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BOUND EXCITON LUMINESCENCE IN PHOSPHORUS DOPED $Cd_{1-x}Mn_xTe$ CRYSTALS

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Measurement of photoluminescence as a function of temperature and of magnetic field in p-type phosphorus doped $Cd_{1-x}Mn_xTe$ is reported. From the conduction band–acceptor level transition, the ionization energy of P-acceptors is obtained to be 54 ± 1 meV. The photoluminescence spectrum in the band edge region exhibits three maxima connected with the recombination of excitons bound to neutral acceptors (A^0, X), excitons bound to neutral donors (D^0, X), and free excitons (X) at energies $E_{(A^0,X)} = 1.606$, $E_{(D^0,X)} = 1.610$, and $E_X = 1.614$ eV, respectively. At $T = 1.4$ K a strong increase in PL intensity of (A^0, X) line 8-fold as a function of magnetic field is found and shown to originate from the magnetic field-induced lowering of the acceptor binding energy and increase in the hole effective volume.

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1. Introduction

Mixed crystals $Cd_{1-x}Mn_xTe$ belong to the group of materials named semimagnetic semiconductors (SMSCs) [1]. One of the most prominent properties of SMSCs is a strong exchange interaction between the spins of carriers and those of localized magnetic ions. In a magnetic field the exchange interaction leads to several unusual optical and transport properties of these materials [2–4]. In particular, for p-type SMSCs the exchange-related effects are very pronounced due to a large exchange constant of the holes. In this paper we present the results of PL measurements as a function of temperature and of magnetic field in p-type phosphorus doped $Cd_{1-x}Mn_xTe$.

2. Experiment

The experiments presented in this work were performed on p-type $Cd_{1-x}Mn_xTe$ grown by Bridgman technique. The manganese mole fraction x ranges from 0.01 to 0.05. At T = 300 K the bulk resistivity and hole concentration are about 1 Ω cm and 1×10^{17} cm^{-3}, respectively. Cadmium phosphide (CdP_2) was used as a doping material (0.05 wt.% or less). The reflection and photoluminescence were measured in the same samples at several temperatures ranging from 1.4 to 77 K and in magnetic fields up to 7 T, in an Oxford Spectromag cryostat. The PL excitation was done with the Ar^+ laser line of 4765 Å, with a typical power of about 50 mW. All spectra were recorded using an ORIEL 1/4 meter spectrograph, working with a 600 lines/mm grating and a cooled CCD camera.

3. Results and discussion

The photoluminescence measurements were performed for P-doped $Cd_{1-x}Mn_xTe$ samples with Mn mole fractions $x = 0.01, 0.02$, and 0.05. For samples with $x = 0.01$ PL spectra have a rich structure, which extends from the excitonic recombination region to the donor–acceptor pair recombination. For samples with higher Mn concentrations the PL spectra were dominated by a broad band connected with donor–acceptor recombination processes. In this paper we focus on the results obtained in $Cd_{0.99}Mn_{0.01}Te$ samples.

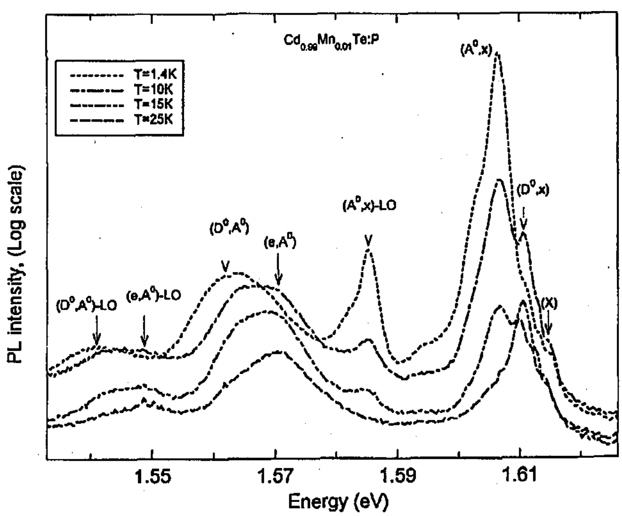

Fig. 1. Photoluminescence intensity (in arb. units) of $Cd_{0.99}Mn_{0.01}Te$:P crystal for selected temperatures: 1.4 K, 10 K, 15 K, and 25 K.

