

Strain-induced speed-up of Mn^{2+} spin-lattice relaxation in $(\text{Cd,Mn})\text{Te}/(\text{Cd,Mg})\text{Te}$ quantum wells: A time-resolved optically detected magnetic resonance study

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This study examines the spin-lattice relaxation rate of Mn^{2+} ions in strained diluted magnetic semiconductor $(\text{Cd,Mn})\text{Te}/(\text{Cd,Mg})\text{Te}$ quantum wells using the optically detected magnetic resonance (ODMR) technique. By adjusting the magnesium (Mg) content in the buffer layer, we created samples with different strain levels. Our time-resolved ODMR results show that the spin-lattice relaxation time becomes faster as strain increases. We also found that the relaxation rate increases with both magnetic field and temperature, showing a power-law behavior. To understand these observations, we used a theoretical model based on six-level rate equations with nonequal level separations. This model suggests that the main factor affecting relaxation in our samples is a “direct” mechanism. The model’s predictions match well with our experimental data. Overall, our findings give insights into spin-lattice relaxation in strained quantum wells and could be important for the development of future quantum and spintronic devices.

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I. INTRODUCTION

Understanding spin-lattice relaxation mechanisms is of paramount importance for potential applications in quantum and spintronic devices [1–4]. In this study, we aim to investigate the impact of strain in the crystal lattice surrounding magnetic ions on their spin relaxation. Our focus is on $(\text{Cd,Mn})\text{Te}/(\text{Cd,Mg})\text{Te}$ quantum wells with incorporated low density of Mn^{2+} ions, which provide an intermediate system between quantum dots and bulk crystals, enabling us to explore the strain dependence.

When studying crystals doped with magnetic ions, it is crucial to consider that even at very low dopant concentrations, a single paramagnetic ion or a spin system cannot be treated as completely isolated from its environment [5]. The investigated system experiences constant energy exchange processes between the magnetic ions and the generalized thermal reservoir [6]. This reservoir comprises lattice phonon vibrations (phonon excitations of the crystal), carriers, and the crystal environment (e.g., helium bath), all of which can affect the availability of relaxation pathways. Consequently, an ion in an excited state (e.g., due to the absorption of radiation) gradually loses the previously absorbed energy over time and returns to the equilibrium. The most common relaxation process in our system is the direct process mechanism [7], also known as the spin-flip process. This process involves a change in the spin projection (transition between energy levels resulting from an external magnetic field splitting due to the

emission or absorption of a single phonon from or into the crystal lattice [8].

Spin-lattice relaxation has been extensively studied in various diluted magnetic semiconductor (DMS) systems. These include bulk crystals [9–11], quantum well systems [12,13], and lower-dimensional nanostructures [14,15]. A range of techniques has been employed to investigate the time-dependent magnetic properties of these systems. These include infrared laser pulse induced electron spin resonance [10], photocarrier-induced heating effects in quantum dots [14], phonon-induced variations in photoluminescence intensity [16], time-resolved Faraday rotation [17], ac-susceptibility detected by Faraday rotation [18], and spin-noise analysis [19]. Among these methods, Optically Detected Magnetic Resonance (ODMR) [13,20–23] stands out. Its high spatial resolution and sensitivity are particularly advantageous for our study, as they allow us to specifically target and analyze the small volume of the sample where strain and magnetic ions are present.

II. SAMPLES, EXPERIMENTAL SETUP, AND METHODS

A. Samples with controlled deformation in QW layer

The samples studied in this paper consist of quantum wells (QWs) created by the molecular beam epitaxy (MBE) method. Different strains in the samples (as well as deformation $\varepsilon_{||}$) were achieved by modifying the magnesium content in the buffer and barrier layers. Detailed characterization of the presented samples (UW1029, UW1030, UW1031) can be found in the article [24], therefore here we describe them only briefly. The representative scheme for all used samples is illustrated in Fig. 1(a), and the composition of each layer is described in Table I. The samples were grown on GaAs

