Fractional quantum Hall effect of a 2D electron system in a silicon MIS structure

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Quantum features have been found in the magnetotransport properties of the 2D electron gas in a silicon MIS structure at $H = 8$–11 T and $T = 1.7$ K. These features are found not only near integer values of the filling factor ν but also at fractional values: $\nu = 2/3, 4/3, 5/3, 7/3, 8/3, 6/5$, and $7/5$. These fractional features, which are caused by electron-electron interactions, suggest a possible ordering in the 2D electron system.

Research on the properties of a two-dimensional (2D) electron gas, which has been carried out most actively in recent years,[1] has resulted in the discovery of the quantum Hall effect.[2] This effect can be summarized by saying that a plot of the Hall resistivity ρ_{xy} vs the density (n) of the electron gas has clearly defined regions of constant values of $\rho_{xy} = h/e^2\nu$ (plateaus) in sufficiently strong magnetic fields, at low temperatures, and at electron densities corresponding to the complete filling of the particular quantum state involved (under the condition $n = \nu^{eH}/h$, where ν is the filling factor, an integer). The deviation of $\rho_{xy}(n)$ from a constant value in these regions may be only 10^{-6} of the value of xy itself, and it decreases with decreasing temperature. When ρ_{xy} remains constant during the filling of some level (i.e., at $\nu = 1, 2, 3, \ldots$), the resistance $R_x \sim \rho_{xx}$ simultaneously reaches a minimum, which tends toward zero with decreasing temperature. Corresponding experiments which have been carried out on silicon MIS structures and heterojunction structures, have revealed many common features, which imply that the effects being observed are quite general.[3]

Additional structural features on the $\rho_{xy}(H)$ and $\rho_{xx}(H)$ curves corresponding to fractional values of the filling factor were discovered comparatively recently in the electron space-charge layers at heterojunctions.[4,5] These features were attributed extremely tentatively to a Wigner crystallization of electrons. More recently, Laughlin[6] has suggested another explanation for the fractional quantum Hall effect, in terms of incompressible Fermi liquid.

This letter reports observation of the quantum Hall effect at fractional values of the filling factor in an electron inversion channel in a silicon MIS structure at $T = 1.7$ K and $H = 8$–11 T.

The MIS structure used in the experiments was fabricated on the (001) plane of p-type silicon. The electron mobility in the inversion channel at $T = 4.2$ K was very high in comparison with the mobilities which have been reported in the literature for silicon MIS structures, reaching 4×10^4 cm^2/(V·s) at a maximum at a gate voltage $V_g = 4$ V (Fig. 1). This circumstance, in our opinion, made it possible to clearly observe the anomalous quantum Hall effect in our experiments. The sample had a rectangular

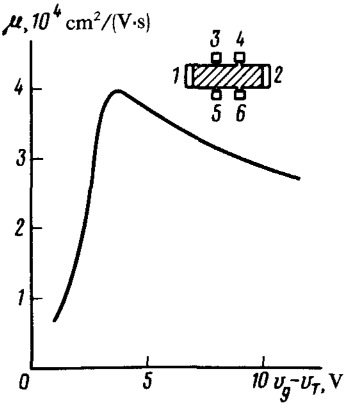

FIG. 1. Electron mobility in an inversion channel as a function of the clamping voltage V_g applied to the gate at $T = 4.2$ K. The inset shows the configuration of the contact on the silicon MIS structure. 3, 4, 5, 6—Contacts of the Hall bridges; 1, 2—drain and source, respectively; hatched region—gate; V_T—threshold voltage.

geometry with two pairs of contacts forming Hall bridges in the form of a square with a side of 400 μm. The measurement current could be varied from 10^{-9} to 10^{-7} A without any substantial changes in the $\rho_{xx}(V_g)$ and $\rho_{xy}(V_g)$ curves. The I-V characteristics remained ohmic over the entire dynamic range of the current. We also wish to emphasize that under these experiments the voltage V_g was varied so slowly that any hysteresis effects associated with relaxation processes, which would be seen during a rapid variation of V_g, were completely eliminated in our case.

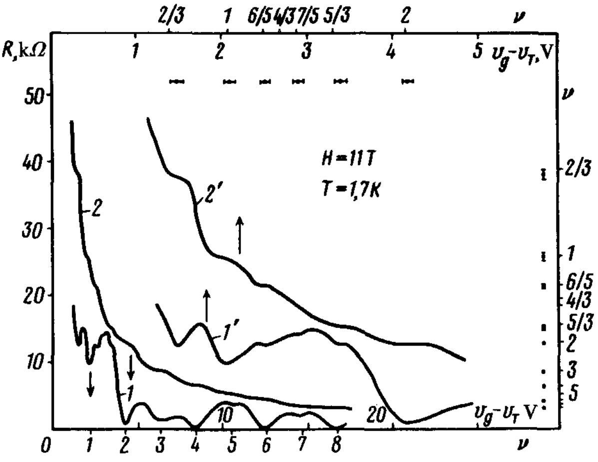

FIG. 2. The Hall resistivity ρ_{xy} (curves 2 and 2′) and the resistivity ρ_{xx} (curve 1 and 1′) vs the gate voltage V_g, reckoned from the threshold voltage V_T, at $T = 1.7$ K and $H = 8.8$ T. The abscissa scales at the bottom show the gate voltage V_g and the filling factor for curves 1 and 2; those at the top show the corresponding quantities for curves 1′ and 2′. The ordinate scale at the left is the resistance scale, and the corresponding filling-factor scale is shown at the right. The resistance scale has been doubled for curves 1 and 1′.

