Evidence for Developing Fractional Quantum Hall States at Even Denominator 1/2 and 1/4 Fillings in Asymmetric Wide Quantum Wells

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We report the observation of developing fractional quantum Hall states at Landau level filling factors $\nu = 1/2$ and $1/4$ in electron systems confined to wide GaAs quantum wells with significantly *asymmetric* charge distributions. The very large electric subband separation and the highly asymmetric charge distribution at which we observe these quantum Hall states, together with the fact that they disappear when the charge distribution is made symmetric, suggest that these are one-component states, possibly described by the Moore-Read Pfaffian wave function.

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Thanks to their potential use in topological quantum computing [1], even-denominator fractional quantum Hall (FQH) states have recently become the focus of renewed attention. These states are enigmatic. In standard, single-layer two-dimensional electron systems (2DESs) confined to GaAs/AlGaAs heterojunctions or to narrow GaAs quantum wells, even-denominator FQH states are observed only in the excited Landau levels, primarily at filling factor $\nu = 5/2$ [2–4]. It is yet not known whether the spin degree of freedom is necessary to stabilize this state [4]. If so, then the $5/2$ state could be described by a two-component (2C) Laughlin-Halperin (Ψ_{331}) wave function [5]. But if it is stable in a fully spin-polarized 2DES, then it is likely the one-component (1C) Moore-Read Pfaffian state [6]. The latter is of particular interest as it is expected to obey non-Abelian statistics and have use in topological quantum computing [1].

The possibility of even-denominator FQH states in the *lowest* Landau level, e.g., at $\nu = 1/2$, has been theoretically discussed in numerous publications [6–13]. FQH states at $\nu = 1/2$ were seen in *bilayer* systems in either double [14] or wide [15–18] quantum well (WQW) systems; a $\nu = 1/4$ FQH state was also observed recently in WQWs [19,20]. In both systems, when the interlayer tunneling is small, the $1/2$ state is well described by the 2C Ψ_{331} wave function; in this case the "components" are the layer indices or, alternatively, the two (symmetric and antisymmetric) electric subbands. In bilayer systems with strong tunneling (large symmetric-to-antisymmetric subband splitting, Δ_{SAS}), however, the situation is unclear. While a Pfaffian FQH state can theoretically exist at $\nu = 1/2$ [7,9–13], experiments indicated that the $\nu = 1/2$ (and $1/4$) FQH states observed in WQWs are stable only when the overall charge distribution in the well is nearly symmetric ("balanced") and that the states disappear when the distribution is made asymmetric ("imbalanced") [16–19]. Moreover, for a given well width, the $1/2$ and $1/4$ FQH states weaken and eventually disappear when the density is reduced and Δ_{SAS} is sufficiently increased. These observations were taken as evidence that these FQH states are 2C [8,9,16–19].

Here we report signatures of $\nu = 1/2$ and $1/4$ FQH states in WQWs with significant charge distribution asymmetry and large subband separation. Ironically, when the charge distribution is made symmetric and the subband splitting is lowered, the states disappear. These observations suggest that these new FQH states are 1C and are possibly described by the Pfaffian wave function.

Our samples were grown by molecular beam epitaxy and consist of GaAs WQWs bounded on each side by undoped AlGaAs spacer layers and Si δ-doped layers. We present data on two samples, A and B, with well widths of 55 and 47 nm, respectively, and a mobility of $\simeq 250\ \mathrm{m}^2/\mathrm{V\,s}$ at a density of $n = 2 \times 10^{11}\ \mathrm{cm}^{-2}$. An evaporated Ti/Au front gate and a Ga back gate were used to change n and control the charge distribution symmetry. Transport coefficients were measured in a van der Pauw geometry in dilution refrigerators. We studied sample A at a temperature $T = 20$ mK in a superconducting magnet with a maximum magnetic field (B) of 15 T, and sample B at 35 mK in a hybrid magnet up to $B = 45$ T.

