Electron-spin dephasing in GaAs/$Al_{0.34}Ga_{0.66}As$ quantum wells with a gate-controlled electron density

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The dynamics of electron-spin coherence in GaAs/$Al_{0.34}Ga_{0.66}As$ quantum wells has been studied experimentally by a pump-probe Kerr rotation technique. The electron-spin dephasing time was measured to be 10 ns for a 17-nm quantum well containing about 10^{10} cm^{-2} background electrons at a temperature of 1.8 K. Decrease of the electron density causes a decrease of dephasing time by an order of magnitude. Local fluctuations of the effective magnetic field of the nuclear spins was established as a dominating spin dephasing mechanism for localized electrons in the quantum wells.

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I. INTRODUCTION

In recent years, electron-spin orientation in semiconductors is considered as a promising way of realization of quantum information processing in solid-state systems.[1,2] According to Ref. 3, a spin system suitable for this purpose should exhibit a low dephasing rate to make possible the implementation of around 10^4 elementary operations during the spin coherence preservation time. Therefore the problem of lifetime and relaxation mechanisms of spin coherence in real systems becomes highly topical.

Initially, the main attention of researchers in the field of spin dynamics in semiconductors was paid to the process of population relaxation between spin sublevels (longitudinal relaxation). Among the semiconductor structures studied so far, the greatest values for the longitudinal electron-spin relaxation times T_1 were detected in quantum dot heterostructures, in which T_1 may reach units of ms.[4,5] Submicrosecond- and microsecond-range times were detected in thick epitaxial layers of *n*-doped GaAs.[6,7]

The study of spin decoherence and spin dephasing in semiconductors has been started more recently.[8–10] The spin coherence may be destroyed by the longitudinal relaxation. However, a more efficient process is typically phase (transverse) spin relaxation. The phases of individual spins may be destroyed, e.g., by a magnetic field fluctuating in time. The characteristic time of this *decoherence* process (irreversible phase relaxation) is often denoted as T_2. For electrons in semiconductor quantum wells (QWs) and quantum dots, the T_2 time is usually a few orders of magnitude shorter than the T_1 time. In an ensemble, the spin coherency may be lost even faster than T_2 as the phases of the spin states may diverge in time due to the inhomogeneous spread of the spin ensemble. This *dephasing* process (reversible phase relaxation)[11] can be characterized by the time T_2^*, which is as a rule considerably shorter than the T_2 time.

Theoretical estimates have shown that the coherence time of the electron spin in semiconductors may reach tens or even hundreds microseconds.[1] In agreement with these predictions, direct measurements using the spin-echo technique gave the spin coherence time T_2=0.52 ms in phosphorus doped silicon crystals.[12,13] Dephasing, characterized by T_2^*, is considerably more efficient. Specifically, measurements of the dynamics of the photoinduced birefringence in thick GaAs layers doped with Si have shown that the electron-spin dephasing time in these systems does not exceed 100 ns.[14] This value is almost three orders of magnitude smaller than the T_2 mentioned above. About the same result ($T_2^* \sim 20$ ns) was obtained for dephasing of the excess electron spins in an epitaxial layer of GaP.[15] The dephasing times measured in quantum-well semiconductor structures are even shorter: about 10 ns for GaAs/(Al,Ga)As QWs,[6,16] and 30 ns for CdTe/(Cd,Mg)Te QWs.[17] In a quantum dot ensemble with an inevitably large inhomogeneity the dephasing time is very short though even spin precession mode locking allows one to observe spin coherency far beyond the T_2^* time.[18,19]

In contrast to decoherence determined by the fundamental properties of the media, which hardly can be modified, dephasing depends on random inhomogenities in a heterostructure and can be, in principle, suppressed by optimization of the structure preparation technology and of the experimental conditions in the spin coherency measurements. In this paper, we show that at least one of the main sources of the spin dephasing, namely, the spread of electron *g*-factor values in a quantum well, can be radically suppressed if the quality of the quantum well is very high.

We have studied experimentally high quality structures with GaAs/(Al,Ga)As QWs containing excess electrons. The effect of various experimental parameters such as applied external electric bias, magnetic-field strength, and temperature on the rate of spin dephasing has been carefully analyzed. It was found that, under optimal conditions, the

electron-spin dephasing time in the structures under study is about 10 ns. The analysis of the experimental data allowed us to come to the following conclusions. First, due to the high quality of the samples, the spread of electronic g factor in 17-nm quantum wells is so small that it does not cause the electron-spin dephasing in magnetic field up to $B=4$ T. Second, the electron-spin dephasing at low temperatures is predominantly related to interaction of the spins with the local fluctuations of the nuclear field.

