Observation of Reentrant Integer Quantum Hall States in the Lowest Landau Level

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Measurements on very low disorder two-dimensional electrons confined to relatively wide GaAs quantum well samples with tunable density reveal a close competition between the electron liquid and solid phases near the Landau level filling factor $\nu = 1$. As the density is raised, the fractional quantum Hall liquid at $\nu = 4/5$ suddenly disappears at a well-width dependent critical density, and then reappears at higher densities with insulating phases on its flanks. These insulating phases exhibit reentrant $\nu = 1$ integer quantum Hall effects and signal the formation of electron Wigner crystal states. Qualitatively similar phenomena are seen near $\nu = 6/5$.

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At low temperatures and subjected to a strong perpendicular magnetic field (B), a low-disorder two-dimensional electron system (2DES) displays a myriad of novel collective states [1–3] arising from the dominance of the Coulomb interaction energy over the kinetic energy and the disorder potential. At high B, when the electrons occupy the lowest ($N = 0$) Landau level (LL) [4], the 2DES exhibits a fractional quantum Hall effect (FQHE) at several series of odd-denominator LL fractional fillings $\nu = nh/eB$ (n is the 2DES density) as it condenses into incompressible liquid states [1–5]. At even higher B, the last series of FQHE liquid states is terminated by an insulating phase which is reentrant around a FQHE at $\nu = 1/5$ and extends to lower $\nu < 1/5$ [6–8]. This insulating phase is generally believed to be an electron Wigner crystal (WC), pinned by the small but ubiquitous disorder potential [6–8]. Based on particle-hole symmetry, one would expect the appearance of similar insulating phases near filling factors $\nu = 1 \pm 1/5$. Surprisingly, however, such phases have not been observed until now even though more than 20 years have passed since the discovery of the reentrant insulating phases near $\nu = 1/5$.

We report here the observation of such insulating phases in very clean 2DESs confined to relatively wide GaAs quantum wells (QWs). These phases are seen near $\nu = 4/5$ and $6/5$, and are manifested by a reentrant $\nu = 1$ integer quantum Hall effect (RIQHE) where the Hall resistance quantizes at the h/e^2 quantum Hall plateau and the longitudinal resistance (R_{xx}) vanishes at very low temperatures. We observe the RIQHE phases only at densities above a threshold density which depends on the QW width and is smaller for wider QWs [9]. Our results suggest that these are likely WC states, similar to those observed near $\nu = 1/5$ in high-quality 2DESs, and it is the larger electron layer thickness in our samples that stabilizes them here near $\nu = 1$. Our data also reveal a remarkable behavior for the $\nu = 4/5$ and $6/5$ FQHE states: they sharply disappear at the threshold density at which a nearby RIQHE state first emerges and then reappear at higher densities, with the RIQHE states on their flanks. This behavior is very distinct from what is seen at very low fillings in very clean 2DESs where the $\nu = 1/5$ FQHE and the flanking insulating phases are always present. Our observations attest to a close and subtle competition between the various correlated liquid and solid states of the 2DES in wide QWs near $\nu = 1$.

Our samples were grown by molecular beam epitaxy, and each consists of a wide GaAs quantum well bounded on each side by undoped $Al_{0.24}Ga_{0.76}As$ spacer layers and Si δ-doped layers. We report here data for three samples, with QW widths $W = 31$, 42, and 44 nm, and as-grown densities of $n \simeq 3.3$, 2.5, and 3.8×10^{11} cm^{-2}, respectively. The low-temperature mobilities of these samples are $\mu \simeq 670$, 910, and 600 m^2/V s, respectively. The samples have a van der Pauw geometry and each is fitted with an evaporated Ti/Au front-gate and an In back-gate. We carefully control n and the charge distribution symmetry in the QW by applying voltage biases to these gates [10,11]. All the data reported here were taken by adjusting the front- and back-gate biases so that the total charge distribution is symmetric. The measurements were carried out in superconducting and resistive magnets with maximum fields of 18 and 35 T, respectively. We used low-frequency ($\simeq 10$ Hz) lock-in techniques to measure the transport coefficients.

