Pis'ma v ZhETF, vol. 94, iss. 12, pp. 934 – 938

Influence of electron localization on the spin dephasing anisotropy in bias GaAs/AlGaAs coupled quantum wells

A. V. Sekretenko, A. V. Larionov [1)]

Institute of Solid State Physics RAS, 142432 Chernogolovka, Russia

Submitted 17 November 2011

Electron spin dephasing anisotropy is studied in GaAs/AlGaAs coupled quantum wells by means of a time-resolved Kerr rotation technique. It is found that the spin dephasing rate is strongly dependent on magnetic field and is significantly anisotropic in the quantum well plane. The presented theoretical model describes the experimental results by taking into account both the electron g-factor spreading and the irreversible electron spin relaxation which are caused by the electron localisation. The suggested theoretical description is in a good agreement with experimental data.

A lot of spintronic investigations deal with a control of electron spin decoherence and relaxation rate by means of electric and magnetic fields, temperature and structural features of semiconductor nanostructures [1]. It is also necessary to know spin relaxation mechanism and as far as possible to affect it. The main mechanism of spin relaxation in GaAs based quantum wells (QWs) is the D'yakonov–Perel' kinetic mechanism [2]. It is caused by the lack of inversion centrum: i) in the bulk semiconductor of which the system is made (bulk inversion asymmetry, or BIA), ii) in the heterostructure (structure inversion asymmetry, or SIA) and iii) in the chemical bonds at heterointerfaces (interface inversion asymmetry, or IIA) [2–4]. SIA can be caused by an external electric field or by deformation, BIA and IIA depend strongly on a size of carrier confinement. Therefore spin relaxation times can be controlled by gate voltage or by special heterostructure design.

Earlier it was theoretically predicted [5] that anisotropy of electron spin relaxation could be observed in III–V nanostructures grown along the axis [001]. It has been demonstrated that the lifetimes of spins oriented along the axes [110], [1$\bar{1}$0], and [001] are different. In particular, by changing the relation between SIA and BIA one can achieve a total suppression of relaxation for the spin oriented along one of [110] axes. Detailed calculations [6] confirmed that the spin relaxation anisotropy exists in real semiconductor heterostructures. The implementation of such idea to control spin relaxation times gives new opportunities for spintronics. The mentioned anisotropy was observed in several experiments [7–9].

Among the quasi-two-dimensional objects based on semiconductor heterostructures, coupled quantum wells (CQW) with bias are of special interest because they provide spatial separation of photoexcited electrons and holes in neighboring quantum wells. GaAs/AlGaAs CQW with bias allow one to tune the electron-hole overlap integral through the tunneling barrier height and hence to control the electrons escape from a quantum well due to radiative annihilation with holes. Additionally, such nanostructures are capable of affecting the structure inversion asymmetry, which is useful for controlling the electron spin relaxation mechanism [10].

In reality all the semiconductor heterostructures have different types of crystal imperfection – residual impurities, interface fluctuations and others which cause random potential fluctuations. This results in the localisation of electrons in the quantum well plane. It was recently shown that localized and nonlocalized electrons can have dramatically different spin dephasing times [11]. In addition authors of Ref. [12] have discovered that the carrier localization leads to the saturation of spin relaxation times at 45 ns for electrons below 4.5 K and at 2 ns for holes below 2.3 K in a n-doped (In,Ga)As/GaAs quantum well.

Our previous study [10] has demonstrated that an external bias is capable and powerful tool for the effective spin-orbit splitting control in CQW. It was shown that one can test and control spin-orbit splitting by means of tracking the spin anisotropy. The goal of the present work is to investigate experimentally the influence of the electron localization on the spin dephasing time anisotropy in GaAs/AlGaAs CQW heterostructures.

