Electron $g$-factor in coupled quantum wells CdTe and CdMnTe

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Abstract. In tunnel-coupled quantum wells (QWs) CdTe (20 nm wide) and CdMnTe (8 nm wide) separated by Cd$_{0.88}$Mg$_{0.12}$Te barrier with a thickness of $L_B = 5, 7, 9, \text{ and } 11$ monolayers (MLs), the dependence of electron $g$-factor on the barrier thickness and temperature is investigated by means of the pump-probe Kerr rotation technique. The renormalization of the electron $g$-factor occurs due to the $s$–$d$ exchange interaction of electrons with manganese ions in a magnetic QW. The most change of the electron $g$-factor value $\Delta g = 0.25$ is registered at the least barrier width of 5 MLs and temperature $T = 5 \text{ K}$. In this case, the penetration of the electron wave function from the nonmagnetic QW into the magnetic one is estimated to be 0.6%.

1. Introduction
One of the main issues of spintronics is the search for new spin systems, having both a fast switching of a spin polarization and a long living spin memory. These systems could be used in quantum information technologies. Diluted magnetic semiconductors based on II-VI semiconductor compounds, such as (Cd,Mn)Te and (Zn,Mn)Se, are often used as model systems for the research of spin dynamics of the charge carriers and magnetic ions Mn$^{2+}$, coupled by a strong $s,p$-$d$ exchange interaction. In particular, such an interaction leads to the ultrafast (picoseconds range) spin relaxation of electrons and holes and an increase in their effective $g$-factors by order of many tens of times [1].

In this paper, we report on a research of the electron $g$-factor dependence on a temperature and on a thickness of the barrier between the nonmagnetic CdTe QW and magnetic CdMnTe one in order to find an influence of the magnetic subsystem of manganese ions on the $g$-factor value in nonmagnetic QW.

2. Samples and experimental setup
The structure under study was grown by molecular-beam epitaxy on GaAs substrate. It consists of two QWs, nonmagnetic, CdTe/Cd$_{0.88}$Mg$_{0.12}$Te, and magnetic, Cd$_{0.88}$Mn$_{0.02}$Te/Cd$_{0.88}$Mg$_{0.12}$Te, divided by nonmagnetic barrier Cd$_{0.88}$Mg$_{0.12}$Te of the width $L_B$. The structure was grown in a single technological cycle in the form of a long strip consisting of 4 parts, which differ only in the barrier thickness, equal...
to 5, 7, 9 and 11 monolayers (MLs), respectively. The widths of the nonmagnetic and magnetic QWs are 20 nm and 8 nm. The structure was not intentionally doped.

The time-resolved pump-probe Kerr rotation (KR) technique [2] was used to study the dependence of electron $g$-factor on the barrier width and temperature. Pump and probe laser pulses with the duration of 1.5 ps and the repetition rate of 80 MHz were emitted by the mode-locked Ti:sapphire laser. Pump beam was circularly polarized to create electron spin magnetization. The $g$-factor values were found by measuring the frequency of oscillation of the probe beam linear polarization plane in a magnetic field $B$ directed in the QW plane perpendicular to the excitation beam (Voigt geometry). The laser photon energy was tuned within the spectral range of a free exciton in the wide QW (see photoluminescence (PL) spectrum in figure 1) to optimize the KR signal.

Figure 1. PL spectrum of the sample with $L_B = 11$ MLs recorded under continuous wave excitation with $\lambda_{exc} = 532$ nm. $B = 0$, $T = 1.7$ K. X and T denote exciton and trion lines.

3. Experimental results and discussion

Figure 1 shows the PL spectrum of the structure measured under continuous wave excitation with $\lambda_{exc} = 532$ nm. It consist of two lines caused by emission of the free exciton and the trion in the wide (nonmagnetic) QW.

