Anticrossings of spin-split Landau levels in an InAs two-dimensional electron gas with spin-orbit coupling

W. Desrat, F. Giazotto, V. Pellegrini, M. Governale, and F. Beltram
NEST-INFM and Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56126 Pisa, Italy

F. Capotondi,* G. Biasiol, and L. Sorba*
NEST-INFM and Laboratorio Nazionale TASC-INFM, Area Science Park, I-34012 Trieste, Italy
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We report tilted-field transport measurements in the quantum Hall regime in an $InAs/In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ quantum well. We observe anticrossings of spin-split Landau levels, which suggest a mixing of spin states at Landau level coincidence. We propose that the level repulsion is due to the presence of spin-orbit and of band-nonparabolicity terms which are relevant in narrow-gap systems. Furthermore, electron-electron interaction is significant in our structure, as demonstrated by the large values of the interaction-induced enhancement of the electronic *g* factor.

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A rich class of magnetic phenomena in two-dimensional electron systems (2DES's) due to the crossing of Landau levels with opposite spin polarizations has recently been the subject of intense theoretical and experimental efforts. Giuliani and Quinn[1] predicted a first-order transition between spin-polarized and spin-unpolarized quantum Hall (QH) states near crossing between Landau levels in a tilted-field configuration at $\nu=2$. By tilting the field, the ratio between the Zeeman energy (E_z) and the cyclotron energy (E_c) increases, eventually reaching unity. It was shown, however, that the transition occurs before coincidence of the single-particle energy levels. It happens when the energy difference between the last-occupied and first-unoccupied single-particle Landau levels reaches a critical value, which depends on the strength of electron-electron interaction.[1,2]

It has been shown that the first-order transition always occurs when the two Landau levels involved in the crossing have similar wave function profiles like in the single-layer single-subband systems.[3,4] In this case the gain in the exchange energy at the transition dominates over Hartree and single-particle energy splitting, leading to an easy-axis anisotropy and to Ising ferromagnetism.[4] In the opposite limit, which can be reached, for instance, in a double-layer system, a second-order phase transition can occur, leading to an easy-plane anisotropic QH ferromagnetic state.[4] In magnetotransport studies, Ising ferromagnetism has remarkable experimental signatures. It is associated either with the complete disappearing of the QH state at the crossing or with the persistence of the QH state with resistance spikes and hysteretic behavior.[5,6] It is now established that these effects stem from the dynamics of magnetic domains and are strongly affected by disorder or temperature. Most of the experimental efforts focused on high-mobility GaAs/AlGaAs heterostructures, but also other materials were exploited in order to have larger *g* factors, so that Zeeman and cyclotron energies become comparable at more experimentally accessible magnetic fields. To this end, AlAs quantum wells and II-VI diluted magnetic semiconductors were studied.[6,7] Transitions between spin-split Landau levels have also been reported in InAs-based single-layer systems like in InGaAs/InP heterostructures[2] and in InAs/AlSb quantum wells.[8]

The spin properties of QH ferromagnets could be radically modified by the presence of additional spin-mixing terms. A few theoretical works investigated the impact of single-particle effects related to Rashba and Dresselhaus spin-orbit couplings on the spin properties of QH states at low filling factors.[9–11] In Ref. 10, an anticrossing of the two lowest spin-split Landau levels due to a new partially spin-polarized spin-density-wave-like state induced by spin-orbit coupling was predicted. These theoretical works indicate that single-particle effects cooperate with Hartree and exchange contributions in determining the spin configuration of QH states. An experimental investigation of the interplay between many-body effects and spin-mixing terms has not been carried out yet. For this purpose, semiconductor heterostructures displaying both large exchange interaction and spin-orbit coupling should be realized.