The sample with GaAs/AlGaAs CQW was grown by molecular-beam epitaxy on [001] oriented GaAs substrate. The CQW consists of two GaAs quantum wells (≈ 120 Å wide) with a narrow (4 monolayers) AlAs barrier between them. They are separated from surrounding layers by 1500 Å thick $Al_{0.33}Ga_{0.67}As$ barriers. The

[1)] e-mail: larionov@issp.ac.ru

bottom gate was formed by a 250 Å wide QW δ-doped with Si, and the top one – by a 180 Å thick semitransparent Au layer deposited on the structure forming a Schottky barrier.

The electron spin dephasing time was measured by means of the time-resolved Kerr rotation technique (TRKR). For details see, e.g. [10]. Ten picosecond Ti:sapphire laser was used as a source of pulsed photoexcitation. In addition to the laser pump beam modulation, the probe beam amplitude was modulated by a chopper at 300 Hz to reduce the influence of the scattered pump beam on the measured signal.

The sample was placed in an optical cryostat (Voigt geometry) with a solenoid up to 6 T at 2 K. The design of the sample holder is suitable for a precise varying the direction between the magnetic field and the crystallographic axes with an accuracy of 1 degree. A used power density of photoexcitation was $P = 25\,\mathrm{W/cm^2}$.

A set of time-resolved Kerr rotation curves detected in a magnetic field of 1 T is presented in Fig. 1a for the

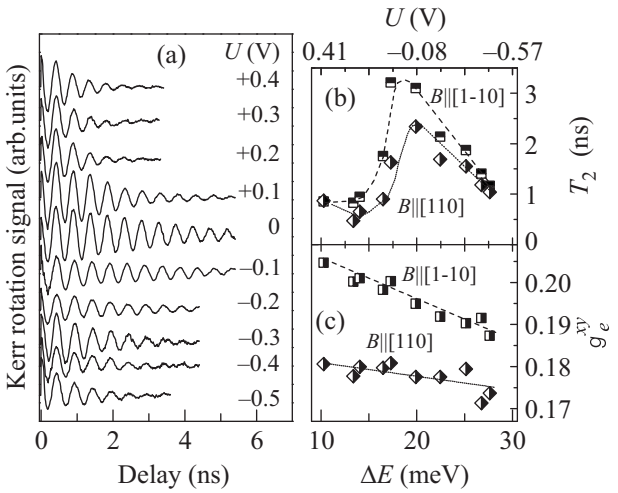

Fig. 1. (a) – TRKR-signal for different applied biases. Spin dephasing time (b) and g_e^{xy} (c) are measured for two angles between magnetic field and axe $x \parallel [110]$. Solid and dashed lines are guides for eyes

different bias U(V). The energies of the pump and probe pulsed laser beams were the same and were set to the maximum of the photoluminescence line (PL) contour corresponding to radiative annihilation of the 1sHH-exciton. The observed periodic oscillations are due to the precession of coherently excited electron spins around the external magnetic field, which (from a quantum-mechanical point of view) corresponds to quantum beats (QBs) between spin-splitted states of the Zeeman doublet. The period of the oscillations is proportional to the electron spin splitting ΔE in the conduction band. The time-resolved Kerr rotation technique is not sensitive to the sign of g-factor, but allows one to measure the g-factors absolute value in the quantum well plane (g_e^{xy}) with high accuracy, as the precession Larmor frequency $\hbar\omega_L = \Delta E = \mu_B g_e^{xy} B$.

The observed signal is fitted by exponentially damped oscillations containing the beating frequency Ω and a single decay time:

$$I = I_0 e^{-t/T} \cos(\Omega t + \phi), \qquad (1)$$

where T – spin lifetime, $\Omega = \mu_B g_e^{xy} B/\hbar$ – the electron Larmor frequency, g_e^{xy} – the in-plane electron g-factor absolute value.

