Unusual Landau Level Pinning and Correlated $\nu = 1$ Quantum Hall Effect in Hole Systems Confined to Wide GaAs Quantum Wells

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In two-dimensional hole systems confined to wide GaAs quantum wells, where the heavy- and light-hole states are close in energy, we observe a very unusual crossing of the lowest two Landau levels as the sample is tilted in magnetic field. At a magic tilt angle $\theta \simeq 34^\circ$, which surprisingly is independent of the well-width or hole density, in a large filling factor range near $\nu = 1$ the lowest two levels are nearly degenerate as evinced by the presence of two-component quantum Hall states. Remarkably, a quantum Hall state is seen at $\nu = 1$, consistent with a correlated $\Psi_{111}$ state.

I. INTRODUCTION

Among the most fascinating phases of two-dimensional electron systems (2DESs) in a strong perpendicular magnetic field ($B_{||}$) are the quantum Hall states (QHSs). These are incompressible phases signaled by vanishing longitudinal resistance ($R_{xx}$) and quantized Hall resistance ($R_{xy}$), and are observed at integral or certain fractional Landau level (LL) filling factors ($\nu$). Adding a layer (or subband) degree of freedom leads to exciting twists. A bilayer electron system with nearly degenerate LLs from different subbands and comparable inter- and intra-layer interaction can support new, two-component (2C) QHSs that have no counterpart in standard single-layer (or one-component, 1C) 2DESs. An example is the $\Psi_{331}$ state, a QHS formed at the even-denominator filling $\nu = 1/2$. The correlated $\Psi_{111}$ QHS, stabilized at $\nu = 1$, is another example. This state is generally considered to be an excitonic superfluid which can support Josephson-like interlayer tunneling and superfluid transport.

Recent experimental studies of 2D hole systems (2DHSs) confined to wide GaAs quantum wells (QWs) have unraveled unique phenomena, arising from the non-trivial spin-orbit coupling of the heavy- and light-holes. Graninger et al. reported a reentrant behavior of the $\nu = 1$ QHS as a function of parallel magnetic field $B_{||}$ in symmetric, wide QW. Later, Liu et al. observed an unusual crossing of the two lowest-energy LLs at $B_{||} = 0$ as a function of $B_{\perp}$. For a given density ($p$) and well-width ($W$), the crossing occurs at a particular filling (Fig. 1(a)); it destroys or weakens the odd-denominator QHS near this filling, and stabilizes a unique even-denominator QHS when it happens at $\nu = 1/2$.

Here we present low-temperature transport data for 2DHSs confined to symmetric, wide GaAs QWs, as we change the tilt angle ($\theta$) between the sample normal and the magnetic field direction. We find that at low and high $\theta$, if $W$ and $p$ are sufficiently large, LLs from different subbands are well separated from each other and the 2DHSs exhibit normal QHSs at the standard fillings $\nu = 2/3, 1, 4/3, 7/5, 8/5$ and 5/3. But near an intermediate $\theta$, the 2DHSs exhibit 2C QHSs similar to those reported in bilayer 2DESs with vanishing subband separation. This observation indicates that the two lowest-energy LLs are nearly degenerate and is consistent with a $B_{||}$-induced LL crossing. Remarkably, as schematically shown in Fig. 1(b), this near degeneracy persists in a large magnetic field range near $\nu = 1$ when $\theta \simeq 34^\circ$, a magic angle which does not depend on $W$ or $p$. Moreover, when the two LLs are degenerate, the 2DHS is compressible at $\nu = 1$ if $p$ and $W$ are large so that $d/l_B \gtrsim 1.3$, but exhibits a QHS when $d/l_B \lesssim 1.3$, consistent with the development of a correlated 2C ($\Psi_{111}$) state ($d$ is the interlayer separation and $l_B$ is the magnetic length).

II. METHOD

Our samples, grown by molecular beam epitaxy on GaAs (001) wafers, consist of GaAs QWs flanked by undoped Al$_{0.3}$Ga$_{0.7}$As spacer and carbon $\delta$-doped layers. The 2DHSs have as-grown densities ranging from 0.98 to 2.12, in units of $10^{11}$ cm$^{-2}$ which we use throughout this report, and very high low-temperature mobilities $\mu \gtrsim 100$ m$^2$/Vs. We made samples in a van der Pauw geometry, $4 \times 4$ mm$^2$, and alloyed In:Zn contacts at their four corners. Each sample is fitted with an evaporated Ti/Au front-gate and an In back-gate to control the 2DHS density and QW symmetry. The data presented here were taken in symmetric QWs. The transport measurements were carried out in a dilution refrigerator with a base temperature of $T \approx 30$ mK and a superconducting magnet up to 18 T. We changed $\theta$ with an in-situ rotator, and used low-frequency (~30 Hz) lock-in technique. Here we focus primarily on $R_{xx}$ traces; the $R_{xy}$ data corroborate $R_{xx}$ and show corresponding plateaus.
III. EXPERIMENTAL RESULTS AT θ = 0