Here we report tilted-field magnetotransport measurements in a 2DES confined in a narrow $InAs/In_{0.75}Ga_{0.25}As$ single quantum well which exhibits significant spin-orbit coupling and large exchange interaction. Anticrossing of spin-split Landau levels at even and odd low filling factors are observed close to degeneracy between Landau levels with similar wave function profiles. We argue that these results offer evidence of the impact of spin-orbit (SO) coupling on the collective spin configuration of QH ferromagnets. The experiments also suggest that additional single-particle spin-mixing terms, originating from band nonparabolicity (NP) (usually neglected at low magnetic fields), can also determine the collective spin configuration of QH states.

The sample consists of an unintentionally doped 30-nm-wide $In_{0.75}Ga_{0.25}As$ quantum well embedded in $In_{0.75}Al_{0.25}As$ barriers and metamorphically grown on a GaAs substrate.[12] A thin 4-nm InAs layer is inserted in the center of the well. The conduction band and density profiles computed by a 1D Poisson-Schrödinger solver[13] are shown in Fig. 1(a). The 2DES is characterized by a carrier density of $n_s=2.73\times10^{11}\ \mathrm{cm}^{-2}$ and a mobility of

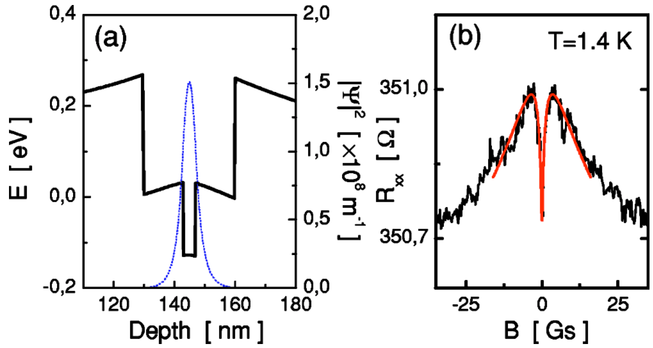

FIG. 1. (Color online) (a) Conduction band (left axis) and density profile (right axis) for the $InAs/In_{0.75}Ga_{0.25}As$ quantum well determined from 1D a Poisson-Schrödinger simulation with a constant background doping $N_{dd}=2.9\times10^{16}$ cm^{-3}. (b) Experimental and theroretical low-magnetic-field dependences of the longitudinal resistance (black and red curves, respectively) at $T=1.4$ K.

$\mu=1.93\times10^5$ cm^2/(V s), which can be tuned by biasing a top gate. Taking into account the confinement correction and the weight of the wave function in the different layers, a five-band $\boldsymbol{k}\cdot\boldsymbol{p}$ calculation yields $m^*=0.034m_0$ (where m_0 is the free electron mass) and $g^*=-10.4$ for the effective mass and g factor, respectively. Magnetotransport measurements in the QH regime were performed by placing the sample in a dilution fridge ($T_{bath}=30$ mK) where it can be rotated *in situ* with respect to the magnetic field (the tilt-angle geometry is shown in the lower inset of Fig. 2). The longitudinal resistance is measured on a 80-μm-wide Hall bar with a phase-sensitive technique using a 20-nA bias current. Figure 2 displays the longitudinal magnetoresistance R_{xx} versus the perpendicular magnetic field $B_\perp$ for different tilt angles θ (the latter are accurately determined from the Hall voltage).

In Fig. 2 several transitions between spin-split Landau levels are observed at even and odd filling factors. These coincidences occur each time the ratio between the exchange-enhanced Zeeman and cyclotron energies is an integer $r=E_z/E_c=1,2,\ldots$, as shown schematically in the right upper part of Fig. 2. First, we focus on the transition at $\nu=6$ corresponding to $r=1$. Two distinct peaks are observed at very low tilt angles (lying at $B\approx1.75$ and 2 T) that merge into a single peak at the coincidence $\theta\sim77.4°$ and split again at larger angles (green lines to guide the eye). This scenario is also observed for higher filling factors $\nu=7$ and 8. Conversely, the evolutions at $\nu=3$ and 5 are characterized by anticrossing as a function of the tilt angle (red lines to guide the eye in Fig. 2).

