Electric field control of spin-orbit splittings in GaAs/AlGaAs coupled quantum wells

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Electron spin dynamics is investigated in n-i-n GaAs/AlGaAs coupled quantum wells. The electron spin dephasing time is measured as a function of an external electrical bias under resonant excitation of the 1sHH intrawell exciton using a time-resolved Kerr rotation technique. It is found a strong electron spin dephasing time anisotropy caused by an interference of the structure inversion asymmetry and the bulk inversion asymmetry. This anisotropy is shown to be controlled by an electrical bias. A theoretical analysis of electron spin dephasing time anisotropy is developed. The ratio of Rashba and Dresselhaus spin splittings is studied as a function of applied bias.

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\textbf{Introduction.} Critical point of spintronic investigations is a control of spin degrees of freedom by electrical means. There are proposals to create electronic devices working due to an electric field effect on the orientation of electron spins. In order to study such phenomena one needs to use a coupling between orbital and spin degrees of freedom. This is possible due to spin-orbit interaction, an universal relativistic effect which, however, can be altered in semiconductors and low-dimensional semiconductor systems by special structure design and/or external parameters. Especially interesting for both fundamental physics and applications is the spin-orbit interaction caused by lack of inversion center in the system. The important example is a class of effects caused by Structure Inversion Asymmetry (SIA) which is present in two-dimensional semiconductor structures\textsuperscript{1,2,3}.

There is a number of works where the SIA degree has been changed in two-dimensional structures by an external gate.\textsuperscript{4} However in most cases the effect of the gate voltage is a change of the electron gas concentration, which produces an additional internal electric field affecting SIA. Among the quasi-two-dimensional objects based on semiconductor heterostructures, Coupled Quantum Wells (CQWs) are of special interest. Electrical bias in such structures does not produce extra carriers but has dramatic effects on SIA. This allows for direct manipulation by spin-orbit interaction even in undoped structures. In addition, CQWs are very suitable objects for spin dynamics study because, due to spatial separation of photoexcited electrons and holes in neighboring quantum wells, the radiative lifetimes are long enough so that the spin lifetime is determined by spin relaxation processes.

SIA manifests itself as a source of spin relaxation of free electrons in two-dimensional semiconductors. It generates an effective magnetic field rotating electron spins which is the basis of the D’yakonov-Perel’ spin relaxation mechanism, for review see Ref. 4. Accordingly, the spin relaxation times measurements give the necessary information about the degree of SIA. In addition to SIA, there is another source for lacking inversion symmetry in semiconductors. This is Bulk Inversion Asymmetry (BIA) present in structures based on noncentrosymmetric materials and also leading to the D’yakonov-Perel’ spin relaxation. If both SIA and BIA are present, new interesting effects appear in spin dynamics. In particular, the spin relaxation anisotropy has been predicted for a spin oriented in the plane of a (001) grown structure.\textsuperscript{2} It has been shown that the anisotropy should change dramatically if the SIA strength is tuned to be comparable to BIA. However, in Refs. 6,7 the anisotropy has been observed for fixed sets of parameters, and in Ref. 8 it has been changed varying the electron concentration by other means. Effect of electrical bias on spin relaxation has been observed due to SIA variation but in specifically oriented (110) structures where SIA and BIA do not interfere and the in-plane anisotropy is absent, or when spin relaxation has not been caused by the spin-orbit interaction at all.\textsuperscript{2}

In the present work we use biased CQW structures for smooth change of spin relaxation anisotropy by electrical means. We demonstrate that spin-orbit interaction can be controlled by electric field in n-i-n GaAs/AlGaAs CQWs.

Time resolved Kerr rotation spectroscopy is an effective technique for creation and study of spin coherence in semiconductors.\textsuperscript{4,5} It allows one to prepare a coherent superposition of electron and (or) hole basis states. When external magnetic field is applied perpendicular to the direction of the circularly polarized light propagation, the spin vector precesses in the plane normal to the applied field. From a quantum-mechanical point of view, this Larmor precession corresponds to quantum beats (QB) between spin-splitted states of the Zeeman doublet. A projection of the spin vector on its excitation direction oscillates and, simultaneously, decays due to decoherence. The decoherence is caused by spin relaxation of electrons and (or) holes which allows one to study various spin relaxation mechanisms by time resolved Kerr rotation measurements.

