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Coulomb blockade of the Aharonov-Bohm effect in $GaAs/Al_xGa_{1-x}As$ quantum dots

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We study the effect of Coulomb blockade (CB) on the Aharonov-Bohm (AB) oscillations, observed in the magnetoresistance of small dots in both the quantum Hall and tunneling regimes. In the quantum Hall regime, where one or more edge states pass freely through the dot, the period of oscillation ΔB is well correlated to the dot size, and the temperature-dependent decay of the oscillations is consistent with the expected form of the single-particle magnetospectrum. In the tunneling regime, however, ΔB is enhanced by more than two orders of magnitude over the value expected from the size of the dot, and the resulting oscillations persist to above a degree Kelvin. This behavior can only be explained by considering the effect of CB on the magnetic depopulation of electrons from the isolated dot; these magneto-Coulomb oscillations are the magnetic analogue of the CB oscillations more conventionally observed using electrostatic techniques. These results demonstrate that by varying the coupling of the dot to the source and drain, the resulting AB oscillations can be used to separately probe both the single-particle and CB-related energy scales of small dots.

I. INTRODUCTION

As is now well understood, electronic transport through isolated quantum dots can be dominated by the effects of Coulomb blockade (CB) at low temperatures.[1] An important criterion for the observation of such effects is that charge within the dot should be well defined. This condition is usually satisfied by employing devices with a double-tunnel-barrier structure to regulate the transmission of electrons through the dot. At zero magnetic field, CB effects are then found to suddenly emerge, once the resistance of both carriers is increased above $h/2e^2$. If, however, the resistance of either barrier is lowered below $h/2e^2$, electrons can flow freely into the dot, and the resulting charge fluctuations render the CB effects unobservable.[1] In the presence of a quantizing magnetic field the situation is more complex, however. Current is carried by edge states and, since each of these follow different equipotential guiding centers, a potential barrier can be used to selectively reflect or transmit them.[2] In small dots, formed by fabricating two point contacts in close separation, an important consequence of this phenomenon is the ability to confine certain edge states within the dot.[3] Under these conditions, since charge is able to flow through the dot via the remaining transmitted edge states, we might expect the effects of CB to be unobservable. However, even though the dot is no longer isolated from the source and drain, some recent reports[4–7] suggest that at high magnetic fields CB effects can persist well into the quantum Hall regime.

In this paper we study the effect of CB on the Aharonov-Bohm (AB) oscillations,[8] observed in the magnetoresistance of small dots, in both the quantum Hall and tunneling regimes. The oscillations are associated with the confinement of edge states within the dot, which quantizes the energy spectrum of each edge state into a discrete ladder of single-particle states.[9] As the magnetic field is varied successive states are then swept past the Fermi level and, since these provide an additional path for the scattering of electrons, oscillations are observed in the magnetoresistance. The scattering can result in either a resonant transmission or reflection of electrons. The former occurs when an edge state is partially transmitted through the point contacts of the dot. The edge state can then be considered as a superposition of extended and confined components, and resonant transmission from source to drain occurs each time a single-particle state of the confined component is coincident with the Fermi level[3] (inter-Landau-level process). In the case of resonant reflection, an electron backscatters between the fully transmitted, but oppositely propagating, edge states of the same Landau level, via a separate edge state confined within the dot[5] (intra-Landau-level process). Ignoring the effects of electron interaction, a single-particle state is swept past the Fermi level each time the flux enclosed by the confined edge state is increased by one quantum.[9] At high magnetic fields the period of the AB oscillations should then be approximately related to the area of the dot A ($\Delta B = h/eA$). More recently, however, it has been argued that the oscillations actually probe an addition spectrum due to single-particle and CB effects.[6] In particular, since at high magnetic fields successive edge states are isolated from each other by bands of incompressible electron gas,[10,11] charge associated with the confined edge states should be well defined. Tunneling into one of these is then predicted to incur a characteristic charging energy, and the period of oscillation should provide a measure of this[6] ($\Delta B \neq h/eA$).

With respect to this issue we observe that in the quantum Hall regime, where one or more edge states pass freely through the dot, ΔB is well correlated to the dot size in good agreement with single-particle predictions. In contrast, in the tunneling regime all edge states in the dot are localized and ΔB is enhanced by more than two orders of magnitude over the value expected from single-particle considerations. We associate this with the influence of

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CB effects in the tunneling regime, and show that the observed period is consistent with the depopulation of single electrons from the dot, on a field scale determined by the dot charging energy.[8,12] We supplement our conclusions with studies of the magnetic field, temperature, and gate-voltage dependence of the oscillations, and with calculations of the self-consistent potential profiles and energy spectra of the dots. Finally, we briefly discuss the observation of telegraph noise[13] in the magnetoresistance when transport is in the tunneling regime. The typical time scale between switching events is of the order of tens of minutes at the highest fields, and we compare our results with a recent study which relates the transmission properties of small dots to the redistribution of single units of charge within them.[14]

II. DEVICE FABRICATION AND EXPERIMENTAL TECHNIQUES

Dots were realized using a standard split-gate technique, in which aluminum gates, defined by electron-beam lithography, were deposited on a $GaAs/Al_xGa_{1-x}As$ wafer.[12] The wafer was patterned into a Hall bar geometry, and had a typical carrier density of $3.5-4.4\times10^{15}$ m^{-2}, and mobility 35–40 $m^2/V\,s$. The devices consisted of a stublike design, in which a central dot was separated from the source and drain by quantum-point contacts. Here we present results from measurements on lithographically square dots with sides of 1 and 2 μm. The samples were clamped to the mixing chamber of a dilution refrigerator, and four-terminal, audio-frequency, magnetotransport measurements were made at cryostat temperatures down to 10 mK. The probe configuration corresponded to a two-terminal measurement, sensitive only to edge-state transmission through the dot[12] [Fig. 1(a) inset]. Great care was taken to ensure good thermal contact to the samples, and a source-drain excitation of 3 μV was typically employed.

