Properties of a 2D hole gas at a silicon surface in ultrastrong magnetic fields

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The properties of a 2D hole gas at a silicon surface have been studied in magnetic fields up to 21 T for the first time. A quantization of the Hall resistance of the 2D holes was achieved. This quantization was found to be independent of the filling factor of the light-hole subband. The Shubnikov oscillations are classified correctly.

Research on two-dimensional (2D) electron systems in strong magnetic fields is one of the most interesting topics in the physics of condensed media, particularly since the discovery of the quantum Hall effect.[1] The overwhelming majority of the studies in this direction have been devoted to the properties of the 2D electrons; there has been much less study of hole systems in strong magnetic fields. In particular, the literature on this topic consists of only a few papers,[2–4] which report measurements of the Shubnikov–de Haas oscillations in magnetic fields up to 10–15 T. New motivation for research in this direction comes from the discovery of the quantum Hall resistance. The study of this resistance in a 2D hole gas is clearly of interest, as has been demonstrated by a recent study[5] of the behavior of 2D holes at a GaAs-AlGaAs heterojunction in magnetic fields up to 20 T.

In this letter we report the first study of the properties of a 2D hole gas at a silicon surface in magnetic fields up to 21 T. We have found a quantization of the Hall resistance of this system, and we conclude that the quantization is independent of the filling factor of the light-hole subband within the accuracy of these experiments.

The test samples are p-channel MOS transistors fabricated on silicon substrates with a (110) surface, which leads to the highest mobility of the holes in the inversion channel. Specifically, this mobility was ~ 2500 cm^2/(V·s) in these samples.

Figure 1 shows the results of the measurements of the diagonal (ρ_{xx}) and Hall (ρ_{xy}) components of the resistivity tensor as a function of the gate voltage V_g. We clearly see that at values of V_g corresponding to the minimum values of ρ_{xx} there is a plateau on the $\rho_{xy}(V_g)$ curve, which is evidence of a quantization of the Hall resistance of the system. The values of ρ_{xy} at these plateaus are h/ie^2, where $i = 1,2,3,4,5,7,9$. The maximum quantization accuracy corresponds to the plateaus with $i = 2$ and 3, for which, at a deviation of 0.25 V from the center of the plateau, we have $\Delta\rho_{xy}/\rho_{xy} \leqslant 2 \times 10^{-3}$ (we cannot offer a more accurate estimate, since we did not carry out precise measurements of ρ_{xy} in these experiments). We might note that, in contrast with a 2D electron gas, this system clearly exhibits a plateau corresponding to the value $i = 1$, although the hole mobility is considerably lower (by a factor of more than

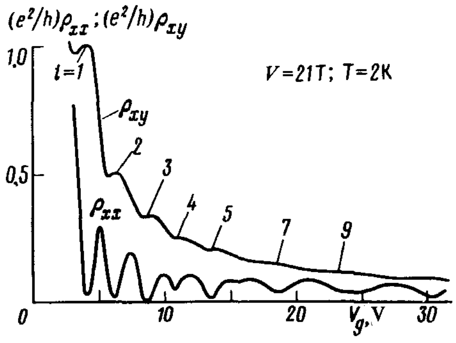

FIG. 1. The resistivity components ρ_{xx} and ρ_{xy} vs the gate voltage.

five) than the electron mobility. The probable explanation is the absence of a valley degeneracy in the 2D hole gas.

Analysis of the $\rho_{xx}(V_g)$ curve in the same figure shows that the Shubnikov–de Haas oscillations corresponding to the crossing of the Fermi level between the spin-split-off states of two different Landau levels (corresponding to even values of i) begin to progressively disappear, and at $V_g > 20$ V we are left with the oscillations due exclusively to the spin splitting of the Landau levels. It follows that the g-factor of the 2D holes at the silicon (110) surface has a value such that the spin splitting is larger than $\hbar\omega_c/2$; i.e., we have $(m^*/m_0)g > 1$, in contrast with the case of 2D electrons, for which we have $(m^*/m_0)g < 1/2$. We should point out that we were able to establish this fact thanks to the simultaneous measurements of the diagonal and Hall components of the resistivity, since the value of ρ_{xy} in the plateau gives us a value of i, which tells us the index of the Landau level and the corresponding spin sublevel.

In this system, the second quantum subband, due to the size quantization of light holes, begins to be filled at a hole concentration $\Gamma_p \approx 2.5 \times 10^{12}$ cm^{-2}. Measurements of the concentration of light holes show that at $\Gamma_p \geqslant 3.8 \times 10^{12}$ cm^{-2} these holes constitute at least 9% of the total concentration of holes. It is interesting in this connection to examine the behavior of the quantum Hall effect when there is a significant filling of the light-hole subband, i.e., at $\Gamma_p \geqslant 3.8 \times 10^{12}$ cm^{-2} or $V_g \geqslant 20$ V. In this region we observe a plateau with $i = 9$; the value of ρ_{xy} near this plateau is $h/9e^2$, and we have $\Delta\rho_{xy}/\rho_{xy} \leqslant 10^{-2}$. These results mean that, within the accuracy of these experiments, we are observing the ordinary quantization of the Hall resistance of heavy holes forming the first quantum subband. Light holes, in contrast, make no contribution. It would be simple to explain this result if the Fermi level were at the tail of the state density of the light-hole Landau level at the time the plateau forms, but experiment reveals the opposite to be the case. The situation can be seen particularly clearly by analyzing the curves of ρ_{xx} and ρ_{xy} vs magnetic field in Fig. 2. The high-frequency oscillations here correspond to heavy holes, while the envelope is an oscillation of the light-hole conductivity. The plateau corresponding to the filling of the $i = 9$ level lies precisely below a minimum of the high-frequency oscillation and a maximum of its envelope due to the light holes. This result means that the Fermi level is at a maximum of the density of states associated with the light-hole Landau level, and it passes

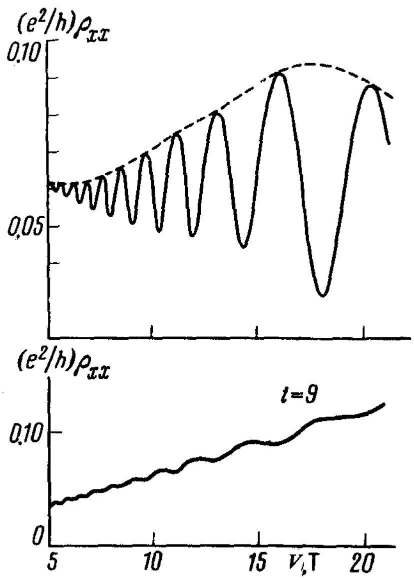

FIG. 2. ρ_{xx} and ρ_{xy} vs the magnetic field at $V_g = 20$ V. The dashed curve is the envelope due to the oscillation of the light-hole conductivity.

through a region of delocalized states at the time during which the plateau exists. It follows that the contribution of light holes to ρ_{xy} would have to be at least 9% in accordance with the number of these holes in the subband. As we mentioned above, however, this is not what we find experimentally. Accordingly, even if the Fermi level does lie in a region of delocalized light-hole states, as it appears at first glance, these holes do not make the expected contribution to the Hall resistance of the 2D hole gas. Further experimental and theoretical research is required to determine the reason for this behavior of ρ_{xy}. We note in conclusion that in these experiments we did not observe the effects reported in Ref. 5, which were interpreted there as a manifestation of a lifting of the Kramers degeneracy of 2D holes.

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