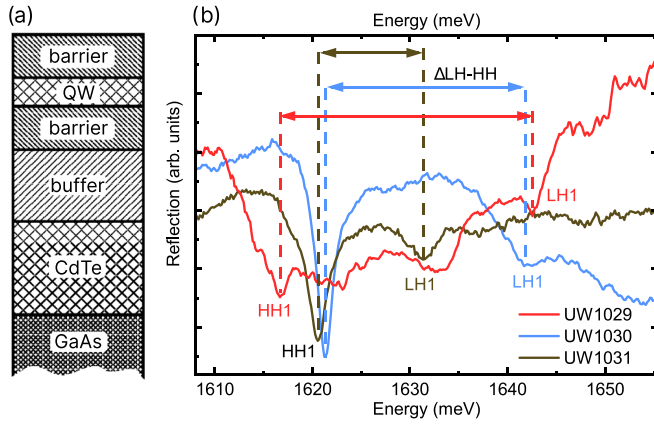


FIG. 1. (a) A representative sample structure, used across the series of samples in this article. The buffer layer is composed of (Cd, Mg)Te, with magnesium content that varies from 0% to 30.7%. Barriers were constructed from (Cd, Mg)Te, while the quantum well (QW) was made from (Cd, Mn)Te, and contained a manganese concentration of less than 0.5%. (b) The reflectivity spectra of studied samples demonstrate the characteristic features corresponding to the heavy-hole exciton (HH) and light-hole exciton (LH). The energy splitting between these two ($\Delta\text{LH-HH}$) is related to the strain present in the QW layer. The larger the $\Delta\text{LH-HH}$, the larger the strain.

substrates, and a CdTe layer of 4 μm thickness was grown on top of the substrate for decoupling from the GaAs lattice constant [25,26]. A (Cd, Mg)Te buffer layer of 2 μm (larger than the critical thickness of (Cd, Mg)Te [27,28]) was used to govern the strain in the samples, and thin (Cd, Mg)Te barriers of 50 nm (smaller than the critical thickness) were incorporated. We have determined the magnesium content using magnesium fluxes and reflectance measurements [29,30]. The thickness of the (Cd, Mn)Te quantum wells (QWs) was selected at 10 nm, which is well below the critical thickness of CdTe lattice relaxation [25,26]. Such a choice ensured good confinement and the appearance of narrow excitonic features. The modified Brillouin function was fitted to the giant Zeeman splitting to verify the manganese (Mn) content [31]. We identified the reflectance spectrum features, including the assignment of heavy-hole excitonic states and light-hole excitonic states, using standard magneto-optical measurements [32–34]. The reflectivity spectra of the samples, revealing identified features, are shown in Fig. 1(b). The energies of the spectrum features confirm the designed strain in the samples. Moreover, XRD measurements have further verified the corresponding deformation values as described in Ref. [24].

TABLE I. Composition of samples used in this article and deformation $\varepsilon_{\parallel}$ calculated for 1.6 K present in the QW layer expressed in permilles.

Sample no.	Buffer Mg (%)	Barrier Mg (%)	QW Mn (%)	$\varepsilon_{\parallel}$ (‰)
UW1029	30.7	30.7	0.30	−3.51
UW1467	23.0	23.0	0.27	−3.22
UW1030	21.2	21.2	0.31	−2.60
UW1031	0.0	21.2	0.26	−0.58

B. Time-resolved ODMR

Optically Detected Magnetic Resonance (ODMR) is a method based on the interaction of photo-created carriers and magnetic ions in a sample. Microwave radiation of constant frequency is delivered to the sample, placed within a constant external magnetic field. When the energy at a specific microwave frequency resonates with a paramagnetic transition at a particular magnetic field, paramagnetic resonance occurs, leading to a decrease in the net magnetization of the sample.

The decrease in magnetization, caused by paramagnetic resonance, is detectable as a change in the optical spectrum due to the exchange interaction between photo-generated carriers and magnetic spins. The ODMR method offers spatial resolution and sensitivity, probing only a small part of the sample (excitation laser was focused on the sample resulting in spot with approximately 100 μm in diameter) and the thin Quantum Well (QW) where the magnetic ions are present (10 nm).

The difference in the optical spectrum at resonant conditions, compared to the spectrum measured without microwave radiation, is defined as the ODMR signal. In this study, time-resolved ODMR was used, employing pulsed microwave radiation and pulsed optical excitation/probing of samples. The microwave pulse period was 14 ms with a pulse width of 2 ms, and the optical probing pulse had the same period of 14 ms with a duration of 0.5 ms.

By changing the delay between the microwave and light pulses, the relaxation curve of the magnetic ions could be reconstructed. This method allows for the measurement of the dynamics of the ODMR signal, and therefore the spin-lattice relaxation rate of Mn^{2+} ions in CdTe QWs. During the experiments excitation power density of the laser was below 0.01 W/cm²—low enough to avoid heating the lattice of the sample, as evidenced by lack of detectable redshift of the spectrum [35].

A well-established method of obtaining high values of microwave radiation at the position of the sample is by using a microwave cavity, commonly employed in EPR measurements. However, this approach is not ideal for optical studies, as optical access to the sample becomes challenging. Moreover, the resonant microwave cavity is typically optimized for a limited number of frequencies. Therefore, in this work, we utilize a sample holder based on printed circuit boards, which effectively creates a closed loop of copper ribbon around the sample. This ensures the correct orientation (perpendicular) of the magnetic component of the microwave radiation with respect to the static magnetic field and the optical axis direction. The employed sample holder yields a robust ODMR signal across a wide range of microwave frequencies—we have tested it from 12 to 42 GHz.