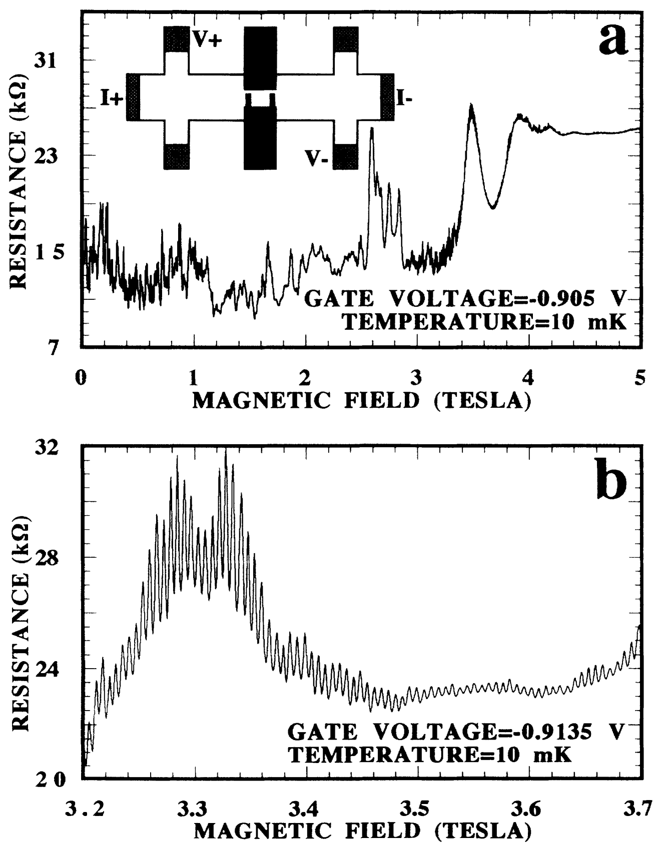

FIG. 1. (a) Low-temperature magnetoresistance of a 1-μm dot. The inset shows a schematic diagram of the dot geometry, with the gates shown in black. Current was passed from leads $I+$ to $I-$, and the corresponding voltage drop was measured between $V+$ and $V-$. The lithographic length and widths of the individual point contacts, were 150 and 200 nm, respectively. (b) An expanded view of (a) reveals AB-type oscillations in the magnetoresistance.

III. EXPERIMENTAL RESULTS

A. Quantum Hall regime

We first consider the results in the quantum Hall regime, where the gate voltage is configured to allow one or more edge states to pass freely through the dot. At the lowest magnetic fields large fluctuations are observed in the magnetoresistance,[15] but as the magnetic field is increased and the edge states form these eventually give way to rough plateaulike features, close to the predicted quantized values[2] [Fig. 1(a)]. A striking feature of the data is the series of periodic oscillations, observed as the magnetic field is swept between successive resistance plateaus [Fig. 1(b)]. When the oscillations first emerge (2.8 T), comparison of the dot and bulk magnetoresistance indicates that two spin-resolved edge states (filling factor $\nu=1$ and 2) are passing through the dot, while an additional six are confined within it. As the magnetic field is further increased, the $\nu=2$ edge state begins to be reflected by the point contacts of the dot, and the oscillations grow in amplitude. Finally, the oscillations quench as the magnetic field is swept on to the last plateau, corresponding to complete confinement of the $\nu=2$ edge state (4 T). At this magnetic field only one edge state is fully transmitted through the dot, and a further three are confined within it. The oscillations are therefore consistent with the resonant transmission of electrons, via the localized component of the partially transmitted $\nu=2$ edge state[3] (Fig. 2). In the absence of charging effects, their period should correspond to the field required to alter the enclosed flux of the edge state by one quantum.[9] Plotting the magnetic-field positions of successive minima, we find approximately periodic behavior across the entire range of observation [Fig. 3(a)]. Since several Landau levels depopulate over this range, the observation of a single period is consistent with our assignment of the oscillations to the $\nu=2$ edge state, and presumably reflects the (exponentially) weaker probability for tunneling into the innermost confined edge states.[4] Equating the average period of oscillation ($\Delta B=6.3$ mT) to a flux change of one quantum, we deduce an area of 0.8×0.8 μm^2 for the corresponding confined edge state. This is in

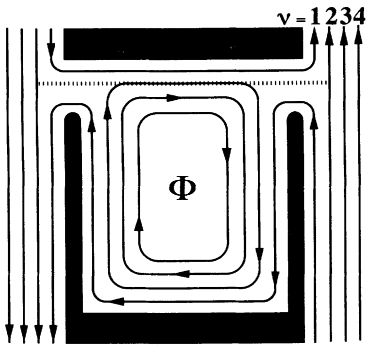

FIG. 2. Schematic diagram of the edge-state configuration in the dot of Fig. 1 at 4 T. Shaded regions correspond to gates, and the magnetic field points out of the page. The edge states are spin resolved, and only the lowest one is fully transmitted through the dot. We associate the AB oscillations with a modulation of tunneling of the partially transmitted $\nu=2$ edge state, via its trapped component in the dot (broken line).

