Observation of a $\nu=1/2$ Fractional Quantum Hall State in a Double-Layer Electron System

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We report the observation, for the first time, of a fractional quantum Hall state at $\nu=1/2$ Landau-level filling in a low disorder, double-layer electron system realized in a 680-Å-wide GaAs/AlGaAs single quantum well. A nearly vanishing diagonal resistance and a Hall resistance quantized at $2h/e^2$ to within 0.3% are observed at $\simeq 15$ T and $\simeq 26$ mK. The activated temperature dependence of the diagonal resistance minimum yields a quasiparticle excitation energy gap of 230 mK.

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In a standard hierarchy picture [1], assuming that the two-dimensional (2D) electrons are all spin polarized, the fractional quantum Hall (FQH) states can only be realized at Landau-level filling factors (ν) with odd denominators. This restriction to odd denominators is a result of the Fermi statistics which requires antisymmetry under particle exchange. If the condition of a spin-polarized ground state is relaxed, FQH states at even-denominator ν become possible [2]. This is the explanation given by Haldane and Rezayi [3] for the experimental observation of the $\nu=5/2$ FQH state [4] which has been seen only at relatively low magnetic fields where the Zeeman energy is small [5]. For other even-denominator fillings, and especially for $\nu=1/2$, although many transport anomalies have been reported for the 2D electron systems in $GaAs/Al_xGa_{1-x}As$ heterostructures [6–8], no evidence of a FQH state has yet been found [9].

Another candidate for the possible observation of an even-denominator FQH state [10] is a double-layer electron system (DLES) where the layer index can be treated as a pseudospin to take into account the additional degrees of freedom. Recent numerical studies [11,12] show that the FQH state at $\nu=1/2$ can be stabilized in a DLES with an appropriate d/l_B, where d is the separation between the layers and $l_B=(\hbar/eB)^{1/2}$ is the magnetic length. Experimentally, a DLES can be realized in a double quantum-well structure [13] where two sheets of electrons are separated by a high band-gap barrier, or in a wide, single, quantum well [14] where the electrons are separated by their own electrostatic repulsion. Experiments in these systems have shown that strong magnetic fields can destroy or weaken [13,14] the integral quantum Hall (IQH) states at odd ν corresponding to the symmetric-antisymmetric energy gap (Δ_{SAS}); this phenomenon has been attributed to the competition between the interwell and intrawell Coulomb interactions [15,16]. However, no observation of a $\nu=1/2$ FQH state has been reported in a DLES prior to this work.

In this Letter, we present IQH and FQH effect data in a high-quality DLES realized in a wide, single, GaAs quantum well. We observe a well-developed FQH state at $\nu=1/2$ with a nearly vanishing diagonal resistance (R_{xx}) and a Hall resistance (R_{xy}) quantized at $2h/e^2$ to within 0.3%. The temperature-activated behavior of R_{xx} allows us to determine the energy gap for the quasiparticle excitations of the $\nu=1/2$ state. The data provide clear evidence, for the first time, for a $\nu=1/2$ FQH state in a DLES.

The idea of realizing a DLES in a wide quantum well and the experimental details were reported in our previous work [14]. Our structure consists of a ~680-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. We used molecular-beam epitaxy to grow this structure. Ohmic contacts were made by alloying In:Sn (80:20) in a H_2 ambience at 430 °C for about 10 min. An evaporated Al front-side gate and an In back-side gate were used to change the densities of the two electron layers. The sample has a van der Pauw geometry and the magnetotransport measurements were performed in a top-loading dilution refrigerator with a base temperature (T) of ~25 mK and in a superconducting magnet with a maximum field (B) of 15.5 T. The sample was mounted on a pivoted platform which could be tilted *in situ* to change the angle (θ) between the sample plane normal and B.