II. EXPERIMENTAL TECHNIQUE

Two GaAs/$Al_{0.34}Ga_{0.66}As$ structures were grown by molecular-beam epitaxy on (001) GaAs substrates for the present study. Each sample contains four QWs with nominal thicknesses of 5, 10, 14, and 17 nm sandwiched between 50 nm $Al_{0.34}Ga_{0.66}As$ barrier layers. Structure 1 ($p340$) was grown on a semi-insulating GaAs substrate. Structure 2 ($p343$) was grown on a n-doped substrate. The top surface of this structure was coated by a semitransparent gold electrode. By applying an electric bias U to the electrode we tune the electron density in the 17-nm QW in the range from about 10^{10} cm^{-2} at a positive bias above 1 V to a negligibly small concentration at $U<-2$ V, for which no effects from excess electrons were observed.

The samples were mounted in a cryostat with a split-coil superconducting magnet generating magnetic fields up to 7 T. The fields were applied either perpendicular to the structure growth axis (transverse field in the Voigt geometry) or parallel to the growth axis (longitudinal field in the Faraday geometry). Most experiments were performed at a temperature $T=1.8$ K which for temperature-dependent measurements could be increased up to 30 K.

We used a pump-probe Kerr rotation technique[9,21] for studying the spin dynamics. A tunable Ti:sapphire laser generating 1.5-ps pulses at a frequency of 75.6 MHz was used as a source of excitation. Its beam was split into pump and probe beams. The circular polarization of the pump beam was modulated from σ^+ to σ^- helicity by means of a photoelastic modulator operating at a 50-kHz rate. The power density of the pump beam on the sample did not exceed 0.5 W/cm^2. The probe beam was linearly polarized, and its intensity was kept at a 10–20 % level of that of the pump beam. We have verified that the signal measured at these conditions was linearly dependent on the pump and probe powers. The reflected probe beam was split by a Glan-Thomson prism and detected by a balanced diode detector and a lock-in amplifier at the frequency of the pump beam modulation. The signal amplitude is proportional to the polarization plane rotation of the probe beam due to the spin orientation created by the pump beam. It was measured as a function of the time delay between the pump and probe pulses.

III. EXPERIMENTAL RESULTS

A. Conditions for observation of spin coherence in a transverse magnetic field

The spin dynamics of carriers and the process of optical spin orientation in semiconductors have been treated in a great number of experimental and theoretical studies.[10,20–22] Here, we consider in brief the main conclusions of these studies, which form the basis for the analysis of our experimental data.

In Kerr rotation experiments, the rotation angle of the polarization plane of the probe beam is proportional to the degree of circular birefringence induced by the pump beam which generates spin oriented carriers. The Kerr signal is contributed by electron and hole spins. In a transverse magnetic field, the optically oriented spins precess about the magnetic-field direction. As a result, their projection onto the direction of observation (which in our case coincides with the structure growth axis) and hence the signal amplitude oscillate in time with a frequency proportional to the field strength. From a quantum-mechanical point of view, these oscillations correspond to quantum beats (QBs) of the spin states split by the magnetic field.[23]

Electron-hole exchange coupling makes the exciton spin insensitive to weak magnetic fields for which the Zeeman splitting is smaller than the energy of the exchange interaction. However, in sufficiently strong magnetic fields such that the exchange coupling is broken, the spin precession of electron and hole in the exciton can be considered independently. A specific feature of the spin states of carriers in low-dimensional structures is a pronounced anisotropy of the heavy-hole g factor.[24] Namely, in QW structures the transverse component of the hole g factor is in most cases negligibly small (see, e.g., Ref. 25). As a result, the hole spin precession period in a transverse magnetic field appears to be much longer than the longitudinal relaxation time $T_{1,h}$ and the precession is therefore strongly damped.

The dynamics of the Kerr signal related to the spin oriented electrons reflects the spin precession in transverse magnetic field and the spin dephasing. The precession is manifested by harmonic oscillations with a frequency corresponding to the Zeeman splitting. The decay of the oscillations (with time T_e) is controlled by several factors. When no excess electrons are present in the QW, the decay is determined by the electron-spin dephasing time $T_{2,e}^*$ and by the exciton recombination time τ_X: $1/T_e=1/T_{2,e}^*+1/\tau_X$.

