# Dynamic Excitations of Fractional Quantum Hall Edge Channels

G. Ernst,* N. B. Zhitenev,† R. J. Haug,‡ and K. von Klitzing
*Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany*
(Received 23 June 1997)

We investigate the electrodynamic properties of charged edge excitations in the fractional quantum Hall regime by means of time-resolved magnetotransport. In samples with a smooth edge potential and an additional screening electrode, the propagation velocity of high frequency signals is related to the width of fractional edge channels. While the observed edge magnetoplasmons around filling factor 1/3 hint at a similar electronic edge structure as around filling factor 1, characteristic deviations appear for other fractions, especially around $\nu = 2/3$. [S0031-9007(97)04426-8]

PACS numbers: 73.40.Hm, 73.20.Mf, 73.50.Jt

Although the edge channel (EC) picture [1] is by now well established in the integer quantum Hall (IQH) regime, the electronic structure in the vicinity of the edge of a two-dimensional electron gas (2DEG) under conditions of the fractional quantum Hall (FQH) effect is still under discussion [2–5]. For a typical 2DEG in a semiconductor heterostructure, the electron density at the edge drops smoothly from its bulk value to zero, the width of the transition region being several hundred nanometers. In a perpendicular magnetic field, the interplay between the smooth confining potential, the Landau quantization, and the electron-electron interaction leads to a phase separation into compressible and incompressible strips near the edge of the sample [2]. In the incompressible regions, the Fermi energy lies in an energy gap arising either from Landau quantization or spin splitting in the IQH regime, or from many-body effects in the FQH regime. In the compressible regions, the so-called edge channels, extended states exist at the Fermi energy. The EC position and width changes as a function of the applied magnetic field, and different methods have been used for a quantitative description [3–7]. It has been found that, in the FQH regime, the charge density profile for a smooth boundary exhibits plateaus at certain fractional filling factors [4,5] similar to the plateaus at integer filling factors, while the edge reconstruction for a steep edge leads to counterflowing edge states [3,4], i.e., the electron density in the vicinity of the edge increases beyond its bulk value, before decreasing to zero.

A variety of experiments have directly probed the EC width in the IQH regime by studying the ground state properties and the low-energy edge excitations [8–11], but experiments in the FQH regime are still scarce. Evidence for a finite EC width in the FQH regime has been given by conventional magnetotransport measurements [12], and low-energy edge excitations have been observed [13,14]. In contrast to the IQH regime [10,11], no direct relationship between their dispersion $\omega(k)$ and the existence of fractional edge channels could be established.

Here, we report on time-resolved magnetotransport measurements of a 2DEG with a smooth edge potential in order to study the dynamic edge excitations in the FQH regime. Investigations of the propagation velocity of an injected voltage pulse show sawtooth oscillations of the delay time with respect to the applied magnetic field with maxima appearing close to integer and fractional bulk filling factors. The asymmetric shape of these oscillations relates them to the magnetic field dependent EC width. The sensitivity of the signal velocity to the presence of fractional edge channels is higher than expected from conventional magnetotransport measurements. Anomalous behavior observed around bulk filling factor $\nu = 2/3$ is discussed.

For the measurements, standard Hall-bar geometries made from AlGaAs/GaAs heterostructures are used. The 2DEG has a carrier concentration $n_0 = 1.0 \times 10^{15}$ m$^{-2}$, a mobility $\mu = 75$ m$^2$/V s, and is located $d = 130$ nm below the surface. In Fig. 1(a), the sample geometry is shown together with a sketch of the experimental setup for time-resolved transport measurements. The largest part of the sample is covered with a metallic top gate. A long voltage pulse with a rise time of 150 ps and an amplitude $V_{\mathrm{in}}$ of several mV reaches contact 1 at time $t = 0$ with contact 3 being grounded. The transient signal is detected at the intermediate contact 2 using the box-car technique described in [15]. All measurements were made in a $^3$He/$^4$He dilution refrigerator at a temperature of 70 mK with magnetic fields up to 13 T, the direction of the field being chosen such that the applied pulse propagates along the shortest, 60 $\mu$m long, connection between the injection (1) and the detection (2) contact.

