Quantization of the Hall Conductivity Well Beyond the Adiabatic Limit in Pulsed Magnetic Fields

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We measure the Hall conductivity, σ_{xy}, on a Corbino geometry sample of a high-mobility AlGaAs/GaAs heterostructure in a pulsed magnetic field. At a bath temperature about 80 mK, we observe well expressed plateaux in σ_{xy} at integer filling factors. In the pulsed magnetic field, the Laughlin condition of the phase coherence of the electron wave functions is strongly violated and, hence, is not crucial for σ_{xy} quantization.

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On recognizing the crucial role of the edge channels in two-dimensional (2D) electron transport in a quantizing magnetic field [1,2], it became pretty clear that the quantization of the Hall resistance, R_{xy}, in Hall bar samples, which corresponds to the quantum Hall effect [3], is not directly connected with that of the Hall conductivity, σ_{xy}. Even if the longitudinal resistance, R_{xx}, is negligible, the measured resistance tensor cannot be converted into the conductivity one: the net Hall current is a sum of the bulk and edge currents, while the conductivities σ_{xx} and σ_{xy} are related to the bulk of the 2D system. Therefore, the conductivity tensor and the accuracy of σ_{xy} quantization should be investigated independently using the Corbino geometry which allows separation of the bulk contribution to the measured current. Such an arrangement was described in the Laughlin [4] and Widom-Clark [5] gedanken experiments. A (Hall) charge transfer below the Fermi level between the coasts of a Corbino sample is induced by magnetic field sweep and thus the shunting effect of the edge currents is completely excluded. The concept of Ref. [4] based on gauge invariance leads to the conclusion that at integer filling factor the conductivity σ_{xy} will be quantized if the magnetic field, B, is changed adiabatically so as to keep the phase coherence of the wave functions on the sample size. The quantization of σ_{xy} follows from the fact that an integer number of electrons is transferred between the ring edges if the magnetic flux changes by one quantum. It is clear that the phase coherence should be the case at field sweep rates when the magnetic flux change, $\Delta\Phi = \tau L^2 dB/dt$, in a sample with size L within the settling time, τ, of the wave function phase is small compared to the flux quantum, h/e:

$$dB/dt < 2\pi\Omega_c B(l/L)^4, \tag{1}$$

where Ω_c is the cyclotron frequency, l is the magnetic length, and the phase settling time is estimated as the ratio of the sample size and the phase velocity of an electron, $\tau = L^2/l^2\Omega_c$.

Doubts about the correctness of the gauge invariance approach were expressed in Ref. [6] and were thought to be supported by results of the microwave studies, e.g., of Ref. [7]. In fact, those studies as well as edge magnetoplasmon [8] and related [9] experiments are not free of edge current contribution so that they do not yield the pure σ_{xy} and cannot be an argument against the approach of Ref. [4]. The value σ_{xy} can be measured in the arrangement of the above gedanken experiments which was employed in the work of Refs. [10–12]. Plateaux with the quantized values of σ_{xy} were indeed observed in the quasistatic measurements of Ref. [10], even though the quantization accuracy was about 1%.

In this Letter, we study for the first time the effect of adiabaticity in sweeping the magnetic field on the accuracy of σ_{xy} quantization. We perform low-temperature measurements of the charge transfer in a Corbino geometry sample subjected to a pulsed magnetic field with sweep rate up to 5×10^2 T/s using the sweep rate as an adjustable experimental parameter. The conductivity σ_{xy} has been found to be quantized at integer filling factor. This result is very similar to the data obtained in quasistatically changing magnetic fields, although at such high sweep rates of the pulsed magnetic field, the phase coherence of the electron wave functions is strongly broken. So, the condition of adiabaticity is *sufficient but not necessary* for σ_{xy} to be quantized.

