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Control of Ferromagnetism in $Cd_{1-x}Mn_xTe$ Based Quantum Wells

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New structures aiming at controlling the ferromagnetic properties of diluted magnetic semiconductor quantum wells are presented. The carrier density is controlled by applying a voltage across a p–i–n diode. A new method, creating a 2D hole gas by adjusting the distance between the quantum well and surface, offers opportunities for a broader range of structures.

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1. Introduction

To control the properties of magnetic materials would be highly desirable from fundamental and technological viewpoints, particularly in view of recent developments in magneto-electronics and spintronics. Diluted magnetic semiconductors (DMS), where ferromagnetic interactions are mediated through free carriers, are particularly attractive since they offer the possibility to modulate the magnetic properties by modulating the carrier density. The first demonstration has been performed by Ohno et al. [1] with III–V DMS layers inserted in a Schot-

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tky diode. They demonstrated that a gate voltage of +125 V changes the Curie temperature T_C by about 1 K in a field-effect transistor based on a (In,Mn)As thin layer.

2. Results and discussion

We have demonstrated [2, 3] electric-field control of ferromagnetism in a $Cd_{0.96}Mn_{0.04}Te$ quantum well (QW). By applying an electric field we were able to vary isothermally and reversibly the magnetism in the QW. The MBE grown semiconductor structure used in Ref. [2] (Fig. 1) consisted of a $Cd_{0.65}Zn_{0.08}Mg_{0.27}Te$ p–i–n diode grown on a $Cd_{0.88}Zn_{0.12}Te$ substrate. The back barrier doped with aluminum (n-type) resided 320 nm away from the QW. A single, 10 nm thick, CdMnTe QW was introduced in the intrinsic layer 10 nm away from the p-type (doped with nitrogen) contact layer. Without any applied voltage, a nominal hole concentration of 2×10^{11} cm^{-2} was present in the QW. As shown in Fig. 1b, clear diode I–V characteristics were obtained allowing us to modify the carrier concentration in the well by applying a reverse bias.

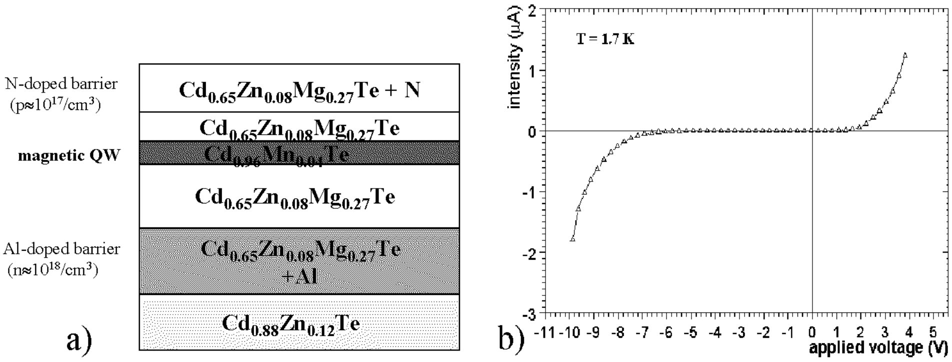

Fig. 1. Sketch of the p–i–n diode and its I/V characteristics.

The onset of ferromagnetism and the carrier concentration were optically determined: the experimental evidence for the presence or not of a ferromagnetic transition was given by the spontaneous splitting, below a characteristic temperature T_c, of the photoluminescence (PL) line corresponding to the energy gap in the QW region. At the same time, a critical divergence of the field induced splitting at $T \rightarrow T_c^+$ was observed. Moss–Burstein shift between the PL and its excitation spectrum (PLE) was used to determine the hole density. The strong decrease in the Moss–Burstein shift, observed for a reverse bias demonstrates the influence of the applied voltage on the hole concentration. The application of a reverse bias of –0.7 V led to a decrease in the hole concentration to zero in the QW. Figure 2a

