Role of ohmic contacts for the current distribution in quantum Hall samples

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Since the discovery of the quantum Hall effect in 1980, several predictions and interpretations of experimental data have been made about the distribution of the current biased externally into the sample. In the last decade we have used a scanning force microscope – sensitive to electrostatics and operated at a temperature of 1.4 K – to investigate the local potential distribution in two-dimensional electron systems (2DESs) under quantum Hall conditions [1]. With the required sensitivity and spatial resolution, such local probe measurements are able to clarify unambiguously the Hall potential and current distribution in quantum Hall samples. Our experimental results and theoretical calculations by Rolf Gerhardts and coworkers [2] have shown that the quantum Hall effect does not necessarily require disorder leading to localization which is the prerequisite usually given in textbooks for the formation of quantum Hall plateaus. In an extensive comparison between magnetoresistance and scanning probe measurements, we have focused in the last years on the role of ohmic contacts and we could visualize the electrical decoupling of bulk and edge of the 2DES even in the presence of contacts.

Our quantum Hall samples are based on a modulation-doped $\mathrm{GaAs/Al_{0.33}Ga_{0.67}As}$ heterostructure grown by molecular beam epitaxy. The 2DES is obtained at the GaAs/AlGaAs heterojunction 40 nm below the surface (electron concentration about $n_\mathrm{s} = 5 \times 10^{15}\,\mathrm{m}^{-2}$, electron mobility between $\mu_\mathrm{e} = 50\,\mathrm{m}^2/\mathrm{Vs}$ and $130\,\mathrm{m}^2/\mathrm{Vs}$). A mesa is formed by wet-etching into the heterostructure and Au/Ge/Ni pads are alloyed in order to contact the 2DES. Over the years, the geometries of the mesa have been varied, as well as the amount and arrangements of the ohmic contacts to the 2DES. In all cases, the width of the mesa was limited by the scan range of our self-made scanning force microscope ($20\,\mu\mathrm{m} \times 20\,\mu\mathrm{m}$). The scanning force microscope probes at 1.4 K and magnetic fields of up to 13 T the local electrostatic potential *change* which appears in our quantum Hall samples with current flow. Therefore, with scanning over the width of a Hall bar mesa, we directly obtain the Hall potential profile which is caused by the externally biased current through the 2DES.

Self-consistent calculations of the electron density profile at the edges of a 2DES in the 1990's have predicted the presence of compressible and incompressible strips in the depletion region at the edges of a 2DES. An incompressible strip is characterized by the fact that its local Landau level filling factor has an integer value. As, locally, the Fermi level lies between two Landau levels, the strip behaves electrically insulating, in contrast to compressible regions behaving metal-like. Our results on the Hall potential profiles have proven the existence of incompressible strips and we could interpret the Hall potential profiles in the following way [3]: Close to integer filling factors $\nu = \mathrm{i}$, the current is flowing without dissipation in the mainly incompressible bulk of the 2DES. The local current density j_x is driven by the local Hall field E_y, e.g., $j_\mathrm{x}(y) = \nu\, e^2/h\, E_\mathrm{y}(y)$. Due to inhomogeneities, the Hall potential drop could even be non-monotonic, e.g., the current takes snake-like pathes through the 2DES bulk. In this regime, the actual Hall potential profile and therefore the current distribution is very sensitive to small magnetic field changes, reflecting the fragile landscape of compressible islands embedded in the mainly incompressible bulk. With reducing the magnetic field (increasing the bulk filling factor to $\nu > \mathrm{i}$), a connected compressible region appears in the center of the 2DES and the dissipationless current flow is restricted to the innermost incompressible strips which move towards the two edges. The Hall potential drops over these two incompressible strips driving the current without dissipation within these incompressible strips along the Hall bar. The Hall potential profile is flat in the compressible bulk. Since the drop of the Hall voltage occurs only over incompressible strips of same local integer filling factor $\mathrm{i} = \mathrm{int}(\nu)$, a quantized Hall resistance value is still obtained, e.g., the Hall voltage V_H and the bias current I are related by $I = \int_\mathrm{y} j_\mathrm{x}(y)\,\mathrm{d}y = \mathrm{i}\, e^2/h\, V_\mathrm{H}$. With reducing the magnetic field, these strips are moving further to the edges and get smaller, loosing their insulating property. Scattering of electrons from the compressible edge into the compressible bulk and further to the opposite compressible edge becomes possible, reducing the Hall potential drop over the innermost incompressible strips, and therefore the dissipationless current flow. The Hall resistance is no longer quantized. Before reaching the next Hall plateau at lower magnetic field, the current is distributed homogeneously over the whole width of the Hall bar – a linear Hall voltage drop is observed.

