Cyclotron resonance in HgCdTe-based heterostructures in strong magnetic fields.

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Abstract. Cyclotron resonance (CR) study of HgCdTe-based quantum wells with both inverted and normal band structures in quantizing magnetic fields was performed. In normal-band sample in addition to electron CR transitions a strong absorption line presumably related to impurity transitions was discovered. Anticrossing of electron and hole Landau levels was observed in inverted-band sample. In semimetallic HgTe quantum wells with inverted band structure, a hole CR line was observed for the first time. The obtained results were interpreted within the Kane\textsuperscript{8} model, the valence band offset of CdTe and HgTe, and the Kane parameter $EP$ being adjusted.

1. Introduction

HgTe/CdTe-based quantum wells (QWs) exhibit a number of remarkable properties. HgTe has inverted band structure and is said to have negative gap about 0.3 eV while CdTe has normal band structure and gap about 1.6 eV. At the critical HgTe QW thickness (6.3 to 7 nm depending on Cd content in the barrier), the forbidden gap is absent and both electrons and holes are characterized by the linear energy-momentum law of massless Dirac fermions \cite{1, 2}. When HgTe QW width exceeds this critical value, the energy band structure is inverted (the conduction band states are formed by p-type wavefunctions while s-type wavefunctions form the valence band states; see, e.g., \cite{1, 3} and references therein).

In the inverted band structure regime, HgTe QWs are shown to be two-dimensional (2D) topological insulators that have attracted a great fundamental interest \cite{1, 2, 4, 5}. It was demonstrated \cite{4} that a quantum spin Hall insulator state exists in such systems that can be destroyed by magnetic field due to crossing of Landau levels of different bands \cite{6}. Actually, these two levels have recently shown to display the effect of the avoided crossing \cite{7, 8}.

In wide HgTe QWs (width above 12 nm) the energy of side valence band maxima exceed the energy of conduction band bottom. Such structures are said to be in semimetallic state where...
2D electron and hole gases exist simultaneously [9]. In inverted QWs hole-like symmetry of conduction-band Bloch functions enhances spin-dependent effects like the Rashba splitting that has been shown to achieve 30 meV [3, 10]. All these properties allows considering HgTe/CdTe-based QWs as perspective base for spintronic devices. On the other hand, narrow HgTe QWs have been proposed as a material for detectors of THz radiation since they possess certain advantages over bulk HgCdTe solid solutions that are widely used for mid-infrared (IR) photodetectors.

In this work we present the results of cyclotron resonance measurements theoretical calculations for three HgCdTe-based samples of different types (normal, inverted and semimetallic) that display some of the properties described above.

2. Experiment

We present the results obtained with three HgTe/Cd$_y$Hg$_{1-y}$Te samples (see table 1). The structures were grown by molecular beam epitaxy on semi-insulating GaAs(013) substrates [11]. The ZnTe and thick relaxed CdTe buffer layers, a 100-nm Cd$_y$Hg$_{1-y}$Te lower barrier layer, a HgTe QW, and a 100-nm Cd$_y$Hg$_{1-y}$Te upper barrier layer were grown one by one, followed by a 50-nm CdTe cap layer.

| Sample number | Growth number | QW width (nm) | $y_{Bar}$ | Band structure | Doping            |
|---------------|---------------|---------------|-----------|----------------|------------------|
| 1             | 110623        | 5.6           | 0.62      | normal         | ND               |
| 2             | 091222-1      | 8             | 0.7       | inverted       | In, 1.3 $\times$ 10$^{11}$ cm$^{-2}$ |
| 3             | 110615        | 20.2          | 0.65      | semimetallic   | ND               |

Figure 1: Landau levels for sample 1. Figure 2: Landau levels for sample 2.

There was no intentional doping in samples 1 and 3. In the sample 2 barriers were symmetrically doped with donors (indium). Sample 1 has normal band structure. Samples 2 and 3 have inverted band structure and sample 3 was in semimetallic state.
Figure 3: Theoretical transition energies (lines) and experimental absorption line positions (markers) for sample 1. Dot lines represent the transitions not observed. Dash line shows the transition presumably involving impurity states. Grey bars show the restrahlen bands.

Figure 4: Theoretical transition energies (lines) and experimental absorption line positions (markers) for sample 2. Grey bars show the restrahlen bands.

Figure 5: Selected transmission spectra for sample 2. Grey bars show the restrahlen bands.

