

# LUMINESCENCE OF $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$ CRYSTALS IN MAGNETIC FIELD: LINEWIDTH, LANDAU QUANTIZATION, AND CARRIER EFFECTIVE MASS

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Received 22 April 2009; revised 20 June 2009; accepted 15 September 2009

$\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  crystal photoluminescence is studied in magnetic field up to 7 T in Voigt geometry at 1.6–1.7 K temperature. The range of magnetic field where the approximation of effective band gap narrowing by the  $s, p - d$  exchange-interaction-induced term correctly describes experimental results is discussed. Luminescence linewidth (FWHM) broadening due to composition disorder and magnetization fluctuations is evaluated. Functional dependence on magnetic field of magnetic part in broadening, the  $\text{FWHM}(B)_{\text{magn.}}$ , is determined. From the patterns of Landau quantization in luminescence spectra the carrier effective mass value  $m_e^* = 0.104$  is calculated and its increase in magnetic field is obtained. Contribution of nonparabolicity and band coupling effects is evaluated in the observed carrier effective mass growth effect.

**Keywords:** photoluminescence, linewidth (FWHM), effective mass, composition disorder fluctuations, magnetic fluctuations

**PACS:** 78.20.Ls, 78.55.Et, 05.40.-a

## 1. Introduction

Semimagnetic semiconductors  $\text{A}^{\text{II}}_{1-x}\text{Mn}_x\text{B}^{\text{VI}}$  are of special interest for their magnetic field tunable optical properties induced by magnetic moments of  $\text{Mn}^{2+}$  electrons from the half-filled 3d shell. Exchange interaction of  $\text{Mn}^{2+}$  magnetic moments with conduction and valence band electrons result in large Zeeman splitting of band states, magnetic polaron formation, and other large amplitude magneto-optical phenomena, such as magnetic-field-induced circular birefringence (Faraday effect) and linear birefringence (Voigt effect) [1–3]. Investigation of semimagnetic semiconductors (SMSCs) goes on for more than several decades and is important both from theoretical and application point of view: due to investigations of  $s, p - d$  exchange interaction and possibility to change the band gap value by changing the concentration of magnetic component and applying magnetic field. Experimental results of light emission in SMSCs usually are interpreted in terms of  $s, p - d$  exchange interaction theory [4] but the accuracy of this theory is rarely discussed. This paper presents such comparison with experimental luminescence data for  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  crystals. We continue our investigation of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence in magnetic field and

present broader analysis of effective band gap narrowing not only in terms of  $s, p - d$  exchange interaction theory approximation, which was performed in our earlier work [5]. This paper also extends our previous investigation of the influence of magnetic field on the luminescence linewidth (FWHM) value. Analysis of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence spectra in magnetic field provides the possibility of determining both the parameters of effective band gap narrowing and carrier effective mass, and their changes in magnetic field. Evaluation of the composition disorder and “magnetic” broadening of luminescence line due to magnetic impurities is of considerable interest as this problem is not yet completely solved in SMSCs case. Section 2 presents the main results of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence and discussion of these results is aiming at evaluation of the three main parameters of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  spectra in magnetic field. In Sec. 3.1 the shift of luminescence maximum (effective band gap narrowing) in magnetic field is compared to the values given by the two most commonly used approximations of the  $s, p - d$  exchange interaction theory. Magnetic field dependence of luminescence linewidth broadening due to composition disorder and magnetic fluctuations is determined in Sec. 3.2. The considerable increase of carrier effective

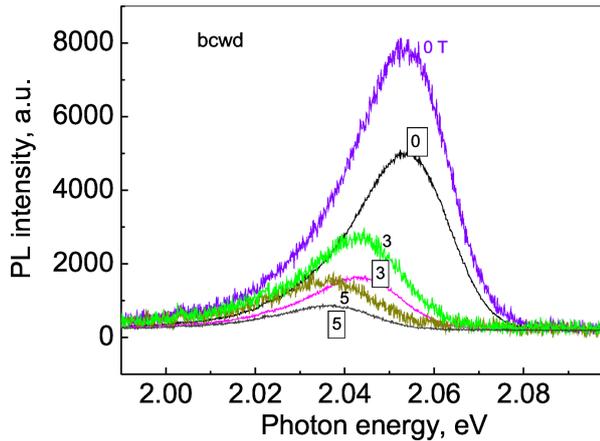


Fig. 1.  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  crystal photoluminescence of  $\pi$  and  $\sigma$  components in bcwd measuring geometry (boxed traces mark the  $\sigma$  spectra, the trace numbers show magnetic field values in T).

mass in magnetic field deduced from Landau splitting features in luminescence spectra is checked for non-parabolicity and band interaction effects in Sec. 3.3.

## 2. Experiment and results

Investigated  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  crystals were grown by the modified Bridgeman technique. Photoluminescence (PL) was measured at the temperature of 1.6–1.7 K in magnetic field up to 7 T. For excitation the Ar laser ( $\lambda = 488$  nm) beam was used directed at the angle of  $45^\circ$  to the cleaved surface of the crystal. Magnetic field was perpendicular to the direction of incident beam (Voigt geometry). Experimental set-up details are reported in [5].