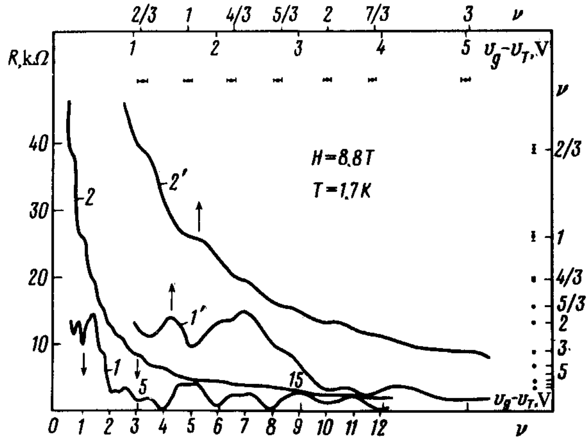

FIG. 3. Dependence of the Hall resistivity ρ_{xy} (curves 2 and 2′) and the resistivity ρ_{xx} (curves 1 and 1′) on the gate voltage V_g, reckoned from the threshold voltage V_T, for $T = 1.7$ K and $H = 11$ T. The gate voltage V_g and the filling factor for curves 1 and 2 are given by the scale at the bottom, while those for curves 1′ and 2′ are shown at the top. The ordinate scale at the left shows the resistance, and the corresponding filling factor is shown at the right. The resistance scale has been doubled for curves 1 and 1′.

Figures 2 and 3 show curves of the resistivities ρ_{xx} and ρ_{xy} vs the gate voltage (reckoned from the threshold voltage V_T) recorded at $T = 1.7$ K and $H = 8.8$ T or $H = 11$ T. The gate voltage determines the density of 2D electrons: $n = (\epsilon_0 \epsilon / de)(V_g - V_T)$, where $\epsilon = 3.9$ and $d = 1660$ Å are the dielectric function and thickness of the insulator. In addition to the clearly defined plateaus on the $\rho_{xy}(n)$ curves and the minima on the $\rho_{xy}(n)$ curves, which appear at integer values of the filling factor ν (they are particularly obvious when ν is a multiple of 4, in which case the given Landau level is completely filled), we see some other structural features: minima of ρ_{xx} and inflection points of ρ_{xy}. We emphasize that the structural features appear simultaneously on the ρ_{xx} and ρ_{xy} curves.

There are three independent methods for determining the filling factor at these structural features. First, one can find ν from the value of ρ_{xy} at the feature: $\nu = h / e^2 \rho_{xy}$. In addition, it can be found from the positions of the structural features on the $\rho_{xx}(n)$ and $\rho_{xy}(n)$ curve when plotted against V_g: $\nu = nh/eH = (\epsilon_0 \epsilon / de^2 H)(V_g - V_T)$. The scatter in the values of the filling factor found by these three independent methods was small in all cases, and it determined the error in ν (Figs. 2 and 3).

Because of the pronounced localization effects at $T = 1.7$ K, we were able to reliably measure ρ_{xx} and ρ_{xy} at $(V_g - V_T) \geqslant 0.9$ V or $n \geqslant 1.2 \times 10^{11}$ cm^{-2}, so that we could not study the region $\nu \leqslant 0.5$ at $T = 1.7$ K and $H = 8$–11 T. In the region $\nu > 0.5$ at $T = 1.7$ K and $H = 8$–11 T we found seven fractional values of ν with odd denominators: 2/3, 4/3, 5/3, 7/3, 8/3, 6/5, and 7/5. The last four of these fractions are being observed here for the first time. The apparent reason why we are observing new fractions for ν with large numerators (the fraction 8/3 was observed at $H = 8$ T) is that in fields $H = 8$–11 T the structural features on ρ_{xy} and ρ_{xx}, which correspond to these fractions, arise in the region of clamping gate voltages, $V_g = 3$–5 V, where the maximum of the electron mobility is observed. The observation of fractions in the region in $\nu > 2$ is evidence that the fractional quantum Hall effect can be observed without a spin orientation of the electrons, and the electrons do not have to belong to a common valley.

These structural features on the $\rho_{xy}(n)$ and $\rho_{xx}(n)$ curves are undoubtedly caused by an electron-electron interaction. We wish to emphasize that the nature of the interaction of electrons at heterojunctions may differ from that in MIS structures. In an MIS structure, where the 2D electron gas is distinguished by its long-range Coulomb nature, it is not obvious that the Laughlin theory[6] applies. We are thus led to inquire just which collective state of the system of 2D electrons corresponds to the observed anomalous features in the quantum Hall effect in the MIS structures. We do not rule out the possibility that these anomalous features are a consequence of the ordering of the electron density in this 2D electron system.

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After this paper had been written, Pudalov and Semenchinskiĭ[7] published a report of an observation of structural features on the $\rho_{xy}(n)$ curve of a silicon MIS structure at filling factors $\nu = 2/3$ and $4/3$.

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