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Spin splitting of Aharonov–Bohm oscillations in a small quantum dot

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Abstract

The influence of magnetic field B on the ballistic conductance G of a small (0.25 μm in diameter) quantum dot has been studied experimentally at 70 mK. In the open regime for $B \simeq 1$ T, the conductance as a function of the gate voltage shows several periods of oscillations superimposed on the quantized conductance plateaus. With the increase of the magnetic field, we observe a splitting of the oscillation minima which eventually leads to a halving of the oscillation period accompanied by a pronounced decrease of the amplitude. At $B \simeq 1.4$ T, the oscillations with halved period appear as small resonances on the flat plateaus. We attribute the observed phenomena to spin splitting effect on the Aharonov–Bohm oscillations and interpret our results using a model of electron scattering between propagating and confined magnetic edge channels. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Experimental investigations [1–11] of submicron size quantum dots electrostatically defined in two-dimensional (2D) electron gas by Schottky gate patterns have revealed a number of magnetotransport phenomena, which originate from the wave nature of electrons and are observable at low temperatures, when electron transport is known to be ballistic.

Typically, when the magnetic field B is about 1 T, the magnetic length is small enough in comparison with the dot diameter D, and the ballistic current through the dot flows via magnetic edge states [12]. In these conditions, one may observe oscillations of the quantum dot conductance associated with interference effects due to circular motion of the electrons in the edge channels around the cavity. One revolution of the electron changes its phase by $2\pi\Phi/\phi_0$, where $\Phi = AB$ is the magnetic flux through the area

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A enclosed by the edge state, and $\phi_0 = h/e$ is the flux quantum. When the magnetic field is swept, or when the area of the dot is changed by the gate voltages, the conductance of the dot oscillates with the period determined by the relation $\delta\Phi = \phi_0$. Taking into account the direct relation between the level splitting Δ due to angular momentum quantization (orbital quantization) in a ring formed by an edge channel and the phase gained by an electron per revolution in this channel, one can say also that the oscillations appear when the energy levels of the quantum dot are swept one by one across the Fermi level of the system. Such Aharonov–Bohm (AB) oscillations of the ballistic conductance through cavities [13] have been observed in many experiments on quantum dots and antidots [1,2,5–11] both in the magnetic-field and gate-voltage dependences.

Several groups have reported [6,7,9,10] experimental observations of the period-halving phenomena in the oscillatory dependence of quantum dot conductance on the magnetic field. Similar behavior has been also observed for AB oscillations in an antidot system [11]. It seems that a unified explanation cannot be applied for all these period-halving phenomena, because the experimental conditions have been different for each case. For medium-sized dots (0.5 μm in diameter) the period halved when application of the gate voltage led to transition from the intermediate regime between the first and second spin-resolved plateaus to the second plateau regime [6,7]. This behavior has been explained [7] in terms of phase locking of spin-up and spin-down states (these states appear in "antiphase" to each other due to Coulomb interaction between the electrons) and different contributions of these states to the transport (in the second spin-resolved plateau, when both spin-up and spin-down states propagate through the dot, the period of the oscillations is halved with respect to the case when only spin-up states are propagating). For large-sized dots (1 μm in diameter) the period halving occured in certain ranges of the magnetic field [9,10], and, in contrast to the experiments [6,7], could not be explained by accounting different spin state contributions, because only one spin-resolved state propagated through the dots. The period halving of AB oscillations in the antidot system [11] cannot be attributed to spin splitting as well. Therefore, in many cases the exact origin of period-halving phenomena still remains unclear.

The observations reported in Refs. [6,7] prove the existence of spin-split, "phase-locked" electron states inside the quantum dots in the magnetic fields around 3.5 T. However, as far as we know, no observations of spin splitting, which would appear and develop with the increase of the magnetic field, have been reported for quantum dots. In fact, a single observation of such spin splitting phenomenon was the splitting (without halving of the period) of AB oscillations in a quantum point contact, which possibly contained an impurity forming an antidot configuration [14]. To observe the development of spin splitting in the quantum dots by AB oscillations, one should keep phase coherence of the electrons in the magnetic fields substantially smaller than 3.5 T. This can be achieved for quantum dots of a smaller size.

