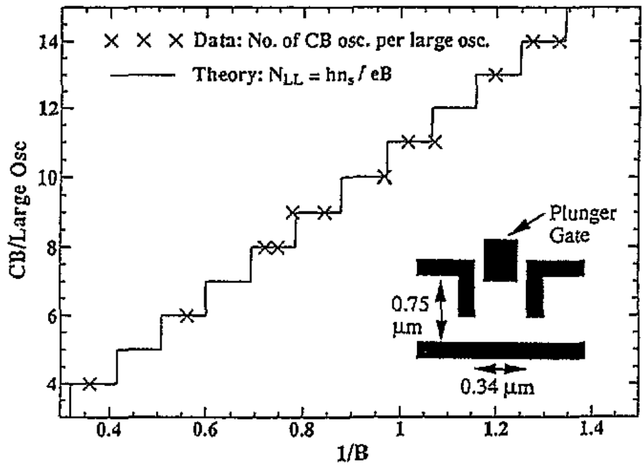

Figure 1. Data points: the number of small CB oscillations per large oscillation period as a function of inverse magnetic field. Line: the theoretical fit to the number of confined LLs in the dot as a function of inverse magnetic field, using an estimate of the sheet carrier density inside the dot, $n_s = 2.6 \times 10^{-15}$ m^{-2}. Inset: a schematic diagram of the gate geometry.

the capacitance of the plunger gate to be calculated. Sweeping each gate in turn allows the capacitance to be measured directly. Adding up all the capacitances, including regions of 2DEG separated from the dot by gates, gives the total capacitance $C_\Sigma = (2.9 \pm 0.2) \times 10^{-16}$ F and the change in electrostatic potential on adding an extra electron is $e/C_\Sigma = 550 \pm 30\ \mu$V. If the barriers are relaxed ($G \sim e^2/h$) periodic oscillations in the magnetoconductance are seen with period $\Delta B = 28 \pm 1$ mT. Interpreting these as Aharonov–Bohm (AB) oscillations [8, 9] gives an active area of $(1.5 \pm 0.1) \times 10^{-13}$ m^{-2} which agrees well with the area estimate above.

With an applied magnetic field and the conductance of both constrictions $G < e^2/h$, the CB oscillations are modulated by a longer oscillation (figure 2(a)) as observed by Staring *et al* [4] and Alphenaar *et al* [5]. The period of the large oscillation scales with the number of spin-split LLs in the dot ($N_{LL} = hn_s/eB$). On increasing the temperature, the large oscillations die out at temperatures $T \geqslant 400$ mK, whereas the small CB oscillations continue beyond $T = 1$ K. Figure 1 shows the number of CB oscillations per large oscillation period as a funtion of magnetic field for conductance $G < e^2/h$, together with a theoretical fit of the number of confined LLs in the dot.

The CB oscillations correspond to removing one electron from the dot per CB period, i.e. $\Delta N/\Delta V^{CB}$ = the reciprocal of the CB period. If the large-period oscillation is attributed to AB oscillations in the outer edge state, the rate of change of area enclosed by this edge state with gate voltage $\Delta V^L/\Delta A$, can be obtained. Combining this with the reciprocal CB period gives the local sheet carrier concentration in the dot as $\Delta N/\Delta A = (2.6 \pm 0.2) \times 10^{15}$ m^{-2}. This value is lower than the bulk 2DEG obtained from the Shubnikov–de Haas method, but a remarkably good fit is found if it is used to determine the number of LLs present in the dot at various fields (the theoretical fit in figure 1).

