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Influence of adiabatically transmitted edge channels on single-electron tunneling through a quantum dot

B. W. Alphenaar, A. A. M. Staring, H. van Houten, M. A. A. Mabesoone, and O. J. A. Buyk
Philips Research Laboratories, 5600 JA Eindhoven, The Netherlands

C.T. Foxon*
Philips Research Laboratories, Redhill RH1 5HA, United Kingdom
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We present a direct comparison of the conductance of a quantum dot in the presence of 2, 1, or 0 adiabatically transmitted edge channels. We observe periodic conductance oscillations as a function of gate voltage for all three cases, and use the Coulomb blockade oscillations observed in the absence of edge channels as a novel electron counter to calibrate the period of the oscillations in the presence of edge channels. We find that the latter set of oscillations cannot be described without invoking Coulomb charging.

Selective reflection of edge channels in a two-dimensional electron gas (2DEG) in high magnetic fields is possible at a quantum point contact (QPC), which consists of a constriction in the 2DEG defined by a split gate electrode.[1] The conductance of a QPC in a high magnetic field is approximately given by

$$G_{\rm pc} \approx \frac{e^2}{h}(N_{\rm trans}+t), \tag{1}$$

with $N_{\rm trans}$ the number of edge channels that are fully transmitted over the barrier in the constriction, and $t \leq 1$ the tunneling transmission probability of the $(N_{\rm trans}+1)$th edge channel. Edge channels corresponding to higher index Landau levels (LL's) are nearly completely reflected.

With two QPC's in series and an additional gate electrode it is possible to form a quantum dot [see Fig. 1(a)] in which the states reflected by the QPC's form a discrete energy spectrum. For a noninteracting electron gas, a peak in the conductance of the dot due to resonant tunneling should be seen when an electron state of the $(N_{\rm trans}+1)$th LL lines up with the Fermi energy in the leads. Periodic conductance oscillations are expected both as a function of electron density (varied by means of the voltage on electrode C), and as a function of magnetic field. Such oscillations (sometimes referred to as Aharonov-Bohm oscillations[2]) have been demonstrated experimentally both as a function of magnetic field[3] and gate voltage[4] in the regime where one or more edge channels are transmitted adiabatically [i.e., $N_{\rm trans} = 2, 1$ as shown in Figs. 1(b) and 1(c)].

Meanwhile, it has become clear that resonant tunneling through a quantum dot can be governed by single-electron charging effects.[5,6] These effects are known to be important if the capacitance of the dot C is small so that the charging energy $e^2/2C \gg kT$, and if the conductance of each point contact $G_{\rm pc} < e^2/h$, so that no adiabatically transmitted edge channels are present [see Fig. 1(d)]. Single-electron charging has been demonstrated experimentally by observations of Coulomb blockade oscillations, i.e., periodic oscillations in the conductance as a function of voltage on a gate capacitively coupled to the dot. In the Coulomb blockade regime, periodic magnetoconductance oscillations of the type seen by van Wees *et*

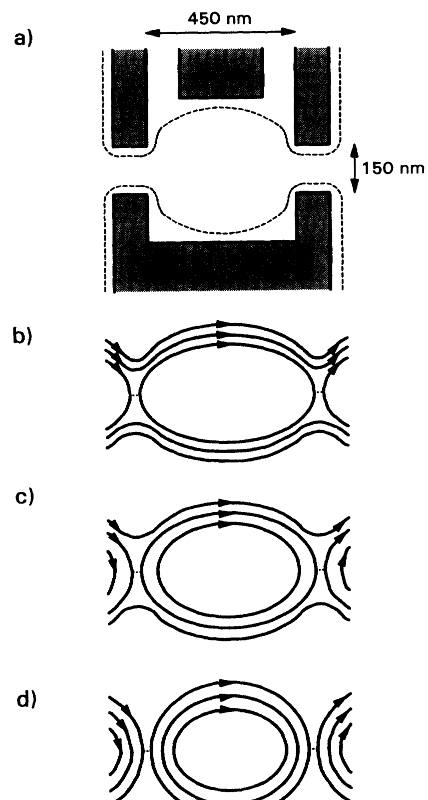

FIG. 1. (a) Schematic drawing of the quantum dot device. The dotted line indicates the edge of the depletion region. (b)–(d) Current paths through the dot in the presence of 2, 1, or 0 adiabatically transmitted edge channels as adjusted by V_B and V_D.