The measured  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence spectra of  $\sigma$  and  $\pi$  components in the backward (bcwd) di-

rection (relative to the incident beam) are presented in Fig. 1. The  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence spectral maximum without magnetic field was found at  $2.0536 \pm 0.0002$  eV for both polarizations ( $\pi$  and  $\sigma$ ). In magnetic field the main luminescence maximum moves towards lower energy at the approximate rate of  $3.2 \pm 0.2$  meV/T for both polarizations (Fig. 2). With the rise of magnetic field the peak luminescence intensity falls exponentially,  $I(B) = I(0) \exp(-B/B_0)$  for both polarizations  $\sigma$  and  $\pi$ . Intensity of  $\pi$  polarized emission exceeds the intensity  $\sigma$  component more than 1.5 times. In the bcwd measuring geometry the magnetic field so steeply quenches the number of luminescent transitions that although the main spectral maximum moves towards lower energies in magnetic field, the other spectra with applied magnetic field remain in the area covered by the  $B = 0$  T spectrum. Two additional narrow peaks of considerably less intensity with spectral position not depending on magnetic field were also observed in luminescence spectra of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  (more details are reported in [5]).

One of the most interesting findings of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence measurements in magnetic field is that although the external shape of luminescence line in magnetic field changes profoundly, the full width at half maximum (FWHM) of the radiation curve remains almost constant. The FWHM is in 24.5–26 meV range and even shows the tendency to decrease with the rise of magnetic field (Fig. 3). In all recorded spectra the main luminescence line is inhomogeneous and of considerably asymmetric shape. We ascribe the emission centres at lower energies to the tails of the density of states in the band gap due to the high doping level of the investigated compound.

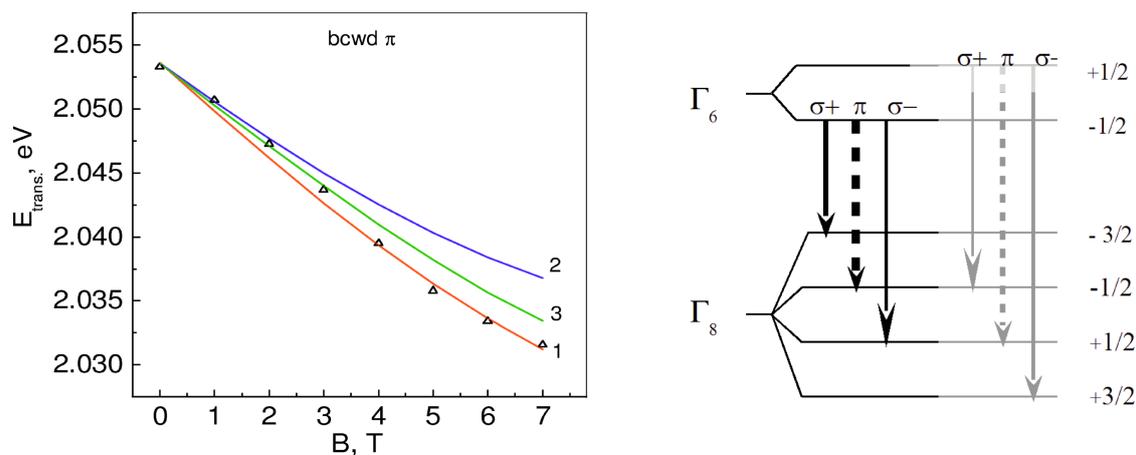


Fig. 2.  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence maximum spectral position in magnetic field of  $\pi$  component in bcwd emitting geometry.  $\Delta$  mark the experimental data, 1 is approximation with s, p – d exchange interaction term only, 2 is energy of radiative transition with all terms included, 3 is the same as in 2, but with obtained value of  $m^*(B)$ . Zeeman splitting scheme and selection rules for radiative transitions in magnetic field are shown on the right-hand side.

