Electron spin polarization through interactions between excitons, trions, and the two-dimensional electron gas

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We use a two-color transient Kerr rotation technique to study the spin dynamics in an *n*-doped $CdTe/Cd_{0.85}Mg_{0.15}Te$ quantum well. The dynamics displays the interplay between excitons, trions, and the two-dimensional electron gas. The spin relaxation of individual species is resolved by spectral selection. The spin dynamics are quantitatively described by rate equations involving the spin populations of excitons, trions, and the electron gas. Under resonant excitation of excitons, spin polarization of the electron gas is generated through trion formation, with the spin coherence partially lost through exciton spin relaxation. A maximum hole spin-flip time is observed around the trion resonance, with a rapid decrease for increasing excitation energy.

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I. INTRODUCTION

The study of electron spin dynamics in low-dimensional semiconductor structures has evoked considerable interest because of potential applications in future spintronic devices and quantum information processing technologies.[1] These applications require long spin coherence times of the carriers, which have been measured in lightly *n*-doped semiconductor quantum wells (QWs) by exciting and probing optical transitions.[2] In these systems, the interband optical properties are dominated by excitons and negatively charged excitons at low temperatures, but the electron spin can persist after recombination of optically excited carriers. Coherent optical generation and manipulation of the electron spins require an understanding of how optical transitions initiate and control the electron spin polarization. In this paper, we use a two-color transient Kerr rotation (TKR) technique to study spin dynamics in a lightly *n*-doped $CdTe/Cd_{0.85}Mg_{0.15}Te$ QW. We observe the interplay of excitons, negatively charged excitons, and the two-dimensional electron gas (2DEG).

Exciton spin dynamics have been addressed mostly in undoped QWs. The exciton spin can relax via simultaneous spin flips of the electron and hole,[3,4] and the spin of the electron in an exciton can precess in an applied magnetic field under the electron-hole exchange interaction.[5,6] Little work has been done on the interactions between the spin polarization of excitons and that of the electron gas in lightly *n*-doped QWs,[7] despite the importance of the exciton transition on optical orientation of the electron gas.

A negatively charged exciton, a trion, first observed in a CdTe QW,[8] plays an important role in the optical spectra of moderately doped QWs.[9,10] The unique signature of a trion in spin dynamics is that it can only contribute to the spin dynamics by its hole spin, because a trion in its singlet state consists of a hole and two electrons with opposite spins. However, upon optical excitation of spin-polarized trions, electrons of a certain spin polarization are removed from the 2DEG to form trions, polarizing the 2DEG with an opposite spin. The spin orientation of the electron gas from resonant trion excitation has been previously reported,[11–13] with the coherent spin polarization of the electron gas modified by the trion recombination.[14] In lightly *n*-doped CdTe QWs, long electron spin coherence times up to 30 ns have been reported.[13,15]

In this work, a two-color transient Kerr rotation technique is used to study an *n*-doped CdTe QW, in which the photon energies of the pump and probe pulses can be independently varied.[16] Different effects from excitation and detection can be well separated in such experiments. For example, spin polarization under different excitation energies can be compared by scanning the pump energy through exciton and trion resonances, with the probe energy fixed near the exciton resonance. We show that the spin of the 2DEG can be polarized through the formation of trions via exciton states. The exciton spin polarization is transferred to the electron gas coherently, with the spin coherence partially lost through exciton spin relaxation. To characterize the spin-polarization process of the electron gas, the interplay between the exciton, trion, and 2DEG spins and their individual spin relaxation need to be taken into account. The observed TKR signals are quantitatively explained with rate equations involving the spin populations of exciton, trion, and the electron gas. Trion spin relaxation also reveals information on the hole spin-flip process, giving the excitation energy dependence of the hole spin relaxation.