Table 2: Transitions between LLs. The first number is the LL number $n$. The letter “c” or “v” means conduction and valence band respectively. The number next to the letter is the number of the level of certain $n$ in the band (counted from the band gap).

| Transition | Normal       | Inverted    |
|------------|--------------|-------------|
| $\alpha$   | 0,c1 $\rightarrow$ 1,c1 | 0,v1 $\rightarrow$ 1,c1 |
| $\alpha'$  | -            | -2,c1 $\rightarrow$ 1,c1 |
| $\alpha$-  | 1,v1 $\rightarrow$ 0,c1 | 1,v1 $\rightarrow$ 0,v1 |
| $\beta$    | -2,v1 $\rightarrow$ -1,c1 | -2,c1 $\rightarrow$ -1,c1 |
| $\beta$-   | -1,v1 $\rightarrow$ -2,v1 | -1,v1 $\rightarrow$ -2,c1 |
| $\gamma$   | -1,c1 $\rightarrow$ 0,c2 | -1,c1 $\rightarrow$ 0,c1 |
| $\gamma$-  | 0,c1 $\rightarrow$ -1,c1 | 0,v1 $\rightarrow$ -1,c1 |

In order to measure the infrared transmittance, the sample was exposed to the radiation of a Globar, which was analyzed by a Fourier transform spectrometer and delivered to the sample via light-pipe optics. The transmitted light was detected by a composite bolometer, which operated at 4.2 K and was placed directly below the sample. The magneto-optical spectra were measured...
in Faraday configuration using a superconducting coil (up to 11 T). All the spectra presented here were normalized by the sample transmission at zero field and then divided by the rate of reference signals (signal without sample) at non-zero and zero magnetic field. The latter have been done to eliminate slope caused by the influence of the field on the bolometer.

3. Theory
The band structure in the absence of the magnetic field and the Landau levels (LLs) in the QWs under study were calculated in the axial approximation in the same way as described in [8, 12, 13] in the four-band model. The calculation is based on the envelope function method proposed by Burt [14]. The envelope functions were found as the solutions of the time-independent Schrodinger equation with the $8 \times 8$ Hamiltonian taking into account built-in strain. To calculate the envelope functions and the corresponding values of the electron energy, the structure was approximated by a superlattice of weakly interacting QWs. The lattice period was chosen such that the interaction between the wells would not significantly affect the energy spectrum. The calculation was performed by expanding the envelope functions in plane waves. The expression for the Hamiltonian of the heterostructure grown on the (013) plane was derived by the method described in [15]. Zeeman term was found to be negligible for our structures and dropped. The components of the built-in strain tensor were calculated with the use of the formulas from [8, 12]. The band parameters of the materials used in the calculation are taken from [13, 16].

In order to get better agreement of the calculations and experimental data on transition energies we have adjusted some parameters of the model [8]. The first one is the valence band offset (VBO) of CdTe and HgTe. Since there is no way to measure this parameter directly it is usually estimated by matching experimental results and calculations. According to [16] VBO is 570±60 meV. We have used the value 620 meV to fit our results. The second adjusted parameter is the Kane parameter $P$ (or $E_P = 2m_0P^2/h^2$). According to the model we use, the wave function of the electron is expanded over the same basis functions in whole heterostructure [14]. Hence parameter $E_P$ depending only on basis functions is also the same for all layers and can be freely adjusted.
adjusted since the reference crystal is chosen arbitrarily. The point one should take care is to keep other parameters in agreement with $E_P$ so that bulk conduction band effective mass $m_c$ not change. The $E_P$ value used was 20.8 eV (instead of 18.8 eV [13]).

4. Results and discussion

Calculated magnetic field dependencies of the LLs for the samples are presented on figures 1, 2 and 6. Color of the levels corresponds to their numbers $n$. We follow numbering convention used in [13] i.e. quantum number $n$ has values from -2 to infinity. Selection rules for Faraday configuration allows transition only between levels whose numbers $n$ differs by one. The transitions that are expected to be observed are represented with arrows and marked with Greek letters. This notation differs for normal and inverted bands and is described in table 2.

The first sample has normal band structure. It was not intentionally doped and has low carrier concentration. In these conditions we can observe the transitions involving the levels closest to the energy gap as shown in figure 1. The transitions that fit the experimental points are $\alpha_-\beta$ and $\gamma-3$. Even though $\gamma-$ transition is allowed by selection rules calculation of the oscillator strengths shows that this transition should not be observed in this geometry. On the other hand the line we see in experiment can not be approximated by any other transitions (see Figure 3). We suppose that in this sample transition between impurity states bound to the related Landau levels takes place.

The Landau levels for the second sample are plotted in Figure 2. It was doped with donors and has finite concentration of electrons in conduction band. This sample has inverted band structure which is notable by the inverted layout of LLs with $n = 0$ and $n = -2$ closest to band gap with respect to normal band structure (Figure 1). These levels display the effect of avoided crossing [7, 8] which can not be described by axial model we use. This effect results in admixture of $n = 0$ in the wavefunction of the level with $n = -2$. Due to this mixing the transition $\alpha'$ between LL with $n = -2$ and lowest LL with $n = 1$ in conduction band is allowed near the crossing point.

The transitions from the crossing levels ($\alpha$ and $\alpha'$) are observed as two close peaks (figure 5) one of which vanishes when magnetic field is far from the crossing point (figure 4). We have also observed points corresponding to $\beta$ and $\gamma$ transitions. The cyclotron resonance (CR) lines marked with black squares on figure 4 demonstrate linear behavior with magnetic field as expected.

