Ultraquantum limit of the Hall conductivity of a two-dimensional electron gas on a silicon surface

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Transport in a two-dimensional electron gas has been studied experimentally in the inversion channels of silicon metal-dielectric-semiconductor structures at temperatures 2–4.2 K in the ultraquantum limit in terms of the magnetic field. The results agree qualitatively with the interpretation that electrons localize at the lowest Landau level.

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Further study of the quantum Hall effect[1] is warranted by the possibility of developing it into an independent method for measuring the fine-structure constant α and also because the effect has yet to be completely explained theoretically.

This letter reports experiments on the conductivity and Hall conductivity of the two-dimensional electron gas in an inversion channel in a silicon metal-dielectric-semiconductor structure at temperatures 2–4.2 K in magnetic fields up to 21 T.

The samples were fabricated on the (100) plane of p-Si and had a rectangular geometry with two symmetric pairs of Hall contacts.

Depending on the particular technological conditions, the maximum electron mobility in the channel, μ_{max}, ranged from 4000 $cm^2/(V\ s)$ (sample C-2) to 18 000 $cm^2/(V\ s)$ (sample B-1) at the experimental temperatures. The measurement procedure was the same as in Ref. 2; the measurement current was 2 μA.

Figure 1 shows the resistivity ρ_{xx} and the Hall resistivity ρ_{xy} vs the gate voltage U_g, which determines the electron density in the two-dimensional channel. We see

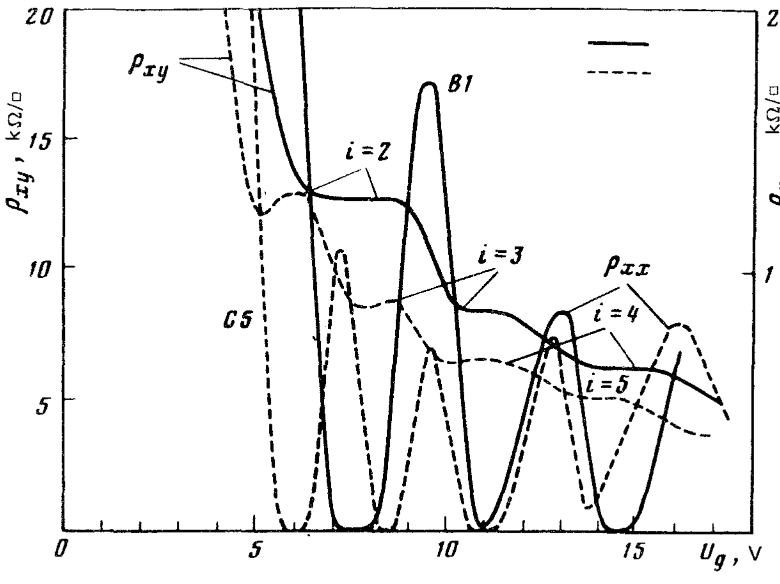

FIG. 1. Curves of $\rho_{xx}(U_g)$ and $\rho_{xy}(U_g)$ for two samples with different mobilities at $T = 2$ K and $B = 20$ T.

that the results are typical of the two-dimensional electron gas under conditions corresponding to the quantum Hall effect.[1] At those voltages U_g where ρ_{xx} vanishes, the $\rho_{xy}(U_g)$ curve has a plateau, on which ρ_{xy} is independent of the properties of the sample and agrees well with the value h/e^2.

The relative error for the data in Fig. 1 was determined by the measurement apparatus (by the N306 x, y chart recorder); it is 10^{-3}.

As a rule, the $\rho_{xy}(U_g)$ plateau becomes wider as the electron mobility in the two-dimensional channel increases, as can be seen from Fig. 1, for example. This result is apparently at odds with the model[3] of a "surface reservoir." How the characteristics of sample affect the plateau width requires a more detailed study.

The lower-mobility samples exhibit a distinctive feature at the low-density edge of the plateau: a nonmonotonic behavior of ρ_{xy} (see the dashed curve in Fig. 1, corresponding to sample C-5). This behavior has been observed previously[4,5]; the reason for it requires explanation, since it may affect the absolute value of the Hall resistivity on the plateau. The nonmonotonic behavior becomes more pronounced as the temperature is lowered.