II. SAMPLES AND EXPERIMENTAL SETUP

The sample is a modulation doped $CdTe/Cd_{0.85}Mg_{0.15}Te$ heterostructure grown by molecular-beam epitaxy on a GaAs substrate. The sample contains two CdTe QWs with widths of 120 and 70 Å, separated by a 50 Å $Cd_{0.85}Mg_{0.15}Te$ barrier. The 120 Å QW is one-side doped by an iodine impurity layer 100 Å from the QW, resulting in a 2DEG density of

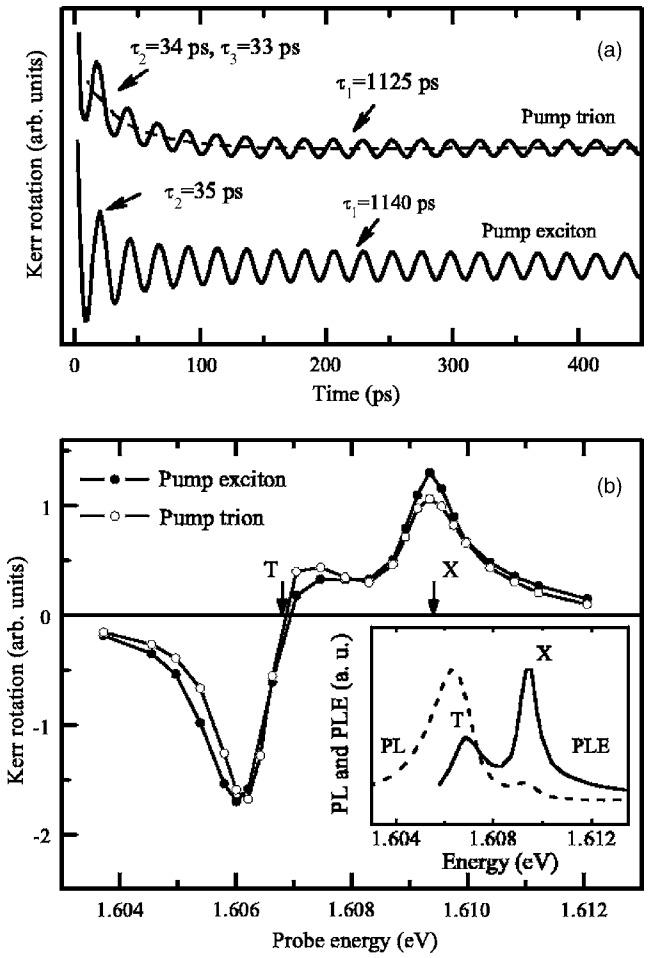

FIG. 1. (a) TKR signals under resonant excitations of excitons and trions, with probe photon energy at the exciton resonance. The time constants shown are obtained from nonlinear fitting. (b) The Kerr rotation amplitude of the 2DEG spin polarization (A_1) as a function of probe photon energy under resonant excitations of excitons and trions. Inset: Low-temperature PL and PLE spectra showing the exciton (X) and trion (T) lines. $B=2$ T and $T=4$ K.

8×10^{10} cm^{-2} in the well. We study the 120 Å QW only. The sample belongs to a set of samples with different doping densities grown on the same wafer. A nonmonotonic dependence of the electron spin coherence on the 2DEG density has been established.[17]

The low-temperature photoluminescence (PL) and photoluminescence excitation (PLE) spectra are shown in the inset of Fig. 1(b). The spectra exhibit exciton and trion lines with an energy separation of 2.6 meV, which is the trion binding energy. The large trion binding energy (as compared with III-V semiconductors) and the relatively narrow linewidths of the resonances allow us to selectively generate excitons and trions by means of optical excitation. There is a Stokes shift of ~0.5 meV between PL and PLE maxima, which originates from carrier localization due to disorder. The PLE spectrum shows that the peak exciton absorption strength is about twice that of the trion. The PL spectrum, however, is dominated by trion recombination. This indicates that the majority of the optically created carriers relax to the trion states. Under resonant excitation of excitons, the conversion of excitons to trions is much faster than the exciton recombination.

We perform TKR measurements in a magneto-optical cryostat, in which a magnetic field of 2 T is applied normal to the QW growth direction (Voigt geometry).[18] Pump and probe pulses are produced by a mode-locked Ti:sapphire laser, and are spectrally filtered (resulting in ~5 ps pulses) to enable independent tuning of their photon energies. The spectral width of the pulses is adjusted to be ~0.2 nm for spectrally resolved measurements. The pump and probe photon energies are scanned near the vicinity of the exciton and trion resonances of the 120 Å QW. Average intensities are about 1 W/cm^2 in the pump (except as specified otherwise in the text) and 0.1 W/cm^2 in the probe beam. The pump (probe) beam is focused onto the sample with a spot diameter of ~100 μm (50 μm). All experiments are performed at 4 K.

