Quantum Hall effect in the absence of edge currents

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Measurements of the Hall conductivity σ_{xy} on samples of the Corbino geometry at integer and fractional ($i = \frac{2}{3}$) filling factors have been carried out. Two different techniques of measurements based on the Laughlin and Widom-Clark "gedanken" experiments were realized. The limits of the two experimental techniques connected with their particularities and the breakdown of the quantum Hall effect are presented. We have also investigated the charge transfer under the conditions of inhomogeneous electron density.

The problem of current distribution in the quantum Hall effect (QHE) regime has quite a long history. Experiments with point potential probes in the plane of two-dimensional (2D) electron gas[1–4] demonstrated unambiguously that the current caused a change in the electrochemical potentials of all internal contacts. Subject to the existence of extended states (below the Fermi level) in the plane of the 2D electron gas these measurements would prove that the Hall current is distributed all over a sample plane. However, the existence of extended states transporting the Hall current over the plane of a real imperfect sample has not yet been proved experimentally, nor has there been reliable experiment to measure σ_{xy} directly. In Ref. 5 the current in the QHE regime is considered to be the charge flow in 1D channels at sample edges. The theory developed in Ref. 5 and subsequent works did not deny the presence of extended states in the plane of 2D electron gas. According to theory[5] these states do not affect the accuracy of quantization in measurements on the Hall bars. Many experiments (e.g., Refs. 6 and 7) confirm the assumption about the existence of edge currents.

Experiments excluding the influence of edge currents on charge transfer in QHE have been realized recently.[8,9] In the present work (i) we report detailed results of measurements performed by the technique;[8,9] (ii) we have realized an alternative method of measurement of σ_{xy}; (iii) the breakdown of QHE has been investigated; and (iv) the charge transfer under the condition of inhomogeneous electron density has been investigated.

I. SAMPLES AND EXPERIMENTAL TECHNIQUE

In these measurements we used samples of the Corbino geometry prepared either of Si–metal-oxide-semiconductor structures or of $GaAs/Al_xGa_{1-x}As$ heterostructures. The metal-oxide-semiconductor field-effect-transistor (MOSFET) parameters were as follows: internal diameter $2r_1 = 225$ μm, external diameter $2r_2 = 675$ μm, SiO_2 was 1300 Å thick, mobility at maximum $\mu = 2$ m^2/V s at $T = 1.5$ K.

The majority of the experiments were carried out on $GaAs/Al_xGa_{1-x}As$ heterostructures. One of the samples (No. 1) was an ordinary Corbino disk having sizes $2r_1 = 0.9$ mm, $2r_2 = 3.9$ mm, electron density $N_s = 3.3 \times 10^{11}$ cm^{-2}, and mobility $\mu = 15$ m^2/V s. The other four samples (Nos. 2–5) were constructed in a more complicated manner. The sizes of the 2D layer were $2r_1 = 2.02$ mm, $2r_2 = 2.3$ mm. Each sample had a gate with diameters $2r_{1g}$ =2.06 mm, $2r_{2g} = 2.26$ mm, so that the gate covered only a part of a sample area with a spacing of 20 μm between the gate and the contact region (guarding rings). The distance between the gate and 2D electron gas was equal to 940 Å. Applying a negative voltage to a gate, one could decrease the electron density in the gated region of a sample. The electron density in the guarding rings remained unchanged. In the homogeneous case the typical values of electron density in these samples were $N_s = 1.9 \times 10^{11}$ cm^{-2} (samples 2 and 5) and $N_s = 3.2 \times 10^{11}$ cm^{-2} (samples 3 and 4). The electron mobility was 40 m^2/V s.

Magnetic fields of up to 16 T were used, and the minimum temperature was 25 mK.

The experimental technique first described in Refs. 8 and 9 is outlined below: A magnetic field was applied normal to the plane of the 2D electron gas and changed linearly with time. Due to the azimuthal electric field, E_ϕ, charge is transferred between contacts in a similar manner to Laughlin's "gedanken" experiment.[10] In the general case a back charge transfer because of finite dissipative conductivity σ_{xx} can be present. However, at minima of σ_{xx} the back charge transfer was negligible during the experiment (~1 h) at sufficiently low temperatures and low enough electric field due to the build-up of charges in the contacts. The charge Q_T transferred from one contact to the other was measured by means of an electrometer.

If the sample has a gate it is possible to measure the charge Q_L brought out of the 2D electron layer by changing the magnetic field in accordance with Widom and Clark's "gedanken" experiment.[11] It is sufficient to connect both (inner and outer) contacts together and to measure a potential difference between them and a gate by an electrometer. The arrangement of the experiment is similar to that used in measurements[12–14] of chemical potential oscillations by the "floating" gate technique. The difference between the two experiments is as follows: To observe the chemical potential oscillations it is necessary for the electron system to be in equilibrium ($\sigma_{xx} \neq 0$), while in Widom and Clark's experiment the thermodynamical equilibrium must be absent.

