ELSEVIER

Physica E 6 (2000) 495–498

PHYSICA E

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Detection of Coulomb charging around an antidot

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Abstract

We have detected oscillations of the charge around a potential hill (antidot) in a two-dimensional electron gas as a function of a perpendicular magnetic field B . The field confines electrons around the antidot in closed orbits, the areas of which are quantised through the Aharonov–Bohm effect. Increasing B reduces each state's area, pushing electrons closer to the centre, until enough charge builds up for an electron to tunnel out. This is a new form of the Coulomb blockade seen in electrostatically confined dots. We have also studied $h/2e$ oscillations and found evidence for coupling of opposite spin states of the lowest Landau level. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 73.23.Hk; 73.40.Gk; 73.40.Hm

Keywords: Antidots; Coulomb blockade; Quantum Hall effect; Aharonov–Bohm effect

Coulomb blockade (CB) in an open system sounds paradoxical. CB arises from the discrete charge of an electron. For charging to happen, it has been generally believed that electrons must be electrostatically confined in a small cavity. Although it has recently been reported that “open” dots can also show charging effects [1–3], they are not completely open systems, still having some degree of electrostatic confinement.

In contrast, an antidot, which is a potential hill in a two-dimensional electron gas (2DEG), is in a completely open system. Thus it has often been assumed that CB does not occur when an electron tunnels through a state bound around an antidot by a large perpendicular magnetic field B (> 0.2 T). Here, electron waves travel phase-coherently around the antidot with quantised orbits, each enclosing an integer number of magnetic flux quanta h/e through the Aharonov–Bohm (AB) effect. Where the potential is sloping, these single-particle (SP) states have distinct energies. Conductance oscillations observed as a function of B or gate voltage have been attributed to resonant tunnelling through such discrete states from one edge of the sample to the other. This causes resonant

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backscattering or transmission depending on the tunnelling direction [4]. Up until now, no charging effect has been taken into account in the system [5,6]. However, Ford et al. [7] proposed that antidot charging should be present to explain double-frequency AB oscillations, where two sets of resonances through the two spin states of the lowest Landau level (LL) were found to lock exactly in antiphase, giving $h/2e$ periodicity, and to have the same amplitudes in spite of different tunnelling probabilities [7,8]. There is as yet no full explanation for these phenomena.

The aim of this paper is to demonstrate that magnetic confinement causes charging in antidot systems, although there is no electrostatic confinement. We have conducted non-invasive detector experiments [9] and obtained clear evidence of charge oscillations around an antidot as a function of B [10]. We have also investigated $h/2e$ AB conductance oscillations. The data show that the resonance only occurs through states of one spin, explaining the matched amplitudes.

The samples were fabricated from a GaAs/AlGaAs heterostructure containing a 2DEG of sheet carrier density $2.2 \times 10^{15} \text{ m}^{-2}$ with mobility $370 \text{ m}^2/\text{Vs}$. An SEM micrograph of a device is shown in Fig. 1(a). A square dot gate (G_{dot}), $0.3 \mu\text{m}$ on a side, was contacted by a second metal layer evaporated on top of an insulator (not shown) to allow independent control of gate voltages. The lithographic widths of the antidot and detector constrictions were 0.45 and $0.3 \mu\text{m}$, respectively. All constrictions showed good 1D ballistic quantisation at $B = 0$. A voltage of -4.5 V on the separation gate (G_{sep}), of width $0.1 \mu\text{m}$, divided the 2DEG into separate antidot and detector circuits. The detector gate (G_{det}) squeezed the detector constriction to a high resistance to make it very sensitive to nearby charge. To maximise the sensitivity, trans-resistance measurements were made by modulating the dot-gate voltage (or the voltage on the side-gate G_{side}) at 10 Hz with 0.5 mV rms and applying a 1 nA DC current through the detector constriction. Simultaneously, the transconductance of the antidot circuit was measured with a $10 \mu\text{V}$ DC source-drain bias, when necessary. The experiments were performed at temperatures down to 50 mK .

Figs. 1(b) and (c) show the transresistance $-dR_{\text{det}}/dV_{G-\text{side}}$ (transconductance $dG_{\text{ad}}/dV_{G-\text{side}}$) versus B of the detector (antidot) circuit in two different field regions: (b) $\nu_c = 2$ and (c) $\nu_c < 1$, where ν_c is the filling

factor in both antidot constrictions, which were determined from the conductance G_{ad} . The filling factors in the bulk 2DEG were $\nu_b = 7$ and 2 , respectively. The oscillations in G_{ad} occur as SP states around the antidot rise up through the Fermi energy E_F . The AB effect causes the overall period ΔB to be h/eS , where S is the area enclosed by the state at E_F . The curve in (b) has pairs of spin-split peaks, whereas in (c) only one spin of the lowest LL is present. The dips in $-dR_{\text{det}}/dV_{G-\text{side}}$ correspond to saw-tooth oscillations in the change ΔR_{det} from the background resistance (see Fig. 1(d)). Here, note that a small increase in B or decrease in V_G has a similar effect on the SP states. Hence, integration with respect to B and $-V_G$ are qualitatively equivalent. Thus the net charge Δq nearby suddenly becomes more positive (making the effective gate voltage less negative) whenever the antidot comes on to resonance (since the dips line up with the zeros in $dG_{\text{ad}}/dV_{G-\text{side}}$). The charging signals are not dependent on the presence of conductance oscillations in the antidot circuit. It is still possible to observe the signal with no applied bias in the antidot circuit, or when the side-gate voltage is set to zero so that there is no tunnelling between that edge and the antidot. Hence we conclude that this charge oscillation is associated with states near the antidot, and interpret it as CB.

