Spin coherence of electrons and holes in ZnSe-based quantum wells studied by pump–probe Kerr rotation

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Spin coherence of resident electrons and holes is measured in ZnSe-based quantum wells by means of time-resolved Kerr rotation technique. At a temperature of 1.8 K spin dephasing time for localized electrons can be as long as 33 ns, and for holes of 0.8 ns. Electron spin precession is clearly observed in a wide temperature range up to 230 K. The electron spin dephasing becomes much shorter of 0.2 ns for the quantum well with a high-density electron gas. Using vector magnet all components of the $g$-factors tensor are evaluated for the electrons and heavy-holes, revealing strong anisotropy for the heavy-holes.

1 Introduction Spin coherence of electrons and holes is one of the key features involved in numerous concepts for spintronic devices. It has been studied in semiconductor structures of different dimensionality, including bulk-like thin films, quantum wells (QWs), and quantum dots [1–3]. Spin dephasing time of electron and hole ensembles and spin coherence time of individual electrons and holes have been found to vary over a wide temporal range from a few picoseconds up to a few microseconds. These studies have been performed for various material systems based on III–V (e.g., GaAs, (In,Ga)As, GaN) and II–VI (e.g., CdTe, ZnSe, (Zn,Cd)Se) semiconductors. Among them ZnSe-based heterostructures have a number of attractive properties. First of all, it is their strong Coulomb interaction, which results in the large exciton binding energy of 20 meV in bulk ZnSe [4] and up to 40 meV in QWs [5]. Second, photoluminescence (PL) is in a blue spectral range of 2.8–3.2 eV. Also the QW structures grown by molecular-beam epitaxy demonstrate very good optical properties: narrow emission lines at low temperatures and high quantum efficiency.

On ZnSe basis several types of QW structures have been grown and investigated. Historically it starts from (Zn,Cd)Se/ZnSe QWs, where the QW is composed of the ternary (Zn,Cd)Se alloy. As a result, exciton resonances are inhomogeneously broadened by alloy fluctuations to about 10 meV [6]. Later, structures with binary ZnSe QWs have been fabricated, for which various alloys have been chosen as barrier materials, like (Zn,Be)Se, (Zn,Be,Mg)Se, or (Zn,Mg)(S,Se), providing a type-I band alignment when electrons and holes are confined in the same ZnSe layer. Exciton resonances in reflectivity, absorption or emission in these QWs are narrow, of a few meVs, which make them very attractive for optical spectroscopy of charged and neutral excitons [5, 7–10]. Also ZnSe/BeTe heterostructures with a type-II band alignment, where electrons and holes are separated spatially being localized in ZnSe and BeTe layers, respectively, have been fabricated and demonstrated several new physical phenomena [11–14].

Spin coherence in ZnSe and its heterostructures has not been studied very intensively. Long-lived spin coherence of 20–30 ns for electrons localized on shallow donors has been reported for $n$-type doped ZnSe epilayers [1, 15]. Spin injection of electrons from GaAs to ZnSe epilayers with conserving their spin coherence has been identified by pump–probe
Faraday rotation [16, 17]. In (Zn,Cd)Se/ZnSe QWs with electron density of \((2−5) \times 10^{11} \text{ cm}^{-2}\) the electron spin dephasing time of 6 ns at liquid helium temperatures has been found, and spin beats in pump–probe Faraday rotation have been detected up to room temperature [6, 18]. While in undoped (Zn,Cd)Se/ZnSe QWs spin dynamics was very fast, 10 ps only at 5 K and increases to 200 ps at 240 K. Similar appearances have been reported for undoped ZnSe/(Zn,Mg)(S,Se) QWs [19]. These short times and their temperature dependences are specific for exciton spin dynamics, for which, e.g., the strong increase of spin lifetime can be caused by motional narrowing due to the faster scattering of excitons with increasing temperature. Much longer electron spin dephasing times up to 6 ns have been observed in ZnSe/BeTe heterostructures with a type-II band alignment, where the two-dimensional electron gas (2DEG) has been formed under photoexcitation in ZnSe layer due to spatial separation of electrons and holes [14]. We are not aware about the studies of electron and/or hole spin coherence in binary ZnSe QWs with a type-I band alignment with a two-dimensional carrier gases formed by modulation doping, or by above-barrier illumination, similar to, e.g., CdTe/(Cd,Mg)Te QWs [20, 21].

