Electron and hole spin relaxation in modulation-doped CdMnTe quantum wells

C. Camilleri, F. Teppe, D. Scalbert, and Y. G. Semenov
Groupe d'Etude des Semi-Conducteurs, UMR 5650 CNRS-Université Montpellier 2, Place Eugène Bataillon, 34095 Montpellier Cedex, France

M. Nawrocki
Institute of Experimental Physics, Warsaw University, 69 Hoża, 00-681 Warszawa, Poland

M. Dyakonov
Laboratoire de Physique Mathématique,UMR 5825 CNRS-Université Montpellier 2, Place Eugène Bataillon, 34095 Montpellier Cedex, France

J. Cibert and S. Tatarenko
Laboratoire de Spectrométrie Physique, UMR 5588 CNRS - Université Joseph-Fourier Grenoble, BP87, 38402 St Martin d'Hères Cedex, France

T. Wojtowicz
Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warszawa, Poland
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We report on the electron and hole spin relaxation times in *n*-type and *p*-type CdMnTe quantum wells with nonmagnetic barriers measured via the time-resolved magneto-optical Kerr effect in a pump-probe experiment. In addition to the decay of the Kerr effect at short pump-probe delays, we show that the hole spin relaxation time may be also estimated from a phase shift induced during the coherent rotation of the Mn spins. The variations of the spin relaxation times are studied as a function of Mn concentration, doping level, and magnetic field applied parallel to the quantum well plane. The results show that the electron spin relaxation is dominated by the exchange scattering with the Mn ions in the quantum well, and good agreement with theory is obtained provided exciton effects are included. Relatively slow hole spin relaxation is observed in the *p*-type samples (hole spin lifetime up to 32 ps) as compared to published values for similar diluted magnetic II-VI heterostructures.

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I. INTRODUCTION

During the past decade, the spin relaxation processes of electrons, holes, and excitons have been intensively studied in GaAs/GaAlAs quantum wells (QW's).[1] Indeed, the high optical and electronic qualities of these quantum structures and their very-well-known properties make them ideal candidates to explore spin-related properties. However, despite this intensive work the spin relaxation processes are still not fully understood in these structures.

Type II-VI QW's have been the focus of much less attention concerning their spin relaxation properties. However, the possibility to incorporate magnetic ions, such as manganese, opens possibilities of spin control, which, for example, have been recently used to demonstrate the spin injection from a diluted magnetic semiconductor (DMS) into a GaAs light emitting diode.[2] In this emerging field of spin-dependent electronics it becomes increasingly important to unravel the spin relaxation processes, in particular for quantum structures containing magnetic ions. Furthermore, recent progress in the growth of DMS-based QW's by molecular beam epitaxy gives great flexibility to elaborate new structures. As an example it is now possible to grow magnetic QW's sandwiched between two nonmagnetic layers. Also *n*-type and *p*-type modulation doping of these structures has been achieved, providing a two-dimensional carrier gas in a strong exchange interaction with the Mn ions confined in the same QW. In the case of *p*-type doping the exchange interaction is strong enough to induce a ferromagnetic interaction and an ordered phase at low temperatures.[3]

The electron and hole spin relaxation times were first estimated from time-resolved photoluminescence of $Cd_{1-x}Mn_xTe/Cd_{1-y}Mn_yTe$ QW's ($x<y$), in which the layer with lower Mn concentration constitutes the QW's, eventually nonmagnetic when $x=0$.[4] A comparison between the carrier spin relaxation in nonmagnetic QW's and in magnetic ones led to the conclusion that the electron spin relaxation times are insensitive to the presence of Mn ions in the QW, a rather surprising conclusion indeed since *s-d* exchange scattering should be very efficient. However, later studies have revealed that these so-called nonmagnetic QW's may exhibit magneto-optical splittings, which in some instances may be larger than those from the magnetic barriers.[5] This effect results mainly from magnetic dilution at the interface and from the fact that the magnetic susceptibility decreases as the Mn concentration becomes larger than 10%–15%. Therefore in our opinion the conclusions of these early studies must be reconsidered. More recently, Akimoto *et al.* measured electron and heavy-hole spin relaxation times in $CdTe/Cd_{0.65}Mn_{0.35}Te$ QW's by time-resolved circular dichroism.[6,7] They found a steep decrease of the electron spin relaxation time τ_e as the QW width decreases, which

