High-mobility two-dimensional (2D) systems can be quantized by a perpendicular magnetic field $B$ into Landau levels (LLs), whose discrete energy spectrum is revealed in magnetotransport as the quantum Hall (QH) effect. Anomalous peaks residing within QH minima of the longitudinal resistance provide evidence for crossings or anticrossings of LLs. In AlAs/AlGaAs [1], InP/GaInP [2], Si/SiGe [3], and InGaAs/InAlAs [4] 2D electron systems, (anti)crossings can be induced in a tilted $B$ field between Landau energies $E_{n,\sigma} = (n + 1/2)\hbar\omega_c + g^*\mu_B B$ with integer $n \geq 0$ and $\sigma = \pm 1/2$ the orbital and spin quantum numbers, $g^*$ the effective Landé $g$ factor, and $\mu_B$ the Bohr magneton. The cyclotron frequency for a heavy hole (HH) or light hole (LH) state (dk) and post-illumination (ill) are reported elsewhere [15]. Four-terminal transport measurements are performed in a Hall bar geometry at ac-frequencies between 10 – 30 Hz and excitation currents between 10 – 200 nA. The density is tuned continuously with a thermally evaporated Al-gate on top of the Hall bar. The density can also be changed with persistent photoconductivity via back-side illumination with an infra-red LED. The maximum mobility in this gated sample is $\mu = 125 \times 10^3$ cm$^2$/Vs at a density of $p = 2.4 \times 10^{11}$ cm$^{-2}$. Above about 300 mK an anomalous peak appears within the $\nu = 1$ minimum of the longitudinal resistance, whose position depends on the illumination history of the sample but not on the front-gate voltage. Superscripts will distinguish the two principal illumination states presented here, the dark state (dk) and post-illumination state (ill). Figure 1(a) shows the longitudinal $R_{xx}$ and transverse $R_{xy}$ resistance at 320 mK after illumination, with the density $p_{\text{ill}} = 1.34 \times 10^{11}$ cm$^{-2}$ chosen such that the anomalous peak sits in the center of the $\nu = 1$ minimum. The peak position $B^\text{ill}_p = 5.6$ T is reproducible in subsequent cooldowns and does not show any hysteresis, and the peak completely disappears in the 50 mK low temperature trace. Figure 2 shows the weak dependence of the peak position on front-gate bias. The front-gate voltage tunes the density from from $p = 1.07$ to $1.78 \times 10^{11}$ cm$^{-2}$ shifting $R_{xx}$ features strongly to the right yet leaving the peak position $B^\text{ill}_p = 5.6$ T practically unaffected (bold lines). In contrast, the illumination state of the sample seems to strongly influence the peak position. In the dark before illumination...
FIG. 1: (a) Longitudinal $R_{xx}$ and transverse $R_{xy}$ resistance at $T = 320$ mK (50 mK) shown in black (grey) for the 2D hole system with $p^\text{ill} = 1.34 \times 10^{11}$ cm$^{-2}$ ($1.40 \times 10^{11}$ cm$^{-2}$). The small peak in the $\nu = 1$ minimum disappears in the low temperature trace. (b) Self-consistent calculation of the LLs for the system in (a). The dashed line shows the oscillating Fermi energy $E_F$ at $T = 320$ mK. The anticrossing of the two lowest LLs coincides with the peak within the $\nu = 1$ minimum. (c) The average spin $\langle S_z \rangle$ in the lowest Landau levels, showing a spin flip at the anticrossing.

Fig. 3 shows how the peak occurs at $B^\text{dk}_p = 7.2$ T for $p^\text{dk} = 1.74 \times 10^{11}$ cm$^{-2}$. Note that an equivalent density to Fig. 3 is reached in Fig. 2 after illumination, demonstrating that the illumination and not density is the critical factor in shifting the peak position to lower fields.

The temperature dependence of the dark-state $R_{xx}$ within the $\nu = 1$ QH minimum is shown in Fig. 3(a). The arrows indicate increasing temperature in the range from 400 to 800 mK. If the observed temperature dependence is interpreted in terms of activated conduction across an energy gap, Arrhenius plots such as in Fig. 3(b) can map out the dependence of the gap energy $\Delta$ on $B$ in the neighborhood of the peak, where:

$$R_{xx} \propto \exp(-\Delta/2k_B T).$$

Arrhenius plots for the $R_{xx}$ peak maximum (□) and neighboring minima (▽, ○) are shown in Fig. 3(b), with the existence of a local activation minimum consistent with an anticrossing at the resistance peak $\Delta^\text{dk} = 250 \mu$eV in Fig. 3(c). The same analysis for the illuminated condition results in a gap of $\Delta^\text{ill} = 105 \mu$eV. At fields further from the anticrossing, the activation gap narrows again presumably because contributions from extended state conduction render Eq. 1 invalid.

