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Suppression of Shubnikov–de Haas resistance oscillations due to selective population or detection of Landau levels: Absence of inter-Landau-level scattering on macroscopic length scales

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The Shubnikov–de Haas resistance oscillations of a wide two-dimensional electron gas are suppressed dramatically when current is injected with a quantum point contact which does not populate the upper Landau level. A similar suppression is observed when a quantum point contact is used as a voltage probe which does not detect the upper Landau level. The results are explained with a model in which the Shubnikov–de Haas oscillations arise from backscattering of electrons in the upper Landau level. It is shown that quantum ballistic transport in high magnetic fields can occur on length scales larger than 200 μm.

Quantum point contacts (QPC's) have proven to be valuable tools for the study of elementary electron transport. In zero magnetic field the conductance of single ballistic QPC's was found to be quantized[1,2] in units of $2e^2/h$. This quantization was explained in terms of the one-dimensional subbands formed in the point contacts, each occupied subband contributing $2e^2/h$ to the conductance. A similar mechanism accounts for the quantization in the presence of a magnetic field.[1]

Since the basic features of electron transport through QPC's are now well understood, they can be employed to study the more complex electron transport in a wide two-dimensional electron gas (2D EG). The transport along the boundary of a 2D EG has been investigated in the ballistic regime, employing two QPC's with a separation less than both elastic and inelastic mean free paths. The current in between the QPC's was shown to be carried by magnetic edge channels,[3] which consist of the current carrying states of each Landau level (LL) located at the boundaries of the 2D EG. In high magnetic fields it was observed that QPC's can selectively populate and detect these edge channels.[4] From these experiments it was concluded that the scattering between adjacent (located at the same 2D EG boundary) edge channels is extremely weak in high magnetic fields. This could be explained by the absence of impurities in between the QPC's, as well as the smoothness of the electrostatic potential which forms the boundary of the 2D EG.

The question now arises up to which length scale this quantum ballistic transport in a magnetic field (absence of scattering between different edge channels[5]) can take place. In zero magnetic field an obvious limitation is imposed by the presence of impurity scattering, which limits the quantum ballistic transport to length scales smaller than the elastic mean free path l_e (≈ 10 μm in high-mobility devices). However, because of the totally different nature of the transport, quantum ballistic transport in high magnetic fields may well occur on length scales much larger than l_e.

Recently, the electron transport through edge channels has been investigated by studying the (deviations from the) quantum-Hall effect.[4,6–8] In this Rapid Communication we study the scattering processes between different edge channels in a wide 2D EG by measuring the Shubnikov–de Haas (SdH) resistance oscillations. A QPC is used either to selectively inject current into particular edge channels, or as a voltage probe which has a controllable coupling to particular edge channels. In both cases a large suppression of the amplitude of the SdH oscillations is observed when the QPC does not inject a current into the upper (highest-occupied) Landau level, or, when used as a voltage probe, the QPC does not detect the upper Landau level.

We first present a model for the SdH oscillations. Figure 1(a) gives a schematic cross section of a 2D EG in a perpendicular magnetic field, showing the occupied electron states of two Landau levels (although in this description these are, in fact, one-dimensional subbands, we will continue to use the term Landau "levels" for simplicity). The electron states which are relevant for electron transport are located at the intersection of the LL's and the Fermi level, and are referred to as edge channels. The two edge channels associated with each LL are located at opposite boundaries of the 2D EG and carry current in opposite directions. A net current I flows as the result of a difference in electrochemical potentials μ_2 and μ_1 between the right- and left-edge channels.[9]

In Fig. 1(a) the Fermi level E_F resides near the bottom of the second LL. If the magnetic field is increased, the bottom of the second LL will approach the Fermi level. In this regime backscattering can be expected, leading to the onset of (longitudinal) resistance.[10] As a result of impuri-

