PHYSICAL REVIEW B VOLUME 46, NUMBER 20 15 NOVEMBER 1992-II

# Effect of Landau-level mixing on quantum-liquid and solid states of two-dimensional hole systems

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(Received 10 July 1992)

Measurements on dilute, low-disorder, two-dimensional hole systems at $GaAs/Al_xGa_{1-x}As$ interfaces reveal insulating behavior near different fractional quantum Hall liquid states. We interpret these insulating phases as pinned Wigner solid states and experimentally show that the filling factor around which they are observed moves to progressively smaller values as the areal hole density is increased. This dependence demonstrates the dramatic influence of Landau-level mixing, or the effective diluteness, on the liquid-solid transitions of a two-dimensional system.

Termination of the fractional quantum Hall (FQH) effect[1] at low Landau-level (LL) fillings has proved to be an intriguing characteristic of two-dimensional (2D) systems in semiconductors. Magnetic freeze-out will terminate the FQH effect in a strongly disordered 2D system, but an ideal 2D system is expected to condense into a Wigner solid (WS) at a sufficiently small LL filling factor, $\nu < \nu_w$.[2-4] The critical filling factor $\nu_w$ should depend on the mean interparticle separation measured in units of effective Bohr radius, $r_s = \pi^{1/2}(e/h)^2(m^*/\varepsilon\varepsilon_0)n_s^{-1/2}$ where $n_s$ is the 2D carrier density, $m^*$ is the effective mass, and $\varepsilon$ is the dielectric constant. Calculations predict a WS ground state at any $\nu$ ($\nu_w = \infty$) in a sufficiently dilute 2D system [$r_s \gtrsim 33$ (Ref. 5)], while in a dense 2D system (small $r_s$) $\nu_w \approx 1/6.5$ (Ref. 3) is predicted. Therefore, at fixed $\nu \gtrsim 1/6.5$, a transition from a gas (or FQH liquid) at small $r_s$ to a WS ground state should occur upon sufficient increase in $r_s$.[6]

LL mixing influences the ground-state energies of a 2D system in an effectively equivalent manner to diluteness. When the LL separation [$\hbar\omega_c = \hbar eB/m^* = (2\pi\hbar^2/m^*)n_s/\nu$ where $B$ is the applied magnetic field] is small compared to the Coulomb energy [$E_c = e^2(\pi n_s)^{1/2}/(4\pi\varepsilon\varepsilon_0)$], substantial LL mixing is expected to reduce the difference between the energies of the FQH liquid and WS states of the system. Early calculations by Yoshioka[7] indeed indicate that LL mixing may reverse the relative positions of the WS and the FQH liquid ground-state energies at large $\nu$ (even near $\nu = \frac{1}{3}$). Note that $r_s \sim E_c/\hbar\omega_c$ scales with the degree of the LL mixing so that in this context, *a system with more LL mixing is effectively more dilute.*