Figure 3(a) shows the perpendicular magnetic field position of the R_{xx} peaks, $B_{R_{xx}max}$, as a function of $1/\cos(\theta)$. Crossings and anticrossings are labeled with the corresponding r. It is clear that at $\nu=5$ two adjacent Landau levels come closer and then repel avoiding the crossing. Even if the measure of the gap at the coincidence is presently lacking, we stress that at $\nu=5$ ($r=2$) the resistance minimum does not reach zero at this very low temperature (see Fig. 2), indicating that the gap is relatively small. A qualitative comparison with the $R_{xx}(B)$ curves obtained on a similar sample where activation energies have been measured at several integer

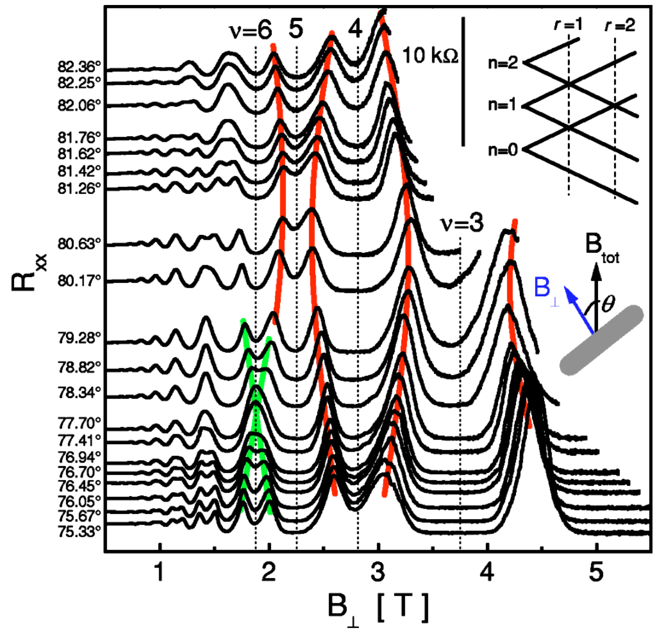

FIG. 2. (Color online) Longitudinal resistance as a function of the perpendicular magnetic field for different tilt angles measured at $T=30$ mK. Curves have been shifted proportionally to $1/\cos(\theta)$ for clarity. Vertical thin dotted lines indicate constant integer filling factors. Crossing at $\nu=6$ and anticrossings at $\nu=3$ and 5 are enlightened by the green and red lines to guide the eye, respectively. Upper inset: schematic diagram of the spin-split Landau levels vs $1/\cos(\theta)$ (i.e., vs E_z for fixed perpendicular magnetic field). Lower inset: sketch of the tilt-angle geometry.

filling factors (data not shown) suggests that the gap at the transition should be less than 0.5 K.

In Fig. 3(b) the R_{xx} peak position is shown with the top gate biased at $V_g=0.5$ V. This positive voltage slightly in-

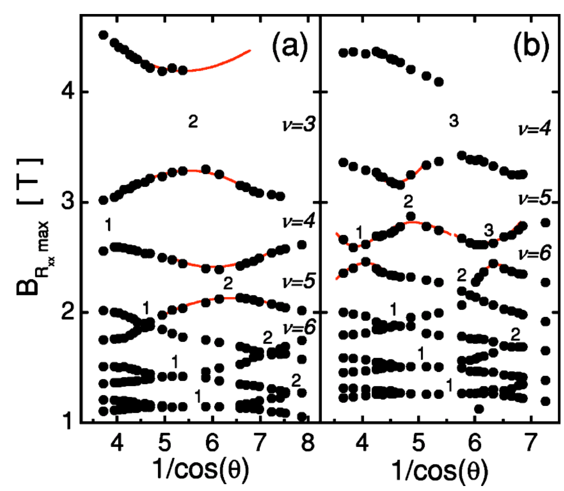

FIG. 3. (Color online) Perpendicular magnetic field position of the longitudinal resistance peaks as a function of the inverse cosine of the tilt angle at gate voltages (a) $V_g=0$ V ($n_s=2.73\times10^{11}$ cm^{-2}) and (b) $V_g=0.5$ V ($n_s=3.65\times10^{11}$ cm^{-2}). Thin red lines to guide the eye have been added to emphasize the anticrossings. The crossings and anticrossings have been labeled with the corresponding value of r.

