Hall potential distribution of a two-dimensional electron system in the quantum Hall regime probed by a scanning force microscope

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Since the discovery of the quantum Hall effect on a two-dimensional electron system (2DES) in high magnetic field in 1980 [K. v. Klitzing *et al.*: Phys. Rev. Lett. **45**, 494 (1980), a variety of theoretical models have been developed describing different paths for the externally biased current through the 2DES [see for review: T. Chakraborty *et al.*: 'The Quantum Hall Effects', Springer]. The so-called edge channel model – the most popular for textbooks [e.g., J.H. Davis: 'The Physics of Low-Dimensional Semiconductors', Cambridge] – relates the quantization of the Hall resistance to the presence of ideal one-dimensional channels which are formed by skipping cyclotron orbits running along the edges of the 2DES. Within another model it is argued that disorder in the samples cause static potential fluctuations leading to localization of the electronic states except for states in the middle of each Landau band: Under quantum Hall condition the current is flowing along a percolation path formed by these extended states through the bulk of the 2DES.

More recent works have predicted for thermodynamic equilibrium the presence of a strip-like structure within the depletion region of typically 1 μm along the edges of the 2DES in high magnetic field [D.B. Chklovskii *et al.*: Phys. Rev. B **46**, 4026 (1992); K. Lier *et al.*: Phys. Rev. B **50**, 7757 (1994)]: As shown in Fig. 24(a) with increasing the electron concentration from the edge towards the bulk, regions of varying and constant electron concentration with metal-like and insulator-like behavior, the so-called compressible and incompressible strips, are formed.