We first describe data taken in a 2DHS confined to a 40-nm-wide QW as a function of density at θ = 0°. In Fig. 2, the QHS transitions (marked by solid circles) which appear when two LLs are nearly degenerate, can be seen moving from low to high ν as we increase p. At p = 0.76, we observe QHSs at the standard fillings, similar to what is seen in systems where LLs from different subbands are well-separated[2]. The ν = 2/3 QHS becomes weak at p = 0.82 but is restored at higher p. The weakening of the ν = 1 QHS at p ≃ 1.01 is evidenced by a profound narrowing of its Rxx plateau, and serves as direct evidence that the two lowest-energy LLs are crossing at ν = 1.123[20]. At p = 1.20, a strong ν = 1 QHS is restored, and a 2C QHS develops at an unusual filling ν = 19/15[18,20]. The transition continues moving to higher ν at p = 1.31. The ν = 5/3 QHS disappears and another 2C QHS develops at ν = 3/2, which is the particle-hole counterpart of the 2C ν = 1/2 (Ψ331) QHS[20]. In the top trace (p = 1.59), the 2DHS reverts back to 1C for ν < 2, exhibiting QHSs at standard fillings. The above evolution of the QHSs, which implies a LL crossing that moves from low ν to high ν as density is increased, is consistent with previous observations and theoretical calculations[13].

The above LL crossing can be qualitatively understood in a simplified picture (see the right panels in Fig. (2)). When confined to QWs, because of their heavier mass in the z-direction, the heavy-hole (HH) subband is lower in energy than the light-hole (LH) subband. But the HHs have a smaller effective mass in the xy-plane than the LHs, so the ground-state (N = 0) LL of the HH symmetric subband, which we refer to as HH-S0 for simplicity, increases faster in energy than the LH-S0 LL as we sufficiently increase B⊥, leading to a LL crossing. In a more quantitative picture, the spin-orbit coupling mixes the HH and LH subbands and LLs, and results in a more complex, non-linear LL fan diagram. However, the crossing between the two lowest-energy LLs is preserved in symmetric QW.[34] In our wide QW samples, the HH and LH subbands are close in energy, so the two levels cross at moderate B⊥.

IV. EXPERIMENTAL RESULTS OF FINITE θ

Data presented in Fig. 3 reveal that QHS transitions can also be induced at a fixed density by varying θ, but the behavior is dramatically different. In Fig. 3(c), we show Rxx vs B⊥ traces measured at p = 2.05 and different θ. The density is high so that the LH-S0 LL is well below the HH-S0 LL at θ = 0° in the range ν < 2 (see Fig. 2(d)), and the 2DHS exhibits 1C QHSs at standard fillings. At θ ≃ 34°, the 2DHS becomes 2C in a large range of fillings 2/3 < ν < 2. This is evinced by the development of insulating phases around ν = 2/3 (i.e., around ν = 1/3 for each component[23]), the complete disappearance of the QHSs at ν = 5/3 and 1, as well as the stabilization of QHSs at twice the standard fillings ν = 4/3, 6/5, 7/5, 2/3, and at unusual fillings such as ν = 19/15 and 29/35[18,20]. At larger θ, the ν = 1 and 5/3 QHSs disappear while many 2C QHSs remain, suggesting the two lowest-energy LLs are separated by a small but finite energy[23].

Figure 3(d) data taken at p = 1.59 exhibit a more complete and revealing evolution. The system is essentially 1C for θ ≲ 20° and θ ≳ 44°, showing strong QHSs at standard fillings[23]. It becomes 2C for ν < 2 when 25° ≲ θ ≲ 44°, exhibiting insulating phases flanking ν = 2/3 and 2C QHSs at ν = 19/5, 6/5, 29/35, etc., while QHSs at ν = 1 and 5/3 become weak and essentially disappear as θ approaches 34°.

Figure 3(c) shows traces taken at p = 1.28 where, at θ = 0, the LL crossing occurs near ν = 3/2, as evidenced by the stabilization of the correlated, 2C QHS at ν = 3/2, and the absence of a QHS at ν = 5/3. Similar to the data of Figs. 3(c) and (d), the system becomes 2C near θ ≃ 34° and 1C when θ ≳ 49°. However, in contrast to Figs. 3(c) and (d) data, the ν = 1 QHS becomes weak at θ = 34° but never disappears. The fact that the system is 2C near ν = 1 suggests that the ν = 1 QHS seen at θ ≳ 34° in Fig. 3(d) is also a 2C QHS; we will return to this later.
V. DISCUSSION

The transition from 1C to 2C as a function of increasing \( B_{\|} \) has been reported previously for electrons confined to wide GaAs QWs. In such systems, the coupling of \( B_{\|} \) to the orbital (out-of-plane) motion of electrons renders the system progressively more bilayer-like at higher \( B_{\|} \) and quenches the energy separation between the \( N = 0 \) LLs of the symmetric and antisymmetric subbands, making them essentially degenerate. Further increasing \( B_{\|} \) does not lift this degeneracy and the system remains 2C at the highest \( B_{\|} \). This is very different from our data shown in Figs. 3(d) and (e), where the 2DHS near \( \nu = 1 \) becomes 2C only near \( \theta \approx 34^\circ \), but is 1C at smaller and \( \theta \) asymmetry.