In a number of experiments we were able to measure charges Q_T and Q_L simultaneously on the same sample.

II. CHARGE TRANSFER BETWEEN CONTACTS

We show the scheme of measurements of a charge transferred between inner and outer contacts in Fig. 1. A large capacitance $C_0 = 0.65$ μF was connected in parallel to the electrometer, the other capacitances were $C_1 \approx C_2 \approx 0.001$ μF. It is easy to obtain the following expression for the potential difference measured by the electrometer:

$$V = \frac{C_2 q_1 + C_1 q_2}{C_1 C_2 + C_1 C_0 + C_2 C_0}. \tag{1}$$

In our case $V \approx Q_T/C_0 \approx (q_1 + q_2)/2C_0$. The charges q_1, q_2 are determined by the value of the nondissipative conductivity at contacts and by the increment of magnetic field,[8,9] hence

$$Q_T = \Delta H \frac{\sigma_{xy}}{c} \frac{\pi}{2} (r_1^2 + r_2^2), \quad \sigma_{xx} \to 0. \tag{2}$$

The results of experiments on the charge transfer were qualitatively the same on all samples investigated. The representative experimental curves for sample 5 are displayed in Fig. 2. A magnetic field of about 13 T was attained in this experiment in 40 min so that the sweep rate $dH/dt = 5.57 \times 10^{-3}$ T/s. In agreement with Eqs. (1) and (2) the experimental dependence $V(H)$ is linear in the ranges of magnetic field where σ_{xx} is small enough. The expected slopes for the dependence $V(H)$ corresponding to conductivity $\sigma_{xy} = ie^2/h$ ($i = \frac{2}{3}$,1,2,3,4) are shown alongside the experimental curves in Fig. 2.

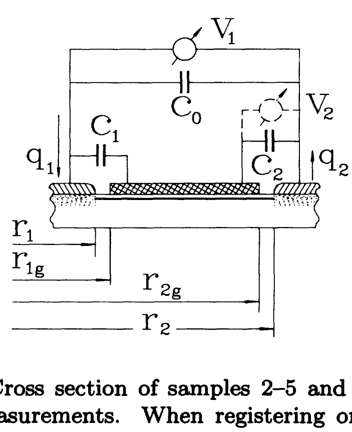

FIG. 1. Cross section of samples 2–5 and an equivalent circuit of measurements. When registering only the transferred charge $C_0 \gg C_1 \approx C_2$. The electrometer for measuring the charge leaving the gated region is shown by the dashed line. In this experiment $C_0 \gg C_2 \gg C_1$.

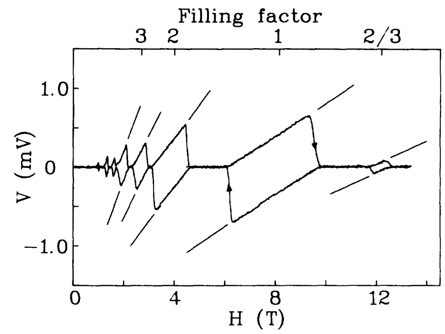

FIG. 2. Potential difference between inner and outer contacts in increasing and decreasing magnetic field. Sample 5, T = 25 mK. The straight lines show slopes expected from Eqs. (1) and (2) for filling factors $\frac{2}{3}$,1,2,3,4.

Generally speaking, the coincidence of expected slopes with experimental ones does not in itself prove the charge transferring from one contact to the other because only the local relation, $j_r = \sigma_{xy} E_\phi$, between electric field and current density at contacts is needed for validity of the formulas (2). Under experimental conditions the maximal value of transferred charge for sample 3 reaches $Q_T \approx 4.5 \times 10^9 e$ (where e is an electron charge) at filling factor $i \approx 1$. It is the fact that the value Q_T/e is more than the number of electrons in the specimen plane (3.4×10^9) which proves that the charge transfer is over the whole plane.

The experimental curves on intervals corresponding to quantized charge transfer were straight lines with good accuracy on GaAs/Al_xGa_{1-x}As samples. Analogous curves on Si MOS structures were less perfect even at minimal filling factors in the highest available magnetic fields. This is probably due to change with magnetic field of effective radii determining the charges q_1 and q_2.

A straight-line interval with corresponding slope at filling factor $i = \frac{2}{3}$ implies the transfer of two electrons in changing the magnetic flux through the sample plane by three quanta.

We should note that the shape of experimental curves discussed above was the same irrespective of the presence of a gate in the case of homogeneous electron density. Indeed, the experimental dependences recorded on a sample without the gate (sample 1) were identical with those on other samples.

III. BREAKDOWN OF QUANTUM HALL EFFECT IN CORBINO GEOMETRY

Our experiments[8,9] were not the first attempt to measure a σ_{xy} value in the Corbino geometry in the QHE regime. Another experimental technique is described in

Ref. 15. At a temperature of 1.5 K a sample was placed in a magnetic field which was modulated at a frequency 100 Hz or more. (The relatively high modulation frequency is needed because of back dissipative current.) In that work the quantized values of σ_{xy} were not observed, which was due, we believe, to a breakdown of the QHE in Corbino geometry.