TABLE I. Main characteristics of the CdMnTe QW's studied in this paper. x_{eff} is the effective Mn concentration in the QW deduced from magneto-optical splittings. The electron density is estimated from the width of the iodine doping layer and the density in a reference sample for *n*-type samples. The hole density is deduced from measurements of the Moss-Burstein shift in the *p*-type samples. T_C is the Curie temperature in *p*-type samples.

Sample	x_{eff}[%]	Carrier density [cm^{-2}]	Well width L_W[Å]	Barrier	T_C[K]
W7	0.45	$n=7\times10^{10}$	80	CdMgTe	-
W5	0.45	$n=3\times10^{10}$	80	CdMgTe	-
M890	1.6	Nominally undoped	50	CdZnMgTe	-
M921	1.7	$p=3.5\times10^{11}$	80	CdZnMgTe	2
M952	2.6	$p=3.4\times10^{11}$	80	CdZnMgTe	2.45

they related to the increase of the overlap between *s* and *d* orbitals. This is a first direct hint that exchange scattering acts efficiently to flip the electron spin. However, here again the dilution effects should be considered carefully, which makes a quantitative analysis of the QW width dependence of τ_e rather difficult because interdiffusion and segregation depend strongly on the growing conditions. In contrast to τ_e, the heavy-hole spin relaxation time τ_h was found to be insensitive to the QW width, a behavior tentatively ascribed to the competition between the quantum confinement which tends to stabilize the heavy-hole spin and the *p-d* orbital overlap which favors spin relaxation. ZnCdMnSe/ZnSe QW's have also been studied by time-resolved Faraday rotation.[8,9] In this case the QW is magnetic and the barrier nonmagnetic. It was found that incorporation of Mn ions decreases both electron and hole spin lifetimes.

The influence of doping on spin relaxation has also been studied in nonmagnetic semiconductors. It was found that *n*-type doping dramatically increases τ_e, up to 130 ns at low temperature in bulk GaAs (Ref. 10) and up to several ns in ZnSe/ZnCdSe QW's or ZnSe epilayers.[11] This quenching of electron spin relaxation was ascribed to the suppression of the electron-hole spin scattering in these *n*-doped samples.[10,11] In view of the above discussion we believe that $Cd_{1-x}Mn_xTe$ QW's with nonmagnetic barriers are better suited to investigate the role of *s-d* and *p-d* exchange scattering in the spin relaxation processes. It is also valuable to look at the possible influence of doping on the carriers spin relaxation times in these structures, because the electron-hole spin scattering constitutes another efficient channel of electron spin relaxation, as evidenced by experiments on doped nonmagnetic semiconductors.[10,11]

Hereafter we report on electron and hole spin relaxation times measured by the time-resolved magneto-optical Kerr effect (TRMOKE) in modulation-doped *p*-type CdMnTe/CdZnMgTe and *n*-type CdMnTe/CdMgTe QW's. These diluted-magnetic, modulation-doped, QW's give us the opportunity to explore the influence of both the electron-hole scattering and carrier-Mn scattering on the electron and hole spin lifetimes.

II. EXPERIMENTS

The QW's studied have low Mn concentrations to minimize the effects of the antiferromagnetic Mn-Mn interactions. We present below measurements of τ_e and τ_h performed on five QW's having different Mn concentrations and different doping levels, in order to assess the role of carrier-ion exchange and electron-hole exchange in the spin relaxation. The sample characteristics are summarized in Table I. Samples W5 and W7 have the same Mn concentration but different *n*-type doping levels, while *p*-type samples have different Mn concentrations but similar doping levels. In the *p*-type samples the carrier concentration can be changed by above-barrier illumination.

