Correlated States of an Electron System in a Wide Quantum Well

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Magnetotransport experiments on a low-disorder electron system in an 800 Å wide GaAs quantum well reveal a dramatic evolution from a double- to a single-layer system as the electron density is decreased or the system is made asymmetric. At an intermediate density of 9.7×10^{10} cm^{-2}, we observe fractional quantum Hall states at Landau level filling factors of $\nu=\frac{3}{5}$, $\frac{1}{2}$, and $\frac{1}{3}$, with an insulating phase separating the $\nu=\frac{1}{2}$ and $\frac{1}{3}$ liquid states. Our data demonstrate that the $\nu=\frac{1}{2}$ state and the insulating phase are most stable in symmetric double-layer systems with appropriate parameters while the $\nu=\frac{1}{3}$ and $\frac{3}{5}$ states have a single-layer origin.

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Electrons at a remotely doped GaAs/AlGaAs heterojunction provide a nearly ideal system for studying electron correlations in two dimensions as manifested, in the presence of a strong magnetic field, by the observation of the fractional quantum Hall (FQH) effect [1]. New collective states at both integer and fractional Landau level filling factors ν and Wigner crystallization have been theoretically proposed for thick or multilayer systems which extend electron correlations in the third dimension [2-6]. Experiments facilitated by progress in epitaxial growth techniques have indeed recently uncovered novel behavior in such systems [7-11]. In particular, observations of new FQH states at the *even-denominator* $\nu=\frac{1}{2}$ have been reported for double-layer electron systems (DLES) in either a wide single quantum well [10] or a double quantum well [11]. No such state has ever been reported in spin-polarized, single-layer, two-dimensional electron systems (2DES), as expected from the standard FQH model for such systems which allows FQH states at exclusively odd-denominator ν [1,12]. In two-component systems, such as a spin-unpolarized 2DES or a DLES, however, the extra (spin or layer-index) degree of freedom can lead to even-denominator FQH states [2,4-6, 13]. In fact, a $\nu=\frac{1}{2}$ state had been predicted for a DLES with parameters similar to those in experiments of Eisenstein *et al.* [11], but very different from those of the system studied by Suen *et al.* [10]. The origin of the $\nu=\frac{1}{2}$ state in DLES in a wide single well is therefore unclear.

In this Letter, we present magnetotransport data for a very high quality, dilute DLES realized in a single 800 Å wide quantum well whose lower density allows us to reach $\nu<\frac{1}{2}$ in our accessible magnetic field. We vary the coupling and interaction between layers by changing the electron distribution and density n_s via the application of front- and back-gate biases. The data reveal a clear evolution from a double- to a single-layer system as n_s is decreased from 1.6×10^{11} to 6.7×10^{10} cm^{-2}, with remarkable behavior at intermediate n_s. For $n_s=9.7\times10^{10}$ cm^{-2}, we observe FQH states at $\nu=\frac{3}{5}$ and $\frac{1}{3}$ that remain stable regardless of the asymmetry in the electron distribution, and a FQH state at $\nu=\frac{1}{2}$ that persists in significantly asymmetric systems but disappears as the distribution is made grossly asymmetric. In the symmetric system with $n_s=9.7\times10^{10}$ cm^{-2}, we also observe an insulating phase which is reentrant around the $\nu=\frac{1}{3}$ FQH state and which disappears as n_s is lowered or the system is made asymmetric. Recent observations of reentrant insulating behavior near the much smaller $\nu=\frac{1}{5}$ in low-disorder, single-layer 2DES at GaAs/AlGaAs heterojunctions have been generally interpreted as consistent with a pinned Wigner solid [14,15]. We discuss our results in terms of calculations [3] which suggest that interlayer interactions in a multilayer electron system with appropriate parameters favor the formation of a Wigner solid at higher ν.

Our structure was grown by molecular beam epitaxy and consists of an 800 Å wide GaAs well bounded on each side by an undoped $Al_{0.35}Ga_{0.65}As$ spacer layer and Si δ-doped layers. When electrons are introduced in such a wide quantum well, the electrostatic repulsion between the electrons forces them into a stable configuration in

