PHYSICAL REVIEW B VOLUME 56, NUMBER 4 15 JULY 1997-II

Magnetoresistance of composite fermions at $\nu = \frac{1}{2}$

L. P. Rokhinson* and V. J. Goldman
Department of Physics, State University of New York, Stony Brook, New York 11974

(Received 7 April 1997)

We have studied the temperature dependence of both diagonal and Hall resistivity in the vicinity of $\nu = \frac{1}{2}$. Magnetoresistance was found to be positive and almost independent of temperature: the temperature enters the resistivity as a logarithmic correction. At the same time, no measurable corrections to the Hall resistivity have been found. Neither of these results can be explained within a theory of noninteracting composite fermions or by an analogy with conventional low-field interaction theory. There is an indication that interactions of composite fermions with fluctuations of the gauge field may reconcile the theory and experiment. [S0163-1829(97)51328-2]

Experimentally, it has been known for some time that in low disorder two-dimensional electron systems (2DES) at filling factor $\nu = \frac{1}{2}$ the diagonal resistivity ρ_{xx} remains finite at low temperatures and exhibits a shallow minimum, while the Hall resistivity ρ_{xy} is nearly linear in magnetic field and does not form a plateau. An understanding of the phenomenon came with the theory[1,2] of composite fermions (CF's), where weakly interacting new particles—composite fermions—were proposed[2,3] to form a metallic Fermi-liquid-like state near $\nu = \frac{1}{2}$. In the mean-field approximation, CF's experience a reduced effective magnetic field $B_{cf} = B - 2n\phi_0$, where n is the electron (and CF) concentration, and $\phi_0 = h/e$ is the flux quantum. At $\nu = \frac{1}{2}$ the external magnetic field is fully cancelled and $B_{cf} = 0$; it has been shown experimentally[4] that some properties of a Fermi liquid are preserved for CF's, in particular, a reasonably well-defined Fermi surface.

Despite some similarity between $\nu = \frac{1}{2}$ and $B = 0$ phenomenology, there are apparent differences in transport properties. For example, magnetoresistance is negative near $B = 0$, while it is positive near $\nu = \frac{1}{2}$. Magnetoresistance at low B has been a powerful tool in the study of weak localization and electron interaction effects. This method relies on the prediction of the classical Drude model that ρ_{xx} is not affected by magnetic field, while $\sigma_{xx} = \rho_{xx}/(\rho_{xx}^2 + \rho_{xy}^2)$ displays negative magnetoconductance via $\rho_{xy} \propto B$. Any magnetoresistance then results from quantum corrections to the conductivity tensor, which, in general, have a different B and T dependence than Drude σ_{xx}^0 and σ_{xy}^0 and, thus, can be separated. The Altshuler-Aronov quantum correction to conductivity $\Delta\sigma_{xx}^{AA}$, due to interaction effects has a logarithmic temperature dependence[5] and is field independent at low B because the correction to Hall conductivity $\Delta\sigma_{xy}^{AA} = 0$.[6] Neglecting the weak localization contribution, for electrons at low B the resulting quantum magnetoresistance $\Delta\rho_q = \rho_{xx}(B) - \rho_{xx}(0) \approx \rho_{xy}^2 \Delta\sigma_{xx}^{AA}$ (for $\Delta\sigma_{xx}^{AA} \ll \sigma_{xx}^0$) is negative, because $\Delta\sigma_{xx}^{AA} < 0$.[6,7]

We have recently reported the observation of a logarithmic correction to the conductivity of CF's, σ_{xx}^{cf}, at $\nu = \frac{1}{2}$ and attributed it to the short-range interaction between CF's.[8] An enhancement of the coupling constant, compared to the low-field regime, was found recently to be a result of an interaction between CF's via the gauge-field fluctuations.[9] Naively, one may also expect that this effect should lead to a negative magnetoresistance, in analogy to the low-B case. However, experimentally positive magnetoresistance and no correction to the Hall resistivity are measured near $\nu = \frac{1}{2}$. Thus, nonzero correction $\Delta\sigma_{xy}^{cf} \neq 0$, in addition to $\Delta\sigma_{xx}^{cf} \neq 0$, both B dependent, is required to reconcile measured corrections to ρ_{xx} and ρ_{xy} with the constraints imposed by the matrix inversion of transport coefficients.

