PHYSICAL REVIEW B VOLUME 49, NUMBER 11 15 MARCH 1994-I

Experimental determination of the dispersion of edge magnetoplasmons confined in edge channels

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(Received 14 December 1993)

For a two-dimensional electron gas in the quantum Hall regime the time dependences of the induced charge and the current through the sample are investigated. The fastest electrodynamical process in the system is the propagation of a wave packet along the edge with the corresponding charge being held by the edge channel structure. The width of the charged strip is determined and the dispersion relation is obtained.

The electronic structure near the physical boundary of a two-dimensional electron gas (2DEG) with a normal magnetic field has been a topic of great interest in recent years.[1–4] The depletion of the 2DEG near the boundary, together with Landau quantization leads to the formation of so-called edge channels (EC)—the regions near the edge, where a noticeable part of the current flows and which are weakly coupled with each other. Recent solutions of the electrostatic problem near the edge[3,4] have shown that the real edge potential is smooth within the length scale of the magnetic length, and that the electron structure near the edge can be described as alternating compressible and incompressible strips along the edge. Most dc transport experiments, discussed on the basis of the EC picture,[1,2] feel only the absence of the complete equilibrium between different EC, and therefore it is difficult to extract all the information about the edge structure.

The excitation spectrum of the EC can contain rich information about their structure. Up to now there is no complete theoretical description of the edge excitations in real systems. The most accurate electrodynamic treatment of the 2DEG in a magnetic field has been done by Volkov and Mikhailov[5] disregarding peculiarities of the electron spectrum near the edge. For a variety of 2DEG systems they investigated in detail the common edge magnetoplasmon (EMP) mode, where the charge oscillates in phase across the edge region, and they found that the velocity is proportional to the Hall conductivity σ_{xy}, and that it depends also on the width l of the charged strip near the edge. The finite width originated from the leakage of the charge from the edge into the bulk with nonzero σ_{xx}. There were few attempts to combine the EC picture with the electrodynamical consideration. In Refs. 6 and 7 the EC were considered in a single-particle model, where the charge can change only in strips of the order of the magnetic length. Talyanskii *et al.*[8] analyzed qualitatively the influence of the EC structure on the EMP in a phenomenological approach. From the other side, Wen[9] calculated neutral excitations of the EC and showed that the Coulomb interaction drastically modifies the spectrum.

Experimentally EMP was studied both in the frequency[7,8,10–13] and in the time domain[14–17] for a variety of electrodynamic environments. Up to now only the common EMP modes have been observed. Without additional screening the connection between the charge and the potential in the wave is extremely nonlocal and the velocity of EMP is only weakly affected by the distribution of the charge. As a consequence the velocity of EMP was found to be roughly proportional to σ_{xy} with small oscillations around integer filling factors[10,16] due to variations of the width l with σ_{xx}. The screening of the Coulomb interaction with the help of gates[8,11,12,15,17] or with the help of back-side metal electrodes[13] reduces the EMP velocity and increases its sensitivity to the charge distribution in the wave. For such conditions the EMP velocity has strong maxima at integer filling factors, where the width l has minima.[11,13,15]

In studying time-resolved transport in a 2DEG, we have recently observed[17] a new type of edge excitation. The dynamics of the potential in the 2DEG on the shortest time scale can be described as the propagation of a wave packet of edge magnetoplasmons along the boundary. The charge in the wave packet oscillates with a common phase, but, contrary to all previous investigations, the mode, where all the charge is confined by the EC structure and the charge in the bulk of 2DEG is not involved in the vibration, has the fastest velocity. The restriction of the charge distribution by the EC structure drastically modifies the dependence of the velocity on filling factor. Some deviations from the macroscopic description,[5] which are thought to be due to the EC, have also been reported in Refs. 8 and 12.