We first describe the electronic structure of our system and its characterization from the low-B magnetotransport data. Figure 1 shows the results of our zero-field, self-consistent Hartree-Fock calculations of the potential and the charge profile for $n_s=1.8\times10^{11}$ cm^{-2} electrons symmetrically distributed in the well [17]. The electrons occupy the lowest two subbands which have symmetric and antisymmetric wave functions, with Δ_{SAS} denoting the difference between the energies of these subbands. The electron distribution in Fig. 1 indicates the presence of two coupled electron layers, separated by a distance d. We experimentally determine Δ_{SAS} from the analysis of the data on the low-field ($\lesssim 0.5$ T) Shubnikov–de Haas effect. The Fourier transforms of R_{xx} vs $1/B$ data show two peaks corresponding to the densities of the two subbands. The sum of these subband densities equals the total density n_s which is independently measured from the quantum Hall data at high B. The difference between the two subband densities directly gives Δ_{SAS}. Our experimentally measured Δ_{SAS} for several n_s are listed in Table I, and are in good agreement with the calculated values. Note in Table I that the parameter d, which we define as the distance between the peaks in the charge-density profile (Fig. 1) and a measure of the interlayer separation, decreases as n_s is lowered. This is a property of the

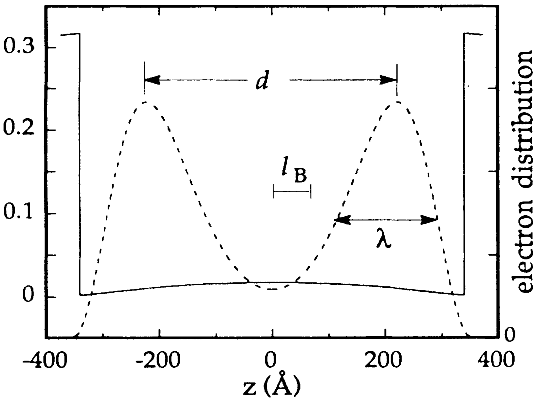

FIG. 1. Results of self-consistent calculations of the conduction-band edge (solid curve) and the electron distribution function (dashed curve) are shown for $n_s = 1.8 \times 10^{11}$ cm^{-2} electrons in a 680-Å well. A conduction-band offset $\Delta E_c = 0.9x$ eV for GaAs/Al$_x$Ga$_{1-x}$As and $m^*/m_0 = 0.067$ for the effective mass have been used. Also shown are the separation between the layers (d), the effective thickness (full width at half maximum) of each layer (λ), and the magnetic length (l_B) at ~15 T where the $\nu = 1/2$ state is observed.

DLES in a wide quantum well [14]. Also listed in Table I are the measured mobilities for different n_s.

In our measurements, we applied front and back gate biases to change n_s and also to "balance" the well, i.e., to make the well potential symmetric and bring the two electron layers into resonance. In the balanced condition, an example of which is shown in Fig. 1, two subbands with symmetric and antisymmetric wave functions and with energy separation Δ_{SAS} are occupied. The total charge distribution in the well, of course, is symmetric. For fixed n_s, if the system is slightly out of balance, the charge distribution is no longer symmetric and the difference between the two subband energies increases with respect to Δ_{SAS}. In our experiments, we judged the balanced condition by minimizing the difference between the measured subband densities and scrutinizing the high-field data [18], while sweeping the front and/or back gate biases and keeping n_s constant.

We now discuss the high-field data in our sample. Shown in Figs. 2(a) and 2(b) are R_{xx} and R_{xy} vs B data (with $\theta = 0°$) for $n_s = 3.1 \times 10^{11}$ and 2.8×10^{11} cm^{-2} at $T \simeq 26$ mK. All the IQH states with odd ν can be observed for $n_s = 2.8 \times 10^{11}$ cm^{-2} [Fig. 2(b)] for which Δ_{SAS}^{meas} is 7.4 K; however, there is no evidence of a $\nu = 1$ state for $n_s = 3.1 \times 10^{11}$ cm^{-2} [Fig. 2(a)] for which

TABLE I. Sample parameters.

n_s (10^{11} cm^{-2})	Δ_{SAS}^{meas} (K)	Δ_{SAS}^{calc} (K)	d (Å)	Mobility (10^5 cm^2/V s)
3.1	~5	6.3	485	8.9
2.8	7.4	7.4	475	8.9
2.3	8.6	9.5	460	7.0
1.8	13	12	445	6.5

