Direct experimental proof of the existence of delocalized states below the Fermi level under conditions corresponding to the integer quantum Hall effect

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The Hall component of the conductivity, σ_{xy}, has been measured in samples in the Corbino geometry under conditions corresponding to the integer quantum Hall effect. The behavior of σ_{xy} as a function of the filling factor agrees with the picture in which the quantum Hall effect occurs as a result of extended states below the Fermi level.

Whether the current is a planar current or an edge current under the conditions corresponding to the quantum Hall effect remains an open question. All the existing theoretical models describing the quantum Hall effect can be put in one of two groups. In the first group, the quantization of the Hall resistivity ρ_{xy} is regarded as a planar effect of a 2D electron gas.[1] If there is an integer filling factor, the Fermi level is in a region of localized states, the dissipative component of the magnetoresistance tensor, ρ_{xx}, tends toward zero, and the Hall current is carried by delocalized states below the Fermi level. The existence of delocalized states near the middle of a quantum level has been demonstrated for the case of large-scale potential fluctuations.[2] In addition, a numerical simulation for the potential of point impurities[3] does not rule out such states. Finally, the scaling theory[4,5] indicates the existence of extended states below the Fermi level.

In the models of the second group, the quantum Hall effect is linked with the properties of edge currents which are flowing along the boundaries of the sample (Ref.

6, for example). In this case the presence or absence of delocalized states under the Fermi level in the plane of a 2D gas is unimportant. It is suggested in Ref. 6 that delocalized states exist only near the boundaries of a 2D electron layer.

A nonzero value of the Hall conductivity σ_{xy} could serve as evidence of the existence of delocalized states under the Fermi level under conditions corresponding to the quantum Hall effect, since this conductivity is the response of the system to an electric field in the plane of 2D electrons.[1] In order to measure the conductivity σ_{xy} it is necessary to eliminate a possible contribution of edge currents to the result of the measurements. Since such a contribution is not ruled out in samples of the Hall geometry, a calculation of the conductivity σ_{xy} from the magnetoresistance tensor may prove incorrect.

In the present experiments, we measured the Hall conductivity on samples of the Corbino geometry. These experiments are an implementation of gedanken experiments of Laughlin[7] and Widom and Clark.[8] The edge current in the Corbino geometry is necessarily an azimuthal current. If the sample is placed at the center of a solenoid which creates a magnetic field H directed normal to the surface, and if this magnetic field varies in time, the vortical electric field E will be directed azimuthally (Fig. 1a), and a contribution of edge currents to the radial Hall current will be ruled out. On the Hall plateau, where σ_{xx} is negligible, a charge is transferred from one bank of the sample to the other by means of a Hall current. A charge

$$\Delta Q(r) = -\frac{\sigma_{xy}}{c}\Delta\Phi(r) = -\frac{\sigma_{xy}}{c}(\pi r^2 \Delta H) \tag{1}$$

flows within a circle of radius r as the magnetic field is increased by an amount ΔH.

To detect the charge transfer, it is sufficient to connect an electrometer across the banks. Figure 1b shows the measurement arrangement; C_1 and C_2 correspond to the

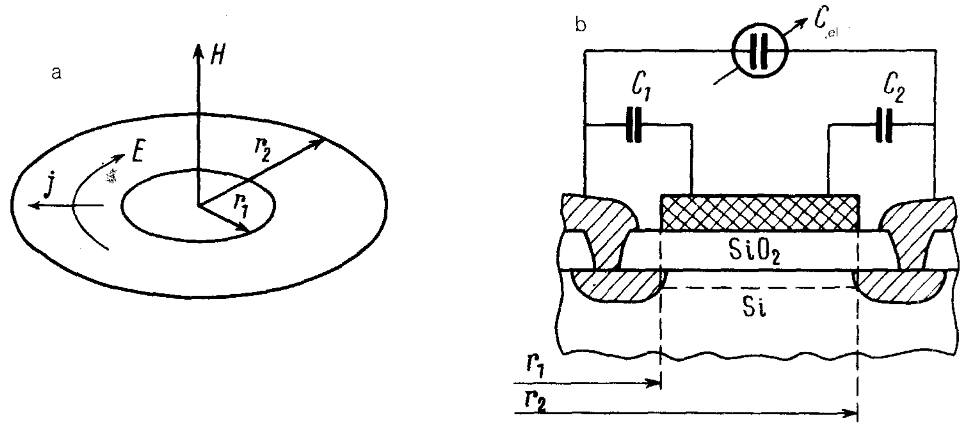

FIG. 1. a—Orientations of fields and currents during an increase in the magnetic field; b—cross section of the sample and equivalent circuit of the measurements.

