Time-Resolved Measurements of Transport in Edge Channels

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(Received 16 February 1993)

In the quantum Hall regime the influence of edge channels on the evolution of the current through the device has been analyzed by time-resolved transport measurements. The observed nonlinear dependence of the time-resolved current on applied voltage is qualitatively in agreement with the model describing edge channels as compressible strips separated by incompressible regions.

PACS numbers: 72.30.+q, 72.20.–i, 73.40.–c

The importance of the physical boundaries of the sample for the properties of a two-dimensional electron gas (2DEG) in the quantum Hall effect (QHE) regime was predicted long ago [1,2]. The confining potential depletes the 2DEG near the edges and leads to the formation of so-called edge channels (EC). But only recently it became clear that these EC are relatively weakly coupled with each other and with the rest of the 2DEG in the bulk. Namely, this weak coupling allows the introduction of the physical concept of the EC and in many cases these small regions are responsible for the properties of the whole system [3]. But the electronic structure near the edge is not yet clear. In a simple one-electron picture the EC are lines along the boundary where corresponding Landau levels intersect with the Fermi level. Their widths are of the order of the magnetic length l_c and the small coupling is due to the spatial separation and the small overlap of the wave functions belonging to different EC. In more realistic models [4–6], which take into account a reasonable description of the confining potential and the electron-electron interaction, phase separation into strips with different filling factors arises. Strips with integer filling factors are incompressible and can provide the necessary weak coupling. Experimental evidence is, however, scarce.

In this work we present the first distinct manifestation of the weak coupling between EC in time-resolved measurements. At high frequencies or at short time scales specific plasma modes in the 2DEG associated with the edge of the sample-edge magnetoplasmons (EMP) [7,8] can be excited. Since the charge is pushed dynamically to the boundary, the EMP should be sensitive to the edge structure. Nevertheless, under usual experimental conditions the relation between charge and potential remains strongly nonlocal and precise determination of the microscopic parameters is rather difficult and controversial [9–12]. We partly suppress this nonlocality by a closely placed metal gate, which screens long-range Coulomb interaction and improves the sensitivity to the electron potential, namely, near the edge.

Unlike previous dynamical investigations, which studied single EMP modes in frequency [9–11] or in time [12] domain, we investigate time-resolved current propagation through the sample after the application of a voltage pulse. The appearance of the Hall voltage in the 2DEG after applying a voltage pulse U_{SD} can be described as the movement of a wave packet of the EMP [13]. Since we worked under conditions where a nonequilibrium population between different EC is possible for the whole path from source to drain [3], we have been able to observe the appearance of a new process at short time scales. This process is connected with the restriction of the wave packet to a strip near the edge due to both the decoupling of the EC from the 2DEG plane and of different EC from each other. The observed strong nonlinearity of the time-dependent current in the applied source-drain voltage U_{SD} can be explained by threshold scattering of electrons from the EC. The general features of this process are in qualitative agreement with the model of Chklovskii *et al.* [5], describing the electrostatics of the EC by compressible and incompressible stripes.

For the measurements, standard Hall-bar geometries were used, made from an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As/GaAs}$ heterostructure with a carrier concentration $n_s = 1.9 \times 10^{15}$ m^{-2} and a mobility $\mu = 70\ \mathrm{m}^2/\mathrm{V\,s}$. The geometry of the Hall bar with three metallic gates on the top is shown in the inset of Fig. 1(a). The distance between the 2DEG and the gates is $d = 120$ nm. The length L under the gates is 0.84 mm along one edge. The narrow gates can be used as capacitive probes. The available temperature ranges were 1.3–4.2 K in a standard cryostat with magnetic fields up to 12 T and 25 mK–1.5 K in a dilution refrigerator with magnetic fields up to 16 T. For all of the measurements shown the magnetic field was perpendicular to the 2DEG and the direction was such that the wave packet propagates directly from contact 2 to contact 3.