III. RESULTS

A. Time-resolved ODMR measurements

Figure 2 presents the ODMR relaxation curves obtained for the measured samples, where deformation present in the QW increases from the left panel (sample UW1031) to the right panel (sample UW1029). The horizontal axis depicts the delay between the MW pulse and the light probing pulse,

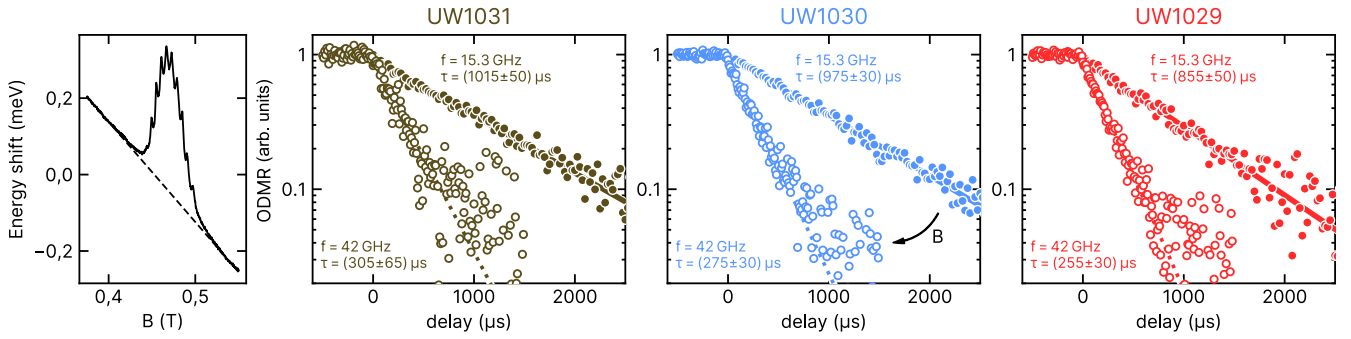


FIG. 2. The left panel presents the ODMR spectrum (solid line) of CdTe quantum well doped with manganese ions (sample UW1031), measured in a presence of microwave radiation ($f = 13.175$ GHz). The y-axis represents the energy of the recombination of the neutral exciton complex (X), as visible in the photoluminescence spectrum, with an offset of 1619.7 meV subtracted. The dashed line corresponds to the position of X without microwave radiation. The ODMR signal is defined as the difference between both lines at resonant magnetic field. Other panels show time evolution of the ODMR signal as a function of the time separating the microwave radiation pulse and the probing light pulse, measured in CdTe quantum wells doped with manganese ions. Solid points and lines correspond to the microwave frequency $f = 15.3$ GHz. Hollow points and dashed lines correspond to the microwave frequency $f = 42$ GHz. The lines represent exponential decay fit curves with the characteristic time τ . The three panels show the results obtained for three quantum wells with different nominal strain values, with the strain increasing from the left panel to the right. The determined values of the parameter D and the strain are presented in Fig. 4. The constant portion of the decay curves reflects the 0.5 ms laser pulse width.

whereas the vertical axis represents the normalized ODMR signal amplitude. Each panel consists of two decay curves: the filled circles correspond to a MW frequency of 15.3 GHz, which is in tune with the resonant magnetic field of 0.547 T. The empty circles were obtained at a MW frequency of 42 GHz, resonating with a magnetic field of 1.5 T. It is evident that the relaxation time is shorter at higher magnetic fields (characteristic decay time approximately 0.3 ms at a higher magnetic field and around 1 ms for a lower magnetic field) for all samples. The results showcased in Fig. 2 were recorded at a temperature of 1.6 K (pumped helium bath).

Since the relaxation rate is highly temperature-dependent, we measured its variation with temperature for sample UW1467, which contains 23% of Mg in the barrier and buffer, and 0.27% of Mn in the QW. The UW1467 sample bears a close resemblance in construction to UW1029. It was selected for temperature-dependent measurements owing to its exceedingly narrow excitonic line of approximately 1.2 meV. Minimizing line width is crucial because of line broadening at elevated temperatures; starting with the narrowest possible lines facilitated the identification of the ODMR signal at higher temperatures. The acquired spin-relaxation rates are depicted in the left panel of Fig. 3. The observed spin-lattice relaxation rate temperature dependence aligns well with the power law $\tau^{-1} = A(T + T')^m + C$, where $T' = 0$ K and the exponent $m = (1.38 \pm 0.1)$ is ascertained for the neutral exciton, implying that the relaxation is governed by a “direct” mechanism involving a single phonon since the exponent is near 1.