The samples are Corbino disks fabricated from two wafers of AlGaAs/GaAs heterostructures containing a 2D electron gas with mobility 1.2×10^6 and 4×10^5 cm^2/Vs at 4.2 K and density 3.6×10^{11} and 3.2×10^{11} cm^{-2}, respectively. Each sample has a circular gate covering a part of the sample area so that the gated region of the 2D electron system is separated from the contacts by guarding rings; see Fig. 1. The radii of the Corbino ring are r_1 and r_2, and the circular gate is restricted by radii r_{1g} and r_{2g}; two sets of the radii are employed: (i) $r_1 = 0.2$ mm, $r_2 = 0.5$ mm, $r_{1g} = 0.305$ mm, and

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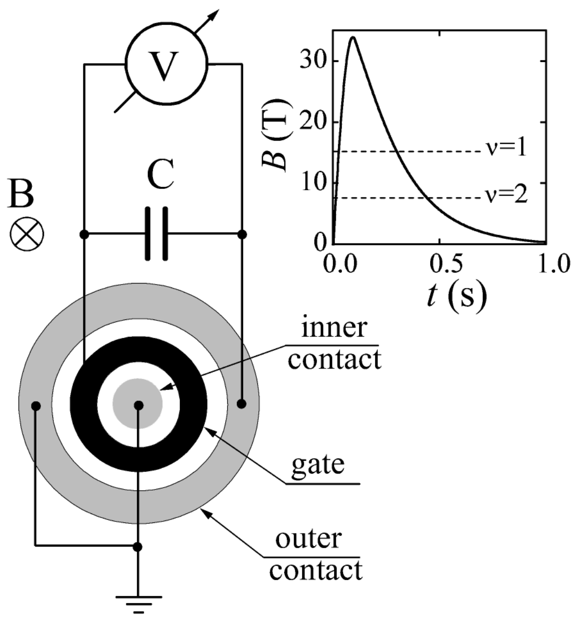

FIG. 1. Schematic view of the sample and measurement circuit. The magnetic field pulse is shown in the inset.

$r_{2g} = 0.39$ mm and (ii) $r_1 = 1.013$ mm, $r_2 = 1.119$ mm, $r_{1g} = 1.025$ mm, and $r_{2g} = 1.108$ mm. The sample is placed into the mixing chamber of a dilution refrigerator with a base temperature of 80 mK. In each pulse, the magnetic field sweeps up to 34 T (or lower) with rising and falling times of about 50 ms and 1 s, respectively (inset of Fig. 1). The azimuthal electric field induced by magnetic field sweep gives rise to an electric current only in the radial direction if $\sigma_{xx} \to 0$. In the experiment we study the charge, Q, brought out of the gated region, which is equal to the difference between the charge exiting and entering the gated region [10]

$$Q = \pi(r_{2g}^2 - r_{1g}^2)\sigma_{xy}\Delta B\,. \qquad (2)$$

This charge induces the voltage, $V = Q/C$, across a sufficiently large capacitance, C, connected in parallel to the gate, which is measured using a preamplifier and a digitizer. The capacitance C allows one to restrict the induced voltage in order to avoid the breakdown of the dissipationless quantum Hall state [13]. The equilibrium ($B = 0$) electron density in the gated region can be changed by using a gate bias, V_g. All data we show in the paper refer to the gate voltage $V_g = 0$; we have checked that for gate voltages between 0 and -80 mV (the threshold voltage $V_{\text{th}} \approx -0.3$ V), the results discussed below are not sensitive to V_g. In the experiment with quasistatically changing magnetic fields [with sweep rates in the range $(1-5) \times 10^{-3}$ T/s], we measure the charge Q using an electrometer.

