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Transition from Ohmic to adiabatic transport in quantum point contacts in series

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Ballistic electron transport has been studied in a device consisting of two quantum point contacts (QPC's) in series, connected by a 1.5-μm-wide cavity. In the absence of a magnetic field the measured device resistance is approximately the sum of the (quantized) resistances of the individual QPC's. In a magnetic field a gradual transition to the adiabatic transport regime is observed, which is reached at $B \approx 1.0$ T. In this regime the device conductance is completely determined by the QPC with the lowest conductance. An explanation is given for the observed transition from Ohmic to adiabatic transport.

Recently, much effort has been devoted to the study of electron transport in the ballistic regime. Elastic and inelastic scattering are absent in this transport regime, and the electron motion is completely determined by the geometry of the conductor. The most elementary device for the study of ballistic transport is a narrow and short constriction (point contact) connecting two wide conductors, which act as electron reservoirs. Quantization of the conductance in the absence of a magnetic field was discovered in quantum point contacts (QPC's), defined in a two-dimensional electron gas (2D EG) by means of a split-gate technique. Upon varying the width of the QPC's with the gate voltage, the conductance increases in quantized steps of $2e^2/h$, each step corresponding with the population of a new one-dimensional (1D) subband.[1,2]

The study of ballistic transport can be extended to more complex devices. An interesting geometry is a configuration of two QPC's in series, connected by a cavity [see Fig. 1(a)]. The first experiments on such a device were performed by Wharam *et al.*[3] A relevant question is how the resistance of a dual QPC device in the ballistic regime is related to the resistances of the individual QPC's. To answer this question we can distinguish two opposite regimes.

Adiabatic transport will take place when the confining electrostatic potential, which forms the QPC's and the cavity, changes smoothly.[4] In a quantum-mechanical description adiabatic transport means that electrons which have been transmitted through the first QPC in a specific 1D subband will flow towards the second QPC with conservation of their subband index N. Depending on whether this subband is occupied in the second QPC, these electrons will either be fully transmitted or fully reflected at this QPC. It follows that the conductance in the adiabatic regime is completely determined by the QPC which transmits the least number of subbands, and which consequently has the largest resistance.

In the opposite regime the confining potential is such that the electrons which have been transmitted by the first QPC are scattered into all available subbands inside the cavity. (The cavity is wider than the QPC's, and consequently accommodates more subbands than the QPC's.) Classically, this means that the electron motion is randomized, and that an approximately isotropic velocity distribution is established inside the cavity. Because of this randomization of the electron motion, the cavity in between the QPC's now acts as a reservoir,[5] and the resistance of the device is now equal to the sum of the resistances of the individual QPC's. This is the Ohmic transport regime.

Deviations from the Ohmic addition rule can occur when the randomization inside the cavity is not complete. Recently, Beenakker and van Houten presented a calculation of the classical conductance of two QPC's in series.[6] They showed that a collimated electron beam may be formed as a result of the specific geometry of the QPC's. This may enhance the conductance of the device above its Ohmic value.

In this Rapid Communication, we study ballistic electron transport through QPC's in series, both in the presence and absence of a magnetic field. Our results show that the transport in zero magnetic field is Ohmic. When the magnetic field is switched on, we observe a gradual transition to the adiabatic regime, which is reached at $B \approx 1.0$ T.

The layout of the device is shown in Fig. 1(a). It is identical to the device used for the study of zero-dimensional electron states in an electron interferometer.[7] Two gate pairs A and B define two 300-nm-wide QPC's A and B, connected by a cavity, in the 2D EG of a $GaAs/Al_{0.33}Ga_{0.67}As$ heterostructure. The bulk 2D EG electron density is $2.3 \times 10^{15}/m^2$ and the elastic mean free path is about 9 μm. Application of -0.2 V to both gate pairs depletes the electron gas underneath them and