In the presence of excess electrons, a trion can be formed from a photogenerated exciton and an excess electron[26] which is a negatively charged complex consisting of a hole and two electrons. At *zero magnetic field*, the orientation of the hole spin is controlled by polarization of the photon, while the spins of the photogenerated and excess electrons (according to the Pauli principle) should be antiparallel to each other.[27] This means that the trion formation extracts electron spins parallel to the hole spins from the excess electron ensemble. As a consequence, an excess spin antiparallel to that of the hole is generated in the electron ensemble. The amplitude of the Kerr signal associated with this spin depends on the ratio of the relaxation rate of the hole spin, $1/T_{1,h}$, to the rate of trion recombination, $1/\tau_T$. In the case of fast relaxation of the hole spin ($1/T_{1,h} \gg 1/\tau_T$), the hole may recombine with equal probability with each of the two electrons in the trion. This recombination does not change the average electron spin in the ensemble, and therefore cannot affect the Kerr amplitude. If the hole spin relaxes slowly ($1/T_{1,h} \ll 1/\tau_T$), then the electron spin taken from ensemble

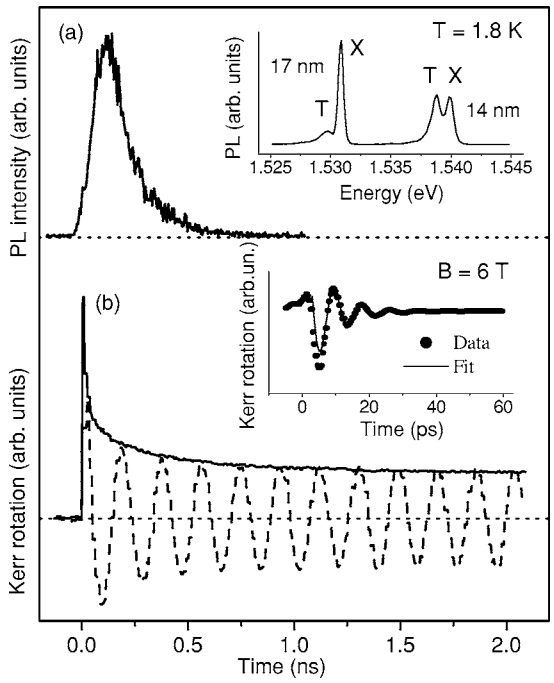

FIG. 1. (a) PL kinetics of excitons in a 17-nm QW of sample 1 excited at energy 1.568 eV. Exponential fit gives a decay time of 110 ps. (b) Dashed line: dynamics of the QB signal in a transverse magnetic field $B=1$ T; solid line: the same at zero field. Inset (a): PL spectrum of sample 1 in the region of exciton peaks of the two widest QWs. Inset (b): QB signal from the 17-nm QW in Faraday geometry (see details in text). $B=6$ T.

is returned with the same orientation, which decreases or even fully compensates the light-induced spin orientation.

In *the presence of a transverse magnetic field*, precession of the excess electron spin changes its orientation with respect to the hole spin and total compensation does not occur even if the hole spin does not relax.[28] In this case, the condition for conservation of the optical orientation after the trion recombination can be represented in the form $\omega_e \gg 1/\tau_T$, where $\omega_e = g_e \mu_B B/\hbar$ is the electron Larmor frequency. Here μ_B is the Bohr magneton, B is the magnetic-field strength, and $\hbar$ is the Planck constant.

Thus the dynamics of the detected signal should contain three components, namely, a nonoscillating signal related to the hole spin orientation and oscillations related to precession of the electron spin in the exciton and of the spin induced in the excess electron ensemble. Generally, the decay of the oscillations should therefore be nonexponential and comprise two components associated with the exciton recombination and the dephasing of the excess electron spins. The signal resulting from resonant excitation of the trions should contain only the last component.

B. Dynamics of hole and electron spins

First, we studied the spin dynamics in the undoped sample 1 with a low concentration of excess electrons caused by nonintentional (residual) doping of the structure. Figure 1 (upper inset) shows the photoluminescence (PL) spectrum of the sample in the vicinity of the exciton peaks of the two widest QWs. It is seen that each peak in the PL spectrum has a pronounced doublet structure due to the exciton (X) and trion (T) recombination lines. Identification of these lines has been done from photoluminescence spectra measured in magnetic fields up to 17 T. Characteristic energy shift, Zeeman splitting, and appearance of trion triplet states in high magnetic fields were similar to the reported properties of trions in GaAs/(Al,Ga)As QWs.[29]

The kinetics of the Kerr rotation signal detected at the exciton peak of the 17-nm QW is shown in Fig. 1(b) for magnetic field $B=0$ and 1 T. The signals have a rapidly decaying initial part transforming into a slowly decaying tail in the absence of the field and into weakly damping oscillations in transverse magnetic field. In accordance with the conclusions of the previous section, we ascribe the rapidly decaying signal to the hole spin orientation. The decay time of this signal is approximately 10 ps, which agrees with the published data on hole spin-relaxation time in similar systems.[30,31]

The conclusion about rapid relaxation of the hole spin is supported by a study of the exciton spin dynamics in longitudinal magnetic field. In this experiment, the linearly polarized pump beam has been used to create a coherent superposition of the optically active exciton states with spin projections +1 and −1 (alignment of the exciton spin[20]). This superposition gives rise to linear birefringence of the sample, which can be detected as a signal of the polarization plane rotation of the reflected probe beam. The longitudinal magnetic field splits the optically active exciton doublet (Zeeman splitting) and the signal oscillates in time due to quantum beats between the doublet components. Relaxation of the hole spin destroys the coherence which results in the oscillation decay. Experimentally the measured oscillations in the linear birefringence signal from the 17-nm QW are given in the inset of Fig. 1(b) for a magnetic field 6 T. A fit to the experimental data by an exponentially damped harmonic function yields the decay time 7 ps, which is close to the value mentioned above.

