Density-Imbalance Stability Diagram of the $\nu_T = 1$ Bilayer Electron System at Full Spin Polarization

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Abstract.
We investigate the evolution of the total Landau level filling factor $\nu_T = 1$ bilayer quantum Hall (QH) state versus density imbalance at full spin polarization under a tilted magnetic field. When the system is well below the compressible-incompressible transition point at the balanced density, the $\nu_T = 1$ QH state extends widely versus density imbalance, continuously merging into the single-layer $\nu = 1$ QH state. In the vicinity of the transition point, the $\nu_T = 1$ QH state is only weakly developed at small imbalance but increases in strength toward $\nu_T = 1/3 + 2/3$, where it is clearly separated from the single-layer $\nu = 1$ QH state. These results suggest that the system at the imbalance of $\Delta \nu = 1/3$ undergoes a transition from the correlated $\nu_T = 1$ QH state to single-layer fractional QH states with increasing density.

1. Introduction
Closely spaced double layers of two-dimensional (2D) charge systems have provided a variety of fascinating quantum states arising from interlayer Coulomb interactions. Of particular interest is the bilayer $\nu_T = 1$ quantum Hall (QH) state in the limit of small tunneling, where all electrons reside in coherent superposition of the states in the upper and lower layers sharing the same phase. This collective state is characterized by broken symmetry with spontaneous interlayer phase coherence. In term of the pseudospin language encoding electrons in the upper (lower) layer as up (down) pseudospin, this state can be viewed as an easy-plane ferromagnet [1], where the spontaneous interlayer phase coherence is represented as a magnetization which develops in the $x$-$y$ plane. As a consequence of the strong interlayer correlation, the $\nu_T = 1$ QH state exhibits various exotic phenomena such as Josephson-like interlayer tunneling [2], quantized Hall drag [3], and/or excitonic superfluidity [4]. The key parameter determining the stability of the state is the ratio between the intralayer and interlayer Coulomb interactions, which is parameterized by $d/\ell_B$ ($d$: distance between the layers, $\ell_B$: magnetic length). It is now established that in the regime of small tunneling the $\nu_T = 1$ QH state exists below a critical value $d/\ell_B \sim 2$.

Most of previous studies on the $\nu_T = 1$ QH system have focused on the regime at balanced density, where both layers are at Landau level filling factor $\nu = 1/2$. The charge density imbalance between the layers, however, should also play a crucial role in determining the nature of the $\nu_T = 1$ QH state, since in the pseudospin space the density imbalance represents the $z$ component of the magnetization induced out of the easy plane by a gate electric field. Several experiments have revealed that the $\nu_T = 1$ QH state is stabilized by a small density imbalance [5, 6, 7], which was discussed in relation with increased pseudospin stiffness in...
the collective mode under density imbalance [8]. Using tunneling spectroscopy as a probe of interlayer coherence, Champagne et al. have investigated in detail the phase boundary between the coherent $\nu_T = 1$ QH state and incoherent state as a function of the total density, or $d/\ell_B$, and the density imbalance [7]. They found that the boundary depends on the two parameters in a rather nontrivial manner; in the vicinity of the phase boundary a small density imbalance stabilized or even restored the coherent state, whereas further increase in the imbalance destroyed it.

All these experiments have been carried out with the magnetic field applied perpendicular to the 2D plane. On the other hand, a recent experiment performed in the balanced density condition under tilted magnetic fields with various tilt angles found a notable role of spin in the phase diagram of the $\nu_T = 1$ system [9]. The experiment revealed that, different from the $\nu_T = 1$ QH state, under a perpendicular magnetic field the incoherent compressible state is not fully spin polarized near the phase boundary. Consequently, the phase boundary shifts to a much larger value of $d/\ell_B$ when the Zeeman energy is increased by adding an in-plane magnetic field. This has a profound implication that the reported phase diagram obtained under perpendicular magnetic fields does not represent the intrinsic property of the system and thus should be modified in the absence of the spin degree of freedom. It is further noted that the collective excitation mode, whose dispersion is expected to be Zeeman independent, does not account for the reported dependence of the phase boundary on density imbalance.

The aim of this work is to investigate the stability of the $\nu_T = 1$ QH state versus density imbalance at full spin polarization using a tilted magnetic field. We present data taken over a wide range of density imbalance from the balanced density to the single-layer limit, where all charges have been transferred to one layer.

