Softening of spin resonance at low temperature in *p*-doped $Cd_{1-x}Mn_xTe$ quantum wells

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Time-domain spin resonances in *p*-doped CdMnTe quantum wells have been studied via time-resolved magneto-optical Kerr rotation. The resonances related to quantum well electrons Mn and electrons excited in the substrate are identified. An additional spin resonance which shows an unusual temperature dependence is detected in one of the samples. The corresponding frequency tends to zero when approaching the Curie temperature. This "soft" spin precession mode has been studied as a function of magnetic field, temperature, magnetic field orientation, and optical excitation density. Its origin is discussed in the framework of the existing collective spin excitation model.

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I. INTRODUCTION

There is currently a renewed interest for diluted magnetic semiconductors (DMS), motivated by the possibility of making them ferromagnetic by *p*-type doping and use for the information storage and processing. In these materials the ferromagnetic interactions between magnetic ions are mediated by holes, and the Curie temperature T_C is expected to be higher in compounds with light anions, where the *p-d* exchange interaction is stronger, while the spin-orbit interaction is weaker.[1] In II-VI compounds T_C appears to be limited to few Kelvin,[2,3] while it is above 100 K in GaMnAs,[4] and is predicted to exceed room temperature in GaMnN and ZnMnO.[5] Although the major features of carrier induced ferromagnetism in these compounds can be described in the framework of the Zener model, a detailed knowledge of the dynamics of the spin excitations is still lacking.

In this context doped DMS nanostructures are of outstanding interest because the concentrations of carriers (either electrons or holes) and magnetic ions can be varied independently, in various quantum confined geometries. It opens a wide range of opportunities to explore the coupling between free carrier and localized spin excitations. In particular, the electrical manipulation of magnetization has been demonstrated in ferromagnetic DMS quantum wells.[6]

Even in paramagnetic systems the spin excitations have a collective character. This is suggested by spin-flip Raman scattering and electrically detected electron paramagnetic resonance studies of *n*-doped CdMnTe quantum wells.[7] The theory of collective spin excitations in doped DMS quantum wells, developed to explain these results, also shed some light on the physics of ferromagnetism in doped DMS.[8] However the issue of collective spin excitations in *p*-doped DMS quantum wells remains open. In particular, it is predicted theoretically that the hole spin anisotropy in quantum wells should affect the dynamics of the heavy holes-magnetic ions coupled spin system in a dramatic way, leading to a softening of the magnetic resonance near the ferromagnetic transition.[9] In a preliminary work we have reported on the observation of a similar softening of spin resonance in a *p*-type CdMnTe quantum well.[10]

In the present paper we complete the experimental findings and the interpretation of the "soft" spin resonance proposed in Ref. 10. The next section describes the experimental setup and the characteristics of the samples. Section III contains an overview of the experimental results. Finally, in Sec. IV we consider the possible origins of the temperature dependent spin resonance, namely, "softening" in the vicinity of the ferromagnetic phase transition due to Mn-hole coupling and temperature dependent effective fields.

II. EXPERIMENTAL SETUP AND SAMPLES

Kerr rotation is a phenomenon by which the linear polarization of the light reflected from the magnetized media is rotated by an angle proportional to the magnetization component along the light propagation direction. In the pump-probe experiments exploiting this phenomenon, the magnetization is created optically by the circularly polarized pump pulse, while the probe pulse polarization after reflection is sensitive to the pump-induced spin of the photoexcited carriers and any perturbation of the magnetic ion spin system. In practice, one measures the angle by which the polarization of

TABLE I. Relevant characteristics of the samples used in this study: x_{eff} is Mn effective concentration and T_C is the Curie temperature. Samples M921a and M921b are two pieces of the same wafer.