Here we report magnetotransport measurements which address the fundamental question of the influence of LL mixing, or equivalently diluteness of a 2D system, on the critical $\nu$ around which the WS-liquid transition(s) occur. We have studied a number of 2D *hole* systems (2DHS) at $GaAs/Al_xGa_{1-x}As$ interfaces with various hole densities, $2.6 \le p \le 12.5 \times 10^{10}$ cm$^{-2}$. Recent measurements near $\nu = \frac{1}{5}$ in very low-disorder 2D *electron* systems (2DES), with similar electron densities at $GaAs/Al_xGa_{1-x}As$ interfaces, show an insulating phase (IP) with an electric-field threshold conduction which has been generally interpreted as consistent with a pinned electron WS reentrant around the $\nu = \frac{1}{5}$ FQH liquid.[8-15] Since $m^*$ at a $GaAs/Al_xGa_{1-x}As$ interface is much larger for holes ($\approx 0.37m_0$) than electrons ($\approx 0.067m_0$), $r_s$ for our 2DHS ($8 \lesssim r_s \lesssim 19$) is significantly larger than for 2DES ($1 \lesssim r_s \lesssim 3$) in the same density range.[16] In effect, these 2DHS are much more "dilute" than their 2DES counterparts and also span a wider range of $r_s$. For $p \lesssim 4 \times 10^{10}$ cm$^{-2}$ ($r_s \gtrsim 15$), we observe reentrant insulating behavior near the FQH liquid at $\nu = \frac{1}{3}$, which is strikingly similar to the IP seen in 2DES in GaAs near $\nu = \frac{1}{5}$. We interpret this IP as a pinned WS state and note that our observation of such similar behavior near markedly higher $\nu$ already points to the significance of $r_s$.[17] As we increase the density from 4 to $12 \times 10^{10}$ cm$^{-2}$, the IP at $\frac{1}{3} < \nu < \frac{2}{5}$ disappears. Similar insulating behavior then sets in at $\frac{2}{7} < \nu < \frac{1}{3}$, and finally this IP disappears too, its onset having moved to lower $\nu$. We also made measurements on a 2DHS with $p = 11.7 \times 10^{10}$ cm$^{-2}$ in a wide parabolic well, which is effectively more dilute than a 2DHS with the same $p$ at a heterointerface because of both a larger $m^*$ and a wider spatial distribution (larger layer thickness) of holes. We observe a remarkable reappearance of a $\nu = \frac{1}{3}$ reentrant IP at this high density. These observations provide the first clear experimental demonstration of the role of LL mixing, or effective diluteness, in determining the critical $\nu$ around which the WS-liquid transitions in a 2D system occur.

We fabricated a series of low-disorder 2DHS at $GaAs/Al_xGa_{1-x}As$ (311)$A$ interfaces and in a wide parabolic quantum well. The samples were grown by molecular-beam epitaxy on undoped GaAs (311)$A$ substrates at $\simeq 630\,^\circ$C and modulation doped with Si, which is incorporated predominantly as an acceptor on the (311)$A$ surface.[18,19] The hole channels were separated from the doped layers by 500–1200 Å of $Al_xGa_{1-x}As$

 

$(0.30 \leq x \leq 0.35)$. Electrical contact was made by alloying In:Zn (95:5) in a hydrogen atmosphere. Magnetotransport measurements on eight samples (labeled $A-H$) cut from six different wafers were performed down to $T \simeq 20$ mK in a dilution refrigerator with $B$ up to $\simeq 15.5$ T and, for some of these samples, from 1.3 to 0.35 K in a $^3$He cryostat. After cooling in the dark to $\simeq 20$ mK, the 2DHS had $4.0\times10^{10} \lesssim p \lesssim 12.5\times10^{10}$ cm$^{-2}$. The measured mobilities of $3\times10^5 \lesssim \mu \lesssim 8\times10^5$ cm$^2$ V$^{-1}$ s$^{-1}$ increased monotonically with density and placed these 2DHS among the highest quality 2DHS ever reported.[19] Well-developed high-order FQH states at $\nu=\frac{3}{7}$ and $\frac{4}{7}$ in our 2DHS with $p$ as low as $6.55\times10^{10}$ cm$^{-2}$ further attest to their low disorder.

