Observation of a Reentrant Insulating Phase near the $\frac{1}{3}$ Fractional Quantum Hall Liquid in a Two-Dimensional Hole System

M. B. Santos, Y. W. Suen, M. Shayegan, Y. P. Li, L. W. Engel, and D. C. Tsui

Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

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In a dilute, low-disorder, two-dimensional *hole* system at the GaAs/AlGaAs heterointerface, we observe a reentrant insulating behavior around the $\nu=\frac{1}{3}$ fractional quantum Hall liquid at $B\simeq 5$ T, strikingly similar to recent observations in low-disorder 2D *electron* systems near $\nu=\frac{1}{5}$. We interpret this behavior as manifesting a weakly pinned hole Wigner crystal around $\nu=\frac{1}{3}$, and suggest that its observation at such large ν is a result of Landau-level mixing which, in the case of much heavier holes, significantly modifies the ground-state energies of the fractional quantum Hall and Wigner crystal states of the system.

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One of the most exciting aspects of the physics of two-dimensional electron systems (2DES) concerns the termination of the fractional quantum Hall (FQH) effect [1] at low Landau-level fillings, ν. It is intuitively clear that strong disorder will terminate the FQH effect by magnetic freeze-out. However, in a pure system, transition to a Wigner crystal (WC) is expected to occur at sufficiently low ν ($\simeq 1/6.5$) and low temperature [2-4]. Thanks to the availability of very low-disorder dilute 2DES, research on this subject has intensified in the last three years and has been fueled by new experimental results as well as controversy [5-15]. Magnetotransport experiments on 2DES in GaAs/AlGaAs heterostructures, which have been the subject of most of these studies [7-10,12-15], have established that at $\nu=\frac{1}{5}$ the ground state is FQH liquid. This is evidenced by the vanishing of the diagonal resistance R_{xx} at $\nu=\frac{1}{5}$ and the quantization of the Hall resistance R_{xy} at $5h/e^2$. At ν slightly above and below $\frac{1}{5}$, however, R_{xx} diverges as $T\rightarrow 0$, indicating an insulating ground state with a strongly nonlinear I-V characteristic. Although there is still no direct and conclusive evidence for the transition to a WC, the results have been generally interpreted as consistent with the formation of a reentrant, weakly pinned *electron* WC near $\nu=\frac{1}{5}$.

In this Letter we report magnetotransport data for a low-disorder 2D *hole* system (2DHS) at the GaAs/AlGaAs heterointerface. The areal density in this sample, $p\cong 4\times 10^{10}$ cm^{-2}, is comparable to the density of some of the 2DES in which the formation of an electron WC near $\nu=\frac{1}{5}$ has been widely discussed [9,13-15]. The magnetotransport data for this 2DHS are strikingly similar to those for the 2DES, with the notable exception that the reentrant insulating phase is observed around $\nu=\frac{1}{3}$ rather than $\nu=\frac{1}{5}$. The observation of such similar behavior at a markedly higher filling factor is most surprising and unexpected. We attribute this difference to the profound effect of Landau-level (LL) mixing on the ground-state energies of the FQH liquids and the WC [16], and interpret the results as further evidence that the reentrant insulating phase is a weakly pinned WC. Such LL mixing is expected to be much more substantial for holes, whose heavier mass reduces the LL separation by a factor of 5 compared to the separation for electrons [17]. We conclude that LL mixing in our 2DHS reduces the difference between the ground-state energies of the WC and the liquid state at $\nu=\frac{1}{3}$ to the point that, in the immediate vicinity of $\nu=\frac{1}{3}$, the ground-state energies cross and the WC becomes the ground state.

Measurements were made on high-quality 2DHS at the GaAs/AlGaAs interface. The samples were grown by molecular-beam epitaxy on an undoped GaAs (311)A substrate and modulation doped with Si, which is incorporated as an acceptor on the (311)A surface [18,19]. The structural details and growth technique are similar to those of Ref. [19] and will be discussed elsewhere. Electrical contact was made at the corners of a 2×2-mm^2 sample by alloying In:Zn (95:5) in a hydrogen atmosphere. Magnetotransport measurements were carried out in a dilution refrigerator with a base temperature of $\simeq 20$ mK. The measured hole density and mobility in this structure, when cooled in the dark, are $p\cong 4.0\times 10^{10}$ cm^{-2} and $\mu\cong 3.5\times 10^5$ cm^2/V s, respectively. All of the three samples studied so far have exhibited the phenomena we report here.

