Role of Density Imbalance in an Interacting Bilayer Hole System

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We study interacting GaAs hole bilayers in the limit of zero interlayer tunneling. When the layers have equal density, we observe a phase-coherent bilayer quantum Hall state (QHS) at a total filling factor $\nu = 1$, flanked by a reentrant insulating phase at nearby fillings which suggests the formation of a pinned, bilayer Wigner crystal. As we transfer charge from one layer to another, the phase-coherent QHS becomes stronger, evincing its robustness against charge imbalance, but the insulating phase disappears, suggesting that its stability requires the commensurability of the two layers.

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When two electron layers are brought into close proximity so that interlayer interaction is strong, new physical phenomena, with no counterpart in the single-layer case, can occur. Examples include unique collective quantum Hall states (QHSs) at even-denominator fractional fillings $\nu = 1/2$ and $3/2$ [1], and at $\nu = 1$ [2–6] (ν is the total filling factor of the bilayer system). These states are stabilized by a combination of interlayer and intralayer Coulomb interaction. The *bilayer* $\nu = 1$ QHS is particularly interesting as it possesses unique, spontaneous, interlayer phase coherence: even in the limit of zero tunneling, the electrons spread between both layers coherently. The state exhibits unusual properties such as Josephson-like interlayer tunneling [5] as well as quantized Hall drag [6].

Here we report magnetotransport experiments on interacting bilayer *holes,* confined to two GaAs quantum wells with essentially no interlayer tunneling, with an emphasis on the properties of the system as the layer densities are made unequal (imbalanced). The results of our study are highlighted in Fig. 1 where the longitudinal resistivity (ρ_{xx}) vs perpendicular magnetic field (B) traces are shown. When the densities in the two layers are equal (balanced), we observe a QHS at $\nu = 1$, flanked by an insulating phase (IP) reentrant around this QHS and extending to filling factors as large as $\nu \approx 1.1$ [Fig. 1(a)]. As we transfer charge from one layer to another while maintaining the total density constant, the IP at $\nu \approx 1.1$ is destroyed but, surprisingly, the $\nu = 1$ QHS becomes stronger [Fig. 1(b)]. The weakening of the IP with charge transfer indicates that this phase is stabilized by a delicate balance of interlayer and intralayer Coulomb interaction and suggests a pinned, *bilayer* Wigner crystal. The strengthening of the $\nu = 1$ QHS with increasing charge transfer, on the other hand, demonstrates the robustness of its phase coherence against charge imbalance.

Figure 1(c) reveals yet another intriguing feature of transport coefficients in an imbalanced, interacting bilayer system: ρ_{xx} exhibits pronounced hysteresis at lower magnetic fields near $\nu = 2$, close to field values where either the majority or the minority layer is expected to be at (layer) filling factor 1. The hysteresis is likely caused by

