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Injection of Optically Generated Spins through Magnetic/Nonmagnetic Heterointerface: Ruling out Possible Detection Artifacts

M. Ghali, J. Kossut and E. Janik

Institute of Physics, Polish Academy of Sciences
al. Lotników 32/46, 02-668 Warsaw, Poland

We report on injection of optically created spin-polarized carriers into CdTe-based materials. The injected spins are initially aligned in a diluted magnetic semiconductor CdMnTe layer located on the top of CdMgTe layer in CdMnTe/CdMgTe spintronic generic model structures. A critical discussion of possible artifacts that may complicate the spin detection and its quantitative analysis is given. Although the spin injection efficiency, $\sim 80\%$, has been found by us to be basically independent of the thickness of the spin detecting layer, there is an essential difference between thin and wide detectors related to the strain-induced lifting of the valence band degeneracy in the former, when assessing the efficiency of the spin injection. Most importantly, we observe an effect of switching the spin injection process on and *off* by an external magnetic field variation within a relatively narrow field range. This effect can be achieved by a careful design of the interface between the diluted magnetic semiconductor and the non-magnetic semiconductor.

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1. Introduction

The detection of the spin injection process in semiconductors is of as fundamental importance for achieving any spintronics based devices as the spin injection process itself. A typical design of a device to study these effects makes use of observation of a circularly polarized light emission from a QW diode (spin-LED) made of nonmagnetic material, which is spatially remote from a spin aligner layer made of a diluted magnetic semiconductor (DMS). Using such generic design it has been shown that the spin injection process can be very efficient [1–3] from both ferromagnetic and paramagnetic aligners. However, there are several sources of possible errors in assessing quantitatively the efficiency of the injection, such as, e.g. geometry of experiments, presence of magnetic circular dichroism, thickness of the detecting layer (which can affect the degeneracy of the valence band), spectral components of the analyzed circularly polarized emission, etc. [4, 5].

In this work we demonstrate that specially designed structures utilizing MBE-grown $Cd_{0.96}Mn_{0.04}Te/Cd_{0.97}Mg_{0.03}Te/CdTe$ QW layers make possible to fairly exclude such artifacts. The CdMnTe layer acts as a spin aligner while the 120 Å CdTe QW collects the electron spins. Both the spin aligner and the spin collector are separated either by the 1000 Å-thick nonmagnetic CdMgTe spacer (sample A) or by only 50 Å-wide spacer (sample B). The results of CW magneto-luminescence measurements from these samples are compared to those obtained for a reference sample consisting of nonmagnetic CdMgTe/CdTe QW structure (sample C). The CdMgTe layers in sample A and B have a band gap only slightly smaller than that in DMS spin aligner in the absence of a magnetic field. By exceeding a certain value of the magnetic field we were able to push the conduction band edge of the nonmagnetic spacer above that in the DMS aligner (and the valence band edge of the DMS below that in the nonmagnetic spacer), thus blocking the spin injection in the higher field region.

2. Possible artifacts in spin detection experiments

Although the spin detection idea is relatively simple in principle, several artefacts might contribute to the results making the discrimination of the real and spurious spin-dependent effects, difficult. Here, we give several examples of such artefacts with some suggestions how to avoid them.

2.1. Diffusion of magnetic impurities

In spin injection experiments the design of the samples is very crucial. Since the spin aligner (SA) must contain a fraction of magnetic atoms (e.g. Mn) to achieve the alignment of the spins, however, one has to carefully avoid diffusion of Mn into the detection region in the sample. Otherwise, any inference concerning the spin injection based on observation of circular polarization emitted from a region into which the injection is supposed to be taking place, are questionable. Even a minute amount of Mn present in those parts can induce a sizable circular polarization of emission. Therefore, it is advisable to incorporate relatively wide spacers between the aligners and detection regions (nonmagnetic quantum wells). In the case of structures made of II–VI materials those spacers should be at least 10 Å wide in view of typical interdiffusion length values in MBE grown samples [6]. Alternatively, one has to check very carefully (e.g. by studying the sign and the magnitude of the electronic g-factor*) if there is no Mn present in the region where the light used for spin detection is emitted from.