Figure 1 shows R_{xx} versus the applied magnetic field B for our 2DHS with $p=4.1\times 10^{10}$ cm^{-2} at $T=22$ mK. The data are striking in that there is a sharp resistance spike at $\frac{1}{3}<\nu<\frac{2}{5}$ whose magnitude exceeds 340 kΩ. This is about 100 times larger than the R_{xx} values at maxima between any integer or FQH states at lower B in this sample. The R_{xx} spike is strongly T dependent and diverges as $T\rightarrow 0$ indicating an insulating phase. By contrast, at $\nu=\frac{1}{3}$, $R_{xx}\rightarrow 0$ as $T\rightarrow 0$, evincing the formation of the FQH state. The inset to Fig. 1 shows that the $\frac{2}{5}$ fractional state is also well developed. The observation of a $\nu=\frac{1}{3}$ FQH liquid and, at the same time, an insulating phase at ν *larger* than $\frac{1}{3}$ provides clear evidence that single-particle localization is not responsible for the insulating phase. The data in Fig. 1 have a surprising resemblance to observations in low-disorder 2DES, except that the resistance spike for the 2DES is

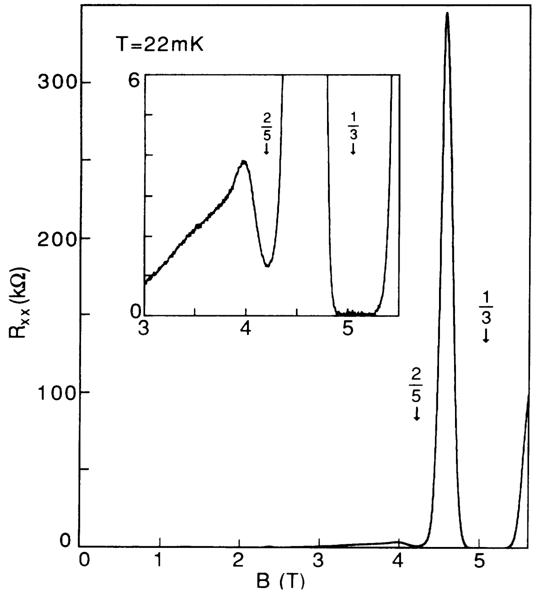

FIG. 1. Diagonal resistance vs magnetic field. Inset: Expansion of the data showing the $\nu=\frac{1}{3}$ and $\frac{2}{5}$ minima. The data were taken with 1×10^{-10} A current excitation.

observed at a markedly different filling factor between $\frac{1}{5}$ and $\frac{2}{9}$ [9,10,12–15].

In Fig. 2 we show more details of the magnetotransport properties of this system at a slightly lower density ($p=4.0\times10^{10}$ cm^{-2}). Figure 2(a) shows the Hall resistance R_{xy} at $T=24$ mK. The data show the quantization of R_{xy} at integer ν and at $\nu=\frac{2}{3}$. In the region of the R_{xx} spike ($\frac{1}{3}<\nu<\frac{2}{5}$) and for $\nu<\frac{1}{3}$, R_{xy} shows anomalous behavior, but in a small field range very near $\nu=\frac{1}{3}$ where $R_{xx}\to 0$, R_{xy} is quantized at $3h/e^2$. Similar observations have been made of R_{xy} in 2DES near $\nu=\frac{1}{5}$ [14]. Figure 2(b), an expansion of the low-field data, shows well-resolved integer and fractional states.

Figure 2(c) shows that as T is raised, R_{xx} in the regions $\frac{1}{3}<\nu<\frac{2}{5}$ and $\nu<\frac{1}{3}$ strongly decreases. At $T=86$ mK a R_{xx} minimum at $\nu=\frac{2}{7}$ is observed while at yet higher T ($=137$ mK), there is an indication of a developing $\nu=\frac{1}{5}$ FQH state. The structure near $\frac{1}{5}$ is observed at temperatures at least as high as 0.5 K and is accompanied by a weak feature in R_{xy}. These observations are qualitatively similar to those for 2DES in the $\nu<\frac{1}{5}$ range where, as T is raised, first the $\frac{2}{11}$ state appears at $T=100$ mK and then the $\frac{1}{7}$ state at $\cong 220$ mK [9,20].