III. EXPERIMENTAL RESULTS

TKR signals under a transverse magnetic field for resonant excitations of excitons and trions are shown in Fig. 1(a). The probe photon energy is tuned to the exciton resonance (1.6093 eV) for both pump energies. By fixing the probe energy, a comparison of TKR signals under different excitation energies is possible. The oscillation signals correspond to the Larmor precession of carrier spins in an external magnetic field. A precession frequency of 43.3 GHz is measured, corresponding to a Landé g factor of $|g|=1.55$, in good agreement with previous results.[19] The TKR signal under exciton generation exhibits two exponential decays of the oscillation with very different time constants. A nonoscillating decay component in addition to the double exponential is observed under trion excitation. We perform a least-squares fitting to the transient signals with the form $\theta_K(t)=(A_1e^{-t/\tau_1}+A_2e^{-t/\tau_2})\cos(\omega_L t)$, where ω_L is the Larmor precession frequency, and τ_1 and τ_2 (A_1 and A_2) are the long and short spin dephasing times (precession amplitudes), respectively. A third term, A_3e^{-t/τ_3}, is included in the fit to account for the nonoscillating decay under trion excitation. The time constants retrieved from the fit are also displayed in Fig. 1(a). Both signals show a long-lived oscillation component that lasts over 1 ns. As this time constant exceeds lifetimes of excitons and trions (measured to be <100 ps in Ref. 10), we conclude that this is the spin Larmor precession of the 2DEG. The short-time constants should be related to the exciton and trion spin dynamics, which will be discussed later.

To study how the probe photon energy affects the TKR signal, we scan the probe energy with the pump photon energy fixed on either the exciton or trion resonance. The Kerr rotation amplitude of the 2DEG spin polarization (A_1) is plotted in Fig. 1(b) as a function of probe energy. The similarity of the probe spectra obtained with exciton and trion excitation confirms spin polarization of the electron gas for both excitation conditions. The spectra also indicate a difference in response sensitivity between detection through exciton and trion resonances (given that the carrier densities excited are different under resonant exciton and trion excitation). The remaining experiments in this paper will be

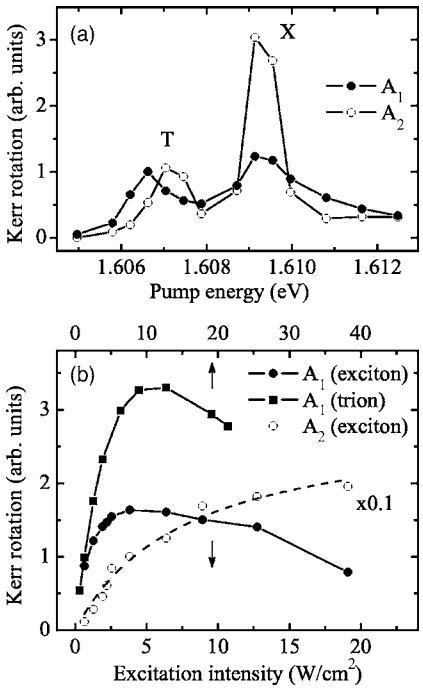

FIG. 2. (a) Kerr rotation amplitudes as a function of pump photon energy for the slow (A_1) and fast (A_2) decay components. (b) Excitation intensity dependence of the Kerr rotation amplitudes (A_1 and A_2) under resonant excitation at excitons and trions. The amplitude A_2 for resonant exciton generation is fitted with a saturation function (dash line). $B=2$ T and $T=4$ K. Probe energy is tuned at exciton resonance.

performed with the probe energy fixed, so that a comparison of amplitudes resulting from different excitation energies is possible. The spectra in Fig. 1(b) show a peak line shape for the exciton resonance and a mixture of dispersive and peak line shapes for the trion resonance. The different line shapes of the resonances result from different nonlinear responses of excitons and trions from spin-polarized electrons.[20] This is supported by a recent work on CdTe-based QWs,[21] where the spin-polarized electron gas is shown to effectively screen excitons, but not trions. The extraction of the different nonlinear responses is, however, not the goal of this paper.