The QHE breakdown was responsible for determining the shape of part of the curves in our experiments. The experimental dependences, shown in Fig. 2, are very specific. The curve recorded in increasing magnetic field reaches a maximum at a lower field than the starting point of the linear region of the curve recorded in the reducing field. To explain the decrease after the peak the dissipative electron flow is necessary to be strongly dependent on electric field. The influence of breakdown is observed to be more pronounced on the series of experimental curves obtained at three different values of capacitance C_0 (Fig. 3). The decrease of the capacitance leads to the increase of a slope of the linear region. The slope is proportional to C_0^{-1} as long as the potential difference between contacts is small enough. As the capacitance C_0 decreases the increase of the maximum value of the potential difference between internal and external contacts tends to saturate. The experimental curve tends to an ultimate shape which is symmetric about the integer filling factor. After reaching this limiting situation, further decreasing of C_0 does not cause any further change. The ultimate curve obtained on the most homogeneous sample only changes sign upon changing sweep direction.

Having stopped the sweep of magnetic field it was possible to stay at any point of ultimate curve for quite a long time. The typical time period during which the signal measured changed appreciably was about 10 min.

Such an ultimate behavior could be achieved in different ways (Fig. 4). The lower curve in Fig. 4 was obtained in a similar way to those in Fig. 2. To record the two upper curves the sample was warmed to a temperature $T \sim 1$ K in constant magnetic field $H = 8.03$ T. In this way the equilibrium electron density corresponding to the filling factor $i \approx 1$ was reached. After cooling a potential difference was applied between the source and drain of

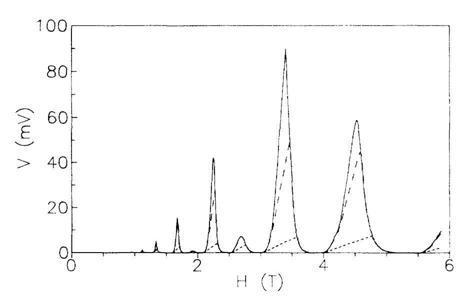

FIG. 3. Experimental curves at three different capacitances C_0: 1.2 nF (solid), 2.8 nF (dashed), 30 nF (dotted). Sample 1, $T = 25$ mK. The solid line is an ultimate curve which does not change in decreasing the capacitance C_0 further.

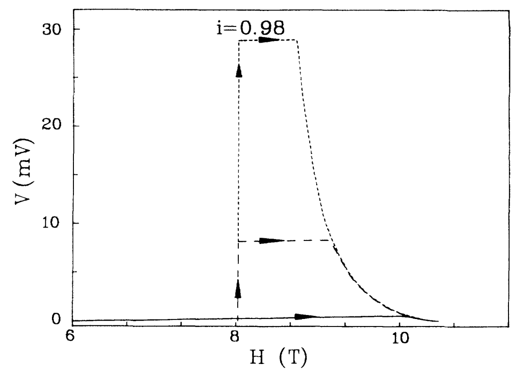

FIG. 4. Different ways to reach the ultimate curve. Sample 2, $T = 25$ mK, $C_0 = 0.65$ μF. Parts of the experimental records coincide with the ultimate curve regardless of prehistory.

the sample. Then the voltage source was turned off and the magnetic field sweep started. One can see, therefore, that the ultimate curve does not depend on the way to reach it.

From expression (1) we can see that there exists a trivial possibility for the dependence $V(H)$ to achieve such an ultimate slope when varying C_0. However, in this case the curve would display a straight-line interval with slope proportional to σ_{xy}. Furthermore, the calculated absolute value of $V(H)$ would far exceed the experimental result.

There is one more trivial possibility of existence of the ultimate curve: In gated samples the voltage arising between contacts when sweeping magnetic field can be of the order of a threshold voltage. However, observation of the similar ultimate curve on an ungated sample causes us to look for another interpretation.

As long as one should expect that in the case of vanishing σ_{xx} the electric field, E, at contacts is larger than that of in the bulk of the 2D electron gas it is possible to connect the behavior of the ultimate curve with the QHE breakdown in the following way: A potential drop between the contacts results in a bending of the Landau levels. If the electric field at the contacts is high enough then electron tunneling from a contact to the 2D layer takes place. The tunneling distance being of the order of magnetic length is small as compared to characteristic scale of the Landau level bending (Fig. 5). Tunneling current flows through an approximately triangular potential barrier:

$$I \sim \exp\left(-\frac{4}{3\hbar}\frac{(2m)^{1/2}}{eE}(\hbar\omega_c/2 - \Delta\epsilon)^{3/2}\right) + \exp\left(-\frac{4}{3\hbar}\frac{(2m)^{1/2}}{eE}(\hbar\omega_c/2 + \Delta\epsilon)^{3/2}\right), \quad (3)$$

where $\Delta\epsilon$ is the separation from the Fermi energy of electrons in a contact to the mid-point between Landau levels. Contributions of the two Landau levels to the current are taken into account. The first term in the formulas