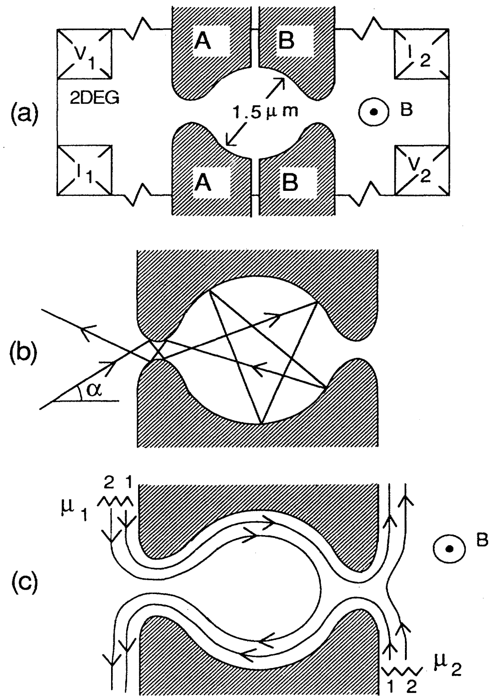

FIG. 1. (a) Schematic layout of the sample. Gate pairs A and B define two QPC's with a cavity in between. Current I_1, I_2, and voltage V_1, V_2 contacts are attached to the wide 2D EG regions. (b) Typical electron trajectory in the absence of a magnetic field, illustrating nonadiabatic transport. (c) Electron flow in edge channels along equipotential lines in a high magnetic field, illustrating adiabatic transport.

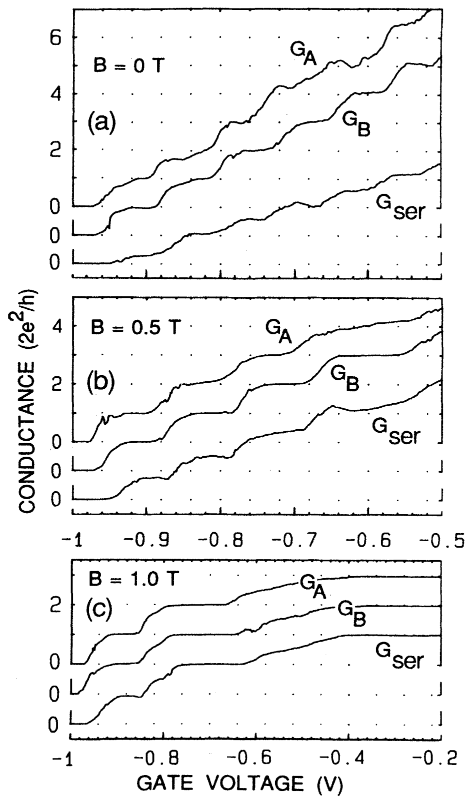

FIG. 2. Comparison between the conductances of the individual QPC's G_A and G_B and the conductance of the complete device G_{ser}, illustrating the transition from Ohmic transport at $B=0$, to adiabatic transport at $B=1.0$ T. The curves have been offset for clarity.

defines the device. At this gate voltage the narrow channels between the gate pairs are already pinched off. A further reduction of the gate voltage creates a saddle-shaped potential barrier in the QPC's, and this reduces both their width and electron density. Application of a negative voltage to only one gate pair (and zero voltage to the other) makes it possible to measure the conductance of the individual QPC's and compare them with the conductance of the complete device. The measurements are performed in a four-terminal setup [see Fig. 1(a)]. The orientation of the perpendicular magnetic field was such that the voltage probes V_1, V_2 measure the electrochemical potentials of the electrons flowing towards the device from either side. The measurements were made at 0.6 K. At this temperature the quantized plateaus in the conductance of the QPC's are reasonably well resolved, whereas possible quantum interference effects resulting from the presence of the cavity are averaged out.

Figure 2(a) shows a comparison between the conductances G_A and G_B of the individual QPC's and the conductance G_{ser} of the QPC's in series,[8] measured in zero field. The measurements of the individual QPC's show a superposition of quantized plateaus and a relatively constant background resistance.[9] This background resistance is determined from the difference between measured and expected values $h/2e^2N$ for the plateau resistances, and is subtracted from the measured data. Although the quality of the plateaus is poor, it is clear that a change of $2e^2/h$ in both G_A and G_B is accompanied by a change of e^2/h in G_{ser}. These results indicate that in zero field the resistances of the QPC's approximately add, and that the transport is Ohmic. A closer look at Fig. 2(a) shows that the conductance at the "plateaus" in G_{ser} is somewhat higher than the values Ne^2/h. This may imply that some collimation effects are present.[6] A detailed study of collimation effects in dual QPC devices will be given in a subsequent paper.[10]

Figure 2(b) shows the results obtained in 0.5 T. The combined effect of the magnetic field and the electrostatic confinement leads to the formation of hybrid magnetoelectric subbands[2] in the QPC's, and the energy separation between these subbands increases with magnetic field. This accounts for the widening of the plateaus compared to the zero-field case. Also, the accuracy of the quantization of G_A and G_B is improved. The plateaus in G_{ser} no longer correspond to multiples of e^2/h. The conductance steps between consecutive plateaus are about $1.5e^2/h$, which means that at this magnetic field the Ohmic addition rule no longer holds.

