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## Spin relaxation anisotropy in two-dimensional semiconductors

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### 1. Introduction

The main task of the new field in electronics — spintronics — is the creation of devices which use spin degrees of freedom for the storage, recording, and readout of information. Contemporary electronics is oriented toward the use of two-dimensional semiconductor structures with a high mobility of charge carriers; therefore, a fundamental problem of studying the processes of spin dynamics precisely in low-dimensional nanostructures exists. The main difference between two-dimensional structures and bulk semiconductors is the anisotropy of physical properties caused by the restriction of the motion of charge carriers along one crystallographic

direction. The main properties of spin dynamics are also connected with this very feature, although the spin can be oriented in any of the three spatial directions, even in two-dimensional systems. Spin relaxation constitutes a process of the disappearance of the ensemble-averaged spin of charge carriers. Indeed, spin-orbit interaction in each microscopic scattering event can result in a change of the sign of the electron-spin projection onto a preferred axis to the opposite sign. The total magnitude of the square of the spin momentum remains unaltered in this case. The process of the loss of the average spin upon the interaction of electrons with, for example, impurities can be described in terms of the following kinetic equations

$$\dot{n}_\uparrow = -Wn_\uparrow + Wn_\downarrow, \quad \dot{n}_\downarrow = -Wn_\downarrow + Wn_\uparrow, \quad (1)$$

where  $n_\uparrow$  and  $n_\downarrow$  are the numbers of electrons with spins up and down, respectively, and  $W$  describes the rate of transitions with spin flips. It follows from Eqn (1) that  $\dot{n}_\uparrow + \dot{n}_\downarrow = 0$ , and for the total spin  $S = (n_\uparrow - n_\downarrow)/2$  we obtain

$$\dot{S} = -\frac{S}{\tau_s}, \quad \tau_s^{-1} = 2W, \quad (2)$$

where  $\tau_s$  is the spin relaxation time. Equation (2) describes the disappearance of the average spin because of the spin flip in each scattering event. The quantity  $W$  can be due to the spin-orbit interaction (Elliott–Yafet mechanism of spin relaxation) or by the contact magnetic interaction of an electron or a hole with magnetic ions. However, in semiconductors at not too low temperatures the most significant mechanism of spin relaxation is the kinetic mechanism suggested by D'yakonov and Perel' [1]. In terms of this mechanism, the disappearance of the average spin occurs not at the instant of scattering, but rather between the instants of collisions, because of the precession of an electron spin in the effective magnetic field caused by spin-orbit interaction. Indeed, in a magnetic field the spin precesses about the field vector in such a manner that only the spin projection onto the field direction is retained, while the average values of the transverse components of the spin are lost. However, if this effective field changes direction, the relaxation of all spin components will occur. This process can be described by the following equation

$$\dot{\mathbf{S}} + \mathbf{S} \times \boldsymbol{\Omega} = \frac{\langle \mathbf{S} \rangle - \mathbf{S}}{\tau}, \quad (3)$$

where  $\boldsymbol{\Omega}(\mathbf{k})$  is the frequency of spin precession in the effective magnetic field;  $\mathbf{S}(\mathbf{k})$  is the spin density of the ensemble of electrons;  $\langle \mathbf{S} \rangle$  is the value of  $\mathbf{S}$  averaged over the angles of the vector  $\mathbf{k}$ , and  $\tau$  is the time of isotropization of the electron distribution function over the angles of the vector  $\mathbf{k}$ . When deriving Eqn (3), it was assumed that the time of energy relaxation is much greater than  $\tau$  and, thus,  $\mathbf{S}(\mathbf{k})$  represents the spin density at a fixed energy. In addition, it was assumed that in formula (3) the electron lifetime is much greater than the spin relaxation time  $\tau_s$ . Usually, the time  $\tau$  proves to be on the order of the time of the momentum relaxation, and  $\Omega\tau \ll 1$  (with  $\langle \boldsymbol{\Omega} \rangle \equiv 0$ ). In this case, the angle of rotation between collisions proves to be small, so that the spin relaxation will occur via particle diffusion. As is seen from Eqn (3), the components of  $\mathbf{S}$  that are dependent on the angles of the vector  $\mathbf{k}$  relax in a time  $\tau$ , and the average spin relaxes in a longer time and, in view of the inequality  $\Omega\tau \ll 1$ , the time of spin relaxation should be relatively large,  $\tau_s \gg \tau$ . It can be