Usually contacts at the edge of a 2DES acting as potential probes are considered as an effective way of equilibrating edge and bulk. This would mean, that, whenever the bulk of the 2DES is compressible, edge and bulk are shortened in their electrochemical potential, and no Hall voltage drop can exist over the incompressible strip present at the etched edges of the 2DES. Our scanning probe measurements have shown that a region of partial depletion (reduced electron concentration) is formed in front of the contact edge within the 2DES (to emphasize, these are good ohmic contacts!). This gives rise to the formation of compressible and incompressible strips in front of the alloyed metal. This partial depletion is not surprising when taking into account that alloyed contacts and the 2DES do have different workfunctions. We found that the innermost incompressible strip decouples – at least beyond a certain strip width – the bulk from the contact. *Bulk and edge are not shortened in their electrochemical potential*. What does this mean for a Hall measurement? The contact probes the electrochemical potential of the compressible edge at this position. Due to the electrochemical potential drop over the incompressible strip, a current is flowing within the incompressible strip in front of the potential probing contact without dissipation. It is part of the current biased into the sample. It does not pass the contact which would cause dissipation.

In the last years, we made an astonishing observation on the Hall bar geometry depicted in Fig. 62. Depending on the orientation of the Hall bar relatively to the crystal orientation of the underlying GaAs-AlGaAs heterostructure, different magnetoresistance curves are measured for the same measurement configurations. In one case, the Hall plateaus are found at the expected positions whereas in the orientation tilted by 90 degree, the plateaus are shifted to lower magnetic field values. Such features remind on what has been observed on quantum Hall samples where gate electrodes in front of ohmic contacts were used to reflect selectively edge states leading to a non-equilibrium situation between adjacent edge states.

