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A HALL INSULATOR: EXPERIMENTAL EVIDENCES

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We have experimentally investigated a metal-insulator transition in two-dimensional electron systems of GaAs/AlGaAs heterojunctions in the extreme quantum limit. It has been observed that the Hall resistance R_{xy} of an insulating phase is close to the classical value $R^0_{xy} = H/n_s ec$ while the magnetoresistance R_{xx} tends to infinity with decreasing temperature. Such behavior supports recent ideas of the Hall insulating state.

In quantizing 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 behavior of the magnetoresistance tensor components when lowering temperature. Quantum liquid in real disordered $2D$ systems was thought either to exhibit the integer or fractional quantum Hall effect or to be the Anderson insulator. In the first case at $T \to 0$ the magnetoresistance $R_{xx} \to 0$ and $R_{xy} = h/ie^2$, where i is integer or 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 temperature vanishes. The same behavior is expected to take place for the Wigner crystal pinned by disorder [1]. In a disordered electron system the Hall crystal is considered to be destroyed.

Recently a new insulating state (Hall insulator) has been predicted theoretically [1-3]. In this state when lowering temperature the resistance R_{xx} grows to infinity while R_{xy} remains finite and close to the classical value $R^0_{xy} = H/n_s ec$, where H is a magnetic field and n_s is an areal density of electrons. It looks as if an insulating state observed in high-quality GaAs/AlGaAs heterojunctions in the extreme quantum limit at filling factors $\nu = eH/hc < 0,23 \div 0,28$ (see Ref. [4] and Refs. therein) were the Hall insulator. To the best of our knowledge, such an indication was available [1] only in paper [5] which concerned the fractional quantum Hall effect at filling factor $\nu = 1/7$. Unfortunately detailed results on the Hall resistance behavior in the insulating state were not reported. In this paper we present results on the temperature dependence of R_{xx} and R_{xy} in the extreme quantum limit. The resistances demonstrate quite different behavior in an insulating state: When decreasing 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 made measurements on two samples of the Hall bar geometry (see inset in Fig.1 *a)* produced from the same wafer of a modulation doped GaAs/AlGaAs heterojunction and provided with a front Schottky gate. Such a structure enabled us to change a carrier density which was checked to be proportional to a gate

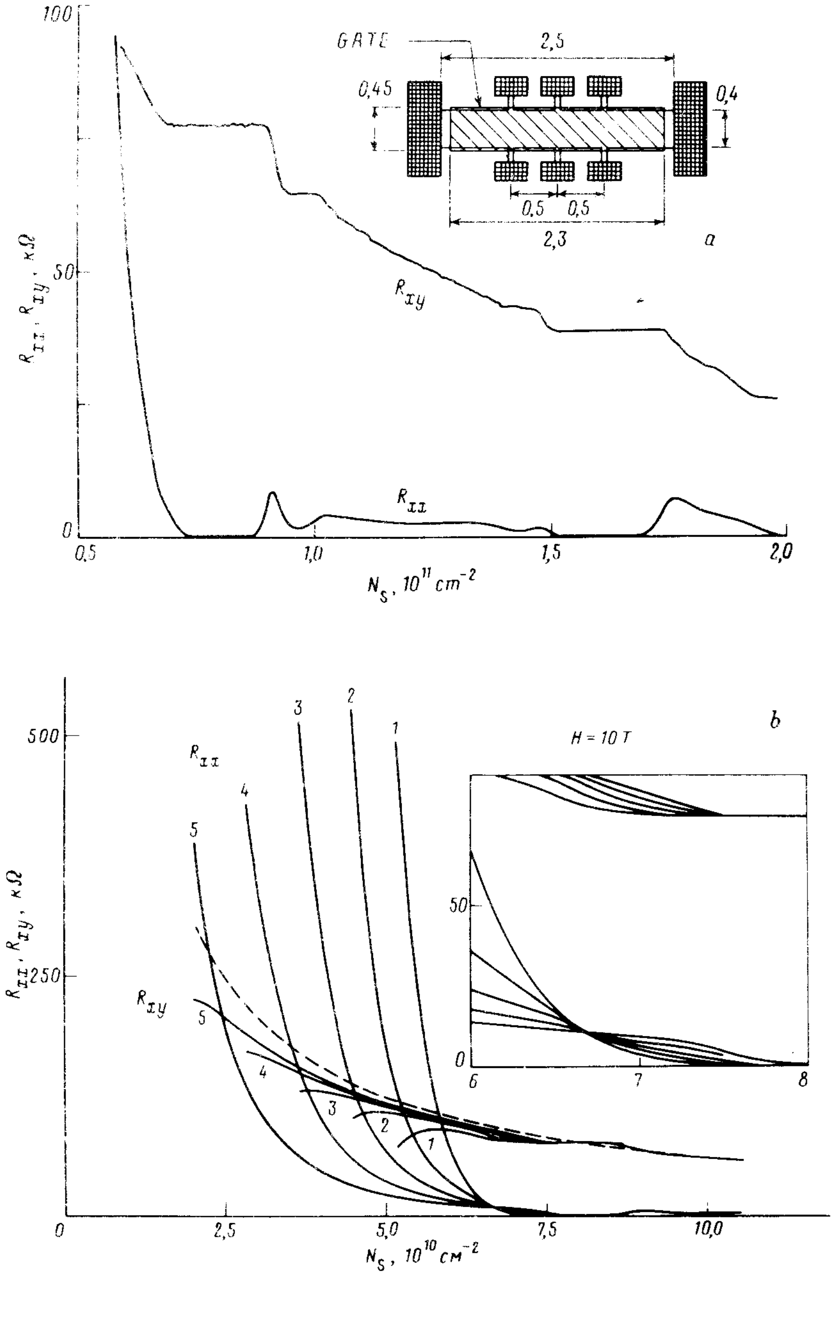

Fig.1. a - Experimental dependences of the magnetoresistance R_{xx} and the Hall resistance R_{xy} on the carrier density controlled by a gate voltage. Magnetic field $H = 10$ T, temperature $T = 68$ mK. Inset: sketch of a sample; b - R_{xx} and R_{xy} versus n_s at different temperatures: *1* - $T = 60$ 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 $R^0_{xy} = H/n_s ec$. Inset: the same curves on an enlarged scale.

