Exchange interaction of carriers with magnetic ions in novel ZnMnSe/BeMnTe heterostructures with a type-II band alignment

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Abstract. (Zn,Mn)Se/(Be,Mn)Te diluted-magnetic-semiconductor heterostructures with a type-II band alignment have been fabricated by molecular-beam epitaxy. Giant Zeeman splitting of the band states, caused by their interaction with the localized magnetic moments of Mn ions, has been observed for the spatially direct- and indirect optical transitions. The value of the $p-d$ exchange interaction constant of holes with magnetic Mn-ions in (Be,Mn)Te $N_0\beta = -0.40 \pm 0.05$ eV has been measured.

Introduction

(Be,Mn)Te is a new material in the family of II–VI diluted magnetic semiconductors (DMS). Published information on magnetic, optical and electronic properties of (Be,Mn)Te is very limited. Magneto-luminescence experiments confirm the giant Zeeman splitting for holes located in (Be,Mn)Te layers of ZnSe/(Be,Mn)Te heterostructures [1, 2]. The rough evaluation of the $p-d$ exchange interaction constant $N_0\beta = -0.4$ eV has been done on the basis of these experiments.

A special interest in (Be,Mn)Te material exists due to its very high p-type dopability. In BeTe free hole concentrations of more than 1×10^{20} cm^{-3} has been reported [3], which in turn could lead to ferromagnetic alignment of the Mn spins mediated by free holes, similar to (Ga,Mn)As. Such ferromagnetic ordering is an important prerequisite for the manipulation of spin-oriented carriers without permanent external magnetic fields. Indeed, ferromagnetic behavior of heavily p-type doped (Be,Mn)Te could recently be demonstrated by transport measurements [4].

ZnSe/BeTe is a heterosystem with a type-II band alignment. Its main specific feature is a large conduction (about 2 eV) and valence (about 1 eV) band offset, which results in a very small penetration of the carrier wave functions into the neighboring layers. The type-II nature of the interface allows to separately access the Zeeman splitting of valence-band states in (Be,Mn)Te by investigation of (Zn,Mn)Se/(Be,Mn)Te heterostructures [1]. In the present work we exploit this advantage of (Zn,Mn)Se/(Be,Mn)Te structures to measure the constant of $p-d$ exchange coupling of free holes in the valence band of (Be,Mn)Te with the spins of Mn ions.

1. Experimental

Results for three $Zn_{1-x}Mn_xSe/Be_{1-y}Mn_yTe$ multiple quantum well structures (MQW) grown by MBE on (100) GaAs substrates are reported here. These structures have the same design and consist of ten pairs of 200 Å/100 Å $Zn_{1-x}Mn_xSe/Be_{1-y}Mn_yTe$. They differ by the Mn content (see data in Table). A Mn effusion cell in the MBE chamber was open during the growth of all layers, Mn content in

(Be,Mn)Te layers was 6.8 times higher that in (Zn,Mn)Se layers due to the difference in their growth rates (see details in Ref. [2]). Structure parameters are summarized in Table.

Photoluminescence (PL) was excited by UV lines of a *cw* Ar-ion laser. Polarized PL spectra were recorded at a temperature of 1.6 K with a charge-coupled-device (CCD). Magnetic fields up to 7.5 T were applied in the Faraday geometry parallel to the structure growth axis. As a result two emission lines appear in PL spectra of these structures with a type-II band alignment: (i) The spatially direct emission (D) at about 2.8 eV, which involves electrons and holes recombining in (Zn,Mn)Se layers, and (ii) spatially indirect emission (ID) at about 1.8 eV caused by electrons and holes from (Zn,Mn)Se- and (Be,Mn)Te layers, respectively.

2. p-d exchange constant in BeMnTe

One can see from the scheme in Fig. 1 that in (Zn,Mn)Se/ (Be,Mn)Te structures the giant Zeeman splitting of the indirect optical transition (ID) is the sum of the splittings in the conduction band of (Zn,Mn)Se and in the valence band
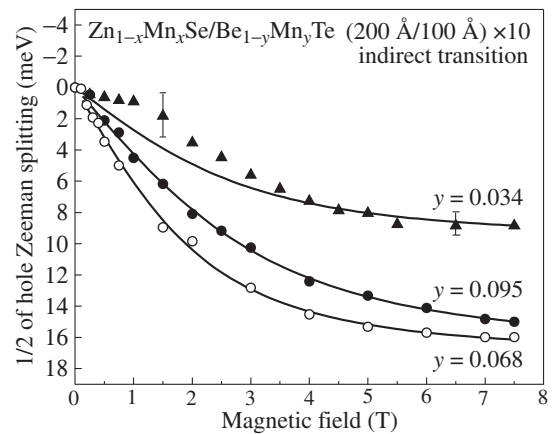
Fig. 1. Photoluminescence spectra of a $Zn_{0.99}Mn_{0.01}Se/Be_{0.932}Mn_{0.068}Te$ MQW recorded with and without magnetic field applied in the Faraday geometry. Pronounced giant Zeeman shifts are seen both for direct and indirect emission lines.

of (Be,Mn)Te. By measuring the giant Zeeman splitting of the direct optical transition (D) in (Zn,Mn)Se layers, one can get the value of the conduction-band splitting in these layers, and therefore get the pure Zeeman splitting of the (Be,Mn)Te valence band. The later we need to determine the $p-d$ exchange constant.