We used a pump-probe technique to time-resolve the Kerr effect, which is an effective tool to detect the electron and hole spin polarization resonantly excited by a circularly polarized pump pulse propagating in the Ox direction normal to the QW plane.[9] The resulting photoinduced birefringence produces a rotation of the linear polarization of the probe pulse which is detected using an optical bridge.[12] The pump and probe pulses were delivered by a mode-locked titanium-sapphire laser with a pulse duration of 200 fs and a repetition rate of 85 MHz. The average intensity of the pump was from a few W/cm^2 to about 30 W/cm^2 and typically 10 times larger than the probe intensity. The pump and probe photon energy was tuned into resonance with the e_1-hh_1 transition of the QW's. The samples were placed in a small superconducting split coil in superfluid helium and a magnetic field up to 2 T was applied in the O_z direction parallel to the QW plane. Sample M890 was studied in a 6 T superconducting magnet in the same configuration, but at a slightly higher temperature. The Voigt configuration is ideal to clearly distinguish the contribution of electron and hole spin polarization separately, because the electron spin precesses freely around the external field, while the heavy-hole spin is locked along the growth axis due to the lifting of *lh-hh* degeneracy by confinement and strain.

The variation of the Kerr angle $\theta_K(t)$, with pump-probe delay *t*, exhibits (Fig. 1) the corresponding damped oscillations of the electron spin plus an exponential decay related to the hole spin, as shown previously for other quantum structures.[6–9] At longer delays, oscillations with a longer period appear, which are related to the precession of Mn spins which have been initially rotated coherently by the hole exchange field.[8] The Kerr rotation at short delays is fitted with $\theta_K(t)=a_h e^{-t/\tau_h}+a_e\cos(\omega_e t)e^{-t/\tau_h}$ which yields τ_e and τ_h. The electron Larmor angular frequency ω_e may be quite

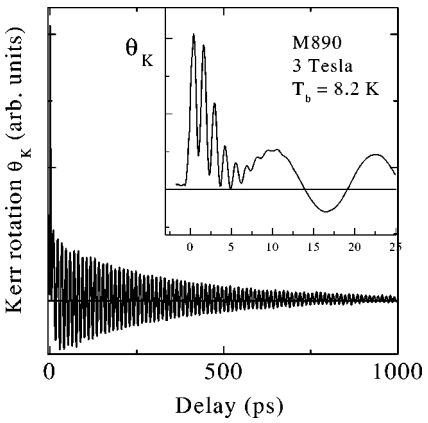

FIG. 1. Typical time-resolved magneto-optical Kerr signal measured on sample M890 with a magnetic field applied in the QW plane. The sample contains a single nominally undoped CdMnTe quantum well. The rapid oscillations visible in the expanded view of the first 25 ps of the time scan are ascribed to the electron spin precession, while the slower oscillations which last up to 1000 ps come from Mn spin oscillations.

large due to the giant splitting of the conduction band induced by the *s-d* exchange interaction, which is proportional to the magnetization. Hence, the field dependence of ω_e can be fitted with a modified Brillouin function,[13] which gives an internal thermometer of the Mn spin temperature T_s. Since in our experiments the sample was generally slightly heated by the laser pulses, when possible, we give both T_s and the helium bath temperature T_b.

III. ELECTRON SPIN RELAXATION

Figure 2(a) summarizes the values of the electron spin relaxation rates obtained on the different samples. We found little influence of the carrier density on the electron spin relaxation, both for *n*-type [compare samples W5 and W7 in Fig. 2(a)] and *p*-type samples (see Fig. 5 below). We have