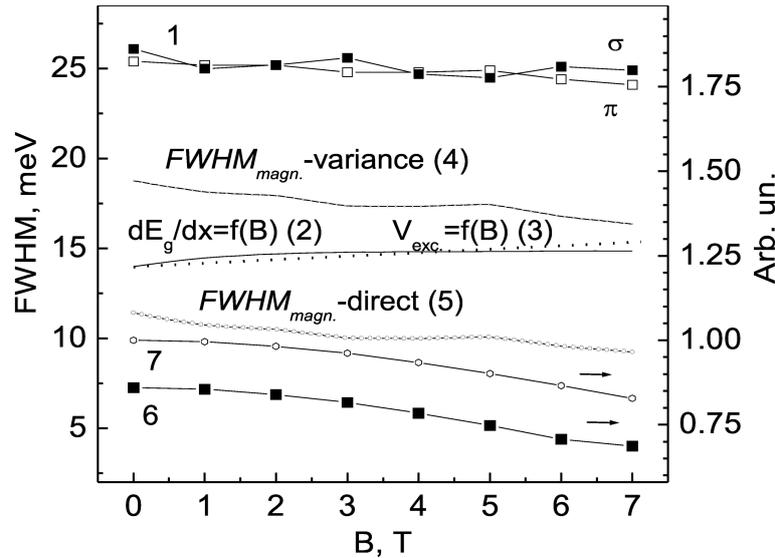


Fig. 3. Luminescence linewidth (FWHM) in magnetic field in bcwd geometry ( $I$  is experiment). Composition-disorder-induced FWHM broadening with contribution of effects:  $dE_g/dx = f(B)$  (2) and  $V_{exc}(B)$  (3). FWHM broadening due to magnetic fluctuations determined by variance subtraction (4) and by direct subtraction (5). Right-hand scale: magnetic field dependence of quantities  $\sqrt{\partial M/\partial B}$  (6) and  $\sqrt{1 - (\langle S_z \rangle/S_0)^2}$  (7).

In luminescence spectra of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  the patterns of Landau level quantization appear at magnetic field of 3–4 T. The value of carrier effective mass was calculated from cyclotronic splitting in luminescence spectra and the considerable increase of its value in magnetic field was obtained (Fig. 4).

### 3. Discussion

#### 3.1. Spectral position of luminescence maximum in magnetic field

For interpretation of magneto-optical experiments of semiconducting compounds with magnetic ions in terms of  $s, p - d$  exchange interaction theory, usually the complete description of transition energy or more rough approximation is applied. Many authors [1, 4, 6] agree that a simplified form of transition energy description is sufficient, but the accuracy of applied approximation in various magnetic field ranges is rarely discussed. Relying on performed analysis of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence results, the accuracy of both possible descriptions of transition energy could be evaluated in weak and stronger magnetic field ranges.

To describe the observed red shift of the main luminescence maximum in magnetic field, a discussion of possible band splitting approximations for SMSCs in magnetic field is necessary. The influence of local magnetic moments of  $\text{Mn}^{2+}$  ions on the band structure of the host semiconductor is determined by the exchange interaction of  $\text{Mn}^{2+} 3d^5$  electrons with band

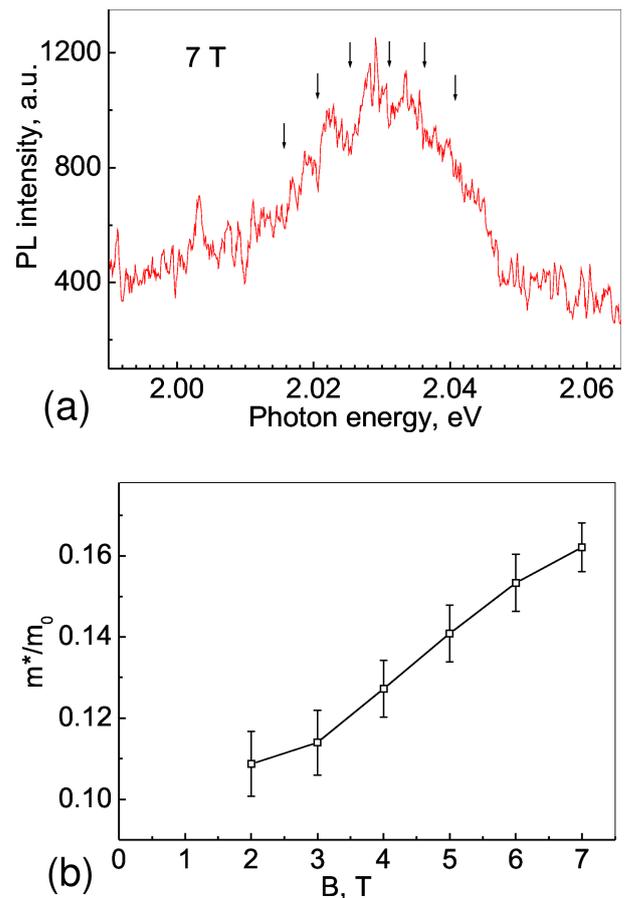


Fig. 4. (a) Landau quantization in  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence in magnetic field of 7 T, arrows mark the determined Landau sub-bands; (b) carrier effective mass value as a function of magnetic field.

(s, p) electrons. In magnetic field the energy splitting of band states is supplemented by an additional term describing the  $\text{Mn}^{2+}$ -ion-induced s, p – d exchange interaction effect:  $xN_0\alpha\langle S_z \rangle$  or  $xN_0\beta\langle S_z \rangle$  (for conduction or valence band respectively) [4]. Here  $N_0$  is the number of elementary cells per unit volume,  $\alpha$  is the s – d exchange integral for  $\Gamma_6$  conduction band electrons,  $\beta$  is the p – d exchange integral for  $\Gamma_8$  band holes,  $\langle S_z \rangle$  is the thermodynamical average of  $\text{Mn}^{2+}$  ion spin along the steady magnetic field  $\mathbf{B}$ , and  $x$  is the Mn mole fraction. As result, the energy of two spin substates of the  $l$ th Landau level in conduction band is described:

$$E_L(\uparrow\downarrow) = E_g + \left(l + \frac{1}{2}\right)\hbar\omega_c \pm \frac{1}{2}(g\mu_B H + xN_0\alpha\langle S_z \rangle), \quad (1)$$

where  $E_g$  is the gap energy,  $\omega_c$  is cyclotron frequency, electron  $g$  factor,  $\mu_B$  is the Bohr magneton.