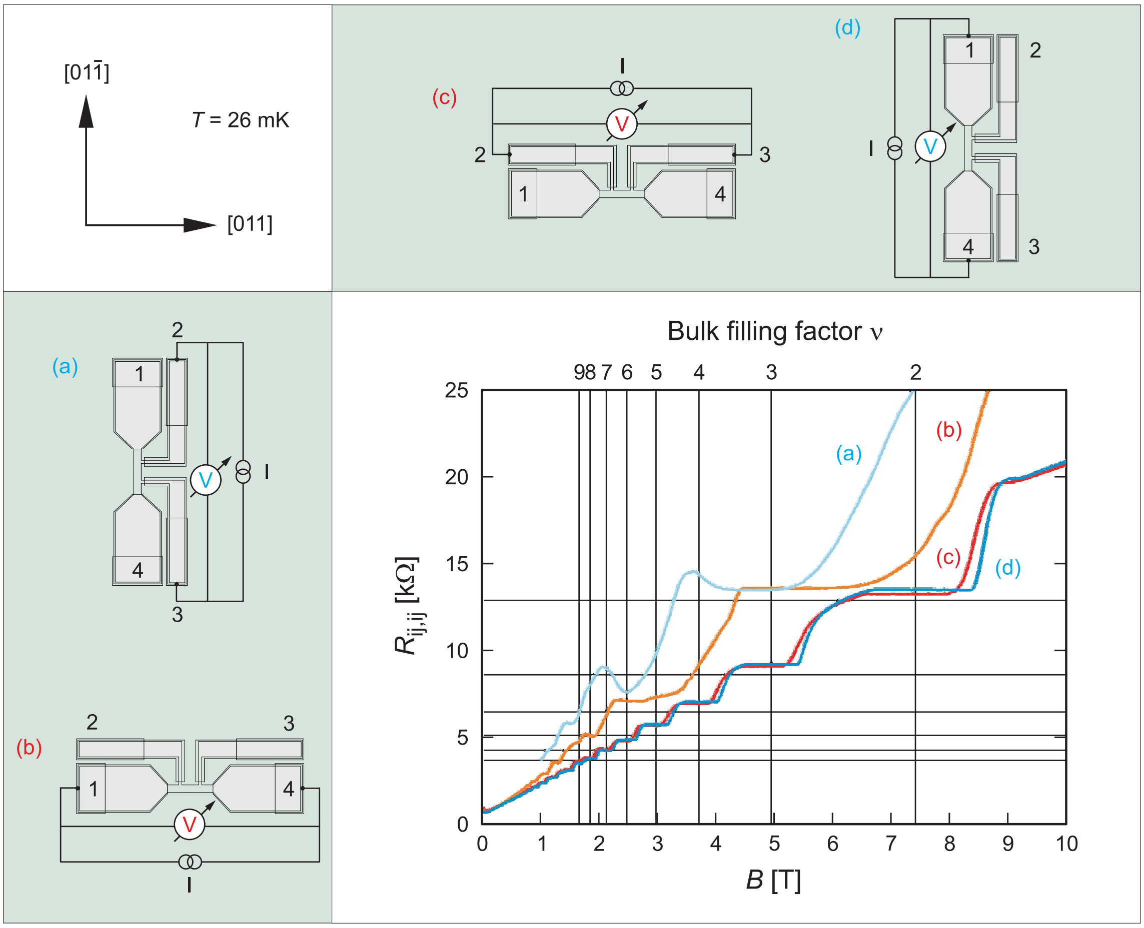

Figure 62: Two-terminal magnetoresistance versus magnetic field on an asymmetrically contacted Hall bar for two different measurement arrangements (a),(b). For the same Hall bar geometry, however tilted by 90 degree, different magnetoresistance curves are measured (c),(d).

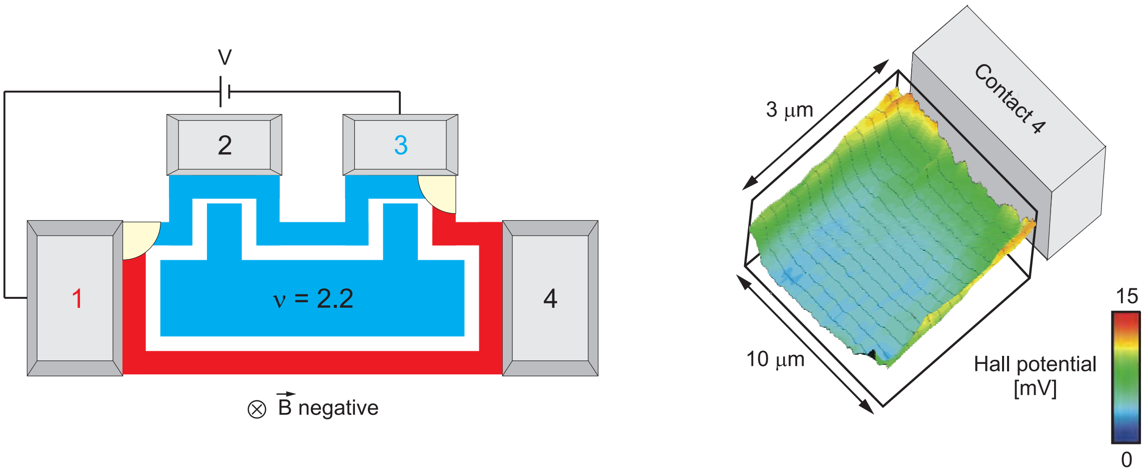

Figure 63: Hall potential landscape (right) in front of contact 4 for the Hall bar depicted (left). For filling factor $\nu = 2.2$, the bulk is compressible, separated by an incompressible strip from the compressible edge. Red/blue indicates high/low potential in the 2DES.

Figure 63 shows an example for the Hall potential landscape in front of a contact of a Hall bar with asymmetrically arranged contacts. Striking is the Hall voltage drop from the edge to the bulk along the etched edges and in front of the alloyed contact. The current follows the path perpendicular to this Hall potential drop, e.g., the current follows here the contour of the Hall bar mesa and does not take a direct path between the biased contacts. Such and many other scanning probe measurements reveal that depending on the orientation of the interface line between alloyed metal and 2DES relatively to the underlying crystal orientation of the heterostructure, the incompressible strip decouples bulk and edge more or less well. This anisotropy in decoupling is the origin of the observed anisotropy in the magnetoresistance measurements.

Stimulated by these findings, we have started structural investigations by transmission electron microscopy to get a better insight into the microscopic formation of an ohmic contact between alloyed Au/Ge/Ni and the 2DES. First results have shown that the diffusion of Al out of the AlGaAs heterostructure layer and the formation of a NiGe phase play a crucial role.

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[1] *For review: Weis, J.* International Journal of Modern Physics B **21**, 1297–1306 (2007).

[2] *Siddiki, A. and R.R. Gerhardts. Physical Review B* **70**, *195335 (2004).*

[3] *v. Klitzing, K., R. Gerhardts and J. Weis.* Physik Journal **6**, 37–44 (2005).