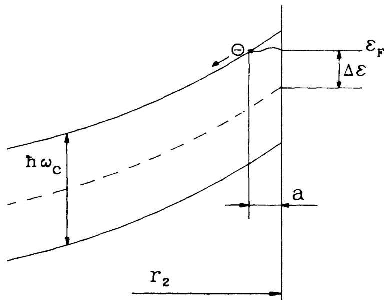

FIG. 5. The bending of Landau levels near external metal contact in an electric field. The lower level is completely filled and the upper one is empty. Electron tunneling from the external metal contact to the empty Landau level causes breakdown. (Electrons of the filled Landau level tunnel into internal contact at the indicated direction of electric field.)

corresponds to the current through the upper level with electron tunneling from external contact. The second one describes the current through the lower level with electron tunneling to internal contact. For the sake of simplicity the contacts are supposed to be symmetric and the temperature $T = 0$.

Assuming the existence of a minimal registered current determined by the time of an experiment t_0 ($I_{\min} \sim Q_T/t_0$), one can obtain the relation between electric fields:

$$\frac{E}{E_0} \approx \left(1 - \frac{2\Delta\epsilon}{\hbar\omega_c}\right)^{3/2} \tag{4}$$

which results with logarithmic accuracy from the equation $I = I_{\min}$ under the conditions

$$\frac{m^{1/2}}{\hbar eE}(\hbar\omega_c)^{3/2} \gg 1, \quad \frac{m^{1/2}}{\hbar eE}(\hbar\omega_c)^{1/2}\Delta\epsilon \gg 1. \tag{5}$$

Here E_0 is an electric field at the contact at the integer filling factor. The interpolation formula (4) defining the dependence $V(H)$ is accurate at $\Delta\epsilon = 0$ and asymptotic at large $\Delta\epsilon$. If thermodynamical density of states is constant within the Hall plateau,[16,17] then the relation

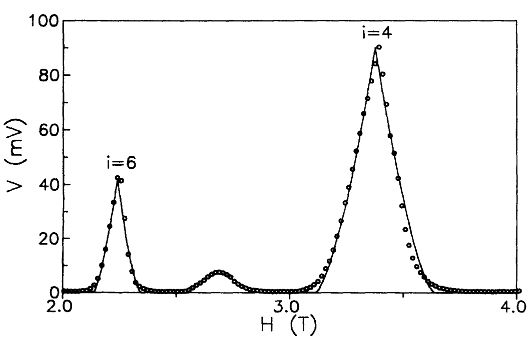

FIG. 6. Experimental ultimate curve on sample 1 (circles) and fit by means of Eq. (4).

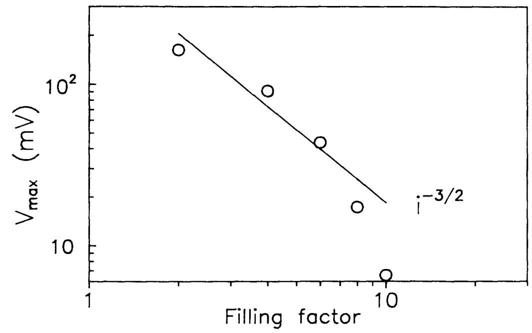

FIG. 7. Dependence of ultimate curve amplitude $V_{\max}$ on filling factor. Sample 1, $T = 25$ mK.

(4) with $\Delta\epsilon = -\Delta H(ie/hc)(\partial N_s/\partial\epsilon_F)^{-1}$ yields the ultimate shape of the curve. The electron density at any point along this curve was assumed to be the equilibrium one.

Expressions (3)–(5) written above are valid only for even filling factors. In the case of odd filling factor one should substitute spin-splitting energy for cyclotron energy in (3)–(5). The value of spin splitting depends on the position of the Fermi level; therefore, the shape of ultimate curve can be different for even and odd filling factors. Moreover, the inequality (5) is not satisfied for odd filling factors even at maximum magnetic field. Below we discuss only the case of even filling factors.

Figure 6 shows for comparison the experimental dependence with the curve plotted according to (4) using two fitting parameters ($V_{\max}$ and $\partial N_s/\partial\epsilon_F$) for each cusp. The agreement with the experiment is obtained for all filling factors $i = 2,4,6,8,10$ at $\partial N_s/\partial\epsilon_F = 0.3m/\pi\hbar^2$. We can double check the above hypothesis by noting that in strong magnetic field the separation between mobility thresholds of neighboring Landau levels is close to $\hbar\omega_c$. Then, the relation $V_{\max} \sim i^{-3/2}$ should be valid for even integer filling factors [see Eq. (3)]. This is indeed found to be the case at the lowest filling factors (Fig. 7). The deviation of experimental points from the expected dependence at large filling factors is a consequence of more rapid decrease of the energy separation between mobility thresholds than $\hbar\omega_c \propto i^{-1}$.