Relaxing the barrier heights of the split-gate constrictions increases the conductance through the dot. The behaviour of the dot may be followed from just CB oscillations at very low conductances ($G \ll e^2/h$), to modulated CB oscillations ($G < e^2/h$). These continue when the conductance rises above e^2/h and also $2e^2/h$, corresponding to one and two transmitted spin-split edge states respectively. This behaviour was originally thought to be

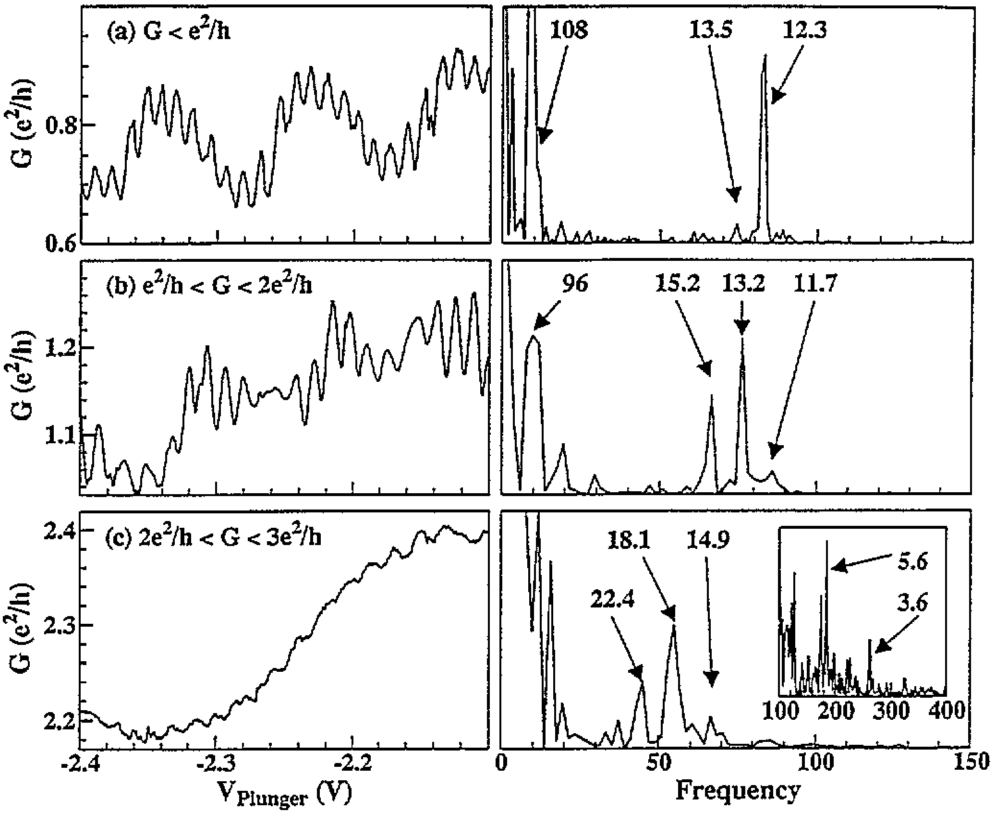

Figure 2. The CB and large-period oscillations for different total dot conductances with power spectra. The period in millivolts for each peak is indicated on each power spectrum. (a) $G < e^2/h$. (b) $G > e^2/h$. (c) $G > 2e^2/h$. Inset: the high-frequency oscillations for the fourth and fifth LL (see the text).

due to the AB effect [9]. Later work demonstrated that the Aharonov–Bohm effect and CB in a dot must be linked [6].

The oscillations are modified each time another edge state is included into the charge transport. Figures 2(a) and 2(b) show data in which the dot conductance increases from $G < e^2/h$ to $G > e^2/h$, and figure 2(c) shows data taken for $G > 2e^2/h$, together with the respective power spectra.

