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Physica E 6 (2000) 709–712

PHYSICA E

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# Ordered magnetic phase in $Cd_{1-x}Mn_xTe/Cd_{1-y-z}Mg_yZn_zTe$ : N heterostructures: magnetooptical studies

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**Abstract**

Photoluminescence magnetospectroscopy is employed to examine the low-temperature magnetic phase that is induced by the carrier-mediated ferromagnetic exchange interaction in modulation-doped $Cd_{1-x}Mn_xTe$ quantum well. Unusual properties of the domain structure are linked to tendency towards spin-density wave formation in this low-dimensional magnetic system.


*PACS:* 75.50.Rr; 75.30.Hx; 75.50.Dd; 78.55.Et

*Keywords:* Diluted magnetic semiconductors; Semimagnetic semiconductors; RKKY interaction; Heterostructures and superlattices

Two recent developments have considerably renewed the interest into mechanisms underlining carrier-mediated ferromagnetic couplings in semiconductor material systems. First, low-temperature epitaxy of $Ga_{1-x}Mn_xAs$ results in a material, in which the critical temperature $T_c$ of a ferromagnetic phase transition attains values as high as 110 K for $x$ as low as 0.05. (see Ref. [1]). Second, it was experimentally confirmed [2] that, according to theoretical prediction [3], free holes in low-dimensional structures of II–VI diluted magnetic semiconductors (DMS) can induce a ferromagnetic order, demonstrating that the well-established methods of modulation of the carrier concentration in semiconductor quantum structures can be applied for a tailoring of magnetic properties.

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1386-9477/00/$ - see front matter 
PII: S1386-9477(99)00178-2

In this Communication, we present new results of investigations, which aim at determining the dependence of the critical temperature $T_c$ in p-doped $Cd_{1-x}Mn_xTe$ quantum well (QW) on the Mn content $x$ and the hole concentration $p$, as well as at establishing the nature of the magnetic order. Due to the excellent structural characteristics of MBE-grown II–VI layered structures, their properties near the ferromagnetic phase transition can be examined by magnetooptical effects [2]. In particular, a Moss–Burstein shift obtained by comparing photoluminescence (PL) and its excitation spectra (PLE) permits the determination of the carrier concentration. The energy distance between the emission lines observed for the two complementary circular polarizations gives, in turn, direct information on the magnitude of the band spin-splitting, and thus on the magnetization inside the domains. At the same time the difference between the integrated intensities of the lines shows how the degree of domain alignment depends on the magnetic field and temperature.

The PL experiments were carried out in Faraday geometry. The photon energy of the excitation beam was tuned below the energy gap of the barrier material. Additional illumination by above-barrier light resulted in a trapping of the photoholes in the barrier, and a partial neutralization of the holes in the QW by the photoelectrons under stationary conditions, allowing us to precisely tune the hole density $p$. The Zeeman splitting of the excitonic features observed in reflectivity between 10 and 50 kOe, together with the well-known values of the band [4], exchange [5], and magnetic [5,6] parameters of $Cd_{1-x}Mn_xTe$, served to obtain an exact value of $x$.

Two types of cryogenic systems were employed: a pumped liquid $^4$He cryostat [2] and a dilution refrigerator. In the dilution refrigerator, a fiber-optic system was used to guide the light to and out of the sample mounted on a cold finger; the temperature was monitored by a calibrated resistor located in close proximity of the sample. Considering the strong temperature dependence of the PL splitting, the actual temperature of the spin-subsystem at a given excitation power was thoroughly evaluated: such an analysis indicated that measurements down to 0.6 K were possible with a reasonable signal-to-noise ratio. Time-resolved PL was measured using a streak camera and excitation light pulses ( $<3$ ps) from a mode-locked Ti-sapphire laser.

Our findings in the absence of external magnetic field are summarized for one of the structures in Fig. 1. The PL line which corresponds to the energy gap in the QW region, below a characteristic temperature $T_C$, features a splitting and a shift of its spectral position. Furthermore, there is a significant increase of the PL decay time below $T_C$. These observations, together with the observed critical behavior of the field-induced splitting at $T \to T_C^+$ (i.e., a diverging susceptibility) [2], constitute the experimental evidences for the presence of a ferromagnetic transition in the modulation-doped p-$Cd_{1-x}Mn_xTe$ QW. As shown in Fig. 2, the dependence $T_C(x)$ is well described by the mean-field model [3] with an enhancement factor $A_F = 2.1$ resulting from the carrier–carrier correlations [3,2].