Typical experimental traces of the voltage induced on the sample in a pulsed magnetic field in the vicinity of filling factors $\nu = 1$ and $\nu = 2$ are shown in Fig. 2 for up and down sweeps. When sweeping the magnetic field up,

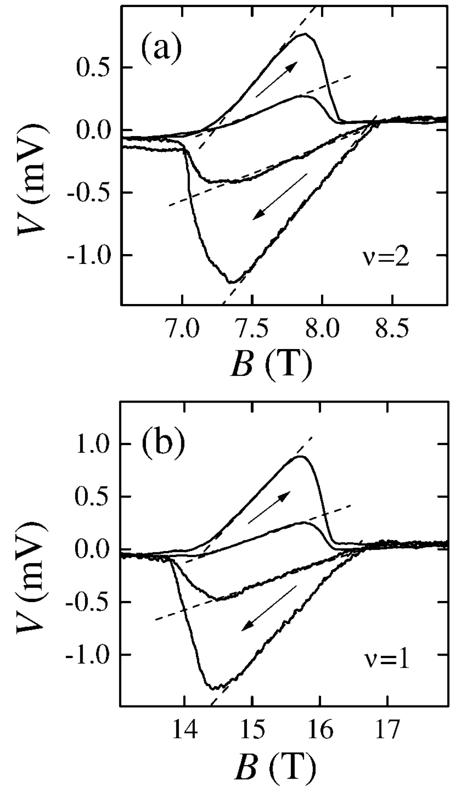

FIG. 2. Experimental traces of the induced voltage on one of the samples in a pulsed magnetic field for $C = 10.4$ and 32 nF at filling factor $\nu = 2$ (a) and $\nu = 1$ (b). The expected slopes $V/\Delta B$ are shown by dashed lines. The sweep direction is indicated by arrows.

at small σ_{xx} the voltage rises linearly with B, in accordance with Eq. (2), until it drops above a certain value of the magnetic field thereby signaling the breakdown of the dissipationless quantum Hall state. On changing the sweep direction, the voltage polarity reverses so that the up and down traces form a hysteresis loop. The asymmetry between its top and bottom parts is caused by larger overheating of the sample in sweeping the field up, which leads to a more pronounced narrowing of the quantum plateaux. A change in the background signal below and above the hysteresis loop originates from chemical potential oscillations [10]. Similar dependences $V(B)$ are observed also at higher integer $\nu \leq 6$ ($\nu \leq 10$) for up (down) sweeps; below we discuss the two lowest filling factors at which the observed structures occupy the widest magnetic field intervals.

It is important that the slope in the linear interval of the dependence $V(B)$ is in excellent agreement with the calculated one using Eq. (2) with the quantized value $\sigma_{xy} = \nu e^2/h$; see Fig. 2. As the magnetic field is increased within the linear interval of $V(B)$, electrons are brought into the 2D system, and the electron density increases, in accordance with Eq. (2), by $\Delta n_s = (\nu e/h)\Delta B$ (where $\nu = 1, 2, \ldots$). As a result of the aligned change of magnetic field and electron density, the filling factor remains approximately constant: it is about 10% larger

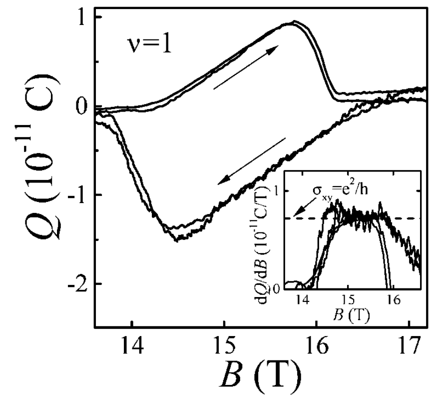

FIG. 3. Charge brought out of the 2D electron system as a function of B for filling factor $\nu = 1$ as obtained from the data of Fig. 2. The arrows indicate the direction of magnetic field sweep. The numerical derivative dQ/dB is displayed in the inset.

(smaller) than the integer ν for the up (down) sweep of the magnetic field (Fig. 2). Thus, the observed dependences $V(B)$ yield well expressed plateaux in σ_{xy} as a function of filling factor.