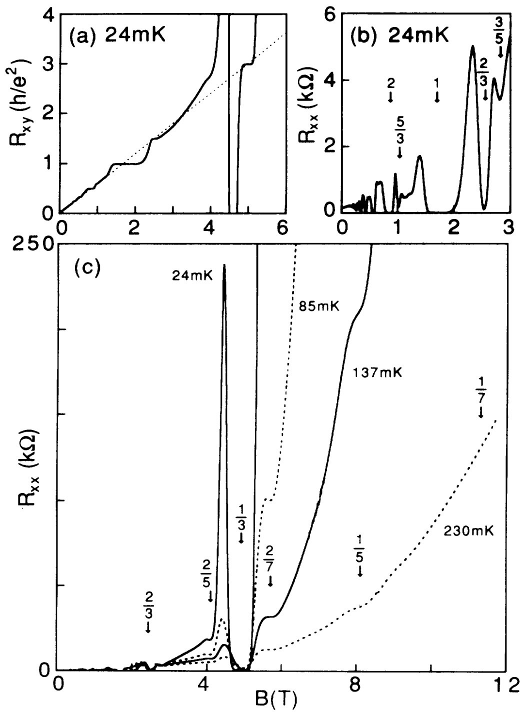

FIG. 2. Details of the magnetotransport coefficients: (a) The Hall resistance R_{xy}, (b) the low-field R_{xx}, and (c) the temperature dependence of R_{xx}.

In Fig. 3 we show the T dependence of the R_{xx} spike at $\nu=0.37$ ($B=4.6$ T in Fig. 1) and the R_{xx} minimum at $\nu=\frac{1}{3}$. From the activated behavior of the $\frac{1}{3}$ data, we determine $\Delta\cong 400$ mK for the gap of the $\frac{1}{3}$ FQH state [using $R_{xx}\propto\exp(-\Delta/2T)$]. The data at $\nu=0.37$ show a strong T dependence; R_{xx} decreases by more than 2 orders of magnitude as T is raised from ~20 to 300 mK. This T dependence of R_{xx}, including its not being simply activated, is strikingly similar to our data for a low-density ($\simeq 5\times10^{10}$ cm^{-2}) 2DES at $\nu=0.21$ in the same range of T [21]. For comparison with 2DES results, it is worth noting that the activation energy we obtain by fitting R_{xx} by the expression $R_{xx}\propto\exp(E_g/T)$ in the high-T range ($T>100$ mK) is $E_g\cong 300$ mK. This is comparable to E_g for the R_{xx} peak at $\nu=0.21$ obtained in a similar T range: $E_g\simeq 600$ mK at $B\simeq 20$ T [10] and

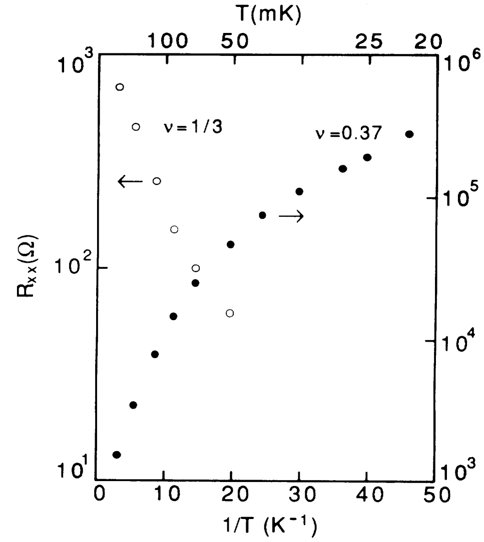

FIG. 3. Temperature dependence of R_{xx} at $\nu=\frac{1}{3}$ (open symbols) and $\nu=0.37$ (solid symbols).

$\simeq 300$ mK at $\simeq 11$ T [21].

Finally, in Fig. 4 we show examples of the I-V characteristics for this sample in the $\frac{1}{3} < \nu < \frac{2}{5}$ region. The data clearly indicate a strong nonlinear behavior. The I-V characteristics shown in Fig. 4 are different from the reported results for the 2DES [9,10,12-14], but we have obtained similar data for some of our 2DES [21]. It is worth emphasizing that the I-V results for 2DES are still controversial; several groups have reported qualitatively different I-V characteristics and have interpreted them in different ways [9,10,12-14].

