Resistivity of 2D electrons with $\nu=1/2$ in a zero magnetic field

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The dependence of the resistivity of 2D electrons with Landau level filling factor $\nu=1/2$ in a zero magnetic field is studied experimentally as a function of the carrier density. It is found that the ratio of the resistivity for $B=0$ and $\nu=1/2$ is a linear function of the carrier density, as predicted by a theory based on the scattering of composite fermions by spatial fluctuations of the effective static magnetic field. © *1997 American Institute of Physics.* [S0021-3640(97)00615-4]

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A new approach for describing the electronic properties of the fractional quantum Hall effect by means of the Chern–Simon gauge field theory was recently proposed in Ref. 1. According to this theory, near a Landau filling factor $\nu=1/2$ electrons are bound with two magnetic flux quanta and form a new quasiparticle — a composite fermion. For $\nu=1/2$ the external magnetic field is completely compensated and the composite fermions move in a nonuniform effective magnetic field induced by fluctuations of the impurity potential. In Refs. 1 and 2 the resistivity of composite fermions due to scattering by fluctuations of the magnetic field was calculated. Assuming that each charged impurity produces a local fluctuation of the effective magnetic field, it was shown that the scattering of composite fermions by a fluctuating magnetic field predominates over Coulomb scattering by the same impurities. It was found that the ratio of the resistivity R_{xx}^{CF} of the composite fermions to the resistivity R_{xx}^{e} of the electrons in a field $B=0$ equals $(k_F ds)^2$, where k_F is the electron Fermi wave number equal to $(2\pi N_s)^{1/2}$, N_s is the electron density, and ds is the distance between uncorrelated charged impurities and 2D electrons. For the case $k_F ds \gg 1$ it was found to be possible to explain the experimental fact that the resistivity of composite fermions in a field $B=0$ is many times greater than that of electrons.[3] However, a detailed comparison of the resistivity of composite fermions with a theoretical calculation was not made.

In the present work these measurements were performed on samples for which the resistivity of the electrons and composite fermions could be varied via the gate voltage. It was found that over more than an order-of-magnitude variation of the resistivity of the fermions, the ratio $R_{xx}^{\mathrm{CF}}/R_{xx}^{e}$ depends linearly on the density, in accordance with the theoretical predictions.[1]

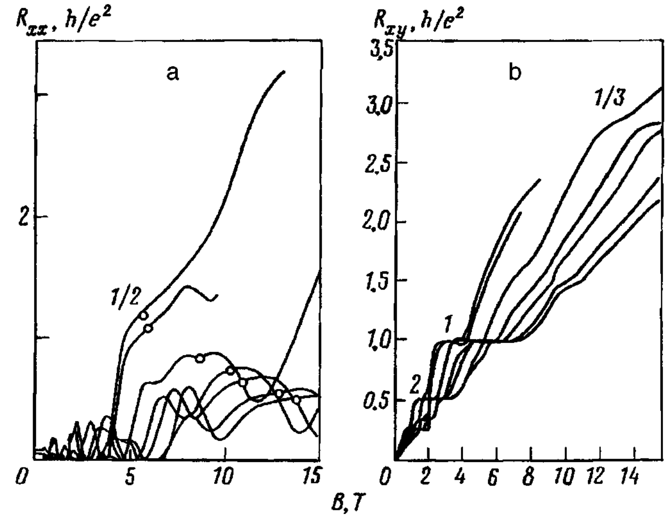

FIG. 1. $T=200$ mK; gate voltage $V_g=0.1$–0.4 V; a — $R_{xx}(B)$; the dots represent the resistivity for $\nu=1/2$; b — $R_{xy}(B)$.

The specimens consisted of AlGaAs/GaAs heterostructures with a 2D electron gas. The Hall bridges had dimensions of 50×100 μm and were coated with a gold and nickel gate. The density was varied over the range $(0.4$–$1.8)\times 10^{11}$ cm^{-2}. The undoped AlGaAs region (spacer) was 60 nm wide. The mobility varied from 15 to 65 m^2/V$\cdot$s. The measurements were performed with an ac current not exceeding 10^{-8} A and at a frequency of 6.6 Hz in magnetic fields up to 15 T. The temperature was varied from 50 mK up to 1 K. Two specimens were investigated. The measurement results obtained for one specimen are presented in detail.