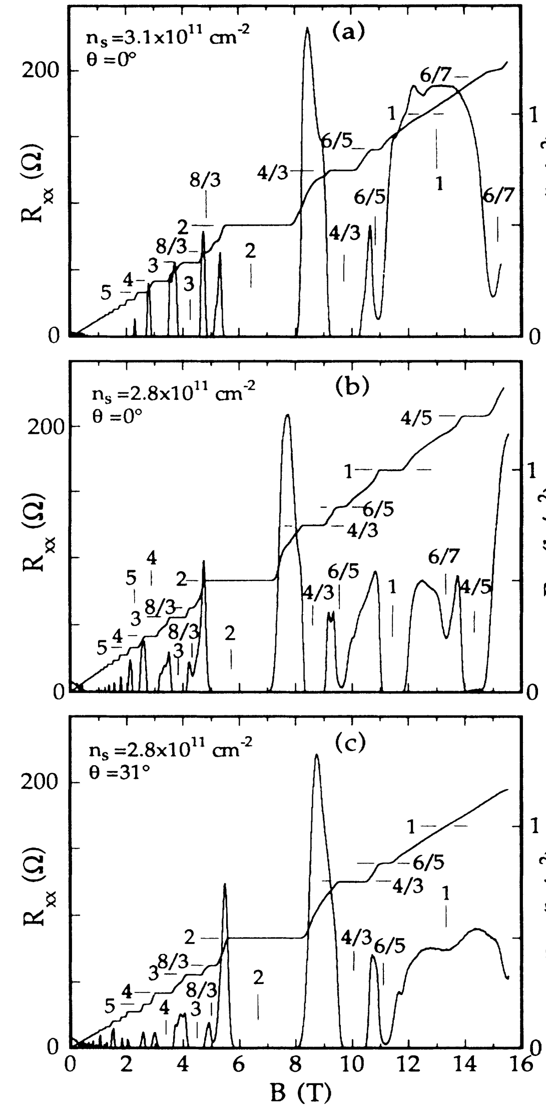

FIG. 2. The diagonal resistance (R_{xx}) and Hall resistance (R_{xy}) are shown for (a) $n_s = 3.1 \times 10^{11}$ cm^{-2} and (b) 2.8×10^{11} cm^{-2} in a balanced 680-Å-wide well in a perpendicular magnetic field ($\theta = 0°$). In (a), there is no evidence of the $\nu = 1$ IQH state while such a state exists in (b) where n_s is only ~10% lower. (c) The disappearance of the $\nu = 1$ IQH state in a tilted magnetic field ($\theta = 31°$). All traces were taken at $T \simeq 26$ mK.

$\Delta_{SAS}^{meas} \sim 5$ K. We attribute this phenomenon to the suppression of the Δ_{SAS} gap by the applied B [13-16,18]. As first demonstrated by Boebinger *et al.* [13], in double quantum wells with sufficiently small Δ_{SAS}, the application of a strong enough B leads to the collapse of Δ_{SAS} which is responsible for the IQH at odd ν. MacDonald, Platzman, and Boebinger [15] and Brey [16] have proposed theoretical explanations for this effect by using the single-mode and the Hartree-Fock approximations, respectively. Our data qualitatively agree with these theoretical results. However, for a quantitative compar-

