A Hall insulator: experimental evidence

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A metal-insulator transition in two-dimensional electron systems of GaAs/AlGaAs heterojunctions has been investigated experimentally in the extreme quantum limit. The Hall resistance R_{xy} of an insulating phase was found to be close to the classical value $R^0_{xy}=H/n,ec$, while the magnetoresistance R_{xx} was found to approach infinity with decreasing temperature. Such behavior supports recent theory about the Hall insulating state.

In quantizing a magnetic field there exists a number of different states of 2D electron systems: compressible and incompressible quantum liquids, Wigner and Hall crystals (for details see Ref. 1). Some of these states can be distinguished by the behavior of the magnetoresistance tensor components upon lowering the temperature. Quantum liquid in real disordered 2D systems was thought to exhibit either the integer or fractional quantum Hall effect or to be the Anderson insulator. In the first case, as $T\to 0$, the magnetoresistance $R_{xx}\to 0$ and $R_{xy}=h/ie^2$, where i is an integer or a fraction with an odd denominator. In the second case delocalized states below the Fermi level are absent; therefore, the resistances R_{xx} and R_{xy} tend to infinity when the temperature vanishes. The same behavior is expected to be observed when the Wigner crystal is pinned by disorder.[1] In a disordered electron system the Hall crystal is considered to be destroyed.

A new insulating state (the Hall insulator) has recently been predicted theoretically.[1–3] In this state the resistance R_{xx} increases to infinity upon lowering the temperature, while R_{xy} remains finite and close to the classical value $R^0_{xy}=H/n,ec$, where H is a magnetic field and n_s is an areal density of electrons. It seems that an insulating state observed in high-quality GaAs/AlGaAs heterojunctions in the extreme quantum limit with filling factors $\nu=eH/hc<0.23$–0.28 (see Ref. 4 and the references cited there) is the Hall insulator. To the best of our knowledge, such evidence was obtained[1] only in Ref. 5, in which the fractional quantum Hall effect with a filling factor $\nu=1/7$ was studied. Unfortunately, detailed results on the Hall resistance behavior in the insulating state were not reported. In this paper we present the results of an experimental study of the temperature dependence of R_{xx} and R_{xy} in the extreme quantum limit. The resistances demonstrate quite different behavior in the insulating state: With a decrease in the temperature, R_{xx} tends to infinity, while $R_{xy}\approx R^0_{xy}$. This is exactly what we should expect for the Hall insulator.

We carried out measurements using two samples of the Hall bar geometry (see the inset in Fig. 1a) which were made from the same wafer of a modulation-doped GaAs/AlGaAs heterojunction and which had a front Schottky gate. Such a structure

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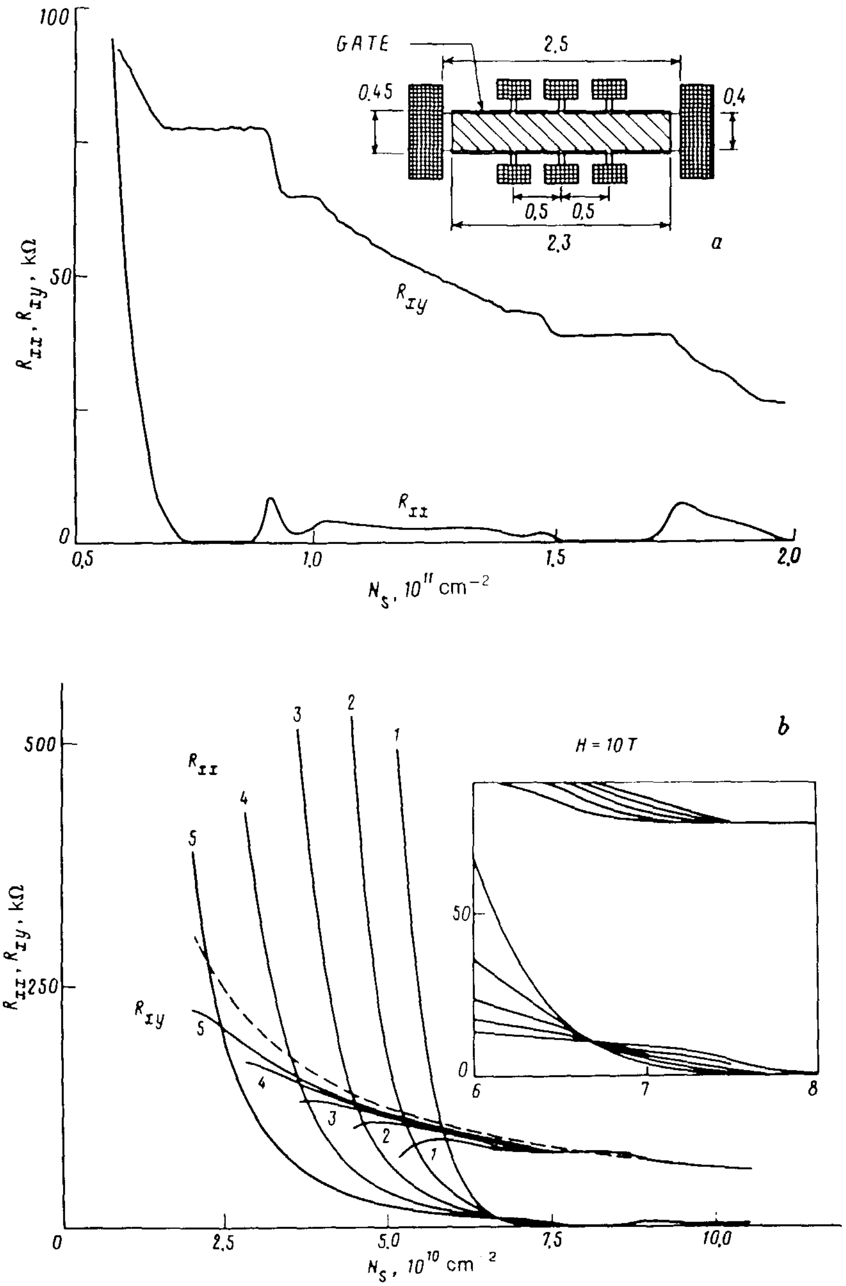