To evaluate the change of energies of luminescent transitions in magnetic field at first we applied the usual approach common to wide-gap SMSCs with parabolic bands and large effective masses. In that case it is assumed that Landau and intrinsic spin splittings are considerably smaller and the exchange-interaction-induced term in band splitting prevails. In this approximation magnetic-field-induced splittings of conduction and valence band edges are described by  $\Delta E_c = -xN_0\alpha\langle S_z \rangle m_j$  ( $m_j = \pm 1/2$ ) and  $\Delta E_v = -(1/3)xN_0\beta\langle S_z \rangle m_j$  ( $m_j = \pm 1/2; \pm 3/2$ ) [2, 3]. As result, the conduction band at  $\Gamma_6$  point splits into two subbands separated by  $6|A_{ex}|$  ( $A_{ex} = (1/6)xN_0\alpha\langle S_z \rangle$ ) and the valence band at  $\Gamma_8$  point into four subbands situated equidistantly with the splitting of  $2|B_{ex}|$  ( $B_{ex} = (1/6)xN_0\beta\langle S_z \rangle$ ) [3, 4]. The  $N_0\alpha$  and  $N_0\beta$  values determined from experiments are 0.22 eV and  $-0.88$  eV, respectively [6].

In the band edge splitting the Zeeman scheme selection rules for allowed transitions are the same as for nonmagnetic semiconductors (Fig. 2). However, experimentally determined energies of luminescent transitions indicate that in the light emission process only transitions related with the lowest level of conduction band are involved. With the calculated  $\langle S_z \rangle$  value we can evaluate the energies of related transitions in magnetic field – that is experimentally detected as the effective band gap narrowing and the red shift of PL maximum with the rise of magnetic field (Fig. 2). From the described band splitting scheme we conclude that the change of energy of  $\pi$  component of emission in magnetic field is

$$-\Delta E_g(B) = 3|A_{ex}| + |B_{ex}|. \quad (2)$$

The average spin  $\langle S_z \rangle$  of  $\text{Mn}^{2+}$  site for Mn mole fraction  $x = 0.3$  can be described by the Brillouin function,  $\langle S_z \rangle = -S_0 B_{5/2} [S g_{\text{Mn}} \mu_B B / (k_B (T + T_0))]$ , if fitting parameters of spin saturation value  $S_0 = 0.52$  and the characteristic temperature  $T_0 = 14.9$  K are used [6]. Here  $B_{5/2}(\zeta)$  is the Brillouin function for spin value  $S = 5/2$ ,  $g_{\text{Mn}} \approx 2$  is Mn ion  $g$  factor.

Luminescence maximum shift towards lower energies in magnetic field for  $\pi$  polarized light is in good but not precise agreement with approximate model discussed above when the Landau and intrinsic spin splittings are not included in calculations (Fig. 2). Till now we have analysed the value of energy of  $\pi$  transition but experimental results show that the changes of energies of  $\sigma$  and  $\pi$  transitions in magnetic field nearly coincide, with slight differences exceeding the error bar limits. Equality of energies of  $\sigma$  and  $\pi$  transitions in that approximate model is proved by us in [5] assuming the  $\sigma$  component of emission as the superposition of two components  $\sigma^+$  and  $\sigma^-$ .

Experimental results of  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence in magnetic field indicate that the band splitting approximation by an exchange-interaction-induced term correctly describes the effective band gap narrowing only at fields  $B > 4$  T (Fig. 2). Applying the complete description of transition energies when the omitted terms of Landau and intrinsic spin splittings are included, the improved agreement with experimental data was obtained only in the low field region. At higher magnetic fields  $B > 2$  T the deviation from experimental data becomes pronounced but in that region the approximate approach holds well. When the magnetic field dependence of carrier effective mass  $m_c^*(B)$  deduced in this work was included in calculations, the better coincidence with experimental results was obtained only at fields  $B \leq 3$  T (Fig. 2, line 3).