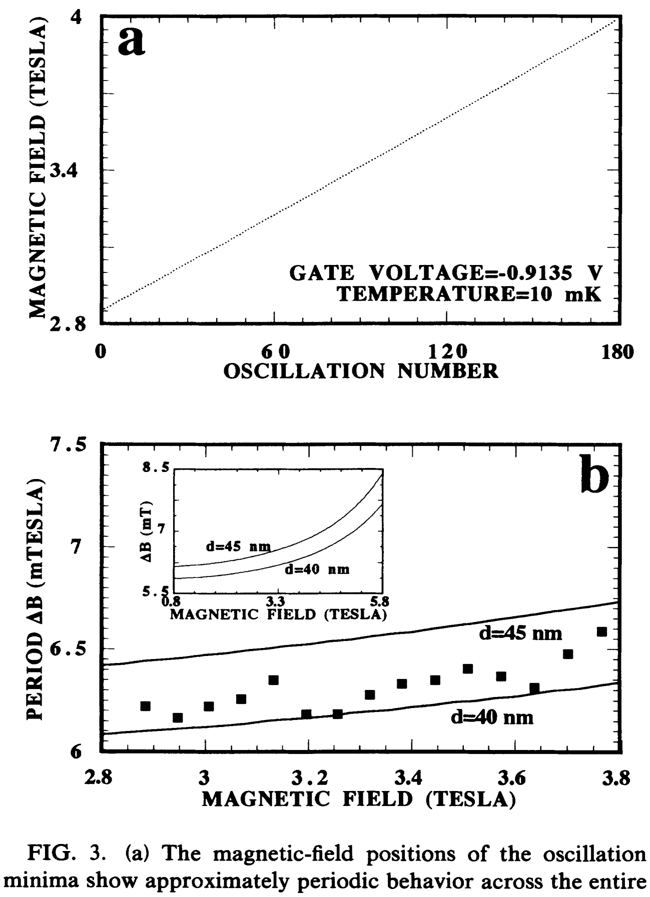

FIG. 3. (a) The magnetic-field positions of the oscillation minima show approximately periodic behavior across the entire field range. (b) Closer inspection, however, reveals the period ΔB increases weakly with magnetic field. Each data point was obtained by averaging over a set of ten consecutive oscillations, and the solid lines are fits to the theory of Ref. 9 for the $\nu=2$ edge state (see text for further details).

good agreement with the lithographic dimensions of the dot, and with self-consistent potential profile calculations[12] (Fig. 4). A small variation in ΔB with magnetic field can be resolved [Fig. 3(b)], but we associate this with a magnetically induced change in the edge-state position[2,3] (Sec. IV, below).

With increasing temperature the oscillations weakened exponentially, until they could no longer clearly be resolved above 0.5 K (Fig. 5). Typically, we expect two processes to contribute to thermal averaging of the oscillations: thermal smearing ($k_B T$), which obscures the discrete nature of the single-particle states and inelastic scattering, which randomizes the phase of the electron as it propagates across the dot. In order to clarify which is the dominant mechanism, we calculate noninteracting single-particle magnetospectra from the self-consistent potential profiles of the dots.[12] While a more detailed description of the calculations will be reported elsewhere,[16] the purpose here is to establish the connection between the experimentally observed behavior, and the predicted spectral characteristics. For the 1-μm dot of Fig. 5 we estimate a single-particle level spacing of 40 μeV in the vicinity of the Fermi level at 3.5 T, consistent with previous estimates.[3,9] This is also in agreement with the observed temperature scale for the quenching of the oscillations, suggesting that thermal obscuring of the single-particle states is the dominant mechanism. The situation therefore appears to be different to that in disordered metal rings, where inelastic scattering gives rise to

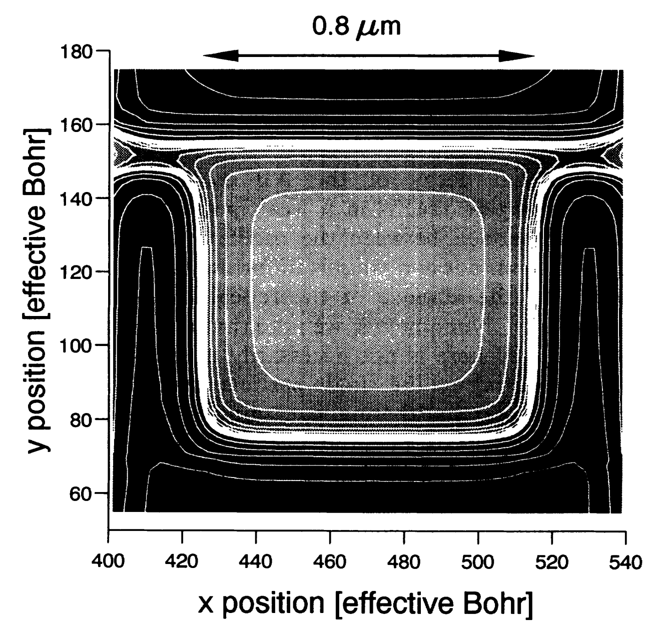

FIG. 4. Contour plot for a dot with a lithographic inner dimension of 1 μm, obtained from a Thomas-Fermi self-consistent electronic-structure calculation at zero magnetic field. The contours are irregularly spaced, with the innermost contours separated by -2.6 effective rydbergs (approximately -15 meV), and the next eleven are spaced 0.4 effective rydbergs apart. The remaining five contours are spaced at greater intervals.