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shown that the equation for the average spin  $\langle S \rangle$  takes on the form [1, 2]

$$\langle \dot{S}_i \rangle = -\tau \left[ \langle \Omega^2 \rangle \langle S_i \rangle - \sum_j \langle \Omega_i \Omega_j \rangle \langle S_j \rangle \right]. \quad (4)$$

Equation (4) was derived on the assumption that  $\tau$  is independent of energy, and from this follows that  $\tau_s^{-1} \sim \Omega^2 \tau$ , i.e., the relaxation becomes more efficient with increasing  $\tau$ . This means that in samples with a high mobility, where  $\tau$  is large, the spin relaxation can be efficient even at a weak spin-orbit interaction.

It will be shown in Sections 2–4 how spin relaxation occurs in two-dimensional semiconductor structures in terms of the D'yakonov–Perel' kinetic mechanism.

## 2. Anisotropy of spin relaxation in asymmetric quantum wells

In two-dimensional structures, the dependence of the precession frequency  $\Omega(\mathbf{k})$  is determined by two factors. First, because of the asymmetry of the well itself, the Rashba effect occurs [3], which leads to the following  $\Omega(\mathbf{k})$  dependence:

$$\Omega = \alpha(k_y, -k_x), \quad (5)$$

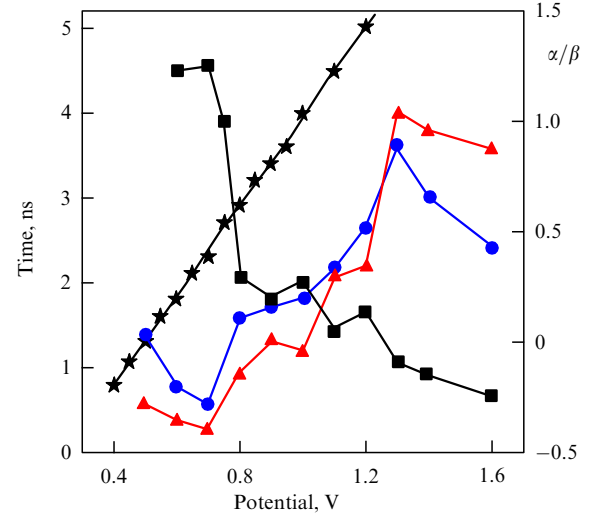
where  $\alpha$  is a coefficient. Second, for semiconductor structures grown on the basis of semiconducting III–V compounds, even in symmetrical wells grown along the (001) axis, there arises a contribution to  $\Omega(\mathbf{k})$  which is called the Dresselhaus contribution [2, 4]:

$$\Omega = \beta(k_x, -k_y), \quad (6)$$

where  $\beta$  is a parameter differing from  $\alpha$ . The substitution of expressions (5) and (6) into equation (4) makes it possible to obtain the spin relaxation times. For asymmetrical quantum wells grown along the (001) axis, the calculations of the relaxation times for the spin orientation along the (001) axis ( $\tau_z$ ), (110) axis ( $\tau_+$ ), and (110) axis ( $\tau_-$ ) yield

$$\begin{aligned} \tau_z^{-1} &= C(\alpha^2 + \beta^2), & \tau_+^{-1} &= \frac{1}{2} C(\alpha + \beta)^2, \\ \tau_-^{-1} &= \frac{1}{2} C(\alpha - \beta)^2, & C &= \tau k^2. \end{aligned} \quad (7)$$