In Fig. 1(a) we show an example of the self-consistently calculated potential and charge distribution for $n = 1.72 \times 10^{11}\ \mathrm{cm}^{-2}$ electrons symmetrically distributed in a 55 nm WQW [21]. The electron system appears bilayerlike at this density and $\Delta_{\mathrm{SAS}} = 25$ K. A remarkable property of the electrons in a WQW is that both Δ_{SAS} and d (the interlayer separation), which characterize the interlayer coupling, depend on n: increasing n makes d larger and Δ_{SAS} smaller so that the system can be tuned from a (thick) single-layer-like electron system at very low n to a bilayer one by increasing n. This evolution with n plays a decisive role in the properties of the correlated electron states in this system [16–19]. Equally important is the symmetry of the charge distribution in the WQW. For a fixed n, as the charge distribution is made asymmetric, the separation (Δ_{01}) between the lowest two energy levels becomes larger than Δ_{SAS} and the system becomes increasingly single-

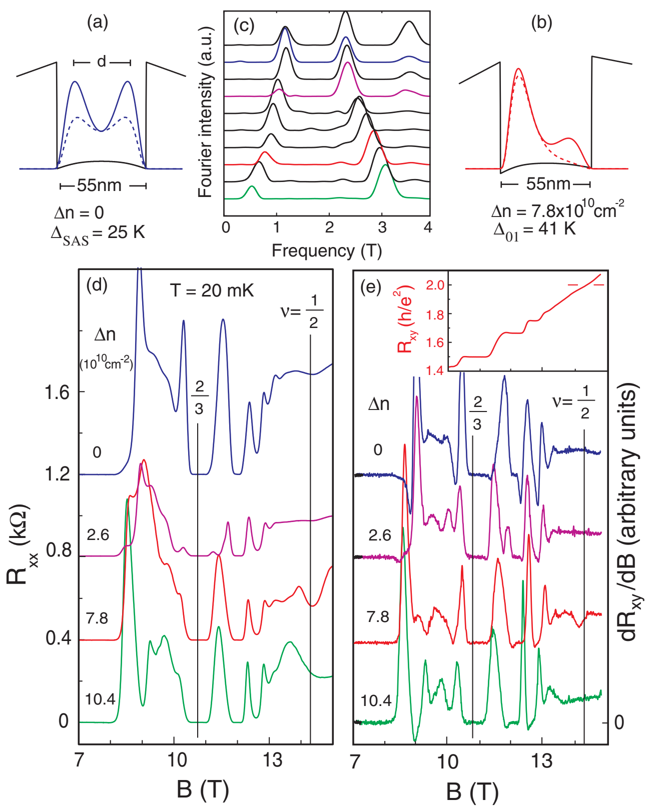

FIG. 1 (color online). (a),(b) Self-consistently calculated potential (black curves), total (solid blue and red curves), and the lowest subband charge distribution (dotted curves) for $n = 1.72 \times 10^{11}$ cm^{-2} electrons in a 55 nm-wide GaAs quantum well as the distribution is made asymmetric. (c) Fourier power spectra of the measured Shubnikov–de Haas oscillations for fixed $n = 1.72 \times 10^{11}$ cm^{-2} and different values of Δn ranging from -1.3 to 10.4×10^{10} cm^{-2} (top to bottom trace) for sample A. The peak at 3.6 T corresponds to the total density in the WQW while the lower two peaks correspond to the two subband densities. (d),(e) Evolution of the magnetoresistance traces at $n = 1.72 \times 10^{11}$ cm^{-2} and for different Δn as given on the left of each trace (in units of 10^{10} cm^{-2}). We observe a developing FQH state at $\nu = 1/2$ for $\Delta n = 7.8 \times 10^{10}$ cm^{-2}.

layer-like. Figure 1(b) shows an example of the calculated charge distribution for the case where n is the same as in Fig. 1(a) but electrons are transferred from one side of the WQW to the other side so that there is a layer density difference of $\Delta n = 7.8 \times 10^{10}$ cm^{-2}. As indicated in Figs. 1(a) and 1(b), the subband splitting increases from 25 K for $\Delta n = 0$ to 41 K for $\Delta n = 7.8 \times 10^{10}$ cm^{-2}. Again, the symmetry of the charge distribution has a profound effect on the correlated states in a WQW [16–19].

Experimentally we control both n and Δn via biasing the front and back gates, and by measuring the occupied subband electron densities from the Fourier transforms of the low-field ($B \leq 0.4$ T) magnetoresistance oscillations. These Fourier transforms exhibit two peaks whose frequencies are directly proportional to the subband densities [see, e.g., Fig. 1(c)]. The difference between these frequencies is therefore a direct measure of Δ_{01}. By monitoring the evolution of these frequencies as a function of n and, at a fixed n, as a function of the back- and front-gate biases, we can determine and tune the symmetry of the charge distribution [16–19]. Throughout this Letter we quote the experimentally determined values for Δn and subband spacings (Δ_{01} or Δ_{SAS}). The calculated subband spacings are in good agreement with the experimental values [16–19].