Figure 1 presents the PL spectra for $Cd_{0.99}Mn_{0.01}Te$ crystal at four selected temperatures: 1.4 K, 10 K, 15 K, and 25 K. At 10 K in the excitonic region the PL spectrum exhibits three maxima located at 1.606, 1.610, and 1.614 eV. Comparing the value of the free exciton energy obtained from the reflection spectrum with the observed PL peak energies, the peak at 1.614 eV is identified as due to the recombination of free exciton in $Cd_{0.99}Mn_{0.01}Te$. In analogue to the case of pure CdTe, the peaks at 1.609 eV and 1.606 eV are attributed to recombination of the excitons bound to neutral donor (D^0, X) and neutral acceptor (A^0, X), respectively. At 1.4 K in the donor–acceptor recombination region one strong peak at $\epsilon = 1.563$ eV is observed. When the temperature increases a new band at 1.569 eV emerges. This band results from the recombination of the conduction band electrons with the holes bound to acceptors and labeled (e, A^0). Assuming that the binding energy of the free exciton ground state equals 0.010 eV [5], the band gap energy of P-doped $Cd_{0.99}Mn_{0.01}Te$ crystal and the ionization energy E_A of P-acceptors are determined to be 1.624 eV and 0.054 eV, respectively. The binding energy (E_B) of the exciton bound to acceptor determined by the energy difference between (A^0, X) and (X) bands is found to be 0.008 eV. The binding energy ratio E_B/E_A for P-doped $Cd_{0.99}Mn_{0.01}Te$ equals 0.145 and is greater than that in P-doped CdTe where it is equal to 0.107 as calculated from data of Ref. [6]. One can see from Fig. 1 that the intensity of (A^0, X) band, which dominates PL spectrum for $T < 10$ K, strongly decreases with increasing temperature. The spectral position of this band is temperature independent. At $T = 10$ K the (D^0, X) band noticeably emerges and shifts together with (X) band toward lower energies as the temperature increases.

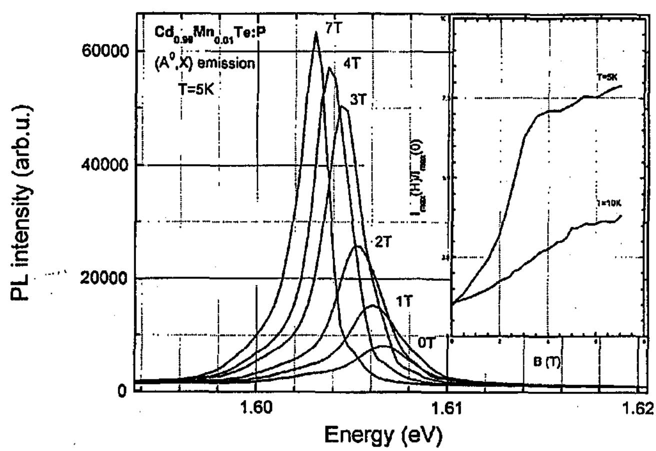

Fig. 2. Excitonic photoluminescence intensity of $Cd_{0.99}Mn_{0.01}Te$:P in selected magnetic fields for $T = 10$ K. The inset shows the magnetic field dependence of PL intensity of (A^0, X) emission.

Figure 2 shows the PL spectra in the excitonic region of P-doped $Cd_{0.99}Mn_{0.01}Te$ at $T = 1.4$ K for different magnetic fields in the Faraday configuration. In the magnetic field the (D^0, X) and (X) lines split into two components for each σ^+ and σ^- polarizations. The splitting of (A^0, X) line is not observed, the magnetic field only shifts this line to lower energies and strongly increases its intensity. At $T = 5$ K as the magnetic field rises from 0 to 3 T the intensity of the $(A^0,\ X)$ line increases sharply about 8 times and then tends to saturation. The inset in Fig. 2 shows magnetic field dependence of the PL intensity of $(A^0,\ X)$ line.

The increase in the binding energy of excitons bound to acceptors in zero--magnetic field in P-doped $Cd_{0.99}Mn_{0.01}Te$ and the magnetic field-induced raise of photoluminescence intensity of $(A^0,\ X)$ band can be explained, if one takes into account the formation of bound magnetic polarons (BMP). As it is well established that exchange interaction between manganese and bound hole spins provides an additional potential well, leading to an increase in the acceptor ionization energy. At zero field, the binding energy consists of a Coulomb part and an exchange (magnetic polaron) part. The polaron characteristic energy is given by [7]

$$\varepsilon_{\mathrm{p}}(H,T) = \left(\frac{0.8\beta}{g\mu_{\mathrm{B}}}\right)^2 \frac{\chi(H,T)}{32\pi a^3}, \tag{1}$$

where the factor 0.8 describes the orbital quenching of the spin splitting [8], β is the exchange constant of the valence band, $\chi = \partial M_0/\partial H$ magnetic susceptibility of Mn ions system, $a = \hbar^2\kappa/(m_{\perp}e^2)$ is the effective Bohr radius. Because of very large value of β in p-type $Cd_{1-x}Mn_xTe$ ($\beta = 0.88$ eV [9]) ε_{p} is very high. The theory of acceptor state [10, 11] for SMSC predicts that in a magnetic field, the acceptor wave function becomes strongly anisotropic. For not too high fields, the Bohr orbit increases in the direction transverse to the magnetic field $\boldsymbol{H}$. This unusual feature has the following consequences: first, reduction of the magnetic polaron effect leading to a decrease in acceptor ionization energy ("boil-off" of free carriers) with increasing magnetic field; second, the increase in the effective acceptor volume results in an increase in the exciton recombination probability in $(A^0,\ X)$ complexes. These two effects cause a strong increase in PL intensity observed in p-type $Cd_{1-x}Mn_xTe$.

In summary, we have demonstrated that the doping $Cd_{1-x}Mn_xTe$ crystals with phosphorus can be used as an effective tool to study optical properties characteristic of SMSCs. We also show that formation of BMP in p-type doped SMSC influences very strongly photoluminescence phenomenon.

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