In Fig. 1 we show the strong $p$ dependence of the diagonal resistance, $R_{xx}(\nu)$, at $T=22$ mK. Figure 1(a) shows $R_{xx}$ vs $\nu$ for sample $A$, a 2DHS with $p=4.07\times10^{10}$ cm$^{-2}$. The maximum of $R_{xx}(\frac{1}{3}<\nu<\frac{2}{5})$ exceeds 340 kΩ, a magnitude ~100 times larger than $R_{xx}$ maxima between any integer or FHQ states in this sample at higher $\nu$. As reported earlier ,[17] $R_{xx}(\nu\simeq0.37)$ and $R_{xx}(\nu<\frac{1}{3})$ diverge while $R_{xx}(\nu=\frac{1}{3})\rightarrow 0$ as $T\rightarrow 0$, indicating IP and a FQH liquid, respectively. The observation of a $\nu=\frac{1}{3}$ FQH liquid and, at the same time, an IP at $\nu$ *larger* than $\frac{1}{3}$ provides strong evidence that single-particle localization is not responsible for the IP. We associate this *correlated* IP, which also has strong nonlinear *I-V* characteristics,[17] with a 2D hole WS. Similar behavior was seen when $p$ was lowered to $2.6\times10^{10}$ cm$^{-2}$ through a persistent photoconductivity effect. In sample $C$ [Fig. 1(b)], a 2DHS with $p=6.55\times10^{10}$ cm$^{-2}$, $R_{xx}(\frac{1}{3}<\nu<\frac{2}{5})$ peaks at only ~20 kΩ, an order of magnitude smaller than in the lower density case yet still ~20 times greater than maxima at larger $\nu$. Measurements on sample $G$ [Fig. 1(c)], a third 2DHS of similar quality but with $p=12.5\times10^{10}$ cm$^{-2}$, reveal further evolution. Increasing $p$ from $4.07\times10^{10}$ cm$^{-2}$ to $12.5\times10^{10}$ cm$^{-2}$ has resulted in a factor of ~100 decrease in the $R_{xx}(\frac{1}{3}<\nu<\frac{2}{5})$ peak while the other peaks at larger $\nu$ have remained ~1 kΩ. The peak in $R_{xx}(\frac{1}{3}<\nu<\frac{2}{5})$ is now similar in size to those at higher $\nu$.

In Fig. 2 we show the $T$ dependence of the peak in $R_{xx}$ at $\nu\simeq0.37$ for samples $A$, $B$, $C$, $E$, and $F$. For sample $A$, the peak increases by over two orders of magnitude as $T$ is decreased from 330 to 22 mK. In samples with increasingly higher density, the $T$ dependence of the peak weakens, especially at low $T$. For the highest density sample, $F$, $R_{xx}$ at $\nu\simeq0.37$ is practically independent of $T$ below 100 mK. Insulating behavior at $\frac{1}{3}<\nu<\frac{2}{5}$, seen when $p=4.07\times10^{10}$ cm$^{-2}$, *has disappeared with increasing density.* Meanwhile, we observe a steep increase in the FQH state energy gap at $\nu=\frac{1}{3}$, $^{1/3}\Delta$, with higher density. Measured gap values for samples $A$ ($^{1/3}\Delta=0.4$ K), $C$ ($^{1/3}\Delta=1.5$ K), and $D$ ($^{1/3}\Delta=3.4$ K, $p=7.5\times10^{10}$ cm$^{-2}$) reveal an almost order of magnitude increase in $^{1/3}\Delta$ with less than a doubling of $p$.

The strong dependences of both $^{1/3}\Delta$ and the $\frac{1}{3}<\nu<\frac{2}{5}$

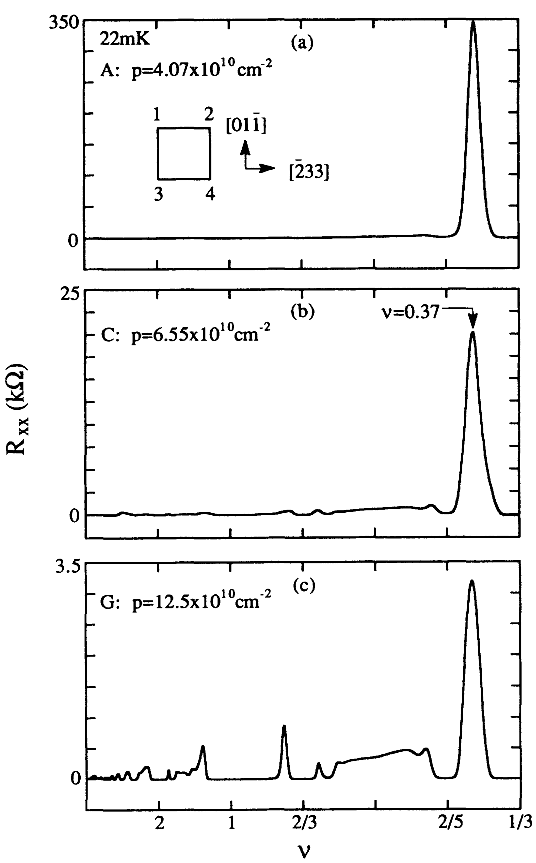


FIG. 1. Diagonal resistance vs filling factor, $\nu=(\pi\hbar/e)(p/B)$, for 2DHS samples with different density. Standard van der Pauw, low-frequency lock-in measurements were taken passing ~0.1 nA between contacts 1, 2 and measuring the voltage between contacts 3,4 [as pictured in the inset of (a)] while sweeping applied perpendicular magnetic field.

