Acceleration of the spin-lattice relaxation in diluted magnetic quantum wells in the presence of a two-dimensional electron gas

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Dynamics of spin-lattice relaxation of magnetic Mn ions in semimagnetic $Cd_{0.99}Mn_{0.01}Te/Cd_{0.76}Mg_{0.24}Te$ quantum wells containing two-dimensional electron gas (2DEG) has been studied by means of an optical detection of injected nonequilibrium phonons. It is found that the spin-lattice relaxation rate is an increasing function of electron concentration and electron temperature. The 2DEG provides an effective channel for the energy transfer from magnetic ions to the lattice. A model accounting for the spin-flip transitions between Mn ions and free electrons describes well our experimental results in a qualitative manner.

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Principles and basic issues of a future spin electronics are discussed nowadays widely. Different possible concepts for the design of electronic devices using spins of the carriers for computation (instead of their charges exploited in conventional electronics) are under consideration. Diluted magnetic semiconductor (DMS) materials combine typical semiconductor electronic properties with a strong enhancement of spin-dependent phenomena. The latter originated in the exchange interaction of the free carriers with localized magnetic moments of magnetic ions. DMS heterostructures offer the unique opportunity of manipulation of the carrier spins and, therefore, are very attractive as model systems.

It was demonstrated very recently that a layer of II-VI DMS, deposited on top of a GaAs-based *n-i-p* light-emitting diode, serves as an effective injector of spin-polarized carriers.[1] A prerequisite for such structures relying on electrical spin injection is the presence of free carriers achieved by doping of the DMS layer. However, the experimental information on the influence of doping and of free carriers on the dynamical magnetic properties of wide-gap DMS's [e.g., (Cd, Mn)Te or (Zn, Mn)Se] is very limited. It is known for metals with magnetic impurities that the free carriers play an important role for spin-lattice relaxation and for energy transfer away from magnetic ions.[2] The Korringa effect and the Knight shift are examples of the effects caused by such interaction. Similar effects have been reported for bulk narrow-gap DMS's with a high concentration of free carriers.[3] However, a study of these phenomena has not been extended, to our knowledge, to wide-gap DMS's. One can expect that the energy and spin transfer between the systems of the carriers, magnetic ions and phonons (i.e., the lattice) can be modified significantly by the presence of a background of free carriers. One should also expect strong modifications in the case of low-dimensional electron systems realized in quantum wells, wires and dots, as the density of states in nanostructures differs qualitatively from that of the three-dimensional (3D) system.

It was reported recently that in (Cd, Mn)Te-based quantum wells (QW's) the magnetic-ion system can be substantially overheated by means of the interaction with hot photocarriers that is enhanced by the presence of a two-dimensional electron gas (2DEG).[4] This result shows that the interaction of magnetic ions with 2DEG is quite strong and that the modification of their spin dynamics might be very significant. In the present paper we explore questions how dynamic magnetic properties of DMS QW's, namely the spin-lattice relaxation (SLR) rate of magnetic ions, are modified by the presence of 2DEG, and how this rate depends on the electron density, electron temperature, and magnetic-field strength.

The investigated samples containing 80-Å-thick $Cd_{0.99}Mn_{0.01}Te/Cd_{0.76}Mg_{0.24}Te$ QW's were grown by molecular-beam epitaxy on (100) GaAs substrates. One structure is nominally undoped and contains 2DEG with the density of $n_e = 6\times10^9\,cm^{-2}$ provided by residual impurities. The remaining structures are modulation doped in the barrier layer and contain up to $1.6\times10^{11}\,cm^{-2}$ electrons. Details of the growth procedure and of optical properties are published in Refs. 4–6. The samples were mounted inside a superconducting magnet in the Faraday configuration and immersed in liquid helium ($T = 1.6\,K$). Photoluminescence (PL) was excited by the 514.5 nm line of an Ar-ion laser. The density of 2DEG in the QW's was evaluated from the optical spectra on the basis of the oscillator strength of negatively charged exciton transition and on its polarization properties (details of the method are published in Ref. 7).