In this paper we report on a detailed study of the coherent spin dynamics of resident electrons and holes in ZnSe-based QW heterostructures with a binary QW material and various barriers of (Zn,Be)Se, (Zn,Be,Mg)Se, and (Zn,Mg)(S,Se). Achieving of long-lived carrier spin coherence and anisotropy of electron and hole \(g\)-factors measured by pump–probe Kerr rotation are under consideration.

### 2 Samples and experimental technique

Three samples of ZnSe-based QWs with a type-I band alignment and with different densities of two-dimensional electron and hole (2DHG) gases have been studied. The structures were grown by molecular-beam epitaxy on (100)-oriented GaAs substrates and contain single quantum wells (SQW) confined between different barrier materials: (Zn,Be,Mg)Se, (Zn,Be)Se, and (Zn,Mg)(S,Se). Band diagrams for these structures are schematically shown in Fig. 1.

Sample #1 (cb1041) is a ZnSe/Zn\textsubscript{0.92}Be\textsubscript{0.08}Mg\textsubscript{0.10}Se single QW structure, where 6.7 nm-thick ZnSe QW is located between 100 nm-thick Zn\textsubscript{0.82}Be\textsubscript{0.08}Mg\textsubscript{0.10}Se barriers with the band gap of 3.06 eV, see Fig. 1a. The band gap of ZnSe at \(T = 1.8\) K is 2.82 eV. In order to prevent the loss of carriers escaping into the substrate and recombining at the surface, this structure was clad between 50 nm-thick Zn\textsubscript{0.71}Be\textsubscript{0.29}Mg\textsubscript{0.18}Se barriers with larger band gap of 3.21 eV, see also details in Ref. [5]. The resident electron density \((n_e)\) of \(n_e = 3 \times 10^{10} \text{ cm}^{-2}\) in this sample is due to unintentional \(n\)-type doping of the thick barrier layers, which delivers the resident electrons for the QW. This electron concentration corresponds to Fermi energy of \(E_F = 0.5\) meV. The zero level of the Fermi energy coincides with the conduction band edge in the QW.

Sample #2 (cb2171) is a ZnSe/Zn\textsubscript{0.92}Be\textsubscript{0.08}Se single QW structure with \(n\)-type modulation doping, see Fig. 1b. It has a 10 nm-thick ZnSe QW embedded between 100 nm-thick Zn\textsubscript{0.94}Be\textsubscript{0.06}Se barriers with a band gap of 2.93 eV and additional 50 nm-thick Zn\textsubscript{0.92}Be\textsubscript{0.08}Se barriers with a band gap of 2.96 eV. Sample has 2 nm-thick layers with Iodine donors symmetrically located on both sides of the well at a distance of 10 nm. These donors provide 2DEG with a density of \(1.4 \times 10^{12} \text{ cm}^{-2}\) and \(E_F = 21.5\) meV. Details of optical and magneto-optical properties of this structure can be found in Ref. [9], where it is denoted as #2D sample.