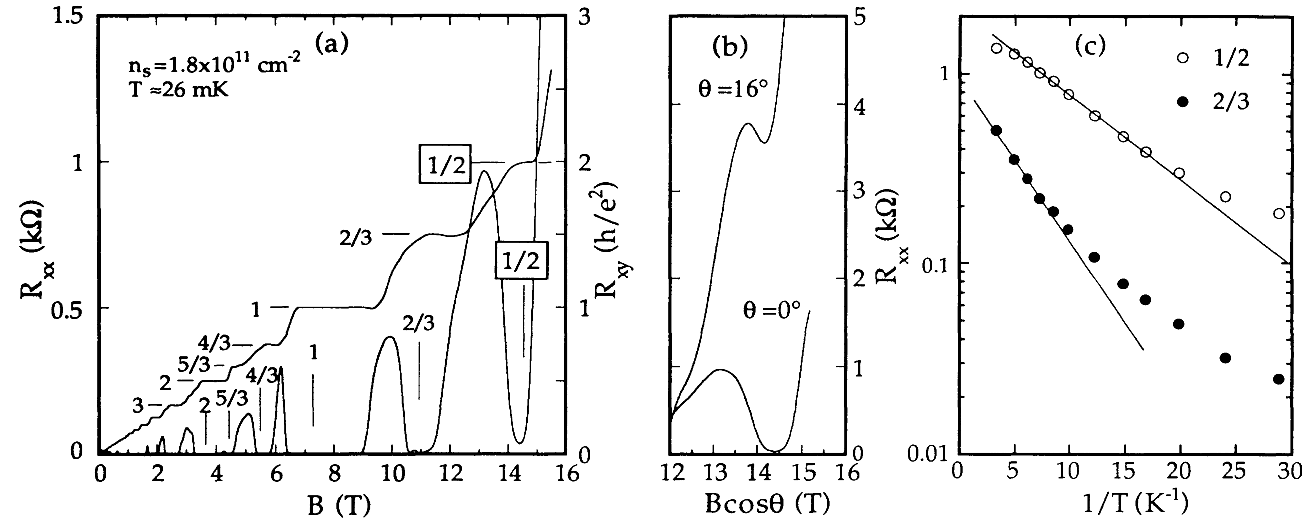

FIG. 3. (a) The magnetotransport data for $n_s=1.8\times10^{11}$ cm^{-2}. A FQH state at $\nu=1/2$ is observed with a deep R_{xx} minimum and a R_{xy} plateau quantized at $2h/e^2$ to within 0.3%. This 1/2 state becomes weak in a tilted magnetic field as shown in (b). The data were measured at $T\simeq26$ mK. (c) The temperature dependence of the R_{xx} minima at $\nu=1/2$ and 2/3. The quasiparticle excitation energy gaps extracted from the activated parts are 230 and 375 mK for $\nu=1/2$ and 2/3, respectively.

ison, further theoretical calculations which take into account the specific parameters of our DLES are needed. In Fig. 2(c), the disappearance of $\nu=1$ IQH state in a tilted B ($\theta\simeq31°$) is illustrated. This collapse of the Δ_{SAS} gap with the application of an in-plane B is also consistent with previous observations in DLES's [13,18].

In Fig. 3 we show data for $n_s=1.8\times10^{11}$ cm^{-2}. As expected from the larger Δ_{SAS} ($\simeq13$ K) for this n_s, the $\nu=1$ IQH state becomes much stronger. The striking features of these data, however, are the deep R_{xx} minimum and the R_{xy} plateau near the half-filling factor. Using the plateau at $\nu=1$ as a reference, we find that the $\nu=1/2$ plateau has a quantized value $2h/e^2$ to within 0.3%. The $\nu=1/2$ R_{xx} minimum is temperature activated in the range $50\lesssim T\lesssim200$ mK as shown in Fig. 3(c). Fitting the data in the activated region by the expression $R_{xx}\sim\exp(-\Delta/2kT)$ gives an energy gap for the 1/2 FQH state: $^{1/2}\Delta\simeq230$ mK.

Several features of the observed $\nu=1/2$ state are worth emphasizing. (1) The state is observed at slightly lower n_s ($\simeq1.7\times10^{11}$ cm^{-2}) also. We could not lower n_s further because of limitations on the back gate bias. (2) In spite of the small size of the measured $^{1/2}\Delta$, the 1/2 state is fairly robust. By changing the front and back gate biases, we intentionally drove the well out of balance while keeping n_s constant. Using the experimentally determined change in subband separation as a measure of the balance, we found that the $\nu=1/2$ state is quite stable against small imbalance in the well: Changing the subband separation by a few percent did not destroy the state. (3) If the DLES is pushed further out of balance, however, the state disappears. (When the system is grossly out of balance, the electrons are transferred to one side of the well and the data indicate the presence of a single electron layer in the system.) This observation implies that the $\nu=1/2$ state in our structure is intrinsic to the DLES. (4) The state is quite sensitive to an in-plane B. Tilting B, we find that the 1/2 state gets much weaker for $\theta>10°$ [Fig. 3(b)], indicating that reduced tunneling and/or the deformation of the one-electron wave function play an important role in destabilizing the 1/2 state. (5) The separation and coupling between the two electron layers also seem to play a crucial role for the existence of the 1/2 state. In a high-quality DLES in a wider quantum well (well width of 1200 Å) with $n_s=1.7\times10^{11}$ cm^{-2}, in which $d=960$ Å and $\Delta_{SAS}=0.2$ K, we did not observe any evidence for a 1/2 state.