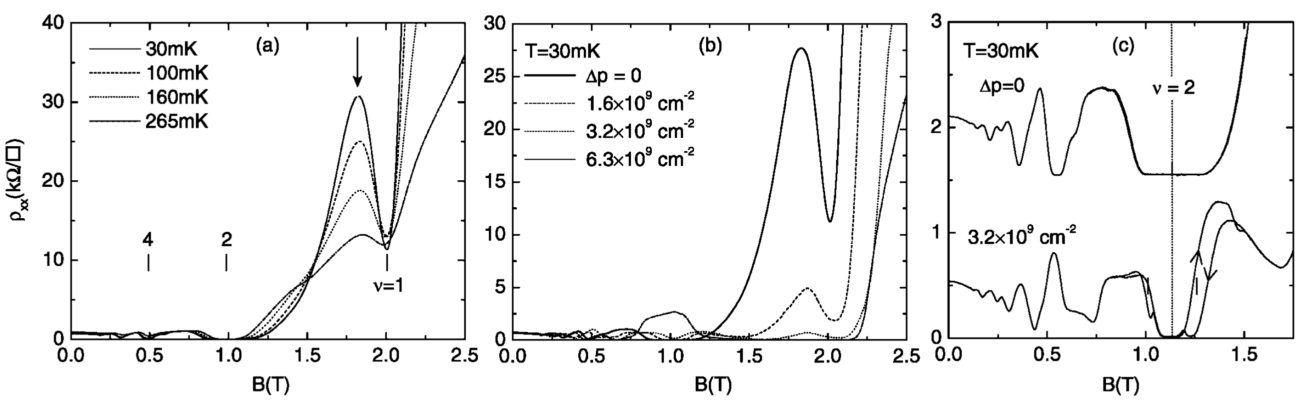

FIG. 1. Resistivity vs magnetic field traces for sample A. (a) Temperature dependence of traces is shown; the total bilayer density is $p_{\rm tot} = 4.9 \times 10^{10}$ cm^{-2}, with both layers having equal densities. The vertical arrow points to the insulating phase developing near the filling factor $\nu = 1.1$. (b) Data at $T = 30$ mK for different values of the charge transfer, Δp, while $p_{\rm tot}$ is kept constant at 4.9×10^{10} cm^{-2}. (c) Data at $T = 30$ mK at slightly larger total density of 5.5×10^{10} cm^{-2}, revealing the development of a hysteresis in the magnetoresistance near total filling $\nu = 2$ when the bilayer is imbalanced. The upper trace is shifted by 1.5 kΩ for clarity. The right (left) tick mark in the lower trace indicates the expected position of $\nu = 1$ for the layer with larger (smaller) density.

an instability in the charge distribution of the two layers. We have included the hysteretic data of Fig. 1(c) for completeness; more details are given elsewhere [7]. Here we focus on two main findings of our work, namely, the robustness of the phase-coherent $\nu = 1$ QHS in imbalanced bilayers and the IP that is reentrant around it.

We studied Si-modulation doped GaAs double-layer hole systems grown on GaAs (311)*A* substrates. We measured six samples from four different wafers, all displaying consistent results; here we concentrate on data taken in three samples from three different wafers. In these samples, the holes are confined to two GaAs quantum wells which have a width of 150 Å each and are separated by either a 110 Å (samples A and C) or 75 Å (sample B) wide AlAs barrier; sample C has typically a larger hole density. We used patterned *L*-shape Hall bars aligned along the $[01\bar{1}]$ and $[\bar{2}33]$ crystal directions. The hole systems grown on GaAs (311)*A* substrates, including bilayer systems used in this study, exhibit a mobility anisotropy stemming from an anisotropic surface morphology, with the mobility being lower for current parallel to $[01\bar{1}]$. Here we present data measured with current along $[01\bar{1}]$; data taken with current parallel to $[\bar{2}33]$ are very similar. In all measurements the Ohmic contacts are connected to both layers. Metallic top and bottom gates were added to control the densities in the layers. We determined the layer densities from a careful examination of the positions (in B) of the QHSs and the Hall coefficient, and from the observation of a small step in the capacitance between the bilayer and the top gate as the top layer is depleted. The measurements were performed down to a temperature of $T = 30$ mK, and using standard low-frequency lock-in techniques.

In Fig. 1(a) we show ρ_{xx} vs B traces for sample A, taken at different temperatures; the total hole density is $p_{\rm tot} = 4.9 \times 10^{10}$ cm^{-2} and the two layers have equal densities. Similar data are shown in Fig. 2 for sample B at $p_{\rm tot} = 3.9 \times 10^{10}$ cm^{-2}. The $T = 30$ mK data show a strong minimum in ρ_{xx} at total filling factor $\nu = 1$, as well as a developing plateau in the Hall resistance (Fig. 2). Owing to the thick AlAs barriers, and the rather large hole effective mass ($m^* = 0.38m_0$, m_0 is the free electron mass) interlayer tunneling is extremely small [8], implying that the observed $\nu = 1$ QHS is stabilized essentially by interlayer coherence [4]. The ratio between the interaction energy of carriers in different layers and in the same layer is quantified by d/l_B, where d is the interlayer distance and $l_B = \sqrt{\hbar/eB}$ is the magnetic length at $\nu = 1$. For the cases examined in Figs. 1(a) and 2, this ratio is 1.45 and 1.12, respectively; these are close to d/l_B for which the coherent $\nu = 1$ QHS was observed in earlier studies of GaAs electron [2,5] and hole [9] bilayers. Also consistent with previous results are our data (not shown), taken on sample C, at densities of $p_{\rm tot} \geq 9.15 \times 10^{10}$ cm^{-2} ($d/l_B \geq 1.98$), which show no sign of a $\nu = 1$ QHS.