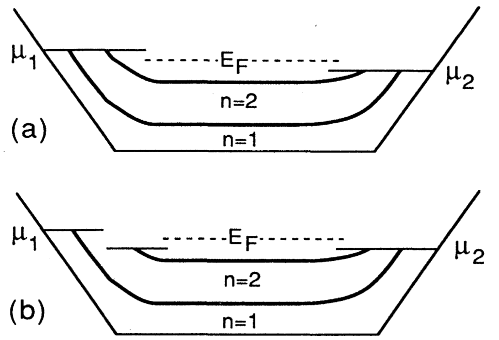

FIG. 1. Occupied electron states in a 2D EG in the presence of a current flow, illustrated for the case of two occupied Landau levels. (a) illustrates the regular situation. Resistance occurs as a result of backscattering of electrons in the second Landau level. (b) illustrates the mechanism for suppression of the SdH oscillations.

ties or macroscopic variations of the electrostatic potential, scattering can take place between edge channels located at opposite 2D EG boundaries. Since the left- and right-edge channels of the first LL remain separated, we assume that these SdH resistance oscillations, which will occur every time the Fermi level crosses the bottom of a LL, are due to backscattering of electrons in the upper LL only.

Figure 1(b) illustrates the mechanism for suppression of these SdH oscillations. The occupation of the electron states is shown when current is injected with a QPC which only populates the first LL (the mechanism for this selective population will be discussed below). As a result the second LL does not carry a net current, and hence there will be no backscattering and no (longitudinal) resistance when the Fermi level crosses the bottom of the second LL.

In order to observe this suppression of the SdH oscillations experimentally, it is also required that the scattering between adjacent edge channels is weak on length scales comparable to the sample dimensions. Otherwise some of the injected electrons will gradually be scattered into the upper LL. Once in the upper LL, they can be scattered back and give rise to resistance.

The model for electron transport in high magnetic fields is obviously highly simplified. In a more realistic approach the confining potential together with the occupation of the electronic states have to be calculated self-consistently.[11] The pinning of the upper LL to the Fermi level, which may result from a self-consistent treatment, might invalidate a description of electron transport in terms of edge channels alone, since in this case not all electron states of the upper LL are necessarily occupied in the interior of the 2D EG. However, we still expect this description to be valid for the low-lying LL's of which all electron states in the interior of the 2D EG will remain occupied.[12] The mechanism for suppression of the SdH oscillations will therefore remain effective.

The experiments have been performed on a similar device as used previously in Refs. 1, 3, and 4. The 2D EG of a $GaAs/Al_{0.33}Ga_{0.67}As$ heterostructure ($l_e = 9$ μm, electron density $= 3.5\ 10^{15}/m^2$) is first patterned into a Hall bar geometry and alloyed contacts 1–6 are fabricated [Fig. 2(a)]. The gate structure is made by optical (hatched area) and electron-beam (darkened area) lithography. Application of a negative gate voltage $V_g = -0.6$ V to both gates depletes the electron gas underneath the gates and defines two adjacent QPC's with a separation of 1.5 μm. At this gate voltage, the electron density in the QPC is yet unchanged, and in high magnetic fields ($B > 1.5$ T) the number of occupied LL's in the QPC and the wide 2D EG are equal.[1] A further reduction of the gate voltage starts to reduce the electron density together with the number of LL's in the QPC's. Pinch-off occurs at -2.2 V.

It was observed in Ref. 4 that a QPC can selectively inject current into only those bulk LL's which are occupied in the QPC itself. At $V_g = -0.6$ V, current will therefore be injected into all bulk LL's. At a somewhat lower gate voltage, when the number of occupied LL's in the QPC is one less than in the bulk, no current is injected into the upper bulk LL anymore. By reducing the gate voltage, the number of LL's which are populated by the QPC can be reduced further. When used as a voltage probe, the number of LL's which are detected can be controlled by the gate voltage in a similar way [Fig. 2(b)].

In the first experiment a three terminal measurement is performed, in which contacts 4 and 5 are current terminals, and the voltage is measured between 1 and 5 [Fig.