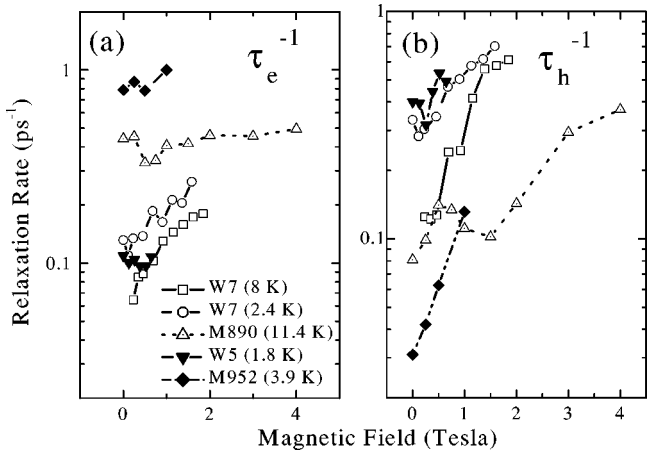

FIG. 2. Semilogarithmic plot of spin relaxation rates measured for different samples (Table I) as a function of in-plane magnetic field, for electrons (a) and holes (b). The Mn spin temperature T_s is given in each case (helium bath temperature T_b was 2.1 K, except for sample M890 where $T_b = 8.2$ K).

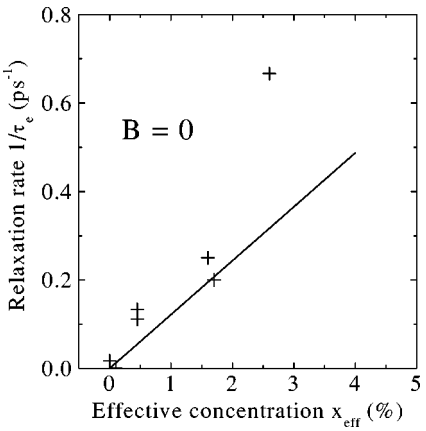

FIG. 3. Electron spin relaxation rates vs Mn effective content x_{eff} for a QW width $L_W = 80$ Å: experimental data (crosses), calculated values (solid line). The value at $x_{eff} = 0$ is taken from Ref. 24. For sample M890 the measured electron spin relaxation rate has been multiplied by a factor 5/8 to account for $L_W = 50$ Å in this sample.

also found that the electron spin relaxation times are only weakly dependent on the excitation density, except for sample W7 which exhibits longer spin relaxation times at higher excitation density. But in that case the temperature changes as well, due to laser heating, so that the variations of relaxation times cannot be ascribed unambiguously to excitation density only [compare squares and circles in Fig. 2(a)]. However, we have examined the influence of temperature on the electron spin relaxation on sample M952, and we found no noticeable variations in the range of temperatures used, 3.9–9.8 K (data not shown).

One can see in Fig. 2(a) that the electron spin relaxation tends to accelerate as the magnetic field increases. This acceleration is weak for samples M952 and M890, which have already short relaxation times in zero field, while a pronounced accelaration is evidenced for sample W7, which has longer electron spin relaxation in zero field. Similar results were obtained before in CdTe/CdMnTe QW's (Ref. 7) (long zero-field electron spin relaxation and pronounced acceleration) and in ZnMnCdSe/ZnSe QW's (Refs. 8 and 9) (short zero-field relaxation and weak acceleration). A weak acceleration of electron transverse spin relaxation, of the order of 30%, is expected theoretically when the field dependence of the magnetic fluctuations is taken into account in presence of alloy disorder.[14] However, larger variations, as observed on sample W7 or in Ref. 7, remain unexplained so far.

The possible role of *s-d* exchange scattering in electron spin relaxation is suggested by the fast increase of the relaxation rate τ_e^{-1} as the Mn concentration increases [Fig. 2(a)]. In Fig. 3 we compare τ_e^{-1} measured in zero field on the different samples with the value expected for exchange scattering process, $\tau_e^{-1} = \frac{35}{8} m^* (N_0\alpha)^2 x_{eff}/\hbar^3 L_W N_0$, assuming infinite barrier height.[15] Here $N_0\alpha = 0.22$ eV is the *s-d* exchange integral, N_0 is the number of cation sites per unit volume, and x_{eff} is the effective concentration of Mn ions contributing to the low-field magnetization. Since we are dealing with an electron bound in exciton, m^* must stand for the exciton in-plane effective mass,[16] which for neutral exci-

