PHYSICAL REVIEW B **81**, 041308(R) (2010)

# Resistance minimum observed at Landau level filling factor $\nu=1/2$ in ultra high magnetic fields

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(Received 18 November 2009; published 21 January 2010)

We study the magnetotransport near Landau level filling factor $\nu=1/2$ in a gated GaAs-$Al_{0.3}Ga_{0.7}As$ square quantum well (width 35 nm) in magnetic field up to 45 T and in a temperature ($T$) range between 50 mK and 1.5 K. The longitudinal resistance at $\nu=1/2$, $R_{xx}(\nu=1/2)$, exhibits a steep valley that is flanked by a pair of rising resistance peaks in low $T$. The $R_{xx}(\nu=1/2)$ shows nonmonotonous dependence on $T$, with a minimum resistance reached at $T\sim0.5$ K. The concomitant Hall resistance $R_{xy}$ is not strictly linear with magnetic field and its slope shows a sharp cusp at $\nu=1/2$, indicating a nonclassical Hall effect. The data are characteristic for ultra high field magnetotransport around $\nu=1/2$ in thick, but single-layer, quantum wells.

DOI: 10.1103/PhysRevB.81.041308 PACS number(s): 73.43.−f, 71.10.Pm, 71.70.Di, 73.21.Fg

High-mobility two-dimensional electron systems (2DESs) in GaAs/AlGaAs heterostructures support a multitude of novel many-electron phases when it is subjected to an intense perpendicular magnetic field ($B$) and very low temperatures ($T$).[1,2] Of particular interest are the quantum phases in a half-filled Landau level [(LL) index $N$] in a single-layer 2DES. Magnetotransport at half-fillings at different $N$ in this system is found to exhibit completely different characteristics in terms of low-temperature magnetotransport resistances, namely, the diagonal resistivity $\rho_{xx}$ and the Hall resistivity $\rho_{xy}$. Composite fermion (CF) Fermi surface,[3–5] even-denominator fractional quantum Hall effect (FQHE),[6–11] and anisotropic states[12–17] are found to correspond, respectively, to the half-filled $N=0$, 1, and 2 Landau levels.

The question concerning the exact ground state at $\nu=1/2$ in a single-layer QH sample remains unsettled. Greiter *et al.*[18] proposed that the ground state at filling factors $\nu=1/2$ is a BCS $p$-wave paired superconductor state, described by a Pfaffian wave function. Bonesteel[19] studied the stability of such paired states and found that the quantum fluctuation would eventually cause pair breaking of the ground state, so the $\nu=1/2$ would remain compressible (gapless) even in extremely low temperatures. Unlike the $\nu=5/2$ state, which is believed to be described by Moore-Read wave function,[10,11] the $\nu=1/2$ state experiences stronger fluctuations because the lowest LL is unscreened. It is suggested that the pseudopontential can be influenced by the finite thickness of the 2DES. Rezayi and Haldane studied the influence of thickness on the phase diagrams for a number of cases.[20] Park *et al.* proposed[21] that paired states could prevail at $\nu=1/2$ in a thick 2DES. Specifically, they suggest that the regime of interest is being $\beta=\lambda/\ell_B>5$, where $\lambda$ is the 2DES thickness and $\ell_B=\sqrt{\hbar/eB}$ is the magnetic length. Recently, quantum Hall-effect plateaus are observed at filling factors $\nu=1/2$ and $\nu=1/4$ in a wide QW.[22] On the other hand, it is known that in thicker 2DES, the system becomes effectively bilayer.[23] It is interesting to investigate a regime where the transport features are essentially single layer but modified by an increasing finite thickness.

In addition to the possibility of paired CF state at $\nu=1/2$, residual CF-CF interactions and fluctuations in a partially filled $N=0$ LL are thought to be responsible for a number of puzzling experimental observations. Jiang *et al.*[24] reported early on a remarkably sharp dip in resistivity at $\nu=1/2$ and very strong positive magnetoresistance around it. However, in the single-interface GaAs-AlGaAs heterojunction studied the magnetoresistance around $\nu=1/2$ is found nearly temperature independent, a fact which is explained by the properties of a CF metal.[5] Subsequently, Rokhinson *et al.*,[25] Wong *et al.*,[26] and Rokhinson *et al.*[27] reported an ln $T$ dependence for the $\nu=1/2$ resistance, which can be attributed to residual CF-CF interactions at half-filling.[28]