In this paper we report observation of magnetotransport phenomena in a quantum dot whose lithographic size (~0.25 μm) is smaller from those used in previous studies. In the first and second quantized conductance plateau regime, starting from a magnetic field $B = 0.8$ T we see oscillations of the quantum dot conductance G as a function of the gate voltage which we identify as AB oscillations. With the increase of B, we observe a gradual splitting of the oscillation minima and, finally, an exact halving of the oscillation period around $B = 1.2$ T. Our experimental data allow us to interpret observed phenomenon in terms of spin splitting of the electron states. Moreover, at $B \simeq 1.4$ T, when the oscillations with halved period appear as small resonance dips on the flat plateaus, we see signs of further subsequent halving of the period.

2. Experimental results

The quantum dots used in this study were fabricated from high-mobility ($\simeq 110\,\mathrm{m^2/(V\,s)}$ at 4.2 K), low-electron-density ($\simeq 3 \times 10^{15}\,\mathrm{m^{-2}}$), modulation-doped (Si) GaAs/AlGaAs heterostructures grown by MBE. A quantum dot of lithographic diameter of 0.25 μm was defined by six surface Schottky gates: four symmetrically placed side gates and two symmetrically placed central gates. All the gates were biased using filtered battery voltage sources. For measurements, the four side gates were connected together, as were the central gates. Standard low-bias ac techniques were used to measure the two-terminal

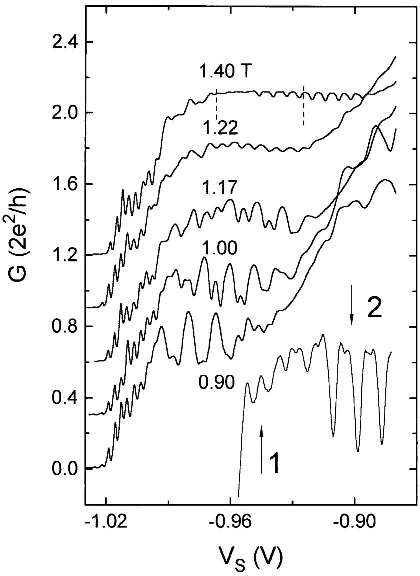

Fig. 1. Dependence of the conductance G on the side gate voltage V_S for $0.9\,T \leqslant B \leqslant 1.4\,T$ at $V_C = -0.5\,V$. The curves are shifted vertically for clarity. The inset shows magnified initial part (between vertical dashed lines) of the first plateau for $B = 1.4\,T$ revealing second halving of the period.

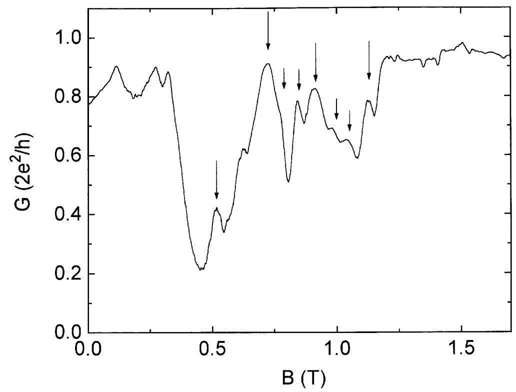

Fig. 2. Magnetic field dependence of the conductance G for fixed $V_S = -0.94\,V$. Long and short arrows indicate positions of major and minor peaks.

conductance at 70 mK which was corrected for a low series resistance.

Fig. 1 shows dependence of the conductance G on the side gate voltage V_S at central gate voltage $V_C = -0.5\,V$ for several values of the magnetic field B applied perpendicular to the plane of the device. In the tunneling regime ($G < 0.5G_0$, $G_0 = 2e^2/h$) we observe oscillations with a period of 3.2 mV. These oscillations are very little affected by the magnetic field and resemble resonant tunneling peaks. In the open regime, oscillations with large period $\Delta V_S \simeq 13$ mV appear on the first plateau at $B = 0.9\,T$. The minima of the oscillations already show signs of splitting. Any change of V_C to lower values leads only to a shift of the curve as a whole to higher V_S without any significant effect on the oscillations. A small increase of the magnetic field dramatically modifies the picture on the plateau, leading to more pronounced splitting, which at $B > 1.2\,T$ leads to oscillations with halved period, with substantially smaller amplitude. An increase of B from 1.2 to 1.4 T does not change the period. However, the shape of the oscillations changes: at 1.4 T they appear as resonant dips superimposed on the flat quantized conductance plateau. At this field we also observe indications of a new set of oscillations appearing on the first half of the plateau with much smaller amplitude and apparently a second halving of the period. We note that $G(V_S)$ dependence at $B = 1.4\,T$ already show signs of spin-resolved transport (a weak indication of an intermediate plateau at $G \sim e^2/h$ is present), and we observe the period halving with the increase of V_S as we move from the regime when only spin-up state is propagating through the dot to the plateau regime when both spin-up and spin-down states are propagating. This phenomenon is analogous to that observed in Refs. [6,7]. Furthermore, we observe large-period oscillations on the second plateau (it is not shown in the figure) starting from $B = 0.78\,T$ and a halving of their period at $B \simeq 1.1\,T$. The period of the oscillations on the second plateau is about 1.5 times greater than on the first plateau.