There still remains a discrepancy between experimental results and the theoretical model that challenges for a deeper look at the values of exchange constants  $\alpha$  and  $\beta$ . Deviations from approximation of transition energy by the s, p – d exchange interaction term are also observed in the spin-flip energy  $E_{s-f}(B)$  measurements in Raman scattering experiments in the same magnetic field range. Here the difference from the s, p – d exchange interaction theory prediction is  $\Delta E_{s-f}(B) \approx 1$  meV at magnetic field  $B < 1$  T and vanishes at fields of 3–4 T for  $\text{CdMnSe(S)}$  [7, 8]. As the s – d exchange interaction constant  $N_0\alpha$  is determined from the same set of experiments at higher magnetic fields  $B > 3$  T, this may result in appearance of uncertainty  $\Delta E_{s-f}(B)$  in determination of spin-flip energy  $E_{s-f}(B)$  at  $B <$

1 T. The mentioned authors suggest that such discrepancies must be proportional to differential susceptibility,  $\Delta E_{s-f}(B) \sim \partial M/\partial B$ , as its value is greatest at low magnetic fields. Deviations of luminescent transition energy values in  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  spectra from the short s, p – d exchange theory approximation at magnetic field  $0 < B < 3$  T are comparable ( $\sim 1.2$  meV). It is reasonable to assume that possible reasons of these discrepancies is the uncertainty in  $N_0\alpha$  determination at low magnetic fields and existence of non-vanishing energy splitting of  $\sim 1$  meV in zero magnetic field [2].

The reduction of exchange constant  $\alpha$  was observed in samples with reduced dimensionality [9] when the decrease of  $\alpha$  by 25% was found for QWs of 4.5 nm width. But our experimental results do not confirm the trend of exchange constants' reduction. Relying on the energy change in magnetic field with all terms included (line 2 and 3, with  $m^*(B)$ , in Fig. 2), the model difference from experimental data points requires the increased value of the sum of exchange constants  $N_0(\alpha + \beta/3)$  at higher magnetic fields  $B > 2$  T. For more precise definition of exchange constants other independent experiments are required.

### 3.2. Luminescence line analysis

Luminescence line broadening with increased part of magnetic component in the compound is the common feature in luminescence spectra of  $\text{A}_{1-x}^{\text{II}}\text{Mn}_x\text{B}^{\text{VI}}$ . Analysis of the line's full width at half maximum in this work is concentrated on the composition-disorder-induced broadening and on the magnetic part in broadening due to magnetic impurities. In our previous work [5] the evaluation of composition-disorder-induced broadening was obtained using the formalism of binomial distribution to describe the random cation distribution in the excitonic volume  $V_{\text{exc}}$  [10, 11]. The standard deviation of compound composition within the excitonic volume given by binomial distribution is  $\sigma_x = \sqrt{x(1-x)/(K V_{\text{exc}})}$ , where  $K$  is the density of cations in the crystal. Related local potential fluctuations could be evaluated by the band-gap energy standard deviation  $\sigma_E = (dE_g/dx)\sigma_x$ . To calculate the full width at half maximum the following relation could be used:  $\text{FWHM} \approx 2.36\sigma_E$  [10]. At the first approximation the value  $dE_g/dx = 1.59$  (difference of the band-gap energies of CdTe and MnTe crystals [1]) was used. Thus the FWHM broadening for  $x = 0.3$  due to composition disorder tends to be 13.9 meV. As the calculated value of band-gap energy standard deviation  $\sigma_E \approx 6$  meV characterizes the fluctuations of random po-

tential profile in the compound, this fact strongly supports the idea of excitons localized by disorder fluctuations in  $\text{A}_{1-x}^{\text{II}}\text{Mn}_x\text{B}^{\text{VI}}$  compounds with higher Mn mole fraction [12–14]. Several other authors [15, 16] arrive at the same relation for disorder-induced FWHM value, though using different probability expressions to describe the composition fluctuations of the compound from the mean value. Some authors [17, 18] obtain more than a half smaller value (for  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$   $\text{FWHM} \approx 5.1$  meV) but due to another coefficient values in the expression for FWHM.

Data on the excitonic linewidth dependence on magnetic field are very scarce [15, 19, 20]. We took an attempt to evaluate more precisely the composition-disorder-induced part in FWHM value in magnetic field by introducing the  $dE_g/dx = f(B)$  value [5]. Corrections made to FWHM value due to  $dE_g/dx$  changes in magnetic field reveal the tendency to broaden the luminescence line (Fig. 3). This result implies that an increased part of magnetic component in the compound increases the influence of internal magnetic field or magnetization on the spin splitting value. As a result, the  $dE_g/dx = f(B)$  increase acts as the enhancement of potential profile contrast in the compound.

Another possible cause of FWHM magnetic field dependence could be included in excitonic volume  $V_{\text{exc}}$  change, which is the key parameter in binomial distribution description. We relied on the excitonic FWHM calculations by [15] where the change of excitonic volume  $V_{\text{exc}}$  in magnetic field was taken into account in  $\text{FWHM}(B)$  value. The value of  $V_{\text{exc}}$  in magnetic field was obtained by the mentioned authors performing the calculations of expectation value of excitonic radius  $\langle(\rho^2 + z^2)^{3/2}\rangle$  in cylindrical coordinates for a dimensionless parameter of magnetic field strength  $\gamma = \hbar\omega_c/(2R)$ , where  $R = m^*e^4/(2\varepsilon^2\hbar^2)$  is an effective Rydberg. Calculations yield the shrinking of excitonic volume in magnetic field that results in the luminescence line broadening and this effect is illustrated in Fig. 3. It is important to note that the magnetic field dependence of effects  $dE_g/dx = f(B)$  and excitonic volume shrinking  $V_{\text{exc}}(B)$  on the FWHM value are of the same extent and only slightly broaden the luminescence line.