Sample	x_{eff}	Hole density $[\mathrm{cm}^{-2}]$	T_C [K]
M921a,b	1.7	3.5×10^{11}	1.5
M952	2.6	3.4×10^{11}	2.4

the probe pulse is rotated after the reflection from the sample, which is proportional to the projection of the spin polarization vector on the probe beam propagation direction. By changing the delay between two pulses we monitor the spin dynamics with subpicosecond resolution. In the experiments discussed below, the magnetic field is applied in the plane of the sample and thus it induces the Zeeman splitting of the spin levels in the plane. Because the photoinduced spin polarization has a component in the light propagation direction, it precesses around the magnetic field with the Larmor frequency, which is proportional to the spin splitting. This precession shows up in the Kerr rotation signal as oscillations at the same frequency. Therefore one can speak about the spin resonance detection in the time domain.

In our experimental setup the 80–100 fs pulses are delivered by a titanium-sapphire laser at a 82 MHz repetition rate. The pump and probe beams are focused on the sample with the same 25 cm focal lens producing a spot of about 300 μm diameter, with an angle between pump and probe about 4 deg. The total power incident on the sample is varied between 10 and 60 $\mathrm{W/cm^2}$. In order to reduce heating of the sample by optical excitation, while keeping a good enough signal-to-noise ratio, a 2:1 pump-probe power ratio is kept throughout this work. We checked however that the results are not affected by this particular choice. The modulation scheme includes both helicity and intensity modulation. The helicity of the pump beam is modulated between left and right circular polarizations at 50 kHz using elasto-optical modulator, while both pump and probe intensities are modulated with a double-blade chopper. The probe beam reflected by the sample is directed onto a balanced optical bridge which yields an electrical signal proportional to the pump-induced Kerr rotation angle. The magnetic field up to 6 T is created by a superconductive split coil, while the samples are in the variable temperature cryostat (1.8–180 K).

All the samples under study contain a single CdMnTe quantum well (QW) modulation doped with nitrogen providing a hole density in the QW about $3.5\times10^{11}\ \mathrm{cm}^{-2}$, as deduced from the Moss-Burstein shift, and exhibit a ferromagnetic ordering at low temperature. The characteristics of the samples are summarized in Table I.

III. EXPERIMENTAL RESULTS

In Fig. 1(a) the Kerr rotation angle as a function of the time delay between pump and probe in the M921a sample is shown for four different temperatures. The magnetic field of 2 T is applied in the QW plane and the laser photon energy is

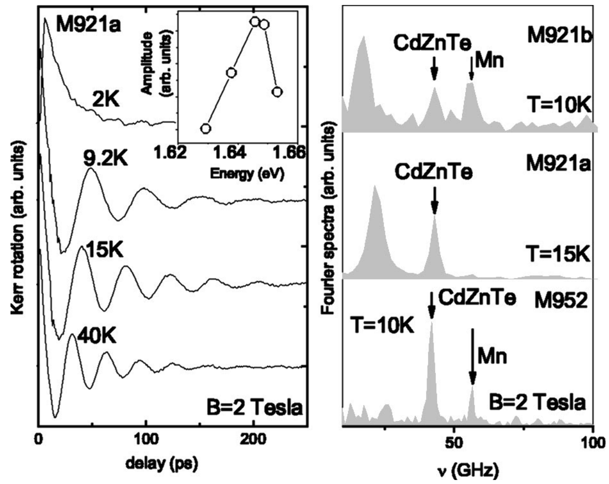

FIG. 1. (a) Time-resolved Kerr rotation in the M921a sample detected for different temperatures, photon energy 1.655 eV. The slowing down of the oscillations is apparent. The variation of the signal amplitude versus photon energy (inset) indicate the signal is related to the QW. (b) Fourier spectra in the low frequency domain obtained for the three samples at $T=10$ K (M921a, M952) and $T=15$ K (M921b), excitation at 1.638 eV. The two temperature independent resonances (Mn ions and substrate electrons) and the "soft" temperature dependent mode can be distinguished.

tuned at 1.655 eV, that is close to the heavy hole-electron optical transition. The oscillations in the signal show up, which slow down when the temperature decreases. Therefore, these results suggest the presence of the spin resonance at a frequency decreasing with the temperature. This phenomenon is the central problem addressed in this work and will be referred to as the softening of the spin resonance. Note, that the QW origin of this resonance is corroborated by the dependence of the signal amplitude on the excitation energy, as shown in Fig. 1(a), inset. It reaches its maximum value in the vicinity of the transition between lowest heavy hole and electron subbands in the QW.