FIG. 1. *a*—Experimental dependences of the magnetoresistance R_{xx} and the Hall resistance R_{xy} on the carrier density controlled by the gate voltage. Magnetic field $H=10$ T, temperature $T=68$ mK. Inset: sketch of a sample: *b*—R_{xx} and R_{xy} versus n_s at different temperatures: *1*—$T=60$ mK, *2*—$T=114$ mK, *3*—$T=195$ mK, *4*—$T=295$ mK, *5*—$T=472$ mK. $H=10$ T. Dotted line represents the calculated dependence $R^0_{xy}=H/n_sec$. Inset—The same curves on an enlarged scale.

enabled us to change the carrier density which was found to be proportional to the gate voltage. The carrier density at zero gate voltage was $n_s = 1.3 \times 10^{11}$ cm^{-2} and the mobility was $\mu = 1.2 \times 10^6$ cm^2/(V · s). The electrical measurements were carried out by the standard lock-in technique at a frequency of 10 Hz. We verified that in our measurements the 90° signal was always much lower than the in-phase signal. The exciting current was less than 1 nA. At this value we did not observe any non-ohmic effects. The samples were placed in the mixing chamber of a dilution refrigerator, which allowed us to obtain temperatures between 1.5 K and 30 mK and to measure them with an accuracy of about ± 2 mK.

Typical experimental results are shown in Fig. 1. Pronounced fractional quantum Hall states were observed for filling factors $\nu = 2/3$, 3/5, 2/5, and 1/3 (Fig. 1a). A set of experimental curves R_{xx} (Fig. 1b), measured at different temperatures, definitely demonstrates a crossover at a carrier concentration $n_s \simeq 6.7 \times 10^{10}$ cm^{-2}, which corresponds to a metal–insulator transition. In our samples this transition occurs at a filling factor $\nu \cong 0.28$ in a wide range of magnetic fields.[6]

At $\nu < 0.28$ the resistance R_{xx} goes to infinity as the temperature tends to zero. At the same time, the Hall resistance R_{xy} does not exhibit any peculiarities at the transition point and approximately follows the classical dependence. Deviations of R_{xy} from the latter at low electron densities may be related to the fact that under the condition $R_{xx} \gg R_{xy}$ the voltage drop between the Hall probes is determined by a mixture of the diagonal and off-diagonal magnetoresistance components. Our results therefore indicate that the Hall resistance of the insulating state at $\nu < 0.28$ is temperature independent and roughly coincides with the value characteristic of the metallic state.

Temperature dependences of R_{xx} and R_{xy} are shown in Fig. 2. We should note that the magnetoresistance increases exponentially with decreasing temperature: $R_{xx} \simeq \exp(T_0/T)^p$, where $p \cong 1/2$.