parasitic capacitances between the banks and the gate, while C_{el} is the input capacitance of the electrometer. An elementary calculation shows that the potential difference which is measured is

$$\Delta V = \frac{\sigma_{xy}}{c}\pi \frac{C_2 r_1^2 + C_1 r_2^2}{C_1 C_2 + (C_1 + C_2)C_{el}} \Delta H, \qquad (2)$$

and the corresponding charge transfer is

$$\Delta Q = \frac{\sigma_{xy}}{c}\pi \frac{C_2 r_1^2 + C_1 r_2^2}{C_1 + C_2} \Delta H. \qquad (3)$$

Experiments were carried out on two silicon (100) metal-oxide-semiconductor structures at a temperature $\approx$25 mK. The samples had a maximum mobility $\mu \approx 2$ $m^2/(V\cdot s)$ at $T = 1.5$ K. The thickness of the silicon dioxide was 1300 Å; the dimension $2r_1$ was 225 μm; and the dimension $2r_2$ was 675 μm. Figure 2, a and b, shows some typical experimental curves. The following sequence of steps was carried out in the course of the measurements. First, a constant voltage source was connected between the gate and one bank of the MOS structure, and a 2D electron layer with a given concentration was produced. The gate was then disconnected from the voltage source, and the magnetic field was imposed at a constant rate. The time taken to reach a field $H \approx 14$ T was typically 40 min or more. The change in the electron concentration due to leakage currents during this field buildup was negligible: $\Delta N_s / N_s \approx 0.5\%$. Before each recording was begun, the magnetic field was established in such a way that σ_{xx} was close to its maximum, and the voltage on the gate was corrected.

It can be seen from Fig. 2a that at the minima of σ_{xx} we do indeed observe a charge transfer from bank to bank. The sign of the charge depends on the direction in which the magnetic field is scanned, i.e., on the sign of ΔH. We verified that ΔV decreases with increasing C_{el}, while ΔQ does not change, in agreement with Eqs. (2) and (3).

There are two circumstances which should be noted here. First, the shape of the $Q(H)$ curves does not depend on the rate at which the magnetic field is scanned. The only lower limit on the scanning rate was that imposed by the zero drift of the electrometer. Second, according to (3) the slope of the $\Delta Q / \Delta H$ curve is proportional to σ_{xy}, so the experiments show whether there is a plateau on the plot of the Hall conductivity versus the filling factor i. Figure 2b shows the results of measurements started at various values of the filling factor. The starting point was reached at a relatively high temperature (0.5–0.7 K), at which the conductivity σ_{xx} was large enough to reach an equilibrium in a short time ($\sim$10 min). The temperature was then lowered to $\approx$25 mK, and a curve of $Q(H)$ was recorded as H was increased. To record the part of the curve corresponding to a decreasing magnetic field, we put the sample back at its starting point at the high temperature. The slope was determined from the central part of the curve between the two extrema. Figure 3 shows the results of a conversion of the experimental curves on the basis of expression (3) for various filling factors. The values of the capacitances appearing in this expression were measured independently.

