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2006 J. Phys.: Condens. Matter 18 3277

(http://iopscience.iop.org/0953-8984/18/12/009)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **18** (2006) 3277–3284 doi:10.1088/0953-8984/18/12/009

Spin-polarized transport through a quantum point contact in strongly quantizing magnetic fields: mimicking the 0.7 scenario

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Received 13 October 2005
Published 7 March 2006
Online at stacks.iop.org/JPhysCM/18/3277

Abstract

We study the influence of a normal magnetic field on the 0.7 feature exhibited by quantum point contacts (QPCs). The magnetic field is used to induce the formation of edge states whose spin splitting and spatial separation can be varied directly via the applied field. By appropriate control of the gate voltage, the QPC can be configured so that its conductance is determined by the two spin-resolved edge states of the lowest Landau level, mimicking the two-channel picture that has been suggested in discussions of the 0.7 feature. Under these conditions, a clear 0.7 feature is only observed at weak magnetic fields, where any spin gap is small and the two edge states are strongly overlapping. A similar feature is also seen at high magnetic fields, but only once the temperature is increased such that the thermal energy is comparable to the size of the spin gap. The connection of these results to the processes that lead to the 0.7 feature is discussed.

1. Introduction

Semiconductor quantum point contacts (QPCs) [1, 2] are a fertile system for investigating the unique features of one-dimensional (1D) carrier transport. A widely used method to implement such structures is the split-gate technique, in which metal gates with a lithographically defined, submicron sized, gap are deposited on the surface of a high-mobility GaAs/AlGaAs heterostructure. By applying a negative voltage to these gates, the regions of two-dimensional electron gas (2DEG) underneath them can be depleted, forcing current flow from source to drain to occur via the narrow constriction that is formed in the gap between the gates. The transverse motion of electrons in such QPCs is confined on a scale comparable to their Fermi wavelength, as a result of which their current is carried by a small number of occupied 1D *subbands* (or *channels*). Each subband is characterized by a unique, quantized, transverse momentum. The gate voltage also induces the formation of a saddle-like potential barrier inside the QPC, and, as the gate voltage is made more negative, the local barrier associated with this rises and drives successive 1D subbands above the Fermi level. At low temperatures ($\leqslant$4.2 K), and under conditions where transport through the QPC is ballistic, the depopulation of each subband is accompanied by a quantized decrease of the conductance, by an amount of $2e^2/h$ ($\equiv G_0$). (The factor of two arises here since each subband is usually spin *degenerate* at zero magnetic field, with each spin component contributing a conductance of $G_0/2$.) When sweeping gate voltage over a wide range, the conductance therefore exhibits a staircase form, with a last plateau expected at $2e^2/h$ before the conductance finally vanishes [1, 2]. Quite remarkably, this result can be explained by a simple, non-interacting, model of electron transport. A crucial component of this model is a cancellation of energy terms in the product of the 1D density of states and the group velocity that appears in the calculation of the current carried by each subband.

While the quantization of the QPC conductance in units of G_0 is now well understood, in the last decade there has been ongoing interest in the origin of an unexpected, plateau-like, anomaly that occurs in the conductance of many QPCs. This '0.7 feature' is observed *below* the last integer plateau, at a value of $\sim 0.7G_0$ [3–8]. In an early study by Thomas *et al* [3], the 0.7 feature was found to move steadily towards $0.5G_0$ under the application of a large magnetic field *in* the same plane as the 2DEG. Since the dominant effect of the in-plane field is known to be to lift the spin degeneracy of the different 1D subbands, these authors suggested that the 0.7 feature may be due to a spontaneous spin splitting of the lowest 1D subband that persists even at zero magnetic field. The notion of a spin-dependent phenomenon still enjoys considerable popularity and forms the basis for a number of theoretical proposals [9–20] (with the notable exception of [21]). Common to these models is the idea that the many-body interactions of electrons in the QPC are significantly enhanced when its constriction is close to pinch-off, since in this regime the saddle minimum lies close to the Fermi level and the local electron density is significantly reduced from that of the 2DEG. Berggren *et al* have argued that, in this limit, the exchange interaction of electrons causes the QPC to function as a spin-dependent barrier, resulting in the development of a *static* net spin polarization (with an equivalent *local magnetic moment*, LMM) in the QPC [13, 17]. An alternative model has been motivated by the experimental work of Cronenwett *et al*, who noted that the 0.7 feature exhibits many aspects in common with the *Kondo* effect, including a zero-bias anomaly in nonlinear conductance and a universal scaling of its temperature dependence [6]. This result is at first surprising, since the Kondo effect is normally associated with the presence of an LMM and the QPC is an apparently open system. Hirose, Meir and Wingreen [14, 16] have proposed a resolution of this issue by arguing that self-consistent effects can cause a (spin-dependent) localized electron state to form in the QPC near pinch-off. In other work, Reilly *et al* [7, 20] have proposed a phenomenological model consistent with the results of many experiments, which attributes the 0.7 feature to the opening of a spin-dependent energy gap that evolves dynamically as the QPC confinement is varied.

