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Spin relaxation in asymmetrical heterostructures

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Electron spin relaxation by the D'yakonov–Perel' mechanism is investigated theoretically in asymmetrical $\mathrm{A^{III}B^{V}}$ heterostructures. Spin relaxation anisotropy for all three dimensions is demonstrated for a wide range of structural parameters and temperatures. Dependences of spin relaxation rates are obtained both for a GaAs-based heterojunctions and a triangular quantum wells. The calculations show a several-orders-of-magnitude difference between spin relaxation times for heterostructure parameters realized in experiments.

1. Introduction

The degrees of freedom of spin have received a great deal of attention throughout the development of semiconductor physics. Recently, the spin properties of carries have been investigated intensely in low-dimensional semiconductor structures. In electronics, much interest in spin has been aroused by recent proposals to construct spin transistors and spin computers based on heterostructures [1,2].

The spin-orbit interaction, governing the spin behavior, is much more complex in semiconductor heterostructures than in bulk systems. The bulk spin-orbit terms take a more interesting form in two-dimensional ($2D$) systems, and, in addition, new terms appear, which are absent in bulk.

In [3] we considered electron spin dunamics in asymmetrical heterostructures. A giant anisotropy of spin relaxation times caused by interference of different spin-orbit terms has been revealed. In this work, we calculate the spin relaxation rates in real asymmetrical structures. A heterojunction and a triangular quantum well (QW) are considered in detail. The effect of heteropotential asymmetry on spin relaxation is investigated in a wide range of electron concentrations and temperatures. We show that the giant spin relaxation anisotropy is governed by external parameters, that opens up new possibilities for spin engineering.

2. Theory

Let us consider a system with spin-orbit interaction described by the Hamiltonian $H_{\mathrm{SO}}(\mathbf{k})$, where $\mathbf{k}$ is a wavevector. $H_{\mathrm{SO}}(\mathbf{k})$ is equivalent to a Zeeman term with effective magnetic field dependent on $\mathbf{k}$. In the presence of scattering, the wavevector changes and, hence, the effective magnetic field changes too. Therefore, in the case of frequent scattering, the electrons move in a chaotically changing magnetic field. The spin dynamics in such a system has diffusion character, which leads to loss of any specific spin orientation. This is called the D'yakonov–Perel' spin relaxation mechanism [4], which is the main spin relaxation mechanism is many $\mathrm{A^{III}B^{V}}$ bulk semiconductors and heterostructures.

For a $2D$ system with any $H_{\mathrm{SO}}(\mathbf{k})$ (where $\mathbf{k}$ lies in the plane of the heterostructure), one can show, similarly to [3] (see also [4–6]), that the spin dynamics of electrons in the presence of elastic scattering is described by the following equations

$$\dot{S}_i(t) = -\frac{1}{2\hbar^2}\sum_{n=-\infty}^{\infty}\frac{\int\limits_0^\infty d\varepsilon(F_+ - F_-)\tau_n A_n^{ji}}{\int\limits_0^\infty d\varepsilon(F_+ - F_-)}\,S_j(t), \tag{1}$$

$$A_n^{ji} = \mathrm{Tr}\left\{\left[H_{-n},[H_n,\sigma_j]\right]\sigma_i\right\}.$$

It should be noted that this is true only for times longer than the momentum relaxation time but shorter than the spin relaxation times. In Eq. (1), S_i are the spin density components $(i = x, y, z)$, the integration is performed over energy $\varepsilon = \hbar^2k^2/2m$, where m is the electron effective mass, $F_\pm(\varepsilon)$ are distribution functions of electrons with the spin projection equal to $\pm 1/2$, σ_i are the Pauli matrices; H_n are the harmonics of the spin-orbit Hamiltonian:

$$H_n = \oint \frac{d\varphi_{\mathbf{k}}}{2\pi}\,H_{\mathrm{SO}}(\mathbf{k})\exp(-in\varphi_{\mathbf{k}}), \tag{2}$$

where $\varphi_{\mathbf{k}}$ is the angular coordinate of $\mathbf{k}$, and the scattering times are given by

$$\frac{1}{\tau_n} = \oint d\theta\,W(\varepsilon,\theta)(1-\cos n\theta), \tag{3}$$

where $W(\varepsilon,\theta)$ is the probability of elastic scattering by an angle θ for an electron with energy ε.