Sample #3 (zq1038) is a ZnSe/Zn\textsubscript{0.89}Mg\textsubscript{0.11}S\textsubscript{0.18}Se\textsubscript{0.62} single QW structure with \(n\)-type modulation doping, see Fig. 1c. It has an 8 nm-thick ZnSe QW, which is separated from the surface by a 50 nm-thick Zn\textsubscript{0.89}Mg\textsubscript{0.11}S\textsubscript{0.18}Se\textsubscript{0.62} barrier with a band gap of 3.02 eV. The doping layer of Chlorine donors has 3 nm thickness and is separated from the QW by a 10 nm-thick spacer, being located from one side only between the QW and surface. In this structure the band gap offset between the QW and barrier material is distributed in ratio 50/50 between the conduction and valence bands, therefore, the confinement potential for electrons is only 100 meV in depth. Relatively close surface vicinity to the QW, which due to charging can cause band bending, and rather large distance for one-side donor layer results in the specific feature of this structure. It is that, despite nominal \(n\)-type doping, in the absence of above-barrier illumination the QW contains resident holes, and not resident electrons.
as it would be expected. This fact is documented by an observation of the hole spin precession in pump–probe Kerr rotation experiment described below in this paper. However, already a weak above-barrier illumination is sufficient to recharge the QW and provide in it resident electrons, which at saturation have the electron density of $6 \times 10^{10}$ cm$^{-2}$, corresponding to $E_{T} = 0.9$ meV. Reflectivity spectra for this structure can be found in Ref. [8], which correspond to n-type regime as the halogen lamp has not been spectrally filtered and provided above-barrier illumination. We will explore the specifics of this structure to study the coherent spin dynamics of both resident holes and resident electrons by tuning their concentrations with additional laser with photon energy of 3.06 eV providing above-barrier illumination.

The samples were placed in a pumped liquid helium at a temperature of $T = 1.8$ K in a vector magnet system consisting of three superconducting split-coils oriented orthogonally to each other [22]. By adjustment of the current through each coil, the magnetic field strength, $B$, can be fixed at a certain value up to 3 T, while the field orientation is variable over the whole sphere. In most cases the Voigt geometry was used, when the magnetic field was applied perpendicular to the structure growth direction ($\mathbf{z}$-axis), chosen to be parallel to the optical excitation axis.

We use time-resolved pump–probe Kerr rotation (TRKR) technique to study coherent dynamics of carrier spins, see for details Ref. [23]. Laser pulses with 1.5 ps duration (spectral width of 1 meV) were generated by Ti:Sapphire mode-locked oscillator at 75.8 MHz pulse repetition rate ($T_{r} = 13.2$ ns pulse separation). In order to reach blue spectral range of QW resonances the laser radiation was frequency doubled using a nonlinear BBO crystal. A lock-in amplifier technique is used to monitor the spin coherence excited by the circular polarized pump pulses. The circular polarization of the pump pulses was modulated from $\sigma^{+}$ to $\sigma^{-}$ at a frequency of 50 kHz using a photoelastic modulator. The probe pulses were linear polarized. The time delay between pump and probe pulses was tuned by a mechanical delay line with a precision of 7 fs. After reflecting from the sample the probe beam was sent through a $\lambda/2$ plate, Wollaston polarizer, and then measured by a balanced photodiode bridge. The laser was spectrally tuned to trion ($T^{-}$) or exciton ($X$) resonances of ZnSe QWs.

3 Experimental results and discussion

3.1 Electron gas of low density In QWs with low-density electron gas ($<5 \times 10^{10}$ cm$^{-2}$) one can neglect electron–electron interactions. At low temperatures the resident electrons are localized in QW plane on well-width fluctuations and are typically isolated by that from each other. Photoluminescence spectrum in this case shows two lines corresponding to emission of neutral and negatively charged excitons. An example of such spectrum measured at $T = 1.8$ K on an 6.7 nm-thick ZnSe/(Zn,Be,Mg)Se QW (sample #1) is given in Fig. 2a. Here exciton and trion lines have emission energies of 2.8303 and 2.8248 eV, respectively. They are separated by 5.5 meV, which corresponds to the trion binding energy [5]. The full width at half maximum of the exciton line is about 2 meV and is mainly due to exciton localization on the QW width fluctuations.

It is known, that the efficient generation of spin coherency for the low-density carrier gases is provided by the resonant pumping of the charged excitons, see, e.g., Refs. [20, 23]. Negatively charged excitons, which are often called as $T^{-}$ trions, are complexes consisting of two electrons and one hole. In the trion photogeneration process one of this electron is the resident electron and the electron–hole pair is generated by photon absorption. After trion recombination, in which trion QWs for the trions in the radiative cone can be as fast as 10–20 ps, the resident electron is left in the QW. And in case when its spin coherence is initiated by the trion generation, the following spin dynamics of the resident electron is not limited by recombination, but only by spin decoherence and spin relaxation. This allows to investigate a long-lived carrier spin dynamics. Note that this approach can be equally applied to the positively charged excitons ($T^{+}$ trions) formed in QWs with resident holes. Results for the structures with both $T^{+}$ and $T^{-}$ trions are given in this paper.