A similar analysis can be performed for the ODMR signal derived from the charged exciton line. In this case to achieve a satisfactory fit, the phenomenological temperature shift of $T' = (2 \pm 0.3)$ K was added, eventually deriving an exponent for the charged exciton as $m = (5 \pm 0.3)$. Due to the low signal-to-noise ratio, the 6 K point sourced from the charged exciton line (open circle marked with a black dot inside) was excluded from the fitting process. The difference

in the measured rate has profound consequences, proving that magnetic ions probed by the charged exciton are not the same as those probed by the neutral exciton and that carriers plays an important role in the relaxation process. This observation will be elaborated upon in Sec. IV.

Additional information about the spin-lattice interaction may be retrieved from the time-resolved ODMR measurements at different values of external magnetic field. The range of magnetic fields that were used during the experiments was limited by our microwave setup that covers frequency ranges of 12–27 GHz and 42–47 GHz which corresponds to resonant magnetic fields (for typical Mn^{2+} g-factor) 0.428–0.963 T and 1.5–1.68 T, respectively.

The spin-lattice relaxation rates as a function of resonant magnetic field for measured samples are presented on right panel of Fig. 3 with symbols. Obtained spin-lattice relaxation rate dependencies are well described by formula $\tau^{-1} = \alpha B^n + \tau_0^{-1}$, where α , n , and τ_0^{-1} are free parameters. The extracted exponents yield $n = (2.91 \pm 0.14)$, $n = (2.89 \pm 0.08)$, $n = (3.21 \pm 0.08)$ for samples UW1029, UW1030, and UW1031, respectively. All exponents are close to the value 3. Similar dependencies discussed in the literature provide n values of 2, 4, 5 for different ions and experimental conditions [9,36]. At this stage, obtained in this work experiment exponent 3 is not easy to interpret. However, as it is shown in Sec. III B, this value in combination with numerical modeling of the system, gives additional evidence that the main spin-lattice relaxation mechanism involves only one phonon.

Interestingly, the fitted curves (solid red line, blue dashed line, dotted line) reveal systematic shift following the strain value present in quantum well layer. This is more clearly seen in Fig. 4 where spin-lattice relaxation time is presented as a function of deformation that is present in the QW layer. The thin dotted line is a result of numerical simulation described in Sec. III B. The spin-lattice relaxation is faster for Mn^{2+} ions incorporated in more strained CdTe material. The black triangle represents spin-lattice relaxation time obtained for