\textbf{Experiment.} The CQW system studied here consists of two 120 Å wide GaAs quantum wells with a narrow (4 monolayer) AlAs barrier between them. The quantum wells are separated from the Si-doped (10\textsuperscript{18} cm\textsuperscript{-3}) GaAs layers by 0.15 µm thick Al\textsubscript{0.33}Ga\textsubscript{0.67}As barriers. The upper part of the structure is covered with a 100 Å GaAs layer. Mesa structures were fabricated on the as-grown...
have verified that \( T \) is independent of the magnetic field strength. The decay rate is a sum of radiative recombination and spin dephasing rates:

\[
1/T = 1/\tau_0 + 1/\tau_s.
\]

We extracted the interwell radiative electron-hole annihilation time \( \tau_0 \) from the photoluminescence measurements (the intrawell one is rather short being of order of tens picoseconds). The dependences of both \( \tau_s \) and \( \tau_0 \) on the applied bias are shown in Fig. 1(b). One can see that \( \tau_s \) is shorter than \( \tau_0 \) for \( U > 0.4 \) V.

Figure 2 demonstrates the polar plot of the spin dephasing time vs the magnetic field orientation in the structure plane for four applied biases. For such investigation it is necessary to rotate the sample relative to the direction of applied magnetic field with a high accuracy. Experimentally we have measured the data for angles from 0 to 90 degrees only (black points). Open points have been obtained by extrapolation to the next three quadrants. One can see that application of an electric field to CQWs gives a good opportunity for change of the spin relaxation anisotropy.

Our measurements are performed at photoexcited carrier concentrations about \((3 \ldots 5) \cdot 10^{10} \) cm\(^{-2}\). For such density the percolation threshold is overcome, so the maximum of the photoluminescence line contour corresponds to radiative recombination of free excitons. The electron-hole exchange interaction is suppressed due to spatial electron and hole separation in CQWs as well as by a magnetic field. Since the hole spin relaxation is rather fast (some picoseconds) we conclude that the observed Kerr signal decay is caused by spin relaxation of electrons bound in excitons. This suggestion is correlated with the fact that pronounced Kerr rotation signal appears at voltage \( U > 0.2 \) V. It could be explained if
originally CQWs are positively charged and one needs to apply some millivolts to compensate an excess hole concentration. So the Kerr signal is caused by magnetization of the electrons orbitally coupled with holes while their spins are independent.

**Theory.** Under excitation of a free exciton its electron propagates in the structure plane with an average momentum $k_e = K m_e/M$, where $K$ and $M$ are the momentum and effective mass of the exciton as a whole, and $m_e$ is the electron effective mass. Therefore SIA and BIA effective magnetic fields appear acting on the spin of an electron bound in exciton. Due to exciton scattering randomly changing a direction of its wavevector $K$, the D’yakonov-Perel’-like spin relaxation takes place where electron spin precession is accompanied by exciton relaxation anisotropy allows one to derive the ratio of SIA and BIA. 

For the D’yakonov-Perel’ spin relaxation mechanism the following expressions exist for the anisotropic spin relaxation rates:

$$\frac{1}{\tau_z} = C(\alpha^2 + \beta^2) \tau_p, \quad \frac{1}{\tau_{x,y}} = \frac{C}{2} (\alpha \pm \beta)^2 \tau_p. \quad (2)$$

Here the times $\tau_{x,y,z}$ are the relaxation times of the spin oriented along $x \parallel [100], y \parallel [110]$, and $z \parallel [001]$, $\alpha$ and $\beta$ are Rashba and Dresselhaus electron constants, respectively, which determine the spin-orbit splittings of free electrons with the wavevector $k_e$: $\Delta_{SIA} = 2\alpha k_e$, $\Delta_{BIA} = 2\beta k_e$, $\tau_p$ is the exciton momentum relaxation time, and $C = (m_e/M)^2 K^2/\hbar^2$, where $K^2$ is the mean value of the squared excited in-plane wavevector.