We have studied several samples fabricated from high mobility ($\mu \approx 2 \times 10^6 \mathrm{cm}^2/\mathrm{V\,s}$) GaAs/Al$_xGa_{1-x}$As heterojunction wafers. The wafers have double Si δ doping; the first layer is separated from the 2DES by a $d_s = 120$ nm thick spacer. 2DES with densities 0.4 and 1.2×10^{11} cm^{-2} were prepared by illuminating a sample with red light. The temperature was measured with a calibrated ruthenium oxide chip resistor. Measurements were done in a top-loading into a mixture dilution refrigerator using a standard lock-in technique. Samples were patterned in either Corbino or Hall bar geometry.

Representative magnetoresistivity data $\rho_{xx}(B_{cf}, T)$ near $\nu = \frac{1}{2}$ are plotted in Fig. 1(a) (note that $\rho_{xx}^{cf} = \rho_{xx}$). Magnetoresistance is positive near $\nu = \frac{1}{2}$ and depends weakly on temperature. A remarkable result is that ρ_{xx} at a given B_{cf} changes logarithmically with temperature for 13 mK$< T <$1000 mK. A simple function

$$[\rho_{xx}(B_{cf}, T) - \rho_{xx}(B_{cf}, T_1)]/\ln(T_1/T)$$

collapses ρ_{xx} vs B_{cf} traces at different temperatures T into a single curve [Fig. 1(b)]. Such a scaling requires that both the $B_{cf} = 0$ part of resistivity $\rho_{xx}(0,T)$, and the part responsible for the magnetoresistance, have terms proportional to $\log T$. We fit the data with a polynomial

$$\rho_{xx}(B_{cf}, T) = \rho_{xx}(0,T) + \alpha(T) B_{cf} + \beta(T) B_{cf}^2 \qquad (1)$$

[dashed lines in Fig. 1(a)] in a classically weak-field region for CF's, $\rho_{xy}^{cf} \leqslant \rho_{xx}^{cf}$ (which corresponds to $|B_{cf}| \leqslant 0.12$ T for the sample in Fig. 1). The value of $\alpha \neq 0$ corresponds to a known term in ρ_{xx} proportional to $B(d\rho_{xy}/dB)$.[10] As is expected from the above analysis, both $\rho_{xx}(0,T)$ and $\beta(T)$ change logarithmically with temperature (Fig. 2). Zero-field