creases the carrier density up to $n_s=3.65\times10^{11}$ cm^{-2} and shifts the filling factors toward higher perpendicular fields. As for the zero-bias case, the large filling factors ($\nu=7$, 8, 9, and 10) exhibit conventional crossings whereas the low fillings ($\nu=4$ and 5) present anticrossings. We note that the transition at $\nu=6$ appears now as an anticrossing. The second transition observed at $\nu=6$ at higher tilt angle corresponds to $r=3$. Thus the effective Zeeman energy is 3 times larger than the cyclotron energy, implying that the electronic g factor is large in our system (e.g., $|g^*|=3[2\cos(\theta)/m^*]=28\pm0.5$) as expected from the presence of the narrow-gap InAs layer. Furthermore, the strong filling factor dependence of the coincidence conditions at fixed E_z/E_c ratio [e.g., at $r=1$, $1/\cos(\theta_c)=3.97$, 4.56, and 5.07 for $\nu=6$, 8, and 10, respectively, where θ_c is the coincidence angle] highlights the large contribution of the electron-electron interaction to the spin gap, as already estimated elsewhere.[14]

Our system exhibits a finite spin-orbit coupling as expected for InGaAs heterostructures.[15] Figure 1(b) shows the longitudinal resistance as a function of the magnetic field at $T=1.4$ K and $\theta=0$ in the low-field region. The resistance enhancement upon reducing B is due to weak localization, while the narrow dip around $B=0$ is due to weak antilocalization induced by spin-orbit coupling.[16,17] Figure 1(b) also reports the result of a theoretical calculation based on the Iordanskii–Lyanda-Geller–Pikus model.[18] From fitting the data, we estimate the effective spin-orbit and phase-breaking magnetic fields $H_{\rm so}=1.5$ G, $H'_{\rm so}=0.8$ G, and $H_\phi=0.067$ G. Figure 1(b) clearly demonstrates that spin-orbit terms are relevant in our system and coexist with many-body interactions.[19]

We are now in the position to discuss the possible origin of the observed anticrossings. To this end we recall that in a single-layer system when two Landau levels come into coincidence the exchange energy leads to an easy-axis ferromagnet characterized by a nonvanishing gap at the transition. This gap is proportional to the Coulomb interaction $e^2/4\pi\varepsilon\ell_B$ (ℓ_B is the magnetic length and ε the dielectric constant) and is typically much larger than k_BT at millikelvin temperatures. Thus the common signature of an easy-axis ferromagnet is the observation of a persistent $R_{xx}=0$ region in the longitudinal magnetoresistance.[2] Disorder, however, may lead to the formation of partially and fully polarized magnetic domains separated by domain walls. In the case of large wall loops, electrons, at coincidence, can diffuse along the walls and can thus backscatter from one edge of the Hall bar to the other, giving rise to narrow resistance spikes in the QH minima regions or even to complete breakdown of the QH state.[5,6,20,21] Spikes and hysteresis of the resistance value with relaxation in time are often associated with the slow and complex domain wall motion.[22,23] Assuming that electron-electron interaction dominates, one may speculate that the anti-crossing-like behavior observed at low filling factors is consistent with the formation of an easy-axis ferromagnet at the transition. This would be rather surprising since the gap associated to an easy-axis ferromagnet is expected to be a fraction of the Coulomb energy which is as large as 70 K at $B=2.5$ T—i.e., much larger than the experimental temperature. The fact that the longitudinal resistance does not reach zero in spite of this large gap could arise from disorder-induced broadening of the Landau levels which in the present system is bigger than in usual high-mobility samples. However, the lack of direct manifestations of easy-axis ferromagnetism, such as resistance spikes or hysteresis in Shubnikov–de Haas traces, is not consistent with this scenario.