2.2. Geometry of collecting of the polarized light emission

Most favorable configuration of the polarized light detection that can give information concerning the efficiency of the spin injection is if the light is collected perpendicularly to the sample surface (as opposed to the edge emission). Only then the selection rules that make possible an unambiguous connection between the light polarization and the spin polarization of the recombining carriers apply strictly. However, in such configuration one has to rule out a possibility of intrinsic magnetic dichroism induced in the layer of the aligner (by making it sufficiently thin, for example).

2.3. Lifting the light–heavy hole degeneracy

Using usual selection rules for optical transitions in zinc blende semiconductors we arrive at a conclusion that $P_{\mathrm{c}} = -0.5P_{\mathrm{s}}$, where P_{c} is the degree of the circular polarization of the emitted light, while P_{s} is the degree of spin polarization along the external magnetic field. However, this is only true in bulk materials, and not in quantum structures where the degeneracy of light and heavy hole states can be lifted. For the same reason the estimate can depend on the thickness of the light emitting parts of the device into which the injection takes place. If the heavy–light hole splitting is large one can use an estimate of the injection efficiency as given by $P_{\mathrm{c}} = -P_{\mathrm{s}}$.

2.4. Magnetic circular dichroism

As the spin aligner is usually located on the top of the spin detection region in most of the proposed spintronics devices, a contribution from magnetic circular dichroism (MCD) should be taken into account or its contribution carefully ruled out [4, 7]. Of course, the ruling it out is important only to properly estimate the degree of the spin injection efficiency, not for the injection process itself.

3. Experimental results

Figure 1 shows magneto-PL peaks recorded from an entire sample A. It is important to mention that the excitation light used in this experiment is *linearly polarized* and no circular polarized excitation was used at all (which is essentially different from the experiment performed in Ref. [3], where circular polarized excitation was mainly used). Such linearly polarized excitation would exclude possible

*This is particularly true in the case of CdTe (g-factor ~ -1.6) and of DMS materials, which show a giant g-factor with a positive sign of its value. However, one has to consider other cases where the intrinsic g-factor of particular nonmagnetic semiconductors (e.g. ZnSe) has a positive sign of its g-factor.