For the time-resolved measurements a long voltage pulse with a sharp front of less than 1 ns was applied to contact 2 relative to ground, with contact 3 grounded through a 50 Ω resistor. The time dependence of the voltage across the 50 Ω resistor was measured with a broadband preamplifier and a sampling oscilloscope. This measured voltage is proportional to the current through the sample. The rising time of this scheme was restricted by the equipment to 2.5 ns (in the dilution refrigerator the rising time was 5 ns due to nonperfect cables). By applying a negative gate voltage it was possible to suppress the current through the sample and to determine the direct cross talk between input and output. This spurious

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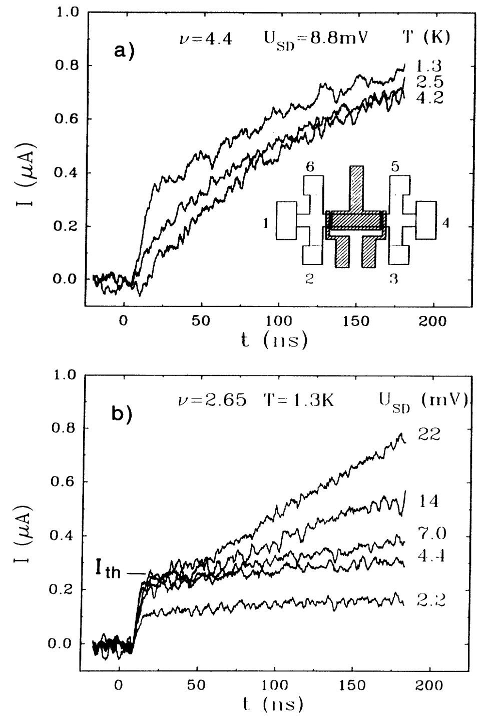

FIG. 1. Current through the sample as a function of time after a voltage pulse $U_{\rm SD}$ has been applied to contact 2 of the geometry shown in the inset. (a) Experimental traces for different temperatures at a filling factor of $\nu = 4.4$; (b) 5 traces for different voltages $U_{\rm SD}$ at a filling factor of $\nu = 2.65$. Threshold current $I_{\rm th}$ is marked by a narrow line.

signal was subtracted from the measurements. A small capacitive coupling at the end of the cables allowed us to obtain the exact time of the appearance of the voltage pulse at contact 2.

In Fig. 1(a) the time dependence of the current through the sample at a filling factor of 4.4 is shown for different temperatures. The rise of the current reflects the appearance of the potential at the drain. For $T = 4.2$ K, this potential spreads along the edge in a strip with a time-dependent width l_σ and appears at the drain with a time constant $t_1 = L/v_1$ ($t_1 = 220$ ns), with L the distance along the edge under the gate (for the ungated region the velocity of potential propagation is larger by about a factor of 10). For the condition of a metallic gate close to the 2DEG the frequency of the EMP was calculated in [8]:

$$\omega = 2\sigma_{xy} q\pi/\epsilon * (d/l)^{1/2} \quad \text{for} \quad l \gg d\,, \tag{1}$$

where q is the wave vector, ϵ is an effective dielectric constant, σ_{xy} is the Hall conductance, d is the distance between the 2DEG and the gate, and l is the width of the charge distribution normal to the edge. Since there is no exact solution for the wave packet propagation, we imply below that l is an average characteristic width for the whole source-drain path and for all wave components in the packet. For the low-damping regime, where Eq. (1) is valid, v_1 is given by $v_1 = \omega/q$. Here, the width $l_\sigma = (\sigma_{xx} t_1/C)^{1/2}$ (with σ_{xx} the longitudinal resistivity and C the capacitance between the 2DEG and the gate) arising from the diffusion in the electric field into the 2DEG plane [13] can be used for a qualitative description. A stationary distribution of the potential is obtained after several microseconds (not shown in the figure).

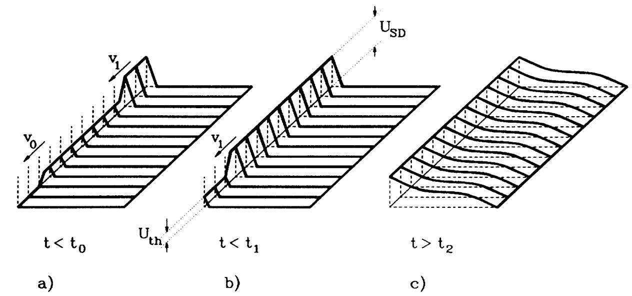

FIG. 2. Schematic picture of the development in time of the electrostatic potential in the sample after application of a voltage $U_{\rm SD}$: (a) Part of the potential (up to $U_{\rm th}$) moves with a fast velocity v_0 in a narrow strip; (b) the rest of the potential moves slower (with v_1) in a wider region; (c) on a long time scale the Hall voltage develops over the whole sample.