Equation (1) is valid for $2D$ electrons with any spin-orbit interaction $H_{\mathrm{SO}}(\mathbf{k})$. Now we consider an asymmetrical zinc-blende heterostructure. There are two contributions to $H_{\mathrm{SO}}(\mathbf{k})$. The first, the so-called bulk inversion asymmetry (BIA) term, is due to lack of inversion symmetry in the bulk material of which the heterostructure is made. To calculate this term, one has average the corresponding bulk expression over the size-quantized motion [6]. We investigate a heterostructure with the growth direction [001]

[¶] E-mail: golub@coherent. ioffe. rssi.ru coinciding with the z-axis and assume that only the first elecrton subband is populated. The BIA-term has the form

$$H_{\mathrm{BIA}}(\mathbf{k}) = \gamma\left[\sigma_x k_x(k_y^2 - \langle k_z^2\rangle) + \sigma_y k_y(\langle k_z^2\rangle - k_x^2)\right], \quad (4)$$

where we choose x- and y-directions to be aligned with the principal axes in the heterostructure plane. Here $\langle k_z^2\rangle$ is squared the operator $(-i\partial/\partial z)$ averaged over the ground state, and γ is the bulk spin-orbit interaction constant. It is seen that H_{BIA} contains terms both linear and cubic in $\mathbf{k}$.

In asymmetrical heterostructures, there is an additional contribution to the spin-orbit Hamiltonian, which is absent in the bulk. It is caused by structure inversion asymmetry (SIA) and can be written as [7–9]

$$H_{\mathrm{SIA}}(\mathbf{k}) = \alpha(\sigma_x k_y - \sigma_y k_x), \quad (5)$$

where α is proportional to the electric field E, acting on an electron:

$$\alpha = \alpha_0 eE. \quad (6)$$

Here e is the elementary charge and α_0 is a second spin-orbit constant determined by both bulk spin-orbit interaction parameters and properties of heterointerfaces. It should be stressed that, in asymmetrical heterostructures, E is caused mainly by the difference of the wavefunction and band parameters at the interfaces, rather than by average electric field [10].

H_{SIA} also contains terms linear in k. From Eq. (1) follows that the harmonics with the same n are coupled in the spin dynamics equations. This leads to interference of linear in wavevector BIA- and SIA-terms in spin relaxation [3].

For $H_{\mathrm{SO}} = H_{\mathrm{BIA}} + H_{\mathrm{SIA}}$, the system has C_{2v}-symmetry. Therefore Eqs. (1) can be rewritten as follows:

$$\dot{S}_z = -\frac{S_z}{\tau_z}, \quad \dot{S}_x \pm \dot{S}_y = -\frac{S_x \pm S_y}{\tau_\pm}. \quad (7)$$

The times τ_z, τ_+, and τ_- are the relaxation times of the spin parallel to the axes [001], [110] and [1$\bar{1}$0], respectively.

If both spin subsystems come to equilibrium before the onset of spin relaxation, then

$$F_\pm(\varepsilon) = F_0(\mu_\pm - \varepsilon), \quad (8)$$

where F_0 is the Fermi–Dirac distribution function and $\mu_\pm$ are chemical potentials of the electron spin subsystems. If the spin splitting is small, i. e.

$$|\mu_+ - \mu_-| \ll |\mu_+|, |\mu_-|$$

then the expressions for the spin relaxation rates $1/\tau_i$ $(i = z, +, -)$ have the form

$$\frac{1}{\tau_i} = \frac{\int\limits_0^\infty d\varepsilon(\partial F_0/\partial\varepsilon)\Gamma_i(k)}{\int\limits_0^\infty d\varepsilon(\partial F_0/\partial\varepsilon)}, \quad (9)$$

where

$$\Gamma_z(k) = \frac{4\tau_1}{\hbar^2}\Big[\big(\gamma^2\langle k_z^2\rangle^2 + \alpha^2\big)k^2 - \frac{1}{2}\gamma^2\langle k_z^2\rangle k^4 + \frac{1+\tau_3/\tau_1}{16}\gamma^2 k^6\Big],$$

$$\Gamma_+(k) = \frac{2\tau_1}{\hbar^2}\Big[\big(\alpha - \gamma\langle k_z^2\rangle\big)^2 k^2 + \frac{1}{2}\gamma\big(\alpha - \gamma\langle k_z^2\rangle\big)k^4 + \frac{1+\tau_3/\tau_1}{16}\gamma^2 k^6\Big], \quad (10)$$

$$\Gamma_-(k) = \frac{2\tau_1}{\hbar^2}\Big[\big(\alpha + \gamma\langle k_z^2\rangle\big)^2 k^2 - \frac{1}{2}\gamma\big(\alpha + \gamma\langle k_z^2\rangle\big)k^4 + \frac{1+\tau_3/\tau_1}{16}\gamma^2 k^6\Big].$$

Equations (9), (10) are valid for any electron energy distribution. If the electron gas is degenerate, then the spin relaxation times are given by

$$\frac{1}{\tau_i} = \Gamma_i(k_{\mathrm{F}}), \quad (11)$$

where k_{F} is the Fermi wavevector determined by the total 2D electron concentration N:

$$k_{\mathrm{F}} = \sqrt{2\pi N}. \quad (12)$$

In this case, the scattering time τ_1 in Eqs. (10) coincides with the transport relaxation time, τ_{tr}, which can be determined from the electron mobility.