Here, we combine time-resolved measurements of the current through the sample with measurements of the charge entering into the 2DEG. The measurements of both quantities give us the possibility to estimate the width of the charged strip for the fastest part of the wave packet. The dispersion relation determined for this mode does not contradict the classical theory[5] under the assumption that in our case the charged width is fixed by the EC structure, and it shows why the restricted mode is the fastest in our system in distinction from previous experiments.[8,7,11,12,16] The variation of the width, which is thought to be of the order of the distance from the edge to the location of the last incompressible strip, with filling factor supports the qualitative validity of the model[3] for our samples.

Two samples prepared in the same standard Hall bar

0163-1829/94/49(11)/7809(4)/$06.00

geometry have been used for the measurements. The geometry was analogous to the one used in Ref. 17 and is shown in the inset of Fig. 1. The lengths of the gates $G1$, $G2$, $G3$ on the top are 50, 740, and 50 μm, respectively. Mobility μ, concentration n_s, and the distance between the 2DEG and the gates are 70 $m^2/V s$, 1.9×10^{15} m^{-2}, 120 nm for the first and 50 $m^2/V s$, 2.3×10^{15} m^{-2}, 90 nm for the second sample. The temperature was 1.3 K in a standard cryostat with magnetic fields up to 14 T. A sketch of the measurement scheme is shown in connection with the sample geometry in the inset of Fig. 1. A long voltage pulse with a leading edge of 350 ps was applied to contact 2 relative to ground with contact 3 grounded through the 50-Ω input resistance of a broadband preamplifier. The output voltage of the preamplifier, being proportional to the current through the sample, was measured by a sampling oscilloscope. Both the preamplifier and the oscilloscope have 6-GHz band width. A GaAs metal-semiconductor field-effect transistor was mounted near the sample, and its gate was connected with gate $G3$ of the sample and through a 1-MΩ resistance with gate voltage supply. This transistor operated as a source follower in combination with a room-temperature preamplifier. The output voltage of the preamplifier is proportional to the change of the charge on the transistor gate. To obtain the input capacitance C_{in} (1.4 pF) and the gain of this source follower an independent calibration has been performed. The gain of the follower was unaffected by the magnetic field. By applying a negative voltage to gate $G1$, we suppressed the current through the sample and determined the direct crosstalk between input and output. This crosstalk signal has been subtracted from the measurements for the analysis. For all the measurement the wave packet propagates along the shorter boundary between contacts 2 and 3.

Figure 1 shows examples of charge and current traces for few noninteger filling factors. At the time $t=0$ the voltage pulse reaches contact 2. This time position can be determined from the residual capacitive coupling. After a certain delay time, sharp rises appear both in the current and charge traces. These fast processes characterize the appearence of a part of the potential wave packet at the drain (or below gate $G3$). The velocity of the wave packet is approximately ten times smaller in the regions under top gates due to screening of the Coulomb interaction. The small area between the gate $G3$ and the drain is not covered by a metallic gate, therefore the charge at the gate $G3$ and the current at the drain appear within our time resolution simultaneously. The corresponding charge in this part of the wave packet is mainly confined within the EC. The restriction is provided by the last incompressible strip with an integer filling factor ($\nu_s=2$ for bulk filling factor $2<\nu<3$ and $\nu_s=4$ for $\nu=4.5$).[17,3] The rest of the wave packet runs slower in a strip with an average width which is determined by the diffusion of charge into the 2DEG plane[5,15,17] and appears at the drain later. Since this width is larger than the width of the charged strip for the fastest process, the charge rises more rapidly than the current after the first jump. Additionally the charge appears under the gate due to diffusion from the EC region, where the potential is already installed by the first part of the wave packet. The variation of the relative part of the fast mode in the wave packet is clearly seen in Fig. 1, where all traces are obtained with the same value of the applied voltage. This part reaches a maximum for the bulk filling factors just above even integers ($\nu=2$ in Fig. 1), and decreases with increasing the deviation from the integer bulk filling factor. This dependence is due to the variation of the width of the last incompressible strip, which holds the charge in the EC region, with filling factor.[3] The amplitude of the fast process also depends strongly nonlinearly on the applied voltage and becomes nearly saturated at some threshold value I_{th}.[17] This nonlinearity reflects the dependence of the scattering from the EC on the potential difference between the 2DEG plane and the EC.