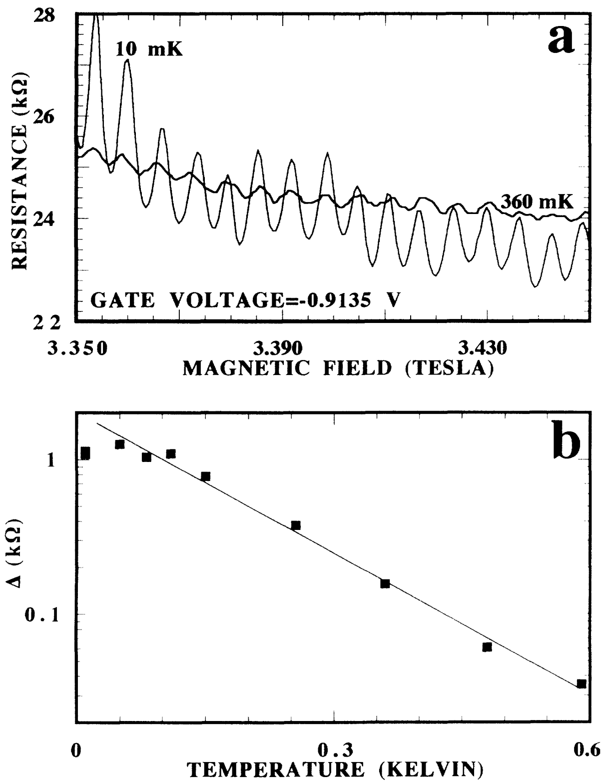

FIG. 5. (a) AB oscillations in a 1-μm dot at two distinct temperatures. (b) The root-mean-square amplitude of oscillation Δ in the same dot decays exponentially with increasing temperature. Δ was obtained by subtracting a monotonic background from the oscillations, and then averaging over a field range containing more than 30 oscillations. The solid line is a least-squares exponential fit to the data.

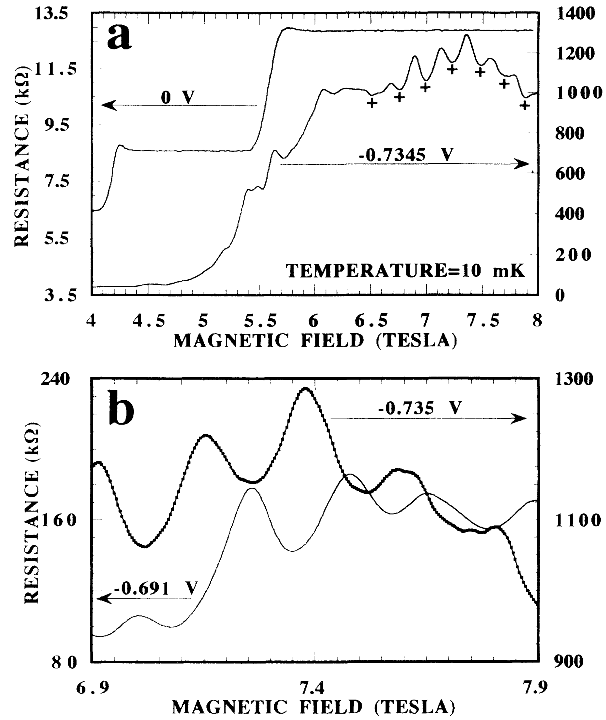

FIG. 6. (a) Magnetoresistance oscillations observed in the tunneling regime of a 2-μm dot. Crosses mark the position of successive oscillations. (b) An expanded view of the oscillations at two distinct gate voltages.

an exponential decay of the AB oscillations,[17] and thermal averaging results in a weak power-law decay.[18] Direct comparison between the oscillations in the two types of system (dot and ring) is unfortunately hampered, however, by the absence of theoretical predictions for quantum dots. Nonetheless, we note that the exponential decay observed here is not necessarily inconsistent with thermal smearing of the single-particle states and point out, for example, that thermal averaging is known to give rise to the (quasi)exponential decay of Shubnikov–de Haas oscillations.[19] We therefore conclude that in the quantum Hall regime, both the magnetic-field and temperature-dependent characteristics of the AB-type oscillations are in good agreement with single-particle predictions for quantum dots.

B. Tunneling regime

The transition from the quantum Hall to the tunneling regime is indicated by the magnetoresistance rising sharply above the last plateau, as the magnetic field is increased beyond some characteristic value B_1 [Fig. 6(a)]. We associate the resistance rise with the guiding center of the lowest edge state dropping below the saddle potential of the dot point contacts,[20] which then act as magnetically defined tunnel barriers to isolate the dot from the source and drain. Consequently, B_1 shifts systematically to lower fields with increasing gate bias, as the barrier height in the point contacts rises. As the magnetic field is increased beyond B_1 eventually all electrons reside in the lowest Landau level ($\nu \leq 2$), and in this regime periodic oscillations emerge in the magnetoresistance [Fig. 6(a)]. The period of these, while independent of gate voltage [Fig. 6(b)], is more than two orders of magnitude larger than that expected from the area of the dot (1–2 mT). In addition, the oscillations were found to decay only weakly with temperature, and could still be resolved at around a degree Kelvin. We associate these characteristics with the increased importance of CB in the tunneling regime, as we discuss below.