When the magnetic field is so strong that the lowest Landau level is filled only partially (at the given density n), the two-dimensional electron gas is in the so-called ultraquantum limit. The only previous study of the Hall effect and of the conductivity in the ultraquantum limit,[6] carried out with an $Al_xGa_{1-x}As/GaAs$ heterojunction, immediately attracted interest, since it revealed features of the Hall resistivity corresponding to fractional quantum numbers, $i = 1/3$ and $i = 2/3$. This fact was interpret-

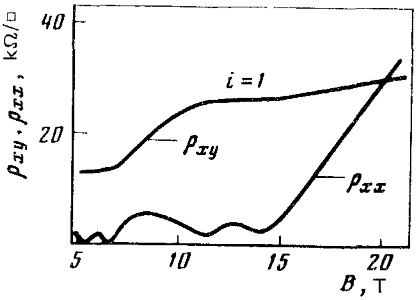

FIG. 2. The ultraquantum limit of $\rho_{xx}(B)$ and $\rho_{xy}(B)$.

ed as a manifestation of an ordering of electrons in the lowest Landau level (a Wigner crystal or a space-charge wave).

In order to attain the ultraquantum limit in our experiments ($B_{max} = 21$ T), we had to make the electron mobility in the inversion channel quite high at a low gate voltage U_g. To achieve low values of U_g in turn required that the carrier density in the channel be lower than eB/h, which is the number of states at the Landau level. In other words, the filling factor of the Landau level must be $\nu = nh/eB \ll 1$. At 10 T and $\nu = 1$, for example, we would have $n = 2.42 \times 10^{11}$ cm^{-2}. These conditions were met only in sample B-1, which had the properties $\mu = 11\,000$ cm^2/(V s) at $U_g = 2.5$ V, corresponding to $n = 2.81 \times 10^{11}$ cm^{-2}.

Figure 2 shows the experimental results on ρ_{xx} and ρ_{xy} vs the magnetic field B for sample B-1 at 2 K with $n = 2.8 \times 10^{11}$ cm^{-2} ($U_g = 1.98$ V). At the ρ_{xx} minima corresponding to $i = 1$ and 2 we see an additional structure, whose origin we will not discuss here. Figure 3 shows σ_{xx} and σ_{xy} vs $1/B$, according to the data in Fig. 2. We see that an extrapolation of the Hall conductivity to the value $\sigma_{xy} = 0$ (the dashed line) yields an intersection at the field $B_l = 27$ T ($\nu_l = 0.43$). This vanishing of σ_{xy} at a finite value of B_l contradicts the classical behavior of the Hall conductivity, but it is consistent with the concept of a localization of electrons at a Landau level.[7]

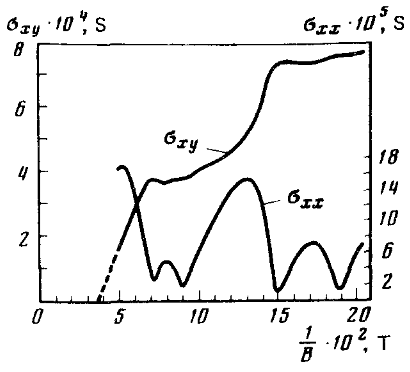

FIG. 3. The ultraquantum limit of $\sigma_{xx}(1/B)$ and $\sigma_{xy}(1/B)$ (the siemens, S, is the same as the reciprocal ohm).

The filling factors in the case of complete localization—both that found through our extrapolation ($\nu_l = 0.43$) and that calculated in Ref. 8 ($\nu_l \cong 0.5$)—seems to us to be a bit too high, since they correspond to the assumption that states near the middle of the Landau level ($\nu = 0.5$) are localized. Furthermore, we cannot rule out the possibility of a smoother behavior $\sigma_{xy}(1/B)$, which would require a definite and sufficiently strong interelectron interaction in the ultraquantum limit. The Si/SiO_2 interface, however, has a far greater degree of disorder than the interface in the $Al_xGa_{1-x}As/GaAs$ heterojunction. It may be that it is the potential fluctuations at the Si/SiO_2 interface which reduce the effect of the Coulomb interaction of the electrons and prevent the formation of a collective state in the two-dimensional electron system. This circumstance is apparently one reason for the difference between our results and those of Ref. 6.

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