The dependence of the delay time on filling factor is plotted in Fig. 2 for both samples. For filling factors where the fast process is well resolved ($2<\nu<3.6$, $4<\nu<5.5$, and $6<\nu<7.2$ for the first and $2<\nu<3.3$,

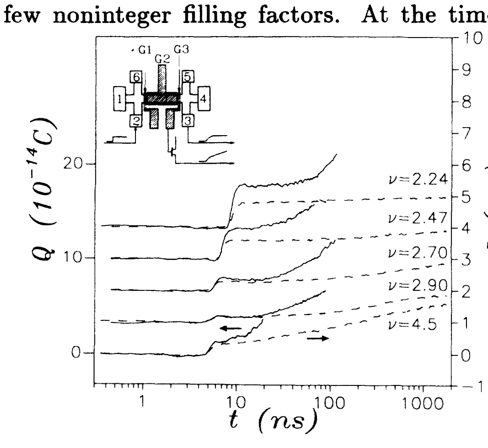

FIG. 1. Charge (solid line) and current (dashed) as a function of the time after a voltage pulse (14.2 mV for all traces) has been applied to contact 2 of the geometry shown in the inset for different noninteger filling factors (second sample). The different traces are shifted for clarity by steps of 1 μA. $t=0$ corresponds to the appearance of the voltage pulse on contact 2. Inset: Geometry of the samples and sketch of the measurements. $G1, G2, G3$ are top gates; 1–6, Ohmic contacts.

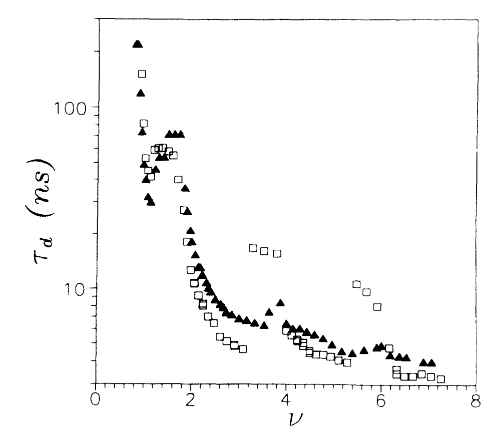

FIG. 2. Delay time in dependence on filling factor. Full triangles, first sample; open squares, second sample.

$4 < \nu < 5.3$, and $6 < \nu < 7.2$ for the second sample) the behavior of the delay time is similar—it increases when approaching even integer filling factors from above. This increase connects with the expected dependence of the width of the charged strip, which is of the order of the width of the edge region up to the last incompressible strip.[3] Below even integers ν the amplitude of the fast current falls under the noise level and the resolvable onset of the signal is not connected with this fast mode (full triangles for $3.6 < \nu < 4$ and $5.5 < \nu < 6$ for the first sample and open squares for $3.3 < \nu < 4$ and $5.3 < \nu < 6$ for the second one). Below ν=2 all the energy gaps are small and there are no decoupled EC. Only near ν=1 the quite large spin-split gap opens, but the temperature of 1.3 K is not low enough to ensure that any part of the charge reaches the drain without scattering into the bulk, since the delay time changes with lowering temperature.