It is by now well established [10,13,16], that the propagation of such a voltage pulse through a 2DEG in a perpendicular magnetic field can be described in terms of edge magnetoplasmons (EMP) [17], which are collective electronic excitations localized near the edge of the 2DEG. The applied voltage pulse is thus transformed into a wave packet of EMPs, and is transmitted along the edge adjacent to the injection contact. The EMP propagation direction is determined by the direction of the Lorentz force acting on the electrons. The velocity depends on the strength of the restoring force and the

 0031-9007/97/79(19)/3748(4)$10.00 

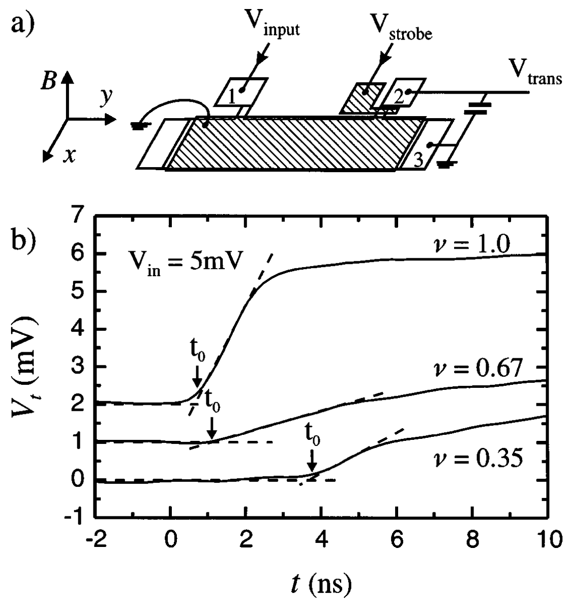


FIG. 1. (a) Sketch of the sample geometry and measurement setup. Gated areas are shaded. A rectangular input pulse $V_{\mathrm{input}}$ is applied to contact 1. The wave packet runs along the shorter boundary to contact 3. The transient potential at the intermediate contact 2 is detected using gate G2 as a sampling switch which is opened and closed by means of the applied strobe pulse. (b) Leading edge of the signal transmitted through the 2DEG for bulk filling factors close to 1, 2/3, and 1/3. The transmission delay $t_0$ increases with increasing magnetic field. Curves are offset by 1 mV.

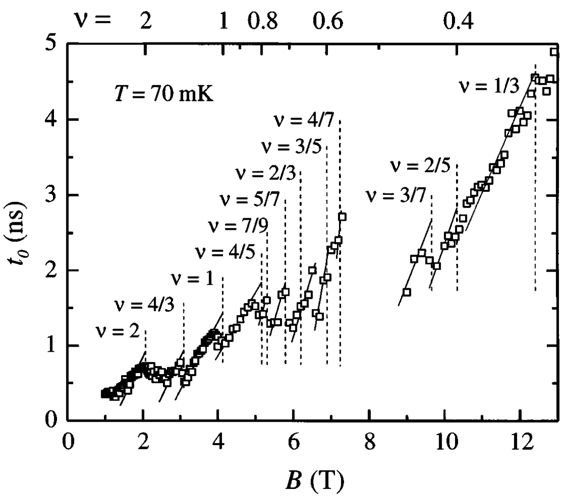


FIG. 2. Dependence of the transmission delay $t_0$ on the applied magnetic field. A sawtooth behavior is superimposed onto an overall increase, with maxima appearing close to the indicated integer and fractional bulk filling factors. Lines are drawn as guides for the eyes to emphasize the sawtoothlike oscillations.

inertia involved in the charge redistribution. In high magnetic fields ($\sigma_{xy} \gg \sigma_{xx}$), the former is proportional to the Hall conductivity, which relates the electric field strength to the resulting current density. The latter refers to the width $l$ of the charge distribution in the EMP mode and the distance $d$ between 2DEG and the metallic top gate, which determine the capacitively stored energy.