We report the $\nu=1/2$ magnetotransport in ultra high magnetic field up to 45 T in a gated square quantum well (QW), in which the effective thickness $\lambda/\ell_B$ as well as the electron wave function in the well can be tuned by a pair of top-bottom gates. The specimens were fabricated from symmetrically Si-doped 35-nm-width GaAs-$Al_{0.3}Ga_{0.7}As$ QW grown by molecular-beam epitaxy on the (001) GaAs substrate, with a 70 nm spacer from either side. 2DES has a density $n_s\approx3.5\times10^{11}/\mathrm{cm}^2$ and a high mobility $\mu\geq3\times10^6$ $\mathrm{cm}^2/\mathrm{V\,s}$ at low temperatures. Total of five specimens were measured and similar data were obtained from all specimens. The specimens were patterned in either a $5\times5$ $\mathrm{mm}^2$ Van der Pauw square (with 8 $\Omega$ contacts diffused around the perimeter) or a 200-$\mu$m-width Hall bar. On gated Hall bar, front- and back-electrostatic gates were processed using a flip-chip technique.[29] Experiments were performed in National High Magnetic Field Laboratory (NHMFL) using a $^3$He-$^4$He dilution refrigerator combined with either a resistive or a hybrid magnet. A base temperature of 50 mK was attained in magnetic field up to 45 T.

Our main results are represented by the data shown in Fig. 1. At low temperatures, the longitudinal resistance at $\nu=1/2$, $R_{xx}(\nu=1/2)$, exhibits a steep valley that is flanked by a pair of rising resistance peaks. The $R_{xx}(\nu=1/2)$ shows a nonmonotonous dependence on $T$, with a minimum resistance reached at $T\sim0.5$ $K$. Moreover, here (as will be shown in Fig. 2) the concomitant $R_{xy}$ is not strictly linear in $B$; its slope in the vicinity of $\nu=1/2$ shows a sharp cusp.

We shall first focus on the $T$ dependence of diagonal resistance, emphasizing the following observations. (1) Temperature-dependent resistivity $\rho_{xx}$ (which scales with $R_{xx}$) exhibits different signs in $d\rho_{xx}/dT$, as is shown in the right-top panel. In a higher-temperature range between $\sim0.5$ K$<T<1.5$ K, the resistivity at $\nu=1/2$, $\rho_{xx}(\nu=1/2)$,

 

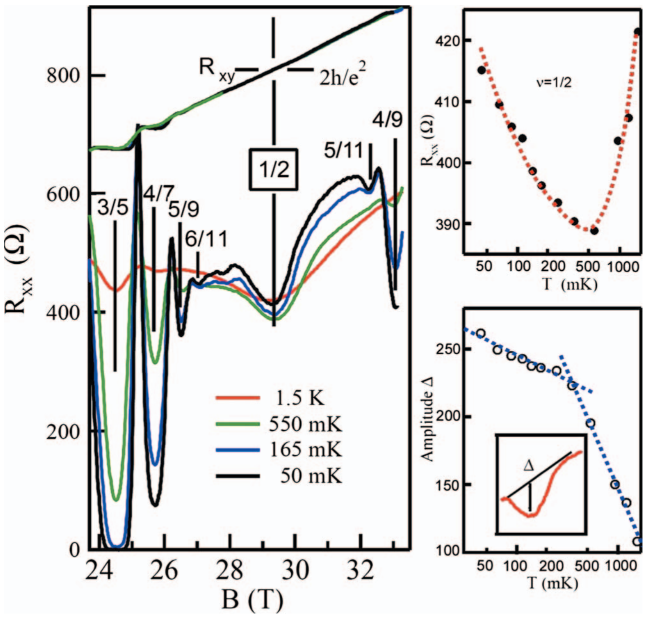


FIG. 1. (Color) The diagonal resistance $R_{xx}$ and Hall resistance $R_{xy}$ near Landau level filling factor $\nu=1/2$ measured in a 35 nm GaAs/AlGaAs QW sample at various temperatures in magnetic field up to 33 T. (Right top panel) the temperature dependence of the resistance at $\nu=1/2$; (right bottom panel) the temperature dependence of the strength of the valley-peak structure around $\nu=1/2$. The dotted lines are guides for the eyes.