Figure 1 displays typical curves of the diagonal (a) and Hall (b) resistivities versus the magnetic field for different gate voltages (0–0.4 V). The points give the resistivity R_{xx}^{CF} at a Landau-level filling factor $\nu=1/2$. One can see that R_{xx}^{CF} decreases with increasing density and magnetic field. Minima at fractional filling factors of 1/3 and 2/3 are visible. One can also see that R_{xx}^{CF} increases logarithmically with decreasing temperature for $T<300$ mK.[4] It was recently shown that these temperature corrections could be due to the interaction between the composite fermions in the presence of a scattering potential.[5] To take account of only the T-independent component of the scattering of composite fermions, we measured the resistivity R_{xx}^{CF} for $T>200$ mK (Fig. 1). For $T=50$ mK the minima at 2/3 and 1/3 vanish, and flat plateaus are observed. Nonetheless, the T-dependent corrections did not exceed 10% of the total resistivity as the temperature varied from 50 mK to 1 K. Figure 2a shows the low-field part of the magnetoresistivity for different gate voltages. For clarity, the same dependence is shown on a logarithmic scale in Fig. 2b. One can see that the resistivity for $B=0$ changed by not more than an order of magnitude, but the Shubnikov–de Haas oscillations arose at the same fields 0.25 T irrespective of density (Fig. 2b). The resistivity in a zero magnetic field is determined by the transport relaxation time, which is more than an order of magnitude greater than

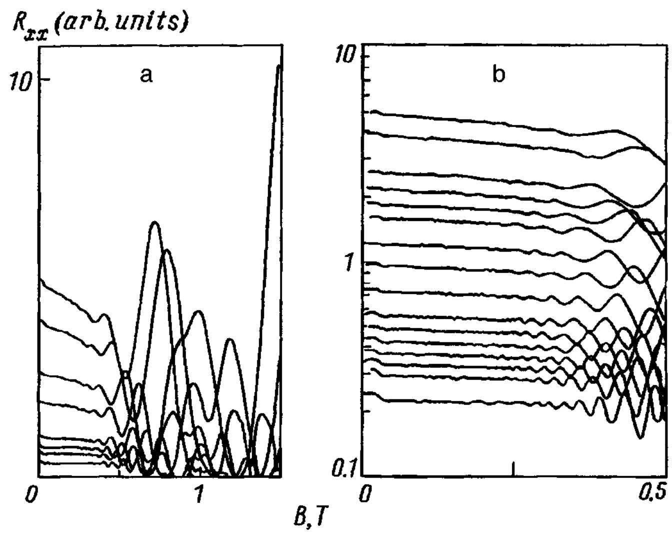

FIG. 2. $R_{xx}(B)$ near $B=0$ on linear (a) and logarithmic (b) scales.

the quantum relaxation time, which determines the amplitude of the Shubnikov oscillations in a magnetic field.[6] This attests to the long-range character of the impurity potential. In the case of a short-range impurity the transport and quantum times are equal to each other.[7] In contrast to the transport relaxation time, for a long-range impurity potential the quantum time has been studied comparatively little (see the discussion in Ref. 7). As the temperature decreased, the resistivity of the electrons in zero magnetic field also increased logarithmically on account of weak localization effects.[8] However, since $R_{xx}^e \ll h/e^2$, these corrections were less than 1%.

Figure 3a displays the experimental density dependences of the resistivity of the electrons (squares) and composite fermions for $\nu=1/2$ (circles). Up to $N_s \sim 1.2\times 10^{11}$ cm^{-2} a power-law decrease of the resistivity with increasing density is observed for electrons and for composite fermions with $\nu=1/2$; this is described to a high degree of accuracy by the relations $\rho_{xx}^e \sim N_s^{-5/2}$ and $\rho_{xx}^{\mathrm{CF}} \sim N_s^{-3/2}$, respectively. As the carrier density increases further, in both cases the rate of decrease of the resistivity decreases. We note that the relation $\mu \sim N_s^{-3/2}$ for electrons near $B=0$ was also observed earlier.[9] Figure 3a also displays several values of the resistivity for $\nu=3/2$ (triangles) in the range $N_s=(0.753\text{–}1.97)\times 10^{11}$ cm^{-2}. For $\nu=3/2$, this density range in the experimental specimens is a transitional range from an integer to a fractional quantum Hall effect and, as one can see, the dependence of the resistivity in this case is substantially different from the corresponding dependences for electrons in a field $B=0$ and composite fermions with $\nu=1/2$. Figure 3b shows the ratio of the resistivity of the composite fermions to the resistivity of the electrons as a function of the density; this function is linear up to $N_s \sim 1.2\times 10^{11}$ cm^{-2}.

Let us now compare the experimental results with theory. In Ref. 1 the resistivity of electrons with $B=0$ (scattering by fluctuations of the Coulomb field) and the resistivity