For the type of breakdown considered to occur, it is necessary for the tunneling current to exceed the thermoactivation dissipative one, i.e., the temperature must be sufficiently low. Otherwise, the mechanism of nonlinearity discussed in previous papers[18–20] is realized.

IV. MEASUREMENTS OF CHARGE LEAVING THE 2D ELECTRON LAYER

As long as the Hall conductivity is quantized when $\sigma_{xx} \to 0$, changing the magnetic field gives rise to a nonequilibrium electron density which differs from the initial one by the value

$$\Delta N_s = \Delta H(ei_0/hc), \tag{6}$$

where i_0 is the integer filling factor. In accordance with Eq. (6), when starting from the magnetic field $H = hcN_s/ei$, the change of filling factor[9] is equal to

$$\Delta i/i = (\Delta H/H)(i_0/i - 1). \tag{7}$$

A method of measurement of the charge Q_L leaving the 2D electron layer was proposed by Widom and Clark.[11] In order to realize it experimentally one needs to connect a second electrometer to the sample (in Fig. 1 it is drawn by the dashed line), the relation between capacitances being $C_0 \gg C_2 \gg C_1$. Using the two electrometers one can check both Q_T and Q_L on the same specimen simultaneously. In our experiment the capacitance C_0 was so large that the signal registered by the electrometer V_2 coincided with one measured when short-circuiting the capacitor:

$$V_2 = \frac{(q_2 - q_1)C_0 + q_2 C_1}{C_1 C_2 + C_1 C_0 + C_2 C_0} \approx \frac{q_2 - q_1}{C_2}. \tag{8}$$

Results showing $Q_T(H)$ and $Q_L(H)$ at several temperatures are presented in Fig. 8. At the selected relation between capacitances C_0, C_1, C_2 the charge Q_T is equal to that q_1 crossing a circumference of radius r_1. To make the comparison easy the charge Q_L is multiplied, in Fig. 8, by the ratio of the squares $r_1^2/(r_2^2 - r_1^2)$. After this both curves must have equal slopes at a quantized value of σ_{xy}.

At the highest temperature $T = 0.88$ K we did not observe the charge leaving the 2D layer. There were only oscillations of the chemical potential of 2D electrons in quantizing magnetic field.[12–14] It is interesting that there exists charge transfer in the absence of the charge leaving the 2D layer.

The conditions for observing the charge transfer are not so rigorous as those to register the charge Q_L. In the first case the characteristic time τ is of the order of $C_0\sigma_{xx}^{-1}\alpha$, where α is a geometric factor. In the second case this time is $C\sigma_{xx}^{-1}\alpha$, where C is the electrical capacitance between a gate and the 2D layer. The accuracy of the experiment grows in increasing τ, which can be obtained by increasing the capacitance. The largest value of capacitance C_0 was restricted because of finite electrometer sensitivity. In our experiment it was $C_0/C \sim 10^3$.

As the temperature decreased the hysteresis caused by the change of the charge in the 2D layer appeared in the dependence $Q_L(H)$. The solid curve at the lowest temperature is shown in Fig. 9. One can see that the lines $Q_T(H)$ and $Q_L(H)$ are not parallel in the intervals of magnetic field where the slope should be proportional to the conductivity σ_{xy}. The slope of the curve $Q_L(H)$ was usually less than that of $Q_T(H)$. The former was slightly larger when starting from the magnetic field corresponding to an integer filling factor. (To create the initial equilibrium electron density in this case, the sample was heated up and then cooled down in a constant magnetic field before starting, as was mentioned above.) The increase of the slope was also observed in cycling, i.e., in changing the magnetic field sweep direction within the hysteresis curve (in Fig. 9 shown by arrows).

For all filling factors the width of peaks on the curve $Q_L(H)$ was less than that on $Q_T(H)$.

It would seem reasonable to explain the discrepancy of the slopes by the finite value of σ_{xx}. The influence of back current on the value of $Q_L(H)$ would increase when decreasing the sweeping rate. In Fig. 10 the dependence $Q_L(H)$ for filling factor $i \approx 2$ is displayed at two sweeping rates. Since the value of slope does not depend on magnetic field sweeping rate there must be other reasons responsible for the small slope of curve $Q_L(H)$.

We can suggest two possible reasons: First, it is possible that charge is not brought out of the whole region covered with the gate. The area of the active region depends on both the filling factor value at the start and a sample prehistory. In starting from an integer filling factor the area is maximum, though it might not have been the same as the whole gate area.

Furthermore, it is necessary to suppose that there is

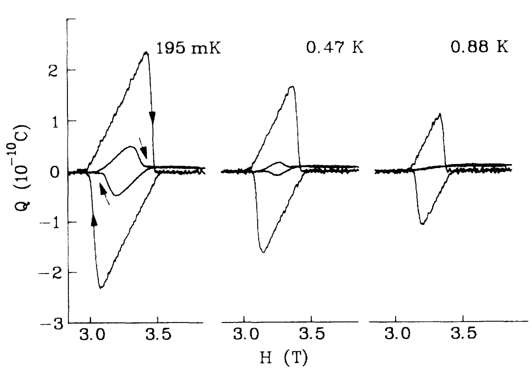

FIG. 8. Simultaneous measurements of charges Q_T and Q_L at different temperatures. The charge Q_L (small loops) is multiplied by a square ratio for convenience of comparison. Sample 3: $C_0 = 0.65$ μF, $C_2 = 0.03$ μF, $C_1 = 0.001$ μF.