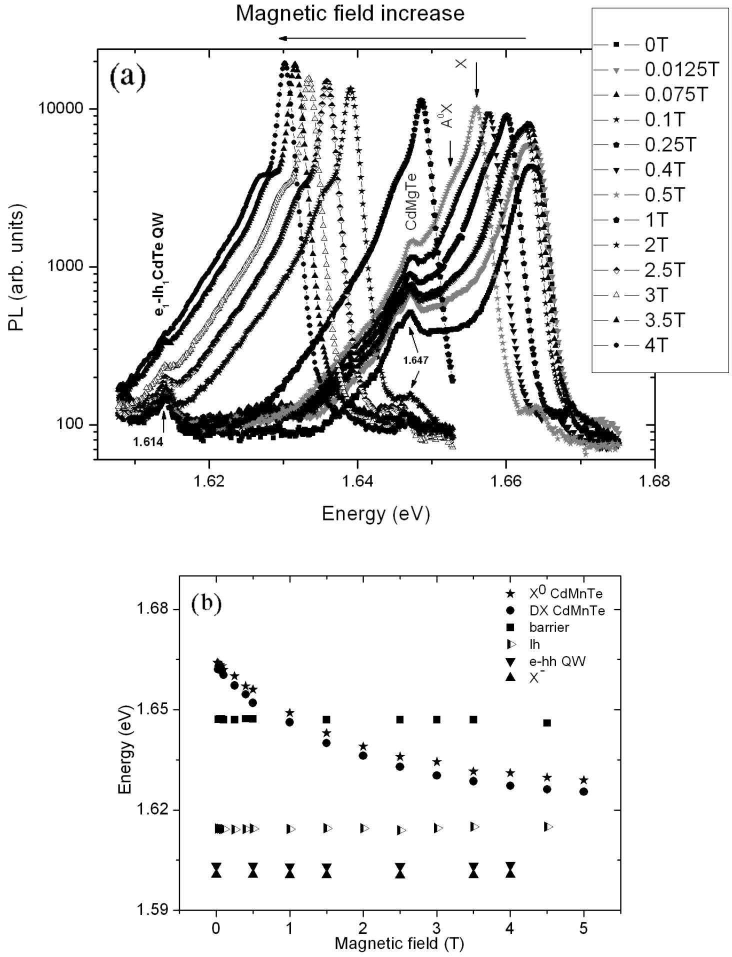

Fig. 1. (a) The PL spectra shows several transitions from several regions in sample A at different magnetic fields. (b) The lower energy component (σ^+) of magneto-PL of the optical transitions from several regions in the structure. The CdMnTe (giant red-shift), $Cd_{0.97}Mg_{0.03}Te$ ($E = 1.647$ eV) and $e_1 - lh_1$ from the CdTe QW.

experimental artefacts, which may arise while utilizing circular polarized excitation in the presence of magnetic field (e.g. birefringence effects). In other words, any circular polarization that might come out from the DMS region or the "detection" region will be naturally separated out from the exciting light polarization.

In sample A, we observe in the high-energy part of the PL spectrum, a broad PL band consisting of two poorly resolved emission bands (see, the inset in Fig. 1), separated by a few meV, due to, respectively, recombination of free excitons (X) at 1.665 eV and that of acceptor bound excitons (BX) at 1.662 eV in the $Cd_{0.96}Mn_{0.04}Te$ layer [8]. Both lines shift to the lower energy as the magnetic field increases due to the s, $p{-}d$ exchange interaction-induced Zeeman splitting (giant Zeeman shift). This shift is proportional to the magnetization and is described by

$$\Delta E_{hh} = \pm\frac{1}{2}(|N_0\alpha| + |N_0\beta|)x_{\rm eff}\langle S_z\rangle,$$

where α and β are the s- and $p{-}d$ exchange coupling constants, respectively, N_0 is the number of unit cells per unit volume, and $x_{\rm eff}$ is the effective fraction of Mn spins [9]. Here $\langle S_z\rangle = B_{5/2}((5/2)\mu_{\rm B}B/k(T_{\rm Mn}+T_0))$ is the average of Mn spin which is described by standard Brillouin function $B_{5/2}(y)$ for Mn spin $= 5/2$, $\mu_{\rm B}$ is the Bohr magneton, k is the Boltzman constant, $T_{\rm Mn}$ is the Mn spin temperature, T_0 is the phenomenological parameter which describes the antiferromagnetic weak long range interaction between Mn–Mn spin [7]. Also clearly visible is the emission from the nonmagnetic $Cd_{0.97}Mg_{0.03}Te$ spacer at 1.647 eV that is nearly independent of the magnetic field. A weak peak at 1.614 eV is ascribed to $e_1{-}lh_1$ transition in the CdTe QW. The most striking feature in Fig. 1, is the *resonance* between the lines due to $Cd_{0.96}Mn_{0.04}Te$ band states and the nonmagnetic $Cd_{0.97}$ $Mg_{0.03}Te$ bands at $B \sim 1$ T (we call it $B_{\rm res}$).

In Fig. 1, we plot also the energies of two additional lines observed in the PL: heavy-hole exciton line X^0 ($E = 1.603$ eV) and charged exciton X^- (1.600 eV) line. These two lines were found in the PL and reflectivity spectra of the CdTe QW (not shown here). We leave out the analysis of the QW emissions for spin detection purposes, as the results are discussed elsewhere [10]. In the following we focus only on the PL from the $Cd_{0.97}Mg_{0.03}Te$ spacer in order to monitor the injected spins from the CdMnTe spin aligner.