The experimental technique that we use here to measure SLR rate combines an injection of nonequilibrium phonons into the sample followed by an optical detection of the induced changes via the exciton photoluminescence.[8–10] Nonequilibrium phonons were generated by a heat-pulse technique. A phonon generator (a 10-nm-thick constantan film) with an area $0.5\times0.25\,mm^2$ was evaporated on the narrow edge of the GaAs substrate and was heated by current pulses of duration ranging from 0.1 to 1 μs at a repetition rate varied from 1 kHz to 5 kHz. The pulse-power density P_h was varied from 25 to 250 W/mm^2. The phonons from the generator propagate through the GaAs substrate, reaching the $Cd_{0.99}Mn_{0.01}Te$ QW's and heating there the Mn ions. In the

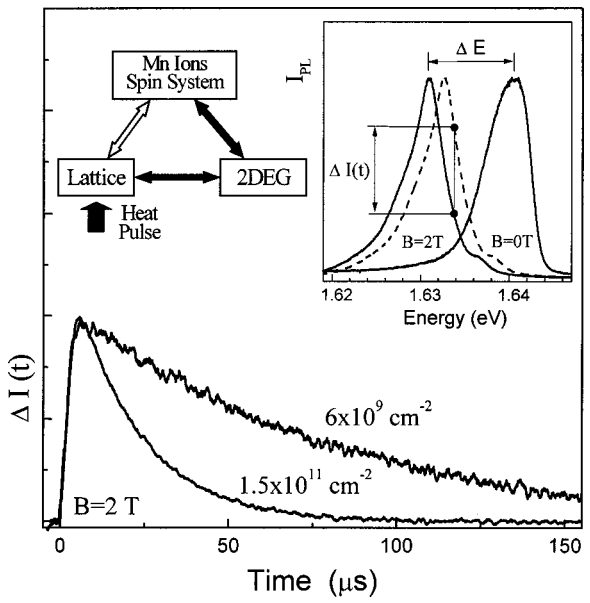

FIG. 1. Time evolution of the phonon-induced variation of the PL intensity (related to the variation of the Mn spin temperature) in two $Cd_{0.99}Mn_{0.01}Te/Cd_{0.76}Mg_{0.24}Te$ QW samples with different n_e detected on the high-energy side of PL line at 1.634 eV. Spectra are normalized to their peak intensity. The inset shows the stationary exciton PL spectra (solid lines) and the spectrum in the presence of nonequilibrium phonons (dashed line) for the sample with $n_e = 1.5 \times 10^{11}\,\mathrm{cm}^{-2}$. For details see Ref. 8–10. The experiments were carried out at $T = 1.6\,\mathrm{K}$ and photoexcitation density $P = 70\,\mathrm{mW/cm}^2$.

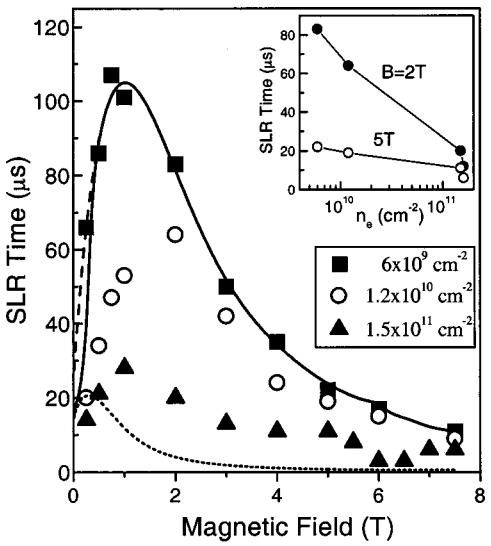

FIG. 2. The dependence of the SLR times on the magnetic-field measured (symbols) and calculated (solid line for $n_e = 1.2 \times 10^{10}\,\mathrm{cm}^{-2}$ and dotted line for $1.5 \times 10^{11}\,\mathrm{cm}^{-2}$) in the regime of low-optical excitation ($P = 70\,\mathrm{mW/cm}^2$) at $T = 1.6\,\mathrm{K}$. The $\tau_{SL}^0(B)$ dependence is shown by a dashed line [see also Fig. 4(a)]. Inset: SLR time as a function of electron density. The lines are guides for the eye.