It should be noted that in Si MOSFET's in the extreme quantum limit ($\nu < 1$) the metal–insulator transition occurs in a different manner:[7] In the insulating state the two components, R_{xx} and R_{xy}, of the magnetoresistance tensor tend to infinity with decreasing temperature. However, in the case of the transition at $\nu > 1$, they behave as well as in GaAs/AlGaAs heterojunctions.[8]

Predictions of the Hall insulating state are based on two different approaches which are applicable at zero temperature. They are the mean field theory[1] and the Kubo formalism.[2,3] Giving similar predictions for the Hall resistance, their results for R_{xx} would be considerably different. In the approximation used in Refs. 2 and 3 the diagonal conductivity at small frequencies is mainly due to the polarization currents which are nondissipative. As a result, the imaginary part of R_{xx} is considerably greater than its real part. This should cause the 90° signal to dominate over the in-phase signal detected by the lock-in amplifier. This was not the case in our experiment, where the temperature-dependent dissipative conductance prevailed in the measured R_{xx}. This implies that our experimental conditions are outside the range of validity of the models[2,3] which ignore all of the temperature-dependent mechanisms of the dissipative conductivity.

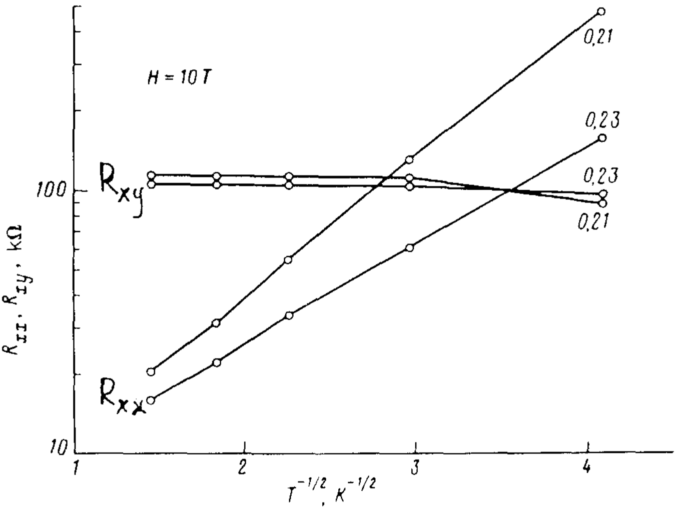

FIG. 2. Temperature dependences of R_{xx} and R_{xy} measured in a magnetic field $H=10$ T, with filling factors $\nu=0.21$ and $\nu=0.23$ (as specified at the curves).

The nature of the insulating state at small filling factors in GaAs/AlGaAs heterojunctions has not been unambiguously established yet. Two alternatives are usually considered. The first one is a transition to the Wigner crystal state and the other is the Anderson localization of electrons due to disorder. The authors[1] suggested that since the Hall resistance R_{xy} of the pinned Wigner crystal is infinitely large, measurements of its value could help to distinguish between the Hall insulator, which is the result of localization, and the Wigner crystal states. It seems, however, that the Wigner crystal might also demonstrate behavior characteristic of the Hall insulating state, where $R_{xy}\cong H/n_sec$. We see at least two possibilities for it. The first one is the sliding with a friction of the Wigner crystal as a whole through the sample. In this case we can use the following arguments to estimate R_{xx} and R_{xy}. The transport current density is $j_x=n_seV_d$, where V_d is a drift velocity. Since the Lorentz force eHV_d/c is cancelled by the Hall electric field, E_y, it follows from these relations that $R_{xy}=H/n_sec$, regardless of V_d. The component R_{xx} tends to infinity with increasing friction, i.e., with decreasing drift velocity. The same result for R_{xx} and R_{xy} is expected for the Wigner polycrystal state (see, e.g., Ref. 9), where large regions of the ideal Wigner crystal with $R_{xx}=0$ and $R_{xy}\cong H/n_sec$ are surrounded by thin shells with large resistivity (for example, regions of pinned crystal).

As to the measured temperature dependence $R_{xx}\simeq\exp(T_0/T)^{1/2}$, we should mention that in a number of papers[10] the authors reported an activated behavior: $R_{xx}\simeq\exp(E/kT)$; however, recently a weaker dependence has been observed.[11] In principle, the dependence $R_{xx}\simeq\exp(T_0/T)^{1/2}$ may be related to the variable-range hopping in strong magnetic fields.

In conclusion, experimental temperature dependences of the components of the magnetoresistivity tensor extrapolated to zero temperature support recent predictions for the Hall insulating state whose finite Hall resistance is close to the classical value. We argue that the Wigner crystal might also demonstrate a similar behavior.

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