Figs. 1(b) and (c) show how the energy of the PL peak and its splitting $\delta E$ vary with the temperature and hole concentration. According to the simple model [3], whose predictions are shown by a dashed line in Fig. 1(c), the band spin-splitting $\Delta$, and thus $\delta E$, are expected to attain rather abruptly the value corresponding to the full polarization of the hole liquid. We see that the experimental values of $\delta E$ reaches the theoretically calculated splitting at the lowest temperatures, a result supporting strongly the general consistency of our interpretation. However, $\delta E$ decreases with rising temperature faster than expected theoretically. Furthermore, $T_C$ is predicted to be independent of $p$ in 2D systems [3], a supposition at variance with the results of Figs. 1(b) and 2(b). We assign these discrepancies to the effect of static disorder upon the energy dependence of the density-of-states (DOS). To check this conjecture, we insert into the self-consistent procedure [3] the hole polarization, $p_\downarrow - p_\uparrow$, calculated from the expression,

$$p_{\uparrow\downarrow}(\Delta) = \frac{A_F m_{hh}}{4\pi\hbar^2} \int_{-\infty}^{\infty} d\varepsilon \frac{1 + \mathrm{erf}[(\varepsilon \pm \Delta/2)/\gamma]}{1 + \exp[(\varepsilon - \varepsilon_F)/k_B T]},$$

in which the step-like DOS of clean 2D systems with the dispersion $\varepsilon_k = \hbar^2 k^2/2m_{hh}$ is broadened by disorder. This broadening is characterized by the parameter $\Gamma = \sqrt{2}\gamma$, the FWHM of the Gaussian distribution of the energy levels which contribute to DOS. As shown in Figs. 1(d) and 2(b), such a model with $\Gamma = 1.7$ meV explains qualitatively the essential features of our data.

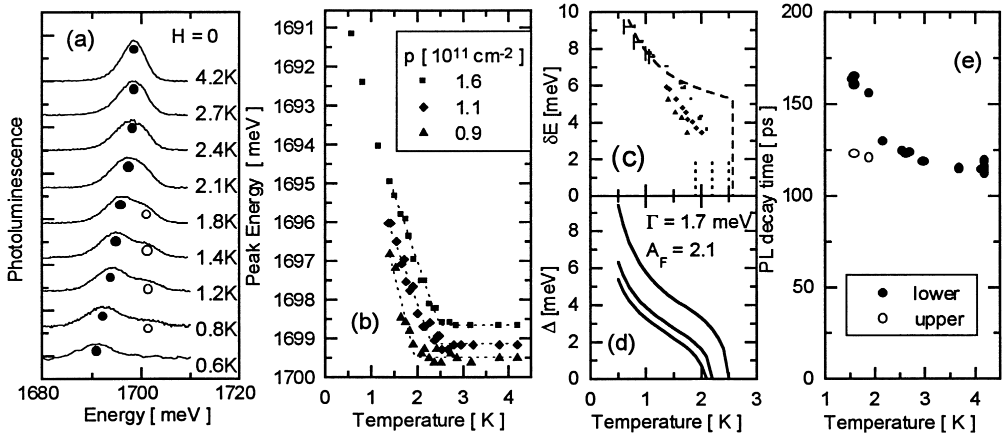


Fig. 1. PL spectra at selected temperatures (a). Peak positions of the low- and high-energy lines are marked by full and empty points, respectively. Temperature dependence of the low-energy peak positions and the line splitting are shown for selected values of the hole concentrations in (b) and (c), respectively. Dashed and solid lines in (c) and (d) are calculated neglecting and taking disorder into account, respectively. Vertical lines in (c) show critical temperatures $T_c$ corresponding to slope changes of the points in (b). PL decay times for upper (empty points) and lower (full symbols) split lines versus temperature are shown in (e).

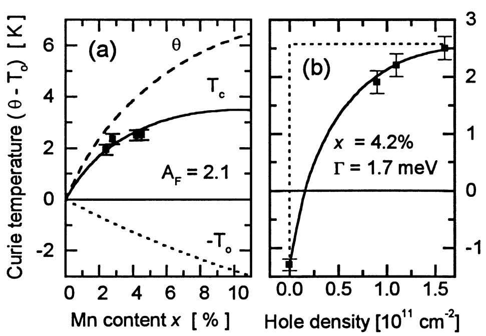


Fig. 2. Critical temperature $T_C = \Theta - T_0$ of the ferromagnetic transition as a function of Mn (a) and hole (b) concentrations. Solid lines are theoretical taking the enhancement factor due to the Coulomb interactions between the holes (a) and also disorder (b) into account. The values of temperature $\Theta$ and $T_0$ corresponding to the ferromagnetic and super-exchange antiferromagnetic interactions are shown in (a) by dashed and dotted line, respectively. The dashed line in (b) is theoretical neglecting disorder ($\Gamma = 0$).