Fig. 2 shows the dependence of the conductance for $V_S = -0.94\,V$ (corresponding to the end of the first plateau at 0.9 T) on magnetic field B applied perpendicular to device plane. Although this picture is less clear than the $G(V_S)$ dependence, it still shows periodic features. Four main peaks (long arrows) in the region from 0.5 to 1.2 T follow each other with a period of about 200 mT. In addition, small amplitude peaks (short arrow) with 65 mT spacing are seen between them. Fourier transform (not shown here) of $G(B)$ dependence also reveals 200 and 65 mT periods. However, since postions of the minor peaks correlate

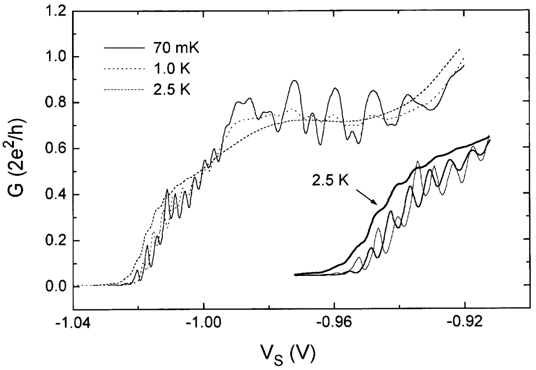

Fig. 3. Temperature dependence of $G(V_S)$ at $B = 1$ T. The inset shows magnified part of $G(V_S)$ in the tunneling regime.

with positions of the peaks in the Shubnikov–de Haas oscillations, we are reluctant to associate them with intrinsic properties of our dot. Region of higher fields, where the conductance is saturated, is difficult to analyze, although a few resonances are seen between 1.2 and 1.5 T.

Effect of temperature on the oscillations at $B = 1$ T is illustrated by Fig. 3. An increase of the temperature to 1 K leads to a decrease of the amplitude of the first plateau oscillations almost by one order of magnitude. At 2 K these oscillations are completely washed out, while the oscillations in the tunneling regime still persist at 2.5 K.

3. Discussion

Below we discuss physical origin of the observed phenomena. The small-period oscillations which are observed in the tunneling regime can be associated with Coulomb blockade phenomenon [15]. This is indicated by their stability with respect to the temperature and magnetic field effects [8]. Coulomb energy for our quantum dot is estimated as $e^2/2C \sim 0.7$ meV and estimated level separation is of the same order. Observed temperature effect on these oscillations can be explained by thermal smearing of the Fermi surface.

The oscillations in the open regime (plateau) can be identified with AB oscillations. Since the dot is small in our experiment, we can see just several oscillations of this kind. The period $\Delta B = 200$ mT in $G(B)$ dependence (see Fig. 2) corresponds to an AB circle of 0.16 μm in diameter, which correlates with the size of our dot at the gate voltages of Fig. 1. On the other hand, the width of the $G(V_S)$ plateau (Fig. 1) at $B = 1$ T allows us to estimate the depletion rate of the quantum point contact (i.e. change of the constriction width w with respect to the side gate voltage) as $\delta w/\delta V_S = 0.58$ nm/mV. Under the assumption that the same depletion rate holds everywhere in the quantum dot, we find that the largest period $\Delta V_S \simeq 13$ mV of $G(V_S)$ oscillations corresponds to a change of the magnetic flux by $\delta\Phi = 0.5\pi DB(\delta w/\delta V_S)\Delta V_S \simeq 0.73\phi_0$. Remembering that this is only a rough estimate, we conclude that the periodicity of $G(V_S)$ dependence is again in agreement with the AB concept.

To determine which edge channels contribute to the interference in our experiment, it is important to note that with the increase of B, when different edge states become well separated from each other, our oscillations transform to resonance dips on the plateaus. Similar dips have been observed experimentally [2,3] and can be explained by resonant reflection of an open (mostly transmitted) edge state from the next, mostly confined edge state. This explanation is supported by a numerical calculation [16]. Another important point is that quantum transport in our case is spin-unresolved. Both spin states penetrate through the constrictions at $B \sim 1$ T and both of them should be taken into account when resonant reflection processes are considered.