Time-resolved Kerr rotation traces measured at resonant $T^{+}$ trion excitation for different magnetic fields in range from 0.5 to 3 T are shown in Fig. 2b. One can see here fast oscillating signals, which frequency increases linearly with growing magnetic field as it is shown in Fig. 2c. From the linear fit of these data shown by a solid line the $g$-factor value of
The electron Larmor precession frequency: spin dephasing time is evaluated. Red line shows fit to the first RSA peak, from which the electron

Figure 3 Spin dynamics in an $n$-type ZnSe/(Zn,Be,Mg)Se QW (sample #1) at various temperatures. (a) Kerr rotation traces measured at $T = 200$ and $230\,K$. (b) Spin dephasing rate versus temperature. Linear fit to the data in the range from 10 to 150 K is shown by line. (c) Example of RSA spectrum measured on $T^*$-trion at low excitation density to achieve the longest $T_{2\,e} = 33\,\text{ns}$. Red line shows fit to the first RSA peak, from which the electron spin dephasing time is evaluated.

$1.13 \pm 0.01$ was received using the following equation for the electron Larmor precession frequency: $\omega_L = (g_e \mu_B B)/\hbar$. Here $\mu_B$ is the Bohr magneton and $\hbar$ the Planck constant. This $g$-factor value corresponds well to the electron $g$-factor, $g_e$, in ZnSe QWs and is close to the value for bulk ZnSe of $g_e = +1.12$, see Ref. [24] and references therein. The electron Larmor precession in Kerr rotation signals can be observed for pump–probe delay times exceeding 10 ns, which is considerably longer than radiative recombination time of trion (10–20 ps). Therefore, this signal can be attributed to the coherent spin precession of the resident electron spins in external magnetic field. Its decay is due to dephasing of the electron spin ensemble caused by $g$-factor dispersion, as is confirmed by the decay acceleration with increasing magnetic fields.

One can see in Fig. 2b that at weak magnetic fields signal decay is very slow and the electron spin dephasing is not completed during 13.2 ns, which is the time period between subsequent pump pulses. It results in pronounced signals at negative time delays, e.g., traces for $B = 0.5$ and 1 T. For these conditions it is difficult to evaluate the electron spin dephasing time, $T_{2\,e}$, by fitting the decay of the KR signal, but the well-known technique of the Resonant Spin Amplification (RSA) [25, 26] can be used. For that the delay is fixed at a small negative value, e.g., $\Delta t = -81\,\text{ps}$ as it is shown for the RSA spectrum in Fig. 3c, and the magnetic field is scanned instead of the scanning pump–probe time delay. The RSA spectrum consists of sharp peaks, which linewidth can be fitted to evaluate the electron spin dephasing time. The experiment is performed in weak magnetic fields of few mT and typically under low pump densities in order to reach the longest times. In the studied sample $T_{2\,e} = 33\,\text{ns}$ at $T = 1.8\,K$ has been measured. This time is very much comparable with the results for localized resident electrons reported for CdTe/(Cd,Mg)Te QWs of 30 ns [27] and (In,Ga)As/GaAs QWs of 45 ns [28].

The long spin dephasing time is about constant from 1.8 up to 15 K, i.e., for the temperature range where the thermal energy is smaller than the typical localization energy for the resident electron of 2 meV evaluated from the exciton linewidth. Further temperature increase leads to strong reduction of $T_{2\,e}$ down to 0.25 ns at 150 K. The spin dephasing rate increases linearly with temperature in the range from 15 to 150 K (Fig. 3b). Such behavior is characteristic for the Dyakonov–Perel spin relaxation mechanism [29, 30], which predicts for QWs: $1/\tau_e \propto T_{2\,e}(T)$. Here $\tau_e$ is the electron spin relaxation time, which can be compared in our case with $T_{2\,e}$, and $\tau_p$ is the electron momentum relaxation time. Experimentally observed linear dependence evidences that in this temperature range $\tau_p(T)$ is weakly temperature dependent. The time shortening is then explained by shifting the electron distribution to higher energies, and respectively to higher $k$-vectors, where the symmetry induced $k$-linear splitting of spin states in conduction band is larger.