Figure 2(c) shows the results at 1.0 T. At this field G_{ser} is almost identical to the conductance of the individual QPC's, which illustrates that adiabatic transport takes place. The fact that G_{ser} shows quantized plateaus determined by the QPC's indicates that inside the cavity very little scattering occurs between the subbands (magnetic edge channels[11]) which are transmitted by the QPC's and those which are reflected. (Note that three Landau levels are occupied in the wide 2D EG regions.) This absence of scattering between edge channels for magnetic fields above ≈ 1 T has also been observed in other experiments.[11,12]

To investigate the transport for the case of nonequal point contacts we have measured G_{ser} as a function of V_B, with V_A kept constant at -0.7 V (Fig. 3). In zero magnetic field four 1D subbands are occupied in QPC A, which results in a resistance of $h/8e^2 \approx 3.25$ kΩ [see also Fig. 2(a)]. At low gate voltage G_{ser} shows plateaus. Figure 3(a) shows that these originate from QPC B. The arrows indicate the value of the plateaus when Ohmic addition of the QPC resistances is assumed, together with a value of 3.8 kΩ for QPC A.[13] For gate voltages less negative than -0.7 V, QPC A has the lowest conductance. The fact that G_{ser} continues to increase when the QPC with the lowest conductance is kept constant provides another illustration that adiabatic transport does not take place. We conclude that in zero magnetic field the device resistance is approximately the sum of the (quantized) resistances of the individual QPC's.

In contrast, Fig. 3(b) shows a similar experiment, performed in $B=1.0$ T. The conductance of QPC A is now fixed at $4e^2/h$ ($V_A=-0.7$ V). Figure 3(b) shows that for

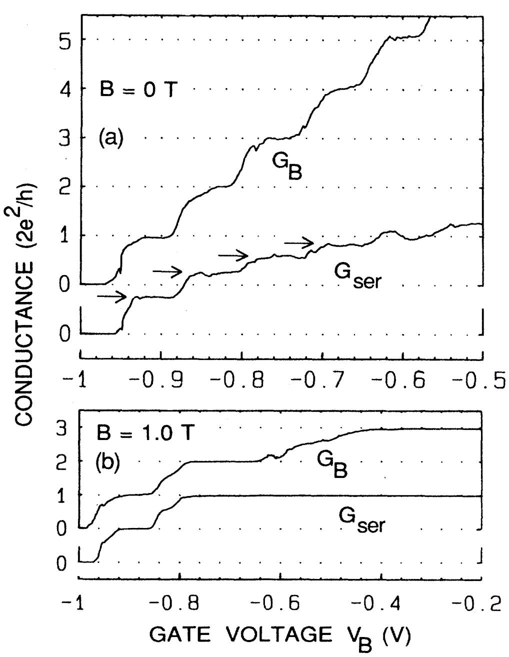

FIG. 3. Comparison between the conductance of QPC B and the conductance of the complete device G_{ser}. The conductance of QPC A was fixed at $\approx 8e^2/h$ at $B=0$ and at $4e^2/h$ at $B=1.0$ T. The arrows indicate the value for the plateaus in G_{ser} when Ohmic addition of the resistances is assumed, together with a value of 3.8 kΩ for QPC A (see text). The curves have been offset for clarity.

$V_B < -0.7$ V the conductance is equal to G_B, and for $V_B > -0.7$ V the conductance is constant and equal to G_A. This illustrates that the conductance G_{ser} is determined by the QPC with the lowest conductance and shows that adiabatic transport takes place.

To understand our results we give a brief description of adiabatic transport. In the absence of a magnetic field the adiabatic motion of an electron in a conductor of width W, and Fermi wave vector k_F is described by the adiabatic invariant[14] $S=(1/\pi)k_F W \sin(\alpha)$, in which α is the angle at which the electrons move [see Fig. 1(b)]. Adiabatic transport implies that when the width W of the conductor, or the electron density (which determines k_F), varies slowly enough, the corresponding change in α is such that S does not change. In a quantum-mechanical description this implies that the subband index N is conserved during adiabatic transport, since semiclassically N can be related to the integer part of S.[14]

We can now obtain a simple condition for adiabatic transport through the device, by noting that in a region where W or k_F changes, the electrons should be reflected several times by the boundaries of the conductor. This makes it possible for α to change in such a way that S is conserved. We now show that this condition for adiabatic transport is not satisfied in zero magnetic field.

In the absence of a magnetic field, the direction of an electron injected into the cavity by a QPC is completely randomized by reflections at the boundaries of the cavity [see Fig. 1(b) for a typical trajectory]. Since the width of the QPC's (less than 300 nm) is small compared to the diameter of the cavity (1.5 μm), one expects half of the electrons to be reflected and the other half to be transmitted. Therefore the cavity acts as a reservoir, and addition of resistances is expected, which is in agreement with the measurements. In order to observe adiabatic transport in the absence of a magnetic field one probably needs a much smoother widening and narrowing of the cavity in between the QPC's.