Figure 3 shows the corresponding dependence $Q(B)$ in a pulsed magnetic field. As seen from the figure, within the whole hysteresis loop, the behavior of the charge Q brought out of the 2D electron system is independent of shunting capacitance C. This implies that the observed linear B dependence of the charge Q is limited by a capacitance discharge that is controlled by the dependence of σ_{xx} on magnetic field [15]. The derivative dQ/dB yields plateaux in σ_{xy} as a function of magnetic field (inset of Fig. 3).

Typical curves of the voltage induced by the charge Q in the quasistatic measurement are displayed in Fig. 4. In addition to the curves obtained by sweeping the magnetic field up and down all way through the hysteresis loop, two more traces correspond to reversal of the sweep direction within the hysteresis loop. The expected linear behavior of

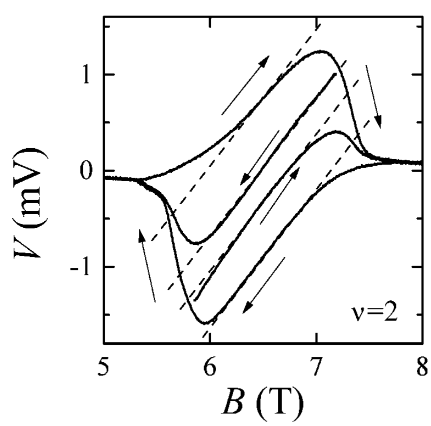

FIG. 4. The induced voltage on another sample in a quasistatically changing magnetic field as indicated by arrows; $C = 30$ nF. Also shown by dashed lines is the expected slope $V/\Delta B$.

V against B is shown for comparison by dashed lines. We emphasize that the accuracy of σ_{xy} quantization for pulsed magnetic fields turns out to be the same or even higher than in quasistatic measurement; cf. Figs. 2(a) and 4.

One can easily see that the above-mentioned adiabatic limit of the inequality (1) is not fulfilled in our experiments. This limit corresponds to the magnetic field sweep rate $\sim 10^{-4}$ T/s if $L = 0.5$ mm, which is already an order of magnitude lower than sweep rates in the quasistatic measurement. Moreover, the conductivity σ_{xy} is still found to be quantized even at much higher sweep rates of the pulsed magnetic field, at least 6 orders of magnitude beyond the estimated adiabatic limit of the expression (1). This finding unambiguously shows that the condition of the phase coherence of the electron wave functions is not crucial for σ_{xy} quantization.

Apparently, our line of reasoning holds if the temperature-dependent dephasing time, $\tau_\phi(T)$, is much larger than the phase settling time τ. The former can be evaluated from the balance condition for thermal electron excitation to the upper quantum level and relaxation of the excited electrons

$$n_0 \tau_\phi^{-1} = n_0 \exp(-\Delta/2k_B T)\tau_{\text{exc}}^{-1}, \tag{3}$$

where n_0 is the quantum level degeneracy, Δ is the level splitting, and τ_{exc} is the lifetime of an excited electron. As known from optical studies (see, e.g., Ref. [16]), the lifetime τ_{exc} exceeds $\hbar\Delta^{-1}$ for both spin and cyclotron splittings. Hence, we obtain $\tau_\phi > \hbar\Delta^{-1}\exp(\Delta/2k_B T) \gg \tau$ in our experiment.

From the expression (1) it follows that for our highest sweep rates, the phase coherence of the wave functions is broken on the length ~ 10 μm, which is still much larger than the magnetic length. In other words, σ_{xy} is found to be quantized when the adiabatic limit is not the case for the whole sample but still holds on macroscopic distances. Whether there exists a maximum sweep rate of the magnetic field for σ_{xy} to be quantized remains to be seen.

In summary, we have measured the Hall conductivity in the arrangement of Laughlin's gedanken experiment in pulsed magnetic fields. Well expressed plateaux in σ_{xy} have been observed at integer filling factors, which is similar to the data obtained in quasistatic measurements. Although in the pulsed magnetic field, the phase coherence of the electron wave functions is strongly broken, the σ_{xy} quantization is still the case. Therefore, the gauge-invariance-based argumentation [4] is sufficient but not necessary for σ_{xy} quantization.

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