However, the "soft" oscillation mode is not the only one which shows up in our structures. Figure 1(b) illustrates the variety of the resonances detected in the three samples under study at excitation energy 1.638 eV and magnetic field of 2 T. First of all the common feature of these Fourier spectra is the spin resonance related to the CdZnTe substrate. In reflection geometry the spin oriented electrons created in the substrate may also contribute to the signal. They give rise to the peak denoted "CdZnTe" in Fig. 1(b). Its field and temperature dependence is discussed in Ref. 10. The corresponding g factor of conduction band electrons in CdZnTe is found to be about 1.45. Note, that in the vicinity of the QW transition the substrate is absorbing, which inhibits the experiments in transmission geometry. The second spectral feature typical for CdMnTe QWs is the Mn spin precession with a temperature independent g factor equal to 2. It is clearly resolved in the M921b and M951 samples while it seems to be completely suppressed in M921a. The lowest frequency feature appears exclusively in M921a and b samples, this is the manifestation of the "soft" mode, which is discussed in details below. It changes the spectral position with the tem-

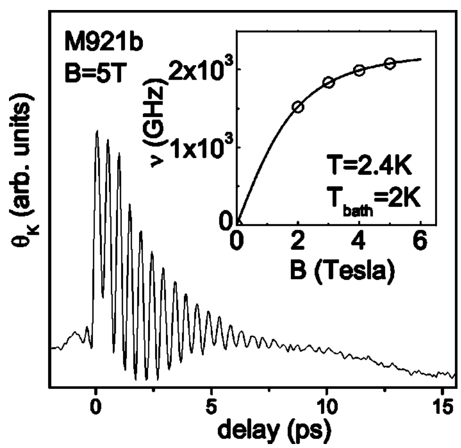

FIG. 2. Kerr rotation in M921b at short delays, $B=5$ T. The rapid oscillations are related to the precession of the electrons in Mn exchange potential. Inset: The precession frequency versus magnetic field (open circles) is fitted with a modified Brillouin function at 2.4 K for lattice temperature (solid line).

perature (see, e.g., the two upmost panels in Fig. 1(b) at 10 and 15 K).

In addition, at terahertz frequencies corresponding to the exchange splitting of the conduction band the precession of the electron spins is detected in M921b and M952 samples. An example of the Kerr rotation curve in the presence of the terahertz electron precession is shown in Fig. 2. One can see that fast oscillations resulting from the precession of the electron spins in the in-plane magnetic field are superimposed with slow modulation due to Mn polarization, "soft" mode, and substrate electrons. The inset shows the electron spin resonance frequency as a function of the applied magnetic field. Since this frequency is proportional to the magnetization, its modified Brillouin function fit[11] provides a measure of the Mn spin temperature which is supposed to coincide with the lattice temperature in these experiments (solid line in Fig. 2, inset). It allows us to quantify the additional heating of the sample induced by the laser pulses, which is about 0.4 K at 10 W/cm^2 excitation density, while the helium bath temperature is kept at 2 K.

Figures 3 and 4 summarize the magnetic field and temperature dependance of the "soft" mode in M921a. The basic features of the "soft" mode behavior in the M921b sample are essentially the same. One can see (Fig. 3), that at fixed temperature the variation of the frequency ν with the magnetic field appears to be almost linear, except at temperatures below 15 K, while the slope depends on the temperature. Therefore, it is convenient to define an effective g factor as the low-field slope of the frequency dependence on the magnetic field. The result is shown in Fig. 4, where the effective g factor of the "soft" mode is plotted together with substrate electrons g factor. It appears clearly that in CdZnTe the g factor remains basically unchanged in the explored temperature range, while for the "soft" mode we observe the rapid decrease below 50 K, which reflects the slowing down of the spin precession. We note, however, that at high temperature the g factors (and hence frequencies) of the "soft" mode and substrate mode are very close, and the "soft" mode weakens which makes its frequency determination rather vague.