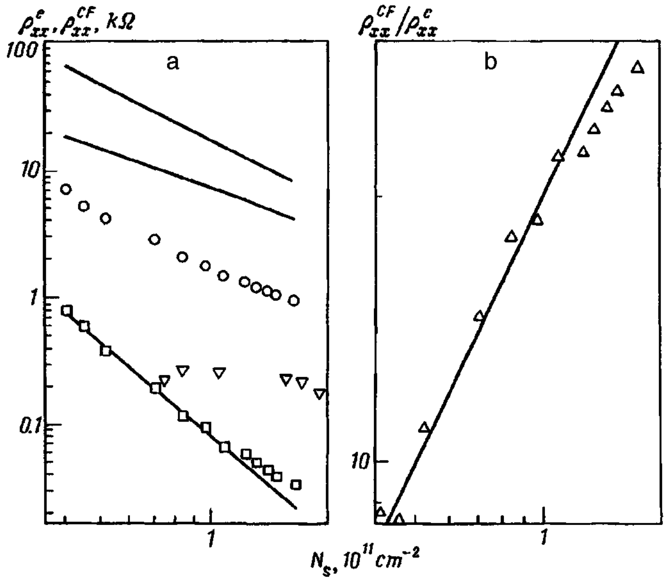

FIG. 3. a — Experimental curves of ρ^e_{xx} (squares) and ρ^{CF}_{xx} (circles) versus the electron density. The resistivity for $\nu = 3/2$ (triangles). *1, 2, 3* — Curves constructed using Eqs. (1), (2), and (3), respectively, for $N_{\mathrm{imp}} = 1.5\times 10^{11}$ cm^{-2} and $ds = 40$ nm. b — Ratio $\rho^{\mathrm{CF}}_{xx}/\rho^e_{xx}$ (dots — experiment, straight line — $\rho^{\mathrm{CF}}_{xx}/\rho^e_{xx} \sim N_s$).

of composite fermions with $\nu = 1/2$ (scattering by fluctuations of the magnetic field) was calculated. The formulas were derived in the Born approximation for electron transport in a heterojunction, where a spacer separates the two-dimensional carrier gas from the scattering impurities. The relation

$$\rho^e_{xx} = \frac{h}{e^2}\,\frac{N_{\mathrm{imp}}}{N_s}\,\frac{1}{16(k_F ds)^3} \tag{1}$$

was obtained for electrons.[1] Correspondingly, for composite fermions

$$\rho^{\mathrm{CF}}_{xx} = \frac{h}{e^2}\,\frac{N_{\mathrm{imp}}}{N_s}\,\frac{2}{k'_F ds}. \tag{2}$$

We note that k_F and k'_F differ by a factor of $\sqrt{2}$, since the electrons are spin-degenerate, while the composite fermions are spin polarized. Substituting in Eqs. (1) and (2) the expression for the wave number in terms of the electron density, we obtain precisely the power-law dependences which, as we noted above, describe the experimental dependences in Fig. 3a. Therefore the theory of Ref. 1 gives the correct functional description of the experimental curves. To make a quantitative comparison of Eqs. (1) and (2) with experiment it is necessary to obtain more accurate values of the parameters N_{imp} and ds in these equations. Since in our case the electron mobility is much lower than in other specimens with approximately the same spacer thickness,[10] it can be conjectured that a large number of residual impurities are present in the spacer which effectively decrease the spacer thickness. Taking $N_{imp}=1.5\times 10^{11}$ cm^{-2}, a fit of Eq. (1) to the experimental dependence of the resistivity for electrons gives an effective spacer thickness $ds=40$ nm. Figure 3a displays the curves corresponding to Eqs. (1) and (2) for $N_{imp}=1.5\times 10^{11}$ cm^{-2} and $ds=40$ nm. For these values of the parameters a numerical discrepancy is observed between Eq. (2) and the experimental dependence for composite fermions.

As we have said, Eqs. (1) and (2) were obtained in the Born approximation. Whereas this approximation is correct for electrons in the entire experimental density range, for composite fermions it is valid, strictly speaking, only in the limit $N_s \gg N_{imp}$ (Ref. 2). A new approach that makes it possible to solve the Boltzmann equation without using the Boltzmann approximation was developed in Ref. 2. Specifically, the following relation was obtained for composite fermions near $\nu=1/2$:

$$\rho_{xx}^{CF}=\frac{h}{e^2}\frac{1}{k_F' ds}\frac{1}{\exp(\alpha)K1(\alpha)}. \tag{3}$$

This relation is displayed in Fig. 3a for $N_{imp}=1.5\times 10^{11}$ cm^{-2} and $ds=40$ nm. Like Eq. (2), for these values of the parameters Eq. (3) gives too high a value of the resistivity of composite fermions, but the quantitative discrepancy with the experimental results is smaller in this case. The slope of the function (3) differs from that of the experimental dependence for $N_s<1.2\times 10^{11}$ cm^{-2} but equals the experimental slope for higher densities, i.e., in the region where the discrepancy with the theory of Ref. 1 appears.

In summary, in this study we have investigated experimentally the electron-density dependence of the resistivity of composite fermions with $\nu=1/2$ and electrons in a field $B=0$. A comparison was made with the theories of Refs. 1 and 2. It was shown that for $N_s<N_{imp}$ the theory of Ref. 1 gives the correct functional description of the behavior of the experimental dependences for both electrons and composite fermions. At the same time, a numerical discrepancy between experiment and the theories of Refs. 1 and 2 is observed. In the theory of Ref. 1 this discrepancy cannot be eliminated simultaneously for electrons and composite fermions by adjusting the parameters.

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