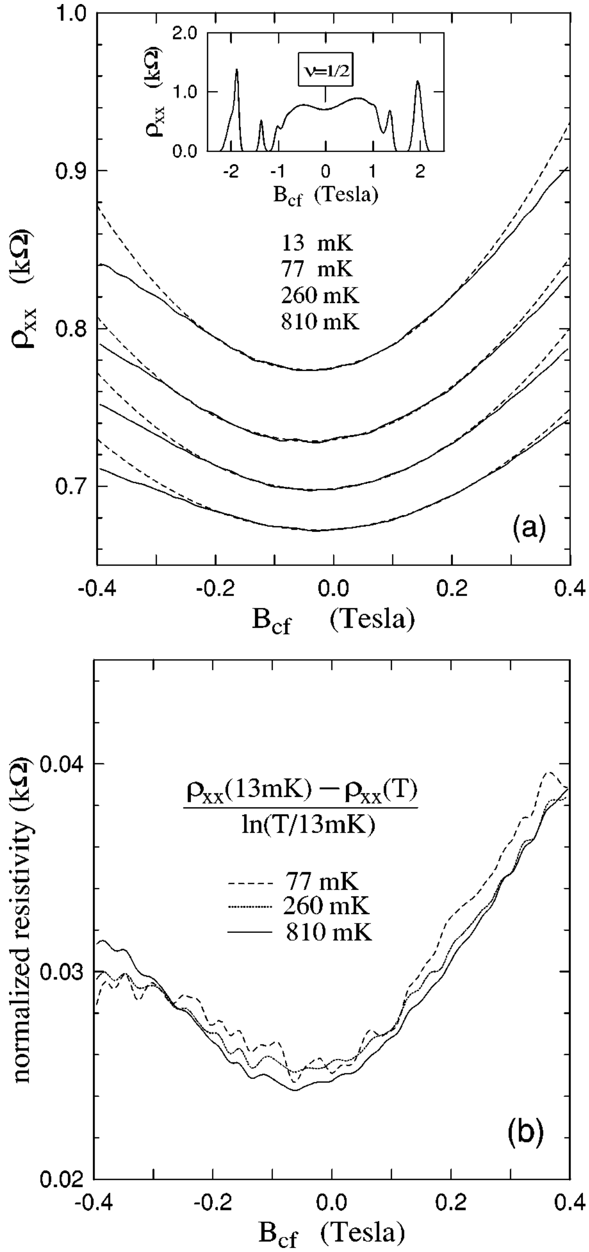

FIG. 1. (a) Magnetoresistivity data ρ_{xx} vs B_{cf} near $\nu=\frac{1}{2}$ for $T=13$, 77, 260, and 810 mK (from top to bottom). Dashed lines are polynomial fits in Eq. (1) in the range $|B_{cf}|<0.12$ T. Resistivity in a larger field range is shown in the inset. (b) The scaling of the difference between ρ_{xx} at 13 mK and other temperatures, normalized by the log of the ratio of temperatures.

CF conductivity $\sigma_{xx}^{cf}(0,T)=1/\rho_{xx}(0,T)$ has a negative logarithmic T-dependent correction, which has been attributed to interaction effects between CF's, analogous to the Altshuler-Aronov-type localization correction for electrons at low magnetic fields.[2,8] However, as is apparent from Fig. 1, there is a positive magnetoresistance near $B_{cf}=0$, in stark contrast to the negative magnetoresistance near $B=0$.

In contrast to the low-field regime, we have found no deviation of Hall resistivity ρ_{xy} from its free-electron value $\rho_{xy}^{0}=B/en$ near $\nu=\frac{1}{2}$ (electron concentration n is determined

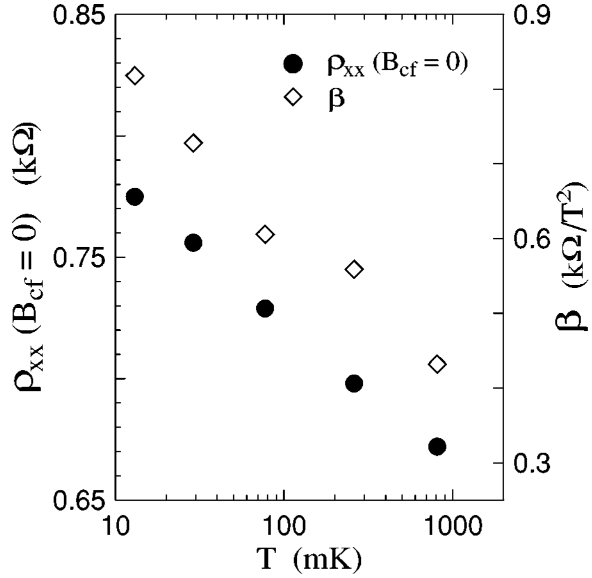

FIG. 2. The $\nu=\frac{1}{2}$ resistivity $\rho_{xx}(0,T)$ plotted as a function of temperature. The coefficient β, defined in Eq. (1), is obtained from the fits in Fig. 1.

from Shubnikov–de Haas oscillations with 2% accuracy). A direct comparison of ρ_{xy} at 35 and 560 mK shows (Fig. 3) that there is no T-dependent correction to ρ_{xy} within experimental error of 0.1% in the range $|\omega_c^{cf}\tau|<3$. This value should be contrasted with the $\approx 15\%$ change of ρ_{xx}. Thus, we conclude that $\Delta\rho_{xy}=0$ near $\nu=\frac{1}{2}$.