The typical KR signal measured in the transverse magnetic field is presented in figure 2. It shows oscillations which can be fitted by the sum of two exponentially damping components, fast and slow:

$$A_1 \exp(-t/\tau_1) \cos(\omega_1 t + \varphi_1) + A_2 \exp(-t/\tau_2) \cos(\omega_2 t + \varphi_2).$$

Depending on the barrier thickness, temperature and energy of the exciting photon, the ratio $A_1/A_2$ varies from 20 to 300, decay times $\tau_1$ and $\tau_2$ vary in the ranges (30÷80) ps and (300÷1500) ps, respectively, and the initial phases $\varphi_1$ and $\varphi_2$ are close to zero. The frequencies $\omega_1$ and $\omega_2$ were used to calculate $g$-factor values according to the

Figure 2. Kerr rotation signal in the sample with $L_B = 5$ MLs. $B = 0.41$ T, $T = 30$ K. The insert shows the KR signal in an enlarged scale along the ordinate axis.
formula \( g = \frac{h\nu}{\mu B} \), where \( \mu \) is the Bohr magneton, \( B \) is an external magnetic field and \( h \) is the Planck’s constant.

The \( g \)-factor dependencies on the temperature and barrier width are qualitatively similar for the fast and slow components but quantitatively they are more pronounced for the slow component (figure 3). The dependencies of the \( g \)-factor on temperature at different \( L_B \) and on \( L_B \) at different temperatures are shown in figure 4 and figure 5, respectively.

![Figure 3. Temperature dependences of \( g \)-factor for the fast and slow components measured on the sample with \( L_B = 5 \) MLs. \( B = 0.41 \) T.](image)

As can be seen in figure 4, the reduction of temperature from 40 to 5 K leads to a decrease in the \( g \)-factor absolute value by \( \Delta g \approx 0.2 \) for the thinnest barrier \( L_B = 5 \) MLs and by \( \Delta g \approx 0.1 \) for \( L_B = 7 \) MLs. For \( L_B = 9 \) or 11 MLs, the \( g \)-factor temperature dependence is practically absent.

![Figure 4. Temperature dependence of \( g \)-factor for slow component measured at different \( L_B \). \( B = 0.41 \) T.](image)

![Figure 5. Dependence of \( g \)-factor on \( L_B \) for slow component at different temperatures. \( B = 0.41 \) T.](image)

The dependences of the \( g \)-factor value on \( L_B \), measured at different temperatures (figure 5), show that at barrier thickness \( L_B \geq 9 \) MLs, the magnetic QW practically does not affect the \( g \)-factor in the nonmagnetic QW. For the fast component, \( \Delta g \) is approximately a half of that of the slow one.

Two QWs separated by a barrier having a thickness of several monolayers cannot be considered as completely isolated. The wave function of the charge carrier, having a maximum in the wide (nonmagnetic) QW, penetrates the barrier and has a non-zero density in the narrow (magnetic) QW. For this reason, the \( g \)-factor of charge carriers excited in the non-magnetic QW is affected by the manganese ions.

The presence of two components with different amplitudes, decay times and frequencies in the oscillating KR signal indicates that an excitation close to exciton resonance in the wide QW leads to
formation of two different spin complexes with nonzero average spins. As for the heavy-hole contribution to the KR signal, it should be neglected because spin relaxation time of heavy-holes is several times shorter than the period of oscillations we recorded in the external magnetic field $B = 0.41 \text{T} [3]$. 

The trion line in the PL spectrum in figure 1 indicates that the resonant photogeneration of excitons is accompanied by the formation of trions, which is possible only if there are resident charge carriers in the wide QW. Since we observed oscillations with the $g$-factor $|g| \approx 1.6$, while the heavy-hole $g$-factor in the QW plane is negligibly small [4], one could conclude that resident carriers are electrons.

Kerr rotation signal is caused by the sum of all magnetizations induced by pump pulse. At resonant excitation of excitons, their initial concentration is dominant. Therefore, we associate the fast component in the KR signal, whose amplitude exceeds the amplitude of the slow component by more than an order of magnitude (figure 2), with the relaxation of the spin magnetization of electrons bound into excitons. In a transverse magnetic field, the frequency of spin oscillations of electrons bound into excitons can be changed due to the exchange interaction with a hole. We ignore this change because it is observed only in a deeply cooled exciton gas, which is realized in narrow (thinner than 10 nm) QWs under strictly resonant excitation of the excitons, at the temperature of superfluid helium, and extremely low pump powers [5].