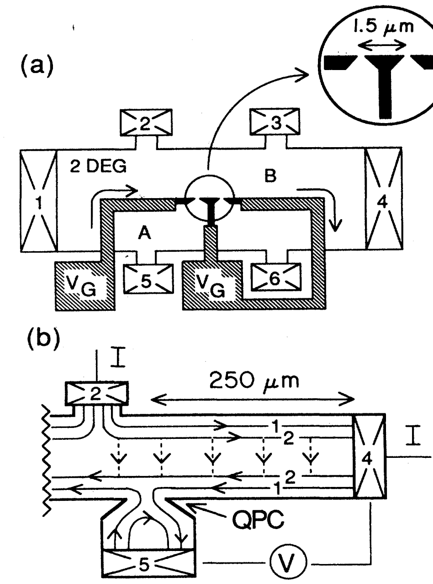

FIG. 2. (a) Sample layout (not to scale). Contacts 1 to 6 are attached to a Hall-bar shaped 2D EG. The gates define two adjacent point contacts. The arrows indicate the flow of electrons along the 2D EG boundary in forward magnetic fields. (b) Suppression of SdH oscillations due to selective detection of edge channels. Dashed lines illustrate the backscattering of electrons in the upper ($n = 2$) Landau level. In this example no resistance is measured, since the QPC only transmits the "empty" $n = 1$ channel, into which no electrons have been scattered.

2(a)]. This experiment measures the resistance of a series configuration of a QPC and a wide 2D EG (region *A*). Curve *a* in Fig. 3 has been obtained in a reverse magnetic field at $V_g = -0.6$ V. [The direction of electron flow along the 2D EG boundary is indicated in Fig. 2(a) for forward fields.] At this gate voltage (and $B > 1.5$ T) current will be injected into all LL's. The QPC will therefore not affect the SdH oscillations. Indeed curve *a* in Fig. 3 shows regular SdH oscillations. It is indicated which LL's are responsible for the consecutive SdH maxima (*n* indexes spin-split LL's). Curves *b*–*e* have been obtained for forward fields. Curve *b* shows the superposition of a quantum-Hall trace and SdH oscillations expected for this field orientation. A further reduction of the gate voltage lowers the electron density in the QPC. The plateaux are now determined by the number of LL's in the QPC and they gradually shift to lower fields.[1] As can be seen by comparing the SdH-peak heights in curve *a* with the residual structure on top of the quantized plateaux [arrows indicate the quantized values $h/(2e^2)$ and $h/(4e^2)$], the magnitude of the SdH peaks is substantially reduced. Note the absence of the $n=3$ peak in curve *c* and the reduction of the $n=4$, 6, and 8 peaks in curves *d*, *e*, and *d*, respectively.

As pointed out above, this suppression does not only show that the SdH oscillations are primarily caused by backscattering of electrons in the upper LL, but also that there is little scattering in region *A* from the LL's which are populated by the QPC into the not populated upper LL. The degree of suppression seems to imply that the majority of electrons injected into region *A* can reach contact 5, which is about 100 μm away from the QPC, without being scattered into the upper LL.

To study this in more detail we have performed a second experiment, in which we measure the SdH oscillations of 2D EG region *B*, employing a QPC as a voltage probe, which has a controllable coupling to the different edge channels. Contacts 2 and 4 are current contacts and the voltage is measured between 5 and 4. Figure 2(b) gives a schematic picture of the electron flow in the sample for the case of two occupied LL's, showing only the relevant contacts. (It has been checked that the presence of a second and identical QPC did not influence the electron transport.) In this example contact 2 injects electrons into all right-going edge channels. At a SdH maximum electrons in the right-going edge channel of the upper LL ($n=2$ in this case) will be scattered into the left-going channel of the same LL. If scattering between this left-going edge channel and the other left-going edge channels is absent, a finite voltage will be measured when the QPC transmits all edge channels. Zero voltage will be measured when the gate voltage is reduced such that the QPC does not transmit the upper channel [this situation is illustrated in Fig. 2(b)]. In this case all electrons entering the QPC originate from contact 4, and therefore the electrochemical potentials of contacts 4 and 5 will be equal.

Figure 4(a) shows a SdH trace obtained at $V_g = -0.6$ V. At this gate voltage the QPC transmits all LL's, and a regular SdH trace is observed. When V_g is reduced, the heights of the SdH peaks decrease progressively. At $V_g = -1.7$ V the $n=3$ peak is almost completely absent (the residual resistance is a few ohms), whereas all other peaks above $B \approx 1T$ are substantially reduced. By comparing Figs. 3 and 4 it can be seen that the $n=3$ and $n=4$ peaks in Fig. 4 are suppressed in the region where the conductance of the QPC is equal to or less than $2e^2/h$, which

