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Scanning gate measurements in the quantum Hall regime at 300 mK

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Abstract

Scanning gate measurements have been performed on a shallow two-dimensional electron gas in a Ga[Al]As heterostructure in the quantum Hall regime at 300 mK. This technique uses the local electrostatic potential induced by the conducting tip of a scanning force microscope for influencing the resistance of mesoscopic structures. Applied at high magnetic fields and low temperatures on a Hall bar sample, it is a further development of previous backscattering experiments with spatially immobile gates. This technique gives insight into the nature of the states in the interior and at the edges of a Hall bar with a width of 4 μm.

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The quantum Hall effect [1–4] (QHE) is one of the unique and fundamental phenomena occurring in two-dimensional electron gases (2DEGs) at low temperatures. One of its most remarkable properties is the precision of the quantization irrespective of the material and its quality, which allows to utilize the effect as a resistance standard [5]. A key ingredient for the understanding of the QHE is the localization of states in the tails of the Landau levels in high magnetic fields and the existence of extended states at sample boundaries or internal edges. The existence of chiral extended states with a transmission probability of unity between neighboring sample contacts is the basis for the description of the QHE in the framework of the Landauer–Büttiker theory of linear transport [6]. Although this model supplies a very intuitive and transparent picture of the effect, it does not settle the question, where in a sample the current flows and how the current density pattern changes with varying magnetic field.

As a consequence, many attempts have been made to measure the internal structure of the electron gas in the QHE-regime. The first experiments using gate electrodes placed across the Hall bar were performed in the late 1980s [7–9]. Early experiments with local probes used the electron–phonon interaction [10] or optical techniques with a spatial resolution down to 1 μm [11–13]. Later it was tried to detect edge channels inductively [14,15]. Recently, edge channels were imaged with a metallic single-electron transistor fabricated near the edge of a 2DEG [16]. Scanning probe techniques with their unprecedented potential of

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spatial resolution have also been employed for the local investigation of 2DEGs in the QHE-regime during the past few years. Among them are measurements with a scanning single-electron transistor [17], experiments using scanned potential microscopy [18], Kelvin probe techniques [19–21], subsurface charge accumulation [22–24] and tunneling between edge channels [25,26].

In the experiment reported here, we have locally investigated a 4 μm wide shallow two-dimensional electron gas realized in a Ga[Al]As heterostructure with a backgate using the scanning gate technique [27–31]. The conducting tip of a scanning force microscope was scanned at constant height and constant tip-sample voltage above the Hall bar structure at a temperature of 300 mK and in magnetic fields up to 9 T. Under these conditions the sample exhibits the quantum Hall effect in conventional magneto-transport measurements. Using the scanning tip as a local gate we mapped the change in longitudinal and transverse resistance as a function of tip position at various magnetic fields and back gate voltages.

The sample was based on a Ga[Al]As heterostructure with a 2DEG 34 nm below the surface. A highly doped region situated 1.3 μm below the 2DEG serves as the back gate electrode. It is isolated from the 2DEG with a layer of ErAs islands [32]. The electron density at 300 mK and zeroback- gate voltage was $n_s = 5.5 \times 10^{15}$ m^{-2}, the mobility $\mu = 8.5$ m^2/V s. A Hall bar sample with a width of 4 μm and a length of 10 μm between voltage probes was fabricated photolithographically. Considering the elastic mean free path of the electrons at low temperatures, $l_e = 1$ μm, we can regard the electron motion to be diffusive on the scale of the sample size.

The microscope used in this experiment is home-built. It is operated in a commercial ^{3}He cryostat with a base temperature of 300 mK and the possibility to apply magnetic fields up to 9 T normal to the plane of the 2DEG [33]. The scan range is more than 8×8 μm^2 at base temperature. The distance between tip and sample surface is controlled in dynamic mode using piezoelectric tuning fork sensors [34–36] and a phase-locked loop. A conductive PtIr tip connected to an external voltage source is attached to the tuning fork. It couples capacitively to the buried electron gas and induces a local potential.