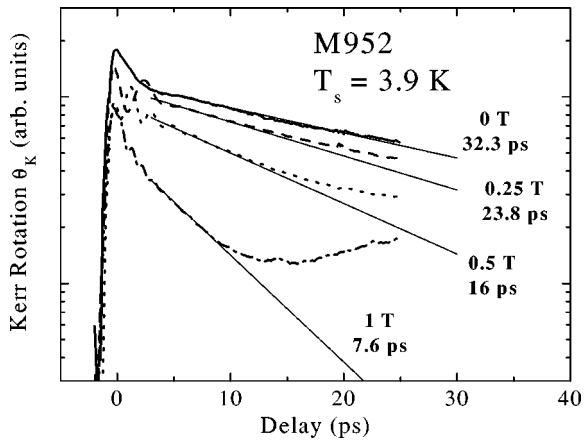

FIG. 4. Semilogarithmic plot of the TRMOKE signal measured on sample M952 for different values of the magnetic field applied parallel to the QW plane. The oscillating part of the signal at short delays is attributed to the precessing electrons, and the longer, nonoscillating, decay is ascribed to the hole polarization.

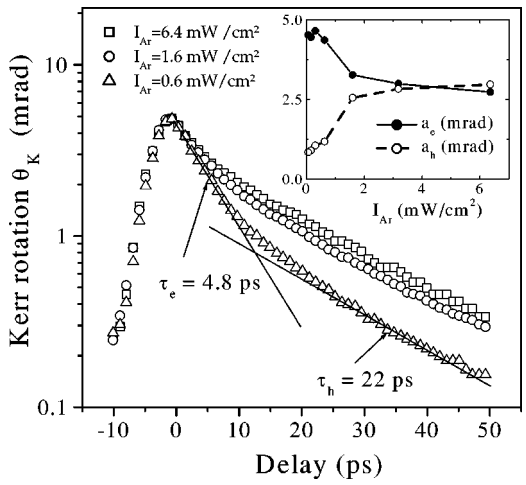

FIG. 5. Semilogarithmic plot of the TRMOKE signal measured on a *p*-doped QW (M921) in zero field and for different illumination intensities I_{Ar} above the QW barrier energy. The illumination is provided by a cw argon laser and depletes the hole concentration in the QW. The electron and hole relaxation times are practically insensitive to the illumination intensity and are indicated by arrows. The inset gives the measured weights of electron and hole contributions to the signal as a function of I_{Ar}.

tons is $m^*=m_e^*+m_h^*$ (we take $m_e^*=0.096m_0$ and $m_h^*=0.25m_0$).[17]

Considering the absence of fitting parameters we find a rather good agreement between experimental and calculated values in support of the *s-d* exchange scattering as being the main relaxation channel for the electron spin.

IV. HOLE SPIN RELAXATION

Henceforth, we focus on the hole spin relaxation. Strikingly, the hole spin relaxation time is longer in our samples having the highest Mn concentration (which are *p* type), a behavior opposite to the electron spin relaxation [Fig. 2(b)]. Here τ_h becomes even longer than τ_e in undoped or *p*-doped samples, a quite unusual result which has never been reported so far. In Fig. 4 we illustrate how τ_h was estimated for sample M952, which exhibits the longest τ_h in our series of samples. At zero field the decay of the TRMOKE is nearly a bi-exponential with two largely different time constants (about 1 and 30 ps). When an in-plane magnetic field is applied oscillations appear at very short delays, which we attribute to the precession of the electron spin, following the standard method.[9] The longer decay is thus attributed to the contribution of the hole spin polarization to the total TRMOKE, which we have fitted with a simple exponential. At longer delays and with increasing field, the signal deviates from this exponential decay due to the coherent rotation of Mn spins which starts to develop. Later on we will propose another clue to ascertain the assignment of the nonoscillating part of the signal to the hole polarization.