Before showing how the charging occurs, it is worth reconsidering the shape of the antidot potential. The conventional picture is a potential hill smoothly increasing towards the centre as shown dotted in Fig. 2(a). However, for $B > 0$, such a potential would require abrupt changes in the carrier density where LL intersect E_F , which is not electrostatically favourable. Chklovskii et al. [11] treated such a problem along the edge of a 2D system and introduced alternating compressible and incompressible strips. Compressible strips require flat regions in the self-consistent potential as depicted by a solid line in the figure. It has always been considered that the potential should not be completely flat in antidot systems [6], since the presence of several SP states at E_F makes AB conductance oscillations impossible in the simple non-interacting picture. However, if CB of tunnelling into the compressible region occurs, conductance oscillations with periodicity h/e can still occur for such a self-consistent potential.

We explain the charging as follows. As B increases, each SP state encircling the antidot moves inwards,

Fig. 1. (a) SEM micrograph of a device prior to second metallisation; (b) and (c) dG_{ad}/dV_{G-side} of the antidot circuit and $-dR_{det}/dV_{G-side}$ of the detector circuit with the gate voltage on G_{side} modulated in two different regimes: (b) $\nu_c = 2$ and (c) $\nu_c < 1$. Vertical dashed lines show the alignment of the dips in the detector signal with zeros in the transconductance oscillations; (d) Illustration of the relation between various lineshapes. Grey lines in Δq and ΔR_{det} are the ideal case, and black curves represent broadened lineshapes.

Fig. 2. Cross-section through the antidot: (a) energy of the lowest LL near the antidot and (b) carrier density distribution. The conventional and self-consistent pictures are shown as dotted and solid lines, respectively. A bulk LL, which is reflected from the constrictions, is also shown. The vertical dash-dotted lines indicate the edges of a compressible region.

reducing its area to keep the flux enclosed constant. This results in a shift of the electron distribution towards the antidot centre. One may think such a shift should not occur due to screening in the compressible region. However, since each state is discrete and

is trapped around the antidot, and the incompressible regions obviously have one electron per state, the total number of electrons in the compressible regions must be an integer. Hence the compressible region also moves inwards with the states. As a result, a net charge Δq builds up in the region. When it reaches $-e/2$, one electron can leave the region and Δq becomes $+e/2$. This is when resonance occurs, as for CB in a dot. At the same time, the compressible region, by losing the innermost state and acquiring one at its outer edge, shifts back to its original position just after the previous resonance. The same argument also applies, of course, even if there is no compressible region, as the states are still discrete.

As in quantum dot systems, the SP energy spacing ΔE_{sp} and the charging energy e^2/C together determine when resonance occurs (C is the capacitance of the antidot). We have deduced these energy scales from the temperature dependence of the charging signals and the antidot conductance oscillations, and the DC-bias measurements of the differential antidot conductance. The detailed analysis is given in Ref. [10]. We found that ΔE_{sp} decreases as $1/B$, as expected. In contrast, Maasilta and Goldman [6] found an almost

Fig. 3. AB conductance oscillations: the two constrictions were squeezed symmetrically between traces, which are offset by $0.2e^2/h$ down the page for clarity. Around $B = 2.6$ T the pure $h/2e$ oscillations are not completely established. The diagrams at right show the geometry of edge channels (solid lines) at around $B = 2.8$ T. The black boxes indicate surface gates. Tunnelling between edge channels is represented by a dotted line.

constant energy gap, which we interpret as the interplay of ΔE_{sp} and a charging energy which is small at low B and saturates at high B .

The presence of charging should help to explain the $h/2e$ AB oscillations. Fig. 3 shows AB conductance oscillations as both constrictions are narrowed keeping the symmetry. On the $\nu_c = 1$ plateau the outer spin state is excluded from the constrictions. Peaks up from this plateau for $B < 2.7$ T are due to inter-LL resonant transmission [4]. This is only noticeable when resonant backscattering is absent, i.e., on the plateau, and is irrelevant in the arguments here. We focus on the resonant backscattering process, which is caused by intra-LL scattering in the constrictions (see diagrams at the right of Fig. 3). The tunnelling probability into the antidot states from the current-carrying edges is controlled by the side-gate voltages. The flat

$\nu_c = 1$ plateau implies that there is no tunnelling into the inner spin state. Hence, at higher ν_c at the same field, where the constrictions are wider, there can also be no such tunnelling, despite the presence of $h/2e$ oscillations. It is not yet clear why the outer spin states should come on to resonance twice per h/e period; however, the equal amplitude of the resonances can be explained since the tunnelling probability for that spin should be almost the same for each resonance.

In conclusion, we have used a non-invasive charge detector to show that tunnelling into antidot states is Coulomb blocked. When states of both spins are occupied, $h/2e$ oscillations are seen but tunnelling is only via states of one spin, showing that there is a strong coupling with states of the other spin.

Acknowledgements

This work was funded by the UK EPSRC. We thank C.H.W. Barnes and C.G. Smith for useful discussions. M.K. acknowledges financial support from Cambridge Overseas Trust.

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