The formation of trions by coupling spin polarized excitons with resident electrons results in a dynamic polarization of resident electrons whose magnetization can persist during long time [6]. The characteristic decay time of the slow component reaches 1.5 ns (see figure 2), which is several orders of magnitude longer than the hole spin relaxation time. Therefore, we conclude that the slow component is formed by the precession of the magnetization of resident electrons. It is worth to note that a negatively charged trion includes two electrons with oppositely directed spins. Therefore, its spin polarization is zero, and it does not contribute to the KR signal.

As can be seen in figure 3, the absolute value of the $g$-factor of electrons bound to excitons is larger, and its change with temperature is less than those of resident electrons. Qualitatively, this can be explained by the fact that the additional localization of an electron, which is bound to an exciton, reduces the penetration of its wave function into the magnetic QW as compared to resident electron and, as a result, reduces its $g$-factor change induced by an interaction with manganese ions.

At a fixed barrier thickness $L_B$, a variation in temperature can lead to a change in the $g$-factor value due to a change in the energy gap [7, 8]. We estimate that such a change in the $g$-factor value is negligible when the temperature changes from 40 to 5 K. Therefore, the $g$-factor changes shown in figures 3–5 result from the $s$-$d$ exchange of electrons with manganese ions in magnetic well. In the phenomenological description of this effect, the expression for the electron $g$-factor is [1, 9]:

$$g = g_0 + g_{\text{exchange}}$$  (1)

where $g_0$ is the electron $g$-factor in the isolated nonmagnetic QW ($g_0 \approx -1.6$ in the 20 nm CdTe/CgMgTe QW [8]) and $g$-factor induced by the $s$-$d$ interaction is

$$g_{\text{exchange}} = (\alpha N_0) \eta x J_0 B_j \left( \frac{\mu_b g_{\text{Mn}} J_b}{k(T + T_0)} \right) \mu B.$$  (2)

Here $\alpha N_0 = 0.22 \text{ eV}$ in CdMnTe alloys, $x$ is the Mn mole fraction, $J = 5/2$ and $g_{\text{Mn}} = 2$ are the spin and $g$-factor of the Mn-ion, $B_j$ is the Brillouin function, $\mu$ is the Bohr magneton, $B$ is the external magnetic field, the effective spin $J_0(x)$ and temperature $T_0(x)$ are the parameters representing antiferromagnetic interactions between Mn ions ($J_0 = J$ and $T_0 = 0$ in the limit of noninteracting ions), and $\eta = \int \psi^2(z)dz$ (where integration is done within the magnetic QW along the structure growth axis) is a parameter characterizing an electron wave function penetration into the magnetic layer.

The sign of $g_0$ in CdTe/CgMgTe QW is negative while the $g_{\text{exchange}}$ sign is positive. Therefore, the influence of magnetic QW should lead to a decrease in the absolute value of $g$. The decrease
should be the greater, the smaller the temperature and barrier thickness $L_B$, which is fully confirmed by the experimental data given in figures 3–5.

As seen in figure 5, at the barrier thickness $L_B = 11$ MLs, $g$-factor value practically does not change with a decrease in temperature from 40 to 5 K, remaining equal $|g| \approx 1.61$. This indicates that at such barrier thickness, the coupling of the magnetic and nonmagnetic QWs becomes very small and $|g| \approx 1.61$ is the absolute value of $g_0$ in the isolated 20-nm-wide CdTe/Cd$_{0.88}$Mg$_{0.12}$Te QW.

The largest deviation of $|g|$ from $|g_0| = 1.61$ is observed at $L_B = 5$ MLs and $T = 5$ K and equals $g_{\text{exchange}} = 0.25$, as one can see in figure 5. Taking into account that $J_0 \approx 0.8J$ and $T_0 \approx 1$ K for $x = 0.02$ [10] we find that in the structure under study the penetration of the resident electron into the magnetic QW is $\eta \approx 0.6\%$. A similar analysis shows that for an electron in an exciton, $\eta \approx 0.3\%$.

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