Electron spin dynamics in the presence of an external magnetic field and for anisotropic spin relaxation is described by the kinetic equation

$$\frac{\partial S}{\partial t} + S \times \Omega + \tilde{\Gamma} S + \frac{S}{\tau_0} = 0. \quad (3)$$

Here $S$ is the electron spin density, $\Omega$ is the Larmor frequency vector, and $\tilde{\Gamma}$ is the tensor of spin relaxation rates diagonal in the axes $x, y$ and $z$: $\Gamma_{xx} = 1/\tau_z$, $\Gamma_{yy} = 1/\tau_y$, and $\Gamma_{zz} = 1/\tau_z$.

If the electron spin is initially oriented along the axis $z$, the temporal behavior of the spin density $z$-component is sought in the form $S_z(t) = S_z(0) \exp(-t/\tau_0 + i\lambda t)$, where $\lambda$ is the complex frequency. Spin dynamics equation (3) yields a cubic equation for $\lambda$:

$$\lambda^3 + \left( \frac{1}{\tau_x} + \frac{1}{\tau_y} + \frac{1}{\tau_z} \right) \lambda^2 + \left( \frac{1}{\tau_x \tau_y} + \frac{1}{\tau_y \tau_z} + \frac{1}{\tau_x \tau_z} \right) \lambda + \frac{\Omega_x^2}{\tau_x} + \frac{\Omega_y^2}{\tau_y} + \frac{1}{\tau_x \tau_y \tau_z} = 0. \quad (4)$$

Here $\Omega_{x,y}$ Larmor frequency projections on the axes $x$ and $y$, and $\Omega_z = 0$ because we consider a magnetic field lying in the structure plane.

Equation (4) has three roots, $\lambda_{1,2,3}$. One of them, $\lambda_1$, is real and does not describe damping of spin oscillations. The imaginary parts of two others ($\lambda_2 = \lambda_3^*$) are equal by the absolute value to the spin dephasing rate. This results in the following spin dynamics law:

$$S_z(t) = A \exp(-t(1/\tau_0 + 1/\tau_s)) \cos(\Omega t + \varphi), \quad (5)$$

which yields Eq. (1) for time-resolved Kerr rotation experiments.

If a magnetic field is strong enough: $\Omega \tau_{x,y,z} \gg 1$ or spin relaxation anisotropy is small: $|1/\tau_x - 1/\tau_y| \ll 1/\tau_{x,y,z}, \Omega$, then one can derive an analytical expression for the spin dephasing time $\tau_s$. In both limits we have the following result:

$$\frac{1}{\tau_s} = \frac{1}{2} \left( \frac{1}{\tau_x} + \frac{\sin^2 \theta}{\tau_x} + \frac{\cos^2 \theta}{\tau_y} \right), \quad (6)$$

where $\theta$ is the angle between magnetic field $B$ and the axis $z \parallel [110]$. Here we ignore the effect of small $g$-factor anisotropy on the value of $\tau_s$ as well as small renormalization of the QB frequency.

**Discussion.** Figure 1(b) demonstrates a fast growth of the spin dephasing time with increasing of applied bias in the range $U = 0.5 \ldots 1.3$ V. This behavior is explained by the D’yakonov-Perel’ spin relaxation mechanism which is dominant for electrons in GaAs-based semiconductor heterostructures. Indeed, scattering from interface microroughness is accelerated with decrease of the confinement size. The momentum relaxation time $\tau_p$ became shorter which suppresses spin relaxation according to Eq. (2). The order of magnitude of $\tau_s \sim 1$ ns corresponds to a reasonable spin splitting constant $\alpha \approx 10^{-7}$ meV cm at $K = 5 \cdot 10^5$ cm$^{-1}$, $m_e/M = 0.3$, and $\tau_p = 1$ ps.