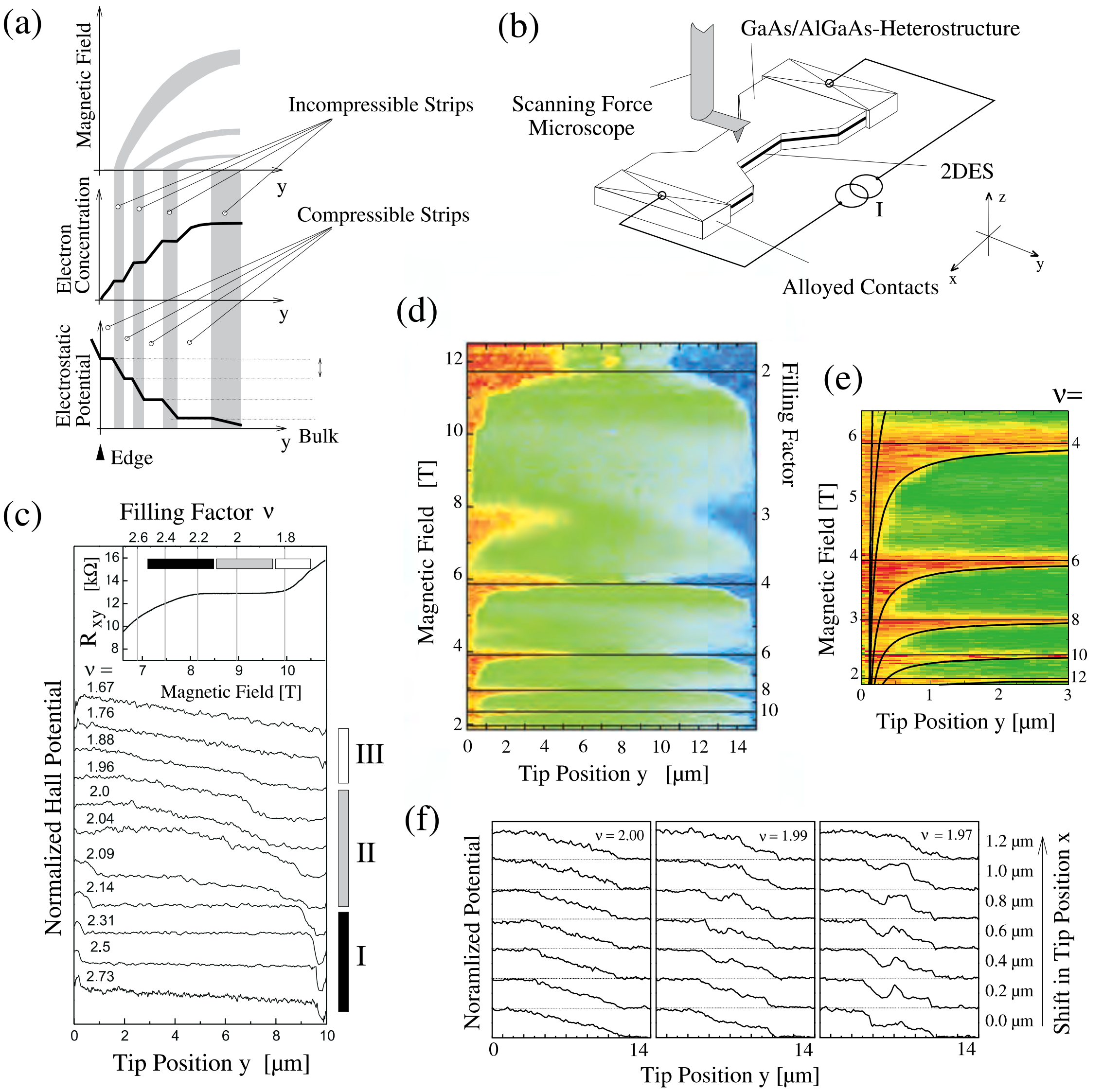

Figure 24: *(a) Compressible and incompressible strips are formed in the depletion region of a two-dimensional electron system at high magnetic field. (b) Sketch of the experimental setup: A scanning force microscope is used to probe the Hall potential profile of the 2DES buried in a GaAs-AlGaAs heterostructure. (c) Hall potential profiles measured around filling factor* $\nu = 2$*. The inset shows the Hall resistance* R_{xy} *around this filling factor (Sheet electron concentration of the 2DES* $n_s = 4.3 \cdot 10^{15}\ \mathrm{m}^{-2}$*, electron mobility* $50\,\mathrm{m}^2/\mathrm{Vs}$*. The smallest width of the mesa is* $w = 10\,\mu\mathrm{m}$ *on a length of* $30\,\mu\mathrm{m}$ *(see sketch in (b)). (d) Hall potential profiles in color-scale ('red' high potential, 'blue' low potential) taken on a wider sample: The evolution from type III to I is repeated at each even integer filling factor. (e) Zoom in of (d) at left edge: Comparison of the Hall voltage with expected position of the incompressible strips (drawn as black lines). (f) Position and magnetic field dependence of the Hall potential profile close to filling factor* $\nu = 2$*.*

Widths and positions of these strips depend on the quantization energy, i.e., the magnetic field. As shown in Fig. 24(a), with increasing magnetic field the incompressible strips from both edges shift into the bulk of the 2DES resulting in an incompressible bulk for magnetic field values corresponding to an integer value of the Landau level filling factor $\nu = hn_s/eB$ (n_s denotes the electron concentration of the 2DES). We have recently imaged these strips close to the edge region of a 2DES by using a single-electron transistor as a local electrometer [J. Weis *et al.*: Physica B **256-258**, 1 (1998); and references in there].

To investigate 2DES under quantum Hall conditions, groups at Berkeley, MIT, and Bell Labs have built low-temperature scanning probe microscopes. To address the unresolved issue of the current distribution within the 2DES under quantum Hall conditions, we have developed a low-temperature scanning force microscope for investigating 2DES samples at temperatures down to 1.4 Kelvin and magnetic fields up to 13 Tesla (Fig. 24(b)). Unfortunately the spatial variations of the electrostatical potential in the 2DES cannot be measured directly since the 2DES is usually buried several tens of nanometers below the surface of a $\mathrm{GaAs}-\mathrm{Al}_{0.33}\mathrm{Ga}_{0.77}\mathrm{As}$ heterostructure: Surface charges and the distribution of the charged donors between surface and 2DES cause spatially varying static potential fluctuations acting on the tip of the scanning force microscope. Therefore a low-frequency modulation and calibration technique has been developed [P. Weitz *et al.*: Appl. Surf. Science **157**, 349 (2000)], allowing us to probe the local electrostatic potential *changes* within the 2DES caused by the externally biased current. The normalized Hall potential distribution is obtained by applying this method.