Our results are in contrast with those of Wharam *et al.*[3] They conclude to have observed almost complete adiabatic transport in a double QPC device. Wharam *et al.* studied an open geometry, while we have a closed cavity in between the QPC's. In view of the above discussion it is possible that almost perfect adiabatic transport did not occur in their device, whereas almost complete Ohmic transport is observed in our device.[15]

In a magnetic field the electrons move along the boundary of the conductor in skipping orbits. In this case the adiabatic invariant is given by $S=e/h\Phi$, in which Φ denotes the magnetic flux enclosed by an arc of the skipping orbit and the boundary of the conductor. (Note that in this case the integer part of S can be identified with the Landau-level index.[16]) On entering the QPC's the cyclotron radius l_c is gradually reduced due to the reduced electron density in the QPC's.[17] Adiabatic transport will take place when the electron density in the QPC's as well as the boundary of the cavity are smooth on a length scale of l_c. Obviously, these conditions are easier satisfied in high magnetic fields.

In this paper we have given a classical explanation for the transition from Ohmic to adiabatic transport, in which we have modeled the boundary of the conductor as a hard-wall potential. This description fails in high magnetic fields, when the cyclotron radius becomes smaller than the width of the depletion regions. (An electric field is present in the depletion regions at the boundary of the conductor. Their width is estimated to be ≈ 200 nm.) Electrons with different subband (Landau level) indices will now flow along different equipotential lines in magnetic edge channels.[11] In this case the mechanism for adiabatic transport is as follows: Whether electrons in a specific edge channel will be transmitted through the device is determined by the QPC with the highest potential barrier. This is illustrated in Fig. 1(c). The conductance of the dual QPC device will therefore be determined by the QPC with the lowest conductance.

Finally, we remark that our simplified picture of adiabatic transport does not allow us to give a quantitative explanation of our data. A fully quantum-mechanical calculation, which takes into account the details of the confining electrostatic potential, is probably required to explain why a magnetic field of 1.0 T already suffices to obtain adiabatic transport with a high degree of accuracy.

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[4]Adiabatic transport in single QPC's has been investigated by L. I. Glazman, G. B. Lesovik, D. E. Khmel'nitski, and R. I. Shekhter, Pis'ma Zh. Eksp. Teor. Fiz. **48**, 218 (1988) [JETP Lett. **48**, 238 (1988)]; L. I. Glazman and A. V. Khaettskii (unpublished).

[5]Classically, no inelastic processes are required for the cavity to act as a reservoir. The only condition is that an isotropic electron distribution is established. In a quantum-mechanical description phase randomization is required also, which can be brought about by inelastic processes, or by a finite temperature which results in energy averaging. The role of phase coherence in series resistors has been investigated by M. Büttiker, Phys. Rev. B **33**, 3020 (1986); IBM J. Res. Dev. **32**, 63 (1988).

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[8]Due to the proximity of both gate pairs, the activation of gate pair A slightly affects the electrostatic potential which forms QPC B and vice versa. As a result the conductance G_{ser} pinches off at a less negative gate voltage than the individual QPC's. We have compensated for this by offsetting all measured traces of G_{ser} by an amount of -0.04 V.

[9]Magnetoresistance measurements show that the electron density underneath the gated areas A and B is reduced even when no gate voltage is applied. This gives rise to a potential step between gated and ungated regions, which causes a partial reflection of the electrons. This creates a background resistance when the conductance of an individual QPC is measured. This resistance is about 1 kΩ at 0 T, 200 Ω at 0.5 T, and is absent at 1.0 T.

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[13]This is somewhat higher than the measured value of $\approx h/8e^2$, which can be accounted for by the slight change in the electrostatic potential in QPC A which occurs when gate B is activated (see Ref. 8).

[14]H. van Houten and C. W. J. Beenakker, in *Nanostructure Physics and Fabrication,* edited by M. Reed and W. P. Kirk (Academic, New York, in press).

[15]We did not observe complete adiabatic transport in a device similar to that of Wharam *et al.*, albeit that the conductance was enhanced over its Ohmic value. See also Ref. 10.

[16]H. van Houten, C. W. J. Beenakker, J. G. Williamson, M. E. I. Broekaart, P. H. M. van Loosdrecht, B. J. van Wees, J. E. Mooij, C. T. Foxon, and J. J. Harris, Phys. Rev. B **39**, 8556 (1989).

[17]We do not consider the low-field regime, where the electrons move through the QPC's in traversing trajectories.