Sample number 3 has inverted band structure. During the experiment was in semimetallic state since its valence band side maxima are above the bottom of conduction band. One can see on figure 6 that because of this feature all Landau levels from the first valence subband have parts lying above the starting point of conduction band LLs. Each level with $n \geq 1$ have maximum at some magnetic field that is decreasing with $n$.

In this sample we observe two intensive lines (see figure 7). The first one is in a good agreement with $\beta$ transition between conduction band levels. The other one goes alongside $\alpha-$ transition between valence band levels. Agreement is not good here probably because axial description is less accurate for valence band than for conduction band. Interband $\alpha$ transition is not observed above 6 T since there should be no carriers on the corresponding LLs in these fields. Few points of low intensity can be attributed to this transition between 4 and 6 T. Weak high-frequency lines probably resulted from some interband transitions (cyclotron or impurity). At the moment, it is difficult to identify them because of the great number of allowed transitions between valence and conduction band LLs in this frequency range.

Thus fields about 8 T we observe electron and hole intraband transitions simultaneously which is only possible for semimetallic structure.
5. Conclusion
We have experimentally studied far infrared magnetoabsorption spectra under quantizing magnetic fields in a series of HgCdTe-based heterostructures including normal-band, inverted-band and semimetallic samples. The results obtained are interpreted on the basis of Landau level calculations within the axial Kane $8 \times 8$ model. Impurity related absorption lines have been revealed in addition to electron CR ones. We have confirmed anticrossing of electron and hole Landau levels in inverted band structure. In semimetallic sample electron and hole CR transitions were observed simultaneously.

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References
[1] Bernevig A, Hughes T and Zhang S C 2006 Science 314 1757–1761
[2] Buttner B, Liu C X, Tkachov G, Novik E G, Brune C, Buhmann H, Hankiewicz E M, Recher P, Trauzettel B, Zhang S C and Molenkamp L W 2011 Nat. Phys. 7 418–422
[3] Gui Y S, Becker C R, Dai N, Liu J, Qiu Z J, Novik E G, Schafer M, Shu X Z, Chu J H, Buhmann H and Molenkamp L W 2004 Phys. Rev. B 70 115328
[4] Konig M, Wiedmann S, Brune C, Roth A, Buhmann H, Molenkamp L W, Qi X L and Zhang S C 2007 Science 318 766–770
[5] Konig M, Buhmann H, Molenkamp L W, Hughes T, Liu C X, Qi X L and Zhang S C 2008 J. Phys. Soc. Jpn. 77 031007
[6] Schultz M, Merkt U, Sonntag A, Rossler U, Winkler R, Colin T, Helgesen P, Skauli T and Lovold S 1998 Phys. Rev. B 57 14772–14775
[7] Orlita M, Masztalerz K, Faugeras C, Potemski M, Novik E G, Brune C, Buhmann H and Molenkamp L W 2011 Phys. Rev. B 83 115307
[8] Zholudev M, Tepe F, Orlita M, Consejo C, Torres J, Dyakonova N, Czapkiewicz M, Wrobel J, Grabecki G, Mikhailov N, Dvoretskii S, Ikonnikov A, Spiran K, Aleshkin V, Gavrilenko V and Knap W Phys. Rev. B In press
[9] Kvon Z D, Olsanetsky E B, Kozlov D A, Mikhailov N N and Dvoretskii S A 2008 JETP Letters 87 502–505
[10] Spirin K E, Ikonnikov A V, Lastovkin A A, Gavrilenko V I, Dvoretskii S A and Mikhailov N N 2010 JETP Lett. 92 63–66
[11] Dvoretsky S, Mikhailov N, Sidorov Y, Shvets V, Danilov S, Wittman B and Ganichev S 2010 J. Electron. Mater. 39 918–923
[12] Ikonnikov A V, Zholudev M S, Spirin K E, Lastovkin A A, Maremyanin K V, Aleshkin V Y, Gavrilenko V I, Drachenko O, Helm M, Wosnitza J, Goiran M, Mikhailov N N, Dvoretskii S A, Tepe F, Diakonova N, Consejo C, Chenaud B and Knap W 2011 Semicond. Sci. Technol. 26 125011
[13] Novik E G, Pfeuffer-Jeschke A, Jungwirth T, Latusek V, Becker C R, Landwehr G, Buhmann H and Molenkamp L W 2005 Phys. Rev. B 72 035321
[14] Burt M G 1992 J. Phys.: Condens. Matter 4 6651
[15] Los J, Fasolino A and Catellani A 1996 Phys. Rev B 53 4630
[16] Becker C R, Latusek V, Pfeuffer-Jeschke A, Landwehr G and Molenkamp L W 2000 Phys. Rev. B 62 10353–10363

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