presence of external magnetic fields an increase of the Mn-ion temperature causes a reduction of the giant Zeeman shift of excitons ΔE. The time-resolved detection of Mn spin temperature is based on monitoring the dynamical shift of the exciton PL line as shown in the inset of Fig. 1 (for details see Ref. 10). It is important to note that our measurements of SLR dynamics are not influenced by the phonon bottleneck effect observed in bulk materials.

The different energy reservoirs, characterized by various corresponding temperatures and relaxation channels, in DMS QW's with 2DEG are shown schematically in Fig. 1. In the first stage of our experiment the injected nonequilibrium phonons heat the Mn system. The heating of Mn ions may be induced directly through interaction of Mn ions with phonons or indirectly, i.e., via the 2DEG that is also heated by the same nonequilibrium phonons. The spin-lattice relaxation process (cooling of the Mn system), due to a direct coupling of the Mn system and the lattice (indicated by an open arrow), is rather slow at low Mn concentrations. In $Cd_{0.99}Mn_{0.01}Te$ it has a characteristic time of about 100 μs.[10] However, the bypassing channel involving the energy reservoir of 2DEG (filled arrows) can be a fast process because the spin-flip exchange scattering of electrons by the magnetic ions provides an efficient energy exchange between these two systems.[4] The efficiency of the bypassing channel is controlled by the electron density n_e. Indeed, an increased SLR rate in QW's with 2DEG has been established in our experiments. In what follows we will first describe experimental findings and, then, compare the data to model calculations.

The dramatic acceleration of SLR in the presence of 2DEG is demonstrated in Fig. 1. The phonon-induced signals $\Delta I(t) = I(t) - I_0$ [here I_0 and $I(t)$ are the PL intensities before and after the heat pulse, respectively] measured in two samples with $n_e = 6 \times 10^9\,\mathrm{cm}^2$ and $1.5 \times 10^{11}\,\mathrm{cm}^{-2}$ in a magnetic field of 2 T are displayed in this figure. We note that the heating of Mn spin system by the nonequilibrium phonons is quite small and changes in the giant Zeeman shift of excitons are linearly proportional to the variation of the Mn spin temperature T_{Mn}. Thus we may consider the measured signal $\Delta I(t)$ to be proportional to the variation of T_{Mn}. The leading edges of $\Delta I(t)$ have a width of about 2 μs, which is about the duration of the phonon pulse reaching the QW's.[9] The decay times τ_{SL} determined from the exponential fit of $\Delta I(t)$ represent the cooling times of Mn system and in our case, with the phonon bottleneck absent, they are actually equal to SLR times of the Mn ions. It is clearly seen in Fig. 1 that the cooling of the Mn system is faster in the sample with higher n_e. It is found that τ_{SL} decreases from 83 μs in the nominally undoped sample to 20 μs in the sample with $1.5 \times 10^{11}\,\mathrm{cm}^{-2}$ electrons.

Figure 2 shows the dependence of τ_{SL} on the magnetic field B for three values of n_e measured at low-density photoexcitation ($P = 70\,\mathrm{mW/cm}^2$). The data for $n_e = 6 \times 10^9\,\mathrm{cm}^{-2}$ is in a good agreement with a dependence of τ_{SL} in nominally undoped (Cd, Mn)Te QW samples.[10] In this particular sample τ_{SL} increases in weak fields and becomes shorter when the magnetic field exceeds 1 T that is similar to results reported also in Ref. 11 for bulk (Cd, Mn)Te. The behavior of τ_{SL} in QW's with 2DEG shows some differences from that in the undoped sample. Although a general behavior seems to be similar for $n_e = 1.2 \times 10^{10}\,\mathrm{cm}^{-2}$ and low magnetic fields ($B < 1$ T) τ_{SL} is much shorter than for $n_e = 6$