decreases with $T$, whereas for $T<0.5$ K, it is increasing with lowering $T$ down to 50 mK, the $T$ lowers in this experiment. In both regimes, the $\rho_{xx}(\nu=1/2)$ is approximately linear with log $T$. (2) On both sides of the half-filling, i.e., $\nu<1/2$ and $\nu>1/2$, the $\rho_{xx}$ increases in lowering $T$, and the resistivity feature around $\nu=1/2$ can be characterized by a steep dip being developed in low temperatures. In the right-bottom panel, the amplitude of resistivity difference, defined as $\Delta\rho_{xx}=\frac{1}{2}(\rho_1+\rho_2-2\rho_{\min})$, is plotted against $T$, where the data can be approximately fit into two lines, and two lines intersects at around 0.35 K. (3) The above features are observed in a relatively narrow filling factor range, where the FQHE states are absent. Specifically, the strong $T$ dependent $\rho_{xx}$'s were observed in the range 27 $\text{T}<B<32$ T, bounded by clearly resolved 6/11 and 5/11 minima. In $T<200$ mK, reproducible $\rho_{xx}$ fluctuations emerge in this magnetic field range (see, e.g., the small amplitude peak-valley-like structure near 27.5 T). The pattern resembles FHQE minima but cannot be assigned to the standard CF series $\nu=p/(2p\pm1)$ around $\nu=1/2$.

We next turn to the Hall resistivity $\rho_{xy}$ at the $\nu=1/2$, which does not follow a strictly classical, i.e., linear with $B$, pattern. We show in Fig. 2 the $\rho_{xy}$ measured in a Hall bar specimen, along with its derivative $B\cdot d\rho_{xy}/dB$, which is obtained numerically on the data of $\rho_{xy}$. From $B\cdot d\rho_{xy}/dB$, the FQHE series around $\nu=1/2$ as well as that around $\nu=3/2$ are clearly observed. We reaffirm that the resistivity rule[30–34] is valid in the FQHE regime in our QW.

We focus on the sharp cusp in $B\cdot d\rho_{xy}/dB$, observed at $\sim\pm29.5$ T, i.e., $\nu=1/2$, as is shown in Fig. 2. The data show unequivocally that the Hall resistivity near $\nu=1/2$ is

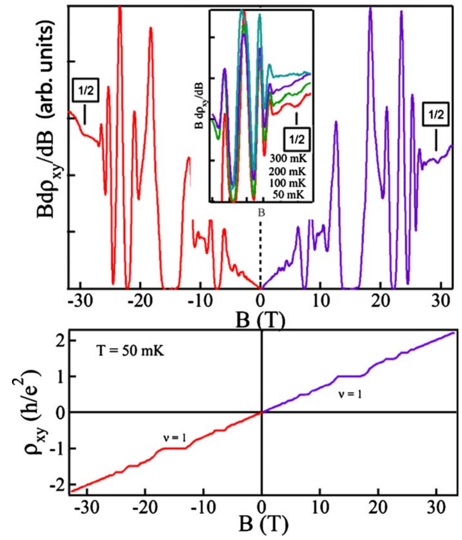


FIG. 2. (Color online) First derivative of Hall resistance with respect to magnetic field shows a sharp minimum at $\nu=1/2$. The inset shows temperature dependence of the derivative; notice that a sharp cusp develops below $T\sim200$ mK.

not classical, as opposed to the metallic behavior proposed for a homogeneous CF metal. More strikingly, the temperature dependence of the data (inset) shows that such sharp cusp develops at a low temperature, below $T\sim200$ mK. We also notice that the cusp is much narrower than the $\rho_{xx}$ minimum around $\nu=1/2$, which indicates a strong deviation from the resistivity rule[30–34] in this filling factor range.