Unfortunately, the lack of series of samples, where only one parameter is changed at a time, is a drawback to disentangle which parameter is driving the observed trend in the hole spin relaxation. However, there exists an efficient way to deplete the hole gas in a *p*-doped QW by illuminating the sample at a photon energy above the barriers of the QW.[18] We have used this property to vary the hole concentration in sample M921. The TRMOKE signal was recorded in zero field with an additional illumination provided by a cw argon laser which photocreates carriers in the barrier (Fig. 5). The semilogarithmic plot of $\theta_K(t)$ reveals a bi-exponential decay. Again from measurements (not shown) with small in-plane magnetic field the longer decay is attributed to the decay of the hole spin polarization and the shorter decay to the decay of the electron spin polarization. Tuning the hole density leaves the spin relaxation times τ_e and τ_h practically unchanged, while the relative weight of electron and hole spin polarizations to the total signal varies rapidly, as can be seen in the inset of Fig. 5. Though not well understood so far, we believe that the change in this relative weight reflects indirectly the variation of the hole density in the QW. Therefore it seems that τ_e and τ_h are rather insensitive to the hole density in this *p*-type QW.

We recall that our *p*-type QW's have CdMgZnTe barriers, different from our *n*-type QW's, and have larger *hh-lh* splittings due to larger strains. Theoretically in QW's the heavy-hole spin relaxation by *p-d* exchange scattering is allowed only if some mixing with the light-hole subbands exists.[16] This mixing exists for *hh* states at $k\neq 0$ and may also be induced by an in-plane magnetic field. Since the admixture of *lh* states into *hh* states must be inversely proportional to the *hh-lh* splitting, longer hole spin relaxation can be expected in our *p*-doped samples where this splitting is larger.

Although such long values of τ_h were not reported before for other II-VI heterostructures containing Mn atoms, relatively slow hole spin relaxation is expected at least from a theoretical point of view.[16] Also, general trends in the spin relaxation of carriers in quantum-confined structures remain difficult to draw due to the spreading in the spin relaxation time values reported.[1] This is generally believed to result from different carrier scattering efficiencies which may be strongly sample dependent.[19] Experimentally very slow re-

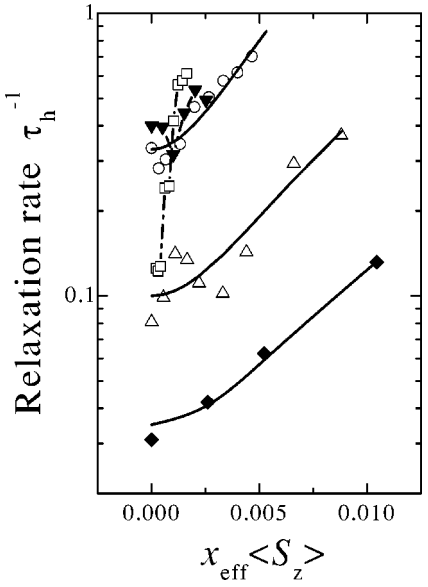

FIG. 6. Same as in Fig. 2(b) with hole spin relaxation rates plotted as a function of $x_{eff}\langle S_z\rangle$. Solid lines are fits to the data (see text).

laxation was evidenced in *n*-type modulation-doped GaAs/GaAlAs QW's, where τ_h values up to 1 ns were deduced from the decay of the photoluminescence polarization.[20–22] *N*-type doping in these structures ensures that the holes recombine with nonpolarized electrons and that the observed polarization is related to the hole spin polarization only.

We found a rapid acceleration of the hole spin relaxation with increasing in-plane magnetic field [Fig. 2(b) and Fig. 7, below] in agreement with previous studies.[7,8] This could be a consequence of the *hh-lh* mixing induced by the in-plane magnetic field already invoked by Crooker *et al.*[9] In the case of a DMS this field-induced mixing will be proportional to the exchange field, and hence to the Mn magnetization *M*. We have also to assume that some mixing exists in zero field; hence the relaxation rate will contain a constant term, plus a term proportional to M^2, and thus to $(x_{eff}\langle S_z\rangle)^2$. To check this idea it is better to plot τ_h^{-1} as a function of $x_{eff}\langle S_z\rangle$ (Fig. 6). The solid lines are fits to the experimental data with $\tau_h^{-1}=a(x_{eff}\langle S_z\rangle)^2+b$. One finds that *a* varies as *b*, as expected because both the zero-field mixing and the field-induced mixing should be inversely proportional to the *lh-hh* splitting.