To explore the short-time behavior in the TKR signals and the origins of the electron-gas spin polarization through optical excitation, we study the TKR spectrum with varying pump photon energy. Specifically, we selectively generate exciton and trion populations, while the probe photon energy remains fixed at the exciton resonance. The transient data are again analyzed by least-squares fitting to a double exponential, and we plot the Kerr rotation amplitude for the slow (A_1) and fast (A_2) decay components as a function of pump energy, as shown in Fig. 2(a). The amplitude of the fast decay component exhibits a sharp peak at the exciton energy, with a full width at half maximum linewidth (0.7 meV) that agrees well with the exciton linewidth in the PLE spectrum (0.8 meV). We assign the fast oscillation decay to exciton spin precession and dephasing. The decay time (τ_2) is a combination of the exciton spin dephasing time and trion formation time. The relatively weak signal of A_2 near the trion energy is probably related to the ionization of trions into excitons, as the trion itself cannot contribute to the oscillatory signal.[13] The amplitude of the slow decay component, which is proportional to the 2DEG spin polarization, is enhanced at both exciton and trion resonances. This enhancement indicates spin polarization of the electron gas through optical excitation of excitons. We propose that excitons polarize the spin of the 2DEG through their conversion to trions, which preserves the spin orientation and polarizes the 2DEG. The spin-flip scattering of excitons by single electrons, for instance, could also polarize the 2DEG. However, since the majority of the optically excited excitons relax to the trion states (evidenced in the PL spectrum), we believe that the trion formation process dominates.

We obtain further information on the exciton and electron-gas spin polarizations by varying the pump excitation intensity. In Fig. 2(b), the excitation intensity dependence of the Kerr rotation amplitudes is shown for resonant excitation at excitons and trions, with the probe photon energy tuned at the exciton resonance. The fast decay amplitude (A_2) for resonant excitation at the exciton, related to the exciton spin polarization, increases monotonically with intensity, and can be well fitted with a saturation function $P_1 I/(P_2+I)$, with P_1 and P_2 constants and I the intensity. The electron-gas spin polarization (A_1), on the other hand, actually decreases at high intensity for excitation at both exciton and trion resonances. The absorption strength at trion energy is about one-half of that at exciton energy. With this correction [by using different scales of excitation intensity for the exciton and trion in Fig. 2(b)], we observe very similar intensity dependence of the 2DEG spin polarization for resonant excitation of excitons and trions. We attribute the decrease of electron spin polarization at high excitation intensity to heating of the electron gas under photoexcitation,[22] which leads to electron delocalization in the quantum well.[13] By exciting trions directly, the electron spin polarization is about twice that from exciton generation [as indicated by the peak A_1 amplitudes in Fig. 2(b) for the exciton and trion]. We will show later that this is due to a similar trion formation time and exciton spin dephasing time; thus, spin coherence is partially lost before an exciton forms a trion.

In Fig. 1(a), a nonoscillating component at short-time delay is observed for trion excitation, with a decay time of $\tau_3 = 33$ ps. The trion only contributes to the spin dynamics through its hole spin, because of the two opposite electron spins in a trion. The nonoscillating component observed in the TKR signal is therefore assigned to the hole spin flip in trions, with τ_3 the hole spin-flip time.[13] We measure the hole spin-flip time as a function of the pump photon energy. For this measurement, the probe photon energy is set near the trion resonance at 1.6066 eV, which gives the highest sensitivity for measuring the hole spin flip. The pump energy is scanned, with its excitation intensity varied to ensure roughly equal optical carrier density (calibrated through the PLE spectrum). The resulting spectrum for the hole spin-flip time is shown in Fig. 3. The hole spin-flip time is maximum around the trion resonance, and decreases rapidly with increasing excitation energy.[23] The observed hole spin-flip times are of the same order of magnitude as previous measurements.[24] Hole states are, in general, an admixture of