al.[3] are generally not observed.[5]

Considering the extent to which Coulomb charging modifies electron tunneling, we have decided to reexamine its influence in the regime where it has previously been ignored: in the presence of adiabatically transmitted edge channels. In this paper, we present a direct comparison of the conductance versus gate voltage and magnetic field for different barrier transparencies, so that 2, 1, or 0 adiabatically transmitted channels are present in addition to the confined levels. We observe periodic conductance oscillations as a function of gate voltage for all three barrier transparencies. We use the oscillations observed in the full Coulomb blockade regime (i.e., no adiabatically transmitted edge channels) as a novel electron counter to calibrate the period of the oscillations observed in the presence of adiabatically transmitted edge channels. In this way we argue that *even in the presence of the transmitted channels the conductance oscillations cannot be satisfactorily described in terms of resonant tunneling without invoking Coulomb charging.* In addition, magnetoconductance oscillations are observed whose peak spacing increases as the number of adiabatically transmitted edge channels decreases from 2 to 1, while irregular fluctuations with a larger activation energy comparable to $e^2/2C$ are seen in the full Coulomb blockade regime. This observation indicates that charging effects become progressively more important as the number of transmitted edge channels decreases, while it confirms that their influence is still significant for barrier transparencies larger than e^2/h.

A schematic drawing of our device is shown in Fig. 1(a). Four gates (labeled *A*–*D* in the figure) define a square 450 × 450 nm^2 on the surface of an $Al_xGa_{1-x}As$/GaAs heterostructure with a 2DEG of mobility 10^6 cm^2/V s and density 3.0×10^{11} cm^{-2}. When the gates are negatively biased, a quantum dot with a diameter of approximately d=400 nm is formed in the underlying 2DEG, and is connected through two QPC's to the two-dimensional leads. Two-terminal conductance measurements are made across the dot using an ac lock-in technique with an excitation voltage below 10 μV. In the experiments, the voltage on gate *A* is left fixed at –0.7 V, and the voltages on gates *B* and *D* (V_B, V_D) are adjusted to control the transmission through the tunnel barriers between the dot and the leads. The conductance is then measured as a function of voltage on gate *C* (V_C), which determines the electron density in the dot. The data described below are from measurements performed on a single device; however, the salient results were accurately reproduced in a second device.

Figures 2(a)–2(c) show the results of conductance measurements as a function of V_C for three different magnetic fields (2.75, 3.20, and 3.50 T, respectively) and a temperature of 50 mK. Each figure displays three traces, corresponding to three different adjustments of the QPC conductances; $G_{\rm pc} = 2.5e^2/h$ in the top traces, $1.5e^2/h$ in the middle traces, and $0.5e^2/h$ in the bottom traces. The traces all show a series of nearly periodic oscillations in the conductance as a function of V_C; however, the period of the oscillations varies from trace to trace. In Fig. 2(b), for example, there are 27 peaks in the top trace, 44 peaks in the middle trace, and 67 peaks in the bottom trace, indicating that the period in the top trace is about 2.5 times that in the bottom trace and the period in the middle trace is about 1.5 times that in the bottom trace. A comparison of the traces measured at the three magnetic fields shows that the number of peaks in the top trace decreases from 31 at 2.75 T to 24 at 3.50 T while the number of peaks in the middle trace decreases from 48 to 42. The number of peaks in the bottom trace, however, remains fixed at 67. Figure 2(d) shows the results of measurements taken with the same parameters as in Fig. 2(b) but at a temperature of 500 mK. The oscillations observed in the top two traces have now nearly vanished, while strong oscillations are still observed in the bottom trace. Further measurements (not shown) indicate that the oscillations in the bottom trace persist up to a temperature of at least 2 K.