In our experiments the QBs are well pronounced, see Fig. 1(a). Therefore the relation $\Omega \tau_{x,y,z} \gg 1$ is true, and we can use Eq. (1) for description of the spin dephasing time angular dependence. It yields

$$\tau_s(\theta) = \frac{D}{1 + b \cos 2\theta}, \quad (7)$$

where $b < 1/3$. The result of the experimental data fitting according to Eq. (1) with $D$ and $b$ as adjustable parameters is shown in Fig. 2 by solid lines. One can see a good agreement between experiment and theory for all values of the bias.

The performed quantitative description of the spin relaxation anisotropy allows one to derive the ratio of SIA and BIA electron spin-orbit splittings. The parameter $b$ in Eq. (1) determines the ratio of the Rashba and Dresselhaus constants:

$$\left( \frac{\alpha}{\beta} \right) = \frac{3b}{1 + \sqrt{1 - (3b)^2}} \quad (8)$$

This expression demonstrates that Kerr rotation measurements do not allow one to distinguish between the constants $\alpha$ and $\beta$. Indeed, the symmetric form of Eq. (4)
yields Eq. (3) either for the ratio $\alpha/\beta$ or for $\beta/\alpha$. However disappearance of the anisotropy at $U \approx 1.3$ V means that one of the spin splittings nullifies. Since the Dresselhaus splitting cannot be tuned to zero by bias, we conclude that it is the Rashba one, and Eq. (3) describes namely the value of $\alpha/\beta$ at $0.7$ V $< U < 1.6$ V. We used Eq. (3) for derivation of the ratio $\alpha/\beta$ and plotted the result in Fig. (3) (see also the values given in Fig. 2). The values $\alpha/\beta > 0$ are taken at $U < 0.7$ V because the ratio should be monotonous function of the bias.

One can see strong variations of this parameter by the electric field: at $U > 0.6$ V the ratio $\alpha/\beta$ decreases monotonously changing its sign at $U \approx 1.3$ V. At this bias the polar plot $\tau_r(\theta)$ is a circle. At higher bias the anisotropy is present again, but the ellipse is rotated by 90 degrees relative to that for low voltage. The observed behavior of the ratio $\alpha/\beta$ is mainly due to change of SIA by applied bias. The structure under study contains some built-in SIA at $U = 0$ due to different properties of the interfaces which can be modeled by different height of the left and the right barriers (see insets to Fig. 3).

External electric field suppresses this built-in asymmetry resulting in the decrease of $\alpha$. At $U \approx 1.3$ V the external and internal SIA compensate each other resulting in realization of the most symmetric confinement potential. This is unambiguously indicated by the spin dephasing time isotropy at this voltage. At higher bias, the external contribution to SIA dominates which leads to change of the sign of the constant $\alpha$. The BIA constant $\beta$ is also sensitive to the external electric field because it is determined by the size of the electron confinement. However $\beta$ has the same sign at any bias therefore the ratio $\alpha/\beta$ changes mainly due to the dependence $\alpha(U)$ (so-called “Rashba effect”).

The spin dephasing time saturation at high bias $U = 1.3 \ldots 1.6$ V presented in Fig. 1(b) can be also explained by the above discussed compensation of SIA. At these voltages, increase of the momentum relaxation rate competes with the suppression of the SIA spin splitting. As a result the spin dephasing time growth slows down in accordance with Eq. (2).

To summarize, the electron spin dephasing time anisotropy is observed in the biased (001) grown n-i-n CQWs. Spin decoherence is studied by means of time-resolved Kerr rotation effect at magnetic field differently oriented in the structure plane. The anisotropy is caused by interference of SIA and BIA spin-splittings in the electron spin relaxation via the D’yakonov-Perel’ mechanism. It is demonstrated that SIA is changed by bias according to the Rashba effect in the studied structure. It is shown that spin-orbit splitting can be controlled by electrical means in n-i-n GaAs/AlGaAs coupled quantum wells.

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