Hole spin relaxation breaks the exchange coupling between the electron and the hole in the exciton, which in turn allows free precession of the electron spin. The result of this precession is the oscillating signal shown in Fig. 1(b). The frequency of the observed oscillations, $\omega_e = 3.5 \times 10^{10}$ Hz, agrees well with the Zeeman splitting of the electron-spin sublevels, $\omega_e = g_{xy} \mu_B B/\hbar$, calculated for this QW for $B=1$ T and a transverse electron g factor, $|g_{xy}| = 0.37$, which is close to the value known from literature.[32] The oscillating part of the Kerr signal can be well described by a damped harmonic function of the form

$$y(t) = (a_1 e^{-t/\tau_1} + a_2) \cos \omega_e t, \tag{1}$$

where τ_1 is the decay time of the fast component, and a_1 and a_2 are the amplitudes of the fast and long-lived components. The decay time of the fast component, $\tau_1 \sim 100-150$ ps, is close to that of the exciton PL shown in Fig. 1(a). Therefore we assign it to electrons bound in excitons.

The origin of the long-lived oscillating signal may be related only to the excess electrons. Presence of excess elec-

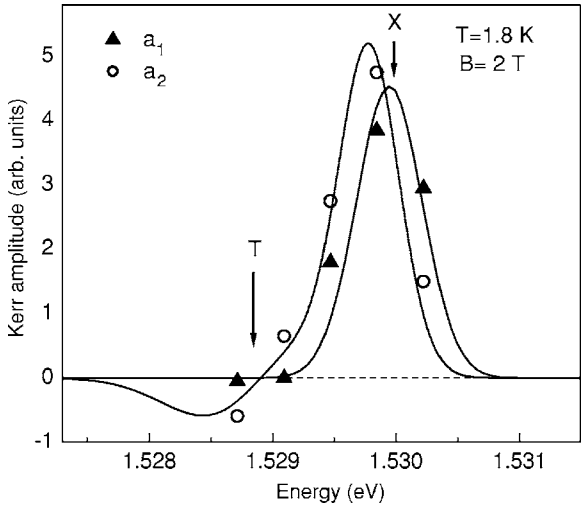

FIG. 2. Spectral dependence of amplitudes of fast (triangles) and slow (circles) components in Kerr signal of a 17-nm QW of sample 1. Lines are guides to the eye. Arrows marked by "X" and "T" show energy positions of the exciton and trion lines, respectively.

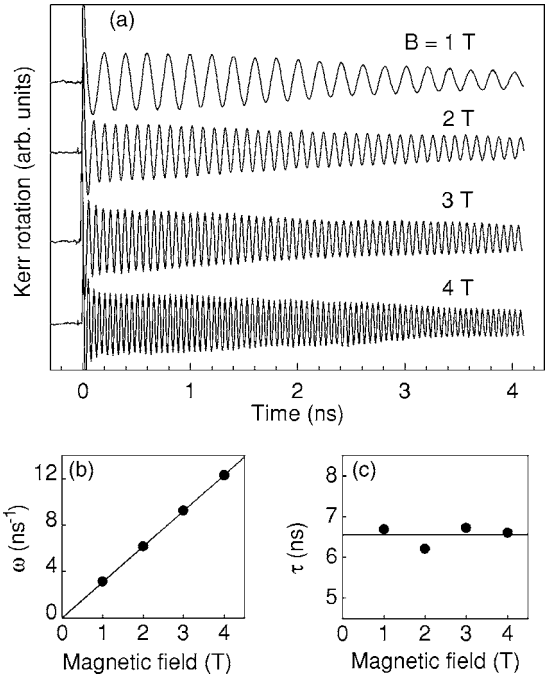

FIG. 3. (a) Kerr rotation signals measured for the 17-nm QW of sample 2 at $U=0.7$ V for different magnetic fields. (b) Field dependence of the QB frequency (circles). Solid line is a fit by a linear dependence $\omega=|g_{xy}|\mu_B B/\hbar$ with $|g_{xy}|=0.34$. (c) Field dependence of the QB decay time (circles). Solid line is a guide to the eye.

trons in sample 1 is also indicated by the doublet structure of luminescence spectrum [see inset in Fig. 1(a)]. The splitting of trion and exciton PL lines equals 1.2 meV, which substantially exceeds the energy difference for monolayer fluctuations in wells of this width and coincides with the binding energy of a singlet trion.[33] The relative intensity of the trion and exciton peaks in the PL spectrum corresponds to a density of two-dimensional electrons of about 10^{10} cm^{-2} (see Ref. 34).