Figure 1 highlights the sharp contrast seen in the data taken at two different densities for a 42-nm-wide GaAs QW. At the lower density, the R_{xx} and R_{xy} traces show what is normally seen in very clean 2DESs: a strong quantum Hall effect at $\nu = 1$ and $2/3$ and, between these fillings, several FQHE states at $\nu = 4/5$, $7/9$, $8/11$, and $5/7$. At the higher n, however, a RIQHE (marked by down arrows) is observed near $1/\nu = 1.20$, as evidenced by an R_{xx} minimum and an R_{xy} quantized at h/e^2. Also evident is a developing RIQHE state between $\nu = 4/5$ and $7/9$, evinced by a dip in R_{xy} [up arrow in Fig. 1(b)]. As we detail below, the RIQHE phases near $\nu = 4/5$, as well as similar phases near $\nu = 6/5$ on the low-field flank of $\nu = 1$, show a spectacular evolution with density.

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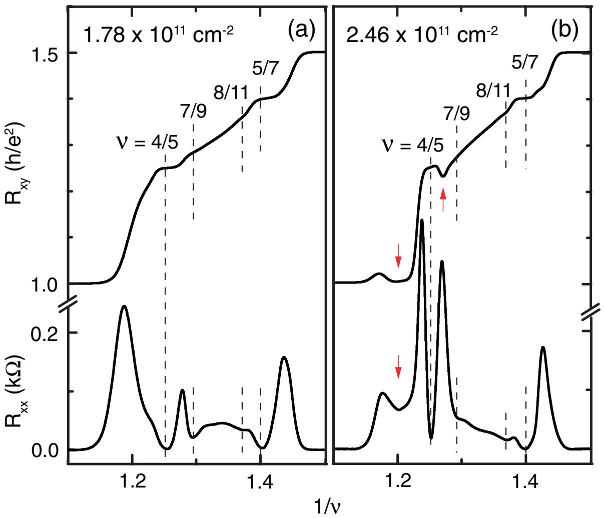

FIG. 1 (color online). R_{xx} and R_{xy} vs $1/\nu$ traces at $T = 30$ mK for a 42-nm-wide GaAs QW at two densities: (a) $n = 1.78$, and (b) 2.46×10^{11} cm^{-2}. In (b), the RIQHE phases observed on two sides of $\nu = 4/5$ are marked by arrows.

Figure 2 illustrates this evolution with a series of R_{xx} and R_{xy} traces in the range $2/3 < \nu < 4/3$, taken as n is changed from 1.78 to 3.41×10^{11} cm^{-2}. At the lowest n, the FQHE is seen at $\nu = 9/7, 6/5, 4/5$, and 5/7. When n is increased to 2.05×10^{11} cm^{-2}, the R_{xx} minimum at $\nu = 4/5$ disappears signaling the destruction of the FQHE, and a minimum in R_{xy} develops near this ν. As n is further increased, the R_{xy} minimum becomes deeper and moves towards $1/\nu = 1.20$, and an R_{xx} minimum starts to appear at the same ν (see down arrows near $1/\nu = 1.20$ in Fig. 2). Meanwhile, the $\nu = 4/5$ FQHE reappears to the right of these minima. As we keep increasing n, the R_{xy} minimum deepens and becomes quantized at h/e^2 for $n \geq 2.46 \times 10^{11}$ cm^{-2}, and the R_{xx} minimum gets deeper and is essentially zero for $n > 2.87 \times 10^{11}$ cm^{-2}. At the highest n these minima merge into the R_{xy} plateau and the R_{xx} minimum near $\nu = 1$.

The traces in Fig. 2 also show that, with increasing n, another R_{xy} minimum starts to develop on the right side of $\nu = 4/5$, as marked by the up arrows at $1/\nu = 1.28$. This minimum, too, becomes deeper at higher n and, as we will show later [Fig. 3(c)], approaches h/e^2.