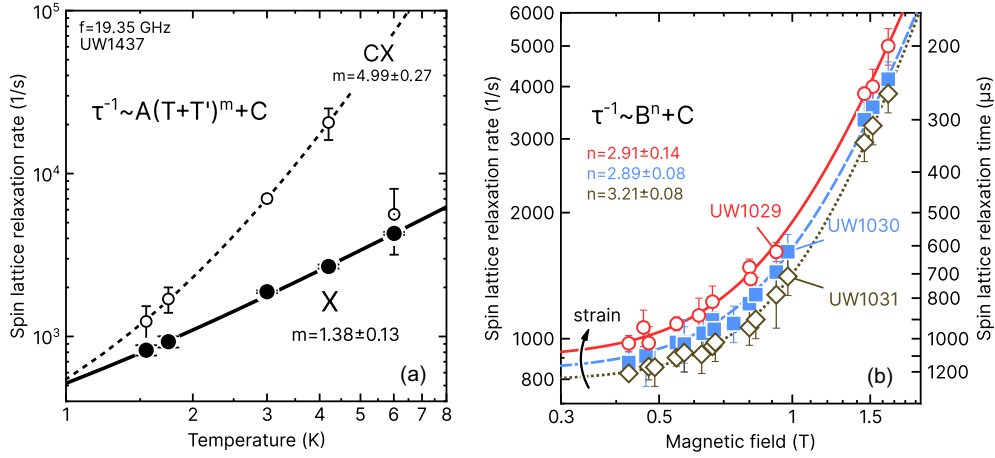


FIG. 3. Spin-lattice relaxation rates of (Cd, Mn)Te/(Cd, Mg)Te QWs determined from time-resolved ODMR measurements. Left panel (a) shows spin-lattice relaxation rate vs temperature extracted from ODMR signal detected on neutral exciton line (X, marked with black dots) and charged exciton line (CX, marked with empty circles) measured for sample UW1467. The solid and dashed lines represent best fit of $\tau^{-1} = A(T + T')^m + C$ formula to the data. Symbols represent experimental data with y-error bars. The determined exponents are $m = (1.38 \pm 0.13)$ for neutral exciton and $m = (4.99 \pm 0.27)$ for charged exciton. The empty circle marked with a black dot inside was excluded from fitting due to the low signal-to-noise ratio. Magnetic field dependence of spin-lattice relaxation rates of neutral exciton line is shown on panel (b) measured at 1.6 K. Symbols represent experimental data, and the solid lines represent the fitted power function of the form: SLRR $\sim B^n + C$ with exponents: $n = (2.91 \pm 0.14)$ for sample UW1029, $n = (2.89 \pm 0.08)$ for sample UW1030, and $n = (3.21 \pm 0.08)$ for sample UW1031. Both the measured points and the fitted lines follow the trend that the greater the deformation in the quantum well, the faster the ion relaxation rate, meaning a shorter relaxation time τ .

the CdTe/ZnTe quantum dot containing a single Mn^{2+} ion [37]. In such a quantum dot the deformation (compressive) is calculated as lattice mismatch between the CdTe and ZnTe materials.

B. Numerical simulations

We aim to understand the observed data through modeling the spin-lattice relaxation in (Cd,Mn)Te/(Cd,Mg)Te quantum wells, using an adapted version of A. Witowski's model [38]. The main assumption of this model is the “direct” relaxation mechanism, where only one phonon is involved, neglecting weak interactions with the nuclear spin. This simplifies the Mn^{2+} system to six energy levels corresponding to the electron spin projections on the quantization axis determined by the magnetic field, with deformation effects reflected by the axial term of the spin-Hamiltonian [parameter D —see Figs. 5(a) and 5(b)]. The simplified spin Hamiltonian is given by

$$\hat{H} = g_{\text{Mn}}\mu_B\hat{\mathbf{B}}\hat{\mathbf{S}} + D\left[\hat{S}_z^2 - \frac{S(S+1)}{3}\right], \quad (1)$$

where manganese electronic spin $S = 5/2$, μ_B is Bohr magneton, g_{Mn} is g-factor of manganese ion, and D is the axial zero-field splitting (ZFS) parameter (D is also called the strain-induced axial-symmetry parameter) [7]. Parameter D can be translated into deformation using spin-lattice coupling parameter $G_{11} = (72.2 \pm 1.9)$ neV, as presented in Ref. [24]. In the case of studied QWs the sign of deformation is opposite to the sign of the spin Hamiltonian D parameter [39]. In cases of less than cubic symmetry, the spin Hamiltonian typically includes an additional term corresponding to the rhombic zero-field splitting (ZFS) parameter E , which accounts for

deviations from axial symmetry. However, in our previous work [24], we demonstrated that the E term for our quantum well samples is negligible $E = (0 \pm 25)$ neV, and the observed spin-resonance spectra are fully reproduced using numerical simulations with $E = 0$, confirming that the axial D term alone is sufficient.

The kinetic model describes the temporal evolution of the occupancies of the six energy levels. The rate coefficients W_{ij} and W_{ji} governing the transitions between levels ($i < j$) are derived from the energy differences between the levels and Boltzmann factors—see Fig. 5(c)—with expressions for W_{ij} and W_{ji} given as

$$W_{ij}^{\uparrow} = A_{|j-i|}(|E_j - E_i|)^3 \frac{1}{e^{\frac{|E_j - E_i|}{k_B T}} - 1} \quad (2)$$

$$W_{ji}^{\downarrow} = A_{|j-i|}(|E_j - E_i|)^3 \left(1 + \frac{1}{e^{\frac{|E_j - E_i|}{k_B T}} - 1}\right). \quad (3)$$

Here, E_i represents the energy of level i , and $k_B T$ is the Boltzmann factor associated with temperature T , $A_{|j-i|}$ are numerical constants discussed in detail in Ref. [40]. The energy spacing between levels $i + 1$ and i is given by

$$\Delta E_{i+1,i} = g_{\text{Mn}}\mu_B B + 2(i - 3)D. \quad (4)$$

We consider only magnetic dipole transitions, which change spin projection by $\Delta S_z = 1$. An example of the evolution of level populations is presented in Fig. 5(d). We then calculate the evolution of the mean spin values, which is approximated by a monoexponential decay [38], with the characteristic decay time being the spin-lattice relaxation time.