At $T = 1.3$ K a part of the total potential appears very rapidly at the drain after a finite delay (zero time corresponds to the appearance of the pulse at the source). The time t_0, which is determined by the sum of the delay time and a characteristic rising time of this fast process, is much less than the time t_1. This new process becomes more distinct by the comparison of traces at different amplitudes $U_{\rm SD}$ of the applied pulses [Fig. 1(b)]. Below a critical value $U_{\rm th}$ of the voltage (corresponding to a steady state current $I_{\rm th}$), all of the potential reaches drain at time t_0 (here $t_0 = 14$ ns). Above $U_{\rm th}$ a nonlinear regime starts. Only the potential with a value of $U_{\rm th}$ reaches the drain at t_0, whereas the rest of the potential above $U_{\rm th}$ develops on a larger time scale due to the above mentioned diffusion process ($t_1 = 340$ ns). Since the velocity of the potential wave is roughly determined by the width of the charged strip, the potential below $U_{\rm th}$ apparently moves in a strip with a narrower width l_0 than l_σ. One can estimate the width l_0 from the value of the velocity by using Eq. (1) (with σ_{xy} given by the integer number of filled EC). For a total filling factor of ν=2.5 we obtain l_0=1.3 μm calculated in using the delay time. Above $U_{\rm th}$ strong scattering of electrons from this l_0 strip occurs and the rest of the wave packet propagates with a diverging width.

Figure 2 shows a rough estimate of the potential which develops in the 2DEG after switching on a large external voltage. A part of the potential propagates with velocity v_0 in a strip with the width of l_0, where l_0 is a characteristic length connected to the sum of the width of all EC. The rest of the wave propagates with velocity v_1

since the corresponding charge left the l_0 strip due to the scattering between the EC and the bulk states. The l_0 process characterized by a steplike increase of the signal after a time delay t_0 is displayed when the EC are not completely equilibrated with the 2DEG in the bulk. As in the case of a nonequilibrated dc transport [3] decoupling is suppressed by increasing the temperature or for large sample size. We observed such decoupling in almost the whole region of filling factors between 2 and 8 and just above 1 at a temperature of $T = 1.3$ K, whereas at $T = 4.2$ K decoupling appears only in the filling factor region between 2 and 3. At a temperature of $T = 1.3$ K for a sample with an increased length L (by a factor of 1.9) decoupling was only observed in the filling factor region between 2 and 3. The final t_2 process (on a time scale of a few μs) is the diffusion of the charge from the boundary into the 2DEG plane in the electric field. It results in the establishment of a stationary distribution of the potential.

Although at a temperature of $T = 1.3$ K separation of the EC did not appear, at lower temperatures we also observed decoupling between different EC. The time dependence of the current observed at $T = 1.3$ K showed additional structures for some filling factors at lower temperatures. In Fig. 3 the time dependence of the current at a filling factor ν=3.3 is shown for different voltages $U_{\rm SD}$ at a temperature of $T = 25$ mK. The negative signal around $t = 0$ is artificial and is due to the capacitive coupling between source and drain [14]. Two steplike features observable in the current at short time scales are marked by thin lines. The second step is connected with the decoupling of all EC from the rest of the 2DEG. The first step observed already at $T = 1.3$ K is assumed to be connected to the decoupling of the innermost EC from all the other EC. This means that the equilibration length between the innermost EC and the other EC is larger than the distance below the gates along the edge. Without any selective injection, different EC are separated here due to the different velocities of the potential packet in strips of different widths.

In Fig. 4, the dependence of the measured threshold current on the filling factor is plotted. The strong asymmetry observable around integer filling factors excludes the possibility of explaining the nonlinearities only in terms of σ_{xx} and σ_{xy}. Therefore, the most striking feature is the divergence of the threshold current in approaching integer filling factors from above. In addition, the sequence of development of these nonlinearities with lowering the temperature, as mentioned above, approximately correlates with the strength of the energy gap in the bulk.