In Fig. 1 PL spectra of the direct and indirect emission of sample #2 are shown for magnetic fields of 0 T and 7.5 T. The Zeeman shift is very pronounced both for direct and indirect optical transitions. The behavior of the direct emission is identical to that of MBE-grown (Zn,Mn)Se epilayers studied in great detail in [5]. We use it to determine exact Mn content in the grown samples on the base of common phenomenological approach suggested by Gaj et al [6]. In this approach the energies of the conduction band (E_C) and the valence band (E_V) states, interacting via strong exchange coupling with the localized spins of Mn-ions oriented by an external magnetic field B, can be described by the following equations:

$$E_C = xN_0\alpha s_e \langle S_z \rangle, \quad s_e = \pm 1/2 \tag{1}$$

$$E_V = \frac{1}{3}xN_0\beta J \langle S_z \rangle, \quad J = \pm 3/2; \pm 1/2 \tag{2}$$

where

$$\langle S_z \rangle = S_{\text{eff}} B_{5/2}\left(\frac{5\mu_B g_{\text{Mn}} B}{2k_B (T + T_0)}\right)$$

is described by the modified Brillouin function, which accounts phenomenologically for the Mn-Mn $d-d$ interaction by introducing two parameters: the effective Mn spin S_{eff} and the effective temperature T_0. The giant Zeeman shift of the heavy-hole states in $Be_{1-y}Mn_y$Te layers in the studied heterostructures is plotted in Fig. 2. It was obtained from the Zeeman shift of indirect emission line. From this shift the contribution of electrons in (Zn,Mn)Se was substracted. A linewidth of the indirect emission band is considerably larger than that of the direct one. That causes relatively large error bar for data points, especially in the sample #1 with the smallest shift. Fitting of the experimental dependencies from Fig. 2 allows us to evaluate the exchange constant $N_0\beta_2$ for $Be_{1-y}Mn_y$Te. For this fit done with Eq. (2) and shown by solid lines the exchange constant and the temperature were taken as a free parameter. The

Mn-ion concentration y in the $Be_{1-y}Mn_y$Te layers has been taken from the Mn content of (Zn,Mn)Se layers corrected by a factor 6.8 arising from the difference in the growth rates. For T_0 and S_{eff} parameters calibrated dependencies of (Zn,Mn)Se have been used. $N_0\beta_2$ and T parameters providing the best fit are given in the Table. The values of $N_0\beta_2$ vary from -0.30 to -0.40 eV, measured with the accuracy of about ± 0.05 eV. One can see that for samples #1 and #3 the Mn temperature deviates from the lattice temperature, which evidences the weak heating of the Mn ion system. For the sample #2 the temperature is very close to the lattice temperature and therefore we consider these data as the most reliable for the evaluation of the $p-d$ exchange constant. The value $N_0\beta_2 = -0.40 \pm 0.05$ eV for (Be,Mn)Te is about two times smaller than -0.88 eV in (Cd,Mn)Te and -1.05 eV in (Zn,Mn)Te. Theoretical approach developed by Larson et al [7] predicts the value of -1.05 eV for the (X,Mn)Te-containing alloys, independent of the cation X character. A considerable deviation of the experimental value in (Be,Mn)Te from the theoretical expectations is stimulating for revising and/or refining this model.

Table 1.

| Sample	x, ZnMnSe	y, BeMnTe	T (K) BeMnTe	$N_0\beta_2$ BeMnTe
#1	0.005	0.034	4	-0.30 ± 0.07
#2	0.010	0.068	2	-0.40 ± 0.05
#3	0.014	0.095	3.3	-0.35 ± 0.05

Interesting to note here that due to the type-II band alignment of the studied structures the transition matrix element for the optical transition, which is indirect in real space and involves conduction-band electrons from ZnSe layers and valence-band holes from BeTe layers, extremely "interface sensitive". This causes very strong optical anisotropy to be decoded by polarized optical spectroscopy [8].

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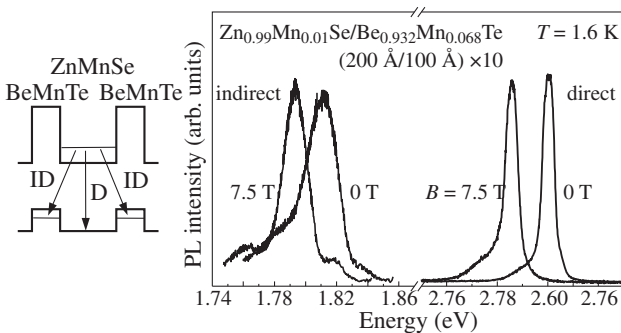
Fig. 2. Giant Zeeman splitting of hole states in $Be_{1-y}Mn_y$Te determined from magnetic-field shift of the indirect emission line for (Zn,Mn)Se/(Be,Mn)Te MQWs. 50% of the splitting is plotted. Experimental data are shown by symbols. Lines are the fitting curves to evaluate the exchange constant $N_0\beta_2$ for $Be_{1-y}Mn_y$Te (see also Table). $T = 1.6$ K.