For nondegenerate electrons, the spin relaxation times are determined, in particular, by the energy dependences of the scattering times τ_1 and τ_3. If $\tau_1, \tau_3 \propto \varepsilon^\nu$, then $\tau_3/\tau_1 = \text{const}$ and

$$\frac{1}{\tau_z} = \frac{4\tau_{\mathrm{tr}}}{\hbar^2}\Big[\big(\gamma^2\langle k_z^2\rangle^2 + \alpha^2\big)\frac{2mk_{\mathrm{B}}T}{\hbar^2} - \frac{\nu+2}{2}\gamma^2\langle k_z^2\rangle\Big(\frac{2mk_{\mathrm{B}}T}{\hbar^2}\Big)^2 + (\nu+2)(\nu+3)\frac{1+\tau_3/\tau_1}{16}\gamma^2\Big(\frac{2mk_{\mathrm{B}}T}{\hbar^2}\Big)^3\Big], \quad (13)$$

$$\frac{1}{\tau_\pm} = \frac{2\tau_{\mathrm{tr}}}{\hbar^2}\Big[\big(\pm\alpha - \gamma\langle k_z^2\rangle^2\big)\frac{2mk_{\mathrm{B}}T}{\hbar^2} + \frac{\nu+2}{2}\gamma\big(\pm\alpha - \gamma\langle k_z^2\rangle\big)\Big(\frac{2mk_{\mathrm{B}}T}{\hbar^2}\Big)^2 + (\nu+2)(\nu+3)\frac{1+\tau_3/\tau_1}{16}\gamma^2\Big(\frac{2mk_{\mathrm{B}}T}{\hbar^2}\Big)^3\Big].$$

Here T is electron temperature and k_{B} is the Boltzmann constant. In the particular case of short-range scattering, $\nu = 0$, and $\tau_1 = \tau_3$ are equal to τ_{tr}, which is independent of temperature.

Spin relaxation times are very sensitive to the relationship between two spin-orbit interaction strengths, $\gamma\langle k_z^2\rangle$ and α. From Eqs. (11), (13) follows that at low concentration or temperature, $1/\tau_z$, $1/\tau_-$, and $1/\tau_+$ are determined by the sum of squared $\gamma\langle k_z^2\rangle$ and α, by their squared sum, and squared difference, respectively. This may lead to a considerable difference between the three times, i. e. to a total spin relaxation anisotropy, if $\gamma\langle k_z^2\rangle$ and α are close in magnitude.

In real $\mathrm{A^{III}B^{V}}$ systems, the relations between H_{BIA} and H_{SIA} may be different. H_{BIA} or H_{SIA} may be dominant [11,12], or they may be comparable [13].

The value of $\langle k_z^2\rangle$ depends on the shape of the heteropotential and will be calculated for the given asymmetrical heterostructures below. The constant γ is known for GaAs from optical orientation experiments [5]. Correct theoretical expressions for γ and α_0 have been derived in terms of the three-band $\mathbf{k}\cdot\mathbf{p}$ model [13,14]. The heterointerfaces give a contribution to α_0 in addition to that from the bulk [15]. At large wavevectors, α_0 starts to depend on k [16,17]. Here we assume concentrations and temperatures to be sufficiently low, allowing us to ignore this effect.

The spin relaxation rates for two types of asymmetrical structures — a heterojunction and a triangilar QW — are calculated below. The scattering is assumed to be short-range ($\nu = 0$, $\tau_3 = \tau_1 = \tau_{\mathrm{tr}}$). All parameters are chosen to correspond to GaAs/AlAs heterostructure: $\gamma = 27\,\mathrm{eV}\cdot\mathrm{\AA}^3$, $m = 0.067m_0$, where m_0 is the free electron mass and $\alpha_0 = 5.33\,\mathrm{\AA}^2$. The time τ_{tr} is taken equal to 0.1 ps and assumed to be independent of the electron concentration.