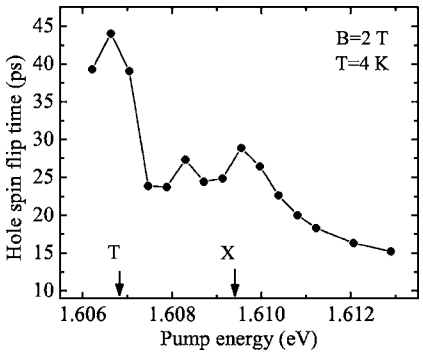

FIG. 3. The hole spin-flip time (in trions) as a function of the excitation energy.

various spin states, and any energy or momentum relaxation process will lead to their spin relaxation.[3,7] This explanation supports our experimental results, where a fast hole spin flip is observed for hot-hole generation. We note that the hole spin flip under resonant excitation of excitons is much faster than that under excitation of trions [also illustrated in Fig. 1(a) as a vanishing nonoscillation decay for exciton generation]. We believe that the enhancement of the hole spin-flip rate in excitons is due to exchange interactions between the electron-hole pairs in excitons, as detailed in Ref. 4. With the two electrons in a trion having opposite spins, the exchange interaction vanishes for the hole, giving a longer hole spin-flip time for trions.

IV. ANALYSIS

To explain the TKR signals observed in Fig. 1(a), the interplay between the spin populations of exciton, trion, and 2DEG under magnetic field needs to be taken into account. We quantitatively model the spin dynamics by using rate equations for the spin populations of exciton, trion, and 2DEG. Disorder, as evidenced from the observed Stokes shift between PL and PLE spectra, is not considered in the model. It has been shown that disorder due to QW width fluctuations affects the electron spin dephasing time.[25] Nevertheless, we do not expect that disorder changes the general trends of the spin interplay between excitons, trions, and 2DEG presented in this paper.

We start with the case of resonant trion excitation. In Fig. 4(a), the schematic diagram reflects the interplay between trions and 2DEG. Without any loss of generality, we assume that a σ^+ polarized pulse at $t=0$ generates spin $+\frac{3}{2}$ trions and spin $-\frac{1}{2}$ electrons in the 2DEG. The trion spin will not precess under the magnetic field because of the two opposite spins of electrons inside a trion and a negligible Zeeman splitting of the heavy-hole spins in the transverse direction. Instead, the trion spin will relax with its hole spin-flip rate and decay exponentially. The trion spin polarization ΔN^T is

$$\Delta N^T(t) = N_+^T(0)\exp(-t/\tau^T), \tag{1}$$

where $\Delta N^T = N_+^T - N_-^T$ is the difference between the spin $+\frac{3}{2}$ and $-\frac{3}{2}$ trion populations and $1/\tau^T = 1/\tau_s^T + 1/\tau_r^T$, with τ_s^T the trion spin relaxation time and τ_r^T the trion recombination

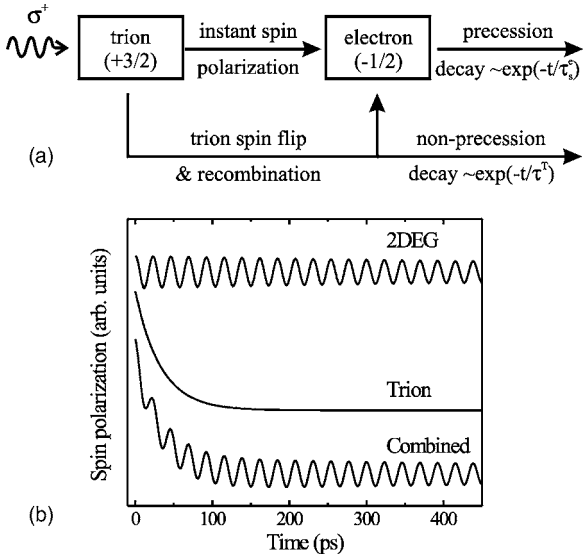

FIG. 4. (a) A schematic diagram displaying the interplay between the spin populations of trions and 2DEG under resonant trion excitation. (b) Calculated transients of the spin polarization of the 2DEG, trions, and the combination of the two.

time. The nonoscillating decay component in Fig. 1(a) corresponds to trion spin relaxation described in Eq. (1); thus, $\tau^T = 33$ ps.