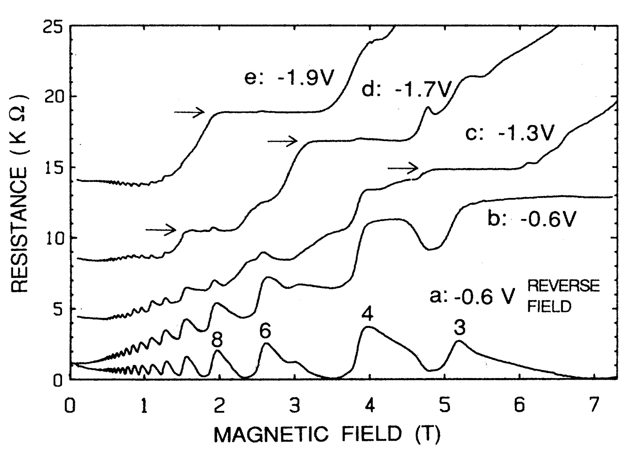

FIG. 3. Resistance of a series configuration of a QPC and a 2D EG for several values of the gate voltage. Curve *a* shows regular SdH oscillations measured in reverse field. Curves *b*–*e* show the (quantized) conductance of the QPC in series with the SdH oscillations of the 2D EG. Curves *c*, *d*, and *e* show suppressed SdH oscillations. The arrows indicate the quantized values $h/(2e^2)$ and $h/(4e^2)$. The curves have been offset for clarity: *c*, +2 kΩ; *d*, +4 kΩ; and *e*, +6 kΩ.

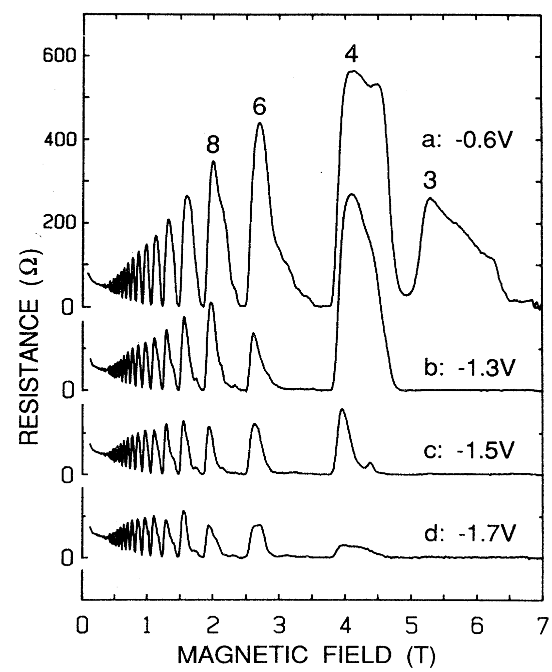

FIG. 4. Shubnikov–de Haas resistance of a 2D EG for several values of the gate voltage, illustrating the suppression of the SdH oscillations as a result of selective detection of edge channels (curves *b*, *c*, and *d*).

means that the QPC transmits the $n=1$ and 2 LL's only. The fact that in this case a negligible voltage is measured implies that between contacts 4 and 5 only few electrons have been scattered into these edge channels. This result, which is consistent with the first experiment, shows that scattering between adjacent edge channels can be extremely weak and that quantum ballistic transport in high magnetic fields can occur on length scales of the order of 200 μm (the distance between contacts 4 and 5).

Our results show that scattering can induce an unequal occupation of edge channels. This difference in occupation can be detected by quantum point contacts acting as selective voltage or current probes. The experiments show that in general the resistance of a macroscopic 2D EG in high magnetic fields cannot be defined without specifying the properties of the current and voltage probes.

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[5]If interchannel scattering is absent, scattering events can only give rise to a phase shift of the electron wave functions, compared to the situation where scattering is absent. Since interference phenomena are not relevant in our case, we can therefore identify the absence of interchannel scattering with quantum ballistic transport.

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[12]The Landau levels will be broadened by an amount ΔE, depending on the amount of disorder in the electrostatic potential. Electron states may also be localized by the disordered potential. For the low-lying Landau levels this is not expected to invalidate the edge-channel description, provided $\Delta E \ll \hbar\omega_c$. This is the case in our high-mobility devices.