Values of spin-lattice relaxation times obtained, from such procedure, for multiple values of strain-related spin

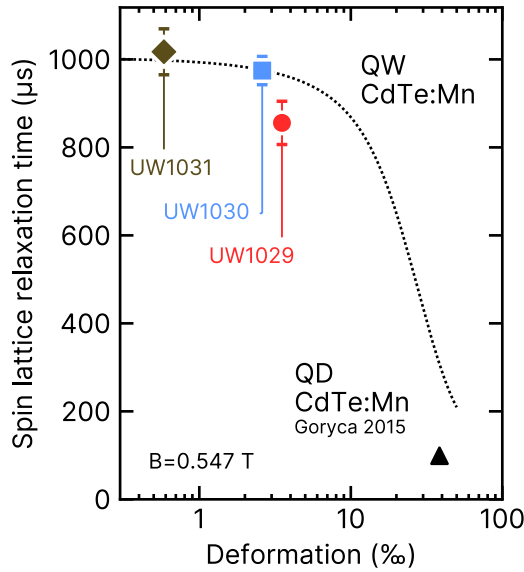


FIG. 4. The relaxation time τ of the Mn^{2+} ion in CdTe determined from ODMR measurements of QWs is shown as a function of the deformation present in the QW. The result was obtained for a microwave radiation frequency of $f = 15.3$ GHz ($B = 0.547$ T) at 1.6 K. As a reference, the value determined for a CdTe quantum dot with a single manganese ion (data from publication [37] interpolated to the magnetic field value $B = 0.547$ T) is added and indicated on the plot with the symbol $\blacktriangle$. The dotted line is a result of numerical simulation described in Sec. III B. The relaxation time decreases as the strength of the crystal lattice deformation around the Mn^{2+} ion increases.

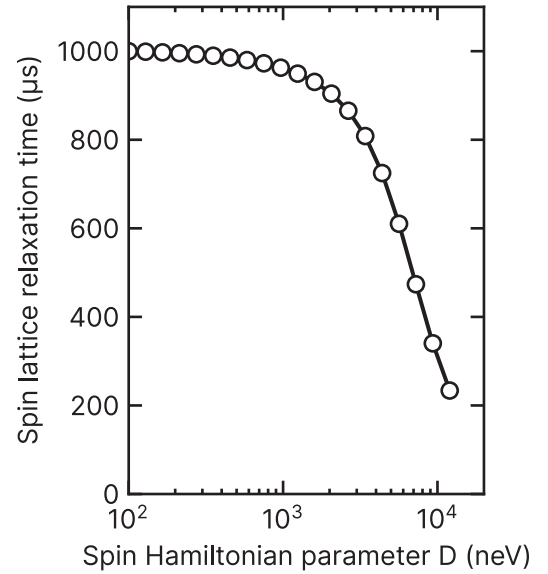


FIG. 6. Spin-lattice relaxation of Mn^{2+} ion in CdTe strained QW vs strain-related spin Hamiltonian parameter D . Each dot represents an exponential-decay-fit to the temporal evolution of mean spin calculated from curves similar to the presented in Fig. 5(d). Obtained result is in qualitative agreement with data presented in Fig. 4.

Hamiltonian parameter D are shown in Fig. 6. The spin-lattice relaxation time becomes shorter with increasing strain-related spin Hamiltonian parameter D . This behavior is in good agreement with measured dependence presented in Fig. 4. Moreover, similar simulations were performed as a function of the lattice temperature and magnetic field. Obtained dependencies of spin-relaxation rate are also in agreement with measured data and are presented in Figs. 7 and 8. While our model does not exactly reproduce the expected temperature exponent of $m = 1$, it successfully captures the strain dependence—achievements that standard models fail to deliver. This slight discrepancy in the temperature exponent may result from the complex interplay between energy level splittings caused by both strain and magnetic field at low temperatures, leading to nontrivial behavior not accounted for in models based on approximations valid only at very high magnetic fields or extremely low temperatures.

IV. DISCUSSION, SUMMARY, AND CONCLUSIONS

It is worth noting that the sensitivity of ODMR measurements is inherently temperature-dependent, as the ODMR signal is based on the Giant Zeeman effect [31]. The amplitude of the Giant Zeeman effect decreases as the temperature of the system rises—this is a result of the decreasing net magnetization of the sample. Therefore, the practical upper limit of temperatures at which ODMR was measurable in our experimental setup was close to 6 K. Other techniques like spin noise spectroscopy, can provide insights into spin dynamics without the low-temperature limitation [19]. The maximum ODMR amplitude for the neutral excitonic line at 6 K was 50 μeV . The analogous value for the signal extracted from the charged exciton was 30 μeV with a standard