One can see in Fig. 3b, that for the temperatures above 150 K the trend for the shortening of $T_{2\,e}$ is changed by the opposite one and the spin dephasing times became about 1 ns long to 230 K. In the frame of the Dyakonov–Perel mechanism it can be explained by shortening of $\tau_p(T)$ in this temperature range. It is remarkable property of ZnSe-based QWs, that the very pronounced electron spin beats can be measured up to about room temperatures, examples of Kerr rotation traces at 200 and 230 K are given in Fig. 3a. This property has been reported earlier for the (Zn,Cd)Se/ZnSe QWs [6], where however the electron localization is considerably stronger due to ternary alloy used for the QW material.

Hole contribution to the Kerr rotation signals in $n$-type QWs can be seen as a shift of the center-of-gravity of the electron beats [23]. Such contribution we found in the studied sample #1, it is zoomed for $B = 3\,T$ in Fig. 2d. It has a decay with a time of 18 ps, which can be rather related to the hole recombination time limited by the $T^*$-trion lifetime, than the fast hole spin decoherence. We will show below in this paper that the spin dephasing times of the resident holes in ZnSe QWs can be as long as 0.8 ns and we are not aware about mechanism, which can accelerate it drastically for the holes in $T^*$-trions.

### 3.2 Electron gas of high density

Now we turn to the structure, where the excitons and trions are screened by the presence of the high-density 2DEG in a QW. Sample #2 is a 10 nm-thick ZnSe/(Zn,Be)Se QW, where the symmetrical modulation doping provides the 2DEG with a density of $n_e = 1.4 \times 10^{12}\,\text{cm}^{-2}$. It corresponds to the Fermi energy of 21.5 meV, which is comparable with the exciton binding energy. Magneto-optical experiments performed for this structure in magnetic fields up to 50 T show
Figure 4 ZnSe/(Zn,Be)Se QW (sample #2) with 2DEG of high density: (a) Photoluminescence spectrum measured under continuous wave excitation at 3.06 eV. (b) Time-resolved Kerr rotation traces at different magnetic fields. Laser spectral energy for the pump and probe is marked by an arrow in panel (a). (c) Electron spin dephasing time $T_{2,e}^*$ versus magnetic field.

Landau-level-like linear shifts of emission lines in fields below 30 T [9].

The PL spectrum of this sample is shown in Fig. 4a. It is much broader than the exciton and trion emissions in weakly doped QWs, compare with Fig. 2a, and has typical shape for the low temperature emission from highly doped QWs with 2DEG of not very high mobility. The sharp high-energy side of the PL band at 2.82 eV corresponds to the recombination of electrons in vicinity of the Fermi level. And the PL band width of 27 meV is about equal to the 2DEG Fermi energy.

Kerr rotation signals in this sample have maximal intensity when the pump and probe laser energy was set in vicinity of the high energy side of PL band, i.e., close to the optical transition at the Fermi level. It was 2.825 eV and is shown by an arrow in Fig. 4a. Kerr rotation traces for different magnetic fields are presented in Fig. 4b. One can see that the spin dephasing dynamics is much faster, compared to the weakly $n$-type doped sample #1. Even at very weak magnetic field of 0.1 T the spin precession is decaying to 1 ns delay. The spin dephasing time is 220 ps at 0.1 T. It decreases down to 70 ps with the magnetic field increasing to 2 T and stays rather constant for further field increase up to 5 T. Magnetic field dependence of $T_{2,e}^*$ is shown in Fig. 4c. Note, that much longer spin dephasing time up to 4 ns have been reported for (Zn,Cd)Se/ZnSe modulation doped QW with $n_e = 5 \times 10^{11}$ cm$^{-2}$ and the Fermi energy of 8 meV [6]. We suggest that in this case carrier localization has dominated over the electron–electron interactions in their contribution to the spin dephasing.