An important characteristic of the isolated dot is that its electrochemical potential can vary with respect to the source or drain. While the electrochemical potential of the latter is effectively pinned by the battery, the single-particle states of the isolated dot depend strongly on magnetic field. In particular, when all electrons occupy the lowest Landau level, the magnetospectrum shows that the single-particle states rise in tandem with the cyclotron energy[12] (Fig. 7). As the magnetic field is increased, we therefore expect electrons to depopulate the dot by tunneling into the source or drain and, ignoring the effects of CB, this should occur each time the highest filled state in the dot is raised above the source-drain elec-

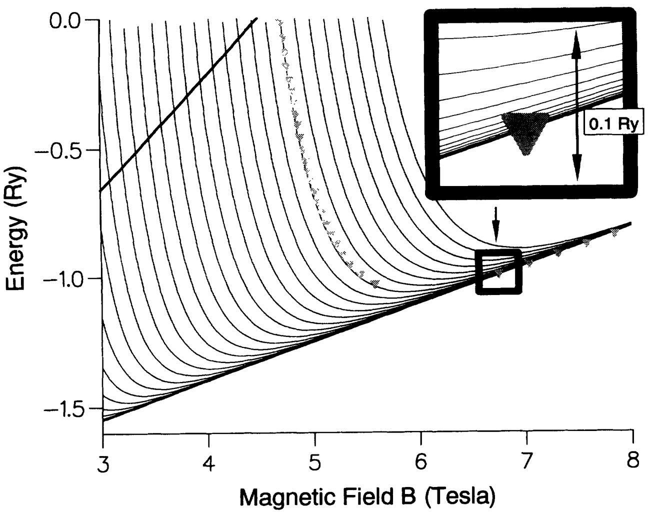

FIG. 7. Noninteracting Wentzel-Kramers-Brillouin model magnetospectrum calculated for the 2-μm dot geometry employed experimentally. Every one-hundredth level is plotted and spin is not included. Triangles mark the highest filled level in the dot as the electron number N changes in unit steps. The second Landau level is the solid line, which intersects the vertical axis at -0.6 Ry. The inset is an enlargement of the high-magnetic-field region: the occupied levels are so densely packed here that they appear as a single solid line, i.e., $E_N(B)-E_{N-1}(B) \ll e^2/C$.

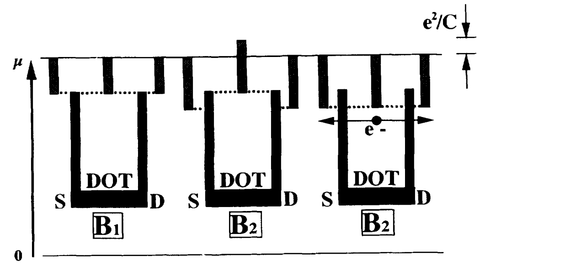

FIG. 8. Schematic of the energetics of the depopulation process at zero source-drain bias. The battery pins the electrochemical potential of the source (S) and drain (D) at a constant value μ, measured with respect to an invariant zero of energy. Black regions indicate the electrostatic potential of the dot, and the dotted lines show the position of the guiding center energy, of an electron at the Fermi surface, measured with respect to the same zero. The shaded bars indicate the amplitude of the cyclotron energy $\hbar\omega_c/4\pi$ (all electrons in lowest Landau level). As the magnetic field is increased beyond B_1, the guiding center drops below the point-contact potential barriers. Further increasing the field, the electrochemical potential in the source and drain remains pinned, while the single-particle states of the dot rise in energy. Ultimately, at magnetic field B_2 the highest filled state in the dot has risen by e^2/C above μ, and the electron in this state tunnels into the source or drain.

trochemical potential.[9] From the bare level spacing in Fig. 7 this gives a period of roughly 1 mT, however, more than two orders of magnitude smaller than that observed experimentally. (Since we estimate self-consistently that roughly 7000 electrons initially occupy the dot, this also implies complete depopulation of the dot over a field scale of less than 1 T.)

A more realistic approach considers that single-electron tunneling changes the energy of the isolated dot by e^2/C, where C is the effective capacitance of the dot.[1] Taking this charging energy into account, we previously showed that tunneling only occurs when the highest filled state in the dot has been raised by e^2/C above the source-drain electrochemical potential:[12]

$$E_N(B)-E_{N-1}(B+\Delta B^*)=e^2/C \ , \tag{1}$$

where E_N is the energy of the Nth level in the dot, measured with respect to the dot bottom (a similar relationship was previously derived by Beenakker, van Houten, and Staring[8]). Calculating the dot capacitance self-consistently[12] ($C=0.73$ fF) we then predict the field scale for successive single-electron tunneling events, by returning to the single-particle spectrum (Fig. 7). As can be seen from the figure, we find a period in good agreement with experiment, and conclude that the oscillations in this regime result from single-electron depopulation of the dot, on a field scale determined almost completely by CB effects (Fig. 8). The periodic nature of the oscillations reflects the fact that the charging energy exceeds the relevant single-particle level spacing by two orders of magnitude (Fig. 7, inset), which is also the origin of the reduced sensitivity of the oscillations to temperature. In particular, since at high magnetic fields the single-particle states rise in tandem with the lowest-Landau-level energy, $E_N(B)$ is well approximated by the corresponding cyclotron energy $E_N(B)=heB/4\pi m^*$, where m^* is the effective mass of the electron. Furthermore, over the magnetic-field range where the oscillations are experimentally resolved, and in contrast to the situation at lower fields (Sec. III A, above), self-consistent calculation (Fig. 7) shows the splitting between single-particle states to be much less than k_BT. We can then consider $E_N(B)\approx E_{N-1}(B)$ and, substituting these results into Eq. (1), obtain the condition for the period between successive depopulation events in the presence of Coulomb blockade:[8,12]

$$\Delta B^*=4\pi m^* e/hC \ . \tag{2}$$

Of course, at lower magnetic fields, where the spectrum is more complicated, or in smaller dots, in which the single-particle level spacing is suitably increased, the depopulation will not necessarily give rise to periodic oscillations.[21] Also note that, while for the relatively large dots studied here good agreement with experiment was obtained by computing magnetospectra from self-consistent dot profiles evaluated at zero magnetic field, a more rigorous treatment should consider the effect of the magnetic field upon the profiles.[10,11]