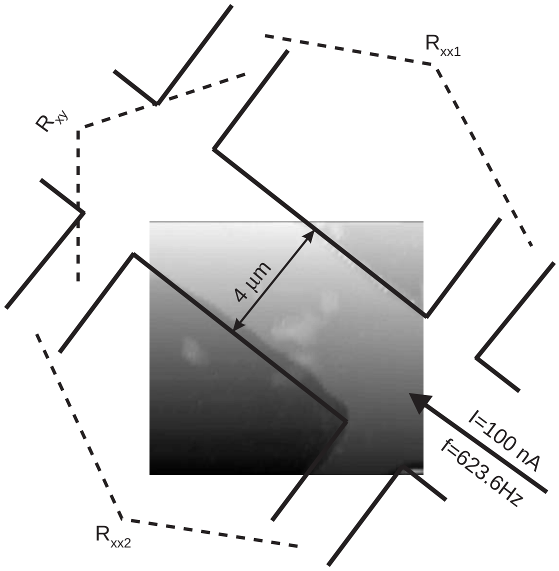

Fig. 1. Topographic image of a part of the Hall bar structure taken at 300 mK. The overlaid solid lines indicate the mesa edges of the structure with the four voltage probes.

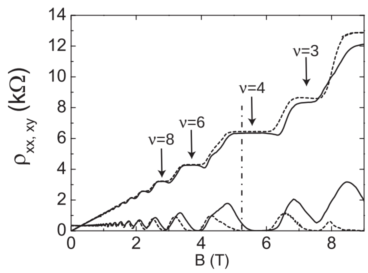

Fig. 2. Longitudinal and Hall resistances of the Hall bar as a function of magnetic field. The dashed curves were measured at 20 Hz, the solid lines at 623.6 Hz. The dash-dotted line indicates at which field the scan in Fig. 3 was taken.

Fig. 1 shows a topographic image of a part of the Hall bar taken at 300 mK. The solid lines in the figure indicate the mesa edges beyond the image and show the voltage probes between which the longitudinal and the Hall voltages (resistances) are measured. An AC current of 100 nA is fed through the sample.

In Fig. 2, we compare the longitudinal and the Hall resistances of the sample measured at low frequency (20 Hz) and at the frequency of 623.6 Hz. This latter measurement frequency was chosen for scanning

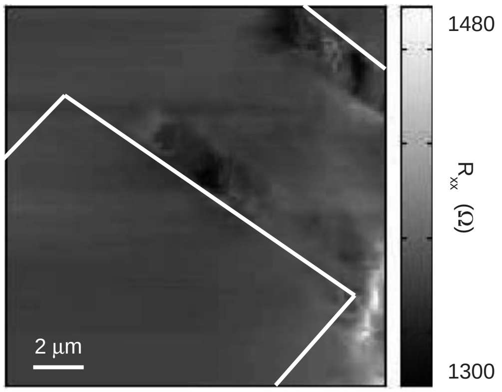

Fig. 3. Longitudinal resistance as a function of tip position at $B = 5.3$ T.

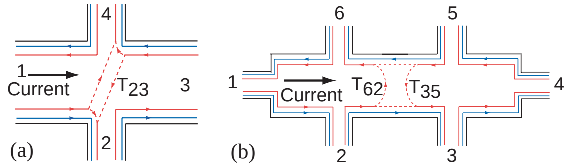

Fig. 4. (a) Schematic representation of scattering between opposite corners of the Hall cross in the Büttiker description of the quantum Hall effect. (b) Schematic representation of scattering between opposite edges of the Hall bar.

in order to achieve a reasonably high measurement bandwidth. Between the two measurements there was a time span of about 1 week during which scanning gate measurements with −6 V applied to the tip were made. We have identified two main causes for the differences between the two sets of traces: first, the higher measurement frequency together with the cable capacitances leads to small dips at the high field edge of the quantum Hall plateaus which can be well understood in an equivalent circuit analysis of the whole setup. Second, repeated scanning at strongly negative tip voltage has modified the details of the ρ_{xx}-trace between filling factors and the overall density has slightly increased [37]. We have therefore reduced the voltage on the tip to −2 V for further data shown in this paper, which was found to minimize the permanent changes caused by the scanning tip.