The spin polarization of the 2DEG under trion excitation is generated through two different sources, initial polarization upon trion formation (instantaneously during pulse duration) and possible spin polarization through trion recombination (release of a spin-polarized electron to the 2DEG after trion recombination). The spin polarization of the 2DEG generated upon trion formation at $t=0$ will precess around the magnetic field, with the projection in the QW growth direction,

$$\Delta N_1^e(t) = -N_+^T(0)\cos(\omega_L t)\exp(-t/\tau_s^e). \tag{2}$$

Here, τ_s^e is the electron spin dephasing time. The trion recombination can also contribute to the electron-gas spin polarization by returning spin-polarized electrons back to the 2DEG after trion recombination. The 2DEG spin polarization at t generated by trion recombination is

$$\Delta N_2^e(t) = \int_0^t [\Delta N^T(t')/\tau_r^T]\cos[\omega_L(t-t')]\exp[-(t-t')/\tau_s^e]dt'. \tag{3}$$

The total 2DEG spin polarization ΔN^e is

$$\Delta N^e(t) = \Delta N_1^e + \Delta N_2^e = B_1\cos(\omega_L t + \phi)\exp(-t/\tau_s^e) + B_2\exp(-t/\tau^T), \tag{4}$$

with

$$B_1 = -N_+^T(0)\sqrt{1-\left(2-\frac{\tau^T}{\tau_r^T}\right)\frac{\tau^T}{[(\omega_L\tau^T)^2+1]\tau_r^T}},$$

$$\phi = \arctan\frac{\omega_L(\tau^T)^2}{[(\omega_L\tau^T)^2+1]\tau_r^T-\tau^T},$$

$$B_2 = -N_+^T(0)\frac{\tau^T}{[(\omega_L\tau^T)^2+1]\tau_r^T}. \quad (5)$$

The results in Eqs. (4) and (5) are simplified by assuming a much longer electron spin dephasing time (τ_s^e) than the trion time constants (τ_s^T and τ_r^T), which is sufficient for a τ_s^e over 1 ns in our sample. The relative contribution of the trion recombination to the 2DEG spin is related to the term $\tau^T/\{[(\omega_L\tau^T)^2+1]\tau_r^T\}$, which will only be significant when the trion spin orientation is partially maintained during its lifetime ($\tau_s^T > \tau_r^T$), and the trion time constants are much shorter than the electron precession period ($\omega_L\tau^T < 1$), so that the electron spin is not out of phase with that of the trions. In our sample, the oscillation period is 23 ps for a magnetic field of 2 T, which is comparable to the trion time constants ($\tau_s^T = 33$ ps). The trion recombination therefore plays a negligible role in the spin dynamics of the electron gas in our sample ($\Delta N_2^e \approx 0$), and the 2DEG spin polarization is generated mainly from trion formation ($\Delta N^e \approx \Delta N_1^e$). The total 2DEG spin polarization therefore follows that described in Eq. (2). The spin dynamics of 2DEG, trions, and the combination of the two (which corresponds to the TKR signal measured) are calculated and plotted in Fig. 4(b), with $\tau^T = 33$ ps, $\tau_s^e = 1100$ ps, and $\omega_L = 2\pi \times 43.3$ GHz. The combined spin polarization represents well the measured TKR signal for trion excitation shown in Fig. 1(a).