To understand these experimental results, we performed numerical calculations of the 2D hole system based on the methods discussed in Ref. [7]. We first determine the Hartree potential self-consistently at $B = 0$ [Fig. 4(a–c)], then we obtain the LLs as a function of $B$ [Fig. 4(d–f)]. For these calculations we use a multiband Hamiltonian that contains the bands $\Gamma_6^c$, $\Gamma_8^v$, and $\Gamma_7^v$, and we take into account all terms of cubic and tetrahedral symmetry which are characteristic of the (110) growth facet of our samples. The hole densities in the calculation correspond either to the gated dark density $p^\text{dk}$ of Fig. 3 or to the gated post-illumination density $p^\text{ill}$ of Fig. 1. In Fig. 4(d), one sees that the uppermost hole LLs do in fact anticross even though $B$ is entirely perpendicular. This confirms that anticrossings between the lowest LLs occur on this facet and might explain the anomalous $R_{xx}$ peak at $\nu = 1$.

The gate and illumination dependences of the peak
observed peak position after illumination, the calculated anticrossing field matches to the experimentally determined anticrossing field. The terplay of HH-LH coupling, spin-orbit coupling (Rashba term), and the Zeeman term. For these samples.

We remark that exchange interactions have been ignored which decreases by about a factor of 2 after illumination. We consider the majority of the field. In agreement with these qualitative arguments, our calculations predict that $B_p$ changes by only 0.2 T when $p$ is varied by means of a front gate as in Fig. 2. Consistent with these results, careful inspection of Fig. 2 shows that the peak position indeed shifts slightly to the right with increasing density as a result of the small increase in $E_{S}$. Our calculations can determine the spin polarization of the system, and predict a spin flip at the anticrossing. Figure 4(c) shows the expectation value of the $z$ component of the spin operator, $\langle S_z \rangle$, for the two lowest LLs. Away from the anticrossing, these LLs are almost pure HH LLs with average spin $\langle S_z \rangle$ closed to $+3/2$ or $-3/2$. At the anticrossing, the spin expectations $\langle S_z \rangle$ of these two levels flip from $+3/2$ to $-3/2$ over a small $\sim 1$ T range.

Novel spintronic devices might be able to utilize the electrostatically tunable anticrossing field to control the ground state spin. One of the most challenging tasks in spintronics is achieving efficient spin injection from ferromagnetic spin-polarized contacts. According to the present work, a 2D hole sample with patterned front-gates and back-gates could create regions of differing electrostatic confinement and therefore different anticrossing fields $B_p$. Assuming $B_{p1} = 5.6$ T and $B_{p2} = 7.2$ T as realized in this experiment, a bias field of $B =$

\[ E_{\text{ill}} = 24.1 \text{ V/cm} \ (N_{Dk} = 1.6 \times 10^{15} \text{ cm}^{-3}) \]
FIG. 4: Hartree potentials and charge density $\rho(z)$ for a 2DHG with density $p^{ll} = 1.34 \times 10^{11}$ cm$^{-2}$ assuming (a) no substrate electric field, and (b) a substrate field which produces a 5.6 T anticrossing. The substrate field in (c) produces an anticrossing at 7.2 T for the density $p^{lh} = 1.74 \times 10^{11}$ cm$^{-2}$. In the corresponding Landau fans (d-f), the ground energy of the 2D subband is defined as $E = 0$. (Fig. 4(e) is reproduced in Fig. 4(b).)

$$(B_{p1} + B_{p2})/2 = 6.4$ T applied uniformly over the sample would leave the $B_{p1}$ regions occupied with $S_z \simeq -3/2$ HHs and the $B_{p2}$ regions with $S_z \simeq +3/2$ HHs. Such reservoirs could be used as spin-reservoirs for spintronics and spin-based quantum computations in a reduced two-component pseudo-spin basis.

In summary, we observed an anomalous peak in the longitudinal resistance of two-dimensional hole systems on (110) oriented GaAs. We performed numerical calculations of the Landau levels and found good agreement of the calculated lowest level anticrossing with the experimental peak position. We measured the activation energy of the anticrossing energy gap, and propose that the spin-flip which occurs at the anticrossing will prove useful in spintronics and in spin-based quantum computations.

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