As the conductance G increases through e^2/h (figures 2(a) and 2(b)), the CB oscillation evolves into two distinct periods of 13.2 and 15.2 $\pm$ 0.5 mV, with a possible small contribution of a third period at 11.7 $\pm$ 0.5 mV. There are eight LLs in the dot at a field of 1.285 T. Above $G = e^2/h$, only $(N_{\mathrm{LL}} - 1)/N_{\mathrm{LL}}$ of the original number of electrons are confined. The cacpacitance between the gate and the confined electrons will have changed by the same ratio $(N_{\mathrm{LL}} - 1)/N_{\mathrm{LL}}$ (see figure 4), and the CB period should therefore change by the inverse of this ratio. Similarly if electrons are also tunnelling directly into the third LL (i.e. the next confined LL) in parallel with the other transport, then a separate dot with $N_{\mathrm{LL}} - 2$ confined LLs should be observed. The measured periods of ΔV^{CB} are in the ratios $15.2 : 13.2 : 11.7 \approx \frac{1}{6} : \frac{1}{7} : \frac{1}{8}$. The CB oscillations are interpreted as direct tunnelling into the thrid, second and first LLs. Note that even though the total dot conductance just exceeds $G = e^2/h$, the edge state of the first LL is not yet fully transmitted. The period of first LL has decreased (11.7 mV above $G = e^2/h$ compared with 12.3 mV below) since relaxing the tunnel barriers allows the edge state to get a little larger, increasing its capacitance to the gate.

Above $G = 2e^2/h$ the conductance trace, figure 2(c), gets more noisy. The Fourier analysis of the data reveals three CB peaks at 14.9, 18.1 and 22.4 mV. The 14.9 mV peak corresponds to six confined LLs in the dot: this was at 15.2 mV when $G < 2e^2/h$, and a shift to a shorter period is expected as described above. The 18.1 and 22.4 mV periods correspond to direct tunnelling into the fifth and fourth LLs respectively, with the ratios $22.4 : 18.1 : 14.9 \approx \frac{1}{4} : \frac{1}{5} : \frac{1}{6}$. The sixth LL is sufficiently well coupled to the leads that the CB in that particular LL is much reduced, possibly by one of the barriers being lower than the other.

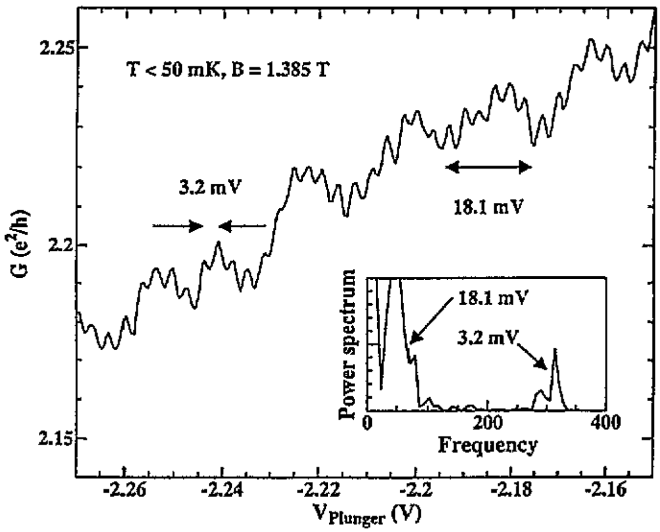

Figure 3. High-frequency oscillations (of period $\simeq 3.2$ mV) coexisting with CB oscillations of period 18.1 mV. $G > 2e^2/h$. Inset: the power spectrum of the data.

In addition to the CB oscillations and the long-period modulation there is another very-high-frequency oscillation present in some of the data for $G > 2e^2/h$. These oscillations have a period of 3–6 mV: figure 3 shows a situation where these oscillations coexist with CB oscillations.

The tunnelling probability is affected by the overall charge on the inner LLs, giving rise to the long-period modulation of the CB. It may also be affected by the arrangement of electrons in the inner LLs. For a CB oscillation to occur, an electron in an inner LL must jump through successive LLs until it reaches a LL from which it may tunnel into the leads. Although the charge on the dot has not changed, the electrostatic potential of a LL will vary slightly from that of its neighbours due to the capacitative coupling between the edge states (see figure 4). The rate of tunnelling into and out of the outer confined LL should be sensitive to the arrangement of charges between the inner LLs; the outer confined LL is acting as a detector of the local potential generated by the inner LLs.

