

Investigations on unconventional aspects in the quantum Hall regime of narrow gate defined channels

J. Horas^{a,*}, A. Siddiki^a, J. Moser^{a,b}, W. Wegscheider^c, S. Ludwig^a

^aCenter for NanoScience and Department for Physics, Ludwigs-Maximilians University, D-80539 Munich, Germany

^bCNM-CSIC, Campus Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain

^cInstitute for Experimental and Applied Physics, University of Regensburg, D-93040 Regensburg, Germany

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Abstract

We report on theoretical and experimental investigations of the integer quantized Hall effect in narrow channels at various mobilities. The Hall bars are defined electrostatically in two-dimensional electron systems by biasing metal gates on the surfaces of GaAs/AlGaAs heterostructures. In the low mobility regime the classical Hall resistance line is proportional to the magnetic field as measured in the high temperature limit and cuts through the center of each Hall plateau. For high mobility samples we observe in linear response measurements that this symmetry is broken and the classical Hall line cuts the plateaus not at the center but higher B field edges of the plateaus. These experimental results confirm the unconventional predictions of a model for the quantum Hall effect taking into account mutual screening of charge carriers within the Hall bar. The theory is based on solving the Poisson and Schrödinger equations in a self-consistent manner.

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At low temperatures, transport in low-dimensional electron systems is dominated by quantum mechanical properties. In particular, a two-dimensional electron system (2DES) subjected to a strong magnetic field perpendicular to the 2DES exhibits the integer quantized Hall effect (IQHE) [1]. In a classical picture, with current driven in one direction (x), the external magnetic field generates forward moving skipping orbits along the edges of the sample due to the Lorentz force. The quantization of this motion results in edge states, resembling perfect one-dimensional channels, that explain basic features of the IQHE [2]. Twenty-five years after their discovery, the standard explanation of the IQHE still employs a single particle picture based on Landau quantization together with localization of electronic states in a disordered background potential. However, this picture discounts the Coulomb interaction between electrons and, as a result,

is unable to account for several important features of the IQHE. These features include the enormous accuracy with which the quantized resistance values can be reproduced experimentally [3] and the local potential and current distributions in narrow Hall bars as recently detected in “local probe” experiments [4,5].

Chklovskii et al. first considered realistic electron–electron interactions together with the confinement potential of narrow Hall bars [6,7]. In this theory, strips of incompressible 2DES replace the edge states. A more recent model takes interactions between electrons explicitly into account within a self-consistent mean field approximation [8,9]. Numerical calculations within this model reproduce the main results of the “local probe” experiments [8]. In low mobility samples the straight line, describing the magnetic field dependence of the classical Hall resistance, cuts the Hall plateaus at its centers, as also assumed within the standard explanations of the IQHE. In contrast, the recent model predicts for even filling factors that the classical Hall resistance line cuts the Hall plateaus

*Corresponding author.

E-mail address: Jose.Horas@Physik.Uni-Muenchen.de (J. Horas).

at higher magnetic fields in a high mobility narrow Hall bar. This asymmetry is caused by the magnetic field dependence of the shape of incompressible strips (ISs) separating compressible regions of the 2DES [10]. We find that in high mobility narrow Hall bars electron–electron interactions and the confinement potential of the channels at the edges cause the spatial distribution of ISs, which determine widths and positions of the QH plateaus. Here, we briefly summarize the findings of the model and compare them with experimental results measured on high mobility samples with narrow electrostatically defined channels.

The screening theory of the IQHE is based on the self-consistent solution of the Poisson and Schrödinger equations to obtain the electron density and electrostatic potential distribution within the sample [8]. The current distribution is calculated by using a local version of Ohm’s law [11] incorporating a relevant model of conductivity, e.g. self-consistent Born approximation [12]. Our numerical calculations start at zero temperature and the electron density distribution at zero field potential. In the next step the positions of ISs and compressible strips are found iteratively at finite field and temperature are taken into account iteratively. The numerical results in Fig. 1a demonstrate the formation of an ISs shown as a function of the magnetic field strength across a narrow Hall bar. Within this strip the local filling factor is exactly $\nu = 2$ (note that the filling factor changes across the width of a narrow Hall bar). Within the compressible regions adjacent to ISs the electrostatic potential is constant because of perfect screening and current only flows within ISs. Here, all current carrying states are occupied. Thus, the longitudinal resistance R_{xx} vanishes and the Hall resistance R_{xy} resumes its quantized plateau value as also shown in Fig. 1a. For $\nu < 2$ (high field side of the ISs in Fig. 1a) only

the lowest Landau level is partly occupied and now ISs are present. As a result of the finite extent of the quantum mechanical wave functions of the electrons in compressible regions very narrow ISs practically vanish [8,13]. Hence, for some magnetic field ranges at $\nu > 2$ no ISs exist along the Hall bar (compare Fig. 1a). At such magnetic fields without ISs R_{xx} becomes finite and R_{xy} deviates from its quantized value. Previous approaches [6,7] employing Thomas–Fermi type approximations ignore the finite extent of the wave functions and the number of ISs is given by the integer multiples of $\nu/2$ (assuming spin degeneracy). Fig. 1b shows the numerical results for R_{xy} in the vicinity of the plateau at $\nu = 2$ for four different temperatures. Temperature broadening first destroys the ISs starting from its narrow side. Hence, with increasing temperature deviations from the plateau start at the low field side and the highest temperature curve cuts through the plateau nearly at its high field edge. Note that in the case of low mobility, disorder widens the ISs in regard to the magnetic field and causes the plateau to extend to higher magnetic fields.