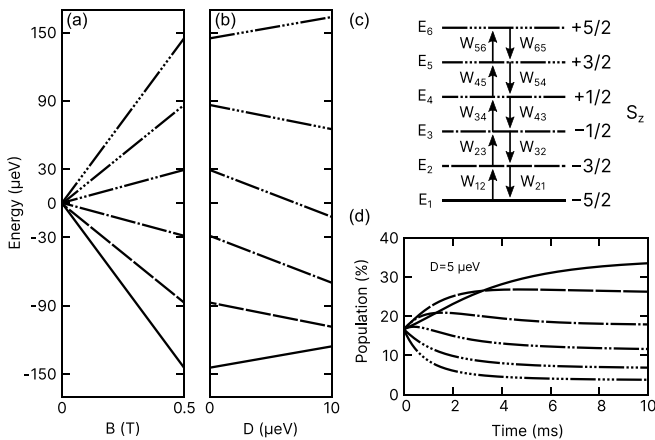


FIG. 5. (a) Zeeman splitting of 6-level Mn^{2+} system (neglecting nuclear spin) vs magnetic field along z -axis for $D = 0$. (b) The same six-level system at constant magnetic field of 0.5 T interacting with strained crystal lattice—horizontal axis presents added ZFS term described by the strain related spin Hamiltonian parameter D . The separation between energy levels can be derived from Eq. (4). (c) Assignment of the electron spin projections on the quantization axis to the different energy levels and designation of transitions between levels. (d) Temporal evolution of energy levels populations shows that the lowest energy level population (solid line) increases with time. The mean spin at each time moment is proportional to the magnetization present in the QW. The simulation assumes an initial state with all levels equally occupied, corresponding to an infinite temperature.

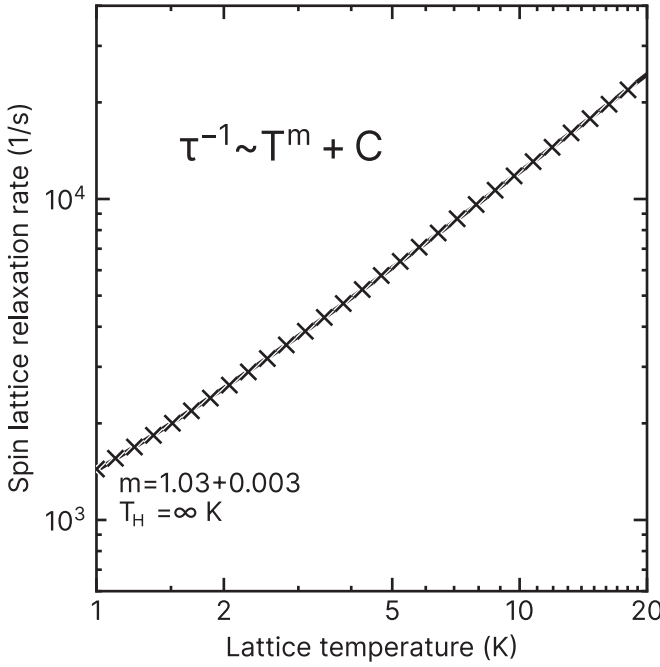


FIG. 7. Numerical simulation of the spin-lattice relaxation rate vs temperature obtained from the solution of Eq. (3) for infinite initial temperature T_H . Symbols represent values obtained from the simulation, and the solid curve represents a fitted power function of the form $\tau^{-1} \sim T^m + C$ with an exponent value close to 1. The obtained dependence qualitatively agrees with the results presented in Fig. 3(a).

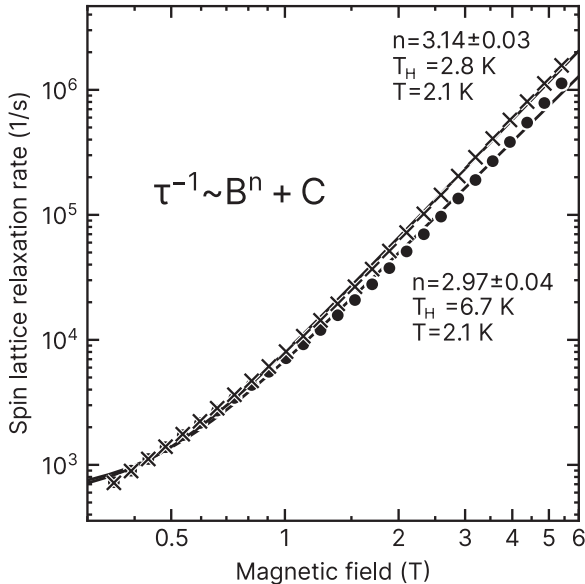


FIG. 8. Numerical simulation of the spin-lattice relaxation rate vs temperature obtained from the solution of Eq. (3) for two initial temperatures T_H . Symbols represent values obtained from the simulation, and the solid curve represents a fitted power function of the form $\tau^{-1} \sim B^n + C$ with an exponent value close to the number 3. The obtained dependence qualitatively agrees with the results presented in Fig. 3(b).