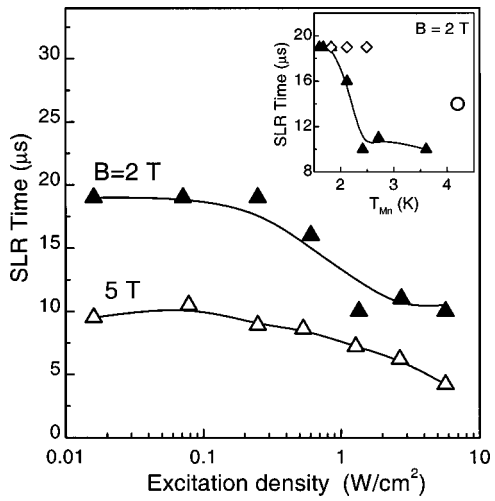

FIG. 3. The dependence of the SLR time on the density of photoexcitation for two values of the magnetic-field detected in a $Cd_{0.99}Mn_{0.01}Te/Cd_{0.76}Mg_{0.24}Te$ QW with $n_e=1.5\times10^{11}\,cm^{-2}$. In the inset the SLR time is plotted as a function of the temperature of the Mn-ion system T_{Mn}. The heating of Mn ions is realized either by the optical excitation (closed triangles), or by phonons from the generator whose power varied from 25 to 250 W/mm^2 (open diamonds) or by an increase of bath temperature to 4.2 K (open circle). The lines are guides for the eye.

$\times10^9\,cm^{-2}$. Then, an increase of τ_{SL} with B is observed and for fields $B>2$ T the values of τ_{SL} do not differ significantly from τ_{SL} measured in the undoped sample. A further increase of n_e up to $1.5\times10^{11}\,cm^{-2}$ leads to a decrease of τ_{SL} in the whole range of magnetic-fields studied. SLR time dependencies on the electron density are plotted in the inset of Fig. 2. One can see that τ_{SL} the variation at $B=2$ T is indeed much stronger than that at the higher field of 5 T. It is interesting to note that in the sample with $n_e=1.5\times10^{11}\,cm^{-2}$ the dependence of $\tau_{SL}(B)$ in high fields is nonmonotonic with a reproducible dip at $B=6.25$ T.

Another interesting experimental finding is a shortening of the SLR time with an increasing density of photoexcitation P. This is illustrated in Fig. 3 for the sample with $n_e=1.5\times10^{11}\,cm^{-2}$. One can conclude, that some additional amount of energy supplied to the system via the photoexcitation causes a reduction of τ_{SL}. An increase of the density of photoexcitation leads to an increase of 2DEG temperature and also to a heating of Mn-ion system.[4] A weak heating of the lattice directly by the laser beam is also possible. In order to determine the heating of which of the three systems (2DEG, Mn ions or the lattice) is principally responsible for the observed reduction of τ_{SL}, we compare the modification of SLR time by different experimental parameters. Results are presented in the inset of Fig. 3 as plots of τ_{SL} vs T_{Mn}, where the temperature of the Mn-ion system was determined from the energy shift of the PL line (see Refs. 8–10) under varying experimental conditions. Three data sets (measured at $B=2$ T) are shown:

(i) Open diamonds corresponding to the lowest-excitation density $P=15\,mW/cm^2$, $T=1.6$ K and for several different power levels of the phonon generator ($P_h=25-250\,W/mm^2$). The temperature of the Mn-ion systems was determined at the maximum of the phonon pulse. It is seen that τ_{SL} does not depend on the initial degree of heating of the Mn ions and the relatively slow cooling of Mn ions goes with the other parameters kept constant, independently of P_h.

(ii) An efficient reduction of τ_{SL} is achieved when the excitation density was increased up to 6 W/cm^2 ($T=1.6$ K and $P_h=250\,W/mm^2$), which is plotted in the inset of Fig. 3 by full triangles.