3.3 Hole gas of low density Oscillating signals in pump–probe Kerr rotation experiments provide a direct access to $g$-factor values, which in turn offer a tool to identify the type of resident carriers in QWs. This identification is based on the fact that the in-plane $g$-factor of the heavy-hole in QW is very small (is zero without admixture of the light-hole states). The method has been demonstrated for GaAs/(Al,Ga)As QWs [31] and CdTe/(Cd,Mg)Te QWs [21], where the switching from the resident holes to resident electrons has been realized by above-barrier illumination. It will be shown in the next Section that this method is also suitable for tuning resident carrier concentration and switching their type in ZnSe-based QWs.

In this Section results for an 8 nm-thick ZnSe/(Zn,Mg)(S,Se) QW (sample #3) in $p$-type regime are given. As we have noted above, in this sample despite of the one-side modulation doping with donors the charge redistribution results in the presence of resident holes in the QW with a density of about $n_h = 1 \times 10^{10}$ cm$^{-2}$. The PL spectrum measured under below-barrier excitation with 2.858 eV is shown in Fig. 5a. It has two lines, exciton and T$^+$ trion, and looks very similar to the spectrum of the QW with low dense resident electrons, compare with Fig. 2a.

Figure 5b shows Kerr rotation traces for different magnetic fields applied in the Voigt geometry and measured under resonant pumping of the T$^+$ trion. The signal has two components oscillating with very different frequencies. During the first 100 ps a fast frequency is detectable, which can be attributed to the fast oscillating photogenerated electrons in T$^+$. It is zoomed for more details in Fig. 6b. This signal

Figure 5 ZnSe/(Zn,Mg)(S,Se) QW (sample #3) in a $p$-type regime without above-barrier illumination: (a) Photoluminescence excited with a continuous wave laser at 2.858 eV (below barrier). (b) Time-resolved Kerr rotation traces for different magnetic fields with a pump and probe photon energy at 2.811 eV (T$^+$ trion). (c) Hole spin dephasing time ($T_{2,h}^*$) versus magnetic field with a fit to the data (line), which shows 1/B-dependence. Hole spin precession frequency versus magnetic field with linear fit to the data (line).
in-plane hole had been reported for GaAs/(Al,Ga)As QWs [32]. The evaluated band mixing of heavy-hole and light-hole states, as is has shows that there is no valuable magnetic field effect on the Larmor precession of the resident holes. Its frequency recombination. The slow oscillating component is related to the time is given by

\[ \Delta g \propto \frac{1}{T^2} \]

environment parameters within the QW. The spin dephasing variations in the hole \[ \Delta g \] factor

\[ \Delta g = \frac{g - g_0}{B} \]

decays with a time of 55 ± 5 ps, being limited by the trion recombination. The slow oscillating component is related to the Larmor precession of the resident holes. Its frequency recombination. The slow oscillating component is related to the time is given by

\[ \Delta g \propto \frac{1}{T^2} \]

depends and allows one to estimate the dispersion of g-factor \[ \Delta g_0 \] from fitting the data. Such a fit, shown by the line in Fig. 5c, renders \[ \Delta g_0 = 0.03 \pm 0.01 \].

Figure 6 ZnSe/(Zn,Mg)(S,Se) QW (sample #3): (a) Time-resolved Kerr rotation traces with additional illumination by continuous wave laser at 3.06 eV (above barrier) and different illumination power. Pump and probe energy is set to trion at 2.811 eV. Panel (b) shows close-ups of the corresponding signal of the first 100 ps without additional illumination, a signal from photocreated electrons is detectable. (c) Electron and hole signal amplitudes (normalized) as functions of illumination power.

Figure 7 ZnSe/(Zn,Mg)(S,Se) QW (sample #3): (a) RSA measurements with pump and probe energy of 2.811 eV resonant to \( T^- \) trion and above-barrier illumination with \( P_{\text{illum}} = 0.28 \) W cm\(^{-2}\). (b) Second RSA maximum fitted with \( T^+_{2,0} = 20.0 \pm 0.5 \) ns.

