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Spin splittings in the n-HgTe/$Cd_xHg_{1-x}Te$(0 1 3) quantum well with inverted band structure

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ABSTRACT

An effective g-factor (g^*) in the conduction band of an inverted band structure of the (0 1 3)-oriented 20 nm wide HgTe quantum well is measured by different ways: from the structure of the Shubnikov–de Haas oscillations and the quantum Hall effect, from their activation development with temperature; from the coincidence effect in tilted magnetic fields and from the activation analysis of the coincidence features taken at constant temperature as a function of the parallel magnetic field component at the fixed filling factor. Probably we present the first observation of the coincidence effect in the regime of the quantum Hall effect that is possible due to $g^*m^*/m_0>1$ in the investigated material. Shown is that while under pure perpendicular magnetic fields the obtained $|g^*|$ value is in the range of $50-60$, considerably smaller and much smaller values are deduced from the experiments that include parallel field component. This could be described by the g-factor anisotropy of $g_\perp/g_{||}\approx 5$. The main source of this giant anisotropy is assumed to be a quasi-two-dimensional nature of the spin splittings in the HgTe conduction band of p-like character although the zero field spin splittings due to strong spin–orbit interaction should also be considered.

1. Introduction

A property of the $Cd_xHg_{1-x}Te$ solid solution to transform its band diagram from the gapless to a gapped one with growing x causes a unique energy structure of the quantum well created in the HgTe/$Cd_xHg_{1-x}Te$ heterosystem: it is inverted (similar to the bulk HgTe) when the HgTe well width d_w is larger than the critical value of 6.3 nm so that the conduction band is formed of the p-like wave functions while it is a usual s-like band (as in a CdHgTe barrier) at small d_w: see reviews Refs. [1,2]. Properties of the p-type conduction band are expected and found to differ from those of a traditional s-like conduction band: it is highly nonparabolic with strong wave-vector dependent intermixing of p- and s-states and strong manifestations of the Rashba (zero-field) spin splittings [3].

HgTe is characterized by a rather large Lande g-factor ($-g=20-25$) for bulk material [4]) that makes it attractive for applications in spintronics and for researches of a variety of phenomena connected with spin polarization. Actual is finding the g-factor for two-dimensional HgTe structures, which may differ considerably from the bulk value. Zhang et al. [5] used coincidence method in tilted magnetic fields [6] and found the effective g-factor g^* to be between -15 and -35 for HgTe quantum wells (QWs) wider than the critical width. Their interpretation of the coincidence effect was based on the assumption that spin splittings depend on the total magnetic field B while the cyclotron splittings depend only on its perpendicular component $B_\perp$ that was reliably proved for a traditional conduction band [6]. In this effect, the phase reversals of oscillations are observed at the angles θ_r to the sample normal corresponding to the relation

$$g^*m^*/m_0=2r\cos\theta_r, \tag{1}$$

with $r=1,2,\ldots$, m^*—the effective mass, m_0—free electron mass. For most of the traditional heterosystems, $g^*m^*/m_0\ll 1$ and the effect is only observed at field configurations very close to orientation parallel to the layers. This implies only small achievable values of $B_\perp$ relating to the field range of Shubnikov–de Haas oscillations with large numbers. On the contrary, for the HgTe bulk parameters, $g^*m^*/m_0\approx 0.75$ that imply angles θ_r not so close to 90° and a possibility to reach the range of $B_\perp$ corresponding to the quantum Hall regime. Other possible candidates for this condition are InSb ($g^*m^*/m_0\approx 0.76$ for bulk parameters), InAs (0.4) and AlSb (0.87).

The purpose of the paper is an overall study of spin splittings in HgTe QW with special attention paid to specificity of the coincidence method in this material under quantum Hall conditions. Our samples are grown on the (0 1 3)-oriented plane that

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may introduce some new features in the energy spectrum as compared to (0 0 1)-oriented ones investigated so far [1,3,5], like overlapped conduction and valence bands, and cause different quality of the samples [2].

2. The sample and experimental results

We study the quantum Hall effect (QHE) in the $HgTe/Cd_xHg_{1-x}Te(0\,1\,3)$ oriented quantum well, $x = 0.6{-}0.73$, $d_w = 20.3$ nm, doped on both sides with 10 nm spacers, with electron density $1.5\times10^{15}\,m^{-2}$ and mobility of $20\,m^2/V\,s$ at liquid helium temperatures. The sample is etched into a Hall bridge.

An example of the quantum Hall structure obtained in magnetic field oriented perpendicular to the layers is in Fig. 1 (temperature $T = 1.8$ K for Figs. 1–5). To study effects under tilted fields we used our specific technique of sample rotation [7] to get the most detailed picture of the influence of a field component $B_{||}$ parallel to the layers on the magnetoresistivity ρ with results presented as $\rho_{xx,xy}(B_\perp, B_{||})$ functions of two variables either in the form of surfaces (see an example in Fig. 2) or as their maps projected onto the $(B_\perp, B_{||})$-plane (example in Fig. 3). Different kinds of these surface's cross-sections could be built (Figs. 4 and 5) without any additional specially organized measurements.