We now discuss the effective mass m^* of 2D holes in the GaAs/AlGaAs heterostructure and then show that m^* plays the crucial role in our observation. In our 2DHS, only the lowest, heavy-hole subband is occupied. Furthermore, the lack of inversion symmetry in a triangular potential well like ours lifts the spin degeneracy of this band, even at $B=0$ [22-24]. As a result, holes occupy two singly degenerate subbands with heavy masses m_+^* and m_-^* and in the extreme quantum limit, $\nu < 1$, all reside in the lowest-energy m_+^* LL. The dispersions of these bands are complicated by nonparabolicity and anisotropy, leading m_+^* and m_-^* to depend on the Fermi energy and B [25]. From preliminary cyclotron resonance experiments on similar 2DHS and at similar B, we have measured $m_+^* \cong 0.3m_0$ [26]. Consistent with the theoretical expectation [25], this value is smaller than $m_+^* = 0.6m_0$ measured by Stormer *et al.* [22] for a 2DHS [at the (100) GaAs/AlGaAs interface] with much higher density ($p \simeq 5\times 10^{11}$ cm^{-2}). We emphasize that our argument for the role played by m_+^* in our observation will not depend sensitively on its exact value.

The main result of our experiment is the observation of a reentrant insulating phase around the $\nu = \frac{1}{3}$ liquid in a 2DHS which is strikingly similar to the insulating phase around the $\nu = \frac{1}{5}$ liquid in low-disorder 2DES. The question is: Why such a similar behavior at markedly different ν? We interpret the observed transport characteristic as that of a weakly pinned WC and suggest that the answer lies in the very different effective masses of electrons and holes in GaAs. For electrons $m_e^* \cong 0.067m_0$ while m_+^* for holes is about 5 times larger. This large m_+^* substantially reduces the LL separation ($=\hbar\omega_c = \hbar eB/m^*$) so that, at moderate B ($\simeq 5$ T), $\hbar\omega_c$ is only a small fraction of the Coulomb energy $e^2(\pi n)^{1/2}/4\pi\epsilon\epsilon_0$ and is comparable to the FQH gap [$\simeq 0.1e^2/(4\pi\epsilon\epsilon_0 l)$] for an ideal 2D system [$l=(\hbar/eB)^{1/2}$ is the magnetic length and $\epsilon \cong 13$ for GaAs]. Therefore, we expect LL mixing to significantly modify the ground-state energies of the FQH and WC states of the system. Such mixing is expected to reduce both the FQH liquid gap at $\nu = \frac{1}{3}$ and the difference between the WC and FQH liquid energies, compared to the ideal ($\hbar\omega_c \to \infty$) system [16]. Near $\nu = \frac{1}{3}$, therefore, a crossing of the WC and FQH state energies is possible and, we believe, is responsible for our observation.

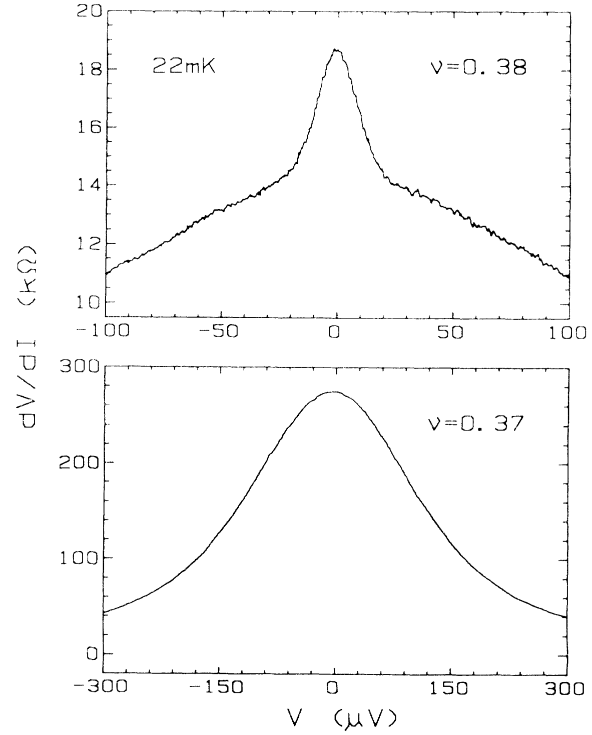

FIG. 4. Four-terminal differential resistance vs measured dc bias at two filling factors.