(iii) We also measured τ_{SL} at $T=4.2$ K ($P=70\,mW/cm^2$ and $P_h=250\,W/mm^2$). An open circle plots the result. It is clearly seen that in this case the temperature of Mn ions is higher than that achieved at the maximum photoexcitation density (compare with the data shown by full triangles). However, τ_{SL} is not as short as at $T=1.6$ K and at the highest excitation densities.

Combining all these observations leads us to the conclusion that the decrease of τ_{SL} with an increase of photoexcitation density cannot be explained simply by the increase of the lattice temperature by the laser beam. This statement comes from the fact that τ_{SL} measured at $T=4.2$ K and $P=70\,mW/cm^2$ is longer than at $T=1.6$ K and high photoexcitation density. We checked that in the studied sample with $n_e=1.5\times10^{11}\,cm^{-2}$ under the actual experimental conditions there is no significant increase in the 2DEG density with an increase of photoexcitation power.[4] We conclude, then, that the elevated electron temperature in the 2DEG at a high-optical excitation density is responsible for the reduction of the SLR time. In the case of the photoexcitation the temperature of 2DEG may significantly exceed the temperatures of the lattice and of Mn-ion system. This conclusion is supported by an observation of similar 2DEG heating caused by photoexcitation in GaAs(Al, Ga)As QW's reported recently in Ref. 12.

For a theoretical analysis of the observed effects we use the approach developed in the recent work of König *et al.*[4] The SLR time measured in the QW's with 2DEG is governed by two possible channels of the energy flow to and from the Mn-ion system (see the diagram in Fig. 1). Therefore, there are two contributions to τ_{SL} the SLR time of the Mn ions τ_{SL}^0, caused by their direct coupling with the lattice, and the characteristic time $\tilde{\tau}_{e\text{-}Mn}$ due to the interaction of the Mn ions with 2DEG:

$$\frac{1}{\tau_{SL}}=\frac{1}{\tau_{SL}^0}+\frac{1}{\tilde{\tau}_{e\text{-}Mn}}. \tag{1}$$

For the value of τ_{SL}^0 we used in our model calculations the SLR time measured in the nominally undoped sample, while $\tilde{\tau}_{e\text{-}Mn}$ was calculated using the formalism presented in Ref. 4. From Eqs. (13) and (24) of this paper we obtain the following expression for the variation of the inverse temperature of Mn ions $\beta_{Mn}=1/k_BT_{Mn}$:

$$\left.\frac{d\beta_{Mn}}{dt}\right|_{e\text{-}Mn}=-\frac{1}{|C_\beta(B)|}\left.\frac{\partial E}{\partial t}\right|_{e\text{-}Mn}=-\frac{1}{\tilde{\tau}_{e\text{-}Mn}}(\beta_{Mn}-\beta_e), \tag{2}$$