An important circumstance is that the parameter  $\alpha$  is determined by the shape of the quantum well and can change upon application of an electric field. In addition, it is seen from formulas (7) that at  $\alpha = \pm\beta$  one of the times can become infinitely large, which means the absence of spin relaxation for spins oriented in the plane of the quantum well along the direction (110) or (1 $\bar{1}$ 0). The possibility of such an anisotropy was noted in Ref. [5], and was observed for the first time in Ref. [6] in the dependence of the Hanle effect on the orientation of the magnetic field in the quantum-well plane. The effect has been demonstrated most vividly in Ref. [7], where the spin relaxation of electrons was investigated in double quantum wells in which the ratio  $\alpha/\beta$  was controlled using an external electric field (Fig. 1). It is seen from Fig. 1 that, at  $V \approx 1.2$  V and  $\alpha = 0$ , the times  $\tau_+$  and  $\tau_-$  coincide, while at  $V \approx 0.7$  V and  $\alpha = \beta$ , they differ severalfold. In addition, it follows from the results shown in Fig. 1 that the lifetime  $\tau_0$  exceeds the spin relaxation times  $\tau_+$  and  $\tau_-$  severalfold; therefore, the total time  $T_s$  of the spin



**Figure 1.** Anisotropy of spin relaxation in the plane of a quantum well depending on an external electric field:  $\blacktriangle$  —  $\tau_+$ ,  $\bullet$  —  $\tau_-$ ,  $\blacksquare$  —  $\alpha/\beta$ , and  $(\star)$  — radiative lifetime  $\tau_0$  of electrons.

disappearance, which is equal to  $\tau_0 \tau_s / (\tau_0 + \tau_s)$ , virtually coincides with  $\tau_s$ .

Another (more obvious) anisotropic effect is the dependence of the relaxation time on the spin orientation relative to the growth axis: the relaxation rate of spin oriented along the growth axis is twice as large as the relaxation rate of spin lying in the plane of the quantum well. The reason for this effect is that if the spin is oriented along the growth axis ( $z$ ), it is subject, according to expressions (5) and (6), to the effective field directed along the  $x$ - and  $y$ -axes. If the spin lies in the plane of the well (e.g., along the  $x$ -axis), its relaxation is affected only by the effective magnetic field directed along the  $y$ -axis. This leads to an increase in the spin relaxation times  $\tau_+$  and  $\tau_-$ . Notice that an exactly twofold difference in the relaxation times is realized only if  $\alpha = 0$  or  $\beta = 0$ .

The anisotropy of the relaxation rate in two-dimensional systems also arises in the case of the Elliott–Yafet mechanism of spin relaxation. It can be shown that in two-dimensional structures the spin-dependent electron scattering is described by the expression [8]

$$V'_{kk'} = V_0(\mathbf{k} - \mathbf{k}') [\boldsymbol{\sigma} \times (\mathbf{k} + \mathbf{k}')]_z, \quad (8)$$

where  $\mathbf{k}$  and  $\mathbf{k}'$  are the initial and final quasimomenta of the electron in the plane of the quantum well;  $z$  is the growth axis;  $V_0(\mathbf{k} - \mathbf{k}')$  is the Fourier image of the scattering potential;  $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ , and  $\sigma_i$  are the Pauli matrices. A specific feature of Eqn (8) is a linear dependence of  $V'$  only on the transverse components of the vectors,  $k_x$  and  $k_y$  or  $k'_x$  and  $k'_y$ . As a result, the effective field leading to the relaxation of spin oriented along the  $z$ -axis can be oriented along the  $x$ - and  $y$ -axes, whereas in the case of spin that is parallel to the  $x$ -axis, only along the  $y$ -axis. It is this feature that leads to a twofold difference in the appropriate times. A calculation with allowance for the ‘golden rule’ yields the expressions [8]

$$\frac{1}{\tau_{zz}} = \frac{2}{\tau_{xx}} = \frac{2}{\tau_{yy}}, \quad \frac{1}{\tau_{zz}} = \frac{1}{\tau_p} \frac{\Delta}{E_g} \frac{k_B T}{E_g}, \quad (9)$$

where  $\Delta$  is the magnitude of spin-orbit splitting in the valence band;  $E_g$  is the forbidden band width;  $\tau_p$  is the momentum