3. Spin relaxation in a heterojunction

In a heterojunction, the extent of the spin-orbit interaction is governed by the $2D$ carrier concentration N; $\langle k_z^2\rangle$ can be estimated as follows [18]:

$$\langle k_z^2\rangle = \frac{1}{4}\left(\frac{16.5\pi Ne^2m}{\kappa\hbar^2}\right)^{2/3}, \tag{14}$$

where κ is the dielectric constant. The mean electric field acting on an electron can be taken equal to half the maximum field in the junction:

$$E = \frac{2\pi Ne}{\kappa}. \tag{15}$$

Figure 1 shows the concentration dependence of the reciprocal spin relaxation times for degenerate electrons in a GaAs/AlAs heterojunction ($\kappa = 12.55$). The inset shows the spin-orbit interaction strengths, $\gamma\langle k_z^2\rangle$ and α, and the absolute value of their difference, as functions of electron concentration.

One can see a spin relaxation anisotropy for all three directions over a wide range of concentrations. $1/\tau_+$ is less than $1/\tau_-$ at small N and greater than $1/\tau_-$ at large concentration. This is due to the fact that the first term in (10) is larger for $1/\tau_-$, and the second, for $1/\tau_+$. Therefore, at a certain concentration, the times τ_+ and τ_- must be equal. From Eqs. (10) (11) follows that this takes place when

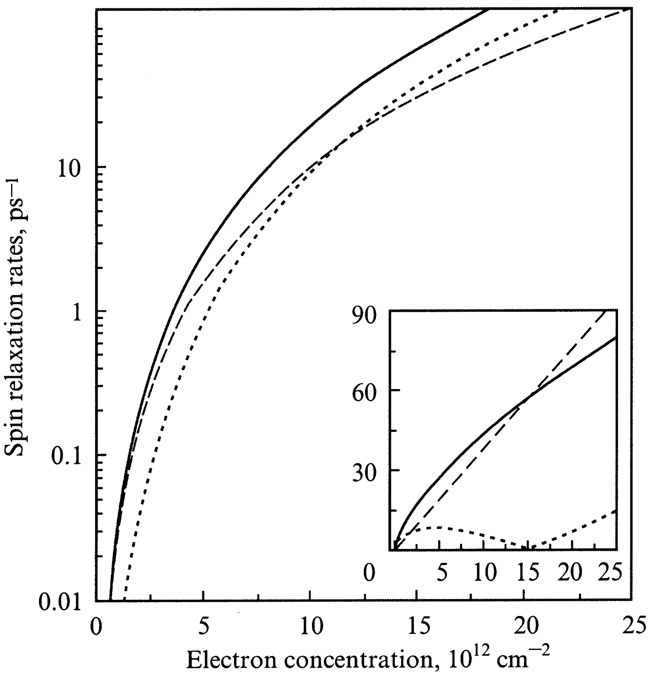

Figure 1. Concentration dependences of the reciprocal spin relaxation times, $1/\tau_z$ (solid line), $1/\tau_-$ (dashed line), and $1/\tau_+$ (dotted line), for a GaAs/AlAs heterostructure at zero temperature. The parameters are given in the text. The inset shows the spin-orbit interaction strengths, $\gamma\langle k_z^2\rangle$ (solid line), α (dashed), and $|\gamma\langle k_z^2\rangle - \alpha|$ (dotted), in $\mathrm{eV}\cdot\mathrm{\AA}$, as functions of the electron concentration $N/(10^{12}\,\mathrm{cm}^{-2})$.

$$k_{\mathrm{F}}^2 = 4\langle k_z^2\rangle, \tag{16}$$

which is fulfilled at $N = 1.1\cdot 10^{13}\,\mathrm{cm}^{-2}$ as illustrated in Fig. 1. At larger concentrations, the spin relaxation is again totally anisotropic.

Despite that $\gamma\langle k_z^2\rangle$ and α are close in magnitude over a wide range of concentrations (see the inset of Fig. 1), all three spin relaxation rates depend on N monotonically. This happens because, as the concentration increases, k_{F} increases as well, and the terms in H_{SO} which are cubic in the wavevector, become important. The growth of these terms with N dominates the change in $(\alpha - \gamma\langle k_z^2\rangle)^2$ in (10), hence the concentration dependence of $1/\tau_+$ is monotonic.

The situation changes in the case of a Boltzmann gas. For non-degenerate electrons, the mean wavevector and the concentration are independent. For temperatures up to 300 K, the characteristic $k^2 \propto 2mk_{\mathrm{B}}T/\hbar^2$ is much less than $\langle k_z^2\rangle$, and the spin relaxation rates are determined by the first terms in (13). As a result, all three spin relaxation times are different up to 300 K at a given concentration. The results of relevant calculations are presented in Fig. 2.