Figures 1(d) and 1(e) show the longitudinal (R_{xx}) and Hall (R_{xy}) resistance vs B for sample A; for the Hall data, we show the derivative dR_{xy}/dB as it is more sensitive to the formation of a FQH state plateau [the R_{xy} trace for $\Delta n = 7.8 \times 10^{10}$ cm^{-2} is also included as an inset to (e)]. The traces are for different charge distributions at a constant $n = 1.72 \times 10^{11}$ cm^{-2}. Clearly, the data for the symmetric charge distribution do not show a FQH state at $\nu = 1/2$. But the data taken at a significant charge imbalance ($\Delta n = 7.8 \times 10^{10}$ cm^{-2}) exhibit a deep minimum near $\nu = 1/2$ in R_{xx} and an inflection point at $2h/e^2$ in R_{xy}, suggesting the formation of a FQH state. This is in sharp contrast to what was seen in WQWs before [16–19]. We emphasize that the surprise here is the signature of a 1/2 FQH state as we *imbalance* the charge distribution and *increase* the subband separation.

Data for sample B, measured in a hybrid magnet with a top field of 45 T, are shown in Figs. 2 and 3. In Fig. 2 we keep the charge distribution balanced and change n by applying appropriate back- and front-gate biases. The R_{xx} traces show the evolution of the state at $\nu = 1/2$ from a FQH state with a well developed R_{xx} minimum and R_{xy} plateau at high n to a compressible state at low n. This evolution is consistent with previously observed trends, although the value of the parameter $\alpha = 0.13$ above which the 1/2 FQH state disappears is somewhat larger than reported before [16–20]; $\alpha = \Delta_{SAS}/(e^2/\epsilon l_B)$ is the ratio of the tunneling energy to the Coulomb energy. We note that sample B is the narrowest WQW in which a $\nu = 1/2$ FQH state has been observed up to now.

But the main surprises reveal themselves again when we imbalance the system. Figure 3(a) shows data for sample B at $n = 2.44 \times 10^{10}$ cm^{-2} and $\Delta n = 7.9 \times 10^{10}$ cm^{-2}. Qualitatively similar to Fig. 1 data, a FQH state at $\nu = 1/2$ emerges. Note that there is no such FQH state when the system is balanced at this n (Fig. 2).

The very high fields provided by the hybrid magnet allow us to explore lower ν in sample B. In Fig. 3(a), concomitant with the emergence of the $\nu = 1/2$ FQH state, we see signatures of a FQH state at another even-denominator filling, $\nu = 1/4$ [22]. In Fig. 3(b) we show data at a higher n; here, the front-gate bias was kept fixed and n was raised by increasing the back-gate bias. Note that, compared to Fig. 3(a) data, the FQH states at $\nu = 1/2$ and 1/4 in Fig. 3(b) remain strong but their positions move up in B, consistent with the higher n.

The data in Figs. 1 and 3 provide evidence for emerging $\nu = 1/2$ and 1/4 FQH states in 2DESs with very large

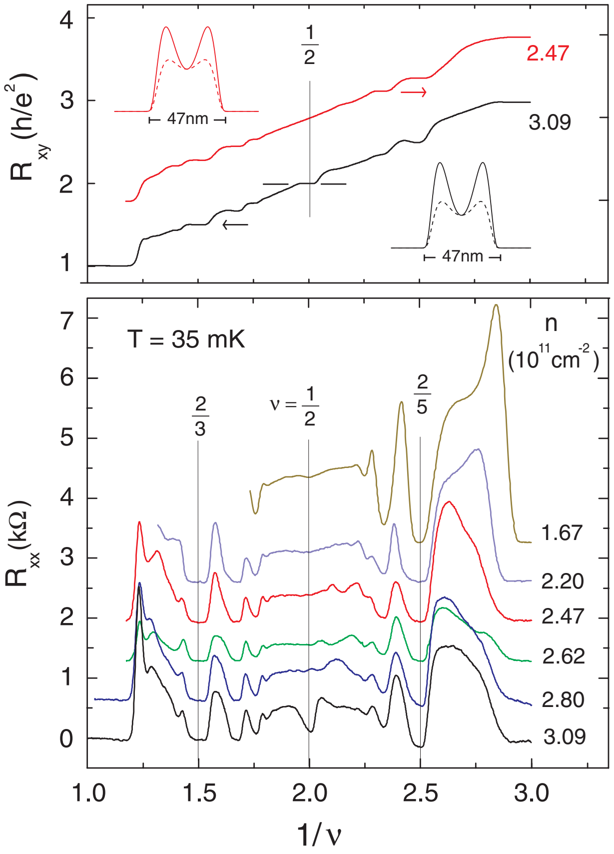

FIG. 2 (color online). Evolution of magnetoresistance traces for sample B. The traces are shown for different total densities (indicated on the right) while the charge distribution is kept symmetric. As n is decreased from 3.09 to 1.67×10^{11} cm^{-2}, Δ_{SAS} increases from 34 to 46 K. We observe a strong $\nu = 1/2$ FQH state only at the highest n. Calculated charge distributions for two representative densities are also shown.