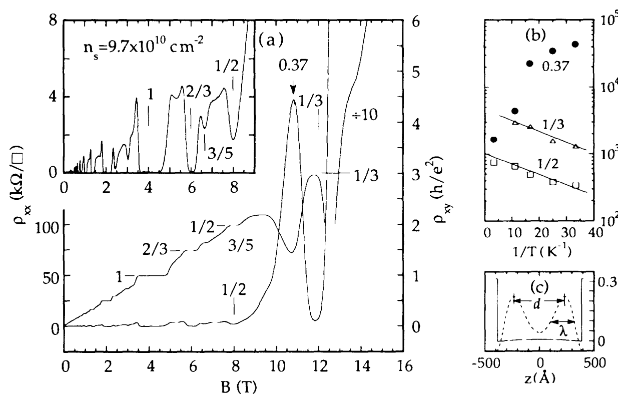

FIG. 1. (a) Magnetotransport data at $T\cong30$ mK for an 800 Å wide well with $n_s=9.7\times10^{10}$ cm^{-2} showing FQH states at $\nu=\frac{3}{5}$, $\frac{1}{2}$, and $\frac{1}{3}$. (b) The temperature dependence of ρ_{xx} for the $\nu=\frac{1}{2}$ and $\frac{1}{3}$ minima and the $\nu=0.37$ maximum. (c) Results of self-consistent calculations of the conduction band edge, E_c (solid curve), and the electron distribution (dashed curve). Also shown are the distance between two layers (d) and the full width at half maximum of each layer (λ).

TABLE I. Sample parameters.

n_s (10^{11} cm^{-2})	Δ_{SAS}^{meas} (K)	Δ_{SAS}^{calc} (K)	d (Å)	Mobility (10^6 cm^2/V s)
0.67	17	16	418	0.94
0.91	13.5	12.7	459	1.1
0.97	12.0	12.1	467	1.2
1.2	9.4	9.7	493	1.3
1.6	5.8	7.1	520	1.5

which two 2DES's are formed at the well's sidewalls. For details of our sample preparation and experimental setup we refer to our previous work [9,10]. In Fig. 1(c) we show the results of our zero-field, self-consistent Hartree-Fock calculations of the potential and the charge profiles for a symmetric distribution of $n_s=9.7\times10^{10}$ cm^{-2} electrons. The electrons occupy the lowest two subbands with symmetric and antisymmetric wave functions, respectively, and are separated in energy by Δ_{SAS}. The data in Table I show good agreement, at several n_s, between our calculated and experimentally measured Δ_{SAS} (determined from analysis of the low-field Shubnikov-de Haas data). Note that increasing n_s makes the distance (d) between the layers larger and Δ_{SAS} smaller. Reduction in the coupling between the layers with increasing n_s is a general property of the DLES in a wide quantum well [9]. Also listed in Table I are the measured mobilities for different n_s.

We apply front- and back-gate biases to change n_s and to bring the two electron layers into resonance by making the well potential symmetric. Since the difference between the two subband energies is larger than Δ_{SAS} if the system is not symmetric, we can achieve symmetry by minimizing the difference between the measured subband densities and scrutinizing the high-field data [9] while sweeping the gate biases and keeping n_s constant. We made measurements on over a dozen symmetric and purposely asymmetric systems with $6.7\times10^{10}\lesssim n_s\lesssim1.6\times10^{11}$ cm^{-2} and $17\gtrsim\Delta_{SAS}\gtrsim6$ K.

In Fig. 1(a) we show the diagonal (ρ_{xx}) and Hall (ρ_{xy}) resistivities as a function of the magnetic field (B) for a symmetric system with $n_s=9.7\times10^{10}$ cm^{-2}. The data reveal a number of integer and FQH states, including the following features in the $\nu<\frac{2}{3}$ range: (1) Our earlier work [10] is confirmed by the observation of a $\nu=\frac{1}{2}$ state with a ρ_{xy} quantized at $2h/e^2$ to better than 0.2% and a temperature activated ρ_{xx} [Fig. 1(b)] which gives an energy gap of $^{1/2}\Delta\sim80$ mK. (2) We observe the first clear odd-*numerator* fractional states (except for the $\frac{1}{2}$ state) in a DLES at $\nu=\frac{3}{5}$ and $\frac{1}{3}$ and weak ρ_{xx} features at $\nu=\frac{2}{5}$ and $\frac{2}{7}$. As we will discuss below, our data show that the $\nu=\frac{3}{5}$ and $\frac{1}{3}$ states have a single-component character. (3) Remarkable insulating behavior is observed near $\nu=\frac{1}{5}$, especially at $\nu=0.37$. The data in Fig. 1(b) show that $\rho_{xy}(\nu=\frac{1}{3})\rightarrow3h/e^2$ and $\rho_{xx}(\nu=\frac{1}{3})\rightarrow0$ while $\rho_{xx}(\nu=0.37)$ increases dramatically as $T\rightarrow0$, indicating a FQH state at $\nu=\frac{1}{3}$ and an insulating phase (IP) at $\nu=0.37$ [16].