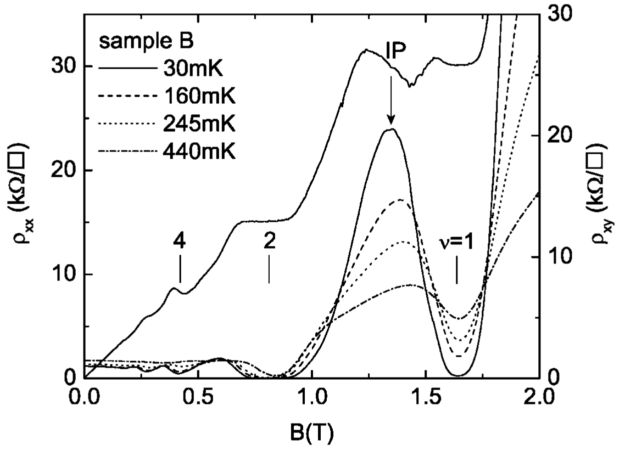

FIG. 2. ρ_{xx} vs B traces, at different temperatures for sample B at a total density of 3.9×10^{10} cm^{-2}, revealing a behavior qualitatively similar to Fig. 1(a). Also shown is the Hall resistivity ρ_{xy} at $T = 30$ mK.

We now focus on the first major finding of our Letter, namely, the behavior of the $\nu = 1$ QHS as a function of charge imbalance between the layers. In Fig. 1(b) we show ρ_{xx} traces for sample A, all taken at $p_{\rm tot} = 4.9 \times 10^{10}$ cm^{-2} [10], but with different densities in each layer. We define the charge transfer from one layer to another as $\Delta p = (p_B - p_T)/2$, where p_B and p_T are, respectively, the densities of bottom and top layers. The data of Fig. 1(b) reveal qualitatively that the $\nu = 1$ QHS is weakest when the layers have equal densities and quickly becomes stronger as Δp increases, i.e., when the bilayer system is imbalanced. We further note that, while the results of Fig. 1(b) were taken by increasing p_B and reducing p_T, we obtain a similar set of traces by transferring charge from the bottom layer to the top one.

To quantify the trend observed in Fig. 1(b), we have determined the energy gap (${}^1\Delta$) of the $\nu = 1$ QHS from ρ_{xx} activation measurements for both samples A and B at $p_{\rm tot} = 4.9 \times 10^{10}$ cm^{-2}, corresponding to d/l_B equal to 1.45 and 1.25, respectively. We obtain the energy gap by fitting an exponential dependence $\rho_{xx} \propto \exp(-{}^1\Delta/2k_BT)$ to the $\nu = 1$ resistivity vs temperature data (k_B is Boltzmann's constant). We note that for sample A at $\Delta p = 0$, a determination of the energy gap at $\nu = 1$ is impeded by the IP developing at $\nu \approx 1.1$. For this point only (shown in Fig. 3 as an open symbol) we have determined a pseudogap energy [11]. The measured ${}^1\Delta$ presented in Fig. 3 quantitatively confirm the conclusion drawn qualitatively from the data shown in Fig. 1(b): ${}^1\Delta$ is minimum at $\Delta p = 0$ and increases when $|\Delta p|$ is increased [12].

Our observation of a $\nu = 1$ QHS in *balanced* bilayer hole systems with a d/l_B ratio of 1.45 or smaller is consistent with previous reports for bilayer electron [2,5] and hole [9] systems. At such small layer separations, the strong interlayer interaction leads to a $\nu = 1$ QHS with spontaneous phase coherence meaning that the

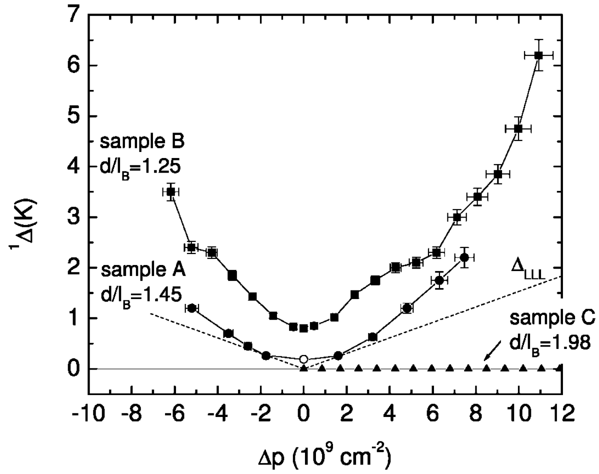

FIG. 3. Energy gap ($^1\Delta$) of the $\nu = 1$ QHS, measured as a function of Δp, at $p_{\mathrm{tot}} = 4.9 \times 10^{10}\ \mathrm{cm}^{-2}$ for samples A ($d/l_B = 1.45$) and B ($d/l_B = 1.25$). Sample C ($p_{\mathrm{tot}} = 9.15 \times 10^{10}\ \mathrm{cm}^{-2}$ and $d/l_B = 1.98$) does not exhibit a $\nu = 1$ QH state in the range of imbalance studied; this is indicated by a zero energy gap. The dotted lines show the expected dependence of the separation (Δ_{LLL}) between the lowest Landau levels of the two hole layers on Δp for all three samples.