4. Polarization-resolved measurements

Here, we show the polarization resolved data obtained from the PL measurements at the wavelengths corresponding to the CdMnTe and the CdMgTe layers. The PL is collected along the applied field axis, which is parallel to the growth axis of the sample. The circular polarization degree (P) was determined from the relation $P = \frac{I^+ - I^-}{I^+ + I^-}$, where I^+, I^- represent the intensity of σ^+ and σ^- components of PL spectra, respectively. Figure 2a, b shows the evolution of P from the different parts of sample A. One can observe a nearly 90% circularly polarized light from the DMS part of the structure. This is expected, indeed, as the $s, p{-}d$ exchange interaction between the Mn ions and the carrier spins in the $Cd_{0.96}Mn_{0.04}Te$ is known to facilitate the spins to populate mostly the spin-down lower energy state. As the conduction electron spin splitting reaches 5 meV at $B \sim 1$ T (and the exciton splitting approaches ~ 30 meV), which is, parenthetically, 50 times larger than the thermal energy $k_{\rm B}T \sim 0.1$ meV at 1.6 K, the $Cd_{0.96}Mn_{0.04}Te$ layer shows fully spin polarized carriers (ideal spin filter). On the other hand, a clear peak in the polarization spectra (Fig. 2a) is seen at the CdMgTe ground-state transition

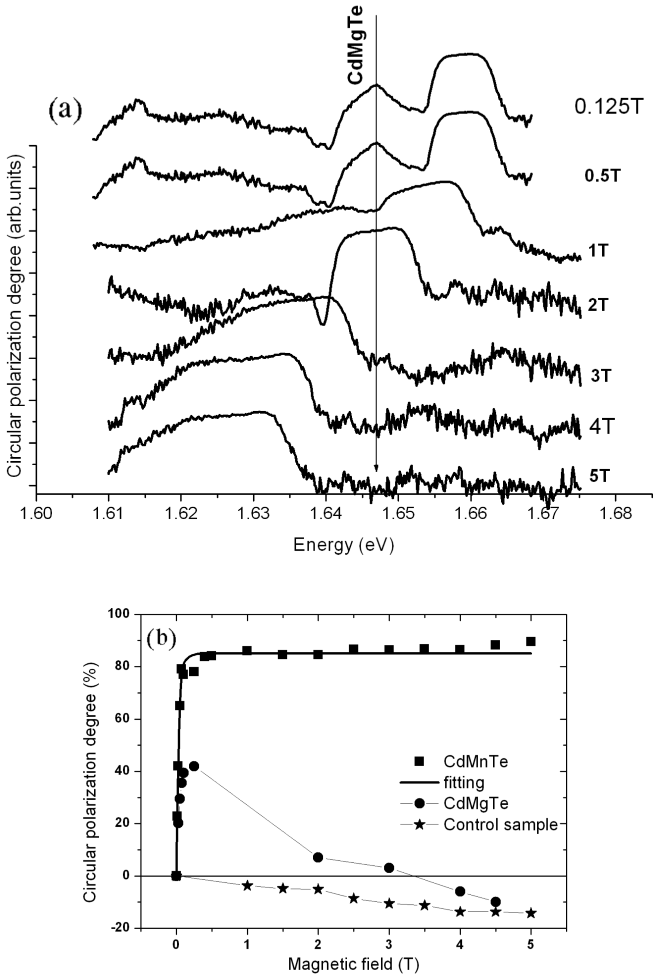

Fig. 2. (a) Spectral analysis of the degree of the circular polarization, in different magnetic fields, of PL emitted from different regions in the structure (sample A). The line is suited at the energy position of excitonic transition from the CdMgTe layer ($E_{\mathrm{g}} = 1.647$ eV). (b) The degree of the circular polarization from CdMnTe (full squares), CdMgTe layer (full circles) in sample A. The star symbols are experimental data from a nonmagnetic control sample measured at the same conditions like for sample A. The data were taken in different magnetic fields under excitation with 476 nm excitation at 1.6 K.

energy ($E = 1.647$ eV) in the presence of magnetic field below 1 T. It can be seen that the circular polarization of this peak is enhanced as the field increases up to ~ 1 T. At higher fields it starts to disappear. These data are clearly depicted in Fig. 2b. We see that P in CdMgTe has the same sign and increases following the $Cd_{0.96}Mn_{0.04}Te$ magnetization as the field increases only until the resonance is achieved at $B_{\rm res}$ between the fully occupied $+\frac{1}{2}$ spin-split state (lower energy Zeeman state in the DMS region, $g > 0$) and the $+\frac{1}{2}$ higher energy spin-state in the CdMgTe layer ($g < 0$).