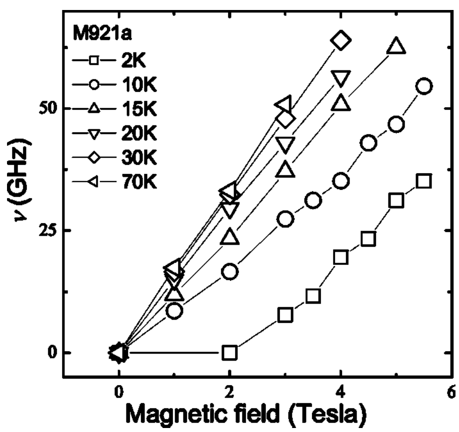

FIG. 3. "Soft" mode frequency as a function of magnetic field intensity and temperature in the sample M921a.

It is known that the interaction between Mn ions and the hole gas can be tuned by changing the susceptibility of the hole gas. Therefore to get insight into the role of the hole gas in the "soft" mode behavior one can saturate the hole polarization by the out-of-plane magnetic field. Since the experiments are performed in reflection geometry we consider two configurations: the plane of the sample oriented parallel (Voigt configuration used throughout this work) and at 45 deg with respect to the field (see Fig. 5, inset). The corresponding positions of the "soft" resonance detected in the M921b sample are compared in Fig. 5. These data indicate that within experimental accuracy the frequency of the soft mode does not change between the two configurations, suggesting an isotropic g factor of the "soft" mode.

An alternative way to modify the hole susceptibility consists in a cw illumination above the barrier of the QW. It is expected to partly deplete the hole gas in these structures.[12] However up to 0.8 W/cm^2 of cw illumination at 514 nm the "soft" resonance frequency appears to be constant. Overall, these results suggest that the frequency of the resonance under consideration does not depend on the hole gas susceptibility.

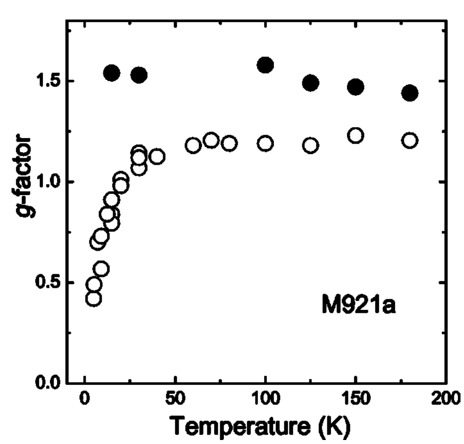

FIG. 4. Effective g factor versus temperature measured in the M921a sample. Open symbols correspond to the "soft" mode and were deduced from Fig. 3 (see text), close symbols correspond to electron spin resonance coming from the CdZnTe substrate.

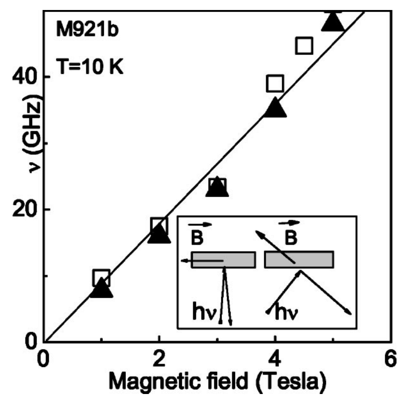

FIG. 5. Comparison between the "soft" mode frequencies measured under magnetic field in the plane of the QW (open symbols) and at 45 deg (close symbols). The inset illustrates the corresponding experimental configurations.