The times τ_+ and τ_- are equal to each other at a certain temperature only. According to (13), the corresponding condition is

$$T = \frac{\hbar^2 \langle k_z^2 \rangle}{m k_\mathrm{B}(1 + \nu/2)}. \tag{17}$$

With the GaAs-parameters and $\nu = 0$ in (14), it can be seen that (17) is satisfied at $T \approx 100\,\mathrm{K}$ for $N = 10^{11}\,\mathrm{cm}^{-2}$ and at $T \approx 290\,\mathrm{K}$ for $N = 5 \cdot 10^{11}\,\mathrm{cm}^{-2}$, in agreement with Fig. 2.

At a fixed temperature, the spin relaxation rates are governed by the electron concentration. According to Eqs. (13), the dependences of $1/\tau_i$ on N are similar to the curves in the inset of Fig. 1. In particular, form Eqs. (13) follows that $1/\tau_z$ and $1/\tau_-$ must be close in magnitude and both greatly exceed $1/\tau_+$. In addition, $1/\tau_+$ depends on concentration non-monotonically. This is confirmed completely by the results presented in Fig. 3. One can see that $1/\tau_+ \ll 1/\tau_z \approx 1/\tau_-$, and the rate $1/\tau_+$ has a minimum when plotted as a function of concentration. This minimum is at $N = 1.4 \cdot 10^{13}\,\mathrm{cm}^{-2}$, when the terms in H_SO linear in the wavevector cancel out. The corresponding condition is

$$\gamma \langle k_z^2 \rangle = \alpha. \tag{18}$$

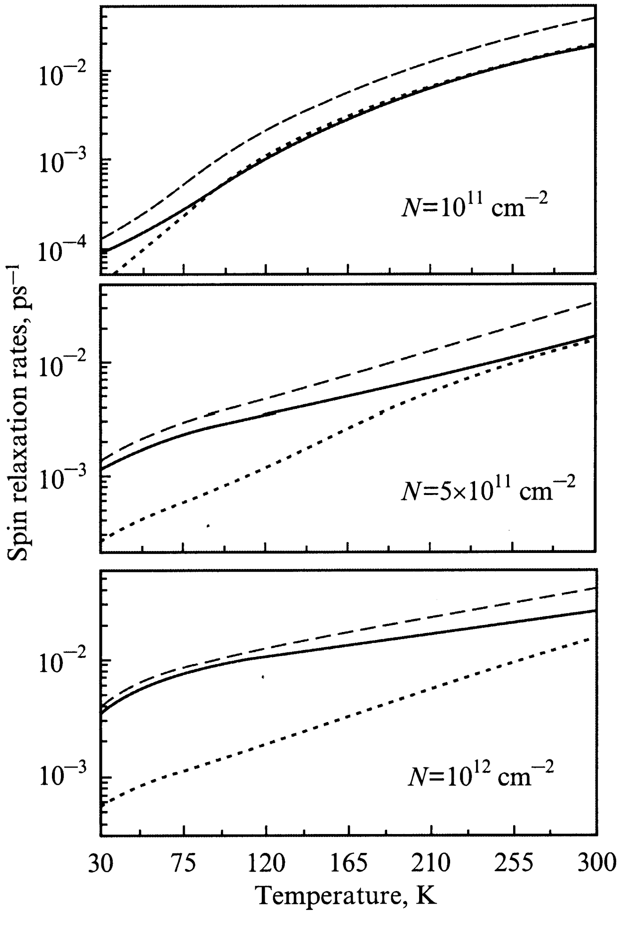

Figure 2. Temperature dependences of spin relaxation rates, $1/\tau_-$ (solid line), $1/\tau_z$ (dashed line) and $1/\tau_+$ (dotted line), for a GaAs/AlAs, heterostructure at different electron concentrations.