Figure 2 shows the dramatic evolution of the symmetric system as n_s is varied by about $\pm30\%$. In Fig.

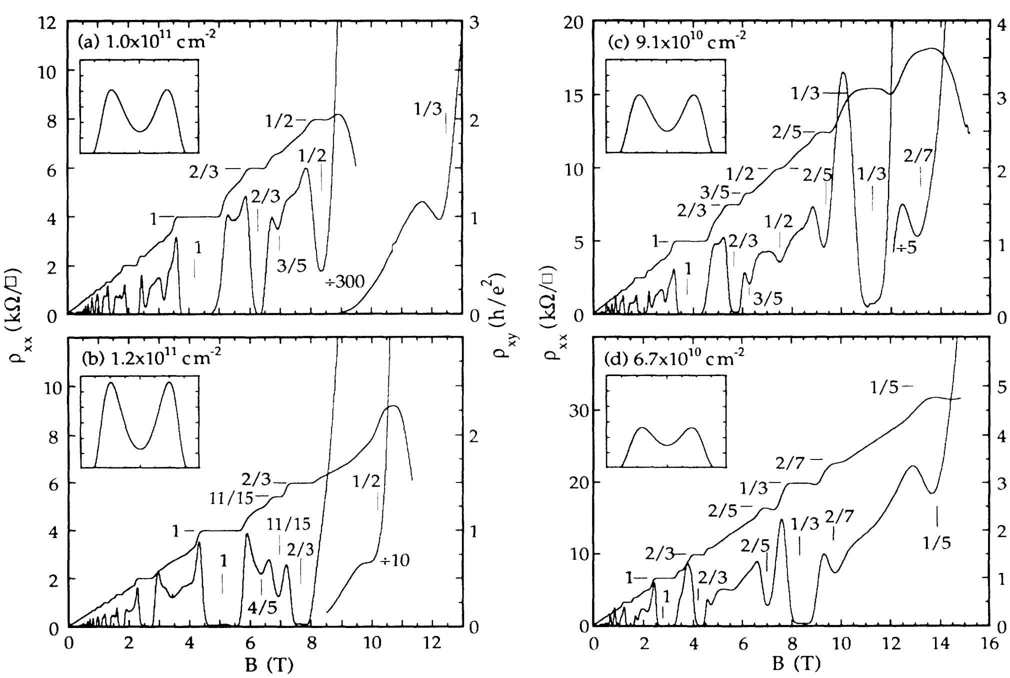

FIG. 2. The evolution of the FQH states in an 800 Å wide well with symmetric charge distribution as n_s is varied. All the data were taken at $T\cong30$ mK. Insets: The calculated electron distributions.

2(a), n_s is only 4% larger than in Fig. 1, but while the $\nu=\frac{1}{2}$ state is similarly strong, the $\nu=\frac{3}{5}$ and especially the $\nu=\frac{1}{3}$ states are weaker and the IP has moved to larger ν. When n_s is further increased [Fig. 2(b)], the $\nu=\frac{3}{5}$ and $\frac{1}{3}$ states disappear as the IP moves closer to $\nu=\frac{2}{3}$ and the $\nu=\frac{1}{2}$ state becomes very weak. The data in Fig. 2(c) are taken for n_s only ~6% smaller than Fig. 1, but show many changes: a weaker $\nu=\frac{1}{2}$ state, a substantially stronger $\nu=\frac{1}{3}$ state, deep ρ_{xx} minima near $\nu=\frac{2}{5}$ and $\frac{2}{7}$, and a ρ_{xx} maximum between $\nu=\frac{2}{5}$ and $\frac{1}{3}$ which is ~15 times smaller than in Fig. 1. The traces in Fig. 2(c) have a noteworthy resemblance to data observed for single-layer 2DES except for the presence of the $\nu=\frac{1}{2}$ state [1]. Data for the lowest n_s shown in Fig. 2(d) reveal that the $\nu=\frac{1}{2}$ state has disappeared while all the odd-denominator FQH states are stronger and, in particular, a $\nu=\frac{1}{5}$ FQH state has emerged.