Fig. 3 is a scanning gate image of the longitudinal resistance taken at a magnetic field of 5.3 T. The corresponding Hall resistance image (not shown) is constant within a few Ohms. This is a magnetic field at which the filling factor is between $\nu = 5$ and 4. Comparison with Fig. 2 shows that the Hall resistance is still on a plateau value while the longitudinal resistance is already significantly larger than the $\nu = 4$ minimum value. The Hall resistance is found to be highly insensitive to the position of the tip induced potential perturbation in the Hall bar. This observation agrees with the well-known experimental fact that the quantization of the Hall effect is very robust against material quality and sample geometry, which makes it ideal for a resistance standard [5]. Scanning the tip in the interior of the Hall bar structure can be regarded as creating distinct realizations of disorder in the sample, however, the quantization of the Hall resistance remains unaffected. In the language of the Büttiker description of the quantum Hall effect [6] a local perturbation can only change the Hall resistance if there is some coupling T_{23} between the innermost edge channels at opposite corners of the Hall cross [Fig. 4(a)]. Within this model the Hall resistance is given by

$$R_H = R_{42,31} = \frac{h}{e^2}\frac{1}{n}\frac{n-2T_{23}}{n-T_{23}},$$

where n is the integer number of well-defined edge channels. With this relation it becomes clear that at $B=5.3$ T the transmission T_{23} is not appreciably different from zero in the absence of the tip (plateau in R_H). In addition, the scanning tip is not capable of increasing T_{23} significantly above zero in any position reached.

The situation is different for the longitudinal resistance in Fig. 3. The longitudinal resistance can be changed by the presence of the scanning tip, in particular when the tip is located near the edges of the sample. This indicates that backscattering between the opposite edges of the sample can be influenced. Within the Büttiker model, local backscattering can be described with a backscattering parameter T_{62} as illustrated in Fig. 4(b). The corresponding equation for the longitudinal resistance is

$$R_L = R_{23,14} = \frac{h}{e^2}\frac{1}{n}\frac{T_{62}}{n-T_{62}}.$$

In a quantum Hall minimum, T_{62} is very close to zero and R_L vanishes. At $B=5.3$ T we have already a finite R_L and therefore a finite $T_{62} = 0.62$ in the absence of the tip. Scanning the tip modifies the backscattering probability T_{62} by ΔT_{62} of typically 0.05 leading to the resistance image depicted in Fig. 3. As a advancement to previous experiments on selective backscattering of edge channels using fixed gate stripes across the Hall bar [7–9], the scanning technique provides additional spatial information where backscattering can be induced or reduced most effectively. The scanning gate image in Fig. 3 could be translated into a spatial map of T_{62}. For example, in Fig. 3 the strongest influence of the tip-induced potential on T_{62} occurs near the edges of the Hall bar. The interpretation of this result is straightforward. When the tip is placed near the edges of the sample, the tip effectively deforms the shape of the edge. This changes the coupling of the innermost edge states at opposite edges and thereby leads to an change in the longitudinal resistance. This effect does not occur homogeneously along the edge, but exhibits structure which is a result of the topology of the underlying quantum states.

In conclusion, we have described scanning gate measurements on a Hall bar at 300 mK in the quantum Hall regime. The method is a further development of backscattering experiments with fixed gate stripes. It gives insight into the local backscattering properties of a two-dimensional electron gas in the quantum Hall regime.

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