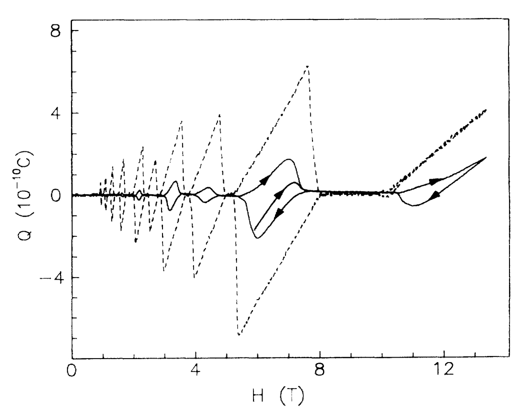

FIG. 9. Measurements of charges Q_T and Q_L on sample 3 at temperature $T = 25$ mK. The charge Q_L (small loops) is multiplied by a square ratio. $C_0 = 0.65$ μF, $C_2 = 0.03$ μF, $C_1 = 0.001$ μF. The increase of the slope of curve $Q_L(H)$ in the range of magnetic fields 6–7 T was obtained by changing sweep direction within the hysteresis loop.

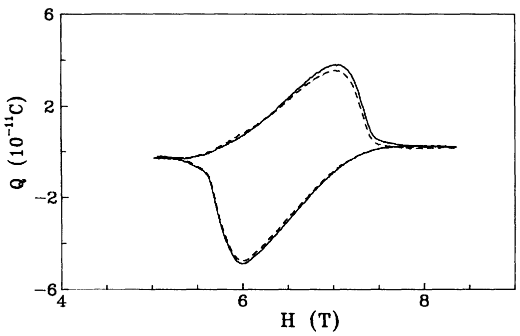

FIG. 10. Dependence $Q_L(H)$ at two sweeping rates of magnetic field: $dH/dt = 5.57 \times 10^{-3}$ T/s (solid) and $dH/dt = 1.39 \times 10^{-3}$ T/s (dashed). Sample 3, $T = 25$ mK.

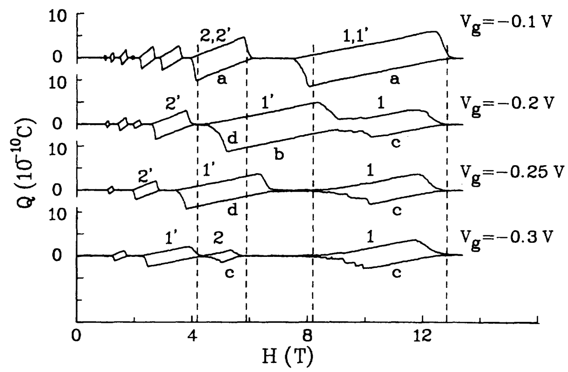

FIG. 12. A set of records $Q_T(H)$ at various gate voltages for sample 3 at temperature $T = 25$ mK. The regions of quantized Hall conductivity in the guarding rings are roughly marked by vertical dashed lines. Different positions of Fermi energy with respect to Landau levels are denoted by letters (see Fig. 11). Digits with and without apostrophes point out the values of quantized Hall conductivity in a gated region and in the guarding rings.

no quantized transport, at least over one of the guarding rings; otherwise, the active region is determined exclusively by radii of those rings. This suggestion was verified in experiments with inhomogeneous electron density controlled by a gate. Applying a negative voltage to the gate, it was possible to realize four different positions of Fermi level with respect to quantum levels as shown in Fig. 11. Experimental observation of the charge Q_L in case (c) of Fig. 11 would prove that both guarding rings are active. Regions of magnetic fields and gate voltages corresponding to the different situations of Fig. 11 were determined by measuring the charge Q_T (Fig. 12). On most of our samples at strong depletion of the region below the gate ($i < 1$) we did not observe the charge leaving the 2D layer, which implies the absence of quantized transport over one of the rings. Yet sample 5 demonstrated a small hysteresis loop at strong depletion below the gate (see the middle curve in Fig. 13). Only on this sample did the slope of dependence $Q_L(H)$ coincide with the expected one (upper dashed line in Fig. 13).

The second reason that could give rise to different slopes of the curves $Q_T(H)$ and $Q_L(H)$ is connected with the large potential difference between the inner region of a 2D layer and contacts due to the change of the charge in the 2D layer. In our experiment this potential difference was of the order of 1 V, so the back charge flow into the region below a gate could be at least partially due to the QHE breakdown caused by electron tunneling. Thus the QHE breakdown can affect the shape of both curves $Q_T(H)$ and $Q_L(H)$.