2. This study: an overview

The suggestion of the various studies mentioned above is that, in the limit where a QPC is configured so that only its lowest 1D subband is weakly conducting (and so all other subbands are fully depopulated), the expected spin degeneracy of this subband may actually be lifted at zero magnetic field. Under such conditions, current flow through the QPC takes place via two distinct transport channels, which contribute very differently to the conductance. Independent support for this idea has recently been provided by measurements of the noise characteristics of QPCs, which showed conclusively the contributions from two different transport channels in the regime where the 0.7 feature is observed [8].

In previous experimental studies of the 0.7 feature, an in-plane magnetic field has often been used to investigate its origins [3, 6, 7]. Little work has focused, instead, on how this feature is affected by the application of a magnetic field *normal* to the plane of the 2DEG. While the advantage of an in-plane field is that it may be used to couple predominantly to the electron spin, without strongly affecting the in-plane motion, studies performed with a normal field should also have several advantages. Of particular value is the ability to exploit the resulting Landau-level quantization to form spin-polarized channels (or edge states) in the 2DEG reservoirs of the QPC. This approach has previously been successfully applied to investigate spin-dependent tunnelling in quantum dots [22]. In this study, we take advantage of edge-state formation to provide a means to *mimic* the conditions believed to lead to the 0.7 scenario. Our experiment relies on the idea that, by varying both the magnetic field and the potential profile of the QPC (via its gate voltage), it should be possible for us to modulate the resulting spin splitting of the different edge channels, as well as their transmission coefficients and spatial overlap. In particular, we are able to configure the QPC so that its conductance is dominated by the contribution from just two spin-split channels, similar to the situation suggested for the 0.7 scenario. At low temperatures, we show that the observation of the 0.7 feature is restricted to weak magnetic fields, where the two spin channels should exhibit a significant spatial overlap and a correspondingly small spin gap. As the magnetic field is increased, the 0.7 feature is suppressed and clear conductance plateaus instead become resolved at $0.5G_0$ and G_0. With increasing temperature, however, a gradual increase of the conductance is observed, with the plateau at $0.5G_0$ moving upwards toward $0.7G_0$. We discuss here how these results provide independent support for the two-channel interpretation of the 0.7 feature.

3. Experimental details

The results presented here are an extension of our earlier work [23] in which we investigated the conductance characteristics (at *zero* magnetic field) of QPC structures with the multi-gate geometry shown in the inset to figure 1. These gates are formed on a GaAs/AlGaAs quantum well, with a two-dimensional electron gas located approximately 200 nm below its top surface. At 4.2 K, the density and mobility of this electron gas are 2.7×10^{11} cm^{-2} and 4×10^6 cm^2 V^{-1} s^{-1}, respectively. By applying a negative voltage (V_{QPC}) to the vertical gates in figure 1, we are able to form a QPC. We then apply a bias voltage (V_{Fing}) to one of the horizontal gates (which we refer to hereafter as the 'finger gates'), while leaving the other floating. Previously [23] we have shown that the main influence of this finger-gate voltage is to modulate the density on one side of the QPC, *without* splitting it into two distinct wires. In this report, we present the results of studies of the influence of a magnetic field on the conductance of device *B* of [23].