Data reported in literature on the luminescence line FWHM dependence on magnetic field are controversial: a FWHM narrowing [19, 20] as well as the FWHM increase [15, 21] are calculated and observed. Our experimental results indicate that the FWHM value shows a tendency to decrease in magnetic field (Fig. 3). As the composition-disorder-induced part in broadening is

already discussed and effects of  $dE_g/dx = f(B)$  and  $V_{\text{exc}}$  shrinking are included, the rest part of broadening we ascribe to fluctuations of magnetic nature. This contribution could be determined by several methods from the difference of experimental linewidth and disorder-induced contribution:

- by subtracting variances:

$$\text{FWHM}_{\text{magn.}} = \sqrt{\text{FWHM}_{\text{exper.}}^2 - \text{FWHM}_{\text{disorder}}^2},$$

- by direct subtraction:

$$\text{FWHM}_{\text{magn.}} = \text{FWHM}_{\text{exper.}} - \text{FWHM}_{\text{disorder}} \text{ (Fig. 3).}$$

The part of FWHM which we ascribe to broadening due to magnetic fluctuations is decreasing with the rise of magnetic field more rapidly than the total FWHM (Fig. 3). It is reasonable to suppose that the magnetic part of FWHM broadening is related to magnetization  $M(B)$  fluctuations which decrease in magnetic field proportionally to differential susceptibility  $\partial M/\partial B$ . Fluctuations of magnetization result in exchange potential fluctuations as the  $\text{Mn}^{2+}$  spins are coupled to excitation spins through the exchange interaction. An effort to account for exchange-potential-induced magnetic fluctuations is taken by authors [22] where the root mean square magnetic fluctuation energy  $o_M$  is described as

$$o_M = \sqrt{\frac{35}{12} \frac{T}{T + T_{\text{AF}}} \frac{1}{(2\pi)^{3/2} a_M^3} \frac{(J N_0)^2 \bar{x}}{N_0}}, \quad (3)$$

where  $\bar{x}$  is the effective concentration of  $\text{Mn}^{2+}$  introduced following Refs. [23, 6],  $J N_0$  is the p–d exchange potential constant,  $a_M$  is effective Bohr radius of donor electron discussed in [8]. Thus the magnetization fluctuations generate fluctuations of radiative transition energy of only  $\sim 1.8$  meV that cannot explain the experimentally obtained part of  $\text{FWHM}_{\text{magn.}}$ , ascribed to magnetic fluctuations in  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence.

As mentioned earlier, the experimentally obtained broadening of magnetic nature could be related to magnetization fluctuations which are proportional to differential susceptibility  $\partial M/\partial B$ . Analysis of  $\text{FWHM}_{\text{magn.}}$  magnetic field dependence obtained by direct subtraction shows that the relative decrease of  $\text{FWHM}_{\text{magn.}}$  is consistent with the change of several quantities characterizing magnetization  $M(B)$  fluctuations:

1. with the strength of spin fluctuation change in magnetic field of a single  $\text{Mn}^{2+}$  ion  $\sqrt{\Delta M^2} = \sqrt{kT(\partial M/\partial B)}$  [24] (Fig. 3, line 6),

2. with the quantity close to the mean-squared angular deviation of a single spin from alignment with the field  $\sqrt{1 - (\langle S_z \rangle/S_0)^2}$  [25] (Fig. 3, line 7).

For  $\text{FWHM}_{\text{magn.}}$  obtained by the variance subtraction such correspondence was not found. Proportionality of the relative decrease of parameters  $\text{FWHM}(B)_{\text{magn.}}$  and  $\sqrt{\partial M(B)/\partial B}$  of type  $\Delta f_1/f_1 = \Delta f_2/f_2 = \text{const}$  indicates that both parameters characterizing different processes are defined by the same type of differential equation. Several important conclusions stem from this fact: first, that both processes are defined by the same power of exponential decay,  $\ln f_1 = \ln f_2$ ; and second, that the physical mechanism responsible for the change of both parameters in magnetic field is the same. The fact that we deal with function  $\sqrt{\partial M(B)/\partial B}$  characterizing the strength of spin fluctuation of a single  $\text{Mn}^{2+}$  ion facilitates the solution of the problem. Relying on the arguments presented above and performing the analysis of experimental  $\text{FWHM}(B)_{\text{magn.}}$  value obtained by direct subtraction, we find that  $\text{FWHM}(B)_{\text{magn.}}$  has the magnetic field dependence

$$\text{FWHM}(B)_{\text{magn.}} = \text{FWHM}(0)_{\text{magn.}} \exp\left(\Delta \sqrt{\frac{\partial M}{\partial B}}\right). \quad (4)$$