Another way to measure a charge leaving the 2D elec-

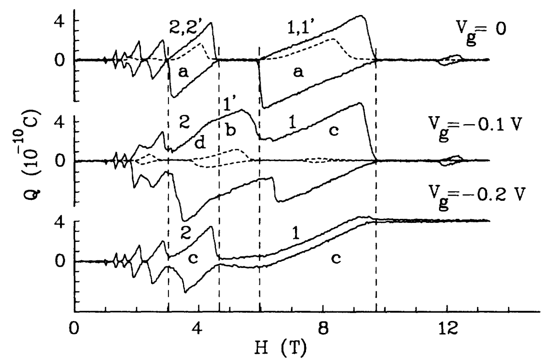

FIG. 13. Dependences $Q_T(H)$ (solid) and $Q_L(H)$ (dashed) at different gate voltages. Sample 5, $T = 25$ mK, threshold voltage $V_{\rm th} = -0.25$ V. Positions of Fermi energy with respect to quantum levels are indicated by letters in accordance with Fig. 11. Vertical dashed lines roughly restrict regions corresponding to different positions of Fermi energy. Digits indicate values of quantized Hall conductivity in e^2/h (digits with apostrophes correspond to quantized conductivity below the gate). The plateau on the lower curve in the region of high magnetic fields may have been connected with magnetic freezing out of the conductivity at small density of 2D electrons below the gate. We should note that depleting a gated region entirely caused the signals to vanish rapidly.

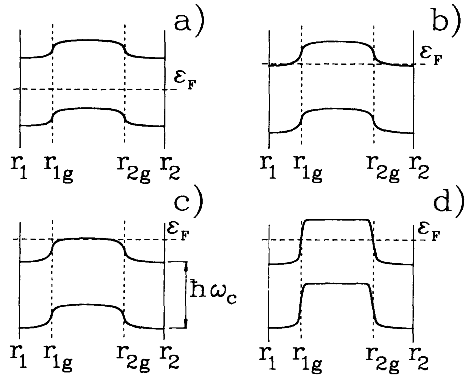

FIG. 11. Positions of Fermi energy with respect to quantum levels in the sample with inhomogeneous density.

tron layer follows from Eq. (1). Changing the ratio between capacitances C_1 and C_2 enables us to measure charges q_1 and q_2 separately. The difference $q_2 - q_1$ measured in such a way agrees satisfactorily with the charge Q_L.

V. ACCURACY OF σ_{xy} QUANTIZATION

As one can see from our measurements so far, the accurate experimental determination of the conductivity σ_{xy} is a more complicated problem than the measurement of resistivity ρ_{xy}. There are two main reasons for this. First, the capacitances C_1 and C_2 must be identical. Otherwise, the deviation from the straight line on a dependence $Q_T(H)$ arises because the charge leaving the 2D layer is added to the transferred one. Secondly, the accuracy of σ_{xy} determination is limited by the finite width of the Corbino disk, since the slopes on the dependence $Q_T(H)$ are proportional to the square of an effective radius which can differ from the geometrical one because of sample inhomogeneity. The sample with close internal and external radii is required for the precise measurement of σ_{xy}. The sample size usually does not exceed several millimeters and the minimal width of the ring must be large compared to the magnetic length. So the best accuracy can be estimated at 10^{-4} to 10^{-5}.

In starting from an integer filling factor in high magnetic field the measured value of the Hall conductivity coincides with $i_0 e^2/h$ within 2% accuracy. The value of σ_{xy} measured at a σ_{xx} minimum demonstrates very weak dependence on the filling factor with small deviations from $i_0 e^2/h$ at plateau edges, discussed below.

About 60 curves $Q_T(H)$ were recorded on the geometrically equivalent samples 2–5 to determine the slopes for filling factors $i = 1,2,3,4$ at different voltages on the gate. Forty curves measured on sample 3, analogous to those shown in Fig. 12, were used to determine the value of the stochastic error. The root-mean-square error in our experimental data for the conductivity σ_{xy} was found to be equal to 3%. To calculate the absolute value of the Hall conductivity the expression (2) with geometrical values of radii is used. The mean value of σ_{xy} on sample 3 reduced to the filling factor $i = 1$ was less than e^2/h by 7%. The same value was found for the other samples and in the case when the charge transfer was controlled by the guarding rings. It should be noted that the value of σ_{xy} determined from such experimental curves is referred to the edge of the plateau following Eq. (7).

Before discussing these results one needs to consider the opportunity to relate the slope of the experimental curve to a certain filling factor. According to Eq. (7), the expected change of filling factor in sweeping magnetic field is not great. The measurements of a charge leaving the 2D layer show that the real change of the filling factor is greater than the expected one: A change $\Delta i/i \approx 5\%$ is observed for $i \cong 2$ at the lowest temperature. Therefore the experimental points on the plateau presented in Refs. 8 and 9 should be shifted to the center. Nevertheless, the slope of the curve obtained when starting from a noninteger filling factor corresponds to σ_{xy} at the plateau edge.