2. Experimental

The sample was fabricated from an electron-doped GaAs double quantum well (DQW) containing 18-nm-thick GaAs wells separated by 10-nm-thick AlAs/GaAs (2.1 nm/0.56 nm) superlattice barrier with the corresponding interlayer distance ($d$) of 28 nm. The structure has a virtually negligible tunneling gap calculated to be $\Delta_{SAS} = 150 \mu$K. The DQW is modulation-doped from both sides with the upper and lower setbacks of 180 and 200 nm, respectively. This enabled a nearly equal electron density of $0.8 \times 10^{11}$ cm$^{-2}$ to be produced in each layer without gate voltages. Transport measurements were carried out using standard low-frequency lock-in techniques with an excitation current of 10 nA or less. The sample geometry is a standard Hall bar with ohmic contacts connecting both layers in parallel. The low-temperature mobility was $9 \times 10^{5}$ cm$^{2}$/Vs at a total density of $1.1 \times 10^{11}$ cm$^{-2}$. The electron densities of the individual layers were controlled through voltages $V_{FG}$ and $V_{BG}$ applied to the surface Schottky front gate and $n^+$-GaAs back gate, respectively. The whole measurement was performed at a temperature of around 50 mK. All data presented here were taken with the sample normal tilted by $\theta = 65^\circ$ with respect to the applied magnetic field $B$.

3. Results and Discussion

Before investigating the effects of density imbalance, we first show the magnetotransport characteristics of our sample in the balanced density condition. Figure 1 depicts the longitudinal ($R_{xx}$) and Hall ($R_{xy}$) resistances taken at $\theta = 65^\circ$, plotted as a function of the perpendicular component $B_\perp = B \cos \theta$. Here we show two representative results with different total densities (a) $\nu_T = 0.71 \times 10^{11}$ and (b) $1.0 \times 10^{11}$ cm$^{-2}$, which correspond to (a) $d/\ell_B = 1.88$ and (b) 2.24, respectively. At both densities, we observe features relevant to the $\nu_T = 1$ QH state, characterized by a minimum in $R_{xx}$ and a plateau in $R_{xy}$. At this high tilt angle, the large Zeeman energy forces the spin to be aligned in the competing compressible state, making it energetically unfavorable. This allows the QH phase to extend to a much larger value of $d/\ell_B \sim 2.3$ at
$\theta = 65^\circ$ than $d/\ell_B \sim 1.9$ at $\theta = 0^\circ$ [9]. The smaller electron density $n_T = 0.71 \times 10^{11} \text{cm}^{-2}$, with the corresponding $d/\ell_B = 1.88$ well below the critical value $\sim 2.3$ for this fully spin polarized system, implies that the system is deep in the QH phase. Accordingly, the $\nu_T = 1$ QH effect is well developed at this density, with a deep $R_{xx}$ minimum and a wide quantized Hall plateau.

On the other hand, at the higher electron density $n_T = 1.0 \times 10^{11} \text{cm}^{-2}$ with the corresponding $d/\ell_B = 2.24$ only slightly below the critical value, the system is close to the phase transition point. Since the energy gap is significantly reduced near the transition point [10], the $R_{xx}$ and $R_{xy}$ features signaling the $\nu_T = 1$ QH effect become much weaker at this density.

![Figure 1. $R_{xx}$ and $R_{xy}$ versus perpendicular magnetic field at the total density of (a) $0.71 \times 10^{11} \text{cm}^{-2}$ corresponding to $d/\ell_B = 1.88$ and (b) $1.0 \times 10^{11} \text{cm}^{-2}$ corresponding to $d/\ell_B = 2.24$. The arrows indicate the $\nu_T = 1$ QH state. The inset shows a schematic illustration of the sample alignment with respect to the applied magnetic field.](image)

To study the stability of the $\nu_T = 1$ QH state versus density imbalance, we recorded $R_{xx}$ as a function of $V_{\text{FG}}$ and $V_{\text{BG}}$ at a fixed magnetic field. Figures 2(a) and 2(b) display color plot of $R_{xx}$ measured at two different magnetic fields (a) $B = 7 \text{ T}$ ($d/\ell_B = 1.88$) and (b) $10 \text{ T}$ ($d/\ell_B = 2.24$); these $d/\ell_B$ values correspond to those in Fig. 1. In the color plot, QH states appear as dark regions. The dash-dotted line in the diagonal direction represents the balanced density condition, while the dashed line in the orthogonal direction indicates the line of constant total filling factor $\nu_T = 1$, or the axis of density imbalance. At $d/\ell_B = 1.88$, the $\nu_T = 1$ QH regime is extended along the line of constant total filling factor over a wide range of imbalance, continuously merging into the single-layer $\nu = 1$ QH regime. Similar behavior has been reported for $\theta = 0^\circ$ [11]. It is also seen in Fig. 2(a) that the $\nu_T = 1$ QH state becomes stronger at around a density imbalance of $\nu_T = 1/3 + 2/3$ and above. In addition to the $\nu_T = 1$ QH state, the data also reveal features running almost parallel to the $V_{\text{FG}}$ or $V_{\text{BG}}$ axes. These features, reflecting mostly the filling factor in each layer, are associated with the formation of $\nu = 2/3$ fractional QH states in individual layers. We note here that at density imbalance of $\nu_T = 1/3 + 2/3$ the $\nu_T = 1$ QH region is clearly separated from those regions with $\nu = 2/3$ fractional QH states.
formed in individual layers. At $d/\ell_B = 2.24$, the $\nu_T = 1$ QH state becomes much weaker and only barely discernible. Yet, it does extend over wide range of density imbalance and develops into a well-defined QH regime at $\nu_T = 1/3 + 2/3$, where it is separated from the single-layer $\nu = 1$ QH state. Turning to the $\nu = 2/3$ fractional QH regions in individual layers, we note that these regions are now connected more smoothly to the QH state at $\nu_T = 1/3 + 2/3$.