The exciton spin precession and dephasing under a transverse magnetic field is illustrated in Fig. 1(a) as the fast oscillating decay. In QWs, the heavy-hole spins are constrained to lie normal to the QW plane by effects of quantum confinements, and are not observed to precess under moderate magnetic fields.[18] The spin of the electron in an exciton does undergo Larmor precession. With a long hole spin-flip time in the exciton, this results in an oscillation between the bright and dark exciton populations,[26] and a modified spin precession frequency due to the electron-hole exchange interaction.[27] To understand the exciton spin relaxation, both the single-particle spin flips of the electrons and holes in excitons, and the exciton spin flip as a whole (simultaneous spin flip of electrons and holes), need to be taken into account. We write down the rate equations for spin polarized carriers, including the electrons (with spins $\frac{1}{2}$ and $-\frac{1}{2}$) and heavy holes ($\frac{3}{2}$ and $-\frac{3}{2}$) in the excitons. We consider the difference between the bright and dark excitons because the TKR signal measured corresponds to the spin population of the bright excitons only. The spin polarization of the bright excitons is

$$\Delta N_{br}^X(t) = \frac{1}{2}N_+^X(0)[\cos(\omega_L t)e^{-t/\tau_1^X} + e^{-t/\tau_2^X}], \quad (6)$$

with

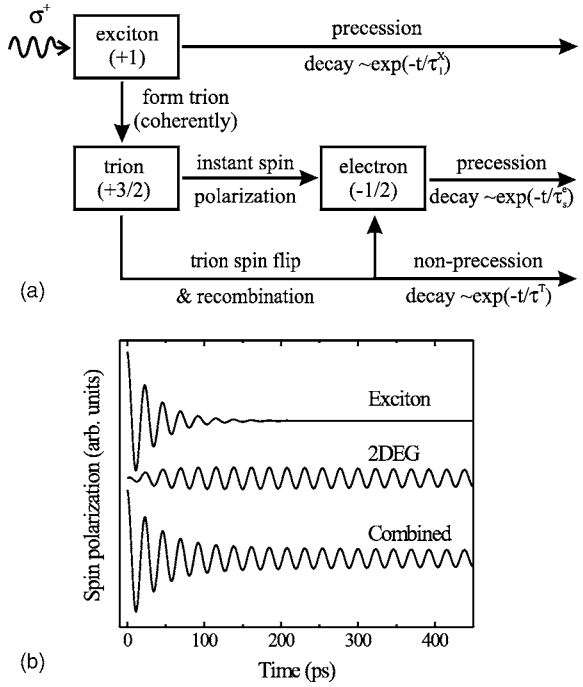

FIG. 5. (a) A schematic diagram displaying the interplay between the spin populations of excitons, trions, and 2DEG under resonant exciton excitation. (b) Calculated transients of the spin polarization of the excitons, 2DEG, and the combination of the two.

$$\frac{1}{\tau_1^X} = \frac{1}{\tau_{es}^X} + \frac{1}{\tau_s^X} + \frac{1}{\tau^{XT}} + \frac{1}{\tau_r^X},$$

$$\frac{1}{\tau_2^X} = \frac{1}{\tau_{hs}^X} + \frac{1}{\tau_s^X} + \frac{1}{\tau^{XT}} + \frac{1}{\tau_r^X}. \quad (7)$$

Here, $\tau_{es}^X(\tau_{hs}^X)$ is the electron (hole) spin-flip time in exciton, τ_s^X is the exciton spin-flip time (as a whole), τ^{XT} is the trion formation time, and τ_r^X is the exciton recombination time. We note that Eq. (6) consists of an oscillating decay term and a nonoscillating decay term. From comparison with the experimental results [Fig. 1(a)], we find $\tau_1^X = 35$ ps and τ_2^X very small with no observable nonoscillation decay ($\tau_2^X < 10$ ps, half period of the oscillation). This indicates a very short hole spin-flip time in our sample. Both the exciton spin flip as a whole (τ_s^X) and the electron spin flip in excitons (τ_{es}^X) are included in our model [Eqs. (7)]. However, they cannot be separately determined based on the current experiments. We therefore treat their combined effects as an overall exciton spin dephasing time τ_s^X. Equations (7) may be rewritten as

$$\frac{1}{\tau_1^X} = \frac{1}{\tau_s^X} + \frac{1}{\tau^{XT}} + \frac{1}{\tau_r^X},$$

$$\frac{1}{\tau_2^X} \sim \frac{1}{\tau_{hs}^X}. \quad (8)$$

The calculated TKR from exciton spin dephasing is plotted in Fig. 5(b), assuming $\tau_1^X = 35$ ps, $\tau_2^X = 0$ ps, and $\omega_L = 2\pi \times 43.3$ GHz.