3.4 Optical tuning from p-type to n-type regimes Tuning of the type and concentration of the resident carriers is illustrated in Fig. 6a. Here Kerr rotation signals measured on trion resonance at small power of pump beam are shown for different above-barrier illumination intensities, \( P_{\text{illum}} \). One can see that with the increasing illumination intensity the long-lived fast electron oscillations appeared. They coexist with the hole oscillations in the range of \( P_{\text{illum}} = 0.04 \sim 0.10 \) W cm\(^{-2}\) and for \( P_{\text{illum}} \geq 0.25 \) W cm\(^{-2}\) the signals are solely contributed by the resident electrons. These changes are illustrated by Fig. 6c where the relative amplitudes of the hole and electron signals are plotted as function of the illumination intensity.

For the regime when the QW is populated by the resident electrons under illumination with \( P_{\text{illum}} = 0.28 \) W cm\(^{-2}\), the electron spin dephasing time was measured by the RSA technique. The RSA spectrum for the resonant pumping of \( T^- \) trion is given in Fig. 7. Fitting of the second RSA maximum leads to the electron dephasing time \( T^{+}_{2,0} = 20.0 \pm 0.5 \) ns. It is considerably longer than the hole dephasing time \( T^{-}_{2,0} = 0.8 \pm 0.1 \) ns measured in the same sample without above-barrier illumination. Lower amplitude of the zero-field RSA peak in respect to the finite-field peaks is due to the initialization process of the electron spin coherence under resonant trion excitation, for details see Ref. [26].

Spectral dependence of the Kerr rotation signals are shown in Fig. 8. Their amplitude is enhanced when the pump and probe photon energy coincides with either trion resonance at 2.811 eV or exciton one at 2.815 eV. Despite the fact that these measurements were performed without above-barrier illumination, the pronounced long-lived electron oscillations appear for resonant exciton pumping. It means that in this case there is a mechanism which provides recharging of the QW. It is further supported by the pump power dependence of the electron and hole amplitudes plotted in the inset of Fig. 8. Here at highest power used the hole contribution is diminished and only electron one is present. It is similar to the effect of above-barrier illumination. Therefore, we suggest that the responsible mechanism involves Auger processes, when, e.g., annihilating exciton provided its energy not to the photon, but to another exciton which carriers escape from the QW in the barriers. In principle, a two-photon absorption may also provide carriers in the barriers, but the
The probability of this nonlinear process should be very weak for relatively low pump densities used in this experiment.

RSA measurements of the electron spin dephasing time for the resonant exciton pumping illustrating in Fig. 9 result in \( T_{2e} = 10.0 \pm 0.5 \) ns. We remind that similar measurements on \( T^{+} \)-trion in the same sample give \( T_{2e} = 20 \) ns (Fig. 7). Such a difference has been reported for CdTe/(Cd,Mg)Te QWs and related to addressing the resident electrons with different localization [20]. Obviously, stronger localized electrons, which are addressed via trion resonant pumping, can longer keep their spin coherence. Note, that the phase of RSA spectrum depends on the relative spectral position of the pump and the excited resonance, which are not the same in our experiment on trion and exciton resulting in opposite phases of the signals in Figs. 7a and 9a.

### 3.5 Electron and hole g-factor anisotropy

The advantage of the vector magnet with a variable magnetic field orientation was used to measure all components of the g-factor tensor for the resident electrons and holes in a ZnSe/(Zn,Mg)(S,Se) QW (sample #3). The direction of the magnetic field can be defined by two angles \( \Phi \) and \( \Psi \) as shown in the schema of Fig. 10.

Angle \( \Phi \) is for \( xy \)-plane and \( \Phi = 0 \) corresponds to the field projection on this plane being parallel to \( x \)-axis. Angle \( \Psi \) is for tilting the field vector out of the \( xy \)-plane. For \( \Psi = 0 \) magnetic field is in the \( xy \)-plane. Then the experimentally measured g-factor has the following relation with its tensor components and angles:

\[
g(\Phi, \Psi)^2 = (g_x \cos \Phi \cos \Psi)^2 + (g_y \sin \Phi \cos \Psi)^2 + (g_y \sin \Psi)^2.
\]

