Phase diagram of the magnetoconductivity of 2D electron systems

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The $\sigma_{xx} - \sigma_{xy}$ phase diagrams of GaAs heterostructures and Si MOS structures have been studied over the temperature interval 0.3–10 K in magnetic fields up to 12 T. In the limit of vanishingly low currents and in the limit $T \to 0$, the dependence $\sigma_{xx}(\sigma_{xy})$ takes quite different forms for different energy sublevels.

Although problems involving the localization of electrons in 2D systems in a strong magnetic field have been studied for a fairly long time now, we still lack clarity in our understanding of these processes. In particular, there has been no experimental study, under conditions corresponding to the integer quantum Hall effect, of the form of the $\sigma_{xx} - \sigma_{xy}$ diagrams for various energy sublevels in the case in which there is no overlap of these sublevels. The information available on the behavior of s_{xx} in the limit $T \to 0$ is quite contradictory.[1,2] The various versions of the theory (Refs. 3–5, on the one hand, and Refs. 6 and 7, on the other) also disagree on the form of the magnetoconductivity phase diagrams.

In this letter we report an experimental study of localization processes through measurements of the temperature dependence of σ_{xx} and σ_{xy} in various spin and valley energy sublevels. In contrast with previous measurements, the present measurements were carried out at very low measurement currents (0.1–10 nA), since the values of the conductivity for a half-integer filling of sublevels are exceedingly sensitive to the magnitude of the current. It turns out that the dependence $\sigma_{xx}(\sigma_{xy})$ takes markedly different forms for sublevels of even and odd index, while the scaling theory[3–5] predicts an identical behavior for all levels.

Experimental procedure and results. We studied rectangular samples of GaAs/AlGaAs heterostructure [GaAs-1: $\mu = 250\,000$ cm^2/(V·s), $n = 4.3 \times 10^{11}$ cm^{-2}; GaAs-2: $\mu = 70\,000$ cm^2/(V·s), $n = 2.2 \times 10^{11}$ cm^{-2}] and a Si MOS structure [$\mu = 35\,000$ cm^2/(V·s)]. The resistivities ρ_{xx} and ρ_{xy} were measured simultaneously with an alternating current with a frequency of 3.7 Hz by means of two phase detectors. At $T = 0.35$ K the kinetic coefficients began to vary with the current when the current exceeded 30 nA; accordingly, all of the results reported below were obtained at a current of 3 nA. The data were stored in a computer, which calculated the conductivities σ_{xx} and σ_{xy}.

Figure 1 shows the behavior $R_{xx}(H) = 10 \cdot \rho_{xx}(H)$ and $\rho_{xy}(H)$ for a GaAs sample at two temperatures. At $T = 1.5$ K, a spin splitting of the first and second Landau levels is partially allowed. Lowering the temperature to 0.35 K causes a complete splitting of these levels and a partial splitting of the third. The Hall plateaus broaden as the temperature is lowered, while the ρ_{xx} peaks become narrower. As the tempera-

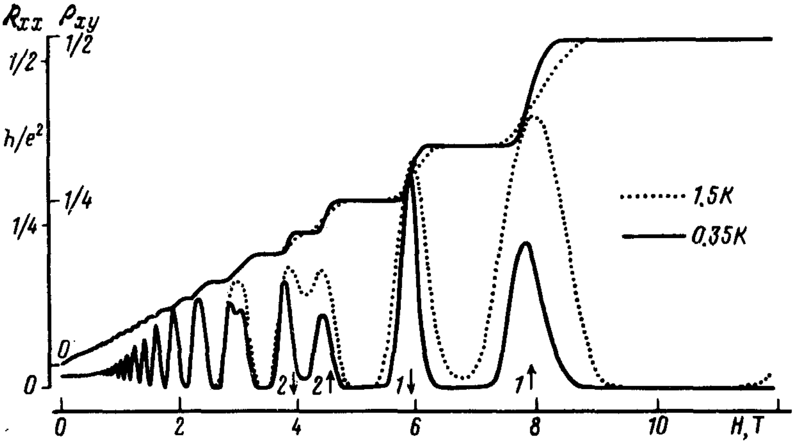

FIG. 1.

ture is reduced, the values of $\rho_{xx}^{\max}$ for levels, 1, 2, and 3 decrease. The ρ_{xx} maxima corresponding to a half-integer filling of the ↑ sublevels are noticeably smaller than the maxima for the ↓ sublevels.