C. Time-dependent characteristics

Given the distinct behavior discussed above it is perhaps not surprising that the time-dependent characteristics of the dots are also found to depend strongly upon the number of edge states passing through them. In particular, we generally find that as the magnetic field is increased, the transition to tunneling is accompanied by the emergence of telegraph noise in the magnetoresistance (Fig. 9). An important feature of the noise is that it is only observed in the presence of a strong magnetic field, and is not detected simply by pinching off the gates to form well-defined tunnel barriers at zero field. Qualitatively similar noise has previously been widely reported in single point contacts, and in these devices is associated with remote impurities inducing changes in the electrostatic potential by trapping.[22–24] The time scale τ between successive trapping events is typically only of the order of a fraction of a second in these devices, however, and the noise is still observed when the device resistance is less than $h/2e^2$. In contrast, the switching noise here occurs with a characteristic τ of up to tens of minutes at the highest magnetic fields. Similar results have recently been reported by van der Vaart *et al.*, who suggest that the switching is actually an intrinsic effect, due to single electrons tunneling between different edge states within the dot.[14] They associate the long τ for the process with the fact that tunneling occurs across a region of incompressible electron gas,[10,11] whose width increases with magnetic field. Our results certainly favor such an "intrinsic" picture; the noise is only observed with all edge states localized in the dot, under which conditions tunneling of an electron between two edge states is expected to result in a readjustment of their respective chemical potentials. This readjustment is in turn believed to be responsible for the discrete change in the dot conductance observed experimentally.[14] More detailed temperature-dependent studies are called for, however, to determine the characteristic energy scales relevant to this process.[13]

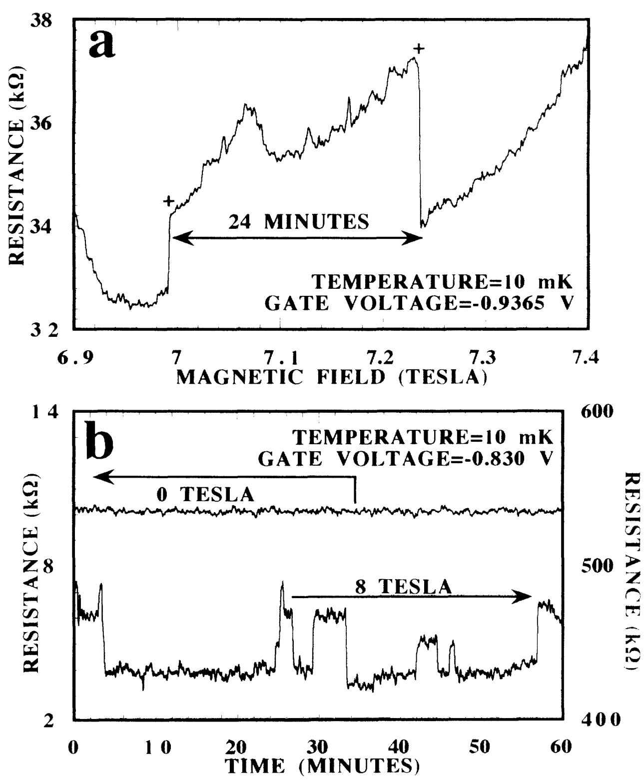

FIG. 9. (a) Telegraph noise (crosses) in the magnetorsistance in the tunneling regime (1-μm dot). While in this figure the discrete resistance jumps appear to have a finite width, this is actually due to the long (3 s) time constant used during the magnetic-field sweep. The magnetic field was swept over approximately 50 min in this figure. (b) The telegraph noise is only observed for magnetic fields such that transport through the dot occurs by tunneling (2-μm dot).

IV. DISCUSSION

Aharonov-Bohm oscillations in the Hall resistance of a quantum dot were reported by van Wees *et al.*, who noted a distinct increase in ΔB as lower-index edge states were confined within the dot[3] (the dot was of similar size to those studied here). While the authors associated this with a magnetically induced reduction in the edge-state area, a recent report suggests an explanation due to Coulomb blockade; tunneling into the dot should incur some charging energy, so that the oscillations probe the addition spectrum due to CB and single-particle effects. Within this model, transmitted edge states partially screen the Coulomb interaction, and ΔB is predicted to depend inversely upon the number of these.[6] While the model qualitatively accounts for much of the behavior observed experimentally, there remain difficulties with such an interpretation. In particular, in most experiments the bare charging energy is up to two orders of magnitude larger than the single-particle level spacing, but ΔB is only found to differ from the dot size by a much smaller factor.[3–5] We instead believe that the observed variation in ΔB in this regime is well accounted for by the expected evolution of the edge states with magnetic field, as originally suggested by van Wees *et al.*[3]

Self-consistent calculations of the potential profile of a charged layer in a high magnetic field reveal the edge states broaden into bands, which are isolated from each other by narrow strips of incompressible electron gas.[10,25] With the boundary defined by a surface gate, the position of the kth spin-resolved edge state from the gate edge is approximately given by[25]

$$d+x_k=d+d[(\nu^2+k^2)/(\nu^2-k^2)] , \quad (3)$$

where ν is the bulk filling factor, $2d$ is the depletion length around each gate at zero magnetic field ($d=V\varepsilon/4\pi^2 ne$), V is the gate voltage, ε is the effective dielectric constant, and n is the bulk carrier density. As the magnetic field is increased the edge states therefore move towards the center of the dot,[26] and knowledge of their positions enables us to predict the resulting evolution of ΔB ($=h/eA$). Taking $d=45$ nm ($V=-0.9$ V, $n=4.4\times10^{15}$ m^{-2}), the self-consistent model [Eq. (3)] is seen to be in excellent agreement with experimental observations, indicating our assignment of the oscillations to the $\nu=2$ edge state is indeed correct [Fig. 3(b)]. Over a wider magnetic-field range ΔB can be seen to increase significantly [Fig. 3(b) inset], suggesting that the variation observed by van Wees *et al.* is indeed consistent with the evolution of the edge-state positions with magnetic field.