The conclusion that the long component of the signal is associated with trion excitations agrees well with the results of studies of the spectral dependences of the amplitudes of the fast and slow components in the QBs signal. In experiment, the amplitude and the shape of the signal were measured as a function of the photon energy. The energy was varied by tuning the Ti:sapphire laser, i.e., the photon energies of the pump and probe beams were scanned synchronously (spectrally degenerate pump-probe regime).

The spectral dependencies of the amplitudes obtained from the experimental data are shown by the symbols in Fig. 2. The spectrum of the fast component coincides fairly well with the exciton peak of the PL spectrum. The slow-component spectrum is shifted towards lower energies, i.e., towards the trion peak position as compared to fast component. The shift is significantly smaller than the exciton-trion splitting, which can be explained by the relatively small contribution of the trion absorption to the excitation of the trionic states. This conclusion is supported by several experimental data related to the trion photoluminescence in semiconductor quantum wells (see, for example, the paper by J. Tribollet *et al.*[35]). In accordance with these data, the ratio of the trion-to-exciton peak intensities in photoluminescence spectra substantially exceeds a similar ratio in absorption spectra. This means that the trion is predominantly formed after exciton absorption. At the same time, the Kerr rotation effect should have a maximum at the trion resonance. In our case of degenerate pump probe, the maximum of the signal should occur somewhere between the maxima of absorption and of Kerr rotation. This maximum occurs between the exciton and trion peaks.

The experimental data given in this section allow us to conclude that the long-lived oscillating signal is due to coherent precession of the excess electron spins. The spin coherence is generated through trions, which are predominantly formed via trapping of excess electrons by the photogenerated excitons.

C. Dephasing of electron-spin beats

In this section, we turn our attention to sample 2, for which the density of excess electrons can be tuned by bias voltage. The dependence of the QB signal for the 17-nm QW on the magnetic-field strength is shown in Fig. 3. The photon energy of the pump and probe beams were tuned to the low-energy tail of the exciton peak. The main contribution to the signal, in this case, comes from the trion states excited through the excitonic absorption. One can see from the figure that the signal consists of the long-lived component only. Increase of the magnetic-field strength is accompanied by a linear increase of the oscillation frequency [see Fig. 3(b)]. The value of the g factor found from this dependence, $|g_{xy}|=0.34\pm0.01$, agrees well with the published data[32] for the transverse component of the electron g factor in GaAs QWs of this width. The decay of the QBs can be better approximated by a Gaussian envelope, $y\sim\exp[-(t/\tau)^2]\cos\omega_e t$, rather than by an exponential one. The decay time τ is found

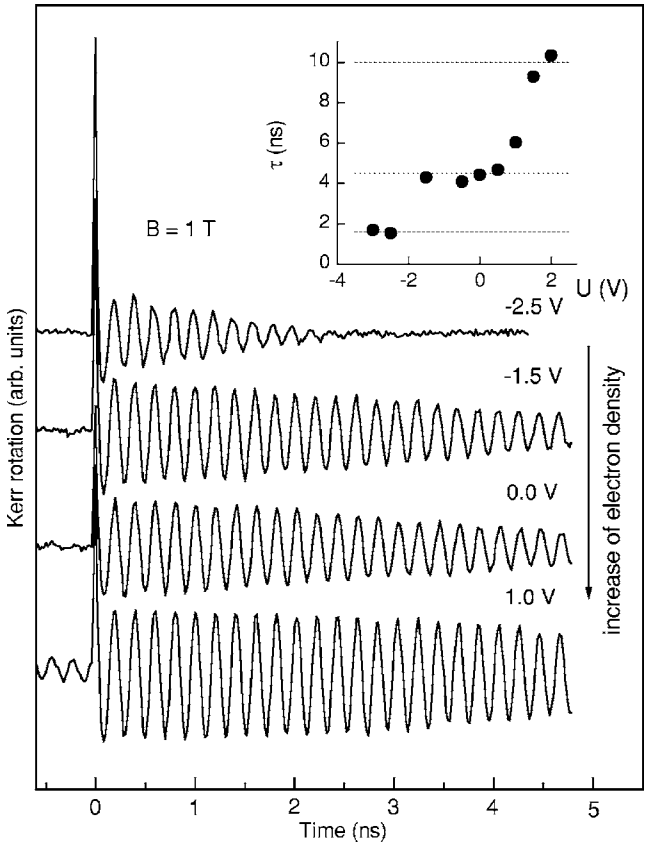

FIG. 4. Dependence of the QB signals in the 17-nm QW of sample 2 on bias. $T=1.8$ K. Inset: Bias dependence of the QB decay time.

to be practically independent of the magnetic-field strength up to $B=4$ T [see Fig. 3(c)].