Finally, we examine the excitation power density effect. An increase of excitation density shifts the "soft" mode to higher frequency, which merely reflects the heating of the sample by the laser pulses. The effect is most dramatic at low temperature where the effective g factor varies rapidly (see Fig. 4). At $T=2$ K and $B=2.5$ T an increase of excitation density from 10 to 60 W/cm^2 raises the lattice temperature up to 4 K which corresponds to the resonance shift from 7 to 17 GHz.

IV. DISCUSSION

In a nonmagnetic semiconductor subjected to an external magnetic field the electron spin precession frequency varies only slightly with the temperature, essentially due to the temperature dependence of the band parameters which determine the conduction band g factor. Hereafter we discuss the possible origins of the observed strong temperature dependence of the spin resonance in our samples.

In general, the strong temperature dependence of a spin resonance frequency in solids may be related either to the presence of (i) internal effective fields rapidly varying with temperature,[13] or (ii) to the softening of a collective spin excitation mode near a phase transition.[9] The effective fields may result from spin polarized carriers, magnetic ions, or nuclear spins (Overhauser shift) which shift the frequency of the electrons, nuclei (Knight shift) or magnetic ions spin resonances. The nuclear spin resonance, however, is known to be situated in megahertz frequency domain, and therefore does not appear in the investigated frequency range. Thus we can restrict the following discussion to the spin excitations of electrons and magnetic ions. We check first the possible explanations of the slowing down of the spin precession based on the existence of effective fields in our system (Sec. IV A). In the Sec. IV B, we propose the phenomenological description of the Mn-heavy hole collective precession "softening" in the vicinity of the ferromagnetic phase transition[9] and then analyze the experimental results in the framework of this theory.

A. Effective fields

Dynamical polarization of nuclei results from the unbalanced spin flips between spin polarized electrons and nuclear spins, when the electrons tend to recover the equilibrium spin distribution. In our structures, the effective nuclear field which would shift the electron spin resonance may by created by the spin oriented electrons either in the CdZnTe substrate or in the magnetic well. Indeed, recent works showed that spin oriented electrons can diffuse across the interface without loosing their spin orientation.[14] Moreover, strong nuclear spin polarization in optical pumping of hybrid magnetic/nonmagnetic semiconductor heterostructures suggest possible spin polarization transfer between the magnetic and nonmagnetic layers.[15,16] Such phenomenon is called proximity effect. However, the nuclear field necessary to account for the observed precession frequencies easily exceeds 1 T. Indeed, in Fig. 3 one can see that at $T=2$ K and $B=2$ T the spin resonance is suppressed ($\nu=0$), indicating that the corresponding effective field should be at least as high as the external field. This value is at least one order of magnitude larger than the estimated value of the nuclear field at saturation in CdTe.[17] Hence, we conclude that effective nuclear field is not sufficient to account for the frequency shifts that we observe.

As concerns the exchange fields which control the interaction between magnetic ions and carriers in the CdMnTe quantum well, we note that their temperature dependence is inverted with respect to our experimental findings. Namely, the effective field created by magnetic ions (see Fig. 2) increases when the temperature decreases. Since at low temperatures this field is much stronger than the external field, it tends to shift electron and eventually hole spin resonances towards higher frequencies when the temperature decreases, which is in contrast with our results. Finally, the carrier exchange field acting on Mn spins is likely to shift the Mn spin resonance line, an effect similar to the Knight shift in nuclear magnetic resonance. This shift has been detected in the case of IV-VI DMS (Ref. 18) and was estimated theoretically in the case of n-doped II-VI DMS.[19] In p-doped CdMnTe quantum wells the exchange field created by fully polarized hole spins is about 0.1 T, which is far too small to account for the shifts observed here.

B. Softening of the spin resonance

In what precedes it is assumed that the carrier spin polarization creates a static mean-field which simply adds to the external field. However under resonant conditions one must consider the dynamical coupling between carriers and magnetic ions spins. In this situation an anticrossing between Mn and two-dimensional (2D) electron gas spin flip excitations gives rise to an important shift of the Mn spin resonance.[7] In our samples the CdMnTe QWs are p doped and such resonant interaction is not possible since the hole spin cannot precess. Instead, the Mn spin precession is damped at low temperatures due to interaction with holes. This "softening" of the spin resonance is considered theoretically in Ref. 9.