Such normalized Hall potential profiles are shown in Fig. 24(c) for different magnetic field values around Landau level filling factor $\nu = 2$. The data are taken as *y*-scans at x_0 in the middle of the mesa as sketched in Fig. 24(b). In addition, in the inset of Fig. 24(c), the quantum Hall curve around $\nu = 2$ is plotted as the reference. Basically three different types of Hall potential profiles can be identified: Coming from high magnetic field values towards the quantum Hall plateau of $\nu = 2$, i.e., approaching $\nu = 2$ from lower Landau level filling factor values, the Hall potential drops linearly across the whole sample (type III). At about $\nu = 1.96$, the profile flattens at the edges and drops rather arbitrarily in the inner region (type II). This is observed until $\nu = 2.09$ is reached. At $\nu = 2.14$, which is still in the quantum Hall plateau regime, the Hall potential drop occurs at pronounced positions at the edge of the Hall bar and the profile is now flat in the inner region of the sample (type I). At filling factor $\nu = 2.50$ the Hall potential starts to drop considerably linearly over the inner region although still a significant drop occurs at the edges. Before entering the Hall plateau regime of $\nu = 3$, the pronounced potential drops at the edges have disappeared and the drop is linear over the whole sample width (type III).

In Fig. 24(d) the normalized Hall potential profiles are given in color-scale over a larger magnetic field range for another sample. The characteristic evolution of the Hall potential profile is clearly repeated at each even integer filling factor $\nu > 2$, but is only observable in outlines around filling factor $\nu = 3$. This behavior can nicely be related to the existence of compressible and incompressible strips at the edges of the 2DES and its evolution with magnetic field. To demonstrate this, in Fig. 24(e) the measured potential profiles at one edge of the mesa are presented on larger scale for bulk filling factors $\nu > 3$. In the same figure the *expected* equilibrium center positions $\mathrm{y} = d_0/(1 - (\mathrm{int}(\nu)/\nu)^2)$ of the incompressible strips, i.e., the positions of local filling factor $\nu_l = \mathrm{int}(\nu)$ for bulk filling factor ν, are plotted. (The parameter d_0 is not a fitting parameter, but is determined by the electron concentration of the 2DES, the dielectric constant of GaAs and the band gap of GaAs due to Fermi level pinning by surface charges on the side walls of the etched mesa.)

Obviously slightly above integer values of the bulk Landau level filling factor ν, the Hall voltage drops at the positions of the innermost incompressible strips at both edges (type I). By the gradient of the Hall potential $\partial_y V_{\mathrm{Hall}}$ in y-direction, the local current density j_x is enhanced in x-direction: $j_{\mathrm{x}} = -\nu_l \cdot \mathrm{e}^2/\mathrm{h} \cdot \partial_{\mathrm{y}} V_{\mathrm{Hall}}$, i.e., a dissipationless current is flowing in the innermost incompressible strips along both edges carrying the externally biased current within this cross-section through the 2DES sample. Slightly above integer Landau filling factors, the innermost incompressible strips at the edges are rather broad being able to maintain the electrochemical potential difference between the compressible edge regions and the compressible bulk. The drops diminish with decreasing strip widths, i.e., with decreasing magnetic field. Just below the next integer value of the bulk filling factor ν the incompressible strip is too small to electrically isolate, and a linear Hall potential profile is obtained (type III), indicating current flow also in the compressible bulk which occurs with dissipation.

As visible in Fig. 24(c), the Hall potential drop at integer filling factor is non-linear within the bulk region (type II). Already little changes of the scan position in x-direction or magnetic field can strongly modify the Hall potential profiles, as demonstrated in Fig. 24(f). The Hall potential profile can even be non-monotonic. We relate this behavior to the presence of inhomogeneities within our sample resulting in a network of compressible electron droplets within the mainly incompressible bulk.

In conclusion, by measuring the electrostatical potential changes induced by an externally biased current, we conclude for the current flow through the 2DES in high magnetic field for our sample: (1) Slightly above integer bulk filling factor with a mainly compressible bulk, a dissipationless current flows in the innermost incompressible strips at both edges driven by the Hall voltage drop over these strips. Dissipation is caused by scattering into the compressible bulk. With decreasing incompressible strip width (by reducing the magnetic field) scattering becomes more probable – the Hall potential drop over the incompressible strips is reduced, the current is spread over the whole sample width to minimize the overall resistance. (2) In the quantum Hall regime with a mainly incompressible bulk, the compressible edge regions carry the electrochemical potential difference of the source and drain contacts into the sample. Electrons redistribute within the network of compressible droplets in the bulk. As the result a dissipative-free current is driven within the incompressible regions where a drop in the electrochemical potential between compressible droplets occurs.

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