The evolution observed on the right side of $\nu = 1$ is qualitatively seen on the left side also, but at higher n. The $\nu = 6/5$ FQHE, for example, disappears at $n = 2.87 \times 10^{11}$ cm^{-2} and a dip in R_{xx} develops near $1/\nu = 0.86$ (see down arrows in Fig. 2), concomitant with R_{xy} lifting up and eventually becoming quantized at h/e^2. A main qualitative consequence of these evolutions is that, at very low temperatures, the $\nu = 1$ Hall plateau and R_{xx} minimum are much wider at the higher densities.

Figure 3(a) illustrates the T dependence of R_{xx} and R_{xy} at $n = 2.46 \times 10^{11}$ cm^{-2}. At the highest T, the R_{xx} and

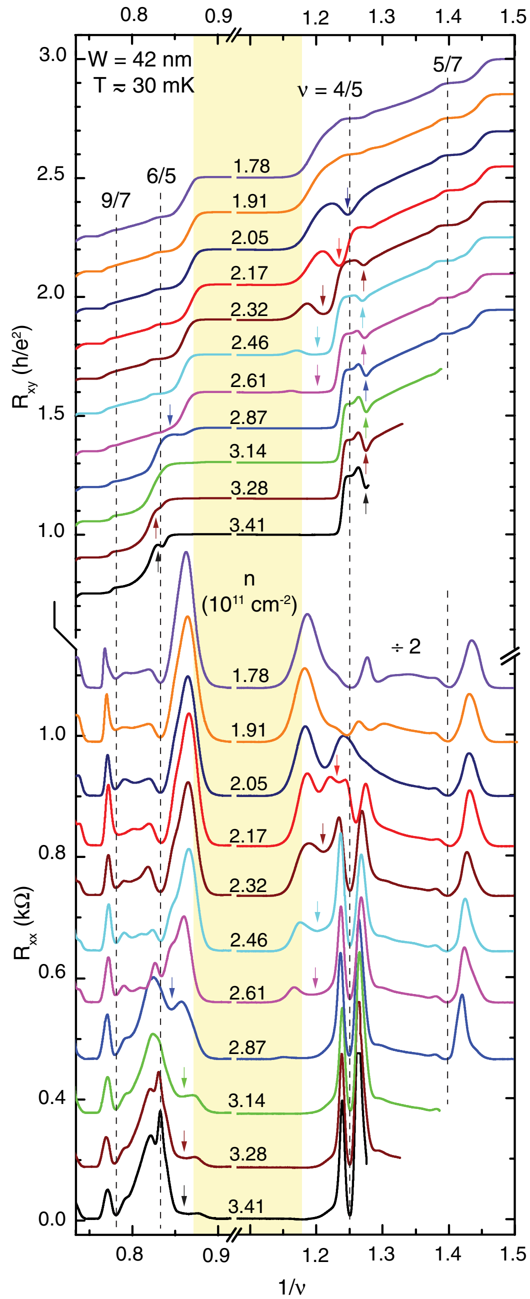

FIG. 2 (color online). Waterfall plots of R_{xx} and R_{xy} vs $1/\nu$ for the 42-nm-wide QW as n is changed from 1.78 to 3.41×10^{11} cm^{-2}. Traces are shifted vertically for clarity. The down arrows mark the development of RIQHE phases near $1/\nu = 1.20$ as n is raised from 2.05 to 2.61×10^{11} cm^{-2}, and near $1/\nu = 0.86$ as n is further increased. The up arrows in the top panel mark the development of similar, albeit weaker, RIQHE phases near $1/\nu = 1.28$ and 0.83. The yellow band marks the range $0.85 \leq \nu \leq 1.15$ $(0.87 > 1/\nu > 1.18)$; see text.