Figure 1(b) compares the transmitted signals for bulk filling factors close to $\nu = 1$, $2/3$, and $1/3$ with $V_{\mathrm{in}} = 5$ mV. The shape of the signal is characterized by an abrupt rise at time $t_0$, followed by a slower increase until saturation. The slope of the leading edge in the FQHE regime is smaller compared to the IQH regime. Nevertheless, the delay $t_0$, defined as the arrival time of the signal at the detection contact, is well defined in both regimes, and can be determined with an accuracy of $\pm 0.2$ ns. When comparing the transmitted signals at closely spaced magnetic field values, the variation of the delay time is defined with even better accuracy. The parasitic oscillations before and after $t = t_0$ are caused by reflections of the pulses in the external circuit. Upon reversal of the magnetic field direction, the propagation direction of the excitation along the edge is inverted: no signal was observed at the detection contact within a time window of 100 ns.

Figure 2 shows the delay time $t_0$ as a function of the applied magnetic field for the magnetic field range between 1 and 13 T, and an input amplitude of $V_{\mathrm{in}} = 5$ mV. The magnetic field dependence is described by an overall increase onto which sawtoothlike oscillations are superimposed. Whenever the bulk filling factor is close to one of the integer or fractional filling factors indicated in Fig. 2, the delay time exhibits a local maximum with a distinct asymmetry (the exceptional behavior around $\nu = 2/3$ will be addressed below): The delay time increases steadily at the low magnetic field side of the local maximum and drops rapidly at the high magnetic field side. Neither the sawtoothlike peaks, nor the large number of contributing fractional filling factors are seen in conventional magnetotransport measurements carried out on the same sample. To be specific, using a current of 10 nA for the measurement of the longitudinal resistance, we observe Shubnikov–de Haas minima in the FQH regime only at $\nu = 1$, $2/3$, $3/5$, $2/5$, and $1/3$, the corresponding voltage drop between source and drain being on the order of $V \approx 10$ nA $\times$ 50 k$\Omega$ = 0.5 mV, and hence an order of magnitude smaller than the voltage pulse applied in the time-resolved transport measurement. We attribute our increased sensitivity to the combined effects of studying the nonequilibrium situation shortly after switching on the current source, and of defining the delay time by extrapolating the rising edge to very small voltage (or current) values. The well-resolved oscillations in Fig. 2 indicate that our experimental arrangement would be sensitive to fractions, which are even closer to $\nu = 1/2$ than the data points shown. However, we did not pursue the limit of sensitivity any further, as the noise in the measurement was strongly enhanced around filling factor $\nu = 1/2$.

Comparing our measurements with earlier investigations of edge excitations in the FQH regime [10,14], and in particular with the extensive study of the magnetic field dependent delay time in [13], we are surprised by the number of fractional filling factors that show up here. Even if we discount the maximum at $\nu = 7/9$, which is defined by one data point only, the number of well-defined oscillations remains impressive. We relate the fact that this rich structure has been observed here but not in [13] to the screened Hall geometry used in our measurement and the shorter distance between injection and detection contact.