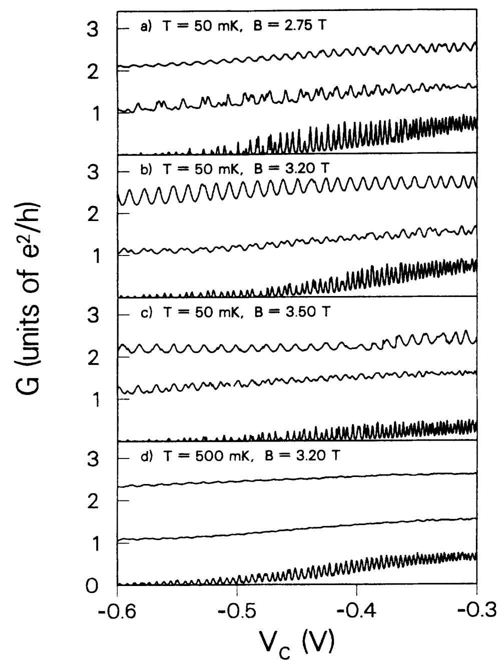

FIG. 2. Dot conductance as a function of the voltage on gate *C* at a series of magnetic fields and temperatures. In the top, middle, and bottom trace of each figure (a)–(d) QPC's are adjusted to conductances of 2.5, 1.5, and $0.5e^2/h$, respectively. The three cases correspond to the three possible current paths shown in Figs. 1(b)–1(d).

The Coulomb charging energy for the dot $e^2/2C \simeq e^2/8\varepsilon d \approx 0.4$ meV, is greater than kT for temperatures up to 4 K. Thus, the very regular oscillations observed for $G_{\rm pc} = 0.5e^2/h$ (the bottom traces in Fig. 2) can safely be attributed to the Coulomb blockade effect. The gate voltage separation between peaks is $\approx e/C_{\rm gate}$ where $C_{\rm gate}$, the capacitance between gate *C* and the dot, is assumed to be independent of $G_{\rm pc}$. This is reasonable since $G_{\rm pc}$ is much more sensitive to changes in voltages *B* and *D* than are the size of the dot and the dot-gate separation, which together determine $C_{\rm gate}$. Since each Coulomb blockade peak corresponds to the removal of one electron from the dot, this allows us to use the Coulomb blockade oscillations in a new way: as a tool to determine the mechanism that governs the period of the oscillations seen at higher barrier transparencies. The number of electrons per peak for the upper traces in Fig. 2 can be determined by dividing the number of Coulomb blockade peaks counted for $G_{pc} = 0.5e^2/h$ into the number of peaks counted for $G_{pc} = 1.5$ or $2.5e^2/h$. The results of this procedure performed on a set of measurements of the type shown in Fig. 2 are plotted versus magnetic field in Fig. 3. The number of electrons per peak is considerably larger for $G_{pc} = 2.5e^2/h$ than for $G_{pc} = 1.5e^2/h$. In both cases, an increase in magnetic field results in an increase in the number of electrons per peak.

We now consider the periodic conductance oscillations for $G_{pc} > e^2/h$ (the upper traces in Fig. 2). The simplest possibility is to ignore Coulomb charging. As discussed in the introduction then, a peak in the conductance is observed due to resonant tunneling when an electron state of the $(N_{\rm trans}+1)$th LL lines up with the Fermi energy in the leads. The frequency at which this occurs corresponds to the rate at which electrons are removed from the $(N_{\rm trans}+1)$th LL. The total number of spin-split LL's in the dot $N_{\rm dot}$ are made up of the $N_{\rm conf}$ LL's of guiding center energy E_g below the barrier height E_b and the $N_{\rm trans}$ additional LL's that are occupied in the dot but fully transmitted over the barriers in the QPC's $(E_g > E_b)$. Assuming that both the $N_{\rm conf}$ and the $N_{\rm trans}$ LL's are depleted at about the same rate, the number of electrons per peak should be simply $N_{\rm dot}$. This argument predicts that the number of electrons per peak should decrease, rather than increase with magnetic field, in contradiction with the observed results (Fig. 3). This discrepancy could in principle be eliminated if resonant tunneling through electron states of the confined LL's with index higher than $(N_{\rm trans}+1)$ also contributes to the conductance of the dot. The tunneling rate, however, decreases exponentially with decreasing E_g,[7] thus, there should be an order of magnitude modulation of conductance peak heights due to resonant tunneling through states belonging to consecutive LL's confined in the dot.[8] This is not observed in our experiment, however.[9]