R_{xy} traces near $\nu = 4/5$ look "normal": There is a relatively strong FQHE at $\nu = 4/5$ as seen from the deep minimum in R_{xx} and an R_{xy} plateau at $5h/4e^2$. Away from $\nu = 4/5$, R_{xy} follows a nearly linear dependence on

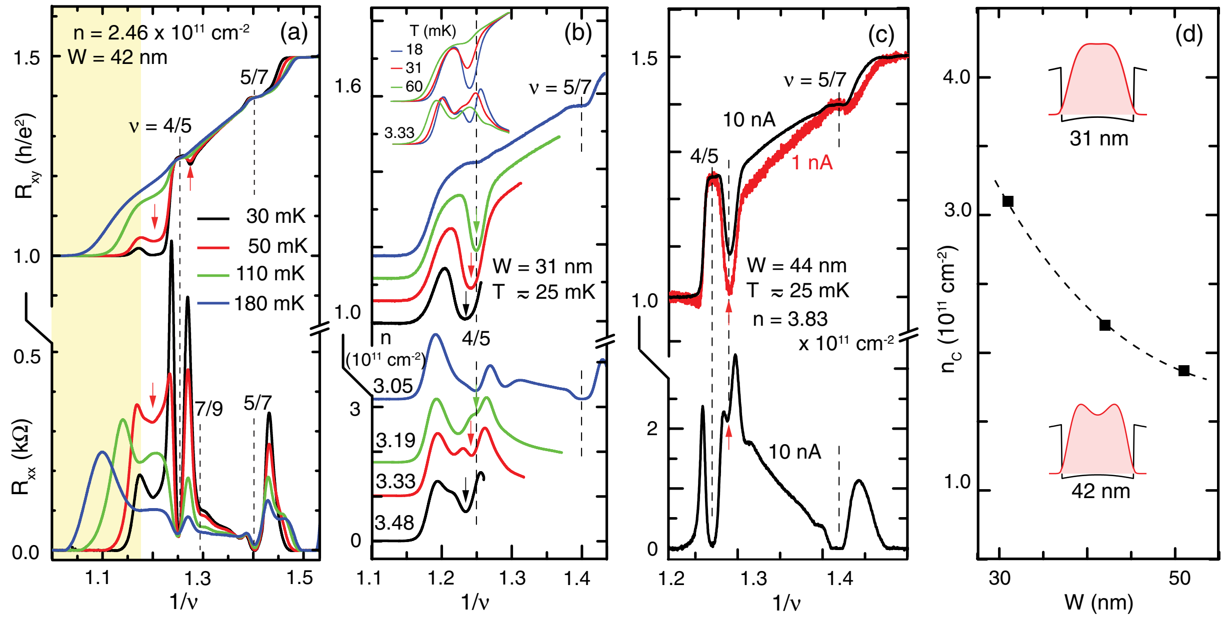

FIG. 3 (color online). (a) Evolution of R_{xx} and R_{xy} with temperature for the 42-nm QW at $n = 2.46 \times 10^{11}$ cm^{-2}. (b) Waterfall plots of R_{xx} and R_{xy} vs $1/\nu$ for the 31-nm QW sample, showing how the RIQHE phase near $1/\nu = 1.20$ starts to develop as n is raised from 3.05 to 3.48 $\times 10^{11}$ cm^{-2}. Data are shifted vertically for clarity. The inset shows the T dependence of the RIQHE at $n = 3.33 \times 10^{11}$ cm^{-2}. (c) R_{xx} and R_{xy} traces for the 44-nm QW at $n = 3.83 \times 10^{11}$ cm^{-2} displaying a RIQHE phase at $1/\nu = 1.28$. (d) Dependence of the critical density n_c above which the RIQHE near $\nu = 4/5$ sets in on QW width W. The insets show the self-consistently calculated charge distribution and potential for the 31- and 42-nm QWs at n_c.

B. As T is lowered, however, R_{xy} develops a minimum near $1/\nu = 1.20$ which eventually turns to a plateau quantized at h/e^2 at the lowest T. Meanwhile, a strong minimum develops in R_{xx} at $1/\nu = 1.20$. On the right side of $\nu = 4/5$, another R_{xy} minimum is developing.