Naturally, at the resonance, it is quite difficult to distinguish between the peaks from the both layers. Thereby we can conclude that the spin polarized carriers originating from the DMS source have passed through the DMS-$Cd_{0.97}Mg_{0.03}Te$ interface keeping their spin polarization where they recombine radiatively in the $Cd_{0.97}Mg_{0.03}Te$ region, emitting circularly polarized light. The most convincing point supporting this scenario is the *abrupt* decrease in polarization degree above $B \sim 1$ T (see Fig. 2b, full circles), until it even changes its sign to negative. We associate such drop of the polarization degree with the reversal in the conduction band alignment between the $Cd_{0.96}Mn_{0.04}Te$ and the $Cd_{0.97}Mg_{0.03}Te$ layers, the polarized carriers from the spin aligner would have to move to a higher potential energy region of the spacer. Moreover, in the control sample C we do not observe any initially rising positive polarization of emission from CdMgTe (the sign of the polarization observed in this sample is opposite since the g-factor of conduction electrons in CdMgTe is opposite to that in CdMnTe). Thus, the *suppression* of the spin injection in this magnetic field range occurs. In other words, we are able to switch off and *on* the spin injection from $Cd_{0.96}Mn_{0.04}Te$ to $Cd_{0.97}Mg_{0.03}Te$ by tuning the magnetic field. In sample B, we have controlled the composition of Mn and Mg to be a little bit higher than that in sample A. The results are shown in Fig. 3, where a similar behavior can be seen except that the $B_{\rm res}$ has been shifted to 1.5 T. This gives an additional support that the controlling of the *cut off* field (i.e. $> B_{\rm res}$) by adjusting the band offset between the CdMnTe and the CdMgTe layers is feasible. Since the CdMgTe layer in sample B is very thin, it cannot be treated as a bulk material (as is the case of sample A). Consequently the relation

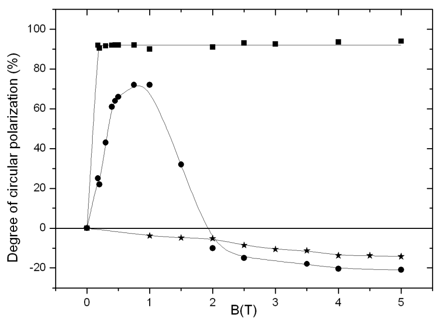

Fig. 3. Magnetic field dependence of the degree of the circular polarization of PL from the $Cd_{0.94}Mn_{0.06}Te$ part (full squares) and from the $Cd_{0.97}Mn_{0.03}Te$ layer (full circles) in sample B. The line connecting the experimental data for $Cd_{0.94}Mn_{0.06}Te$ represents fitting of the data with the function $P = P_0 \tanh(\Delta E/2k_{\rm B}T)$. The line connecting the $Cd_{0.97}Mn_{0.03}Te$ data is to guide the eyes. The stars refer to experimental data from sample C.

$P_c = P_s$ is more appropriate to estimate the efficiency of the spin injection. We may conclude, therefore, that the efficiency in this particular sample is similar to that in sample A (where the relation $P_c = 0.5P_s$ is applicable) and reaches about 80%†. Furthermore, these results make no doubt that the polarization of the emitted light from $Cd_{0.97}Mg_{0.03}Te$ is not due to magnetic circular dichroism in the spin aligner itself. If we imagine any contribution from MCD-related effects in our sample, one should observe a significant value of the polarization at higher magnetic fields (where the band gap of the $Cd_{0.97}Mg_{0.03}Te$ is higher than that in the $Cd_{0.96}Mn_{0.04}Te$, and thus, most of the emitted light is absorbed in the DMS layer). The absence of this effect, in our results, unambiguously excludes any artefacts related to MCD.

Acknowledgments

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† We have observed two optical transitions from the CdMgTe layer with a slightly different polarization degree and the details will be published elsewhere.