We attribute the evolution in Fig. 3 data to a \( B_{\|} \)-induced LL crossing. Unfortunately, no accurate calculations of LLs in the presence of both \( B_{\perp} \) and \( B_{\|} \) are available, particularly for 2DHSs with multiband structure. The tilted-field geometry implies complicated couplings between Landau harmonic oscillators from different subbands, and makes numerical calculations extremely demanding. Qualitatively, we can explain the crossing as follows. The densities of Fig. 3 data are sufficiently large so that the LH-S0 level is lower than the HH-S0 level near \( \nu = 1 \) at \( B_{\parallel} = 0 \) (Figs. 2(c) and (d)). Finite \( B_{\|} \) introduces additional confinement of the 2DHS in the \( z \)-direction, raises the LH-S0 LL relative to the HH-S0 LL, and causes a crossing of these levels at intermediate \( \theta \) (see Fig. 4(d)).

The most remarkable feature of Fig. 3 data, however, is not the LL crossing at an intermediate \( \theta \). Rather, it is the behavior of the 2DHS near the crossing angle, suggesting a very unusual "pinning" or near-pinning of the LLs in a very large range of \( \nu \) (Fig. 1(b)). Note in Fig. 3 that at a given density the system exhibits 2C behavior in the entire range of \( \nu < 4/3 \) at \( \theta \approx 34^\circ \). This is very different from the \( \theta = 0 \) data of Fig. 2 where the LL crossing features for any given density appear near a specific \( \nu \) which moves from low to high values as the density is increased. Moreover, in Fig. 3 the angle \( \theta \approx 34^\circ \) at which the 2DHS becomes 2C appears to be independent of the 2DHS density. In other 2DHS samples, confined to QWs with \( W \) ranging from 35 to 50 nm, we have observed similar phenomena as in Fig. 3 at the same \( \theta \approx 34^\circ \). This independence of the 2C behavior on \( \nu, p, \) and \( W \) at this critical angle is astonishing, and demands a theoretical explanation.

The evolution of the QHS at \( \nu = 1 \) is also very intriguing. As seen in Fig. 3, it disappears completely at \( \theta \approx 34^\circ \) when \( p = 2.05 \) but only becomes weak at \( p = 1.28 \). In Fig. 4(a) we summarize our results for many 2DHSs, illustrating the conditions for the stability...
of the $\nu = 1$ QHS. Data are shown as a function of $\theta$ and $d/|B|$, which compares the interlayer ($e^2/4\pi\epsilon d$) and intra-layer ($e^2/4\pi\epsilon l_B$) correlations and is widely used to characterize bilayer QHS. Figure 4(a) shows that no LL crossing at $\nu = 1$ can be induced via tilting if $d/|B| \gtrsim 1.0$, and the $\nu = 1$ QHS is always strong. When $d/|B| \gtrsim 1.0$, at $\nu = 1$, the LH-S0 level is lower than the HH-S0 level at $\theta = 0$, and the two levels cross at $\theta \approx 34^\circ$; see Fig. 4(d). At the crossing, we observe a QHS at $\nu = 1$ if $d/|B| \gtrsim 1.3$, and the ground state becomes compressible if $d/|B| \gtrsim 1.3$.

The $d/|B| \gtrsim 1.3$ condition for the stability of the $\nu = 1$ QHS at the crossing, and the fact that the 2DHs is 2C at nearby fillings, suggest that it is a 2C QHS with strong interlayer correlations, likely the $\Psi_{111}$ state reported in GaAs bilayer electron or hole systems confined to double QWs. In those systems, when the lowest LLs from different subbands are degenerate, the $\nu = 1$ QHS is stable at $d/|B| \gtrsim 2$, and turns into a compressible state if $d/|B|$ becomes large. Also note that in our experiments the energy separation between the two crossing LLs increases as $\theta$ deviates from $\approx 34^\circ$ (see Fig. 4(d)). We show in Fig. 4(c) a schematic “phase diagram” for the stability of the $\nu = 1$ QHS as functions of $\Delta$ and $d/|B|$. The resemblance of Fig. 4(c) to the phase diagram of $\nu = 1$ QHS in double QW [21] is striking. We emphasize that in our experiments, we are essentially tuning $\Delta$ through zero as we tilt the sample near $\theta \approx 34^\circ$; see Figs. 4(d).

In conclusion, 2DHs confined to wide GaAs QWs and with sufficiently high density, reveal an unusual crossing of the two lowest-energy LLs near $\nu = 1$ as we tilt the sample in magnetic field. It appears that a magic angle $\theta \approx 34^\circ$, essentially independent of the QW width, density, or $B_\perp$ (filling), suggesting a pinning of the LLs near the crossing. The crossing and the pinning likely stem from the complex interplay of the heavy- and light-hole states reported in $B_{||}$, and should stimulate further theoretical investigation. Near this angle, the 2DHS becomes 2C at $\nu < 2$ and, if $d/|B|$ is small, exhibits a $\nu = 1$ QHS, consistent with a correlated, 2C, $\Psi_{111}$ state.

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