It is possible to describe qualitatively these essential features in the framework of the model by Chklovskii *et al.* [5]. Different EC are macroscopic regions with noninteger filling factors. They are separated both from each other and from the plane of the 2DEG by incompressible strips with integer filling factors. The width of each incompressible strip is roughly proportional to the corresponding energy gap and inversely proportional to the deviation $\delta\nu$ from the total filling factor. By increasing the filling factor, a new incompressible strip which separates the EC from the 2DEG plane appears above each integer filling factor. This strip is the largest one among other incompressible strips between different EC and therefore the decoupling due to this strip should be displayed first in the experiment with lowering temperature. At a temperature of $T = 4.2$ K decoupling was displayed only for filling factors between ν=2 and ν=3, where one can expect the widest incompressible strip due to the largest Landau gap. At a temperature of $T = 1.3$ K we observed the decoupling due to the strips with even filling factors (Landau gaps) in the whole range from ν=2 to ν=8, e.g., between ν=2 and ν=4 the incompressible strip with ν=2 causes the observed decoupling, between

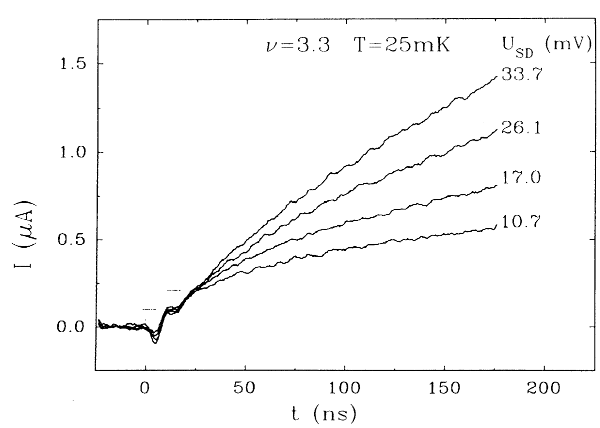

FIG. 3. Current through the sample as a function of time at a temperature of $T = 25$ mK. The two steps observed are marked by narrow lines.

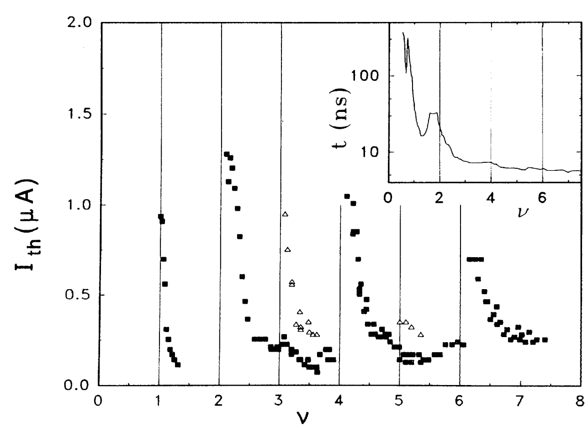

FIG. 4. Threshold current $I_{\rm th}$ as a function of filling factor for a temperature of $T = 25$ mK. The open symbols characterize the appearance of two threshold currents. The inset shows the measured time delay as a function of filling factor.

ν=4 and ν=6 the incompressible strip with ν=4, etc. An incompressible strip with an odd filling factor was only displayed above ν=1 at this temperature. In lowering the temperature no drastic changes occurred in the observed values of threshold current (full symbols in Fig. 4 at T = 25 mK). But above filling factors ν=3 and ν=5 new incompressible strips with odd filling factors are resolved. Since the corresponding spin-splitted energy gaps are smaller than the Landau gaps, these strips are narrower and are only observed at lower temperatures. The measured threshold currents are marked by open triangles in Fig. 4. So above odd filling factors the low-threshold step (full symbols) corresponds to the decoupling between the Landau energy separated EC and the higher-threshold step (open symbols) corresponds to the EC separated from the bulk by the spin-splitted energy gap. The microscopic mechanism of the breakdown is, however, not yet clear.

The inset of Fig. 4 shows the dependence of the delay time on filling factor. At a temperature of T = 25 mK and for filling factors larger than ν=2, the delay time is dominated by the fast l_0 process and therefore the measured times are close to our resolution limit. Below a filling factor of ν=2 the delay time increases due to the absence of the l_0 process. The minimum close to a filling factor of ν=1 displays the reappearance of the l_0 process caused by the opening of an exchange enhanced spin gap in the plane. Around ν=2/3 a dip in the dependence of the delay time arises but there is no distinct separation of the l_0 process.

In summary, we have demonstrated a new way to study EC by time-resolved transport measurements. The observed nonlinearity on applied voltage is qualitatively in agreement with the model by Chklovskii *et al.* [5]. At low temperatures the decoupling between different EC is observed. Therefore, this new method allows the study of individual EC and we are confident that it will also shed light on the particularly controversial fractional quantum Hall regime [4,15].

We would like to thank V. Fal'ko for helpful discussions and J. Kuhl and A.J. Peck for a critical reading of the manuscript.

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