Interlevel hybridization phenomena in the coincidence effect under quantum Hall regime in a HgTe quantum well

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Abstract. As found from quantum magnetotransport under tilted magnetic fields in a (013)-oriented n-Cd₀.₇Hg₀.₃Te/HgTe/Cd₀.₇Hg₀.₃Te quantum well of ~20nm width, the positions of magnetic level coincidences agree quite well with a traditional description of the coincidence effect like in a simple \( \Gamma_6 \) band in spite of the \( \Gamma_8 \) character of the conduction band in HgTe. The coincidence angles yield the effective \( g^* = 33 \) while \( g^* = 50\div60 \) is obtained with different magnetotransport techniques under fields oriented perpendicular to the layers. The difference is settled when assuming the \( g \)-factor anisotropy of \( g_\perp/g_\parallel \approx 2 \). Level anticrossings are revealed at high values of perpendicular magnetic fields, corresponding to the quantum Hall regime. They manifest themselves in a splitting of the coincidence magnetoresistivity peaks and in a shift of the split-off peaks from the integer filling factors \( \nu \) to the neighbouring half-integer filling factors. The anticrossing at \( \nu = 3 \) is found to be significantly stronger than the neighbouring ones at \( \nu = 2 \) and \( \nu = 4 \) that is tentatively explained in terms of formation of easy-axis quantum Hall ferromagnetic states in the vicinity of the expected crossings.

1. Introduction
In a HgTe quantum well (QW) within the HgTe/Cd\(_x\)Hg\(_{1-x}\)Te heterosystem, a unique inverted band diagram is realized when the well width \( d_w \) is larger than the critical value of 6.3nm so that the conduction band is formed of the \( p \)-like wave functions of the \( \Gamma_8 \) symmetry. Properties of the \( \Gamma_8 \) conduction band differ considerably from those of a traditional \( s \)-like \( \Gamma_6 \) conduction band, in particular, due to a strong spin-orbit interaction [1]. In spite of that the \( \Gamma_8 \) conduction band demonstrates coincidences of spin sublevels under tilted magnetic fields very much alike as in a \( \Gamma_6 \) band [2,3]. A large value of \( g^* m^*/m_0 \geq 1 \) (\( g^* \) is the effective \( g \)-factor, \( m^*/m_0 \) is a ratio of the effective to free electron masses) in HgTe layers makes it possible to observe the coincidences at perpendicular fields high enough to reach the conditions of the quantum Hall effect (QHE), while in most of the traditional heterostructures the coincidences were seen only on Shubnikov – de Haas oscillations. We report a study of specific manifestations of the coincidences in HgTe QW under QHE regime.

2. Experiment
The sample is a HgTe/Cd\(_x\)Hg\(_{1-x}\)Te (013)-oriented QW, \( x = 0.6 \div 0.73, d_w = 20.3 \)nm, doped on both sides with 10nm spacers, with electron density \( n_e = 1.5 \times 10^{15} \text{m}^{-2} \) and mobility of 20\(\div\)25m\(^2\)/V\cdot s at low
temperatures. Electron density may be increased by about 20% via the IR illumination that is accompanied with significant improvement of the sample quality. Investigations under tilted magnetic fields were performed by measuring of the magnetoresistivity (MR) tensor components $\rho_{ij}$ as a function of the tilt angle in a series of fixed total magnetic fields. Then the data obtained were rebuilt into the continuous functions of two variables $\rho_{ij}(B_\perp,B_\parallel)$, where $B_\perp$ and $B_\parallel$ are the field components perpendicular and parallel to the layers.

Figure 1. Magnetoresistivity $\rho_{xx}(B_\perp,B_\parallel)$ at $T = 0.32$K presented (a) as a map and (b) in 3D. The beams in (a) going from zero correspond to constant $r$ values in eqn.(1) and those going down from $B_\parallel = 16$T represent varying $r$ as described by eqn.(2).

Figure 2. (a): Evolution of the magnetic levels with tilt $\theta$ in a simplest one-electron approach for a $\Gamma_6\rightarrow\Gamma_5$ like conduction band. Coincidences occur at integer $r$ values. Each interlevel gap is characterized by its filling factor $\nu$. Traces for coincidences on the $(B_\perp,B_\parallel)$ plane at the fixed angles $\theta$, in fig.1a are built for motion along dashed verticals here while the down sloped traces described by (2) -- for motion along upper spin sublevels with coincidences characterized by the fixed values of $\nu - r = 1,3,5,...$.