For the quantitative analysis, we use a macroscopic hydrodynamic description which yields the EMP velocity [15]

$$v_g = \frac{\partial \omega}{\partial k} = \frac{e^2 \nu}{h} \frac{d}{\epsilon_0 \epsilon_r l}, \tag{1}$$

with $d$ being the distance between 2DEG and top gate, and $\epsilon_0 \epsilon_r$ being the dielectric constant of the material in between. Except for fundamental constants and these material parameters, the velocity depends on the filling factor $\nu$ of the innermost incompressible strip and on the width $l$ of the compressible region at the edge. While the overall increase of the delay time with increasing magnetic field stems from the decreasing Hall conductivity $e^2 \nu/h$, we attribute the superimposed sawtooth behavior to the oscillating width $l$. The observed asymmetry indeed indicates that the origin of the oscillations lies in the magnetic field dependence of the electronic edge structure: With increasing magnetic field, all compressible and incompressible strips shift towards the center of the hallbar. At the indicated filling factors the innermost incompressible strip, which confines the compressible edge region, vanishes in the bulk of the 2DEG, and the nearest incompressible strip, which is positioned closer to the edge, becomes the boundary line between edge and bulk. Thus, for the propagation of the EMP wave packet all edge channels at one edge of the sample are coupled, and we observe only one common EMP mode [10]. The width $l$, therefore, measures the width of all edge channels [18].

The derivation of Eq. (1) relies on the fact that the innermost incompressible strip is sufficiently wide to decouple electrostatically the compressible regions at the edge from the bulk, while all other incompressible strips are too narrow for this purpose. The observed asymmetry manifests that this condition is fullfilled at least within a finite magnetic field range on the low magnetic field side of each local maximum. The decrease of the delay time on the high magnetic field side corresponds to a situation where the innermost incompressible strip is not yet strong enough, and the width $l$ is not well defined. For the quantitative analysis, we use therefore only those delay times on the low magnetic field sides, where Eq. (1) is applicable.

In our further analysis, we concentrate on the fractional filling factors in the lowest Landau level. Equation (1) allows us to obtain the width $l$ of the compressible edge region from the measured delay times. First, we compare the data belonging to the strongest fraction $\nu = 1/3$ with those belonging to the integer $\nu = 1$. Assuming that the width of the incompressible strip is small compared to the width of the compressible regions, we identify the width $l$ with the position of the innermost incompressible strip. Since $l$ measures the total width of the compressible region, $l = 0$ is defined as the point where the electron density goes to zero. Knowing the electron density $n = \nu eB/h$ and the position of the incompressible strips, we can replot the data in the form of an electron density profile. Figure 3 compares the data for the magnetic field ranges $3 < B < 4$ T and for $10.5 < B < 12$ T, the filling factor of the innermost incompressible strip being $\nu = 1$ and $1/3$, respectively. They clearly fall onto the same curve, and approach the bulk density far away from the boundary. This curve (solid line) can thus be regarded as the electron density profile $n(l)$ without magnetic field. The width of the depletion layer which separates the boundary of the 2DEG from the physical edge of the sample cannot be deduced from these measurements.

On the basis of the electron density profile derived in Fig. 3, one can calculate the position of the incompressible strips for all fractional filling factors. Figure 4 compares the width $l$—calculated from the delay times using Eq. (1)—with the position of the corresponding incompressible strips. We use solid lines for the range of $l$ values present in the data shown in Fig. 3, and dashed lines for the extrapolations to the known values $n = 0$ at the boundary and $n = n_0$ for large $l$. All $l$ values fall into the same range $0.4 \leq l \leq 1.2$ $\mu$m, confirming the self-consistency of our interpretation. In addition to the good agreement of the data belonging to filling factor $\nu = 1/3$ and 1, also the $\nu = 4/5$ data are well described by this simple approach. For all other fractions, however, we observe systematic deviations: the values for the width $l$ are smaller than expected according to the analysis of the $\nu = 1$, $1/3$ data. Disorder cannot account for the observed deviations, as it leads to a reduction of the width of the incompressible strips and hence wider compressible strips [19]. Including the finite width of the incompressible strips does not