The transport model we employ for a qualitative phase analysis is schematically shown in the lower part of Fig. 4. Two propagating edge channels corresponding to two different spin states ($s = \mathrm{u,d}$) couple to two confined edge channels of different spins due to wave function mixing occurring in narrow regions near the constrictions (shown by short straight lines). Outside of the scattering regions electron transport is assumed to be adiabatic. Since we neglect spin-flip processes, the mixing takes place between the propagating and confined edge channels of the same spin and the ballistic conductance is calculated as a sum of different spin channel contributions. Using the formalism described in detail by Kirczenow [17], we obtain

$$G = \frac{e^2}{h}\sum_{s=\mathrm{u,d}} \frac{4[t_s\sin(\varphi_{1s}/2) + (1-t_s)\sin(\varphi_{0s}/2)]^2}{Q_s^2 - 4[t_s\cos(\varphi_{1s}/2) + (1-t_s)\cos(\varphi_{0s}/2)]^2},$$
$$Q_s = 1 + t_s^2 + (1-t_s)^2 + 2t_s(1-t_s)\cos[(\varphi_{1s}-\varphi_{0s})/2], \tag{1}$$

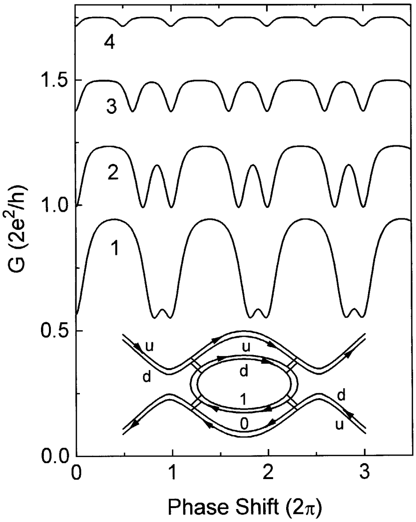

Fig. 4. Dependence of the conductance G calculated from Eq. (1) on the phase shift φ, corresponding to one revolution of an electron around the cavity. Four graphs (2, 3 and 4 are shifted by $0.25G_0, 0.5G_0$, and $0.75G_0$, respectively) correspond to different transmission coefficients and spin phase shifts: (1) $t=0.9$ and $\psi=0.4\pi$; (2) $t=0.95$ and $\psi=0.6\pi$; (3) $t=0.98$ and $\psi=0.8\pi$; (4) $t=0.995$ and $\psi=\pi$. Interedge phase shifts $\varphi_{1s}-\varphi_{0s}$ are equal to 2π. Lower part shows schematic diagram of edge states and mixing between them.

where t_s are the transmission probabilities of the individual conducting channels (the four mixing regions are assumed to be identical and symmetrically placed so that the scattering phase shifts [17] do not contribute in the overall transmission of the dot), and φ_{is} are the phase shifts gained by electrons after one revolution around the dot in the propagating ($i=0$) and confined ($i=1$) edge channels. These phase shifts are related to the areas A_{is} enclosed by respective edge states according to $\varphi_{is}=2\pi BA_{is}/\phi_0$. One can expect that t_{u} and t_{d} do not differ considerably from each other, since the spatial separation between the states with different spins is small in comparison with the magnetic length. On the other hand, it is important to take into account the difference between $\varphi_{i\mathrm{u}}$ and $\varphi_{i\mathrm{d}}$, because spin splitting causes the spin-up and spin-down electrons to move along the equipotentials enclosing slightly different areas. Further, it seems reasonable to assume that variation of the gate voltage V_{S} produces approximately equal changes of all the areas A_{is}, at least for small intervals of V_{S} corresponding to several oscillations on the same plateau. Assuming this, we calculated dependence of the conductance on $\varphi=\varphi_{1\mathrm{u}}$ at fixed phase shifts $\varphi_{1\mathrm{u}}-\varphi_{0\mathrm{u}}=\varphi_{1\mathrm{d}}-\varphi_{0\mathrm{d}}=2\pi$. To take into account smearing of the Fermi surface due to finite temperature T, we have averaged Eq. (1) with the weight factor $\varphi_T^{-1}\exp(\delta\varphi/\varphi_T)/[1+\exp(\delta\varphi/\varphi_T)]^2$, where "angle" of thermal smearing φ_T is defined as $2\pi T/\Delta$ (in the calculation we put $T/\Delta=0.033$, which corresponds to $T=70\,\mathrm{mK}$ and $\Delta=0.2\,\mathrm{meV}$). Gradually increasing the transmission probability $t=t_{\mathrm{u}}=t_{\mathrm{d}}$ and spin phase shift $\psi=\varphi_{1\mathrm{u}}-\varphi_{1\mathrm{d}}$, we obtain a set of oscillation pictures (see Fig. 4) which is similar to that we observe experimentally by increasing the magnetic field (Fig. 1). When the phase shifts $\varphi_{1\mathrm{u}}-\varphi_{0\mathrm{u}}$ and $\varphi_{1\mathrm{d}}-\varphi_{0\mathrm{d}}$ are different, split minima in the calculated G curves show an asymmetry. Such an asymmetry is present also in the experimental results.