As a result of such fitting the dependences of electron spin dephasing time (T_2) and g_e^{xy} vs. applied bias were obtained that is shown on Figs. 1b and 1c, correspondingly. The lower scale here corresponds to the Stark energy shift between 1sHH exciton levels in the neighbouring quantum wells (see, e.g. [13]). In the studied CQW the electron-hole recombination time is much longer then the measured time ($\tau_{\mathrm{rec}} \gg T_2$). It means that we deal with the electron spin dephasing time according to expression: $T^{-1} = T_2^{-1} + \tau_{\mathrm{rec}}^{-1}$ [10]. The influence of holes on the Kerr rotation signal is neglected due to the short hole spin dephasing time (of the order of 10 ps).

One can see that the spin dephasing time is strongly nonmonotonic at applied bias. It can be caused by a nonmonotomic dependence of spin-orbit splitting due to Rashba and Dresselhaus terms interference [10]. The difference in the spin dephasing times for two mutually orthogonal directions of magnetic field and axis $x \parallel [110]$ can as well be attributed to this interference. The decreasing of g_e^{xy} vs. applied bias, in turn, reflects the decreasing of quantum well confinement [14].

Additionally we performed the detailed measurements of the spin dephasing time as a function of external magnetic field. A typical magnetic field dependence of the TRKR-signal is shown in Fig. 2a for the two laser photon energies corresponding 1sHH exciton and trion PL-lines maxima (see Fig. 2b). In contrast to magnetic field dependence in n-i-n CQW-structure [10] one can see in Fig. 2a a strong drop of the spin dephasing time with increasing magnetic field. We attribute such behavior to the electron g-factor spreading caused by the random potential fluctuations and discuss in details below.

Due to the narrow laser line width (0.1 meV) we could tune the laser along the PL-line contour with a spectral resolution of 0.2 meV. The measured spin dephasing time demonstrates a strong wavelength dependence similar to that observed in [11]. A typical TRKR-spectrum is presented in Fig. 3. When the laser is tuned

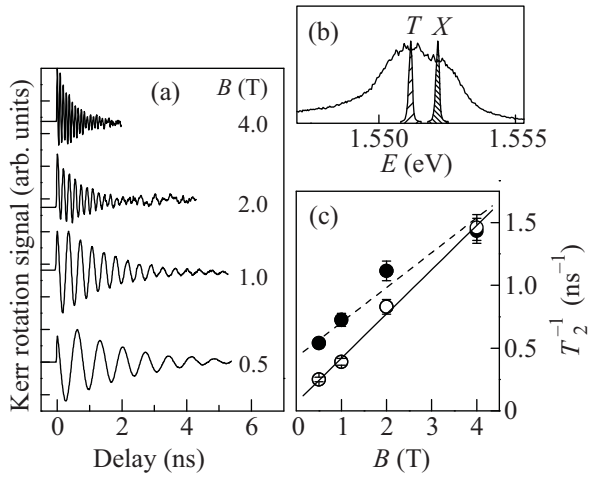

Fig. 2. (a) – TRKR-signal in magnetic field of 0.5, 1, 2 and 4 T. Laser energy $\hbar\omega_{\rm laser} = 1.5520$ eV. (c) – Spin dephasing rate (T_2^{-1}) dependence vs. magnetic field for two laser photon energy, corresponding to 1sHH exciton (1.522 eV, dark symbols) and trion (1.521 eV, open symbols) PL-lines maximum (b). Solid lines correspond to the fitting by Eq. (2). The exciton and trion PL maxima are marked by letters, $U = 0.0$ V ($\Delta E = 17.5$ meV)