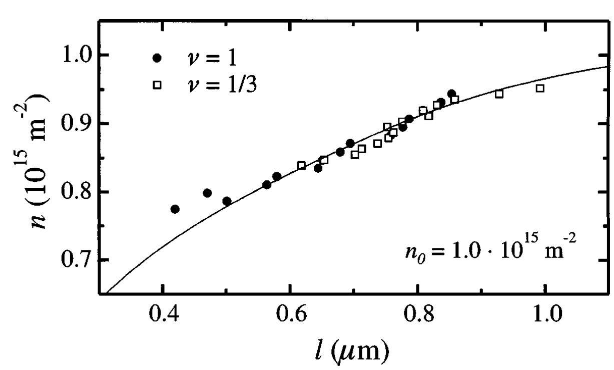


FIG. 3. Calculated electron density of the innermost incompressible strip vs measured width of the compressible region at the edge. Solid line: Estimated electron density profile used in Fig. 4.

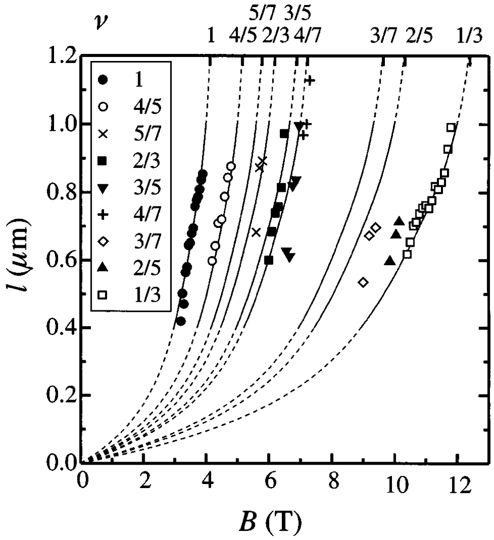


FIG. 4. Calculated width of the compressible edge region confined by the incompressible strip with filling factor. Lines show the expected position of each incompressible strip using an electron density profile estimated from the measured delays around filling factor 1 and 1/3 (see text).

help either, since we expect the largest corrections at the strongest fractions. Assuming that part of the signal leaks into the bulk [10] also leads to a reduction of the transmission velocity, and hence a longer instead of a shorter delay time. Therefore, we conclude that either the static description of the fractional edge, or the hydrodynamic model for the edge excitations used here are not adequate to account for all fractional filling factors.

Particularly interesting are the deviations around $\nu = 2/3$, since the delay time is not only smaller than expected, but the maximum delay is also shifted to a larger magnetic field [20]. The significance of these deviations at $\nu = 2/3$ is enhanced when contrasted with the data for $\nu = 4/5$, which fit very well with the $\nu = 1$, $1/3$ data, although the energy gap at $\nu = 4/5$ is smaller than at $\nu = 2/3$. The shift of the maximum position might be an indication of a magnetic field dependent charge density profile with a maximum within the edge region, as it is predicted for a sufficiently steep edge [3,4]. Even for a small overshoot, an incompressible strip with $\nu = 2/3$ can still exist for a bulk filling factor $\nu < 2/3$. The differences between $\nu = 1$, $1/3$, and $2/3$ can be explained, if such a maximum in the electron density profile appears only for certain filling factor ranges, e.g., around $\nu = 2/3$ but not around $\nu = 1$ or $1/3$. In this scenario, an additional EMP mode propagating in the opposite direction should exist. However, since this counterpropagating mode is neutral, it will be difficult to observe it in our setup.

We would like to thank B. Farid, A. MacDonald, and S. Mikhailov for useful discussions, H. Hess for critical reading of the manuscript, and K. Eberl for providing the heterostructures. N. Z. was supported by the Alexander von Humboldt Foundation.

*Present address: Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974.
†Present address: Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.
‡Also Institut für Festkörperphysik, Appelstr. 2, D-30167 Hannover, Germany.