Within the mean-field theory, transport properties of 2DES near $\nu=\frac{1}{2}$ closely resemble those near $B=0$. Let us examine mechanisms which may lead to the positive magnetoresistance within the $\{\nu=\frac{1}{2}\}\leftrightarrow\{B=0\}$ analogy. At low B, there are no corrections to ρ_{xy} due to weak localization.[11] Near $\nu=\frac{1}{2}$, the disorder-induced fluctuations of electron density δn produce static fluctuations of the gauge-field $\delta B_{cf}=2\delta n\phi_0$, and the first-order correction to ρ_{xx} is suppressed.[12] The second-order correction is ~ 100 times

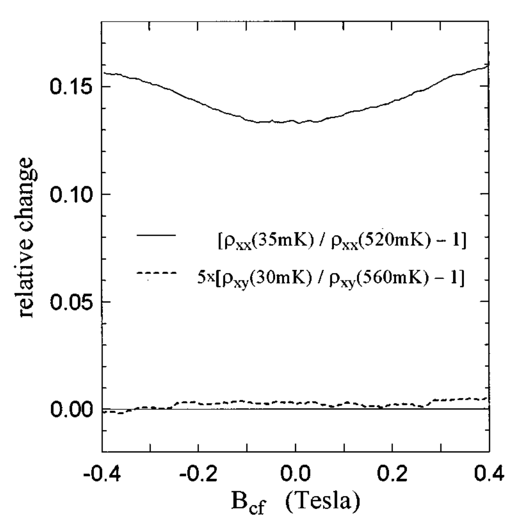

FIG. 3. Relative change of ρ_{xx} and ρ_{xy} with temperature. Note that the change in ρ_{xy} is multiplied by a factor of 5.

less than the measured logarithmic term in $\rho_{xx}(0,T)$.[13] Also, static fluctuations of the gauge field would suppress quantum interference at $\omega_c^{cf}\tau \approx 1$, although the positive magnetoresistance is observed at much higher effective magnetic fields.

Another possible source for positive magnetoresistance is a classical correction to the Drude resistivity ρ_{xx}^0, which results from the fact that an average size of potential fluctuations is larger than the Fermi wavelength. Simple arguments[14] lead to the following positive quadratic in the B_{cf} correction to ρ_{xx}^0:

$$\Delta\rho_{cl} \propto \rho_{xx}^0 \left(\frac{d_s}{r_c}\right)^2, \tag{2}$$

where d_s is the spacer thickness and $r_c = \hbar k_F / eB_{cf}$ is the cyclotron radius. Recent experiments[15] show that, in the presence of a spatially nonuniform magnetic field, a positive magnetoresistance is observed in 2DES at low magnetic fields. However, the classical magnetoresistance has been calculated for $T=0$ and thus does not have any temperature dependence. We do not expect appreciable temperature dependence for this scattering mechanism, at least for $T<0.5$ K, when phonon scattering is negligible,[16] inconsistent with the observed $\log T$ dependence of resistivity. Thus, the classical correction alone cannot explain the experimental results.

The logarithmic temperature dependence of $\beta(T)$ strongly suggests that the positive quadratic magnetoresistance originates from the interaction effects between CF's. This conclusion is further supported by the observation that both $\rho_{xx}(0,T)$ and $\beta(T)$ deviate from $\log T$ dependence at about the same T. However, matrix inversion of transport coefficients, combined with Onsager relations and experimental observations that (i) $\Delta\rho_{xy}/\rho_{xy}^0 \ll \Delta\rho_{xx}/\rho_{xx}^0$ (Fig. 3), and (ii) both ρ_{xx} and ρ_{xy} are nonsingular near $\nu=\frac{1}{2}$, impose certain constraints on the corrections to the Drude conductivity tensor. Assuming that both corrections are small ($\Delta\sigma_{xx} \ll \sigma_{xx}$ and $\Delta\sigma_{xy} \ll \sigma_{xy}$) they can be expressed in the following form:

$$\Delta\sigma_{xx}^{cf}(B_{cf},T) \approx f(\gamma)(1-\gamma^2)\Delta\sigma_{xx}^{cf}(0,T), \tag{3a}$$

$$\Delta\sigma_{xy}^{cf}(B_{cf},T) \approx 2\gamma f(\gamma)\Delta\sigma_{xx}^{cf}(0,T), \tag{3b}$$

where $\gamma=\rho_{xy}^{cf}/\rho_{xx}^0 \propto B_{cf}$ ($\gamma=\omega_c^{cf}\tau$ in the Drude model), $f(\gamma)$ is an even smooth function of B_{cf}, and $f(0)=1$. Note that the B and T dependencies are separated, and T enters only through the zero-field correction to diagonal conductivity $\Delta\sigma_{xx}(0,T)$. Indeed, experimentally determined $\Delta\sigma_{xx}$ and $\Delta\sigma_{xy}$ are both B dependent and $\Delta\sigma_{xx}$ changes sign at $\rho_{xx} \approx \rho_{xy}^{cf}$ (Fig. 4).