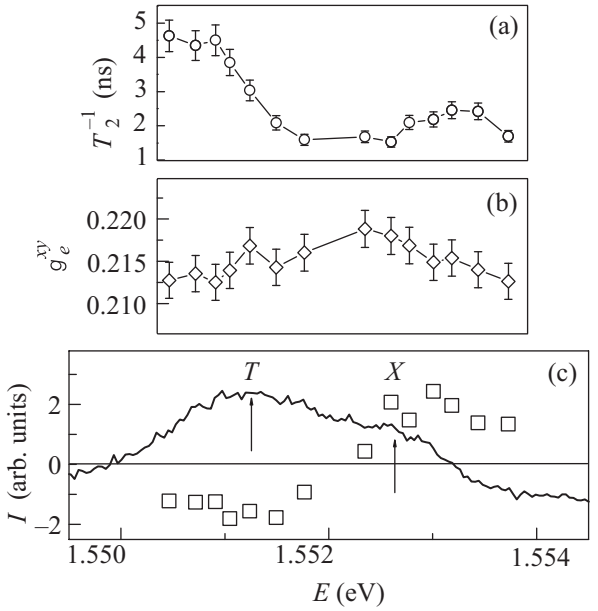

Fig. 3. (a) – Laser photon energy dependence of the TRKR-signal. Spin dephasing time dependence along PL-line contour. (b) – g_e^{xy} dependence along PL-line contour. (c) – TRKR-signal amplitude (symbols) and PL-intensity (solid curve). The exciton and trion PL maxima are marked with letters, $U = 0.0$ V ($\Delta E = 17.5$ meV), $B = 0.75$ T

from higher to lower energy, the beatings amplitude reaches its maximum at the 1sHH exciton PL maximum position. Then the amplitude drops and the signal disappears. At the trion PL the beatings are observed again, but with the opposite phase according to [15]. Here, the maximum amplitude corresponds to the trion PL maximum. No TRKR-signal is observed at other energies. The spin dephasing time has two maxima: at the 1sHH exciton PL maximum and at the red edge of the trion PL, the latter being much more pronounced ($\tau_s^T \approx 4.5$ ns and $\tau_s^X \approx 2.5$ ns).

Thus we can suggest the following explanation of the spectral dependences. The trion oscillator strength is directly proportional to the concentration of electrons with the corresponding spin projection (see, e.g. [15]). When the probe beam is turned to the trion resonance the reflections for two orthogonal circular polarizations are different. This way the Kerr rotation signal is formed. Its sensitivity to the spin of the electrons with a specific localization energy depends on the difference between the probe beam energy and the electron localisation energy. On the other hand, the TRKR-signal at the 1sHH exciton energy position is determined mostly by the scattering of excitons on free carriers. It means that the changing of laser beam energy allows one to probe different localized (or nonlocalized) electron states.

The spin dephasing time in the studied CQW, as well as in the *n-i-n* CQW [10], is found to be dependent on the magnetic field orientation in the structure plane (Fig. 4). Due to the special design of the sample holder we could set any angle between the magnetic field and the crystallographic axis with an accuracy of 1 degree in the range of about 90 degrees (black symbols in Fig. 4). For each applied bias the anisotropy was measured at several wavelengths along the PL-line contour corresponding to different *detunings*: $\delta = \hbar\omega_{\rm laser} - E_T$, where E_T corresponds to the energy position of trion PL maximum). The obtained experimental data were fitted using expression (7) from [10] (solid lines on Fig. 4). One can see a good agreement of the fitting and experimental results. It unambiguously indicates that the studied electron spin dynamics in magnetic field is described by the kinetic equation (eq.(3) in [10]) with anisotropic spin relaxation tensor. At the same time the observed spin relaxation anisotropy is markedly varying along the PL-line contour. It means that it essentially depends on electron localisation. By this reason we can analyse only the anisotropy parameter b and cannot correctly determine the ratio of the Rashba and Dresselhaus constants like we did it in [10].