Since the curves used to determine the mean value of σ_{xy} correspond to the plateau edges of the dependence σ_{xy} on H, one of the possible reasons for the observed discrepancy is that the plateau edges bend down by 4–7%. One can see such bending in Fig. 3(a) of Ref. 9. Another possibility is that the effective radius is 3.5% less than the mean one. The effective radius must be within the interval limited by geometrical dimensions, so in our case it can change by 10%. The effective radius will be less if the dissipative conductivity does not vanish in the external part of a sample for some reason. However, the last assumption contradicts the fact that the lower value of σ_{xy} was also obtained on sample 5 in which both guarding rings were active.

On two samples (2 and 5) we observed the nonzero signal $Q_T(H)$ at the fractional filling factor $i = \frac{2}{3}$. The largest value of a slope on the dependence $Q_T(H)$ corresponds to the conductivity $\sigma_{xy} h/e^2 = 0.63 \pm 0.03$. The quantized charge transfer could be observed when the fractional filling factor was realized either in the whole sample or in the guarding rings only.

VI. CONCLUSION

The experimental results discussed above prove that in the QHE regime charge can be transferred over the plane of a 2D electron gas through delocalized states of Landau levels below the Fermi level. To investigate the electron transport below the Fermi level in Corbino geometry two types of experiments can be used: (i) measurement of a charge transferred between contacts and (ii) that of a charge leaving a 2D electron layer. The first experiment can be easily realized. It is more convenient and does not impose the rigorous requirements on the residual value of diagonal conductivity. The maximal potential difference between contacts reached in this experiment is limited by the QHE breakdown caused by electron tunneling from a contact to a 2D layer.

In experiments with inhomogeneous electron density it has been found that the quantized charge transfer is determined by the regions adjoining contacts if between them there is a region with the dissipative conductivity.

In our opinion one of the problems for future experiments is to determine the minimal ring width at which the quantized value of Hall conductivity can be realized. Another problem is to increase the accuracy in measuring the Hall conductivity. It is necessary to fabricate samples with the same radius r_1, but with smaller width $\Delta r = r_2 - r_1$. Reasonable sizes $r_1 \approx 0.1$ cm and $\Delta r \approx 10^{-3}$ cm would ensure the accuracy in determining σ_{xy} not worse than 1%.

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[1]G. Ebert, K. von Klitzing, and G. Weimann, J. Phys. C **16**, 5441 (1983).
[2]E.K. Sichel, H.H. Sample, and J.P. Salerno, Phys. Rev. B **32**, 6975 (1985).
[3]H.Z. Zheng, D.C. Tsui, and A.M. Chang, Phys. Rev. B **32**, 5506 (1985).
[4]F.C. Zhang and T. Chakraborty, Phys. Rev. B **30**, 7320 (1984).
[5]M. Büttiker, Phys. Rev. B **38**, 9375 (1988).
[6]B.E. Kane, D.C. Tsui, and G. Weimann, Phys. Rev. Lett. **59**, 1353 (1987).
[7]R.J. Haug, J. Kucera, P. Streda, and K. von Klitzing, Phys. Rev. B **39**, 10 892 (1989).
[8]V.T. Dolgopolov, N.B. Zhitenev, and A.A. Shashkin, Pis'ma Zh. Eksp. Teor. Fiz. **52**, 826 (1990) [JETP Lett. **52**, 196 (1990)].
[9]V.T. Dolgopolov, N.B. Zhitenev, and A.A. Shashkin, Europhys. Lett. **14**, 255 (1991).
[10]R.B. Laughlin, Phys. Rev. B **23**, 5632 (1981).
[11]A. Widom and T.D. Clark, J. Phys. D **15**, L181 (1982).
[12]V.I. Nizhankovskii, V.G. Mokerov, B.K. Medvedev, and Yu.V. Shaldin, Zh. Eksp. Teor. Fiz. **90**, 1326 (1986).
[13]V.M. Pudalov, S.G. Semenchinskii, and V.S. Edel'man, Solid State Commun. **51**, 713 (1984).
[14]A.M. Dabiran, R.T. Zeller, F.F. Fang, S.L. Wright, and P.J. Stiles, Surf. Sci. **196**, 712 (1988).
[15]D.A. Syphers, K.P. Martin, and R.J. Higgins (unpublished).
[16]V. Mosser, D. Weiss, K. von Klitzing, K. Ploog, and G. Weimann, Solid State Commun. **58**, 5 (1986).
[17]M.G. Gavrilov and I.V. Kukushkin, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 79 (1986).
[18]A.A. Shashkin, V.T. Dolgopolov, and S.I. Dorozhkin, Zh. Eksp. Teor. Fiz. **91**, 1897 (1986).
[19]S.I. Dorozhkin, A.A. Shashkin, N.B. Zhitenev, and V.T. Dolgopolov, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 189 (1986).
[20]V.I. Dyakonov, Solid State Commun. **78**, 817 (1991).