In the following we argue that anticrossing can instead arise from spin-mixing terms, eventually leading to easy-plane ferromagnetism.[3,4,21] Before discussing the impact of these terms it is important to notice that easy-plane ferromagnetism can also occur in the absence of spin-mixing terms when a sufficiently large Hartree energy characterizes the transition. This is, however, improbable in our system, given the very similar wave function profiles of the two degenerate Landau levels along the direction perpendicular to the 2DES.[3,4] We note that the appearance of an easy-plane anisotropy in a single-layer system may occur at very large tilt angles only when the orbital effect of the in-plane magnetic field leads to a modification of the density profile.[3] In Fig. 3(b), the first anticrossing at $\nu=6$ is observed at $\theta_c\approx75.4°$ for which the impact of the in-plane field is still weak. To describe the repulsion of Landau levels close to the coincidence additional effects need to be considered. SO coupling can play an important role[9–11] but it cannot couple any pair of Landau levels.[24,25] Whereas the levels mixing at $r=1$ and $r=3$ (i.e., the difference between the orbital numbers of the degenerate levels is $\Delta n=1$ and $\Delta n=3$, respectively) is allowed and can lead to anticrossings at even filling factors, the coupling of Landau levels with $\Delta n=2$, $r=2$ is prohibited. Therefore, in order to describe the anticrossing observed at $\nu=5$ we need to consider additional terms with the appropriate selection rules. For example, terms arising from band NP, such as $g''\mu_B(1/\hbar^2)\{\boldsymbol{\sigma}\cdot\boldsymbol{\Pi},\boldsymbol{B}\cdot\boldsymbol{\Pi}\}$, where $\boldsymbol{\sigma}$ is the vector of the Pauli matrices, $\boldsymbol{\Pi}=\boldsymbol{p}+q\boldsymbol{A}$ the kinetic momentum, and the set of curly brackets stands for the anticommutator.[26] Selection rules and anticrossing-energy gaps can be obtained considering the three-dimensional NP [see, for example, Eq. (5) of Ref. 26] and Dresselhaus terms, projecting them on the two-dimensional plane, and computing matrix elements of the resulting Hamiltonian between Landau levels after the inclusion of the Rashba contribution. Using typical $k\cdot p$ estimates for the NP coupling constants and considering the typical magnetic fields in our experiment, anticrossing gaps ~0.5 K can be obtained consistent with the experimental findings at $\nu=5$ ($r=2$). The values of the anticrossing gaps derived from SO coupling can be estimated from the weak antilocalization measurements. We found values of the order of 1 K consistent with the observed anticrossing behavior at $r=1$ and $r=3$.

For a more quantitative comparison with the experimental results shown in Figs. 2 and 3, a many-body approach along the lines of Refs. 3 and 10 needs to be carried out. Such a task is out of the scope of the present work. The single-particle model, however, highlights that transitions at $r=1$ are governed by the k-linear terms (Rashba and linear Dresselhaus terms[24,26]) which couple adjacent Landau levels. Similarly, the model suggests that the anticrossings at $r=2$ are due to NP terms, while those at $r=3$ to the cubic terms of the Dresselhaus interaction. The NP terms are usually neglected in experiments on spin-mixing effects in semiconductors. They, however, play a significant role in the present experiment due to the large magnetic fields.

Finally we point out that the proposed scenario relating level repulsion with spin-mixing terms is also consistent with the tilted-field results obtained in InGaAs heterostructures with no InAs layers (lower SO coupling) where no anticrossings were observed.[14]

In conclusion, longitudinal magnetoresistance traces in a tilted-magnetic-field configuration on an InAs/InGaAs quantum well exhibit anticrossings of spin-split Landau levels at low filling factors. We propose that spin-orbit interaction and nonparabolicity effects can induce the observed anticrossings. The microscopic nature of the quantum Hall ground states originating from the interplay between exchange energy and spin-mixing terms remains an open intriguing issue for further investigations.

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*Also at Dipartimento di Fisica, Università di Modena e Reggio Emilia, I-43100 Modena, Italy.

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