The anisotropy parameter (b) dependence on the applied bias was derived using expression (eq. (7) in [10]) and is shown in Fig. 5. The obtained b values can be divided in the two groups. The first group is the bunch close to trion PL maximum position (open square and

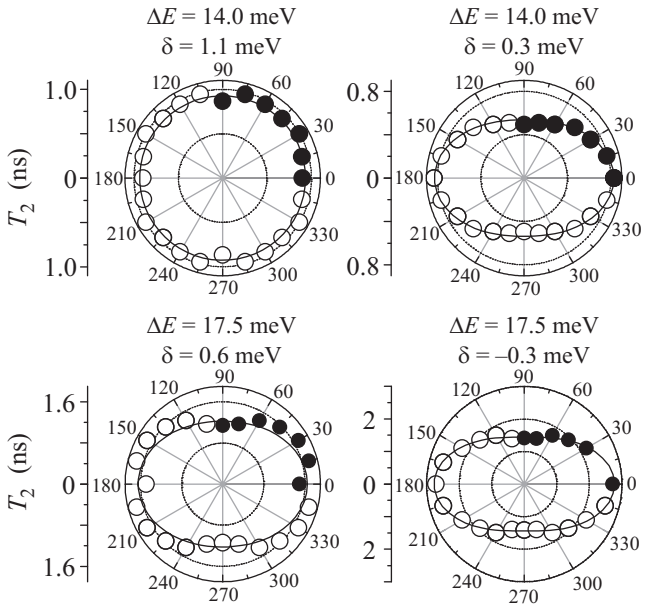

Fig. 4. Spin dephasing time measured as a function of the angle between **B** and the axis $x \parallel [110]$ at two applied biases for different *detuning*. Experimental data is shown with black points, the solid line is the theoretical approximation. Open symbols – extrapolation to the next three quadrants, $B = 0.75$ T

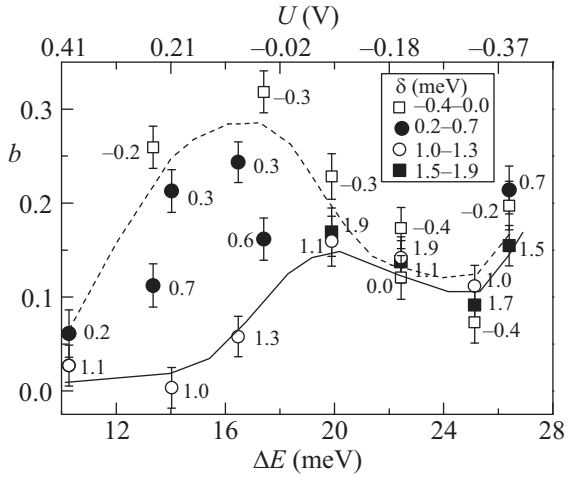

Fig. 5. The anisotropy parameter b dependence vs. the applied bias. Applied biases from $+0.4$ to -0.4 V. $\delta = -0.4 \ldots 1.9$ meV (marked by numbers), $B = 0.75$ T. Solid and dashed lines are guides for eyes

black circular symbols), the second group is related to 1sHH PL maximum position (black square and open circular symbols). A small deviation of δ in every group is due to a shift of PL-lines (both trion and 1sHH PL-lines) with variation of applied bias. The behavior of b vs. the applied bias is strongly nonmonotonic and essentially determined by the laser energy photoexcitation that, as we suppose, is related to a different electron energy localisation.

There are two contributions to the decay rate of spin components transversal to the field. The first one is related to the spread of localized electrons g-factors Δg which results in the Larmor frequency spread $\Delta\Omega = \Delta g \mu_B B/\hbar$ and, correspondingly, in the spin dephasing with the rate $1/\Omega$. Moreover, even in the absence of magnetic field, the localized electron spin decays due to e.g. nuclear fluctuations which act as random magnetic fields, and due to other spin relaxation processes. Below the corresponding contribution to the spin decay rate is denoted as $1/\tau_0$. As a result, the total transversal spin relaxation rate can be estimated as

$$\tau_s(B)^{-1} = \tau_0^{-1} + 80\Delta g B, \qquad (2)$$

where B is given in Tesla, τ_0 – in nanoseconds and 80 – dimensional constant $(\mathrm{T} \cdot \mathrm{n})^{-1}$.