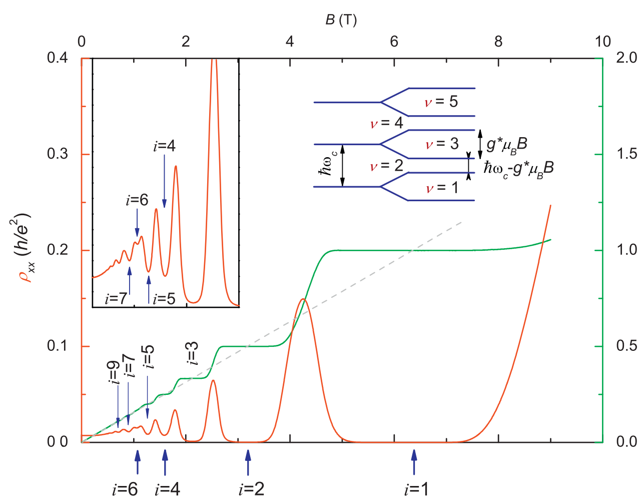

Fig. 1. Quantum Hall effect under perpendicular field configuration. Note that odd-numbered features prevail (left inset). Right inset: the qualitative layout of spin levels for prevailing odd-numbered features.

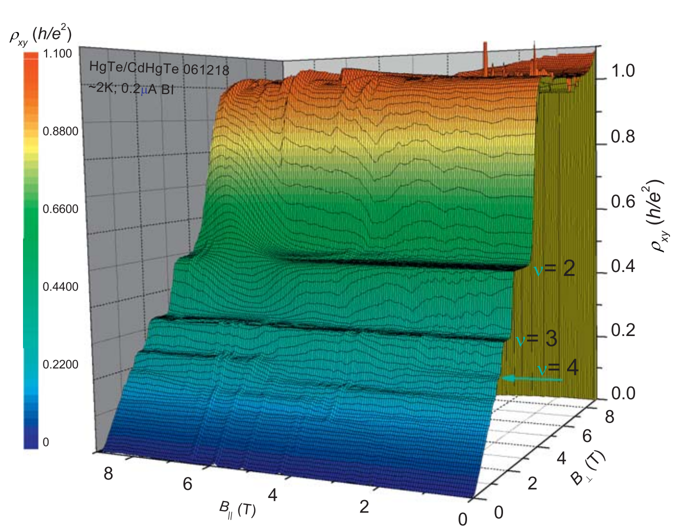

Fig. 2. Development of QHE with addition of $B_{||}$ component: $\rho_{xy}(B_\perp, B_{||})$ as a continuous surface. Note the local smoothing the plateaus away.

3. Discussion

3.1. Fields perpendicular to the sample

QHE structure in the sample investigated is characterized by that the odd-numbered features prevail over the even-numbered ones (Fig. 1, left inset). This means that spin splittings are larger

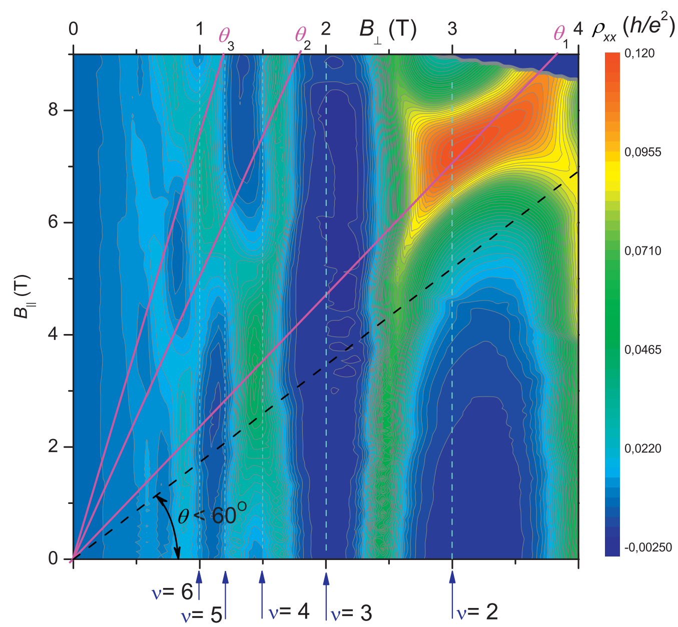

Fig. 3. Development of QHE with addition of $B_{||}$ component: $\rho_{xx}(B_\perp, B_{||})$ presented as a map.

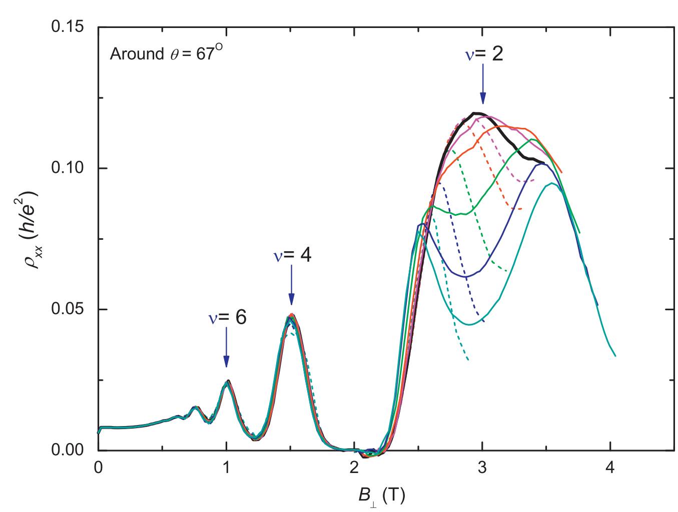

Fig. 4. Cross-sections of $\rho_{xx}(B_\perp, B_{||})$ surface (Fig. 3) taken along the beams for fixed angles in the $(B_\perp, B_{||})$-plane around the critical angle $\theta_1 = 67^\circ$ (black line). Solid lines are for angles $\theta < \theta_1(66.5^\circ, 66^\circ, 65^\circ, 64^\circ, 63^\circ)$ and the dashed ones for $\theta > \theta_1(67.5^\circ, 68^\circ, 69^\circ, 70^\circ, 71^\circ)$.