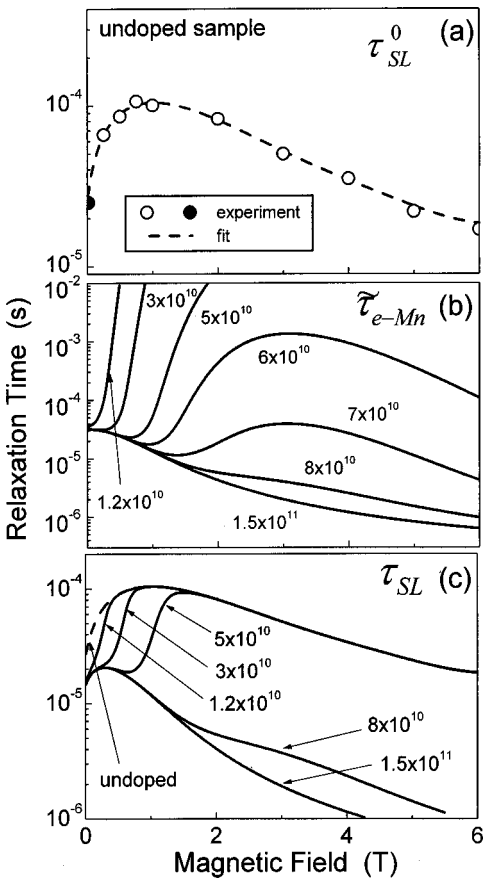

FIG. 4. Model calculations of the SLR time as a function of the magnetic field using the approach of Ref. 4. (a) $\tau_{SL}^0(B)$ dependence (dashed line) is taken to be given by an interpolation of the experimental data for the undoped sample from this paper (open circles) and from Ref. 11 (full circle). (b) $\tilde{\tau}_{e-Mn}(B)$ dependencies calculated from Eq. (3) for different electron densities. (c) $\tau_{SL}(B) = 1/[1/\tau_{SL}^0 + 1/\tilde{\tau}_{e-Mn}]$ for different electron densities. The dashed line again shows $\tau_{SL}^0(B)$.

$$\tilde{\tau}_{e\text{-}Mn} = \left|\frac{C_\beta(B)}{C_\beta(0)}\right| [T_{e\text{-}Mn}(B,\varepsilon_F,\beta_e,\beta_{Mn}) + T_s(\varepsilon_F,\beta_e,\tau_s)], \tag{3}$$

where $\partial E/\partial t|_{e\text{-}Mn}$ is the energy flux between Mn-ion system and 2DEG, $\beta_e = 1/k_B T_e$ is the inverse temperature of free electrons, $C_\beta(B)$ is the heat capacity of magnetic ions in the presence of a magnetic field, and ε_F is the Fermi energy of 2DEG. $T_{e\text{-}Mn}$ and T_S are characteristic times calculated by means of Eqs. (14) and (25) of Ref. 4. We note here that $T_S \propto \tau_S$, where τ_S—the only free parameter of the present model—is the spin-relaxation time of electrons. For the calculations we take $\tau_S = 10^{-10}$ s as evaluated in Ref. 4.

Figure 4 shows the results of model calculations of the magnetic-field dependence of the SLR time. In Fig. 4(a) the function $\tau_{SL}^0(B)$ is evaluated as the interpolation of experimental data for the undoped sample (open circles show our data and full circle is a data point at $B = 0$ T from Ref. 11). The field dependencies $\tilde{\tau}_{e\text{-}Mn}(B)$ calculated from Eq. (3) for different electron densities are plotted in Fig. 4b. Finally, $\tau_{SL}(B)$ calculated using Eq. (1) is shown in Fig. 4(c). The results in this plot can be directly compared with the experimental data. Analyzing the results of Fig. 4 one observes that for $n_e < 7\times10^{10}\,\mathrm{cm}^{-2}$ τ_{SL} at low fields ($B < 1-2$ T) is dominated by $\tau_{e\text{-}Mn}(B)$, but at high fields it is determined by the $\tau_{SL}^0(B)$ dependence. The situation is different for $n_e \geqslant 7\times10^{10}\,\mathrm{cm}^{-2}$, where $\tilde{\tau}_{e\text{-}Mn}$ yields the main contribution to τ_{SL} in the whole range of the magnetic fields.

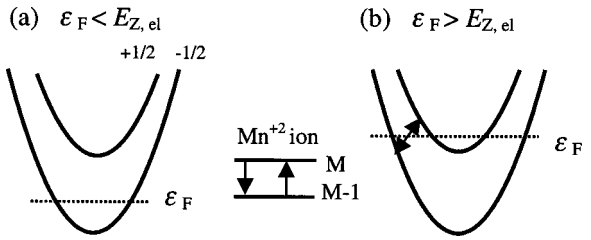

FIG. 5. Schematic energy diagram illustrating spin-flip transitions in the presence of a magnetic field B: (a) spin-flip transitions are not allowed at low n_e because of energy conservation; (b) the number of possible transitions increases with an increase of B when n_e is sufficiently high.