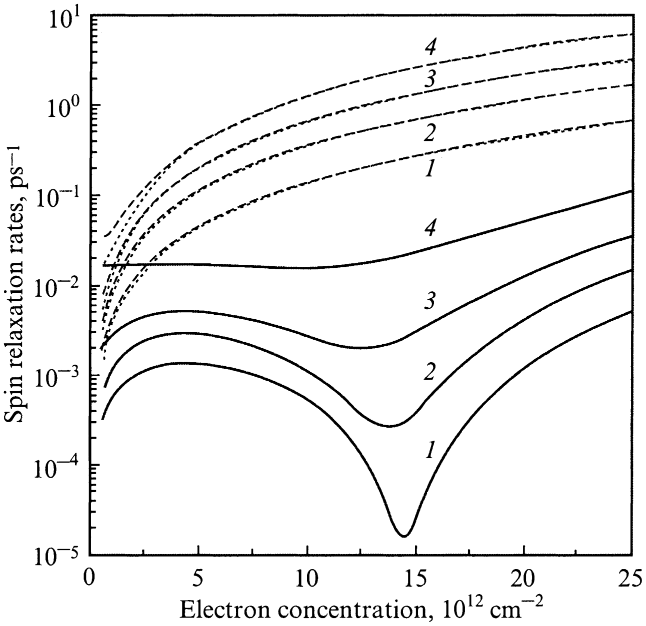

Figure 3. Concentration dependences of the reciprocal spin relaxation times, $1/\tau_+$ (solid line), $1/\tau_z$ (dashed line), and $1/\tau_-$ (dotted line), for Boltzmann electron gas in GaAs/AlAs heterostructure at temperatures T, K: *1* — 30, *2* — 77, *3* — 150, *4* — 300.

At this concentration, the spin relaxation time τ_+ is very large but remains finite owing to the terms cubic in k. Therefore the difference in the spin relaxation times is more pronounced at low temperature. At high T, the cubic in the wavevector terms become significant in H_SO, and the minimum in $1/\tau_+$ disappears. However $1/\tau_+$ is still much less than $1/\tau_-$, i.e. huge spin relaxation anisotropy occurs in the plane of the heterojunction even at room temperature.

4. Spin relaxation in a triangular quantum well

In this Section, we investigate spin relaxation in the following asymmetrical system. We consider a structure with infinitely-high barrier at $z < 0$ and constant electric field E at $z > 0$.

In the framework of this model,

$$\langle k_z^2 \rangle = a \left(\frac{2meE}{\hbar^2} \right)^{2/3}, \tag{19}$$

where

$$a = \frac{\int\limits_0^\infty dx \left[\mathrm{Ai}'(x - \beta) \right]^2}{\int\limits_0^\infty dx \left[\mathrm{Ai}(x - \beta) \right]^2} \approx 0.78. \tag{20}$$

Here $(-\beta)$ is the first root of the Airy function:

$$\mathrm{Ai}(-\beta) = 0, \quad \beta \approx 2.338.$$

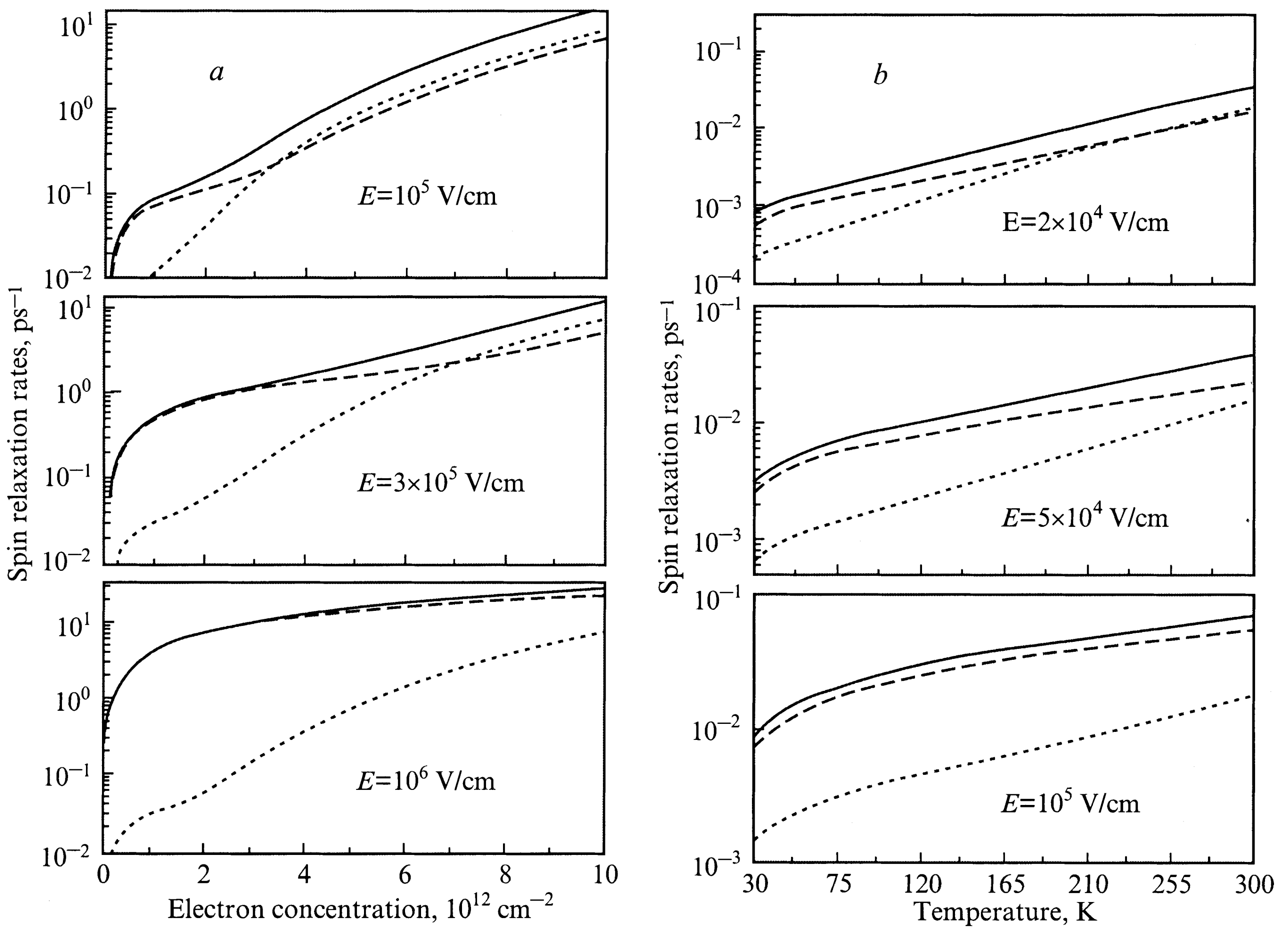

Figure 4. Spin relaxation rates, $1/\tau_z$ (solid line), $1/\tau_-$ (dashed line), and $1/\tau_+$ (dotted line), in a triangular GaAs QW at different electric field; *a* — degenerate electron gas, *b* — Boltzmann gas.

The value of α is determined by the difference of both the wavefunction and band parameters at the interfaces [10]. This may lead to a more complicated dependence of α on E than (6). However if E is not too high, we have a the linear law and, therefore, we use Eq. (6) in our calculations.

In Fig. 4 the spin relaxation rates are plotted for the triangular GaAs QW at different electric fields. It can be seen that total spin relaxation anisotropy occurs for both degenerate and Boltzmann gases in wide ranges of concentrations and temperatures. The times τ_+ and τ_- coincide only at a specific concentration or temperature. For degenerate electrons, according to Eq. (16), the corresponding curves intersect at $N \approx 3.4 \cdot 10^{12}\,\text{cm}^{-2}$ for $E = 10^5$ V/cm and at $N \approx 7 \cdot 10^{12}\,\text{cm}^{-2}$ for $E = 3 \cdot 10^5$ V/cm in agreement with Fig. 4, *a*. For a Boltzmann gas, the intersection of τ_+ and τ_- occurs according to (17), at $T \approx 150$ K for $E = 10^4$ V/cm and at $T \approx 240$ K for $E = 2 \cdot 10^4$ V/cm. This is also confirmed by Fig. 4, *b*.

The behavior of the reciprocal spin relaxation times in electric field is illustrated in Fig. 5 for both degenerate and Boltzmann electron gas. The dependences of $\gamma\langle k_z^2\rangle$ and α on electric field are similar to those in the inset of Fig. 1: their values are close in magnitude, so the difference between them is very small. This leads to a minimum in the dependence of $1/\tau_+$ on E. The cancellation condition (18) is fulfilled at $E \approx 1.9 \cdot 10^6$ V/cm. The electric field of this strength can be created in heterostructures containing a gate, allowing experimental observation of the non-monotonic spin relaxation rate dependence shown in Fig. 5.

5. Conclusion

It has been shown [19–21] that inclusion of both the BIA and SIA terms (4) and (5) into H_{SO} leads to conduction band spin-splitting anisotropy in **k**-space in $\text{A}^{\text{III}}\text{B}^{\text{V}}$ semiconductor heterojunctions. However, the spin relaxation analysis performed in [20] ignored this effect.

The authors of [22] showed that the BIA and SIA terms interfere in weak localization but are additive in spin relaxation. In this paper, we demonstrate that the terms in H_{SO} linear in the wavevector cancel out in spin relaxation as well.

In a recent experiment [23], the spin relaxation anisotropy was observed for uncommonly used (110) GaAs QWs. In this experiment, the spin relaxation in the growth direction