Comparison of this model with the experimental results suggests attributing the observed halving of the oscillation period to spin splitting effect. The increase of B not only lifts the transmission probability due to enhanced separation of the edge states but also produces splitting of the states with different spins. The splitting should become important at $B=1\,\mathrm{T}$, because at this field we begin to observe it in the Shubnikov–de Haas oscillations of 2D gas in our sample at 70 mK. As the electron states with different spins are resolved, the areas $A_{i\mathrm{u}}$ and $A_{i\mathrm{d}}$ become different. As a result, *spin splitting of the AB oscillations* takes place. However, the experimentally observed locking of the spin phase shift ψ to π with the increase of B cannot be explained within a model of noninteracting electrons. The equality $\psi=\pi$ means that zero-dimensional quantization in the edge channels gives a set of equally spaced levels with alternating spin-up and spin-down states. This is understandable if one assumes that as the magnetic field increases and the edge channels become more localized, the splitting of the electron states is governed by Coulomb interaction rather than by Zeeman effect. It seems reasonable that the electron state configuration with spin-up and spin-down levels in "antiphase" is favorable for minimization of the Coulomb energy, especially when the exchange interaction is concerned [18].

Further halving of the period observed in the beginning of the plateau in a field of 1.4 T can, in principle, be explained as a manifestation of higher harmonics in the AB oscillations. To illustrate this, we did calculations for a more complicated model, which included, in addition to that shown in Fig. 4, mixing between forward- and backward-propagating electron waves in open (0*s*) edge channels near the constrictions. With the same assumptions as before (when all the phases φ_{is} change in an equal way), the conductance given by this model shows more complex behavior as a function of φ_{1u} than the conductance of Eq. (1) and shows an additional (with respect to the spin splitting effect) halving of the period. In particular, when transmission probabilities are close to 1 and $\psi = \pi$, we obtain a picture with alternating resonant dips of larger and smaller amplitude which is similar to that we observe experimentally at 1.4 T (see inset of Fig. 1). Another higher-harmonic feature, a splitting of the oscillation *peaks*, is also obtained from this model. This splitting we see at 1 T in the beginning of the first plateau (Fig. 1). The fact that the smaller-period features are seen only in the beginning of the plateau, where contribution of the 0*s*–0*s* mixing should be more significant, is consistent with the model described above.

4. Conclusions

In this paper we described our investigations of ballistic magnetotransport of electrons in a quantum dot whose size is considerably smaller than the sizes of the quantum dots investigated previously. The phase coherence in this dot at 70 mK holds even at zero magnetic field. This allowed us to observe the large-amplitude AB oscillations of the ballistic conductance at small enough magnetic fields (around $B = 1$ T), when the edge channels start to be well-defined. With the increase of magnetic field, we have observed splitting and, finally, period halving of the AB oscillations. We attribute this to spin splitting of the electron states. As the magnetic field increases and the confined edge states become more localized, the oscillations associated with spin-up and spin-down states in the dot progressively come in antiphase and stay phase-locked so that the exact halving of the AB oscillation period takes place.

Previous observations [6,7] of AB oscillations (carried out for larger quantum dots in higher magnetic fields) have revealed already phase-locked spin-up and spin-down states. In contrast to this, we report the direct observation of progressive spin splitting of electron states in quantum dots which is detected by splitting of AB oscillations and eventual halving of their period. Since the phase locking develops as a result of Coulomb interaction between the electrons in confined edge states, our data can be useful for deeper understanding of the role of Coulomb interaction on the electron energy spectrum of quantum dots.

Furthermore, we have observed indications of further subsequent period halving, which we attribute to higher AB oscillation harmonics due to different types of mixing between interfering edge states. The effect of higher harmonics could be also taken into account for interpretation of period halving phenomena in those cases [9,10] when only one spin-resolved state propagates through the dot and the halving cannot be explained by the spin splitting.

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