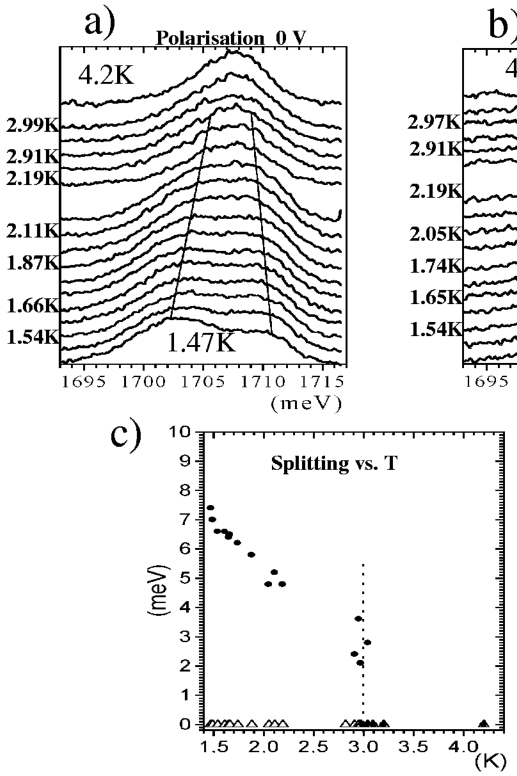

Fig. 2. Photoluminescence spectra of a $Cd_{0.96}Mn_{0.04}Te$ QW introduced in a CdZnMgTe diode measured at various temperatures: (a) without bias, (b) with a –1 V bias. Figure c shows the evolution of splitting (i.e. magnetization) between low and high energy lines as a function of temperature (●: without voltage, Δ: –1 V). Above $T_C = 2.9$ K the splitting vanishes.

presents PL spectra collected for the *p*–*i*–*n* structure shown in Fig. 1 in the absence of an external magnetic field at various temperatures. As shown, the phase transition occurs below approximately 3 K in this sample. As shown in Fig. 2b, at a reverse bias of –1 V no signature of the ferromagnetism is observed in the PL spectra down to 1.5 K. Figure 2c shows the zero-field splitting of Figs. 2a, b, proportional to the local Mn magnetization due to the giant Zeeman effect, as a function of temperatures for the two values 0 V and –1 V of voltage across the *p*–*i*–*n* diode.

In the structure studied in Ref. [2] and shown in Fig. 1, N and Al were used for *p*- and *n*-type doping, respectively. We present here the observation of high carrier densities and carrier-induced ferromagnetism in CdMnTe QWs incorporated, close to the surface, in nominally undoped samples. The 10 nm thick CdMnTe QW was embedded in $Cd_{0.65}Zn_{0.08}Mg_{0.27}Te$ barriers (Fig. 3a). As shown in Fig. 3b, for a

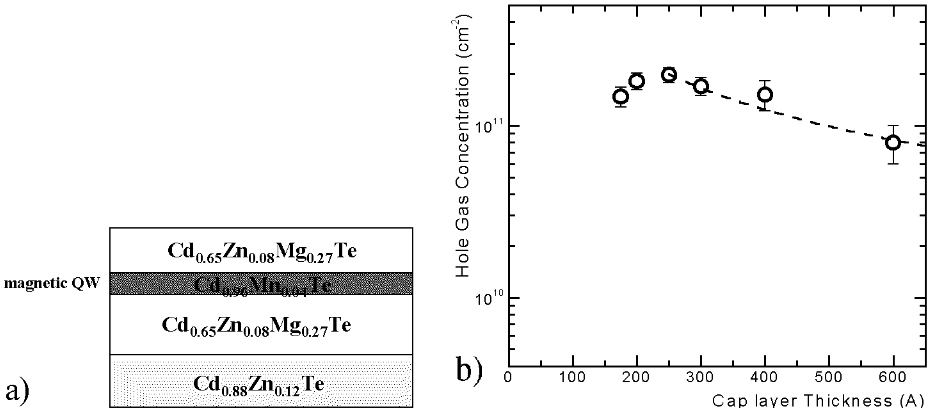

Fig. 3. (a) Sketch of the samples, (b) hole gas concentration deduced from Moss–Burstein shift measurements in $Cd_{0.99}Mn_{0.01}Te$ QW located at different distances from the surface. Dashed line is a guide for the eyes.

QW with a Mn content of about 1%, varying the distance of the QW from the surface allowed us to change the hole density (up to 2×10^{11} cm^{-2} for a QW located 20 nm below the surface) and thus the magnetization of the DMS QW. For a cap layer of 25 nm and 4% of Mn in the QW, a ferromagnetic phase transition was optically observed with a critical temperature T_c of about 2.5 K.