deviation of $8.5 \mu\text{eV}$. The obtained temperature dependence of the spin-relaxation rate for the neutral exciton strongly suggests a one-phonon relaxation mechanism [6]. The spin-relaxation rate obtained from the charged exciton shows a much stronger dependence on temperature. One explanation for this observation could be that charged excitons are probing different populations of manganese ions. One can imagine local, submicrometer-scale spatial fluctuations of potential, where a charged exciton forms more frequently. The manganese ions located in such a charged area may have more possibilities of transferring energy to the crystal-lattice, as more quasiparticles are involved. Therefore, in case of manganese ions interacting with charged excitons the temperature exponent m of the spin-lattice relaxation rate may be greater than 1. During the experiments the laser spot had a diameter of approximately $100 \mu\text{m}$ resulting in clear visibility of both charged and neutral excitons. In our case both the charged and neutral exciton exhibited resonance at the same magnetic field—we do not observe excitonic Knight shift [41–44].

In our measurements, we observed spin-lattice relaxation rates of approximately $2 \times 10^3 \text{ s}^{-1}$ at 1 T and 4 K for a Mn concentration of 0.26% ($x_{\text{Mn}} = 0.0026$). This aligns well with the trends of the relaxation rates reported in the literature. For instance, Lambe and Kikuchi [45] reported a slower relaxation rate of $1 \times 10^2 \text{ s}^{-1}$ at 4.2 K for a lower Mn concentration of 0.01% ($x_{\text{Mn}} = 0.0001$). Witowski *et al.* [11] observed faster relaxation rates of $2 \times 10^4 \text{ s}^{-1}$ at 1 T and 4.2 K for $x_{\text{Mn}} = 1\%$, with higher rates at greater concentrations. Similarly, Goryca *et al.* [46] reported relaxation rates close to $5 \times 10^3 \text{ s}^{-1}$ at 1 T and temperatures between 1.5–4.7 K for Mn concentrations comparable to ours. Combined together, these results hint that the relaxation rate increases with the Mn content. Conversely, a pure direct mechanism should not exhibit a significant dependence of the relaxation rate on Mn concentration. Therefore, the inferred increase in relaxation rates with higher Mn concentrations suggests that apart from the direct mechanism discussed in our work, also additional factors may play a role here. However, it is important to note that this speculation is based on a collection of samples grown in completely independent processes at different facilities. Deeper understanding of these factors would require a study involving a systematic series of samples with varying Mn concentrations grown under identical conditions.

The model presented in Sec. III B, which assumes a one-phonon scattering mechanism, reproduces all observed trends: spin-lattice relaxation vs temperature, vs magnetic field, and vs deformation. However, the obtained by simulation exponent $n \approx 3$ is not common in the literature in the context of the direct spin-lattice relaxation mechanism. This discrepancy can be attributed to the energy regimes at which the measurements were taken. In this work, the energy splittings corresponding to the paramagnetic resonance and zero field splitting are of the same order as the thermal energy. This is evident in Fig. 5(d). In equilibrium, the most occupied level is the lowest energy level (solid curve). Yet, in a steady state, the highest energy level (marked by a line interrupted by four dots) still has a nonzero occupation, close to 4%. As a result, it is challenging to provide an easily approximated analytical solution, as is typically presented in literature [6,7,9,36,40]

for high-magnetic field, low-temperature regime, or for low-magnetic field, high-temperature regime.

Similarly, observed speed-up of spin-lattice relaxation rate of Mn^{2+} ions (despite the vanishing orbital momentum of manganese $2+$ ion) originates from evolution of manganese energy levels due to the zero-field-splitting term—Fig. 5(b). As deformation increases, the energy levels change their spacing. The leading effect responsible for the overall speed-up is the increased energy separation between higher energy levels, which corresponds to a higher phonon density of states. Again this unexpected outcome is a result of energy scales present in the system—energy levels shifts are comparable with shift caused by Zeeman splitting.

In summary, in this work we presented systematic study of spin-lattice relaxation rate measured by time-resolved optically detected magnetic resonance (ODMR) on $(\text{Cd},\text{Mn})\text{Te}/(\text{Cd}, \text{Mg})\text{Te}$ MBE-grown quantum wells. We controlled the strain of Mn-doped QW layer by choosing the magnesium content present in the buffer layer and barrier

layers. We observed that spin-lattice relaxation rate increases as the deformation present in the quantum well increases. The spin-lattice relaxation rate dependence vs magnetic field and temperature combined with numerical modeling suggest that direct process is a dominant mechanism responsible for energy transfer from Mn^{2+} spins system to the CdTe crystal lattice.

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