All these findings contradict the results of the conventional low-field interaction theory, which predicts[11] $\Delta\sigma_{xy}=0$ and a field-independent $\Delta\sigma_{xx}$. A recent theory investigated interaction effects between CF's in the presence of disorder beyond the mean-field approximation.[17] Corrections $\Delta\sigma^{cf}$, obtained in Ref. 17, can be written as Eqs. (3) with $f(\gamma)\equiv 1$ and $\gamma \equiv \omega_c^{cf}\tau$. These corrections to conductivity lead to the following corrections to the resistivity tensor:

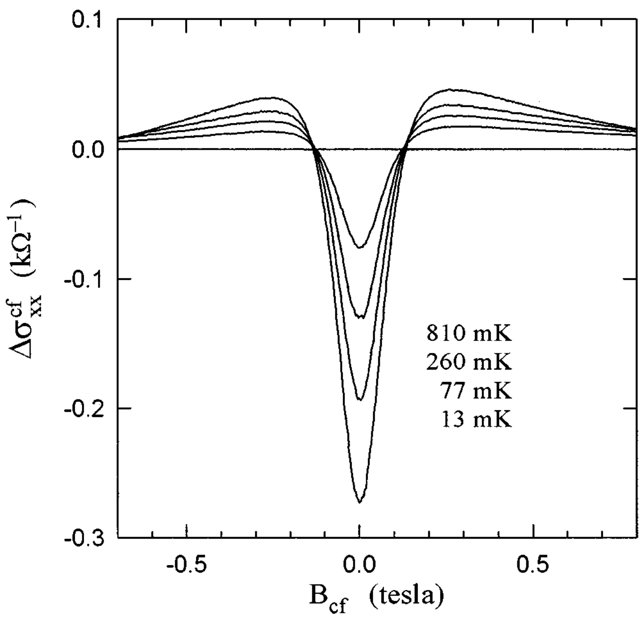

FIG. 4. Deviation of σ_{xx}^{cf} from the Drude value is shown near $\nu=\frac{1}{2}$ for $T=13$, 77, 260, and 810 mK. Note the change of sign of $\Delta\sigma_{xx}^{cf}$ at $\rho_{xx}^{cf}=\rho_{xy}^{cf}$.

$$\Delta\rho_{xx}(B_{cf},T) \approx \Delta\rho_{xx}(0,T)[1+(\omega_c^{cf}\tau)^2]^2, \tag{4a}$$

$$\Delta\rho_{xy}(B_{cf},T) \approx -\rho_{xy}^0[\Delta\rho_{xx}(0,T)/\rho_{xx}^0]^2[1+(\omega_c^{cf}\tau)^2]. \tag{4b}$$

Qualitatively, Eqs. (4) predict a positive magnetoresistance and a vanishing term linear in $\Delta\rho_{xy}$. However, thus calculated $\Delta\rho_{xx}$ overestimates β from Eq. (1) by a factor of 20, if we use $\omega_c^{cf}\tau=\rho_{xy}^{cf}/\rho_{xx}^0$, with $\rho_{xx}^0=0.65$ kΩ. Also, a large quadratic correction to the Hall resistivity, $\Delta\rho_{xy}/\rho_{xy}^0 > 2.5\%$, estimated from Eq. [4(b)], is inconsistent with experiment ($<0.1\%$, see Fig. 3).

Our main results can be summarized as follows: (i) experimentally, the resistivity has a logarithmic temperature dependence near $\nu=\frac{1}{2}$, which implies that both B-independent resistivity and magnetoresistance have $\log T$ dependence, and (ii) there is no measurable correction to the classical Hall resistivity near $\nu=\frac{1}{2}$. From analysis of possible mechanisms which may lead to a positive magnetoresistance, we conclude that the observed T dependencies cannot be explained either within the theory of noninteracting CF's or by the analogy with interaction effects between electrons at low magnetic field. However, the similar $\log T$ dependence of resistivity at $\nu=\frac{1}{2}$ and of magnetoresistance suggests that both corrections have the same physical origin, namely, interactions between CF's and the gauge field.