We *can* model the results of Fig. 3 though, if we take Coulomb charging into account for $G_{pc} > e^2/h$. We extend recent arguments for the $N_{\rm trans} = 0$ case[10] to our problem by considering a separate Coulomb charging energy of the $N_{\rm conf}$ LL's existing in the presence of the adiabatically transmitted edge channels. This is reasonable, since a magnetically induced tunnel barrier consisting of an incompressible electron gas region exists between each of the edge channels. Resonant tunneling electrons thus face a nonzero Coulomb charging energy associated with a change in the electron population of the confined LL's. This leads to Coulomb blockade oscillations as a function of gate voltage with a period corresponding to the removal of an electron from any one of the $N_{\rm conf}$ LL's. The removal of electrons from one of the $N_{\rm trans}$ LL's in the dot does not give rise to a conductance peak because charge in these levels is not localized and can therefore be changed continuously. This implies that

$$\frac{\text{electrons}}{\text{peak}} = \frac{N_{\rm conf}+N_{\rm trans}}{N_{\rm conf}} = \frac{N_{\rm dot}}{N_{\rm conf}}. \tag{2}$$

Figure 3 shows solutions of Eq. (2) for $N_{\rm trans} = 1$ and $N_{\rm trans} = 2$. We determine $N_{\rm dot}$ assuming parabolic confinement in the dot[11] of oscillator strength $\hbar\omega_0 = 0.6$ meV and Fermi energy $E_F = 7$ meV corresponding to an electron density of 2.2×10^{11} cm^{-2} and a dot diameter of 400 nm. The fit between the theoretical and experimental results is fair. In both cases, the number of electrons per peak is seen to increase—from 2 to 3 in the upper curve and from 1.3 to 1.5 in the lower curve—as $N_{\rm dot}$ decreases from 4 to 3.

The presence of the $N_{\rm trans}$ LL's enters only in the form of a nearby electron reservoir, coupled capacitively to both the gates and the confined LL's. This enhances the effective capacitance, and decreases the charging energy $e^2/2C$. A calculation of the charging energy of the confined LL's in the presence of adiabatically transmitted edge channels is still in progress,[12] but we note that the assumed increase in C with the number of adiabatically transmitted edge channels can account for the reduction of the activation energy with increasing barrier transparency in the conductance traces in Fig. 2.

We now briefly discuss the magnetoconductance of the dot. Figure 4 shows the conductance as a function of

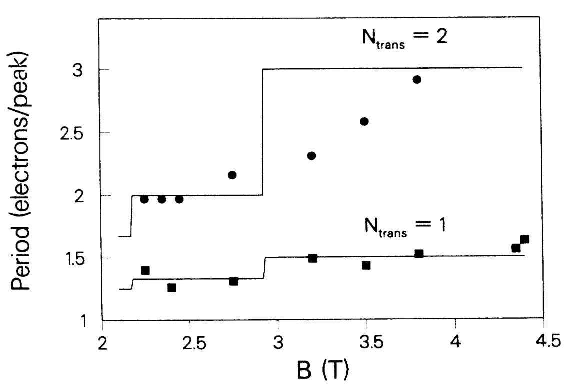

FIG. 3. Period of the conductance oscillations (in units of electrons per peak) vs magnetic field for $G_{pc} = 2.5e^2/h$ (circles) and $G_{pc} = 1.5e^2/h$ (squares). The solid lines are theoretical fits for $N_{\rm trans} = 2, 1$ adiabatically transmitted edge channels (see text).