We believe that in the studied CQW electron spin dephasing rate is determined by both the g-factor spreading and the irreversible spin relaxation. To understand whether one or both of these terms are anisotropic, we performed measurements of the spin dephasing rate as a function of magnetic field for the two orthogonal magnetic field orientations in the structure plane: **B** $\parallel [110]$ and **B** $\parallel [1\bar{1}0]$ (black and open symbols in Fig. 6, correspondingly). Using the fitting Eq. (2) of the

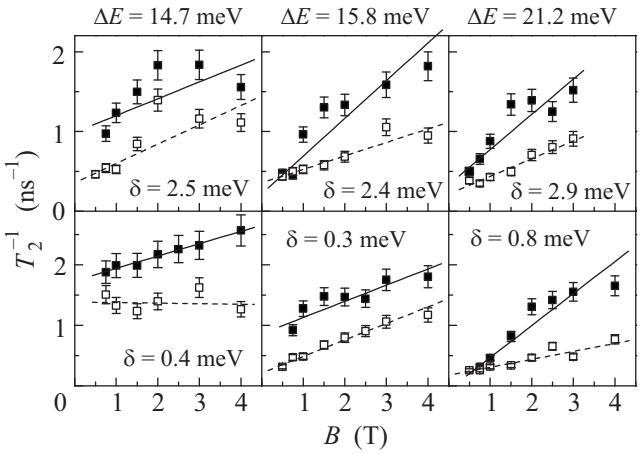

Fig. 6. Spin dephasing rate as a function of magnetic field directed along [110] (black symbols) and $[1\bar{1}0]$ (open symbols). The solid lines are the fitting of the experimental data by Eq. (2). Note that the relative measurement error of τ_s is constant

experimental data one extracts values of τ_0 and Δg. We present the obtained data in Table. Comparing the data with Fig. 6 shows that both the electron g-factor spreading and irreversible relaxation time τ_0 are anisotropic.

Spin dephasing time τ_0 in the $B = 0$ limit and g-factor spreading Δg for the two orthogonal magnetic field orientations

ΔE (meV)	δ (meV)		τ_0 (ns)	Δg (10^{-3})
14.7	2.5	$\mathbf{B} \parallel [110]$	1.0 ± 0.1	2.6 ± 0.6
		$\mathbf{B} \parallel [1\bar{1}0]$	2.8 ± 0.3	3.0 ± 0.4
	0.4	$\mathbf{B} \parallel [110]$	0.6 ± 0.06	2.5 ± 1.0
		$\mathbf{B} \parallel [1\bar{1}0]$	0.72 ± 0.06	0 ± 0.6
15.8	2.4	$\mathbf{B} \parallel [110]$	5 ± 1	5.9 ± 0.5
		$\mathbf{B} \parallel [1\bar{1}0]$	2.8 ± 0.3	2.1 ± 0.3
	0.3	$\mathbf{B} \parallel [110]$	1.2 ± 0.1	3.3 ± 0.6
		$\mathbf{B} \parallel [1\bar{1}0]$	4.7 ± 0.7	3.4 ± 0.3
21.2	2.9	$\mathbf{B} \parallel [110]$	3.0 ± 0.5	5.5 ± 0.6
		$\mathbf{B} \parallel [1\bar{1}0]$	4.6 ± 0.8	2.8 ± 0.3
	0.8	$\mathbf{B} \parallel [110]$	*	*
		$\mathbf{B} \parallel [1\bar{1}0]$	5.7 ± 0.7	1.6 ± 0.2

The data are obtained using Eq. (2) for different Stark shifts and δ from Fig. 6

In conclusion, we have experimentally found that the electron spin dephasing anisotropy in GaAs/AlGaAs CQW significantly depends on the electron localisation in QW-plane. We found that the anisotropic spin dephasing rate is determined by both the electron g-factor spreading and the irreversible electron spin relaxation that are anisotropic and can be controlled by bias. The suggested theoretical model is in a good agreement with experimental data.

We acknowledge fruitful discussions with L.E. Golub and M.M. Glazov. This research was supported by the Russian Foundation for Basic Research.

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