We are grateful to M. Shayegan for MBE material and to I. Aleiner for stimulating discussions. This work was supported in part by NSF under Grant No. DMR-9318749.

*Present address: Department of Electrical Engineering, Princeton University, Princeton, NJ 08544.

[1] J. K. Jain, Phys. Rev. Lett. **63**, 199 (1989).

[2] B. I. Halperin, P. A. Lee, and N. Read, Phys. Rev. B **47**, 7312 (1993).

[3] V. Kalmeyer and S.-C. Zhang, Phys. Rev. B **46**, 9889 (1992); S. Kivelson, D.-H. Lee, and S.-C. Zhang, *ibid.* **46**, 2223 (1992).

[4] V. J. Goldman, B. Su, and J. K. Jain, Phys. Rev. Lett. **72**, 2065 (1994); R. L. Willett, R. R. Ruel, K. W. West, and L. N. Pfeiffer, *ibid.* **71**, 3846 (1993); W. Kang, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, *ibid.* **71**, 3859 (1993).

[5] B. L. Altschuler, A. G. Aronov, and P. A. Lee, Phys. Rev. Lett. **44**, 1288 (1980).

[6] A. Houghton, J. R. Senna, and S. C. Ying, Phys. Rev. B **25**, 2196 (1982);S. M. Girvin, M. Jonson, and P. A. Lee, *ibid.* **26**, 1651 (1982).

[7] M. A. Paalanen, D. C. Tsui, and J. C. M. Hwang, Phys. Rev. Lett. **51**, 2226 (1983).

[8] L. P. Rokhinson, B. Su, and V. J. Goldman, Phys. Rev. B **52,** R11 588 (1995).

[9] D. V. Khveshchenko, Phys. Rev. Lett. **77**, 362 (1996).

[10] A. M. Chang and D. C. Tsui, Solid State Commun. **56**, 153 (1985); H. L. Stormer, K. W. Baldwin, L. N. Pfeiffer, and K. W. West, *ibid.* **84**, 95 (1992).

[11] P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).

[12] V. Kalmeyer and S.-C. Zhang, Phys. Rev. B **46**, 9889 (1992).

[13] A. G. Aronov, A. D. Mirlin, and P. Wölfle, Phys. Rev. B **49**, 16 609 (1994).

[14] Drude field-independent resistivity is obtained under the assumption that a scattering event is unaffected by magnetic field. This assumption is justified for a short-range scattering, i.e., if the size of the scatterer is less than the inverse Fermi wave vector $1/k_F$. In high mobility 2DES the relevant spatial scale is determined by the spacer thickness $d_s \gg 1/k_F$. During the time $t_{sc} \approx d_s/v_F$, which it takes for an electron to traverse a scatterer of the size d_s, its trajectory is curved by a magnetic field and the electron spends a longer time within the potential of the scatterer compared to the motion along a straight line. Simple geometrical arguments give an estimate of the increase of t_{sc} as $(\Delta t_{sc})/t_{sc} \approx (d_s/r_c)^2$, r_c is the cyclotron radius, which leads to a corresponding increase of the transport cross section. As a result, resistivity acquires a positive correction quadratic in the magnetic field Eq. (2). The correction can be obtained from the solution of the Boltzmann equation in a random magnetic field (Ref. 18): the result agrees with the estimate Eq. (2) with a numerical coefficient ≈ 0.1. Calculations reproduce magnitudes of both resistivity and magnetoresistance within a factor of 3 for studied samples.

[15] F. B. Mancoff, R. M. Clarke, C. M. Marcus, S. C. Zhang, K. Campman, and A. C. Gossard, Phys. Rev. B **51**, 13 269 (1995).

[16] W. Kang, S. He, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **75**, 4106 (1995).

[17] D. V. Khveshchenko (unpublished).

[18] L. P. Rokhinson, Ph.D. thesis, SUNY at Stony Brook, 1996.