Data taken on the 31- and 44-nm-wide QW samples reveal the generality of these phenomena. Figure 3(b) shows data for the 31-nm QW. Similar to the data of Fig. 2, as n is increased, the $\nu = 4/5$ FQHE is quickly destroyed and R_{xy} develops a deep minimum which approaches the $\nu = 1$ plateau at h/e^2 near the highest B that we can achieve in this sample. The resemblance of the traces shown in Fig. 3(b) to the top four R_{xy} and R_{xx} traces in Fig. 2 is clear. Note, however, that in the narrower QW of Fig. 3(b) we need much higher n to reproduce what is seen in the wider QW of Fig. 2.

In Fig. 3(c) we show data for the 44-nm QW at a very high density ($n = 3.83 \times 10^{11}$ cm^{-2}). Given the larger QW width and higher n of this sample compared to the Fig. 2 sample, we expect the RIQHE near $1/\nu = 1.20$ to be fully developed, and the RIQHE on the high-field side of $\nu = 4/5$ whose emergence is hinted at in the Fig. 2 R_{xy} traces (see up arrows near $1/\nu = 1.28$ in Fig. 2) to become more pronounced. This is indeed seen in Fig. 3(c): the R_{xy} trace shows a very deep minimum on the high-field side of $\nu = 4/5$ at $1/\nu = 1.28$, nearly reaching the $\nu = 1$ plateau at h/e^2 when the smallest sample current (1 nA) is used to achieve the lowest electron temperature for this sample. Note also the appearance of a small but clearly visible R_{xx} minimum at $1/\nu = 1.28$, consistent with the development of the RIQHE at this filling [12].

A natural interpretation of the RIQHE phases we observe near $\nu = 4/5$ and 6/5 is that these are pinned WC phases, similar to the insulating phases seen around the $\nu = 1/5$ FQHE and extending to $\nu \ll 1/5$ [6–8]. In the present case, electrons at $\nu = 1 \pm \nu^*$ can be considered as a filled LL, which is inert, plus excess electrons or holes with filling factor ν^*, which could conduct. At sufficiently small values of ν^* and low temperatures, these excess electrons or holes crystalize into a solid phase which is pinned by disorder and does not participate in transport. Thus the magnetotransport coefficients, R_{xx} and R_{xy}, approach those of the $\nu = 1$ IQHE.

The RIQHE phases we observe are reminiscent of similar states that are seen in the higher LLs ($N > 0$) [13–17] and are generally believed to be "bubble" phases where several electrons are localized near each WC lattice site. Although bubble phases are not expected in the lowest LL [17], simple WC states are not theoretically ruled out. Surprisingly, however, there have been no prior reports of RIQHE phases near $\nu = 1$ in the lowest LL in clean 2DESs. Li *et al.* [9] reported a RIQHE between $\nu = 2/3$ and 3/5 and its particle-hole symmetric state, a reentrant insulating phase between $\nu = 1/3$ and 2/5, in samples where the 2DES resides in a QW made of an $Al_xGa_{1-x}As$ alloy. They interpret the RIQHE they observe as a WC state and argue that it is the strong short-range (alloy) disorder in the QW which favors a pinned WC state in their samples. There is no such disorder in our samples, and also the RIQHE phases we observe are much closer to $\nu = 1$. Moreover, in our samples, the RIQHE phases set in only above a critical density (n_c) which depends on the QW width, W [see Fig. 3(d)]. We suggest that it is the large electron layer thickness (spread of the electron wave function perpendicular to the 2D plane, see Fig. 3(d) insets) in our wide QW samples that induces the WC formation. Supporting this conjecture, theoretical work [18] indeed indicates that in wide QWs, thanks to the softening of the Coulomb interaction at short distances, a WC phase is favored over the FQHE liquid state if the QW width becomes several times larger than the magnetic length (l_B). In our samples, W/l_B is large and ranges from $\simeq 4.6$ to $\simeq 6.0$ at n_c where we start to observe the RIQHE near $\nu = 4/5$, qualitatively consistent with the theoretical results.