The electron concentration in the 17-nm QW of sample 2 was varied by applying an electric bias to the top electrode of the sample. The QBs detected in a transverse magnetic field of 1 T at different biases are shown in Fig. 4. The appearance of the QB decay is seen to strongly depend on the bias. This dependence may be divided into three regions (see inset in Fig. 4). At negative bias below −2 V, the decay time is about 1.5 ns. As the negative bias increases to −1.5 V, the decay time increases to 4.5 ns and remains practically constant in the range from −1.5 to +0.5 V. For positive biases greater than 1 V the decay time increases to 10 ns.

In the interpretation of the data, one has to keep in mind that the gold electrode on the sample surface forms a Schottky barrier of 0.7 V height. As a result, the energy structure of the conduction band is substantially tilted, as shown schematically in Fig. 5(b). Due to that, the bottom of the conduction band in the QW is located above the Fermi energy of the doped substrate without external bias, and the electrons are not able to penetrate the substrate and reach the QW. Under this condition, the main source of the excess electrons in the QW is most likely provided by residual background doping. It is exactly these electrons that are responsible for the oscillating signal in the bias range from −1.5 to +0.5 V. For large values of negative bias, the tilt of the bottom of the conduction band becomes so steep that tunnelling

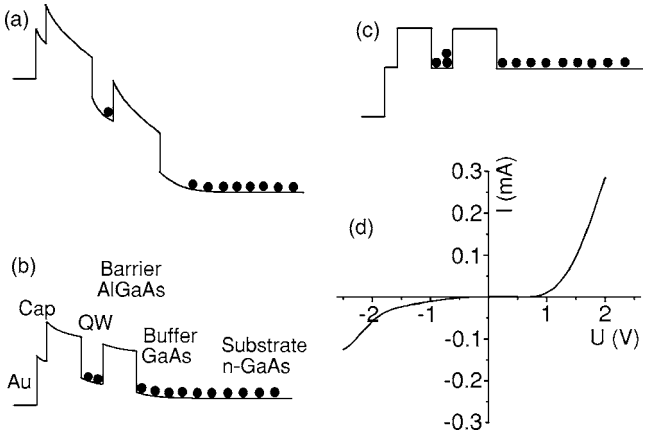

FIG. 5. Schematic diagram of the conduction band in sample 2 for the following electric biases applied to the top electrode: (a) $U=-2$ V, (b) $U=0$ V, and (c) $U=+1$ V. (d) I-V characteristics of sample 2.

of electrons from the QW to the substrate becomes possible [see Fig. 5(a)]. This process strongly reduces the electron concentration in the QW. As seen from Fig. 4, this decrease of carrier concentration results in the strong shortening of the spin oscillation decay time at $U=-2.5$ V.

A positive bias voltage compensates for the Schottky barrier effect and reduces the tilting of the conduction band. For voltages exceeding +1 V, the Schottky barrier is completely compensated [see Fig. 5(c)], and an electronic current from the doped substrate to the QW appears as seen from the I-V curve shown in Fig. 5(d). As a result, the electron concentration in the QW increases. This increase is accompanied by a noticeable increase in the oscillation decay time in Fig. 4, i.e., by a slowdown of the electron-spin dephasing rate. Based on the data from Figs. 4 and 5, we conclude that the coherence lifetime of the electron spin in the QW under study increases monotonically with electron concentration.

The effect of a temperature change on the electron-spin dynamics in the 17-nm QW of sample 2 is shown in Fig. 6. The measurements were performed in a transverse magnetic field of $B=1$ T. The signals measured at temperatures $T=6$ and 12 K reveal some additional modulation from two long-lived oscillations with slightly different frequencies. Such a signal is probably caused by simultaneous excitation of QW segments which differ by one monolayer in thickness, leading to corresponding changes of the electron g factor. However, the temperature increase does not affect the shape of the detected signal, i.e., the spin relaxation time is not temperature dependent in this interval. Further temperature increase leads to an abrupt shortening of the dephasing time, as can be seen from the inset, where the dephasing time τ_2 of the long-lived component is shown.