The possibility of a FQH state at $\nu=1/2$ in DLES's has been theoretically discussed in several papers [10–12]. The results in these papers are based on numerical calculations for few-particle systems. In Ref. [11] the DLES is modeled as two idealized, zero-thickness sheets of electrons and no tunneling was allowed. The layer index is treated as a pseudospin, and the system is equivalent to a single-layer 2D electron system in which the layer separation in effect reduces the short-range electron interaction potential [19]. Reference [12], on the other hand, models the confinement of the electrons by two δ-function potentials allowing some tunneling between the two layers. Although the models and the details of these calculations are different, the general theoretical prediction is that the $\nu=1/2$ FQH state is possible in DLES's, especially for $d/l_B\sim2$.

Our results provide clear experimental evidence for the existence of a $\nu=1/2$ FQH state in a high-quality DLES. While our observation is in qualitative agreement with the theoretical predictions, the parameter $d/l_B\simeq7$ for our system is significantly larger than $d/l_B\sim2$ near which the $\nu=1/2$ state is expected, from the calculations of Refs. [11,12], to be most stable. This is not surprising given that the confinement potential and electron distribution in our system are quite different from what the model calculations use. Even in the model of Ref. [12], where the finite thickness of the electron layers and tunneling are taken into account, the layers have an extremely narrow width ($\lambda \simeq 0.1 l_B$) compared to the width ($\lambda \simeq 2.7 l_B$ at 15 T) of the layers in our system (see Fig. 1). Therefore, the interlayer and intralayer interactions in our DLES are quite different from those of the theoretical models, and evidently lead to a stable $\nu = 1/2$ state in our system at $d/l_B \simeq 7$. For large enough values of d/l_B and sufficiently small λ, of course, it is clear that the interlayer correlations become weak, the DLES splits into two independent layers, and the 1/2 state can no longer be expected. Consistent with this expectation, we have not observed the $\nu = 1/2$ state in several DLES's with $d/l_B \gtrsim 8$ and $\lambda/l_B \lesssim 2.6$.

Our measured energy gaps for both the $\nu = 1/2$ and 2/3 states [Fig. 3(c)] are quite small compared to Δ for the odd-denominator FQH states such as the 1/3 or 2/3 in single-layer 2D systems. The experimentally measured gap for the 2/3 state in high-quality, single-layer 2D electron systems at similar B is about 10 K [20]. Our small ${}^{2/3}\Delta$ is not surprising, however, if we consider the large effective width of the electron distribution in our system. The FQH states at $\nu = 1/3$ and 2/3 are known to become weak in nearly-uniform-density, wide electron systems in parabolic quantum wells, when the width of the electron layer is greater than $\sim 3 l_B$ [21]. It is interesting to note that our measured ${}^{1/2}\Delta \simeq 230$ mK is comparable to the gap reported for the only other even-denominator FQH state observed so far, namely, ${}^{5/2}\Delta \simeq 100$ mK for the 5/2 state at $B \simeq 4$ T [22].

Finally, we point out an interesting observation on the strength of the FQH effect in our DLES. In Fig. 2(b) and some other lower n_s data with the 2/3 state in our B range, we observe a series of strong states at $\nu = 2$, 4/3, 1, 4/5, and 2/3 which are equally spaced along the B axis (and have equal incremental $1/\nu = 1/4$). The strength of these states is especially transparent from our data at higher temperatures (~ 350 mK) where only these states are observed at $\nu \leq 2$. In Fig. 3, the strong states in the range $\nu \leq 1$ are at $\nu = 1$, 2/3, and 1/2 which are again equally spaced in B (with equal incremental $1/\nu = 1/2$). The same sample at two different n_s ($\Delta n_s \approx 1 \times 10^{11}$ cm^{-2}) seems to show different sequences of FQH states. It is especially striking that in the high-n_s data the 4/5 state is as strong as the $\nu = 1$ state, whereas in the low-n_s data it is not resolved. At the present time, we have no understanding of these features; whether the FQH states indeed follow two sequences and what the causes are obviously require further theoretical and experimental work.

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