As the experimentally obtained  $\text{FWHM}(B)_{\text{magn.}}$  follows this dependence with the accuracy of 4%, the value  $\text{FWHM}(0)_{\text{magn.}} \approx 11.4$  meV could be assumed as determined merely by magnetization fluctuations of magnetic impurity in zero magnetic field. This result of  $\text{FWHM}(0)_{\text{magn.}}$  value does not confirm the value of 1.8 meV given by theoretical expression (Eq. (3)) by Warnock [22]. We suppose that experimentally determined  $\text{FWHM}(B)_{\text{magn.}}$  value closely following the functional dependence of angular deviation of a single spin is more reliable. Values of magnetization fluctuations of  $\sim 1$  meV obtained by other authors [7, 8] differ about  $\sim 10$  times from the result determined in this work, and this fact could be explained by the different nature of processes in which these fluctuations have been determined. We can conclude that in the case of luminescence of semimagnetic  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  magnetic fluctuations influence the  $\text{FWHM}(B)_{\text{magn.}}$  value through the value of scattering potential, as also suggested in [24].

### 3.3. Landau quantization and carrier effective mass change effects

In  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$  luminescence spectra at stronger magnetic fields  $B > 2$  T the patterns of intensity os-

Table 1. Carrier effective mass values  $m_e^*$  in magnetic field.

	0 T	7 T	Method
$m_e^*$	0.104	0.163	experimental value (this work)
		0.118	with nonparabolicity coefficient $\eta = 0.54$ for CdTe
		0.116	$k^4$ terms, Wallis [30]
	0.125	0.124	<b>kp</b> method, Kane [31]

cillations appear with the period of oscillations increasing with magnetic field (Fig. 4). We identified the observed splittings in Cd<sub>0.7</sub>Mn<sub>0.3</sub>Te luminescence spectra with the expected Landau quantization of density of states in magnetic field. The observed density of states' splitting in magnetic field  $E_L(l+1) - E_L(l) = \hbar\omega_c$  gives a possibility to determine one of the basic material parameters, carrier effective mass value  $m_e^*$ . It is important to note that the determined from Landau splitting value of carrier effective mass  $m_e^* = 0.104 \pm 0.007$  (at  $B \rightarrow 0$ ) (Fig. 4) coincides very well with the values of  $m_e^* = 0.107$  [26] and  $m_e^* = 0.11$  [27] for Cd<sub>0.7</sub>Mn<sub>0.3</sub>Te determined by other authors. The carrier effective mass value calculated from experimental spectra shows a nonlinear increase in magnetic field (Fig. 4). Possible reasons of an increased carrier effective mass value in magnetic field and the extent of several effects playing major role in changing the effective mass value in the band will be evaluated in this section. The influence of magnetization  $M(B)$  on the value of internal magnetic field was found to change the value of effective mass only in the third decimal number.

The effect of carrier effective mass growth in magnetic field even in nonmagnetic semiconductors is observed for a long time [28] and widely reported [29]. Due to the relatively high value of  $E_g$  in semimagnetic II-VI semiconductors the nonparabolicity and band interaction effects are usually omitted, but the experimentally obtained higher values of carrier effective mass require a more precise evaluation of the mentioned effects in magnetic field. Methods which enable one to take into account the band nonparabolicity are the inclusion of fourth order terms in effective mass theory [30] and the **kp** method [31], on which we have based our calculations. The account of  $k^4$  terms in conduction energy expansion in the theory of cyclotron resonance was performed in [30]. But the calculated values of effective mass in magnetic field according to this theory do not give the experimentally observed increase in magnetic field (Table 1). We evaluated the nonparabolicity and band interaction effects with Kane's theory [31], based on **kp** method calculations.

The nonparabolicity of conduction band was evaluated by these methods:

1. By conduction band nonparabolicity approximation with nonparabolicity coefficient  $\eta$  for energy  $E$  in the band:

$$m_e^*(P) = m(0)(1 + 6\eta E), \quad \eta = 0.54 \text{ (CdTe [32])}. \quad (5)$$

2. With Kane model [31] when spin,  $\Delta$  (spin-orbit splitting),  $P$  (interband momentum matrix element,  $P^2/m_0 = 8010.5$  meV [26]) are taken into account:

$$\frac{1}{m_e^*} = \frac{1}{m_0} + \frac{2}{3} P^2 \left( \frac{2}{E_g} + \frac{1}{E_g + \Delta} \right). \quad (6)$$

The values of carrier effective mass calculated by the mentioned methods are given in Table 1. The value without magnetic field is  $m_e^* = 0.107$  [26].

Summarizing the obtained results of the employed methods, it should be noted that the most probable cause of increased  $m_e^*$  value – the nonparabolicity and band coupling effects – have a minor influence in experimentally observed increase of carrier effective mass in magnetic field. These effects even slightly decrease the value of carrier effective mass as the band gap narrows in magnetic field. Another important effect which may influence the carrier effective mass value, the magnetic polaron formation, is still left for evaluation.