While the AB oscillations in the quantum Hall regime are well described by single-particle predictions, we cannot conclude that CB effects do not persist here. Indeed, recent reports have demonstrated that many of the transport properties in this regime can only be explained by invoking charging effects.[4,7] In these experiments, the dot is configured to completely confine several edge states at a given magnetic field, and when a separate plunger gate is swept CB oscillations associated with the various trapped edge states are observed. This is a different situation from our experiment, in which the magnetoresistance oscillations are associated with a single edge state. More importantly, however, the oscillations are only observed for magnetic fields such that the edge state is partially transmitted through the point contacts of the dot.[3] The edge state can then be considered as a superposition of a confined and an extended component, and in this sense it is not obvious that the charge associated with it is well defined. As the magnetic field is increased the edge state ultimately becomes completely confined within the dot and in this regime, where we would expect the effects of CB to be most strongly observed, the oscillations quench. Such an interpretation is consistent with the recent experiment of Field *et al.*, who reported a decrease in the charging energy for a given edge state as it leaked progressively into the source and drain.[7]

In the tunneling regime the behavior is very different. The magnetoresistance can increase to an order of several MΩ, which in a simple picture[2] corresponds to a total edge-state transmission probability of roughly 1%. All edge states are therefore confined within the dot, and the magnetic field can be used to vary the total energy of the dot with respect to the electrochemical potential of the source and drain. These "magneto-Coulomb oscillations" are therefore the magnetic analogue of the CB oscillations more conventionally observed using electrostatic techniques.[1]

V. CONCLUSIONS

The main finding of this report is that CB only influences the AB oscillations observed in the magnetoresistance of quantum dots when the dot is weakly coupled to the source and drain. In the quantum Hall regime, ΔB is well correlated to the dot size, and the temperature-dependent decay of the oscillations is inconsistent with the expected form of the single-particle magnetospectrum. In the tunneling regime, however, ΔB is enhanced by more than two orders of magnitude over the value expected from the size of the dot, and the resulting oscillations persist to above a degree Kelvin. This behavior can only be explained by considering the effect of CB on the magnetic depopulation of electrons from the isolated dot; these magneto-Coulomb oscillations are the magnetic analogue of the CB oscillations more conventionally observed using electrostatic techniques. These results demonstrate that by varying the coupling of the dot to the source and drain, the resulting magnetooscillations can be used to separately probe both the single-particle and CB-related energy scales of small dots. In the tunneling regime, telegraph noise in the magnetoresistance is believed to be consistent with single-electron tunneling across the incompressible strips that separate successive edge states.

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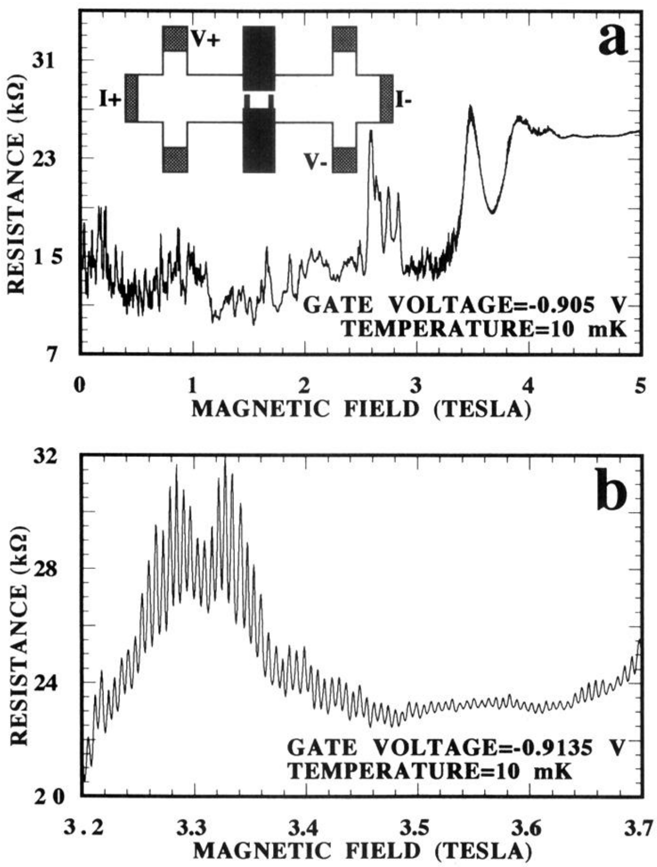

FIG. 1. (a) Low-temperature magnetoresistance of a 1-μm dot. The inset shows a schematic diagram of the dot geometry, with the gates shown in black. Current was passed from leads $I+$ to $I-$, and the corresponding voltage drop was measured between $V+$ and $V-$. The lithographic length and widths of the individual point contacts, were 150 and 200 nm, respectively. (b) An expanded view of (a) reveals AB-type oscillations in the magnetoresistance.