To further illustrate the origin of the FQH states in our system, we applied front- and back-gate biases to change the relative populations of the electrons near the front or back walls of the well while keeping n_s constant. Examples of data for such asymmetric systems are shown in Figs. 3(a)-3(c). All three systems have $n_s \cong 9.7\times10^{10}$ cm^{-2}, but each has a different amount of charge Δn_t transferred from one side of the well to the other. From the values of front- and back-gate voltages used, we estimate Δn_t to be about 8×10^9, 1.2×10^{10}, and 1.7×10^{10} cm^{-2} for the three systems shown in Fig. 3. The data indicate that as the system becomes more asymmetric, the $\nu=\frac{1}{2}$ state gradually weakens and eventually disappears while all the odd-denominator states at $\nu=\frac{3}{5}$, $\frac{2}{5}$, $\frac{1}{3}$, and $\frac{2}{7}$ remain the same or become stronger [17]. The $\nu=\frac{1}{2}$ state is clearly strongest in the symmetric DLES, but is still stable in systems with substantial asymmetry. Its presence in the system of Fig. 3(b), where we estimate that one side of the well has 1.7 times the density of the other, is particularly remarkable [18].

We summarize our experimental observations before discussing their implications. (1) In our 800 Å wide well the $\nu=\frac{1}{2}$ state is observed in symmetric DLES with $9\times10^{10} \lesssim n_s \lesssim 1.1\times10^{11}$ cm^{-2}. Referring to Table I and Fig. 1(c), this range corresponds to $5 \lesssim d/l \lesssim 6$, $\lambda/l \sim 2.6$, and $0.07 \lesssim \Delta_{SAS}/(e^2/\epsilon l) \lesssim 0.09$ where $l=(\hbar/eB)^{1/2}$ is the magnetic length and ϵ is the dielectric constant for GaAs. (2) The $\nu=\frac{1}{2}$ FQH state is strongest for symmetric DLES with $n_s=9.7(\pm0.3)\times10^{10}$ cm^{-2} and is flanked by the odd-numerator $\nu=\frac{3}{5}$ and $\frac{1}{3}$ states. As the DLES is made asymmetric or n_s is lowered, the $\nu=\frac{1}{2}$ state becomes weaker and then disappears while the $\nu=\frac{1}{3}$ and $\frac{3}{5}$ states remain as strong or get stronger. These observations clearly demonstrate that the $\nu=\frac{1}{2}$ state is most stable in symmetric DLES with appropriate parameters while the $\nu=\frac{1}{3}$ and $\frac{3}{5}$ states have a single-layer origin.

At present there are two possible theoretical explanations proposed for a FQH state at $\nu=\frac{1}{2}$ in our system. The first is based on generalized two-component Laughlin

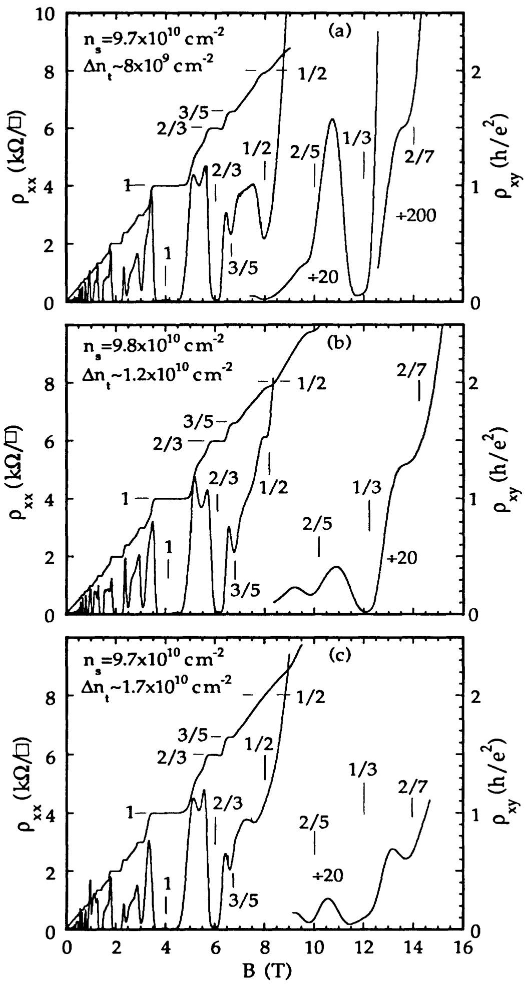

FIG. 3. The evolution of FQH states for an 800 Å wide well with $n_s=9.7\times10^{10}$ cm^{-2} as the charge distribution is made more asymmetric. Δn_t denotes our estimate for the charge transferred from one side of the well to the other at zero B.