charged carriers are spread between both layers coherently, even in the limit of zero interlayer tunneling. Our observation of a $\nu = 1$ QHS in an imbalanced bilayer carrier system in the limit of *zero tunneling,* on the other hand, is new. As we discuss below, it further confirms the phase-coherent nature of the $\nu = 1$ QHS and demonstrates the robustness of this remarkable state against charge imbalance.

Previous measurements of the $\nu = 1$ QHS in imbalanced bilayers have focused on electron systems with rather strong tunneling; e.g., the tunneling energy Δ_{SAS} was ≈ 6.8 K in Ref. [13], and ≈ 15 K in Ref. [14]. For balanced states, the measured $\nu = 1$ QHS energy gaps measured in both of these studies were of the order of Δ_{SAS}. In Ref. [13], an increase of $^1\Delta$ with increasing charge imbalance was reported, consistent with the expected increase in the subband separation energy. In our hole bilayers, on the other hand, $^1\Delta$ is determined by interaction and the resulting phase coherence, and not by the subband separation. This is obvious for $\Delta p = 0$, where our estimated subband separation, $\Delta_{\mathrm{SAS}} \leq 1\ \mu$K [8], is orders of magnitude smaller than the measured $^1\Delta$ (which is, e.g., about 1 K for sample B). For finite Δp, the subband separation in our samples, in which interlayer tunneling is negligible, is essentially equal to the energy separation between the lowest Landau levels of the two layers, $\Delta_{\mathrm{LLL}} = (2m^*/\pi\hbar^2)|\Delta p|$. Note that this subband separation is independent of the layer separation and therefore the same for all three samples. In Fig. 3, we have indicated Δ_{LLL} by dotted lines. Data of Fig. 3 clearly show that the energy Δ_{LLL} is not what stabilizes the $\nu = 1$ QHS is our samples. Indeed, at a given Δp, the energy gap at $\nu = 1$ varies from zero when d/l_B is large (sample C with $d/l_B \geq 1.98$, in which no $\nu = 1$ QHS is observed in the range of imbalance studied here), to several K for sample B, where $d/l_B = 1.25$ (Fig. 3). What determines the strength of the $\nu = 1$ QHS is therefore not the single-particle Δ_{LLL} but rather the interaction and the ensuing phase coherence.

In analogy with the real spin, the additional degree of freedom of the electrons in bilayer systems is commonly described by a pseudospin: if the electron is in the top (bottom) layer, then the pseudospin is pointing up (down) along the z axis, which is defined by the growth direction. The stability of the phase-coherent $\nu = 1$ QHS against charge imbalance can be understood in a Hartree-Fock mean-field theory [15], where it is assumed that the pseudospin points in the same direction for all electrons in the lowest Landau level. The favored direction will be a result of the competition between the bias between the layers, which tends to align the pseudospins along the z axis, and the capacitive energy cost, i.e., the Coulomb repulsion between the layers, which forces the pseudospin to lie in the x-y plane (i.e., the plane of the 2D system). Moreover, thanks to the exchange interaction, all pseudospins prefer to be aligned. As a compromise, the pseudospin will lie in the x-z plane with the z component increasing as the bilayer is further imbalanced. It should be noted, however, that according to Ref. [15] it is also found that the gap of the $\nu = 1$ QHS is independent of the charge imbalance, in contrast to the results of our measurements. Experimentally, we find that the gaps show an approximately quadratic dependence on Δp for small Δp. In sample B, we also observe a "kink" in the dependence of the gap on Δp around $|\Delta p| = 5 \times 10^9\ \mathrm{cm}^{-2}$; we do not know the origin of this kink.

We now come to another important finding of our study, namely, the IPs observed near $\nu = 1$. Data of Figs. 1(a) and 2 reveal an IP, reentrant around the $\nu = 1$ QHS, which extends to fillings as large as $\nu \approx 1.1$. Remarkably, a charge transfer of only a few percent from one layer to another is sufficient to destroy this IP. This conclusion is drawn from the T dependence of ρ_{xx} at $\nu \approx 1.1$, an example of which is shown in Fig. 4. It is appealing to interpret the IP as a pinned, *bilayer* Wigner crystal (WC) state. In previous studies of various low-disorder, 2D carrier systems, similar IPs, reentrant around fractional QHSs at low Landau level fillings were reported [16]. Based on a variety of measurements and calculations, such IPs are believed to be pinned WC states, although so far there has been no definitive proof.