4. Experimental results

In figure 1, we illustrate the influence of the normal magnetic field on the conductance at 0.02 K. In these, and all other, measurements, the conductance was determined by passing current between probes 5 and 4, while measuring the voltage across probes 1 and 8. In the regime of well-resolved quantum Hall transport, the resulting conductance ($G = I_{54}/V_{18}$) inferred in this way is directly proportional to the transmission of the QPC alone [24]. The behaviour shown in figure 1 corresponds to the usual [25] magnetic depopulation of subbands in the QPC with increasing magnetic field. At zero magnetic field, the conductance exhibits a number of well-resolved plateaus, indicating the high electronic quality of our 2DEG. With increasing magnetic

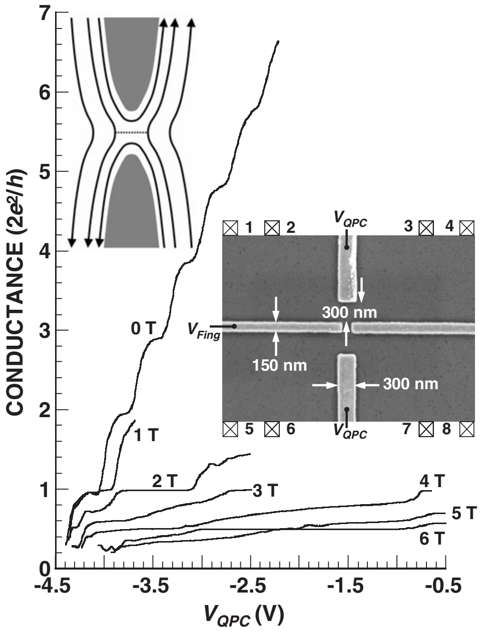

Figure 1. Main panel: QPC conductance at different magnetic fields at 20 mK. Upper inset: schematic illustration of the edge state configuration in the QPC under typical conditions of interest. Lower inset: scanning-electron micrograph of our device. Lighter regions are metal gates and the ohmic contacts and gate connections are schematically indicated.

field, the number of one-dimensional subbands that carry current is steadily reduced, an effect that is accompanied by an overall decrease in the QPC conductance.

In the main panel of figure 2, we show the results of more detailed measurements that focus on the influence of the magnetic field in the region near the last conductance plateau (at G_0). (For reference we also show as an inset the magneto-resistance of the 2DEG, which was obtained without any voltage applied to the QPC or finger gates.) Three distinct regimes of behaviour can be seen in the main panel of figure 2. (i) *Weak magnetic fields* (0–1 T). Here, an increase of the magnetic field increases the visibility of the plateau at G_0. This effect is well known from prior studies of QPCs, where it has been attributed to a suppression of backscattering at the QPC input and output [25]. In addition to this behaviour, the plateau-like features near $0.5G_0$ and $0.7G_0$ also become more clearly resolved. The presence of this *multiple* structure below the last plateau was discussed in some detail in [23], where we analysed the transmission characteristics at zero magnetic field. (ii) *Strong magnetic fields* (4–8 T). Here, spin degeneracy of the Landau levels is strongly lifted, as is demonstrated by the clear splitting of the Shubnikov–de Haas oscillations in the inset to figure 2. In this magnetic-field range, the conductance decreases monotonically from G_0 to $0.5G_0$ as the QPC gates are biased more negatively, *without any evidence for a feature near* $0.7G_0$. (iii) *Intermediate magnetic fields* (1–4 T). In this transitional regime, the broad initial (at 1 T) plateau at G_0 collapses onto that at $0.5G_0$ as the magnetic field is increased and well-defined edge states begin to form.