The spin interactions between excitons and the 2DEG are proposed to be through trion formation via exciton states. The spin interplay between excitons, trions, and electrons under resonant exciton excitation is displayed in Fig. 5(a). Any time a trion is formed from an exciton that consists of a $-\frac{1}{2}$ electron, a spin polarization of $-\frac{1}{2}$ is added to the 2DEG. The 2DEG spin polarization generated by trion formation for $[t', t'+dt']$ is

$$d\Delta N^e(t') = -[N_+^X(0)/\tau^{XT}]\cos(\omega_L t')e^{-t'/\tau_1^X}dt'. \quad (9)$$

Here, both bright and dark excitons can form trions and contribute to the 2DEG spin polarization. The hole spin orientation in the excitons does not matter in the spin polarization of the 2DEG, because it is the spin coherence of the electron in the exciton that is passed to the 2DEG. The $\cos(\omega_L t')$ term in Eq. (9) indicates a coherent spin transfer from exciton to the 2DEG; i.e., the spin of the electron gas will precess in phase with the exciton spin under the magnetic field. The resulting 2DEG spin polarization under resonant exciton generation is then

$$\Delta N^e(t) = [N_+^X(0)\tau_1^X/\tau^{XT}]\cos(\omega_L t)(e^{-t/\tau_1^X} - e^{-t/\tau_s^e}). \quad (10)$$

Equation (10) is obtained by assuming long electron spin dephasing time (τ_s^e) and negligible electron spin polarization from trion recombination process. The 2DEG spin precession is shown to first rise due to trion formation, and then decay according to the electron spin dephasing. The calculated 2DEG spin dynamics, as well as the overall signal including the exciton spin polarization (corresponds to the experimental results), is plotted in Fig. 5(b). The overall spin polarization agrees well with the measured TKR signal shown in Fig. 1(a).

The 2DEG is spin polarized through trion formation for resonant excitations of both excitons and trions. The degree of spin polarization, however, differs for the two excitation conditions due to exciton spin dephasing. The 2DEG spin polarizations under resonant excitation of trion and exciton are described in Eqs. (2) and (10), respectively, and the ratio between the two at long delay time is

$$\frac{N_+^T(0)}{N_+^X(0)}\frac{\tau^{XT}}{\tau_1^X} \approx \frac{N_+^T(0)}{N_+^X(0)}\left(1+\frac{\tau^{XT}}{\tau_s^X}\right), \quad (11)$$

with the assumption that the exciton recombination time is much longer than the trion formation time (evidenced from the small exciton recombination signal in PL spectrum). The ratio in Eq. (11) compares the 2DEG spin polarization at a long delay time for exciton and trion excitations, which corresponds to amplitude A_1 retrieved from the experimental results. With an equal number of carriers generated initially $[N_+^T(0)=N_+^X(0)]$, the 2DEG spin polarization under trion excitation is $(1+\tau^{XT}/\tau_s^X)$ times that under the exciton generation. In Fig. 2(b), the peak 2DEG polarization for trion generation is about two times that for exciton generation, which indicates similar time constants for the trion formation time and exciton spin dephasing time ($\tau^{XT} \approx \tau_s^X$). In our sample, excitons form trions at the same rate as they lose their spin coherence through exciton spin relaxation. Therefore, only half of the spin coherence is passed to the 2DEG.

V. CONCLUSION

In summary, we use the transient Kerr rotation technique to study the spin dynamics of excitons, trions, and the 2DEG in an *n*-doped $CdTe/Cd_{0.85}Mg_{0.15}Te$ QW. The spin relaxation of individual species is distinguished with the help of spectral selection. We show that to characterize the spin polarization of the electron gas, the interplay of the spin dynamics between excitons, trions, and the 2DEG must be taken into account. Optically generated exciton spins interact with those of the 2DEG through trion formation. The spin polarization of excitons is transferred to the electron gas coherently, with spin coherence partially lost through exciton spin relaxation. The hole spin-flip process is faster in excitons than in trions due to the electron-hole exchange interaction. The observed TKR signals are quantitatively explained with rate equations involving the spin populations of exciton, trion, and the electron gas.

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