In the present case, it may appear surprising that a WC state occurs at such high filling factors. However, this interpretation is consistent with earlier experimental and theoretical studies [16], which suggest that, in interacting bilayer systems a WC state with commensurate layer lattices can be stabilized at filling factors higher than in the single-layer case. For example, while a

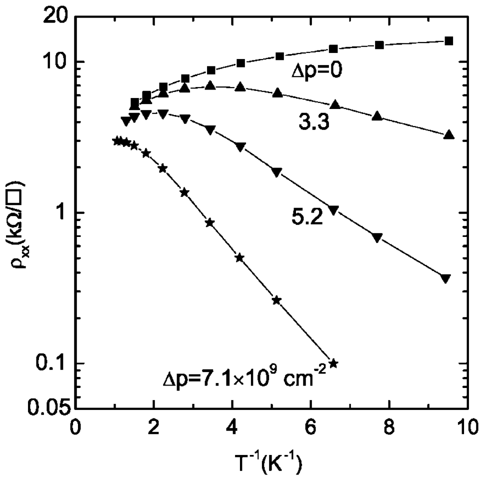

FIG. 4. Temperature dependence of ρ_{xx} at $\nu \approx 1.1$, measured at several values of Δp in sample B at $p_{\mathrm{tot}} = 4.9 \times 10^{10}$ cm^{-2}.

single-layer GaAs electron system displays a reentrant IP (interpreted as a pinned WC) near $\nu = 1/5$, an interacting GaAs bilayer electron system exhibits a similar IP around $\nu = 1/2$ [17]. Experimental studies have also revealed that single-layer, dilute, GaAs hole systems exhibit an IP near $\nu = 1/3$, a higher filling factor than the corresponding single-layer GaAs electrons ($\nu = 1/5$); this is also consistent with the WC picture: thanks to the Landau level mixing facilitated by the larger hole effective mass, the WC state is favored at higher fillings [16]. Based on these observations, the formation of a WC state reentrant around $\nu = 1$ in a bilayer 2D hole system with strong interlayer interaction appears plausible. We add that our measurements on a sample with the same density and structure as sample A, but with a wider (300 Å thick) barrier, confirm this interpretation: for the wider barrier sample, we see no sign of a $\nu = 1$ QHS but instead an IP reentrant around a reasonably strong QHS at $\nu = 2/3$, consistent with what is expected for a bilayer hole system without interlayer interaction. This observation proves that the interlayer interaction plays the crucial role in moving the IP to higher fillings.

The data of Fig. 4 reveal an intriguing feature. When the bilayer system is balanced, ρ_{xx} monotonically increases with decreasing T. For sufficiently large imbalance ($\Delta p = 7.1 \times 10^9$ cm^{-2}), the decrease of ρ_{xx} with decreasing T is also monotonic. When only slightly imbalanced, however, ρ_{xx} at $\nu \approx 1.1$ initially increases as T is lowered but then at the lowest temperatures it decreases [18]. This nonmonotonic T dependence is unusual and may be caused by a competition between the WC state and the nearby phase-coherent $\nu = 1$ QHS. Indeed for $\Delta p = 7.1 \times 10^9$ cm^{-2}, the $\nu = 1$ QHS is quite strong and, at the lowest temperatures, exhibits a ρ_{xx} minimum that extends to $\nu \approx 1.1$. This may account for the very strong T dependence of the $\nu \approx 1.1$ ρ_{xx} minimum at $\Delta p = 7.1 \times 10^9$ cm^{-2}.

Our observations highlight the rich and subtle nature of many-body states that exist at nearby fillings in GaAs bilayer hole systems in the limit of zero tunneling but with small layer separation. When balanced, such systems show a phase-coherent $\nu = 1$ QHS state, flanked by a reentrant IP, possibly a pinned bilayer WC state that is stabilized at such high fillings because of interlayer interaction. When the bilayer is imbalanced, the $\nu = 1$ QHS state survives and even gets stronger, consistent with its phase-coherent origin. The IP, on the other hand, disappears, suggesting that its stability requires commensurability (of the WC lattices) in the two layers.

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