(b): Anticrossings that substitute the crossings as revealed experimentally (unscaled).
3. Results and discussion

Large spin splittings in our sample are directly manifested in the prevailing of quantum Hall (QH) features with odd-numbered filling factors $\nu$ over the even-numbered ones \cite{3}. In analogy with a simple $\Gamma_6$ band, it puts the limits to the $g^*$-factor values as $1 < g^* m^*/m_0 < 2$ and using $m^*/m_0 = 0.024$ as obtained from the cyclotron resonance in a similar sample \cite{5} we get $42 < g^* < 84$. Another way for estimations is to compare the fields for onsets of the oscillations and of their splittings, which yields $g^* m^*/m_0 = 1.38$, in agreement with previous condition, and $g^* = 58$ for the same $m^*$. The gaps between magnetic levels were obtained from the activation temperature dependencies of the magnetoresistivity minima under perpendicular fields and yielded $g^* = 50.4$ from the line slope through the odd-numbered points and $m^*/m_0 = 0.022$ from that through the even-numbered points.

A conventional technique to measure $g^*$ by magnetotransport in a $\Gamma_6$ band is via the coincidence effect, when at tilts $\theta_r$ of magnetic field relative to the sample normal either all the even-numbered or all the odd-numbered gaps are successively closed according to the relation \cite{6}:

$$g^* m^*/m_0 = 2r \cos \theta_r, \quad r = 1, 2, 3, \ldots, \quad (1)$$

with $r$ being a ratio of the spin splitting $g^* \mu_0 B$ ($\mu_0$ – Bohr magneton) to the cyclotron splitting $\hbar \omega_c$, $\omega_c = eB/m^*$. Our results for $\rho_{xx}(B_\perp, B_\parallel)$, together with estimations by eqn.(1) are presented in fig.1a. An excellent agreement is seen between the beams drawn for the coincidence angles and the MR peaks. Moreover, when there are many coincidences one can see an additional system that they line up: note a set of beams going down from some finite value of $B_\parallel = B_\parallel^0$. This additional system is especially pronounced in the 3D presentation of the results (fig.1b). In a simple one-electron scheme of the level motion with a tilt, like in a $\Gamma_6$ band (fig.2a), this second system of coincidences is described when going along the upper spin sublevels. Thus each line of the second system corresponds to the constant value of the difference between the filling factor $\nu$ and $r$: $\nu - r = M = 1, 3, 5, \ldots$, and the equation for the trajectories on the $(B_\perp, B_\parallel)$ plane for the tilts far enough from the perpendicular configuration reads:

$$B_\parallel = \frac{2}{g^* (m^*/m_0)} \left( \frac{\hbar}{e} n_s - MB_\parallel \right), M = 1, 3, 5, \ldots \quad (2)$$

According to eqn.(2), all the beams of the second system should go from a single point.
confirmed in the experiment [10] where the observed persistent existence of the QHF state might be formed on approaching of two single subband spin sublevels in tilted fields. It was [8-10] that is reviewed and analyzed in detail in papers [11,12]. According to theory [11] the easy-axis tilted fields reaching the range of high enough perpendicular fields where the QH regime is achieved of anticrossings since their discovery in the first experiments with the conditions for coincidences in temperatures the coincidence elevation in \( \rho_{\text{coincidences}} \) at integer \( \nu \) into a peak corresponding to a gap shut down. This effect was indeed observed in ref.3 on the same sample. In the data presented here, the electron density is either slightly (less than 10%) or significantly (about 20%) increased by illumination that caused a dramatic changes in the structure of coincidences as shown in fig.3: while at initial density \( n_s = 1.5 \times 10^{15} \text{m}^{-2} \) an only weakly splitted coincidence peak exists at \( \nu = 2 \) (fig.3a), almost in accordance with expectations, the peak splits strongly after a small increase in \( n_s \) with its components shifted from the integer \( \nu \) to the neighboring half-integer values, leaving a decreased bridge at integer \( \nu \), and the effect is still enhanced with further increase in the \( n_s \) (figures 3b, 3c). These changes in the structure of the coincidences might reflect transformations in the magnetic level picture with their crossings at coincidences evolving into anticrossings (fig.2b). The existence of an anticrossing implies a gradual interchange in the characters of the two approaching magnetic levels within some range of magnetic fields where these levels acquire hybridized wave functions.