IV. DISCUSSION: MECHANISMS OF ELECTRON-SPIN DEPHASING

The decay of electron-spin coherence in a transverse magnetic field can be contributed by several processes. One of these processes is a transition between the spin-split sublev-

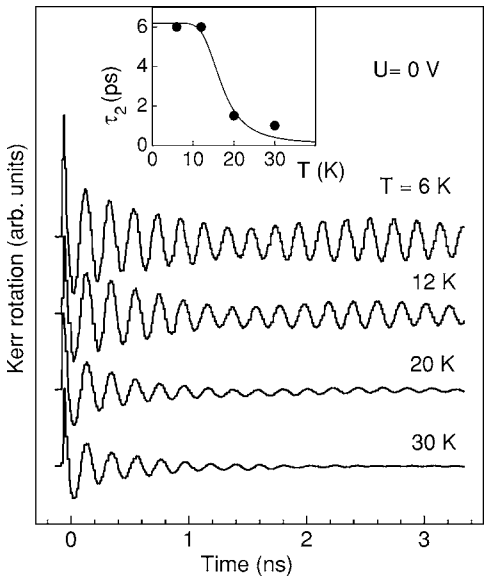

FIG. 6. Temperature dependence of the QB signal in the 17-nm QW of sample 2 in a transverse magnetic field. $B=1$ T. Inset: dependence of the long-lived component decay time τ_2 on temperature. Circles are the experimental data, solid line is a guide to the eye.

els with simultaneous emission (absorption) of a phonon. In transverse magnetic field, such a transition does not change the instantaneous spin projection onto the direction of observation, but reverses the spin precession direction. This results in decay of the oscillations due to spin decoherence. The probability of this process increases with the phonon occupation number, i.e., with increasing temperature.

Another mechanism of spin decoherence and spin relaxation for a moving electron has been suggested by Dyakonov and Perel.[36] It may be considered as the electron-spin precession about an effective magnetic field due to the electron motion.[20] This process changes in a random way the frequency of the precession in a transverse magnetic field which results in spin relaxation. The efficiency of the Dyakonov-Perel (DP) mechanism increases with the kinetic energy of the electron, i.e., with increasing electron density and, correspondingly, increasing Fermi energy, as well as with increasing temperature.

Spin dephasing, on the other hand, can be caused by the spread of the electron g factor in the electron-spin ensemble and/or by the presence of local magnetic fields in the structure. Both factors give rise to decay of the ensemble coherence, but their effect depends differently on the magnetic-field strength. The spread of the precession frequencies related to the inhomogeneity of the g factor increases linearly with external magnetic field. Correspondingly, the spin dephasing rate associated with this spread also rises linearly with the field.[37,38] At the same time, the frequency spread associated with local magnetic fields is determined only by their value and practically does not depend on the external field.

The above considerations allow us to analyze the experimental data and to extract information about the mechanisms of electron-spin dephasing in the structures under study. The independence of the oscillation decay time on temperature in the range 6–12 K in Fig. 6 indicates inefficiency of the spin-phonon relaxation and the relaxation via the DP mechanism at low temperatures. Inefficiency of the DP mechanism at $T=1.8$ K is also evident from the bias dependence of the oscillation decay time. As seen from Fig. 4, the increasing excess electron density up to 10^{10} cm^{-2} at positive bias is accompanied by an increase rather than a decrease of the decay time.

The DP mechanism should dominate for further increase of the electron density. It was not possible to reach this regime for our undoped QWs, in particular, because the increase of positive bias applied to sample 2 results rather in a strong increase of electric current than the electron density [see Fig. 5(d)]. However, the temperature data shown in Fig. 6 allow us to estimate the kinetic energy of electrons (of about 1 meV) for which the DP mechanism decreases the spin dephasing time relative to the value of about 6 ns observed at optimal experimental conditions for the 17-nm QW in sample 2. Electron gas with the Fermi energy of the same value should have the density of about 3×10^{10} cm^{-2} as it follows from the well-known relationship between these quantities (see, e.g., Ref. 39). This value is approximately three times larger than the maximal electron density realized in our experiments. An estimate using the theoretical density dependence of the spin-relaxation time controlled by the DP mechanism on the electron density reported for bulk GaAs in Ref. 16 gives rise to an even larger value.

The independence of the QB decay time on the magnetic-field strength [see Fig. 3(c)] for the 17-nm QW of sample 2 allows us to conclude that the spread of the electron g factor in this case is extremely small ($<0.1\%$) and it does not noticeably affect the dephasing rate. This result indicates the high structural uniformity of the 17-nm QW. We would like to note here that the g-factor spread in similar heterostructures typically determines the QB decay already at a magnetic field of $B\sim1$ T or even less.[15,17]

Thus we suggest that the main mechanism responsible for the decay of the spin coherence in the studied sample at $T<10$ K arises from randomly varying magnetic fields ΔB_l acting on the electron spins. The value of this spread may be evaluated from the experimental data because the relevant spread of the precession frequencies, $\Delta\omega=g_e\mu_B\Delta B_l/\hbar$, is related to the measured decay time τ by $\Delta\omega=1/\tau$. Using the measured electron g factor we estimate that the relaxation time $\tau\sim10$ ns corresponds to a $\Delta B_l\sim3$ mT. Since this value is substantially larger than the random external magnetic fields which could be present in our setup, the most probable reason for these varying fields are the local magnetic fields in the structure. Possible sources of local fields acting on electrons in n-doped semiconductors are (i) the anisotropic exchange interaction between electrons localized on neutral donors [40] and (ii) fluctuations of the effective magnetic field associated with the hyperfine interaction of the electron and nuclear spins.[41]