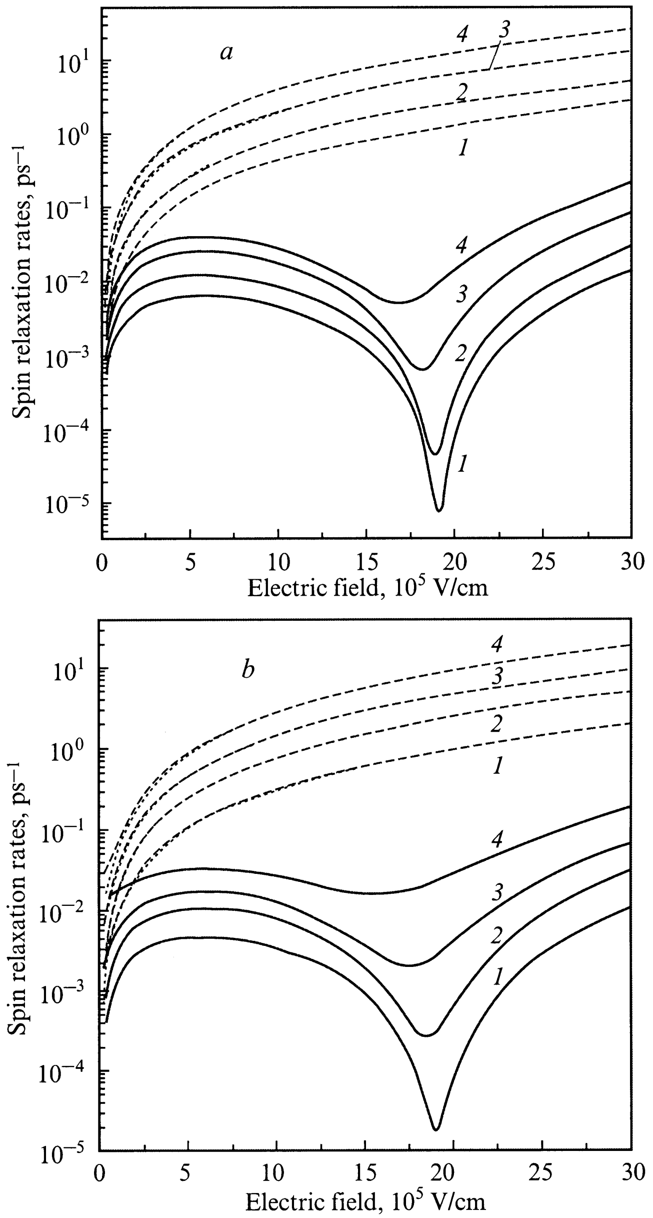

Figure 5. Spin relaxation rates $1/\tau_+$ (solid line), $1/\tau_z$ (dashed line), and $1/\tau_-$ (dotted line), in a triangular GaAs QW as functions of the electric filed; *a* — degenerate electrons at concentration N, cm^{-2}: *1* — 10^{11}, *2* — $3 \cdot 10^{11}$, *3* — $5 \cdot 10^{11}$, *4* — 10^{12}; *b* — Boltzmann gas, at temperatures T, K: *1* — 30, *2* — 77, *3* - 150, *4* — 300.

was suppressed because of the "built-in" anisotropy of the sample resulting from the presence of heterointerfaces. In the present paper, we predict spin relaxation suppression in the plane of a heterostructure. Moreover, all three spin relaxation times are different in out case, and this effect takes place in ordinary (001) heterostructures.

To observe the predicted spin relaxation anisotropy, one can perform time-resolved measurements similar to those in [23]. In steady-state experiments, spin ralaxation can be investigated by means of the Hanle effect. To obtain the spin relaxation times, one has to take into account of the fact that, in asymmetrical heterostructures, the Landé g-factor has not only diagonal in-plane components (g_{xx}) but also off-diagonal ones (g_{xy}) [24]. The degree of photoluminescence polarization in a magnetic field $\mathbf{B} \perp z$ is described by the following expression

$$P(\mathbf{B}) = \frac{P(0)}{1 + \left[\mu_\mathrm{B}(g_{xx} \pm g_{xy})B/\hbar^2\right]^2 \tau_z \tau_\mp}, \qquad (21)$$

where the upper and lower signs correspond to the experimental geometry $\mathbf{B} \parallel [110]$ and $\mathbf{B} \parallel [1\bar{1}0]$, respectively ($\mu_\mathrm{B}$ is the Bohr magneton).

We show that the linear in the wavevector terms in the spin-orbit Hamiltonian interfere, which leads to a huge anisotropy of the spin relaxation times. At a high concentration or temterature, this effect starts to disappear owing to domination of the cubic in k terms in H_SO which are present only in H_BIA. However the higher-order terms in H_SIA are not forbidden by symmetry either. These terms can also interfere with these in H_BIA, and cause adiitional non-monotonic peculiarities in the dependences of the spin relaxation times on the structure parameters.

In conclusion, we have calculated the spin relaxation times for a $\mathrm{A^{III}B^{V}}$ heterojunction and triangular QW. The observance of spin relaxation anisotropy in all three directions is predicted in a wide range of structure parameters and temperatures.

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