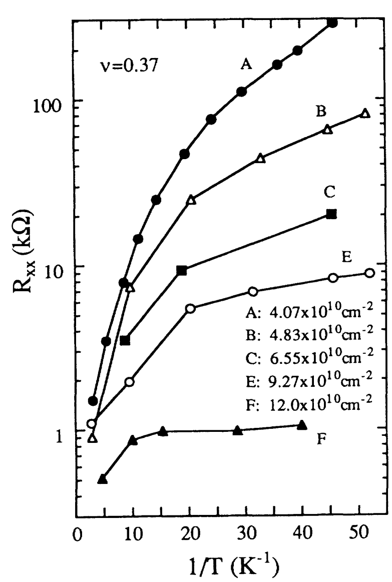


FIG. 2. Temperature dependence of $R_{xx}(\nu=0.37)$ for 2DHS samples with different density.

IP on density can be related to LL mixing. Yoshioka[7] demonstrated the profound effects of LL mixing by calculating that inclusion of the lowest two LL's strongly reduces ${}^{1/3}\Delta$ in a 2DES from its ideal ($\hbar\omega_c \rightarrow \infty$) value. Using $\lambda \equiv (e^2/4\pi\varepsilon\varepsilon_0 l)/\hbar\omega_c$ [where the magnetic length $l=(\hbar/eB)^{1/2}$ and $\varepsilon \approx 13$ for GaAs] as a measure of LL mixing, he found an ~40% reduction in ${}^{1/3}\Delta$ when $\lambda=3$. He also showed that the difference the WS and $\nu=\frac{1}{3}$ FQH liquid energies decreases with increasing $\lambda$, leading to a WS ground state above a sufficiently large $\lambda$. By extrapolating the $\lambda=3$ results, he roughly estimates a critical $\lambda \approx 6$. Since $\lambda \approx 6.1$ ($r_s \approx 15$) in sample $A$ at $\nu=\frac{1}{3}$, the very small ${}^{1/3}\Delta$ measured is expected and a crossing of the WS and FQH liquid ground-state energies *near* $\nu=\frac{1}{3}$ is plausible. According to this interpretation, decreasing $\lambda(\sim m^*/p^{1/2})$ by increasing $p$ should result in a larger ${}^{1/3}\Delta$ and a shift in the crossing of the WS and FQH liquid energies to lower $\nu$. In agreement with this expectation, the measured ${}^{1/3}\Delta$ increases sharply with higher $p$ and insulating behavior at $\frac{1}{3}<\nu<\frac{2}{5}$ is not observed when $\lambda \approx 3.5(r_s \approx 8.5)$ in samples $F$ and $G$.