(Jastrow) wave functions first proposed by Halperin [13] for a spin-unpolarized 2D system and later adopted to DLES [5,6]. Numerical calculations, which are generally done for few-particle systems and typically assume two idealized 2D sheets of electrons with little or no tunneling, predict new FQH states for a DLES. In particular, the two-component $\Psi_{3,3,1}$ and $\Psi_{5,5,1}$ states are proposed to be FQH ground states at $\nu=\frac{1}{2}$ and $\frac{1}{3}$, respectively [5,6]. The $\Psi_{3,3,1}$ state is predicted to be stable for $d/l \sim 2$, consistent with the recent experimental observation of a $\nu=\frac{1}{2}$ FQH state in DLES in double quantum wells with $d/l<3$ and little tunneling [11]. It is clear from our data that the $\nu=\frac{1}{3}$ state in our DLES has a single-component origin and is *not* the $\Psi_{5,5,1}$ state. Whether our $\nu=\frac{1}{2}$ state corresponds to the $\Psi_{3,3,1}$ state is less clear. The parameters d/l and Δ_{SAS} for the DLES where we observe a $\nu=\frac{1}{2}$ state are much larger than those of Ref. [11] and are well outside the range where the theories predict a stable $\nu=\frac{1}{2}$ state, although according to recent calculations performed by He [19] for the specific DLES of Ref. [10], the $\Psi_{3,3,1}$ may still be a good ground state at $\nu=\frac{1}{2}$. However, associating the $\nu=\frac{1}{2}$ state in our system with $\Psi_{3,3,1}$ raises a number of interesting questions. First, it implies that in a given system, we observe single-component states at $\nu=\frac{3}{5}$ and $\frac{1}{3}$ on the two sides of the two-component $\Psi_{3,3,1}$ state. Second, the $\nu=\frac{1}{2}$ state in our DLES is present even when the system is significantly asymmetric. Third, unlike the DLES of Ref. [11], the $\nu=\frac{1}{2}$ state in our system is very sensitive to the application of an in-plane magnetic field [10]. It will be interesting to see whether the calculations based on the $\Psi_{3,3,1}$ state can explain these experimental observations.

An alternative candidate for the $\nu=\frac{1}{2}$ state is the "paired Hall state" of Greiter, Wen, and Wilczek [20] which is a novel FQH state in a new universality class of incompressible liquids. In a ten-electron calculation, they show that the reduced short-range component of Coulomb repulsion in a single-layer 2DES with sufficiently large layer thickness, or in a DLES like ours, may lead to a stable $\nu=\frac{1}{2}$ FQH state. The data presented here are qualitatively consistent with these calculations. However, it is worth emphasizing that no $\nu=\frac{1}{2}$ FQH state has so far been observed in wide parabolic wells which contain high-quality 2DES with very large layer thicknesses (3 to 7 times l) [8].

In summary, we have presented here a collection of experimental data on the evolution of a DLES as the electron distribution is made more asymmetric or as n_s is varied. We hope that these results lead to an understanding of the origin of the $\nu=\frac{1}{2}$ FQH state in DLES in wide single quantum wells by providing a test of more quantitative calculations for the specific parameters and conditions of our experiments.

Finally, we focus on the IP observed for $n_s \gtrsim 9.5\times10^{10}$ cm^{-2} in our symmetric system. For $n_s=9.7\times10^{10}$ cm^{-2} the IP is reentrant around a well developed $\nu=\frac{1}{3}$ FQH state (Fig. 1). The observation of a $\nu=\frac{1}{3}$ FQH liquid and, at the same time, an IP at ν larger than $\frac{1}{3}$ strongly suggests that single-particle localization is not responsible for the IP. Our measurements also show strong nonlinear I-V characteristics in the $\frac{1}{3}<\nu<\frac{1}{2}$ regions. These features are surprisingly similar to recent observations in low-disorder single-layer 2DES at GaAs/AlGaAs heterojunctions at much smaller $\frac{1}{5}<\nu<\frac{2}{9}$ [14,15]. The 2DES results have been generally interpreted as consistent with the formation of a pinned Wigner crystal reentrant near the $\nu=\frac{1}{5}$ FQH state. Similar interpretation of the data in Fig. 1 implies that in our DLES the ground-state energies of the FQH liquid and Wigner solid are significantly modified by interlayer interactions so that a crossing of the liquid and solid states occurs at such a markedly larger ν.

This is plausible. Oji, MacDonald, and Girvin [3] have calculated the effect of interlayer coupling on the magnetoroton modes of multilayer systems. They find that the effect of coupling is particularly strong near the magnetoroton minimum and, in multilayer systems with appropriate parameters, can lead to the vanishing of the FQH liquid gap. This vanishing, they argue, can be associated with an instability toward a ground state in which each of the layers condenses into a 2D Wigner crystal. Although the parameters of our system are again different from those of the calculations of Ref. [3], these calculations and the data of Fig. 1 are certainly suggestive.

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