Figure 2 shows $\sigma_{xx} - \sigma_{xy}$ diagrams for sample GaAs-1 (the values of the conductivity are expressed in units of e^2/h). As the temperature is lowered from 9.2 to 0.35 K, the Landau levels split, and vanishing values of σ_{xx} occur at $\sigma_{xy} = 3e^2/h$ and $5e^2/h$. The $\sigma_{xx}(\sigma_{xy})$ curves corresponding to the 1↑ and 2↑ sublevels run well below the curves corresponding to the 1↓ and 2↓ sublevels, and this difference increases with decreasing temperature. Furthermore, at $T = 0.35$ K the $\sigma_{xx}(\sigma_{xy})$ curves for the ↑ sublevels become asymmetric. The dashed lines connecting the curves correspond to

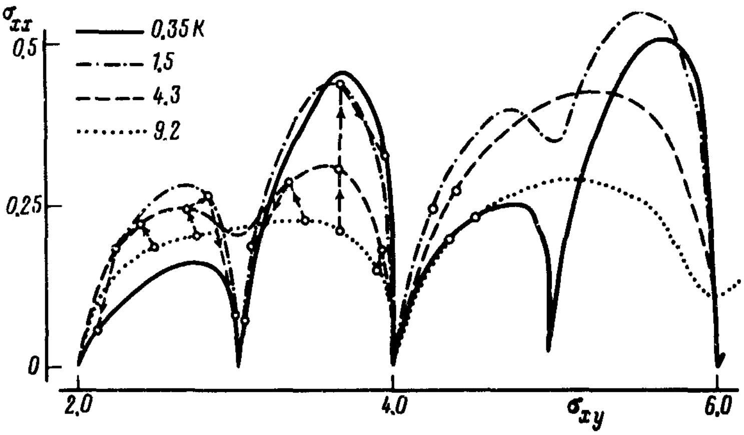

FIG. 2. Phase diagrams for sample GaAs-1.

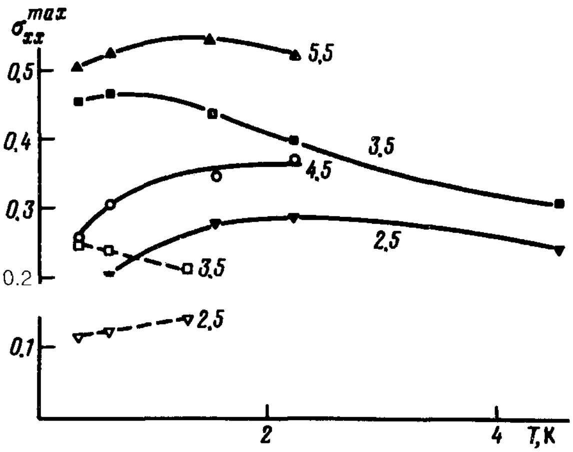

FIG. 3. Curves of $\sigma_{xx}^{\max}(T)$ for GaAs-1 (solid lines) and for a Si MOS structure (dashed lines). The curves are labeled with the filling factors.

identical values of the filling factor ν. As the temperature is lowered, they tend toward the points $(0, Ne^2/h)$, where N is an integer. Increasing the measurement current reduces the difference between the conductivities of the even and odd sublevels; in general, an increase in the current is equivalent to an increase in the temperature.