To compare the experimental results with calculations we have plotted the calculated dependencies $\tau_{SL}(B)$ for undoped sample (fitted curve given by the dashed line) as well as for $n_e = 1.2\times10^{10}\,\mathrm{cm}^{-2}$ and $n_e = 1.5\times10^{11}\,\mathrm{cm}^{-2}$ in Fig. 2 (solid and dotted lines, respectively). First it is important to mention that at low $B = 0.25$ T we have a reasonable agreement in the absolute values of the measured τ_{SL} with the calculated values for the corresponding n_e. This strongly supports our main idea of the SLR of Mn ions via the interaction with the 2DEG.

It is seen in Fig. 2 that the theoretical dependencies of $\tau_{SL}(B)$ differ very much for different values of n_e. For relatively low-electron concentration ($n_e = 1.2\times10^{10}\,\mathrm{cm}^{-2}$) a rapid increase of τ_{SL} with B is observed and then, for higher B, τ_{SL} follows the SLR time in an undoped sample (see the solid curve in Fig. 2). Qualitatively this is explained by the fact that for this electron concentration the Fermi level is very low ($\varepsilon_F = 0.3$ meV). The giant Zeeman splitting of the conduction band, caused by the exchange interaction of the electrons with magnetic ions, is equal to $E_{Z,el} = \mu_B g_{\mathrm{eff}} B$. Due to the large value of effective g factor ($g_{\mathrm{eff}} \sim 50$) the splitting $E_{Z,el}$ exceeds ε_F even in relatively small magnetic fields. As a result, only the lower-spin subband of electrons with $s_z = -1/2$ is occupied, while the upper subband with $s_z = +1/2$ is empty as its energy significantly exceeding the Zeeman splitting of Mn ions $E_{Z,Mn} = \mu_B g_{Mn} B$ ($g_{Mn} = 2$). This is schematically shown in Fig. 5(a). Thus, the energy transfer from Mn ions to the 2DEG becomes almost impossible at high magnetic fields, when the giant Zeeman splitting $E_{Z,el}$ essentially exceeds ε_F. Such behavior is in qualitative agreement with the experimental findings (Fig. 2).

However, the experimentally observed increase of τ_{SL} with magnetic field is not as rapid as the one predicted theoretically. The reason for this behavior may be that the density of 2DEG is not uniform and it actually fluctuates in the plane of the QW. Analyzing the oscillator strength of trion resonance in reflection experiments we evaluate the mean density of 2DEG.[7] However, in the present, nonequilibrium phonon

experiments, the measured PL signals come mainly from the spatial regions with a maximum electron density. These regions are heated more effectively by nonequilibrium phonons because of a stronger coupling between phonons and the Mn system via the electron gas (see the diagram in Fig. 1). Correspondingly these regions have a minimum τ_{SL}. Thus the experimentally measured curve shown in Fig. 2 for $n_e = 1.2\times 10^{10}\,\mathrm{cm}^{-2}$ should be compared with the theoretical curve for some higher effective n_e, which yields a better agreement between the model and the experiment.

The theory predicts also a different behavior for high $n_e = 1.5\times 10^{11}\,\mathrm{cm}^{-2}$ (dotted curve in Fig. 2), which corresponds to a degenerate Fermi gas ($\varepsilon_F = 3.5\,\mathrm{meV}$). The calculated value of τ_{SL} decreases with increasing magnetic field. Qualitatively this may be explained by an increase of the number of ''active'' electrons near the Fermi level that participate in the Mn$\leftrightarrow e$ energy transfer while the Zeeman splitting of Mn ions increases (Fig. 5b). However, such a rapid decrease of τ_{SL} with B is not observed experimentally. The discrepancy between the field dependence of τ_{SL} measured in the experiments (Fig. 2) and the calculations for $n_e = 1.5\times 10^{11}\,\mathrm{cm}^{-2}$ may be due to two reasons that are not taken into account by the model. The first reason is a possible increase of the spin-relaxation time τ_S of electrons in 2DEG at high B.[13] This will lead to an increase of $\tilde{\tau}_{e\text{-}Mn}$ and, correspondingly, to an increase of the measured SLR time τ_{SL}. The second reason of the discrepancy between the experiment and the theory may be in the Landau quantization of the electron spectrum of 2DEG, which is ignored in our model. This quantization brings 2D electron levels with different spin projections $s_z = \pm 1/2$ out of resonance with the Mn Zeeman splitting, which makes the probability for electron spin-flip transitions in the 2DEG negligible.