It is worth noting that the effect is nonmonotonously \( \nu \)-dependent: while for \( \nu = 2 \) at low temperatures the coincidence elevation in \( \rho_{\text{coincidences}} \) is almost vanishing, those for its neighbors at \( \nu = 2 \) and \( \nu = 3 \) on the same trajectory for \( \nu-r = 1 \) are still quite pronounced, with the difference reaching an order of magnitude (figs.1,3). It means that the anticrossing at \( \nu = 3 \) is much larger than for \( \nu = 2 \) and \( \nu = 4 \), \( \Delta E_3 \gg \Delta E_2, \Delta E_4 \) (fig.2b). The related anticrossings are marked in fig.2a by filled circles for \( \nu = 2 \) and \( \nu = 3 \) and a hollow circle for \( \nu = 4 \). With increasing temperature the coincidence elevation for \( \nu = 3 \) increases faster than for its neighbors and the difference gradually disappears. The larger value of \( g^*m^* \) in HgTe creates more rigorous conditions for offering the QH regime at the coincidences within a single spatial subband than in previous studies [8-10] where only a monotonous depression of the anticrossings with increased \( \nu \) has been observed.

Spontaneous formation of the quantum Hall ferromagnetic (QHF) state is utilized for explanation of anticrossings since their discovery in the first experiments with the conditions for coincidences in tilted fields reaching the range of high enough perpendicular fields where the QH regime is achieved [8-10] that is reviewed and analyzed in detail in papers [11,12]. According to theory [11] the easy-axis QHF state might be formed on approaching of two single subband spin sublevels in tilted fields. It was confirmed in the experiment [10] where the observed persistent existence of the \( \nu = 2 \) MR minimum under tilted fields in the GaAs QW was explained quantitatively by formation of the easy-axis QHF state while the simultaneous observation of the reentrant behavior of the \( \nu = 4 \) minimum explained as being due to a decrease in the magnetic anisotropy energy because of a tendency to similar spatial distributions across the QW of the wave functions of the two approaching levels at smaller fields. Our observation of the opposite tendency, i.e. that the \( \nu = 3 \) anticrossing is stronger than the \( \nu = 2 \) one, might be explained by the action of another factor in Eqn. (21) of [11] for the magnetic anisotropy

\[
B_0^0 = \frac{2}{g^*(m^*/m_0)} \frac{h}{e} n_s \quad (3).
\]
energy: \( \text{exp}(-d/l) \) \((d\) is the effective QW width, \(l \equiv \sqrt{\hbar/eB_\perp} \)), which increases with decreasing field.

Additionally, the Landau number difference \(\Delta N = 2\) for the coincidence at \(\nu = 3\), as opposed to \(\Delta N = 1\) for \(\nu = 2\) and \(\nu = 4\), might lead to a larger difference in spatial distributions of the wave functions of the crossing levels [10] that would support the same tendency. Sharp transformations in the observed oscillation structures, especially around the expected coincidences, with small changes in the system (changes in \(n_s\), and probably in the spatial distribution of defects created by illumination – compare figures 1 and 3a-c) support the phase-transition-like nature of the anticrossings inherent to the easy-axis QHF.

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References

[1] Konig M, Buhman H, Molenkamp W et al. 2008 *J. Phys. Soc. Jpn.* 77, 031007
[2] Zhang X C, Ortner K, Pfeuffer-Jeschke A et al. 2004 *Phys. Rev. B* 69, 115340
[3] Yakunin M V, Podgornyh S M, Mikhailov N N, Dvoretsky S A 2010 *Physica E* 42, 948-951
[4] Suslov A V 2010 *Rev. Sci. Instr.* 81, 075111
[5] Kvon Z-D, Danilov S N, Mikhailov N N, Dvoretsky S A et al. 2008 *Physica E* 40, 1885-1887
[6] Nicholas R J, Brummel M A, Portal J C, Cheng A Y et al. 1983 *Solid State Comm.* 45, 911-914
[7] Dorozhkin S I 1989 *Solid State Commun.* 72, 211-214
[8] Koch S, Haug R J, v.Klitzing K, Razeghi M 1993 *Phys. Rev. B* 47, 4048-4051
[9] Daneshvar A J, Ford C J B, Simmons M Y et al. 1997 *Phys. Rev. Lett.* 79, 4449-4452
[10] Jungwirth T, Shukla S P, Smrcka L, Shayegan M, MacDonald A H 1998 *Phys. Rev. Lett.* 81, 2328-2331
[11] Jungwirth T, MacDonald A H 2000 *Phys. Rev. B* 63, 035305
[12] Girvin S M 2000 *Physics Today* 53, 53-45