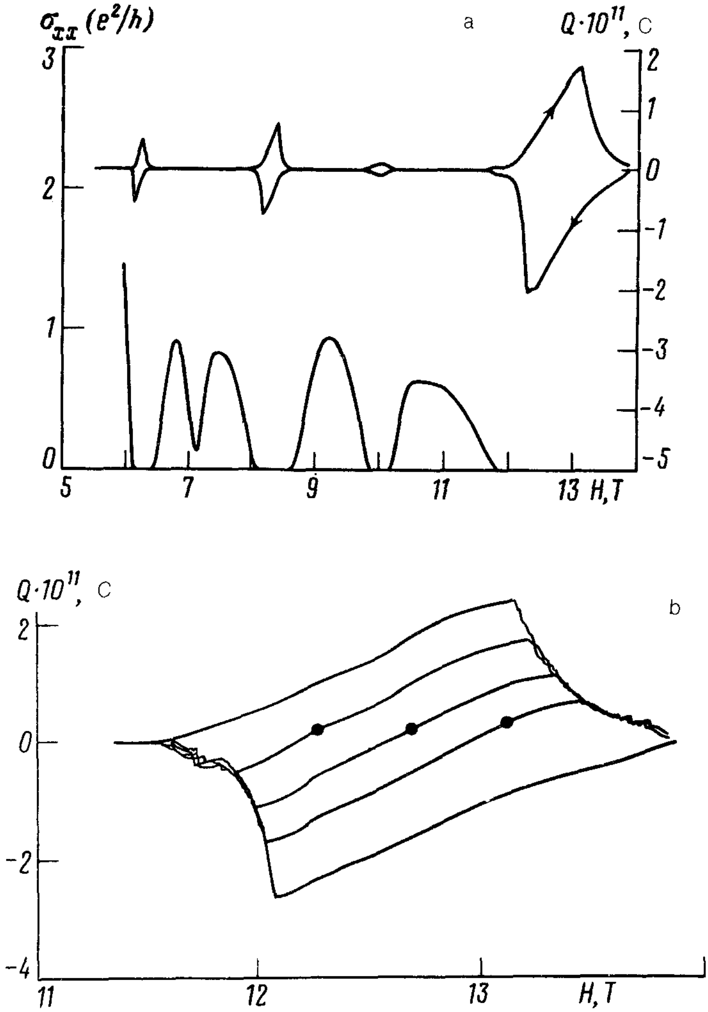

FIG. 2. a—The charge transfer (the upper curve) and σ_{xx} versus the magnetic field (the arrows show the direction in which the magnetic field is scanned); b—charge transfer versus the magnetic field for starting points corresponding to various filling factors.

The observed picture corresponds to the model in which the quantum Hall effect is realized by virtue of extended states below the Fermi level. Within the experimental error ($\pm 5\%$), the value of σ_{xy} near integer filling factors is equal to the number of quantum levels under the Fermi level, multiplied by e^2/h. At the filling factors $i \approx 2$ and 4, we can clearly see a plateau on the σ_{xy} curve.

In conclusion we note that several previous attempts have been made to measure the potential difference between the banks of a sample as the magnetic field was varied.[9-11] The potential difference observed in Refs. 9 and 10, however, arose because

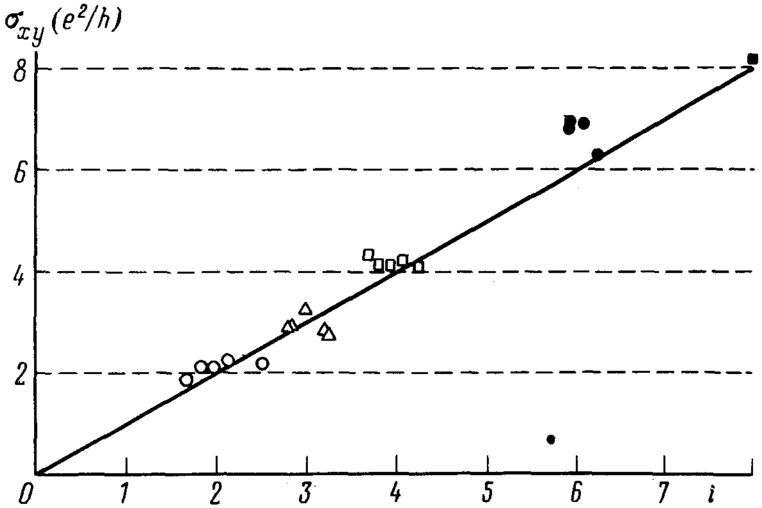

FIG. 3.

of a rectification of parasitic stray pickup.[10] The results of Ref. 11 can be interpreted as demonstrating the possibility of a charge transfer from bank to bank in an azimuthal electric field, but they do not allow any conclusions about the value of σ_{xy} or about the particular states (at or below the Fermi level) which are responsible for the charge transfer.

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