subband spacings and significantly asymmetric charge distributions. Moreover, at a fixed n, as the charge distribution is made symmetric and the subband spacing is lowered, the 1/2 and 1/4 states disappear, in contrast to previous observations. These characteristics suggest that these are 1C states. We emphasize that at higher imbalances, the subband separation and charge distribution start to resemble those of single-layer 2DESs in conventional GaAs/AlGaAs heterojunctions or (narrow) quantum wells which are known not to support a $\nu = 1/2$ or 1/4 FQH state. It is thus not surprising that the states we observe disappear with larger magnitudes of charge imbalance.

Can these states have a 2C origin? The natural candidates would be the "imbalanced" $\Psi_{m_b m_f m}$ states where $m_f \neq m_b$ are odd integers and m is an integer [23–25]. In Table I we list the relevant characteristics of such states when their total ν is close to either 1/2 or 1/4. Near $\nu = 1/2$ the candidates states are (530) and (730), and near $\nu = 1/4$ (752) and (753). Note that these states have unequal layer densities, with a front- to back-layer layer density ratio (n_f/n_b) which is comparable to the experimental ratios where we observe the 1/2 and 1/4 states. In Fig. 3 we mark the expected positions of R_{xx} minima and R_{xy} plateaus for the (530), (730), (752), and (753) states. The observed R_{xx} minima are clearly closer to exact 1/2 and 1/4 fillings than any of these 2C states. The R_{xy} traces, including the one shown in Fig. 1(e), show inflection points which are close to the expected $2h/e^2$ value although the expected plateau for the (730) state is also close. At $\nu = 1/4$ the R_{xy} plateau is reasonably well quantized; in Fig. 3(a) its value is closer to $4h/e^2$ than to the values expected for the (752) and (753) states. The deviation of the observed plateau value from $4h/e^2$ ($\simeq 2\%$) is in fact comparable to the deviations reported in previous mea-

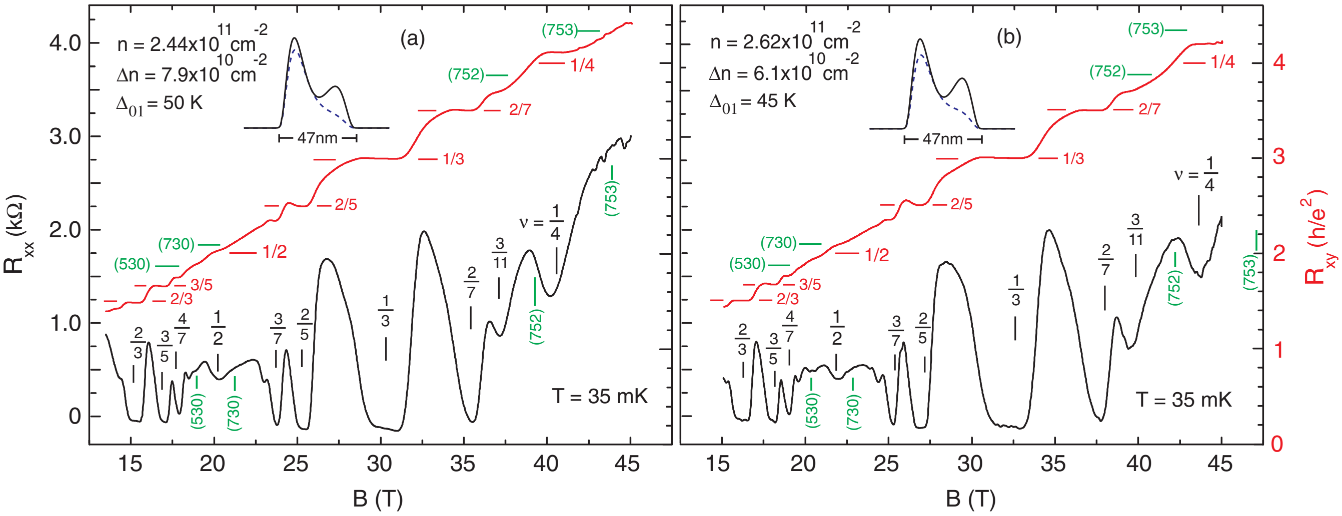

FIG. 3 (color online). Magnetoresistance traces for sample B. The *expected* positions of R_{xx} minima for the commonly observed, odd-denominator FQH states, as well as $\nu = 1/2$ and 1/4, are marked. Also shown are the positions of R_{xx} minima expected for the imbalanced 2C states (530), (730), (752), and (753). For R_{xy} traces, the *expected* positions of the plateaus for various FQH states are indicated by horizontal lines. Calculated total and lowest subband charge distributions are also shown.