The dispersion relation for the edge magnetoplasmon mode in a gated 2DEG was calculated in Ref. 5 with constant σ_{xx} and σ_{xy} throughout the sample:

$$v = (2\sigma_{xy}\pi/\kappa)(2d/l_0)^{1/2}, \quad l_0 \gg d. \tag{1}$$

Here v is the velocity of the wave, κ is the averaged dielectric constant, l_0 is the characteristic length for the wave potential perpendicular to the edge connected to the cutoff length of the Coulomb interaction on short distances. This cutoff length must be comparable with the width of the charged strip. The potential consists of two different parts, which correspond to nonscreened or to perfectly screened (with the help of the two metal plates below and above the 2DEG) geometries. For the first part the charge spreads on the length l_0, for the second one—on the length $\sqrt{dl_0}$. Hence one should expect from this classical approach a relation for the delay time

$$\tau_d = (KL/\sigma_{xy})\,(l/d)^p, \tag{2}$$

where $0.5 \leq p \leq 1$, K is a numerical coefficient [equal to 0.73 in accordance with Eq. (1)], L is the length of the gated region, and l is the width of charged strip. Although the charge is held near the edge due to quite different reasons for the approach by Ref. 5 (low σ_{xx} across the whole sample) and for our experiment (low σ_{xx} in the incompressible strip), we believe that the velocity depends in a similar way on the Coulomb cutoff length for weakly decaying excitations.

Simultaneous charge and current measurements allow us to determine the width of the charged strip and to obtain the dispersion relation for the fast process. We assume that the charge (and potential) can be described as being constant in the strip with width l (inside EC region) and then falls off rapidly. The exactness of this assumption can be proved by calculation of the potential distribution in the wave. Then the potential of the fast part is $U_H = Ih/\nu_s e^2$, where I is the measured current and ν_s is the filling factor of the last incompressible strip. The corresponding carriers, reaching the gate $G3$, charge a sequence of capacitors $C_x = C_0 lb$ (C_0 is capacitance per unit area, b is the length of the gate $G3$) and $C_{\rm in}$ up to the voltage U_H. Hence, from the measured ratio of charge and current on the sharp rise, the value of l can be extracted. To compare with Eq. (2), we use not the full σ_{xy}, but $\nu_s e^2/h$, since electrons from the highest Landau level do not contribute to the wave packet. Results of this treatment are shown in Fig. 3 for both samples together with least-square fittings. Fitting parameters are $p = 0.74 \pm 0.06$ and $K = 0.73 \pm 0.12$ for the first sample and $p = 0.70 \pm 0.05$, $K = 0.84 \pm 0.11$ for the second one. These parameters are well inside the limits of the above mentioned theory,[5] although the distribution of the charge is thought to be quite different from the one calculated in Ref. 5.

The quite strong dependence of the velocity on the value of l is responsible for the fact that the mode restricted by the EC runs faster than the common bulk and EC mode. For the previous experiments in the weakly screened geometry,[10,16] the velocity depended mostly on σ_{xy}, since the dependence on l in the weakly screened geometry is logarithmic[5,7] and the mode with the maximal σ_{xy} is the faster one. In the experiments,[11,13,15] where screening can be considered as strong in the sense that $d < l$ (d here is characteristic distance up to the screening metal surface), the restricted mode did not survive due to its decay by scattering between the EC and the bulk on large distances. For our condition the restricted EC mode with a smaller σ_{xy}, but also with a smaller l, became the fastest. The relatively small distance between the source and the drain allows its observation, since it decays by scattering between the EC and the bulk with the distance.

In Fig. 4 we plot all our data for the width l, obtained both from charge to current ratio and from the measured delay times by using dispersion relation (2) with the fitting parameters. We assume that this measured width is of the order of the distance from the edge up to the begin-