voltage. The carrier density at zero gate voltage was $n_s = 1,3 \times 10^{11}$ cm^{-2} and a mobility was $\mu = 1,2 \times 10^6$ cm^2/Vs. Electrical measurements, reported here, were performed by the usual lock-in technique at a frequency of 10 Hz. We checked that in our measurements the 90° signal was always much less than the in-phase one. The exciting current was less than 1 nA, the value at which 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 from 1,5 K down to 30 mK and measure them with accuracy of the order of ± 2 mK.

Typical experimental results are shown in Fig.1. Well pronounced fractional quantum Hall states were observed for filling factors $\nu = 2/3$, $3/5$, $2/5$, and $1/3$ (Fig.1*a*). A set of experimental curves R_{xx} (Fig.1*b*), measured at different temperatures, definitely demonstrates a crossover at carrier concentration $n_s \cong 6.7 \times 10^{10}$ cm^{-2} which corresponds to a metal-insulator transition. In our samples this transition occurs at filling factor $\nu \cong 0,28$ in the wide range of magnetic fields [6]. At $\nu < 0,28$ the resistance R_{xx} goes to infinity when temperature tends to zero. At the same time the Hall resistance R_{xy} does not show any peculiarity 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 Hall probes is determined by a mixture of the diagonal and off-diagonal magnetoresistance components. So, our results indicate that the Hall resistance of the insulating state at $\nu < 0,28$ is temperature independent and roughly coincides with the value characteristic of metallic state.

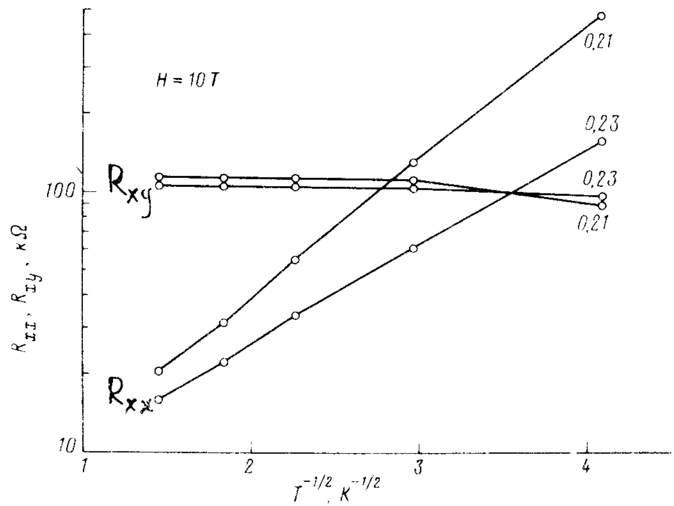

Fig.2. Temperature dependences of R_{xx} and R_{xy} measured in magnetic field $H = 10$ T at filling factors $\nu = 0.21$ and $\nu = 0.23$ (as specified near the curves)

Temperature dependences of R_{xx} and R_{xy} are displayed 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 mentioned that in Si MOSFET's in the extreme quantum limit ($\nu < 1$) metal-insulator transition occurs in a different manner [7]: In an insulating state the both components R_{xx} and R_{xy} of magnetoresistance tensor tend to infinity when 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 applicable at a zero temperature. These are a mean field theory [1] and a Kubo formalism [2,3]. Giving similar predictions for the Hall resistance, their results for R_{xx} are considerably different. In the approximation used in Refs. [2,3] the diagonal conductivity at small frequencies is mainly due to polarization currents which are nondissipative. As a result an imaginary part of R_{xx} considerably exceeds its real part. This should cause predomination of the 90° signal over in-phase signal detected by the lock-in amplifier. This was not the case in our experiment where temperature-dependent dissipative conductance prevailed in the measured R_{xx}. This implies that our experimental conditions are out of the range of validity of models [2,3] which neglect all temperature-dependent mechanisms of the dissipative conductivity.

The nature of the insulating state at small filling factors in GaAs/AlGaAs heterojunctions has not 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 in the pinned Wigner crystal the Hall resistance R_{xy} is infinitely large, therefore measurements of its value could help to distinguish between the Hall insulator, being the result of localization, and the Wigner crystal states. However it seems to us that the Wigner crystal might also demonstrate behavior characteristic of the Hall insulating state, when $R_{xy} \cong H/n_s ec$. 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}. Density of a transport current is $j_x = n_s e V_d$, where V_d is a drift velocity. Since a Lorentz force eHV_d/c is compensated by the Hall electric field, E_y, it follows from these relations that $R_{xy} = H/n_s ec$, independently 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 Wigner policrystal state (see, e.g., [9]) when large regions of the ideal Wigner crystal with $R_{xx} = 0$ and $R_{xy} \cong H/n_s ec$ 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] authors reported activated behavior: $R_{xx} \simeq exp(E/kT)$ but 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 components of the magnetoresistivity tensor extrapolated to a zero temperature support recent predictions for the Hall insulating state with finite Hall resistance close to the classical value. We argue that the Wigner crystal might also demonstrate the similar behavior.

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