Here we propose a physically transparent phenomenological description of the dynamics of the coupled spins in DMS quantum well. The approach is based on the Bloch equations and addresses the magnetic ions interaction with 2D heavy hole gas. Basically it is equivalent to the mean-field theory proposed in Ref. 9. It allows a straightforward introduction of the hole spin relaxation time which is shown to be comparable with Mn Larmor precession period, while in Ref. 9 the relaxation is supposed to be instantaneous.

Assuming uniform evolution of the spin system ($k=0$ spin wave) the Bloch equation for the Mn spin magnetization $\vec{M}$ in the presence of an external magnetic field $\vec{B}_0$ applied along x axis in the plane of the quantum well and coupled to the 2D hole gas reads

$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times [\vec{B}_0 + \vec{B}_h(t)], \tag{1}$$

where γ is the gyromagnetic ratio and $\vec{B}_h$ the exchange field created by the holes. For simplicity we have neglected the damping of the Mn spin precession. The hole exchange field $\vec{B}_h$ is related to the heavy-hole gas magnetization $\vec{m}(t)$ through

$$\vec{B}_h(t) = \frac{\beta}{g_h g_{\mathrm{Mn}}\mu_B} m(t)\vec{e}_z = \lambda m(t)\vec{e}_z, \tag{2}$$

where β stands for the p-d exchange integral, g_h is the heavy-hole g factor in the QW growth direction z, $g_{\mathrm{Mn}}=2$ is the Mn g factor and $\vec{e}_z$ is the unit vector along z. This equation accounts for the fact that due to quantum confinement heavy hole spin is frozen in the growth direction or, equivalently, its in-plane g factor is vanishing,[20] which imply the in-plane magnetization equal to zero. Conversely, the holes get spin polarized in the field created by the magnetic ions $B^z_{\mathrm{Mn}}(t)=\lambda M^z(t)$ according to

$$m(t) = \int \chi_p(t-t')dt' B^z_{\mathrm{Mn}}(t'). \tag{3}$$

Here we are only concerned by the z component of the Mn field vector B^z_{Mn}, since it is the only one which can affect the hole spin polarization. $\chi_p(t)$ represents the time-dependent Pauli susceptibility of the hole spins which accounts for noninstantaneous hole spin relaxation. It depends on the static susceptibility χ_0 and longitudinal hole spin relaxation time τ_h as $\chi_p(t)=\chi_0/\tau_h\Theta(t)\exp(-t/\tau_h)$, where $\Theta(t)$ is the Heaviside function. Note, however, that in small (exchange) fields arising from the small oscillations of Mn magnetization around the external field the difference between longitudinal and transverse relaxation times vanishes. Because we are interested in the eigenfrequencies of the system it is convenient to rewrite the susceptibility in the frequency space. We get

$$\chi_p(\omega) = \chi_0/(1 + i\omega\tau_h). \tag{4}$$

The above equations describe the temporal evolution of the coupled Mn spin magnetization and two-dimensional heavy hole gas in the presence of external magnetic field $\vec{B}_0$. Let us assume that M_x is constant, that is, the small oscillations of the magnetization around the external field $\vec{B}_0$ are considered. In this case, the eigenfrequency ω of the coupled spin system oscillating near its stationary state reads

$$\omega = \omega_0[1 - \zeta(\omega)]^{1/2}, \tag{5}$$

where $\omega_0=\gamma B_0$ is the Larmor frequency of the uncoupled magnetization. The dimensionless parameter

$$\zeta(\omega) = \lambda^2\chi_{\mathrm{Mn}}\chi_p(\omega) \tag{6}$$

is formally the same as ζ introduced in Ref. 9. The same parameter enters in the calculation of the ferromagnetic transition.[21] This is easily shown by writing down the static equations for coupled Mn and hole magnetization

$$M_z = \chi_{\mathrm{Mn}}(B_z + \lambda m_z), \tag{7}$$

$$m_z = \chi_p(0)(B_z + \lambda M_z) \simeq \chi_p(0)\lambda M_z, \tag{8}$$

from which one gets

$$M_z = \frac{\chi_{\mathrm{Mn}}}{1 - \lambda^2\chi_{\mathrm{Mn}}\chi_p(0)} \quad B_z = \frac{\chi_{\mathrm{Mn}}}{1 - \zeta(0)} B_z. \tag{9}$$