We present the following evidences, supporting the single-layer origin of the observed magnetotransport near $\nu=1/2$. Figure 3(a) shows the simulated electron wave functions corresponding to, respectively, the subbands $E_1$ and $E_2$ at 4 K and in zero-magnetic field using the materials parameters for the 35 nm QW. The calculations have taken into account the Coulomb and Hartee-Fock exchange energies. The subband splitting is $\Delta_{12}=E_2-E_1\approx82.5$ K, corresponding to $\alpha\equiv\Delta_{12}/(e^2/\varepsilon\ell_B)\sim0.3$, hence a single-layer 2DES.[23] The distribution of electrons along the $z$ direction can be characterized by a finite thickness $\lambda=29.5$ nm and we estimate $\beta\approx6$ for $\nu=1/2$ at 30 T. We also calculate pseudopotential ratio $V_1/V_3$ for our sample at $\nu=1/2$. Comparing with the ideal Coulomb interaction, $V_1/V_3$ is about 10% smaller for our sample, whereas, $V_1/V_3$ is about 17% smaller at $\nu=5/2$.[20] The repulsive part of the Coulomb interaction is reduced for our sample due to finite thickness, but the 2DES remains as a single layer.

Figures 3(b) and 3(c) show, respectively, the low-$B$ and the high-$B$ diagonal resistances in a gated Hall bar sample. By independently applying the gate potential to the front and the back gates, we were able to tune the symmetry of the electron profile along the $z$ direction, while keeping the electron density constant. The beats in SdH shown in case (B) indicate the occupation of the second subband with a density of $3\times10^{10}/\text{cm}^2$ and the electron profile is symmetric; (A) and (C) show that the electrons occupy only the lowest subband as the QW being tuned to asymmetric. It is an important observation that the shape of the diagonal resistance

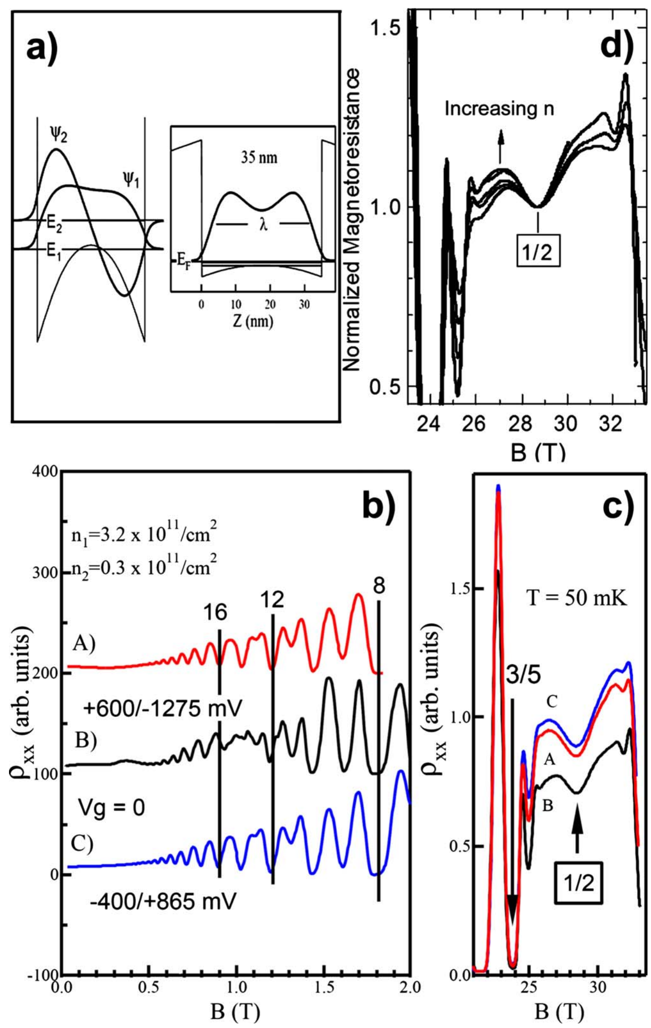


FIG. 3. (Color online) (a) Simulations of the electron wave function, electron-density distribution, and energy separation $\Delta_{12} = E_2 - E_1$, of the first excited subband from the ground-state band for the 35 nm QW. (b) Using a front gate and a back gate, the electron distribution in the QW is tuned toward front (a), back (c), and symmetrical (b); traces are shifted vertically for clarity. (c) The $\nu = 1/2$ magnetoresistance minimum is not dependent on the electron distribution, indicating a single-layer behavior. (d) Using a front gate and a back gate, the electron distribution is tuned to symmetrical at various densities; the relative strength of the $\nu = 1/2$ minimum is shown to be enhanced as the electron density increases. The electron densities represented are, respectively, 2.73, 3.10, 3.47, 3.78, and $3.91 \times 10^{11}/\mathrm{cm}^2$. For comparison, $R_{xx}$ is normalized by the value at $\nu = 1/2$ and the magnetic field axis is scaled with an electron density of $3.47 \times 10^{11}$ cm$^2$ ($V_g = 0$).