The data shown in figure 3 were taken at a slightly different magnetic field (1.385 T compared with 1.285 T for the previous data). There are still eight LLs present and, since the conductance $2e^2/h < G < 3e^2/h$, two of the eight edge states are fully transmitted.

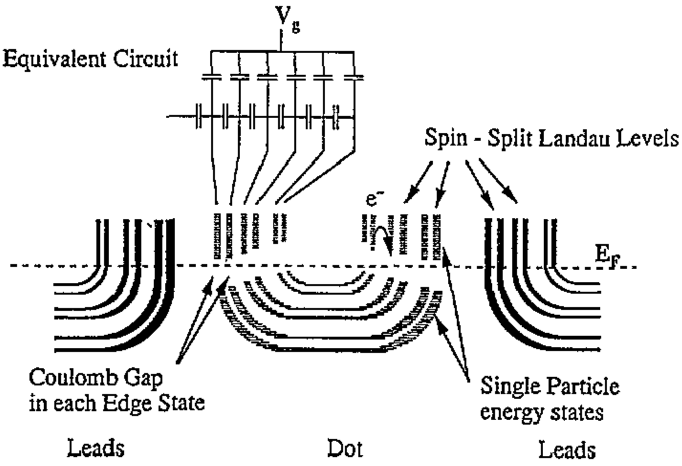

Figure 4. A schematic diagram of the energy levels of the dot and leads, including an equivalent circuit showing all the various capacitative couplings. Each edge state is made up of many single-particle states and has a Coulomb gap. Electrons have sufficient thermal energy to tunnel from one edge state to another, changing the electrostatic potential of one edge state with respect to the others.

The entrance and exit tunnel barriers were set slightly differently, and the Fourier spectrum of these data (inset to figure 3) shows that the CB with period 18.1 mV is dominant, due to direct tunnelling into the fifth LL. If the high-frequency oscillation is due to the tunnelling rate being sensitive to the arrangement of electrons on the four LLs within the edge state of the fifth LL, then the frequency should reflect the possible arrangements of charge between the fifth and all the inner LLs, i.e. five possible configurations of charge. Alternatively if tunnelling to the sixth LL was occurring, it would pick up six different arrangements of charge. The measured ratio is $18.1/3.2 \simeq 5.7$.

For the data shown in figure 2(c), the high-frequency spectrum should be more complicated since there are three periods of CB oscillation present of 22.4, 18.1 and 14.9 mV, corresponding to direct tunnelling into the fourth, fifth and sixth LL respectively. Using the model suggested above, the high-frequency oscillations should thus appear at $22.4/4 = 5.6$ mV, $18.1/5 = 3.6$ mV and $14.9/6 = 2.5$ mV. The high-frequency spectrum, figure 2(c), of the data shows two distinctive peaks at the frequencies predicted for the fourth and fifth LLs. The peak for the sixth LL, if present, is well within the noise. The Fourier spectra of the data taken below $G = 2e^2/h$ do not show any clear high-frequency oscillations.

At this particular magnetic field the LLs are only just spin split, i.e. the energies of the (first, second), (third, fourth), (fifth, sixth), and (seventh, eighth) LLs are almost equal and these edge states are very close to each other spatially (see figure 4). Therefore the coupling required to produce the high-frequency oscillations will be much stronger above $G = 2e^2/h$ when tunnelling directly into the sixth LL is picking up the charge rearrangement in the fifth LL. Below $G = 2e^2/h$, the edge states involved in direct tunnelling to the leads may well be too far away for the potential variation on inner LLs to be picked up.

In conclusion we have measured the conductance of a quantum dot in a magnetic field and found both small- and large-period CB oscillations superimposed. The periodicity of the CB oscillations is seen to change, reflecting tunnelling into inner confined LLs . A high-frequency oscillation is observed which may correspond to detection of charge redistribution between edge states.

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