On the other hand, the formation of Landau levels should result in a number of resonances for the SLR time at certain values of B when the energy separation between Landau levels (n_i, $s_z = -1/2$) and (n_j, $s_z = +1/2$) is equal to the Zeeman splitting of Mn ions. Calculations, based on the known parameters for the exchange interaction (exchange constant for the conduction band $N_0\alpha = 0.22\,\mathrm{eV}$ and electron effective mass $0.96m_0$[14]), show that two such resonances should occur at $B = 1.4$ and 3.6 T between the pairs of Landau levels ($n_i = 2$, $n_j = 0$) and ($n_i = 1$, $n_j = 0$), respectively. No well-distinguished resonances were observed in the experiments at these fields, which, we think, is due to the relatively large broadening of Landau levels in our sample. Another type of the pseudoresonance may, in principle, occur when the Fermi level is located almost in the middle between the two Landau levels with the same n and different spin $s_z = \pm 1/2$. Then the spin-flip transitions probability near the Fermi level possesses a maximum and the SLR time may decrease at the corresponding field strength. Actually, the dip observed experimentally at $B = 6.25\,\mathrm{T}$ in the sample with $n_e = 1.5\times 10^{11}\,\mathrm{cm}^{-2}$ (see Fig. 2) corresponds to filling factor $\upsilon = 1$ and is consistent with this idea. However, the modeling of the pseudoresonance assuming the Gaussian shape of Landau levels does not give us a good quantitative agreement with the measured width and depth of the observed dip. We may speculate that this disagreement is due to a higher density of localized ''tail'' states of the Landau levels, than it is given by the Gaussian distribution used in our estimations.

Let us now turn to the experimental dependence of the SLR time on the excitation density shown in Fig. 3. It may be qualitatively explained by an increase of the electron temperature in 2DEG. The heating of 2DEG at elevated excitation densities has been studied in Ref. 4. An acceleration of the energy transfer rate between 2DEG and magnetic ions with increasing electron temperature is expected to occur in degenerate 2DEG. In such case, an increase of the thermal energy k_BT_e leads to a smearing of the Fermi edge and, correspondingly, to an increase of the number of electrons that participate in the spin-flip transitions. This argument is valid provided that the thermal energy k_BT_e is smaller than 2DEG Fermi energy. The number of electrons, which are active in the spin-flip transitions, is proportional to k_BT_e. Then, 50% decrease of τ_{SL} observed experimentally (Fig. 3) means that the electron temperature is twice higher than the lattice temperature and thus $T_e = 4\,\mathrm{K}$ for $P = 6\,\mathrm{W/cm}^2$. This explanation and the estimated value of T_e are supported by calculations performed using the model developed in Ref. 4, which predicts an enhancement of the energy transfer between 2DEG and magnetic ions with an increase of the electron temperature.

To conclude, in modulation-doped quantum wells with 2DEG of low density ($n_e \leqslant 1.5\times 10^{11}\,\mathrm{cm}^{-2}$, $\varepsilon_F < 4\,\mathrm{meV}$) a strong increase (reaching an order of magnitude) of the SLR rates is found experimentally. It is evident that a new effective mechanism of spin-lattice relaxation operates when the energy from Mn-ion system is first transferred to 2DEG and, then, from 2DEG further to the lattice. Therefore, the presence of 2DEG significantly modifies dynamic magnetic properties of DMS heterostructures. This sensitivity provides a new method of controlling the character of the spin dynamics, such as spin-lattice and spin-spin relaxation rates, by changing the density of free carriers, which is important for designing new spintronic devices. We stress here that not only the dynamics of cooling, but also the heating dynamics should depend strongly on the presence of free-carrier gases. One can predict that 2D hole gas should cause even stronger effects due to stronger p-d exchange coupling with the Mn system. We have preliminary experimental data confirming this expectation.[15]

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