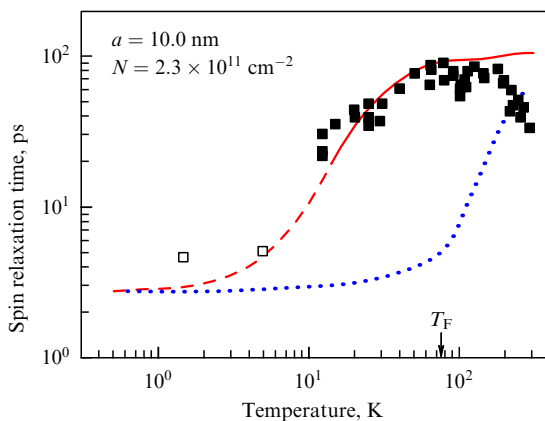
relaxation time, which is inversely proportional to  $|V_0|^2$ ;  $T$  is the temperature, and  $k_B$  is the Boltzmann constant. In a bulk cubic crystal, all the times are equal and proportional to  $(k_B T/E_g)^2$ .

### 3. Spin relaxation in degenerate semiconductor structures

As follows from formulas (7), the spin relaxation time  $\tau_s$  in terms of the kinetic mechanism is inversely proportional to the time  $\tau$  of isotropization of the distribution function, which, in turn, is proportional to the momentum relaxation time. This means that in heavily doped bulk crystals the kinetic mechanism will be suppressed because of the small momentum-relaxation time  $\tau_p$ . In two-dimensional systems, the impurities can be spatially separated from the electrons; then, in heavily doped structures  $\tau_p$  also proves to be large, so that we obtain  $\Omega\tau_p \sim 1$ . In this case, the problem of the role of electron–electron collisions in the process of spin relaxation arises. A specific feature of the situation is also that electron–electron interactions do not affect the momentum relaxation time, since in such interactions the total momentum of the system remains unaltered.

It was first shown in Ref. [9] that if in the collision integral in equation (2) for  $\mathbf{S}(\mathbf{k})$  we take into account only electron–electron collisions, then the spin relaxation in the regime of the D'yakonov–Perel' mechanism takes place. The microscopic reason for the relaxation, as before, is the spin precession in the effective magnetic field  $\mathbf{\Omega}(\mathbf{k})$ , and the interaction of particles leads to the isotropization of the distribution function, so that the time  $\tau$  of the isotropization of the distribution function proves to be equal to  $\tau_p\tau_{ee}/(\tau_p + \tau_{ee})$ , where  $\tau_{ee}$  is the isotropization time due to electron–electron collisions.

An important feature of the D'yakonov–Perel' mechanism during frequent electron–electron interactions is a sharp temperature dependence of  $\tau_s$  caused by the fact that in a degenerate electron gas the isotropization time of the distribution function may be estimated as  $\tau \sim 1/T^2$ . Combined experimental and theoretical investigations (see Fig. 2)

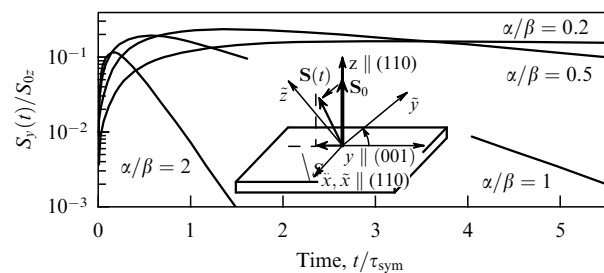


**Figure 2.** Temperature dependence of the spin relaxation time of an electron gas:  $a$ , the width of the quantum well;  $N$ , the concentration of electrons;  $T_F$ , the temperature of the degeneracy of the electron gas; ■, experimental data [10]; solid curve, theoretical results [10] for  $\Omega\tau \ll 1$ . The result of the corresponding calculation without allowance for electron–electron collisions at low temperatures,  $\tau_{ee} \gg \tau_p$ , is shown by a dashed line; □, experimental results [10].