Having established that the IP at $\nu>\frac{1}{3}$ disappears with increasing density, we now focus on the data at $\nu<\frac{1}{3}$. When the density is very low (sample $A$), $R_{xx}(\nu<\frac{1}{3})$ substantially increases as $T\rightarrow 0$ and precludes the observation of weak $\nu=\frac{2}{7}$ and $\frac{1}{5}$ FQH features which can be observed at higher $T$.[17] At higher densities, when the onset of insulating behavior is expected at smaller $\nu$ and the effect of LL mixing is less important at constant $\nu$, these states should become observable at low $T$. In Fig. 3 we show higher $B$ field data for sample $C(r_s \approx 12)$ at 22 mK. Unlike in sample $A$, a deep $\nu=\frac{2}{7}$ minimum appears next to a large 230-kΩ peak. The magnitude and $T$ dependence (inset of Fig. 3) of the $R_{xx}(\frac{2}{7}<\nu<\frac{1}{3})$ peak is very similar to that of the $R_{xx}(\frac{1}{3}<\nu<\frac{2}{5})$ peak in sample $A$. An $R_{xx}$ increase of over an order of magnitude upon decreasing $T$ from 100 to 22 mK indicates an IP in this narrow region of $\nu$. In contrast to experiments on 2DES, this is the first observation of clear insulating behavior around a higher-order FQH state minimum. Such data argues against attributing this insulating behavior to a disorder-induced Hall insulator.[20] A deep minimum at $\nu=\frac{1}{5}$ is observed at higher $T$. The $T$ dependence of $R_{xx}(\nu \simeq 0.30)$ weakens at higher density (sample $E$) until no insulating behavior is observed at $\frac{2}{7}<\nu<\frac{1}{3}$ when $p=12.5\times 10^{10}$ cm$^{-2}$.[21] The IP has again been shifted to smaller $\nu$ by increasing density.

This dramatic evolution of the IP in 2DHS at GaAs/$Al_xGa_{1-x}$As interfaces critically demonstrates the general behavior of 2D systems when density is increased to reduce $r_s$ and the degree of LL mixing. While in qualitative agreement with theoretical calculations,[6] the onset of insulating behavior in our 2D systems occurs at somewhat larger $\nu$ than predicted for a given $r_s$. These calculations, however, oversimplify the experimental situation by neglecting the presence of FQH liquid states. Electron correlation effects, especially at $\nu$ near FQH liquid states, must be included to make a more realistic comparison of theory with our observations.

Finally, we focus on the importance of another parameter, namely the finite layer width of a real (experimental) 2D system, which has already been observed to cause the collapse of the FQH effect in a 2DES when sufficiently increased.[22] Hole-layer thickness is expected to play a significant role in modifying Coulomb interactions and therefore the energies of collective states. To explore consequences on insulating behavior in 2DHS, we studied a thick hole system in a modulation-doped, wide, parabolic $Al_yGa_{1-y}$As quantum well.

The magnetotransport data for such a 2DHS with $p=11.7\times 10^{10}$ cm$^{-2}$ are presented in Fig. 4. The $R_{xx}$ spike at $\nu \simeq 0.37$ exceeds 350 kΩ at 23 mK and decreases strongly with increasing $T$. In contrast, $R_{xx}(\nu=\frac{1}{3})\rightarrow 0$ as $T\rightarrow 0$. Observation of a well-developed $\nu=\frac{1}{3}$ FQH state again makes single-particle localization an unlikely cause for the IP at $\nu \simeq 0.37$. A $\frac{1}{3}<\nu<\frac{2}{5}$ IP at such high $p$ is surprising since our 2DHS at GaAs/$Al_xGa_{1-x}$As inter-

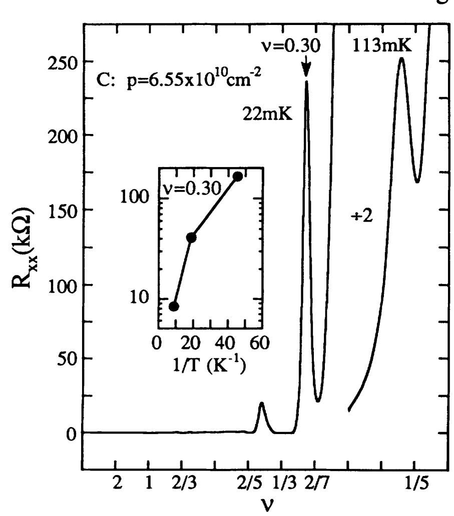


FIG. 3. Diagonal resistance vs filling factor for sample $C$. The temperature dependence of $R_{xx}(\nu=0.30)$ is shown in the inset.