To interpret the behaviour shown in figure 2, we consider the nature of edge-state transport in the QPC. As can be inferred from the data in the inset to figure 2, for magnetic fields less than 6 T more than two spin-resolved edge states are occupied in the 2DEG. When the QPC

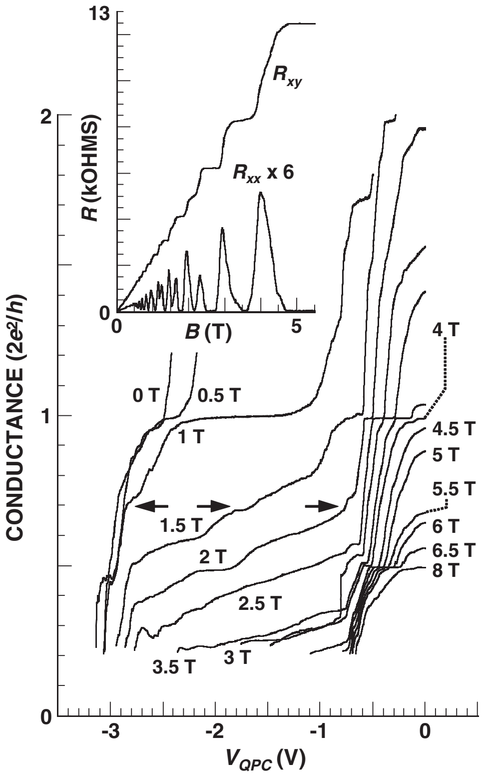

Figure 2. Main panel: expanded view of the influence of the magnetic field on the conductance in the region near G_0. The temperature is 20 mK. Inset: longitudinal (R_{xx}) and Hall (R_{xy}) resistance of the 2DEG, which was measured with no voltage applied to the gates.

conductance drops below the G_0 plateau, however, only the two spin-split edge states of the lowest Landau level contribute significantly to the conductance. One of these edge states should be fully transmitted (at least while the conductance remains larger than $0.5G_0$) while the second must tunnel through the saddle potential at the centre of the QPC. Under such conditions, there is therefore a similarity with the two-channel scenario that has been proposed for the 0.7 feature. By changing the magnetic field and gate voltage in figure 2, we are able to modify the contribution of these two separate channels to the conductance. At magnetic fields above 4 T, we have noted already that the conductance decreases monotonically from near G_0, to a plateau at $0.5G_0$, without any evidence for the 0.7 feature. In this magnetic-field range, the pronounced spin splitting of the edge states should ensure that they are spatially well separated [26, 27] and so are largely independent of each other. As V_{QPC} is made more negative, and the QPC saddle barrier is driven upwards, the conductance of one of the two channels can therefore be cleanly cut off while leaving the other fully transmitting. The signature of this process should be a monotonic decrease of the conductance, from G_0 to $0.5G_0$, just as we observe in our experiment.

As the magnetic field is lowered from 4 T, the overlap of the two edge states should increase, along with the conductance of the QPC (this can be seen in figure 2 simply by looking at the behaviour at fixed V_{QPC} as a function of magnetic field, particularly in the range -3 V $< V_{QPC} < -1$ V). An interesting feature in figure 2 is that it is only when the magnetic

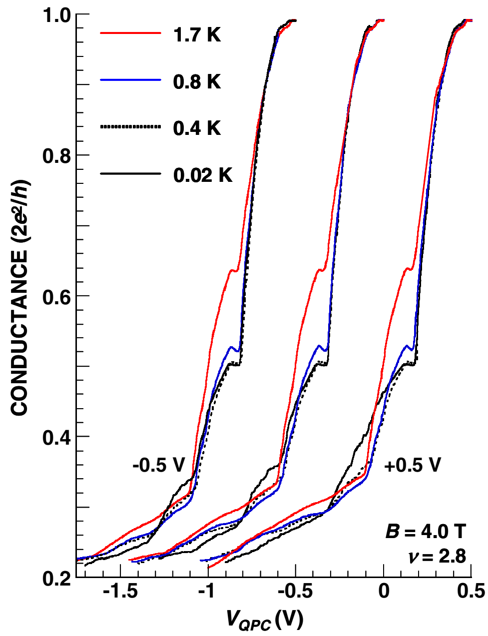

Figure 3. Influence of temperature on the QPC conductance at a magnetic field of 4 T. The data shown were obtained for three different values of the finger-gate voltage: −400, −425, and −450 mV, from left to right, respectively. The left and right data sets have been shifted horizontally by the amounts indicated.