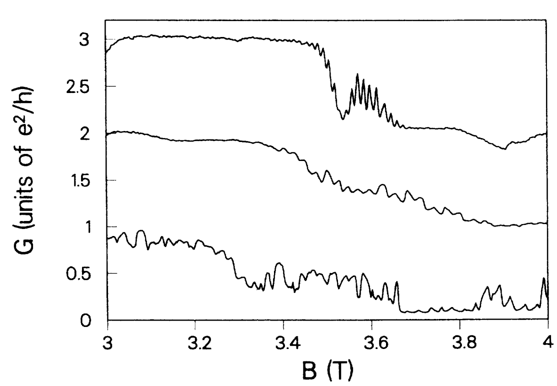

FIG. 4. Dot conductance as a function of magnetic field for three different barrier transparencies. At B=3.5 T, the top, middle, and bottom traces correspond to QPC conductances of 2.5, 1.5 and $0.5e^2/h$, respectively.

magnetic field at a temperature of 50 mK. The constrictions are adjusted so that the conductance drops from 3 to $2e^2/h$ in the top trace, 2 to $1e^2/h$ in the middle trace and 1 to $0e^2/h$ in the bottom trace. Magnetoconductance oscillations are observed with a typical spacing $\Delta B = 13$ mT in the top trace and $\Delta B = 26$ mT in the middle trace. More random fluctuations are observed in the bottom trace. The oscillations in the top two traces disappear for $T \sim 250$ mK, while the fluctuations observed in the bottom trace survive to $T > 1$ K.

We speculate that the magnetoconductance oscillations are due to resonant tunneling through localized states belonging to the $(N_{\mathrm{trans}} + 1)$th LL modified by single-electron charging effects. The increase in peak spacing observed between the top two traces is thought to be due to the increasing influence of Coulomb charging as the number of edge channels in contact to the 2DEG decreases. In the bottom trace, the Coulomb charging energy becomes dominant, and the periodic magnetoconductance oscillations are replaced by large-scale fluctuations. We do not attempt to describe the magnetoconductance of the dot in more detail. What is needed is a self-consistent calculation based on precise knowledge of the full energy spectrum in the presence of both confined and adiabatically transmitted edge channels.

In conclusion, we have studied the conductance of a quantum dot in the presence of 2, 1, or 0 adiabatically transmitted edge channels. We observe periodic conductance oscillations as a function of gate voltage in all three cases, and demonstrate that the number of electrons added to the dot per peak is determined by the ratio of the total number of LL's in the dot to the number of LL's confined to the dot. We also observe magnetoconductance oscillations whose spacing increases as the number of adiabatically transmitted edge channels decreases. Our results demonstrate that the formation of LL's in a high magnetic field causes single electron charging effects to be of importance for barrier conductances greater than e^2/h. This finding necessitates a reinterpretation of earlier experimental results on single[3,4] and multiple quantum dots.[13]

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*Present address: Department of Physics, University of Nottingham, Nottingham NG7 2RD, United Kingdom.

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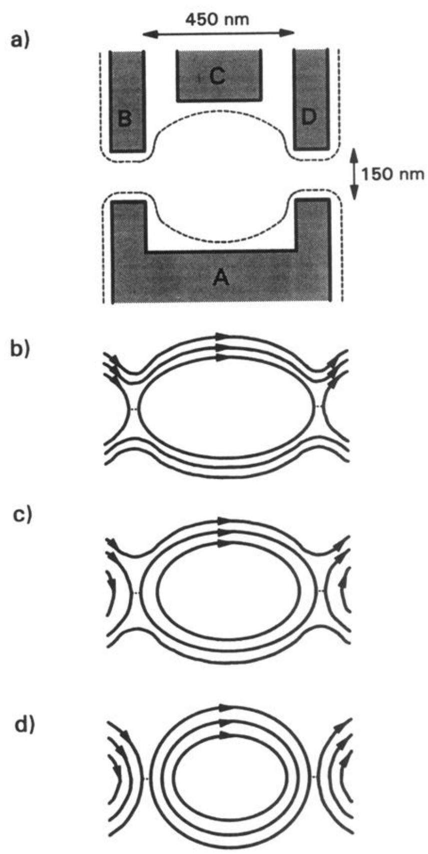

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