The presence of a hole gas in the QW demonstrates the existence of surface states electrically active as acceptors, which we tentatively attribute to the formation of a surface oxide layer during exposition of the sample to the air. Indeed a negligible concentration of carriers was observed when we protected the sample from oxidation by depositing an amorphous Te layer. Yang et al. [4] observed by surface photovoltage spectroscopy an acceptor surface state on CdZnTe layers, due to the presence of TeO_2. In the same way, Wasik et al. [5] evidenced free electron trapping by surface defects in CdTe/CdMgTe heterostructures with QW lying close to the surface. In order to be able to control the oxidation of the surface and consequently the hole density in the CdMnTe QW, we performed a detailed surface study of the oxidation kinetics of the surface of $Cd_{0.65}Zn_{0.08}Mg_{0.27}Te$ (001) by X-ray photoelectron spectroscopy (XPS). Figure 4 presents the XPS spectra of the 3*d* core levels of Te before (a) and after (b) oxidation for 13 hours at room temperature and oxygen pressure of 1 bar. The second line, which appears at a higher binding energy (575.8 eV) for the oxidized sample, corresponds to the formation of TeO_2 [6]. In Fig. 4c, we plotted time evolution of the TeO_2 line relative intensity to the total intensity (lines corresponding to CdZnMgTe and TeO_2). Using a photoelectron escape depth of 1.2 nm for the Te 3*d* core level [7], we estimate that a ratio of 0.25 corresponds to the formation of about 1 ML of oxide. Thus it appears that the oxidation of the surface is rather difficult. The optical determination of the hole density shows that a hole density 1×10^{11} cm^{-2} is obtained in

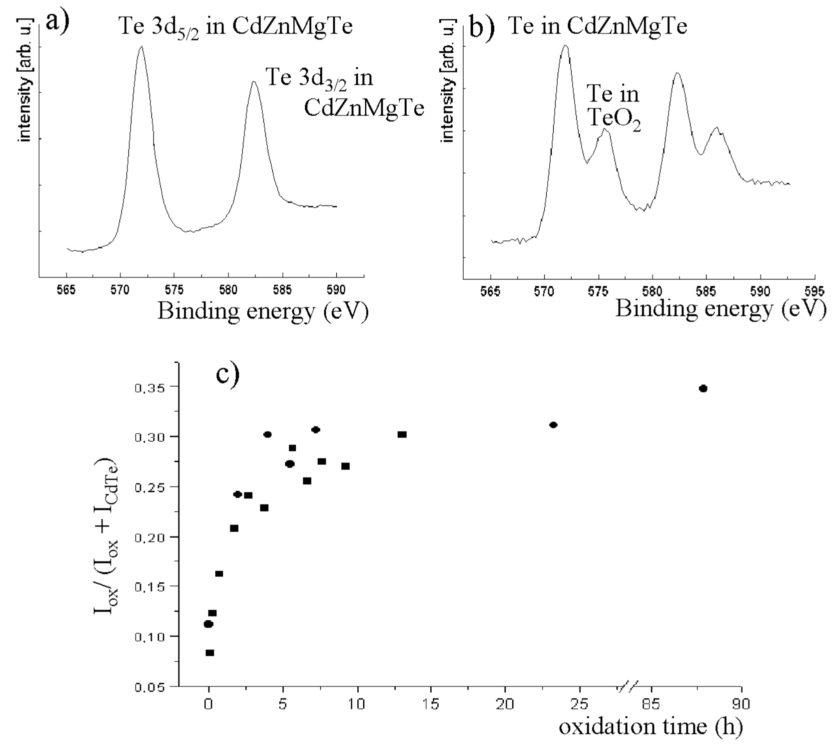

Fig. 4. XPS spectra of Te 3*d* core levels obtained for clean $Cd_{0.65}Zn_{0.08}Mg_{0.27}Te$ (001) surface (a) and after 13 hours of oxidation (b). Intensity of Te 3*d* peak corresponding to tellurium oxide relative to the total intensity of the Te peaks, as a function of oxidation time (c) for two samples (● and ■).

a 4%Mn CdMnTe QW located 25 nm below the surface for an oxygen exposition of 88 hours.

In summary we show that doping of a CdMnTe QW from the surface states can be as effective as usual modulation doping with nitrogen. The presented new way of doping enlarges the possibilities of controlling carrier-induced ferromagnetism in quantum wells.

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