In a relevant study, high-frequency (microwave) resonances were observed very close to $\nu = 1$ ($\nu^* < 0.15$) in high-quality 2DESs and were interpreted as signatures of a pinned WC [19]. We have highlighted this filling range with a yellow band in Figs. 2 and 3(a). This is the range where we see a deep R_{xx} minimum and a very well quantized R_{xy} (at h/e^2), signaling a strong $\nu = 1$ quantum Hall effect. In our samples, however, we observe RIQHE phases at relatively large values of ν^*, extending to $\nu^* > 1/5$. In particular, $1/\nu \simeq 1.28$ where we see the RIQHE on the right side of $\nu = 4/5$ corresponds to $\nu^* \simeq 0.22$. This is clearly outside the ν^* range where Chen *et al.* observed microwave resonances, indicating that the RIQHE phases we are reporting here are distinct from the phase documented in Ref. [19]. Also the RIQHE we observe at $1/\nu = 1.20$ ($\nu^* \simeq 0.17$) is separated from the deep quantum Hall effect region very near $\nu = 1$ by maxima in R_{xx} and R_{xy} [see, e.g., the right-hand-side edge of the yellow band in Figs. 2 and 3(a)]. This observation provides additional evidence that two distinct insulating phases exist. If so, then these resistance maxima imply additional scattering at the domain walls separating these phases.

It is worth noting that microwave experiments at very small ν have revealed two distinct resonances [20]. One resonance (''*A*'') was seen in the insulating phases reentrant around $\nu = 1/5$, and another (''*B*'') was dominant at very small fillings ($\nu < 0.15$). These resonances were tentatively interpreted as evidence for the existence of two different types of correlated WCs, stabilized by the crystallization of composite fermions with different numbers of flux quanta attached to them. Such an interpretation is corroborated by theoretical calculations [21,22]. It is tempting to associate the RIQHE phases we observe reentrant around $\nu = 4/5$ ($\nu^* = 1/5$) with the type "*A*" WC and the resonance seen very near $\nu = 1$ ($\nu^* < 0.15$) in Ref. [19] with the type "*B*" WC.

A very intriguing aspect of our data is the disappearance followed by a rapid reemergence of the $\nu = 4/5$ ($\nu^* = 1/5$) FQHE when the RIQHE near $\nu = 4/5$ starts to be seen [23]. This behavior has no counterpart near $\nu = 1/5$ where a FQHE is *always* seen at $\nu = 1/5$ in single-layer 2DESs of sufficiently high quality [6–8]. Can the disappearance and reappearance of the $\nu = 4/5$ FQHE state in our samples be related to a spin-polarization [24–26] or subband-polarization [10,27] transition? Based on the relevant parameters of our samples, namely the Zeeman energy (E_Z) and the subband separation (Δ), we believe this is highly unlikely. At n_c, the ratio of E_Z to the Coulomb energy ($E_C = e^2/\epsilon l_B$) in our samples ranges from 0.019 to 0.024, about a factor of two larger than the ratio at which spin transitions of FQHE states are typically seen [24–26]. The ratio Δ/E_C, which varies from 0.6 to 0.2 at n_c in our samples, is also much larger than the ratio ($\simeq 0.06$) near which one-component to two-component FQHE transitions were seen in wide QWs [10,27]. More importantly, when the $\nu = 4/5$ FQHE disappears, R_{xy} at $\nu = 4/5$ immediately starts to dip down towards h/e^2, suggesting a transition to a RIQHE phase (see, e.g., the R_{xy} trace at $n = 2.05 \times 10^{11}$ cm^{-2} in Fig. 2). This is in sharp contrast to R_{xy} maintaining its value of $5h/4e^2$ on the classical Hall line, if the $\nu = 4/5$ FQHE state made a transition to another FQHE state or to a compressible liquid phase.

The fact that the disappearance of the $\nu = 4/5$ FQHE we observe is always accompanied by the emergence of RIQHE phases leads us to speculate that it likely signals the existence of multiple types of WC phases with ground-state energies very close to that of the FQHE liquid phase. Theoretical calculations indeed indicate that such WC phases, which are based on composite fermion FQHE liquid wave functions, might exist [21,22].

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