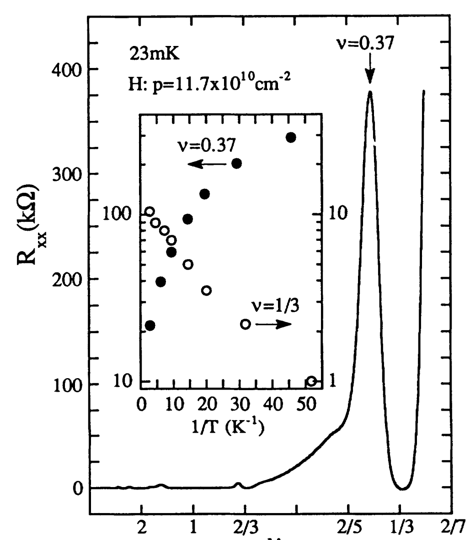


FIG. 4. Diagonal resistance vs filling factor for sample $H$, a 2DHS within a parabolic well. The temperature dependences of $R_{xx}(\nu=\frac{1}{3})$ and $R_{xx}(\nu=0.37)$ are shown in the inset.

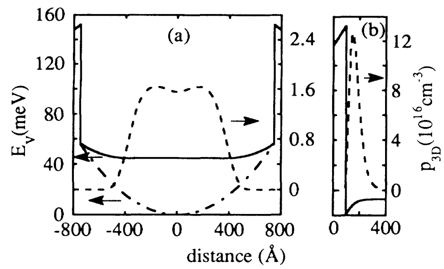


FIG. 5. The hole potential energy, $E_V$ (solid lines), and the hole concentration, $p_{3D}$ (dashed lines), as determined by self-consistent calculations of the Schroedinger and Poisson equations for a 2DHS with $p = 11.7 \times 10^{10}$ cm$^{-2}$: (a) within a parabolic well and (b) at a GaAs/$Al_xGa_{1-x}As$ interface. Holes confined within a wide parabolic $Al_yGa_{1-y}As$ quantum well screen the potential due to the quadratically graded Al composition. The hole potential energy, which varied quadratically (dashed-dotted line) along the distance from the empty well's center, flattens and a wide distribution of holes is obtained.

faces (Figs. 1 and 2) show no insulating behavior at these $\nu$ and $p$. The IP in the wide 2DHS closely resembles that in a thinner 2DHS (sample $A$) with an $\sim 3$ times smaller $p$. To explain this behavior the structural differences between these types of 2DHS must be examined.

Two characteristics of holes confined in a wide parabolic well render this 2DHS effectively more dilute than one at a heterointerface with the same $p$. First, the layer thicknesses are substantially different. Self-consistent calculations of the charge distribution and the potential energy in the parabolic well of sample $H$ are shown in Fig. 5(a). For comparison, results of similar calculations for a 2DHS with the same $p$ at a GaAs/$Al_xGa_{1-x}As$ interface are shown in Fig. 5(b). Note that the hole layer width in the parabolic well ($\sim 750$ Å) is more than $\sim 7$ times larger than at the heterointerface ($\sim 100$ Å). Second, $m^*$ is expected to be closer to the bulk value, $\approx 0.5 m_0$, since holes are less confined in the wider system. Indeed, cyclotron-resonance experiments[16] show that $m^* \approx 0.45 m_0$ in a sample from the same wafer as $H$, while $m^* \approx 0.37 m_0$ is measured for several representative samples from the same wafers as $A$–$G$. Both the greater layer thickness and larger $m^*$ of the 2DHS in the parabolic well make it effectively more dilute. This qualitatively explains the observation of an IP near $\nu = \frac{1}{3}$ in sample $H$, a 2DHS with relatively high $p$.

In summary, our measurements on a number of 2DHS show reentrant insulating behavior near FQH liquids whose $\nu$ depends on hole density and layer thickness. The data demonstrate the role of LL mixing, or the diluteness of a 2D system, in determining the $\nu$ around which WS-FQH liquid transitions occur. We hope that these observations inspire much needed theoretical studies of transitions between correlated electron phases.

We thank D. C. Tsui, K. Hirakawa, and S. R. Parihar for discussions and V. Bayot and J. J. Heremans for technical assistance. This work was supported by the National Science Foundation, Army Research Office, Alfred P. Sloan Foundation, and Advanced Technology Center for Photonics and Opto-Electronic Materials established at Princeton University by the State of New Jersey.

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