(This figure is in colour only in the electronic version)

field is reduced in this manner that the 0.7 feature is observed (see arrows in data at 1, 1.5 and 2 T). This suggests that the observation of the 0.7 feature requires the presence of just a *modest* spin gap, under which condition the two channels contributing to transport should possess significant spatial overlap. This conclusion is consistent with the scenario proposed by Reilly *et al* [7], who have attributed the observation of the 0.7 feature to the opening of a small spin gap, comparable in size to the thermal energy.

In the discussion above, we have emphasized the use of the magnetic field to modulate the size of the spin gap in the QPC, and so to modify the conditions under which the 0.7 feature is observed. Another approach available to us is to vary the temperature. This should be of particular value at higher magnetic fields, where we have argued that the presence of a large spin gap precludes the observation of the 0.7 feature. In figure 3, we show the results of measurements of the QPC conductance at a fixed magnetic field of 4 T (for which the corresponding filling factor $\nu = 2.8$) and at several different temperatures. The data shown here were obtained for three different values of the finger-gate voltage and illustrate the reproducibility of the behaviour that we discuss. At low temperatures, all three data sets show a clear plateau near $0.5G_0$, with no evidence for the 0.7 feature, consistent with the presence of a well-resolved spin gap. As the temperature is increased above ∼1 K, and the thermal excitation of carriers across the spin gap is increased, there is a clear trend for the $0.5G_0$ plateau to move up towards $0.7G_0$. This observation is significant for two reasons. Firstly, it demonstrates that the 0.7 feature is associated with two separate transmission channels, the second of which becomes populated with increasing temperature in figure 3. A simple estimate for the spin splitting is consistent with this idea. By assuming a g-factor of 0.4 for GaAs, we obtain a spin gap (Δ_s) of magnitude $\Delta_s/k_B \equiv g^*\mu_B B/k_B \sim 1$ K at 4 T. This value is in agreement with the observed temperature scale on which the 0.7 feature develops in figure 3.[4] Secondly, our results appear consistent with the suggestion of Reilly *et al* [7, 20] that the occurrence of the 0.7 feature is related to the opening of a spin gap that is comparable in size to the thermal energy.

In this report, we have focused on using a normal magnetic field to mimic the conditions leading to the 0.7 scenario. Before concluding, however, we should comment on an important *difference* between this experiment and those in which the 0.7 feature is usually observed. The 0.7 feature is typically studied at zero magnetic field, but we have reproduced it here by forming spin-polarized edge states at high magnetic fields. While this approach is certainly instructive, it makes it difficult for us to provide more than a qualitative discussion of our results in the context of the different theories for the 0.7 feature. Nonetheless, we do believe that our results are significant, in demonstrating that the 0.7 feature appears to be associated with a situation where a weakly resolved spin gap is present.

In conclusion, we have studied the influence of a normal magnetic field on the 0.7 feature. The magnetic field was used to induce the formation of edge states whose spin splitting and spatial separation could be varied directly via the applied field. By appropriate control of the gate voltage, the QPC could be configured so that its conductance was determined by the two spin-resolved edge states of the lowest Landau level, mimicking the two-channel picture that has been suggested in discussions of the 0.7 feature. Under these conditions, a clear 0.7 feature was only observed at weak magnetic fields, where any spin gap should be small and the two edge states are strongly overlapping, or at high magnetic fields when the temperature was increased such that the thermal energy became comparable to the size of the spin gap. We believe that these results provide new insight into the conditions that lead to the observation of the 0.7 feature.

Acknowledgments

The authors gratefully acknowledge the support of the Office of Naval Research (N00014-98-0594), the National Science Foundation (ECS-0224163) and the Department of Energy (DE-FG03-01ER45920). Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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