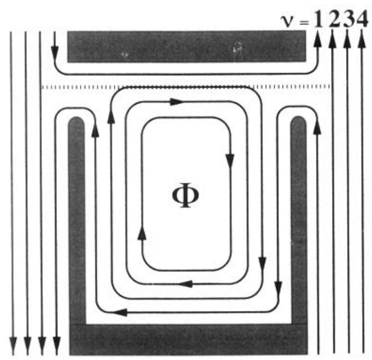

FIG. 2. Schematic diagram of the edge-state configuration in the dot of Fig. 1 at 4 T. Shaded regions correspond to gates, and the magnetic field points out of the page. The edge states are spin resolved, and only the lowest one is fully transmitted through the dot. We associate the AB oscillations with a modulation of tunneling of the partially transmitted $\nu=2$ edge state, via its trapped component in the dot (broken line).

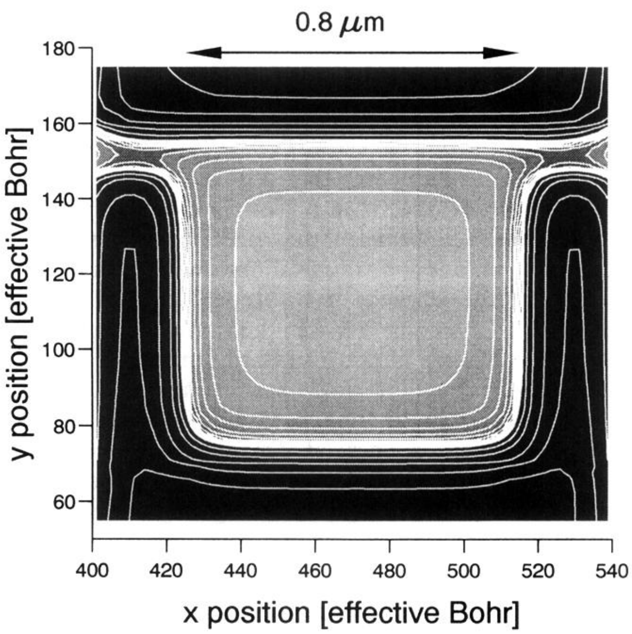

FIG. 4. Contour plot for a dot with a lithographic inner dimension of 1 μm, obtained from a Thomas-Fermi self-consistent electronic-structure calculation at zero magnetic field. The contours are irregularly spaced, with the innermost contours separated by -2.6 effective rydbergs (approximately -15 meV), and the next eleven are spaced 0.4 effective rydbergs apart. The remaining five contours are spaced at greater invervals.

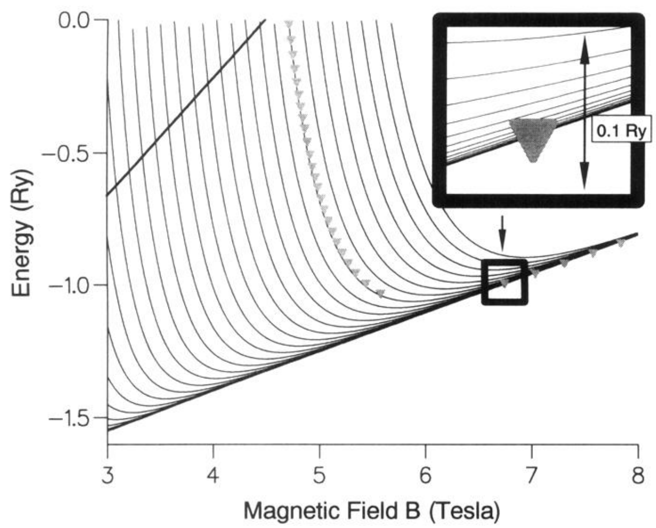

FIG. 7. Noninteracting Wentzel-Kramers-Brillouin model magnetospectrum calculated for the 2-μm dot geometry employed experimentally. Every one-hundredth level is plotted and spin is not included. Triangles mark the highest filled level in the dot as the electron number N changes in unit steps. The second Landau level is the solid line, which intersects the vertical axis at -0.6 Ry. The inset is an enlargement of the high-magnetic-field region: the occupied levels are so densely packed here that they appear as a single solid line, i.e., $E_N(B)-E_{N-1}(B) \ll e^2/C$.

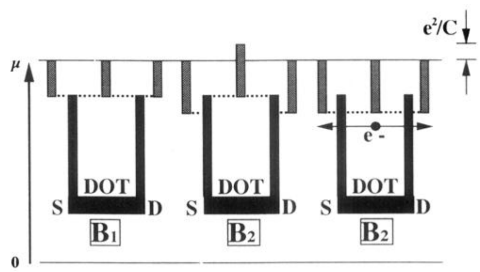

FIG. 8. Schematic of the energetics of the depopulation process at zero source-drain bias. The battery pins the electrochemical potential of the source (S) and drain (D) at a constant value μ, measured with respect to an invariant zero of energy. Black regions indicate the electrostatic potential of the dot, and the dotted lines show the position of the guiding center energy, of an electron at the Fermi surface, measured with respect to the same zero. The shaded bars indicate the amplitude of the cyclotron energy $h\omega_c/4\pi$ (all electrons in lowest Landau level). As the magnetic field is increased beyond B_1, the guiding center drops below the point-contact potential barriers. Further increasing the field, the electrochemical potential in the source and drain remains pinned, while the single-particle states of the dot rise in energy. Ultimately, at magnetic field B_2 the highest filled state in the dot has risen by e^2/C above μ, and the electron in this state tunnels into the source or drain.