Turning to the properties of the ferromagnetic phase we note that the easy axis is expected to be oriented along the growth direction as a result of the interaction between the hole spin and the strain and confinement potential [3,7,8]. The spectra in Faraday geometry give, therefore, information about the relative concentration of domains with the two relevant orientations, as shown schematically in Fig. 3(a). The difference in the integrated intensities of the two circularly polarized components contributing to the PL line, normalized to their values at $H = 0$, is depicted as a function of the magnetic field at 1.53 K in Fig. 3(c).

A number of conclusions emerge from this plot. First, we see that the domains become aligned in a magnetic field of the order of 100 Oe. Second, since we know the magnitude of the spin-splitting, and thus the corresponding magnetization, we are in position to evaluate the contribution of the Mn spins to the macroscopic magnetic induction from the system of aligned domains, $B_s = 4\pi M_s = 14 \pm 1 Gs$ at 1.5 K. Such a small value of $B_S$ makes the dipole interaction weak, and substantiates a posteriori our assumption that the spontaneous magnetization is oriented perpendicularly to the surface. Finally, the data point to small coercive force, $H_C < 4$ Oe. The virtual absence of hysteresis in the studied ferromagnet is further supported by the observation that the spectra for the two polarizations, that is the concentrations of the two kinds of the domains, are identical at $H = 0$, even after cooling the sample from above $T_C$ down to 1.5 K in the magnetic field of 500 Oe or after 15 min of illumination by circularly polarized light.

We suggest that these unusual domain properties result from the proximity to the spin-density-wave

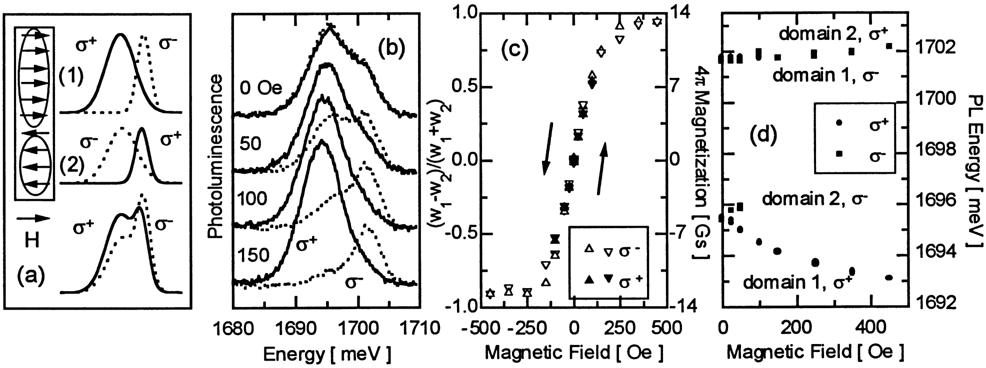


Fig. 3. Schematic (a) and experimental results on domain structure studied by polarization-resolved luminescence spectroscopy of modulation-doped p-$Cd_{0.957}Mn_{0.043}Te$ at 1.53 K. Peak positions are shown in (d), while (c) presents the difference $(w_1 - w_2)/(w_1 + w_2)$, where $w_i = I_i(H)/I_i(0)$, are the normalized integrated intensities $I$ of the two contributions to the line at each polarization for the field swept up and down.

instability in this low-dimensional magnetic system. Indeed, following the procedure developed previously [3] (see also Ref. [9]), the characteristic temperature $T_{\mathrm{SDW}}(q)$ of the spin wave instability corresponding to the wave vector $q$ is given by $T_{\mathrm{SDW}}(q) = \Theta_{\mathrm{F}}(q)$, where $F(q)$ is the static Lindhard function of the carrier magnetic response function. According to our numerical evaluation, $F(q) = 1$ for $q \leqslant 2k_{\mathrm{F}}$, even if the complex structure of the relevant hole subband is taken into account. This means that the ground state may involve SDW with various $q$ values.

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