Sample W7 exhibits a quite different behavior at 8 K (open squares), with a much faster increase of τ_h^{-1}. However, in this case, a rather high excitation density was used, resulting in a large difference between the helium bath temperature and the effective Mn spin temperature.

Another method for determining τ_h is based on the measurement of the phase shift of the coherent Mn spin rotation after the initial pulse. By phase shift we mean the difference between the observed phase value and the phase which could be expected for the case of an infinitely short exciting pulse. Due to the exchange field of polarized carriers, such a pulse would initially (at $t=0$) produce a *y* component of the magnetization, so that the measured value of its *x* component would change in time as $M_x(t)=M_{x0}\sin(\omega t)$. In fact, a phase shift of the Mn Larmor precession exists, which was already noticed in previous works.[7,8] In Ref. 8 this phase shift was attributed to a hypothetical time-dependent demagnetization field. In Ref. 7 numerical simulations of the Mn spin dynamics taking into account spin interactions with electrons and holes were performed, resulting in good agreement with the observed phase shifts. Such a phase shift may be understood if one takes into account the finite duration of the exchange field produced by the polarized carriers created by the excitation pulse. It has been argued that because of their rapid precession the electrons have little influence on the Mn spin dynamics,[7,8] and hence we will ignore them in the following and consider only the exchange field of the polarized holes for which free precession is not possible. We will also assume, as is the case in our experiments, that the pump pulse duration is much shorter than the hole spin relaxation time τ_h. Then the hole exchange field, directed along *x*, may be described as appearing abruptly at $t=0$ and later decaying as $\exp(-t/\tau_h)$. If we consider times that are shorter than the transverse Mn spin relaxation time T_2, the Mn spin dynamics can be described by the Bloch equations

$$\dot{\mathbf{M}}=\mathbf{M}\times(\boldsymbol{\omega}_h(t)+\boldsymbol{\omega}),$$

$$\omega_h(t)=\omega_{h0}\exp(-t/\tau_h),$$

where $\boldsymbol{\omega}$ is the external field (along *z* within the QW plane) and $\boldsymbol{\omega}_h(t)$ is the exchange field due to hole (along *x* normal to the QW plane), both expressed in units of frequency for the Mn spins (note that $\omega_h \ll \omega$). We assume that the initial magnetization $\mathcal{M}_{eq}$ is in equilibrium in the external field applied parallel to the QW plane. We are interested in the motion of **M** after the pump pulse, at delays $t \gg \tau_h$, and, more specifically, in the component M_x which is detected through the TRMOKE. For delays $t \gg \tau_h$ it is easy to obtain

$$M_x(t)=M_0\sin(\omega t+\varphi),$$

$$M_0=\mathcal{M}_{eq}\omega_{h0}(\omega^2+\tau_h^{-2})^{-1/2},$$

$$\tan(\varphi)=-\omega\tau_h.$$

This result shows that a phase shift $(-\pi/2<\varphi<0)$ occurs due to the fact that excitation of the Mn spin precession takes place over a time equal to the coherence time of the photoexcited hole spin, τ_h. In the limit case when $\omega\tau_h \ll 1$, the exchange field acts as a sudden perturbation of the Mn spin system and $\varphi=0$. For finite τ_h, the exchange field $\boldsymbol{\omega}_h(t)$ appears suddenly during the laser pulse and decays slowly in a time $\sim\tau_h$. Hence the excitation of the Mn spins is maintained for a finite time and a phase shift $\sim\omega\tau_h$ follows. For $\omega\tau_h \gg 1$, this can be viewed as an adiabatic process, where the total field $\boldsymbol{\omega}+\boldsymbol{\omega}_h(t)$ changes its direction and keeps a constant amplitude and the Mn magnetization precesses around the total field. During the adiabatic process the angle between **M** and the total field does not change. Hence after an integer number of periods and $t \gg \tau_h$ (when $\omega_h=0$) the orientation of **M** with respect to $\boldsymbol{\omega}$ is the same as its orien-