The ferromagnetic phase transition occurs when M_z diverges, i.e., for $\zeta(0)=1$. For the sake of clarity in what precedes we have neglected the z dependence of the hole spin density. In a more realistic calculation a factor $W=L\int|\psi(z)|^4dz$, where $\psi(z)$ is the hole envelope function and L the quantum well width, appears in the expression of ζ.[9] Now, more generally than in Ref. 9, ζ is now a complex parameter and thus the eigenfrequency ω has a nonzero imaginary part, which is responsible for the damping of the precession due to the non-instantaneous response of the hole spin. The factor $(1-\zeta)$ is thus responsible for the slowing down of the precession near the phase transition, while far above the transition one recovers $\omega=\omega_0$. This is the softening of the spin resonance.[9] In the limit $\tau_h\to 0$, Eq. (5) is equivalent to Eq. (8) in Ref. 9. In the opposite limit $\tau_h\to\infty$ the softening disappears, i.e., $\omega\to\omega_0$. In other words, the shorter the spin relaxation time is, the stronger the hole spin polarization couples to the Mn magnetization.

The p-type DMS QW excited by the circularly polarized light pulses in Voigt configuration is exactly the system in which the soft mode can show up. Indeed, in this case Mn spins are brought out of their parallel to the in-plane field equilibrium orientation by the exchange field produced in the growth direction by the photo-excited holes.[22–24] Therefore we can tentatively interpret the slowing of the precession in our samples as the "softening" of the Mn spin resonance. It appears, however, that at low temperatures the behavior of the two samples (M921a and b) meets only partly this model, while the high temperature limit remains poorly understood.

Since in the M921 sample the hole spin relaxation time was estimated to be about 20 ps at the zero field and is known to decrease rapidly with increasing magnetic field,[24] we assume $\omega\tau_h \ll 1$ in Eq. (5). In that case the effective g factor for the soft mode above the Curie temperature reads

$$g(T) = g_\infty[1 - \zeta(T)]^{1/2}. \tag{10}$$

In the framework of the model used $g_\infty=g_{\mathrm{Mn}}$. The temperature dependence of ζ is mainly due to magnetic susceptibility, which follows a Curie-Weiss law $\chi\propto(T-\theta)^{-1}$ where θ is the Curie-Weiss temperature of the system of the Mn ions.

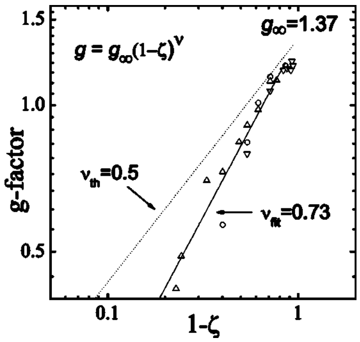

FIG. 6. Logarithmic scale plot of the soft mode effective g factor as a function of $1-\zeta$ (see text). Open symbols represent the experimental data, solid line is the best power law fit ($\nu=0.73$), dotted line corresponds to the slope $\nu=0.5$, predicted theoretically.