[1] B. I. Halperin, Phys. Rev. B **25**, 2185 (1982); for a review, see C. W. J. Beenakker and H. van Houten, in *Solid State Physics*, edited by H. Ehrenreich and D. Turnbull (Academic Press, New York, 1991), Vol. 44; R. J. Haug, Semicond. Sci. Technol. **8**, 131 (1993).
[2] C. W. J. Beenakker, Phys. Rev. Lett. **64**, 216 (1990); A. Chang, Solid State Commun. **74**, 871 (1990).
[3] A. H. MacDonald, Phys. Rev. Lett. **64**, 220 (1990); X. G. Wen, Phys. Rev. Lett. **64**, 2206 (1990); M. D. Johnson and A. H. MacDonalds, Phys. Rev. Lett. **67**, 2060 (1991); Y. Meir, Phys. Rev. Lett. **72**, 2624 (1994).
[4] L. Brey, Phys. Rev. B **50**, 11 861 (1994); D. B. Chklovskii, Phys. Rev. B **51**, 9895 (1995).
[5] M. Ferconi, M. R. Geller, and G. Vignale, Phys. Rev. B **52**, 16 357 (1995); O. Heinonen, M. I. Lubin, and M. D. Johnson, Phys. Rev. Lett. **75**, 4110 (1995).
[6] P. L. McEuen *et al.*, Phys. Rev. B **45**, 11 419 (1992); D. B. Chklovskii, B. I. Shklovskii, and L. I. Glazman, Phys. Rev. B **46**, 4026 (1992); K. Lier and R. R. Gerhardts, Phys. Rev. B **50**, 7757 (1994).
[7] J. Dempsey, B. Y. Gelfand, and B. I. Halperin, Phys. Rev. Lett. **70**, 3639 (1993); M. M. Fogler and B. I. Shklovskii, Phys. Rev. B **52**, 17 366 (1995); A. Manolescu and R. R. Gerhardts (to be published).
[8] R. J. F. van Haren, F. A. P. Blom, and J. H. Wolter, Phys. Rev. Lett. **74**, 1198 (1995).
[9] S. Takaoka *et al.*, Phys. Rev. Lett. **72**, 3080 (1994).
[10] N. B. Zhitenev *et al.*, Phys. Rev. Lett. **71**, 2292 (1993); N. B. Zhitenev *et al.*, Phys. Rev. B **49**, 7809 (1994); G. Ernst *et al.*, Surf. Sci. **361**/**362**, 102 (1996).
[11] V. I. Talyanskii *et al.*, Phys. Rev. B **50**, 1582 (1994); K. Bollweg *et al.*, Phys. Rev. Lett. **76**, 2774 (1996).
[12] A. M. Chang and J. E. Cunningham, Solid State Commun. **72** 651 (1989); L. Kouwenhoven *et al.*, Phys. Rev. Lett. **64**, 685 (1990); S. W. Hwang, D. C. Tsui, and M. Shayegan, Phys. Rev. B **48**, 8161 (1993).
[13] R. C. Ashoori *et al.*, Phys. Rev. B **45**, 3894 (1992).
[14] M. Wassermeier *et al.*, Phys. Rev. B **41**, 10 287 (1990).
[15] N. B. Zhitenev *et al.*, Phys. Rev. B **52**, 11 277 (1995).
[16] G. Ernst *et al.*, Phys. Rev. Lett. **77**, 4245 (1996).
[17] For a review, see V. A. Volkov and S. A. Mikhailov, Zh. Eksp. Teor. Fiz. **94**, 217 (1988) [Sov. Phys. JETP **67**, 1639 (1988)].
[18] For certain filling factor ranges and input amplitudes, EMP modes on decoupled edge channels can be observed [10], which show up as a sequence of steps in the transmitted signal. In the data shown here, however, only one steplike increase is found, and hence only one EMP mode is visible.
[19] B. Y. Gelfand and B. I. Halperin, Phys. Rev. B **49**, 1862 (1994).
[20] In addition to the maximum delay, the maximum transmitted amplitude is also shifted towards higher fields.