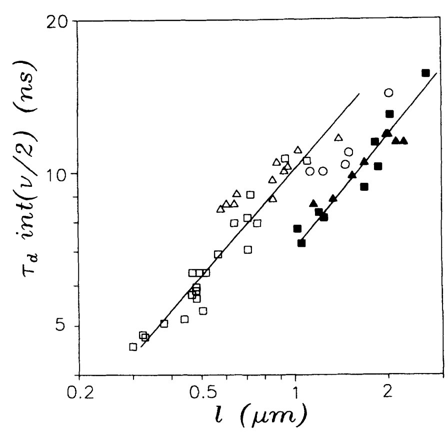

FIG. 3. Determination of the dispersion relation. The measured delay times are multiplied with half of the number of filled edge channels to take into account the prefactor in the dispersion relation (see text) and are plotted vs the width of the charged strip, determined from the ratio between charge and current in the wave. Full symbols, first sample: squares, bulk filling factor region between $\nu = 2$ and $\nu = 4$, triangles, $4 < \nu < 6$. Open symbols, second sample: squares for $2 < \nu < 4$, triangles for $4 < \nu < 6$, and circles for $6 < \nu < 8$. Straight lines are least-square fits to the data (parameters are in the text).

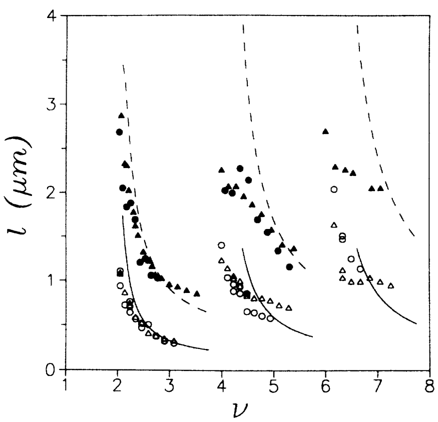

FIG. 4. The width of the charged strip plotted vs bulk filling factor. Full symbols, first sample; open symbols, second sample; circles, the width is determined from the ratio between charge and current in the wave; triangles, the width is determined from the measured delay times by using the dispersion relation. The lines show the position of the last incompressible strip calculated using theory by Chklovskii *et al.* for a depletion length of 135 nm (full lines) and of 370 nm (dashed lines).

ning of the last incompressible strip. All the characteristic features of this picture—increase of the width in approaching even integers from above, periodic dependence on filling factor with an increasing mean value—are qualitatively in good agreement with the model of Chklovskii *et al.*[3] Quantitative deviations are inevitable, since the calculations of Ref. 3 were performed for a quite different electrostatic environment. The depletion near the edge in Ref. 3 has the form $\nu(x)/\nu_0 = [(x-\delta)/(x+\delta)]^{1/2}$, where x is the distance from the edge and δ is the characteristic depletion length. The last incompressible strip lies always on the soft $(1-\delta/x)$ tail of this depletion, where quantitative results of Ref. 3 are hardly reliable. Due to the softness of this depletion, the position of the last strip is very sensitive even to small changes of the electrostatic potential near the edge. Nevertheless, we show the position of the last strip calculated from Ref. 3 for δ = 135 nm and δ = 370 nm. These values of δ are chosen to fit experimental points around ν_0=3, where ν_s/ν_0 reaches minimum for our data and the rigid part of the depletion potential is felt better. Theoretical dependences coincide with experimental points in the middle of each filling factor region (around $\nu = 5$ and $\nu = 7$ in addition to the fitted point at $\nu = 3$). The overall dependence of the theoretical curves is found also in the experimental results. However, the theoretical curves are steeper and the deviations are larger for the higher filling factor range. Although the characteristic depletion lengths extracted from the theoretical curves are of reasonable order in comparison with other experimental results, the absolute width of EC region looks surprisingly large.[18]

In conclusion, simultaneous time-resolved measurements of charge and current in a 2DEG allowed us to study the wave packet of EMP, which is restricted by the EC structure. The width, which is on the order of the distance between the last incompressible strip and the edge, is determined and the dispersion relation is found. An influence of the edge on the electron spectrum is felt on surprisingly large distances (up to 3 μm).

We would like to thank R.R. Gerhardts and J. Kuhl for useful discussions and Y. Kershaw for a critical reading of the manuscript. N.B.Z. acknowledges support from the Alexander von Humboldt Foundation.

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