We conducted experiments on several samples with different geometries. They were all performed on GaAs/AlGaAs heterostructures containing a 2DES 100 nm below the surface. The electron density and mobility of the 2DES used for the measurements shown in Fig. 2 are $n_e = 1.8 \times 10^{11} \text{ cm}^{-2}$ and $\mu = 2.96 \times 10^6 \text{ cm}^2/\text{Vs}$. The inset of Fig. 2 displays a scanning-electron-microscope picture of the sample surface. All metallic gates (lighter gray) are biased with $V_g = -0.25 \text{ V}$ in respect to the 2DES in order to define a $10 \mu\text{m}$ wide Hall bar. At this gate voltage the 2DEGS beneath the gates is locally depleted, while the contacts (openings between gates) are still open. Instead of etching a Hall bar we use gated structures in order to provide a lateral confinement potential as smooth as possible. A small source–drain AC-current is applied,

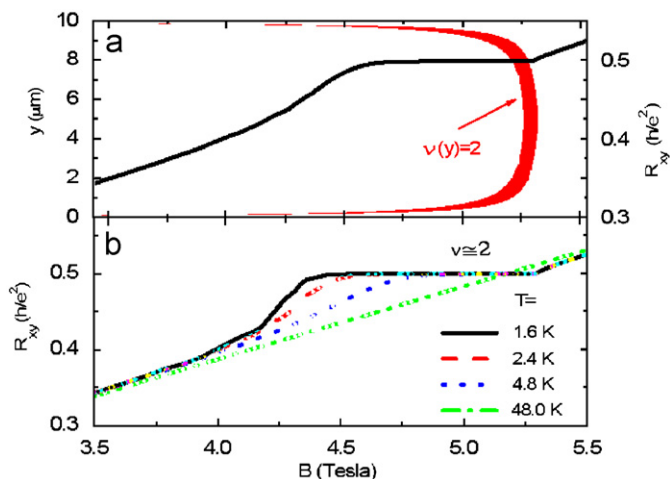


Fig. 1. (a) Calculated position of the incompressible strip at $\nu = 2$ in a $10 \mu\text{m}$ wide Hall bar as a function of the magnetic field. For the calculation we used $k_B T/E_F^0 = 0.02$ and assumed an average electron density of $3.79 \times 10^{11} \text{ cm}^{-2}$. Also shown is the Hall resistance R_{xy} (black line) calculated for the same conditions. (b) Calculated R_{xy} as a function of magnetic field, at various temperatures.

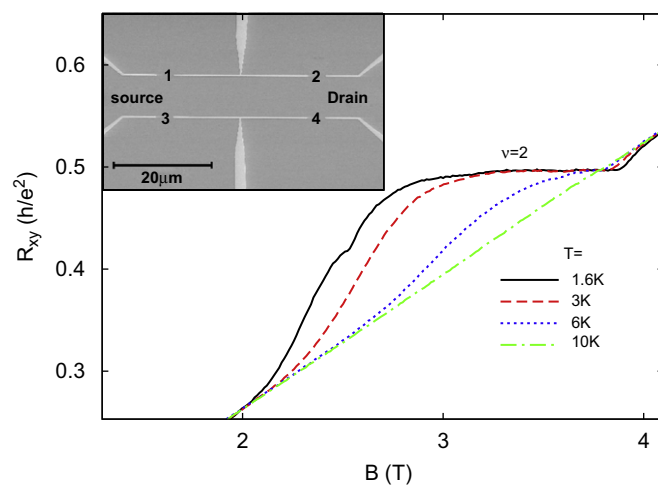


Fig. 2. Measured Hall resistance R_{xy} of a gate defined high mobility Hall bar for different temperatures in the vicinity of $\nu = 2$. The inset shows a scanning electron micrograph of the samples surface. Light gray areas are metal gates used to define the Hall bar with a width of $10 \mu\text{m}$.

meanwhile the Hall resistance R_{xy} is measured using the contacts 1–2 (or 3–4) and R_{xx} is measured using 1–3 (or 2–4).

In Fig. 2 we show R_{xy} for several temperatures measured in the vicinity of filling factor $\nu = 2$. Comparison with the numerical calculations (Fig. 1b) shows excellent qualitative agreement. For a similar measurement on a sample with a smaller mobility of $\mu \sim 1 \times 10^6 \text{ cm}^2/\text{Vs}$ and an identical $10 \mu\text{m}$ wide Hall bar we find the expected low mobility behavior, namely that the high temperature line of R_{xy} cuts through the center of the quantized plateau.

In summary, on a gate defined Hall bar in a high mobility 2DES we observe an asymmetric contraction of the plateaus of the Hall resistance as temperature increases. The plateaus mainly shrink on their low magnetic field side finally causing the high temperature curve of the classical Hall resistance to cut through the plateau at its high magnetic field side. For low mobility samples we observe the usual symmetric behavior, where the high temperature curve cuts through the center of the plateau. Our findings perfectly match the predictions of a model taking into

account electrostatic interactions of electrons and the overlap of their quantum mechanical wave functions.

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