The samples under study were characterized by high quality, with the volume density of impurities not exceeding 10^{14} cm^{-3} which corresponds to a two-dimensional impurity concentration in the 17-nm QW of 10^8 cm^{-2}. At the same time, the density of the excess electrons in the QWs under

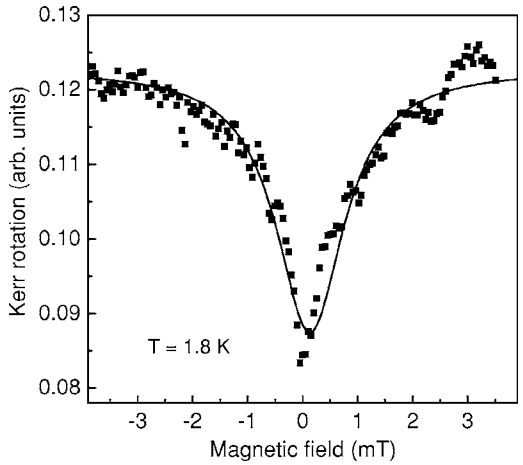

FIG. 7. Magnetic-field dependence of the Kerr rotation signal from the 17-nm QW of sample 2 measured at a negative time delay of about 1 ns (approximately 10 ns after the previous pump pulse). $U=+0.8$ V, $T=2$ K. Solid line is a fit by a Lorentzian.

study evaluated by means of the relative intensity of the trion and exciton peaks lies in the range of a few 10^{10} cm^{-2}, i.e., it is larger by at least two orders of magnitude. This means that the electrons localized on donors are only a small portion of excess electrons, and they cannot contribute noticeably to the signal. This is why we exclude the anisotropic exchange interaction as possible mechanism of the spin dephasing.

Hyperfine interaction of an electron with a limited number of nuclear spins acts on the electron as a fluctuating effective magnetic field (nuclear field).[41,42] The transverse component of this random field adds up to the external transverse magnetic field. This gives rise to a spread of the frequencies of the electron-spin precession and, as a consequence, to a decay of the spin QBs. To estimate the mean value of the nuclear field fluctuations in the structure under study, we measured the dependence of the Kerr rotation signal on an external longitudinal magnetic field oriented along the direction of observation. According to the conclusions of Ref. 41, the interaction with the nuclear fluctuations should lead in this situation to a dip in the magnetic-field dependence of the degree of electron-spin orientation. In a first approximation, the dip can be considered as a Lorentzian centered at zero field, with its full width at half maximum (FWHM) corresponding to the ensemble-averaged field of nuclear fluctuations ΔB_n. As one can see from the data of Fig. 7, such a dip is indeed observed. Note that its FWHM $\Delta B_n=2\pm1$ mT is within the experimental error consistent with the value $\Delta B_l \sim 3$ mT determined above. Thus we conclude that the nuclear fluctuations limit, in our case, the coherence lifetime of the ensemble of electron spins.

This conclusion agrees well with the dependence of the dephasing time on the bias voltage, i.e., on the electron density described in Sec. III. The mean value of the fluctuating nuclear field is inversely proportional to the square root of the number of nuclei coupled to the electron. When there are very few electrons in the QWs (e.g., at $U=-2.5$ V), they occupy QW potential fluctuations and are strongly localized so that their wave function covers a relatively small number of nuclei. In this case, the magnitude of the nuclear field fluctuations is at a maximum, which causes the fast decay of the QBs ($\tau\sim1.5$ ns). When the bias rises to zero and further to positive values, the electron density increases and the strongly localized sites become completely filled. As a result, the fraction of the electrons in states with laterally much more extended wave functions increases. For such electrons, nuclear fluctuations are less important. This explains the nearly tenfold increase in the QB decay time observed experimentally.

V. CONCLUSION

Nuclear field fluctuations are usually considered as the main reason for the low-temperature electron-spin relaxation in quantum dots[41] and in low-level doped semiconductors containing strongly localized on donor impurities[16] or on QW thickness fluctuations[43] excess electrons. In this paper, we have shown experimentally that this mechanism is dominant also for spin coherency decay in high quality QWs, for which the conditions of electron localization are not so rigorous. An electron-spin dephasing time of 10 ns was measured for a 17-nm $GaAs/Al_{0.34}Ga_{0.66}As$ QW containing about 10^{10} cm^{-2} background electrons. Decrease of the electron density enhances electron localization and causes a decrease of dephasing time by an order of magnitude due to hyperfine interaction with nuclear spins. The same effect of acceleration of the spin dephasing was found with increasing temperature when the electrons become delocalized. The DP mechanism comes into operation in this case due to increase of kinetic energy of the electrons at elevated lattice temperatures.

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