Figure 3 shows the temperature dependence of the conductivity for a half-integer filling of the $\sigma_{xx}^{\max}(T)$ sublevels for the same sample. As T is lowered, the conductivity increases; it goes through a maximum at some T_{sc} and then decreases. The value of T_{sc} for the odd sublevels ($\nu = 2.5$ and 4.5) is significantly higher than T_{sc} for the corresponding even sublevels. At $T = 0.35$ K the values for $\sigma_{xx}^{\max}$ for $\nu = 2.5$ and 4.5 are smaller by a factor of about two than that for $\nu = 3.5$ and 5.5. A corresponding relation between the heights of $\sigma_{xx}^{\max}$ is observed for the Si MOS structure for $\nu = 2.5$ and 3.5. The electrons of these sublevels $(0+\downarrow$ and $0-\downarrow)$ belong to different valleys and have an identical spin direction. In sample GaAs-2, with a lower conductivity, the values of $\sigma_{xx}^{\max}$ for $\nu = 2.5$ and 3.5 differ by no more than 20%, having values of $0.4e^2/h$ and $0.5e^2/h$, respectively, at $T = 0.6$ K.

Discussion of results. We will discuss the results on the basis of the scaling theory. The increase in the conductivity with decreasing temperature in the semiclassical region—at $T > T_{sc} \sim \Gamma/K$ (Γ is the level width)—stems from a contraction of the Fermi distribution.[9] According to Refs. 3–5, at $T < T_{sc}$ the value of $\sigma_{xx}^{\max}$ should approach a certain value $\sigma_0 \sim 0.45e^2/h$ (Ref. 8). This conclusion, which was reached for the integer quantum Hall effect, has been confirmed experimentally[9] for a sample with a comparatively low conductivity. The results shown in Fig. 3 for the $1\downarrow$ and $2\downarrow$ sublevels in GaAs-1 and the results for GaAs-2 are also consistent with Refs. 3–5.

Such a behavior of $\sigma_{xx}^{\max}$, however, is expected in the theory only in the case of a relatively pronounced disorder. Otherwise, a fractional quantum Hall effect arises as the temperature is lowered, and σ_{xx} vanishes at $\sigma_{xy} = (1/3)e^2/h$, $(2/3)e^2/h$, etc.[10] The case of a slight disorder does not contradict the curves in Fig. 3 for $\nu = 2.5$ and 4.5 (GaAs-1) or for $\nu = 2.5$ and 3.5 (Si). It may be that the difference in the shape of the state density or in scattering processes causes the conductivities corresponding to the even and odd sublevels in GaAs to lie on different sides of a separatrix which separates regions of the integer and fractional quantum Hall effects in the phase plane, at $T \approx T_{sc}$. As a result, the curves of $\sigma_{xx}(\sigma_{xy})$ begin to be attracted to different separatrices: an integer separatrix and a fractional separatrix, which lies considerably lower. It may be that the onset of the fractional quantum Hall effect explains the asymmetry of the $\sigma_{xx}(\sigma_{xy})$ curves for the ↑ levels. This interpretation of the data in Fig. 3 allows us to estimate the critical value of the conductivity at the maximum of the separatrix: $\sigma_{\square} \approx (0.35\text{–}0.45)e^2/h$. In the Si MOS structure, the conductivity for both sublevels is considerably lower than our estimate of $\sigma_{\square}$, so we would expect on the basis of the scaling theory that $\sigma_{xx}^{\max}$ would decrease with a further lowering of the temperature. This suggestion is supported by the onset of a fractional quantum Hall effect with $\nu = 4/3$ in this MOS structure at $T < 1$ K.

In summary, the behavior found here can be interpreted for the most part on the basis of the scaling theory. However, final conclusions regarding the reasons for the difference between the magnetoconductivities corresponding to the even and odd levels will have to await measurements at lower temperatures and a study of the scattering processes and the shape of the state density for the different sublevels.

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