Yoshioka [16] first demonstrated the effect of LL mixing on the FQH liquid energy gap by showing that the inclusion of the lowest two LL's substantially lowers Δ (for $\nu = \frac{1}{3}$) from its ideal value. From his numerical calculation as a function of the LL mixing parameter $\lambda = (e^2/4\pi\epsilon\epsilon_0 l)/\hbar\omega_c$, he found an $\sim 40\%$ reduction in Δ for $\lambda = 3$. He also found that as λ increases, the separation between the WC and the $\frac{1}{3}$ liquid decreases and, at sufficiently large λ, the WC becomes the ground state [16]. He gives a rough estimate of the critical λ (~ 6.2) above which the WC state is favored, but cautions that this is based on extrapolating the $\lambda < 3$ data and that for large λ (small $\hbar\omega_c$) it is necessary to take more than the lowest two LL's into account. Since $\lambda \simeq 5$ (at $B=5$ T) in our 2DHS, a very small Δ is expected and a crossing of the WC and FQH liquid ground-state energies *near* $\nu = \frac{1}{3}$ is possible. In agreement with this expectation is our measured $\Delta \simeq 400$ mK, which is much smaller than the ideal $\Delta \simeq 11$ K or the $\Delta \simeq 4$ K that we have measured for a 2DES with roughly the same density and quality as our 2DHS. Our interpretation of the insulating phase near $\nu = \frac{1}{3}$ as a *hole* WC is therefore consistent with Yoshioka's results.

It is also instructive to consider the parameters of our 2DHS in a simple picture of crystal-liquid (gas) transition in a degenerate system of charged particles at $T=0$ [27]. In the absence of B, the ground state of a sufficiently dilute system is expected to be the WC. Calculations by Ceperly [28] give critical $r_s \simeq 33$ (r_s is the mean interparticle separation measured in units of the effective Bohr radius). At sufficiently large B (low ν), the WC is expected to be the ground state for any r_s (Ref. [3] finds $\nu \simeq 1/6.5$ as the critical ν below which WC has lower energy). Based on these considerations, Platzman gave a *heuristic* but simple "phase diagram" for the transition between the WC solid and liquid (or gas) in the r_s vs ν plane [27], noting that $\nu r_s = [e^2(\pi n)^{1/2}/4\pi\epsilon\epsilon_0]/\hbar\omega_c$ is in effect a measure of the LL mixing. In this diagram, for a fixed ν (e.g., $\nu=0.37$), if the ground state is the liquid (or gas) for small r_s, a transition to the WC can be expected as r_s is increased. This agrees with our experimental findings that the WC is the ground state near $\nu=\frac{1}{3}$ in our 2DHS with $r_s \sim 10$, but not in the 2DES with $r_s \sim 2$ which have been studied so far.

Finally, we mention two important points. First, according to our picture, in 2DHS with density much higher than ours such that $\nu=\frac{1}{3}$ is reached at much larger $\hbar\omega_c$, the WC phase near $\nu=\frac{1}{3}$ should disappear. There exists published data on a high-density 2DHS which shows a $\nu=\frac{1}{3}$ FQH state at $B \cong 25$ T [24]. This data, however, was taken at high T ($=0.47$ K) and it is not clear whether an insulating phase will appear near $\nu=\frac{1}{3}$ at lower T. Additional experimental and theoretical work is certainly needed to map out the phase diagram of the WC-liquid (gas) transitions in this system. Second, it is clear from the arguments of the previous paragraph that our GaAs 2DHS ($p \simeq 4\times10^{10}$ cm^{-2}) with an $r_s \simeq 10$ is equivalent to an about 30 times more dilute ($n \simeq 1\times10^{9}$ cm^{-2}) GaAs 2DES. Such a high-quality, dilute 2D system in GaAs, or any other semiconductor, is unprecedented [20]. It should bridge the gap between the quantum 2D systems in semiconductors and the classical system of 2D electrons on liquid He ($r_s \sim 1000$) and is expected to be a new experimental ground for exciting many-body physics.

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Note added.—We have recently fabricated high-quality 2DHS with larger density. Our preliminary magnetotransport results indicate that, as expected, the $\frac{1}{3}$ FQH state (and also the $\frac{1}{5}$ state) gets stronger with increasing p and, for $p \gtrsim 8\times10^{10}$ cm^{-2}, the insulating phase near $\nu=\frac{1}{3}$ disappears. We have also learned of recent work on low-density 2DES at the Si/SiO$_2$ interface where insulating behavior around *integer* quantum Hall states has been observed [29].

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