**Figure 2.** $R_{xx}$ mapped as a function of $V_{FG}$ and $V_{BG}$ at (a) $d/\ell_B = 1.88$ ($B = 7$ T) and (b) $d/\ell_B = 2.24$ ($B = 10$ T) under tilted magnetic fields with $\theta = 65^\circ$. (c) $R_{xx}$ traces along $\nu_T = 1$ as a function of the filling factor difference $\Delta \nu = \nu_f - \nu_b$, where $\nu_f$ ($\nu_b$) denotes the filling factor in the front (back) layer. $\Delta \nu$ is determined by setting $\Delta \nu = 1/3$ ($-1/3$) at the point where the linear extrapolation of the $\nu = 2/3$ region in the front (back) layer intersects with the $\nu_T = 1$ line. At $d/\ell_B = 2.24$, there are pronounced peaks in $R_{xx}$ which clearly separate the state at $|\Delta \nu| \leq 1/3$ from that at $|\Delta \nu| > 0.4$, whereas at $d/\ell_B = 1.88$ such a peak is absent. This suggests that the nature of the $\nu_T = 1$ QH state at $d/\ell_B = 2.24$ has changed between these two situations. We remark that at $d/\ell_B = 2.24$ the $R_{xx}$ mapping shows features associated with the $\nu = 1/3$ fractional QH state formed in individual layers. In addition, the $\nu_T = 1$ QH state increases in strength toward $|\Delta \nu| = 1/3$, i.e., the crossing point of the $\nu = 1/3$ and $\nu = 2/3$ fractional QH regions in the individual layers. From the features observed, we suppose that the system at $|\Delta \nu| = 1/3$ undergoes a transition from the interlayer correlated $\nu_T = 1$ QH state at $d/\ell_B = 1.88$ to independent single-layer fractional QH states at $d/\ell_B = 2.24$. By measuring the tunneling conductance between the layers together with the
Hall resistance in one layer, Champagne et al. have shown that under perpendicular magnetic fields such a transition occurs around \(d/\ell_B = 1.80 \sim 1.84\) [7]. It is noteworthy that this value of \(d/\ell_B\) coincides with the coherent-incoherent phase transition point at \(\Delta \nu = 0\) in their sample. This suggests that the interlayer correlation is lost all together over the entire range of \(|\Delta \nu|\). In marked contrast, in the present case, the \(\nu_T = 1\) QH state does exist at \(\Delta \nu = 0\) at the same \(d/\ell_B\) where the two layers seem to be uncorrelated at \(|\Delta \nu| = 1/3\). One clue may be that the \(\nu = 2/3\) QH state has two ground states with different spin polarizations. We verified by a separate experiment that in our sample the single-layer \(\nu = 2/3\) QH state is likely to be spin unpolarized. At present, however, it remains unknown how the interlayer correlation is lost with the increase in \(|\Delta \nu|\) and specifically how the spin polarization is concerned with this issue.

Another interesting feature is the camelback shape observed in the \(R_{xx}\) trace at \(d/\ell_B = 1.88\) with its local minimum at \(\Delta \nu = 0\). The asymmetry with respect to \(\Delta \nu = 0\) is probably due to unintentional asymmetry in the sample. The camelback feature becomes less pronounced at \(d/\ell_B = 2.24\). This shape indicates that a finite but small density imbalance makes the \(\nu_T = 1\) QH state less stable. A similar feature has been reported for a bilayer hole system [11], where it was discussed in conjunction with a phase diagram proposed taking account of the ground state energies of two independent single-layer states. However, such behavior was not observed in previous activation gap measurements under a perpendicular magnetic field [5, 6], which showed a minimum in the gap at \(\Delta \nu = 0\). We do not know the origin of the different behavior; a possible cause may be sample disorder or different current distribution between the two layers.

4. Conclusion

In summary, we have investigated the evolution of the bilayer \(\nu_T = 1\) QH state versus density imbalance when the system is in full spin polarization under a tilted magnetic field. At \(d/\ell_B\) much smaller than at the transition point, the \(\nu_T = 1\) QH state evolves over a wide range of density imbalance and continuously develops into the single-layer \(\nu = 1\) QH state. In the vicinity of the transition point, on the other hand, the \(\nu_T = 1\) QH state becomes significantly weaker and merges into a well-developed QH regime at \(\nu_T = 1/3 + 2/3\), where it is separated from the single-layer \(\nu = 1\) QH regime. These observations suggest that the system at the imbalance of \(\Delta \nu = 1/3\) undergoes a transition from the correlated \(\nu_T = 1\) QH state to independent single-layer fractional QH states with increase in \(d/\ell_B\).

5. Reference

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