have shown that such a relaxation of spins does take place. At high temperatures,  $T \sim T_F$ , the results of calculations with allowance for electron–electron collisions demonstrate good agreement with experimental data. The theoretical curve (dashed line) was constructed using formulas analogous to Eqn (7) at  $\beta = 0$  under the condition that the time  $\tau_p$  is estimated from the temperature dependence of mobility. At low temperatures,  $T \sim 5$  K, electron–electron collisions are suppressed and the result of the calculation (dashed line) demonstrates agreement with the experimental data (open squares). It has been shown in Section 2 that the anisotropy of the processes of spin relaxation is caused by the dependence of the effective magnetic field on the electron momentum rather than by the processes of isotropization of the distribution function. This means [10] that in the case of an efficient electron–electron interaction as well, when  $\mathbf{\Omega}(\mathbf{k})$  is caused simultaneously by the Rashba and Dresselhaus effects, a dependence of the rate of spin relaxation on the spin orientation in the plane of the quantum well arises.

### 4. Anisotropy of spin relaxation in structures grown along the (110) axis

As is seen from Eqn (4), in the general form the spin relaxation is described by a second-rank tensor relating the rate of changes in the average spin to the spin magnitude itself. In cubic crystals, such a tensor reduces to a scalar, but in low-symmetry two-dimensional structures the tensor of the inverse relaxation times is characterized by three independent parameters. The principal axes of the tensor of the spin-relaxation times can be noncoincident with the natural geometric axes of the sample. As was first indicated in Ref. [12], such a case is realized in asymmetrical wells grown along the (110) axis. In structures with such a crystal orientation, the relaxation of spin oriented at the initial instant of time along the growth axis will lead to the appearance of a spin component oriented in the plane of the quantum well. A microscopic reason for this effect in structures with the growth axis (110) may be the combined action of the Rashba and Dresselhaus effects. Indeed, for such structures the effective magnetic field caused by the Dresselhaus effect has only a  $z$ -component, but depends on  $k_x$  (Fig. 3). The Rashba field has components  $B_x$  and  $B_y$  proportional to  $k_y$  and  $k_x$ , respectively. It is shown in Fig. 3 that one of the proper axes of the tensor of spin-relaxation times will coincide with the  $x$ -axis, and two other axes will make angles  $\theta$  with the  $y$ - and  $z$ -axes. The results of the calculations [12] (see Fig. 3) demonstrate that at  $\alpha \sim \beta$  and times of the order of  $\tau_s$  the spin component  $S_y$  can reach  $\sim 10\%$  of the initial value  $S_{z0}$ .



**Figure 3.** Generation of spin density  $S_y$  in asymmetrical quantum wells because of the anisotropy of spin relaxation:  $S_{0z}$ , the magnitude of the initial spin orientation along the  $z$ -axis, and  $\tau_{sym}$ , the spin relaxation time in a symmetrical quantum well.

## 5. Conclusions

In this paper, we considered the main features of the anisotropy of spin relaxation for electrons in low-dimensional semiconductors. It has been shown that the anisotropy arises both because of natural causes (the presence of a growth axis, and the restriction of the free motion in this direction) and as a result of the mutual action of the Rashba and Dresselhaus effects. It is basic that the magnitude of  $\alpha$  can be controlled using technological means or an external electric field.

Because of the anisotropy of spin-relaxation times, the spin does not relax along some directions in the plane of the quantum well, which opens up the possibility of using the anisotropy effect for spin storage.

It can be shown that in quantum wells where the majority carriers are holes such effects can also show themselves, although some important features exist in this case, since the total projection of the hole momentum,  $\pm 3/2$  or  $\pm 1/2$ , is always oriented along the growth axis.

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