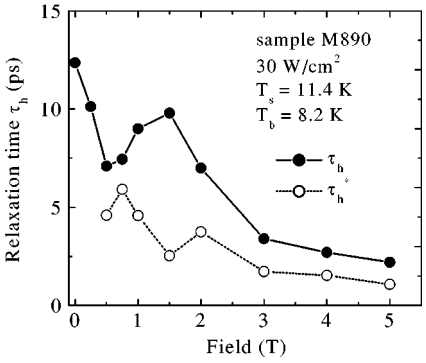

FIG. 7. Comparison between the hole spin relaxation times determined by two independent methods: τ_h obtained from the fit of $\theta_K(t)$ at short delays and τ_h^* obtained from the determination of the phase shift of Mn spin precession and the analytical expression given in the text.

tation at $t=0$ with respect to $\boldsymbol{\omega}+\boldsymbol{\omega}_h(0)$, and the normal component M_x has its maximum value: it follows that in this case $\varphi=-\pi/2$.

We will show now that, using the analytical expression above, τ_h can be deduced from precise measurements of the phase shift φ. To do that, one must determine precisely the pump-probe coincidence and take care to avoid any unphysical phase shift introduced by the response time of the detection apparatus. The method has been tested on sample M890 up to 5 T. The result is shown in Fig. 7 where we compare τ_h as obtained previously with $\tau_h^*=-\tan(\varphi)/\omega$. The overall agreement between the two methods can be considered as satisfactory, taking into account the limited accuracy of the present measurements. τ_h is found to decrease with increasing field in agreement with the previous determination. Further experiments with an improved accuracy will be necessary to conclude whether the systematically lower value of τ_h^* compared to τ_h in Fig. 7 has a physical meaning.

One should mention that an additional phase shift was predicted by Kavokin,[23] as a result of a reduction of the Mn Larmor frequency when holes are present in the QW. However, we sought for this effect unsuccessfully in our samples. Moreover, if it exists, it should increase φ and lead to an overestimated τ_h in contradiction with our results.

Contrary to our findings, in Ref. 9 an accumulation of the phase shift was observed at delays much longer than τ_h (see Fig. 14 of Ref. 9). It is worth noticing that the phase shift produced by the transient hole exchange field increases with $\omega\tau_h$, while the effect predicted in Ref. 23 disappears as $\omega\tau_h\rightarrow\infty$. Since, in Ref. 9, τ_h is significantly shorter (less than 1 ps) than in our case, Kavokin's effect could be the main source of phase shift in this situation, and therefore should persist as long as holes have not recombined.

V. CONCLUSION

In summary, we have reported measurements of electron and hole spin relaxation times in CdMnTe/Cd(Zn)MgTe modulation-doped QW's of *n* and *p* type by using the time-resolved magneto-optical Kerr effect. The obtained results indicate that the electron and hole spin lifetimes are practically insensitive to the carrier densities in the QW's. The electron spin lifetime τ_e shortens as the Mn content increases in the QW's, confirming the predominant role of electron-Mn exchange scattering in the spin relaxation. We found good agreement between experimental and theoretical electron spin relaxation times, provided the acceleration of the electron spin flip by the electron-hole correlation in the bound exciton state is taken into account, as originally suggested in Ref. 16. The hole spin exhibits an opposite behavior not understood so far. The samples with long hole spin relaxation times are of *p* type and have CdMgZnTe barriers. QW's with CdMgZnTe barriers have strains larger than QW's with CdMgTe barriers and, therefore, larger *hh-lh* splittings. This could contribute to the longer hole spin relaxation in these structures. Clearly more systematic measurements on a series of specially designed QW's will be required to assess the hole spin dynamics in these magnetic quantum wells. The significance of the hole spin lifetime measurements has been confirmed by an independent method based on the existence of a phase shift in the Mn spin rotation. We have derived a simple analytical expression which relates the phase shift to the hole spin relaxation time.

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