Note that this temperature is negative due to antiferromagnetic Mn—Mn interactions. Thus, one may write $\zeta=(T_C-\theta)/(T-\theta)$ where the numerator is fixed by the condition $\zeta=1$ at the transition point. Strictly speaking this expression is valid as far as the Pauli susceptibility of the hole gas can be considered independent of the temperature. This condition is fulfilled at temperatures lower than the Fermi temperature, that is below 70 K in our samples. An estimation of θ using the relation $\theta=-8xS(S+1)J_1/k_B$, with the nearest-neighbor exchange integral $J_1=6.9$ K (Ref. 25) yields $\theta\approx-10$ K. The Curie temperature value in CdMnTe $T_C=1.5$ K was obtained from the photoluminescence experiments.[26] It is the temperature at which a zero-field splitting of the photoluminescence line appears. For the above given values of T_C and θ we plot in a logarithmic scale the variation of the g factor as a function of $1-\zeta$, in order to check the power law dependence predicted by the theory. One can see (Fig. 6), that the g factor obeys a power law but with a slope slightly steeper than 0.5. The experimental data are best fitted with $g(\zeta)=g_\infty(1-\zeta)^\nu$ leaving g_∞ and ν as free parameters. We get $g_\infty=1.37$ and $\nu=0.73$. Alternatively, taking θ as a free parameter and fixing $\nu=0.5$ yields $\theta=-20$ K while g_∞ remains close to 1.4. A more realistic treatment should take into account the deviation of χ_{Mn} from the Curie-Weiss law at temperatures $T<\theta$, but such refinement seems superfluous at this stage owing to the obvious disagreements between theory and experiments discussed below.

The value of $g_\infty=1.4$ disagrees with the model which in the high temperature limit yields the value of $g_\infty=2$ corresponding to the free precession of Mn spins not coupled to the holes. It could however be attributed to the uncertainties in the identification of the soft mode frequency at high temperatures, where the signal becomes weaker (roughly speaking it decreases as the magnetic susceptibility), and approaches the spin resonance related with the substrate.

Another experimental result, which makes difficult the interpretation of the spin resonance temperature dependence in the framework of the coupled Mn and hole precession, is the behavior under oblique magnetic field. Namely, the theory inhibits the Mn-hole spin coupling if the hole gas is fully polarized, since in this case the Pauli susceptibility vanishes. This condition is fulfilled either in the magnetically ordered phase, or above T_C under a sufficiently strong magnetic field out of the plane of the sample. In the latter case the hole gas gets fully polarized, that is $p=\Delta_{hh}\rho$, where p is the hole density, Δ_{hh} is the spin splitting of the heavy-hole subband, and ρ is the 2D density of states per spin. Thus, at $T=10$ K in the field $B>1.5$ T oriented at 45 deg with respect to the growth axis (see Fig. 5) the resonance is expected to keep its high temperature position. However, no effect related to the saturation of polarization was observed. Additionally, in the in-plane magnetic field a resonance associated with free Mn spin precession shows up in the M921b sample This is an indication that at least a part of magnetic ion spins do not interact with the hole gas. Finally in the sample M952 despite the relatively slow hole spin relaxation (about 30 ps in zero field and at 3.9 K,[24] an estimation based on Eq. (3) predicts a reduction of the precession frequency of about 20%, which is not observed.

Overall, although the theory of the spin resonance softening is the only one able to reproduce qualitatively the observed temperature dependence of the g factor, it fails to account for the inefficiency of the hole gas polarization to suppress the softening. The fact that the temperature dependent resonance was observed either alone (M921a), or together with the free (uncoupled) Mn spin precession mode (M921b) suggests that the origin of the “soft” mode may be related to the Mn spins in a more intricate way.

In conclusion, we have observed a temperature dependent spin resonance in the sample containing p-doped CdMnTe QW. The slowing down of the precession at the temperatures close to the ferromagnetic phase transition was detected via time-resolved magnet-optical Kerr rotation. The corresponding precession mode was clearly distinguished from the other spin resonances in the QW (electrons, uncoupled magnetic ions) and electrons in the substrate. The unusual temperature behavior of this resonance could not be fully understood in the framework of the existing models. Nevertheless, the experimental results meet the predicted behavior for the collective mode of the 2D hole gas coupled to the Mn spins in the vicinity of the magnetic phase transition, for which we propose a simple phenomenological description. To get deeper insight in the physical origin of the observed “soft” mode further experimental and theoretical work is necessary.

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