#### 4. Conclusions

Experimental results of Cd<sub>0.7</sub>Mn<sub>0.3</sub>Te luminescence indicate that possible definitions of energies of radiative transitions in magnetic field (approximation by exchange-interaction-induced term only and complete description with cyclotronic and intrinsic spin splittings included) cannot precisely describe the energies of luminescent transitions in full magnetic field range. The complete form of definition of transitions energies (with all terms included) is correct in description of experimental values of energies at weak magnetic fields  $B < 2$  T. Meanwhile, the band splitting approximation by exchange interaction term gives a good coincidence with experimental data at higher magnetic fields  $B > 4$  T. For the experimentally observed effective band gap narrowing description the increased value of the sum of exchange constants  $N_0(\alpha + \beta/3)$  is required at higher magnetic fields  $B > 2$  T.

The FWHM broadening induced by composition disorder is calculated assuming the binomial distribution

of magnetic component and is found to be 13.9 meV. In the FWHM magnetic field dependence the effects of  $dE_g/dx = f(B)$  and excitonic volume shrinking are taken into account, but the mentioned effects do not give the experimentally observed slight narrowing of luminescence line. The luminescence line broadening due to magnetic fluctuations is related to magnetization fluctuations which are proportional to differential susceptibility. The FWHM broadening due to magnetic fluctuations could be determined from experimental FWHM( $B$ ) dependence by direct subtraction of composition disorder contribution if the minimal possible power of exciting laser beam is used in experiment. The broadening due to magnetic fluctuations in zero magnetic field is found to be  $\text{FWHM}(0)_{\text{magn.}} \approx 11.4$  meV. We have managed to describe the FWHM broadening due to magnetic fluctuations and have found that  $\text{FWHM}(B)_{\text{magn.}}$  follows the exponential decay in magnetic field governed by the strength of spin fluctuation value of a single magnetic impurity.

Carrier effective mass value calculated from the density of states' splitting in magnetic field is found to be  $m_c^* = 0.104 \pm 0.007$  and this result is consistent with results of other authors for  $\text{Cd}_{0.7}\text{Mn}_{0.3}\text{Te}$ . The carrier effective mass growth in magnetic field, obtained from Landau quantization, is checked for the influence of nonparabolicity and band coupling effects. Contribution of these effects is evaluated and it is found that these effects do not play a major role in the observed carrier effective mass increase in magnetic field.

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## $\text{Cd}_{0,7}\text{Mn}_{0,3}\text{Te}$ KRISTALŲ LIUMINESCENCIJA MAGNETINIAME LAUKE: LINIJOS PLOTIS, LANDAU KVANTAVIMAS IR KRŪVININKŲ EFEKTINĖ MASĖ

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### Santrauka

$\text{Cd}_{0,7}\text{Mn}_{0,3}\text{Te}$  kristalų liuminescencija tirta 1,6–1,7 K temperatūroje magnetiniame lauke iki 7 T Voigto geometrijoje. Eksperimentiniai liuminescencijos maksimumo poslinkio magnetiniame lauke rezultatai rodo, kad spindulinio šuolio energijos magnetiniame lauke galimi aprašymai (aproksimacija vien pakaitinės  $s, p - d$  sąveikos nariu arba pilnas aprašymas, atsižvelgiant į narius dėl ciklotroninio ir savitojo sukininio suskilimų) negali tiksliai apibūdinti efektyvaus draudžiamų energijų tarpo kitimo visame magnetinių laukų intervale. Pilnasis rekombinacinės energijos aprašymas (su visais nariais) tiksliai apibūdina eksperimentines energijos vertes tik silpnuose magnetiniuose laukuose  $B < 2$  T. Tuo tarpu taikant aproksimaciją vien pakaitinės  $s, p - d$  sąveikos nariu gaunamas geras sutapimas su eksperimento rezultatais esant stip-

resniems magnetiniams laukams ( $B > 4$  T). Eksperimentiškai stebimam efektyviam draudžiamų energijų tarpo siaurėjimui aprašyti reikalinga didesnė pakaitinių konstantų  $N_0(\alpha + \beta/3)$  vertė, kai  $B > 2$  T. Linijos pločio (FWHM) priklausomybėje nuo magnetinio lauko įskaityti  $dE_g/dx = f(B)$  ir eksitoninio tūrio  $V_{\text{exc}}(B)$  mažėjimo reiškiniai, kurie nežymiai platina liuminescencijos liniją. Nustatyta, kad linijos (FWHM) išplitimas dėl magnetinių fluktuacijų magnetiniame lauke mažėja pagal eksponentinę funkciją, kurios rodiklis yra magnetinio jono sukininių fluktuacijų jėgos vertė. Iš Landau kvantavimo liuminescencijos spektruose apskaičiuota krūvininkų efektinės masės vertė  $m_e^* = 0,104 \pm 0,007$  ir rasta, kad šis parametras magnetiniame lauke didėja netiesiškai. Įvertinus neparaboliškumo ir juostų sąveikos įtaką nustatyta, kad šie reiškiniai nepaiškina stebimo  $m_e^*(B)$  augimo magnetiniame lauke.