does not depend on the QW symmetry. We further examine the transport near $\nu = 1/2$ in the gated QW by keeping the QW symmetric while tuning $n_s$ shown in Fig. 3(d). In this plot, the electron density varies from 2.73 to $3.91 \times 10^{11}/\mathrm{cm}^2$, corresponding to approximately $5.5 < \lambda/\ell_B < 6.5$. We observe that the resistance minimum becomes steeper with increasing $\lambda/\ell_B$.

In addition, we have checked the $\nu = 1/2$ features in a tilted magnetic field [Fig. 3(d)] and found that such features remain robust in all the tilt angles measured (up to tilt angle 35°). On the contrary, the known bilayer $\nu = 1/2$ FQHEs are extremely sensitive to either an asymmetry of the electron distribution or a modest in-plane magnetic field.[23] We thus conclude that experimental observations exclude the transport features near $\nu = 1/2$ in our QW being a bilayer origin.

In summary, in a QW 2DES with a well width 35 nm, low-temperature magnetotransport experiments in magnetic field up to 45 T have uncovered remarkable features near $\nu = 1/2$. In low temperatures (<200 mK), the $\rho_{xx}$ exhibits a sharp nonmonotonous temperature-dependent minimum centered at $\nu = 1/2$. The concomitant $\rho_{xy}$ is not classical; its slope in the vicinity of $\nu = 1/2$ shows a sharp cusp. Moreover, the resistance around $\nu = 1/2$ shows a pair of rising peaks and reproducible peak-valley-like structures. The data are characteristic for ultra high field magnetotransport around $\nu = 1/2$ in thick, but single-layer, quantum wells.

Surprisingly, the $T$ dependence of $R_{xx}(\nu = 1/2)$ here (as well as that in Ref. 25) remarkably resembles the Kondo resistance in metals with dilute magnetic impurities.[35] Kondo effect (in zero-magnetic field) in this QW can be ruled out based on that (1) we have measured the $T$ dependence of the resistance of the same QW at $B = 0$ and have not found any Kondo-like minimum down to temperature 50 mK and that (2) high-mobility 2DES with similar mobility of ours contains rather low concentration of residual impurities,[36] less than $10^{13}/\mathrm{cm}^3$, whereas Kondo effect occurs within a typical transition-metal impurity concentration on the order of 1 ppm (approximately $\sim 10^{15}/\mathrm{cm}^3$) to 1000 ppm.[35] We therefore believe that residual impurities (if any magnetic) here are too dilute to cause Kondo effect in zero-magnetic field. Moreover, in high magnetic fields, such as 30 T, the CF states are fully spin polarized[37] and Kondo mechanism is unlikely relevant.

At this point, there exists no satisfactory theoretical explanation for these dramatic observations. Interactions between CFs play important role and may influence magnetotransport near $\nu = 1/2$. For example, a logarithmic correction to Hall conductivity due to interaction of CFs is considered to account for modest positive magnetoresistance around $\nu = 1/2$.[28] On the other hand, current theories based on a homogeneous CF Fermi sea cannot explain the peculiar temperature dependence of $R_{xx}(\nu = 1/2)$ and a sharp cusp in concomitant Hall resistance around $\nu = 1/2$. We interpret our data as being indicative of competing CF phases in the vicinity of $\nu = 1/2$. Phenomenologically, the temperature-dependent steep positive magnetoresistance around $\nu = 1/2$ resembles the magnetoresistance around $\nu = 5/2$ in Ref. 6, which develops into re-entrant insulating phases in very-high mobility QWs.[8] It would be interesting to examine whether there exist novel inhomogeneous phases[16,17] in the vicinity of $\nu = 1/2$, which are competing with the homogeneous CF phases.

We acknowledge many helpful conversations with D. C. Tsui, H. L. Stormer, W. Pan, C. L. Yang, Y. W. Sue, J. K. Jain, Y. S. Wu, E. H. Rezayi, and X. C. Xie. This work was supported by DOE Grant No. DE-FG02-06ER46274. A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-0084173, by the State of Florida, and by the DOE.

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