Magnetic field rotation in \( xy \)-plane (varying angle \( \Phi \) and keeping \( \Psi = 0 \)) corresponds to the Voight experimental geometry and is used for measuring the in-plane anisotropy of g-factors. It is pronounced for the heavy-holes: \( |g_{hx}| = 0.06 \pm 0.01 \) and \( |g_{hy}| = 0.08 \pm 0.01 \) (see Fig. 10a). For \( 100 \)-oriented QWs the \( D^{*} \) highly symmetric case, for which \( x \parallel [-110] \) and \( y \parallel [110] \) axes are equivalent and, respectively, \( g_{hx} = g_{hy} \) is expected would be valid only for ideally symmetrical confinement potential. While, as one can see in Fig. 1c, the sample #3 has a one side modulation doping, which reduces the structure symmetry down to \( C_{2v} \) [34]. We suggest that this is the reason for the observed in-plane anisotropy of the heavy-hole g-factor. Contrary to the heavy-holes the electron in-plane g-factor is pretty isotropic with \( |g_{ex}| = |g_{ey}| = 1.18 \pm 0.01 \), as it is shown in Fig. 11a.

With turning the magnetic field out of QW plane, the amplitude of the oscillating contribution to the Kerr rotation signal becomes weaker. When the field is oriented in Faraday geometry (\( \Psi = 90^\circ \)), i.e., parallel to the \( z \)-axis, precession of the spins oriented by light along the \( z \)-axis cannot occur. Instead, an almost pure exponential decay is detectable, as it is shown in Ref. [22]. For the magnetic field orientations...
approaching $z$-axis the spin precession gets too weak to obtain reliable values for the $g$-factors. For the heavy-holes this typically happens for $\Psi > 8^\circ$, while for electrons for $\Psi > 75^\circ$. In this case the $g_z$ component was evaluated using Eq. (1) by fitting the available experimental data.

Experimental results for the heavy-holes and magnetic field tilted in $xz$- and $yz$-planes are shown in Figs. 10b and 10c, respectively. From fitting we find $|g_{h,z}| \approx 1.8 \pm 0.2$. Similar measurements performed on sample #3 in $n$-type regime under above-barrier illumination results in $|g_{e,z}| = 1.13 \pm 0.01$, see Fig. 11b.

Pump–probe Kerr rotation technique does not provide direct information on the $g$-factor sign. A detailed consideration of the $g$-factors in ZnSe-based QWs based on the magneto-optical data in high magnetic fields up to 44 T and the literature data can be found in Ref. [5]. It is concluded that $g_{e,z}$ components of both electrons and heavy-holes are positive and $g_{e,z} \ll g_{h,z}$. Basing on that we can summarize the received information for the $g$-factor components in an 8 nm-thick ZnSe/(Zn,Mg)(S,Se) QW (sample #3):

$$ g_{e,z} = +1.13 \pm 0.01, $$
$$ g_{e,z} = g_{e,y} = +1.18 \pm 0.01, $$
$$ g_{h,z} \approx +1.8 \pm 0.2, $$
$$ |g_{h,y}| = 0.06 \pm 0.01, $$
$$ |g_{h,z}| = 0.08 \pm 0.01. $$

4 Conclusions Coherent spin dynamics of electrons and holes is studied by a pump–probe Kerr rotation technique in $n$- and $p$-type ZnSe-based QWs with a binary material of quantum wells. We demonstrate experimentally long-lived spin coherence of electrons (up to 33 ns) and holes (up to 0.8 ns) at low temperatures when the resident carriers are localized by potential fluctuations induced by quantum wells width variations. Such long spin dephasing times are comparable with the ones reported for QWs based on other material systems like CdTe/(Cd,Mg)Te, GaAs/(Al,Ga)As, and (In,Ga)As/GaAs. In the highly $n$-type doped QWs with a dense two-dimensional electron gas the electron spin dephasing is considerably shorter of about 0.2 ns. The Kerr rotation signals are apparent up to 230 K. In weakly $n$-type doped QWs the electron spin dephasing rate increases linearly with temperature in the range from 15 to 150 K. This behavior can be explained by the Dyakonov–Perel spin relaxation mechanism. All $g$-factor tensor components for resident electrons and heavy-holes are measured.

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