TABLE I. Characteristics of some of the 2C $\Psi_{m_b m_f m}$ states near $\nu = 1/2$ and 1/4.

m_b	m_f	m	ν	ν_b	ν_f	n_f/n_b
5	3	0	8/15	1/5	1/3	5/3
3	3	1	1/2	1/4	1/4	1
7	3	0	10/21	1/7	1/3	7/3
7	5	2	8/31	3/31	5/31	5/3
5	5	3	1/4	1/8	1/8	1
7	5	3	3/13	1/13	2/13	2

surements of the $\nu = 1/4$ state [19,20]. The plateau in Fig. 3(b), however, is equally close to $4h/e^2$ and the (753) plateaus. Note that the *field positions* of the $\nu = 1/4$ plateaus in both Figs. 3(a) and 3(b), as revealed, e.g., by plotting dR_{xy}/dB vs B, agree very well with the observed positions of R_{xx} minima. In other words, the observed plateaus are slightly *above* the classical Hall resistance line. This deviation possibly stems from the admixture of the R_{xx} signal into R_{xy}, caused by a slight misalignment of the contacts in our van der Pauw shaped sample [26].

The imbalanced 2C states listed in Table I are unlikely to explain our data. First, the traces in Figs. 1 and 3 exhibit R_{xx} (and dR_{xy}/dB) minima at several odd-denominator ν whose field positions are consistent with what is expected in a simple, 1C 2DES. Second, there is no obvious reason why the particular imbalanced 2C states listed in Table I should be stable. This is especially true for the states near $\nu = 1/4$ where the 2C candidate states have very low layer fillings. For example, the (753) state has $\nu_f = 2/13$ and $\nu_b = 1/13$ and the lower density layer has intralayer correlations similar to a single-layer 2DES at $\nu = 1/7$. The stability of such a state is highly unlikely, given the extremely weak nature of the $\nu = 1/7$ FQH state in the highest quality, single-layer samples. Third, and most importantly, suppose, e.g., that (753) is the FQH state we observe near $\nu = 1/4$. As we bring the system to balance (at a fixed n), we lower the subband spacing. This should favor the 2C states and we would therefore expect to see a 2C (553) FQH state at $\nu = 1/4$ when the system is balanced. This is contrary to our observations [22].

The experimental results presented here suggest the stability of 1/2 and 1/4 FQH states in strongly asymmetric WQWs for certain parameters such as well-width, electron density, and charge imbalance. More extensive measurements are likely to unravel the full parameter range where these states are stable. But our results already challenge the theories by providing a set of parameters for which the stability of the $\nu = 1/2$ and 1/4 Pfaffian states, or possibly other, yet unknown FQH states, could be tested.

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[21] All our self-consistent calculations were performed at $B = 0$ where electrons occupy the lowest two subbands. At $\nu < 1$, in a single-particle picture electrons should all reside in the lowest subband. In an interacting system, however, the Coulomb energy can far exceed the subband splitting and allow the antisymmetric subband to mix into the correlated ground state to lower its energy.

[22] The traces taken at balance at $n = 2.44$ and 2.62×10^{11} cm^{-2} for sample B do not show $\nu = 1/4$ FQH states.

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[25] In principle, m_f and m_b can also be nonintegers, e.g., 3 and 5/2. For $m = 0$, this corresponds to layer fillings 1/3 and 2/5 and the bilayer system $\nu = 11/15$. Such an imbalanced 2C FQH state has indeed been observed in WQWs with much smaller Δ_{01} [H. C. Manoharan *et al.*, Phys. Rev. Lett. **79**, 2722 (1997)]. However, such states are unlikely to explain our data, especially the state near $\nu = 1/4$. The (7, 13/3, 3) state, e.g., has $\nu = 1/4$ but its $n_f/n_b = 3$ is larger than in data of Fig. 3. More problematic, similar to the (753) state, the stability of this state is questionable as we discuss in the text.

[26] Such admixture can often be corrected for by reversing the direction of B and averaging the R_{xy} traces. We could not reverse the hybrid magnet polarity.