

Giant spin relaxation anisotropy in zinc-blende heterostructures

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Spin relaxation in-plane anisotropy is predicted for heterostructures based on zinc-blende semiconductors. It is shown that it manifests itself especially brightly if the two spin relaxation mechanisms (Dyakonov-Perel and Rashba) are comparable in efficiency. It is demonstrated that for the quantum well grown along the [001] direction, the main axes of spin relaxation rate tensor are [110] and $[1\bar{1}0]$. [S0163-1829(99)09643-5]

I. INTRODUCTION

Spin relaxation processes have significant effect in optical and kinetic properties of semiconductors. They play an important role in optical orientation of electrons and nuclei¹ and in anomalous magnetoresistance caused by weak localization.² Both theoretical calculations and experimental data analysis have been carried out assuming that one spin relaxation mechanism dominates only. Therewith in spite of the strong anisotropy of spin-orbit scattering, the relaxation times of spin lying in the plane of a heterostructure with zinc-blende lattice turn out to be independent on orientation with respect to crystallographic axes.

Real heterostructures differ from investigated ideal objects in that several spin relaxation mechanisms exist.^{3,4} A spin relaxation mechanism due to only cubic in wave-vector terms of the bulk Hamiltonian was investigated for rectangular quantum wells (QW's) in Ref. 5. It was noted that even in an asymmetrical GaAs QW, the efficiency of another mechanism due to linear in two-dimensional wave-vector terms is negligibly small. The authors of Ref. 4 analyzing experimental data on anomalous magnetoresistance in $\text{In}_x\text{Ga}_{1-x}\text{As}$ QW's demonstrated that the both mechanisms may be comparable in efficiency. But in Refs. 3 and 4, it was mentioned that the both mechanisms are additive in spin relaxation.

This communication is devoted to an investigation of spin relaxation processes when several mechanisms of spin-orbit scattering exist. We show that contributions of these mechanisms interfere and their simultaneous action leads to the strong anisotropy of spin relaxation even in the plane of a QW.

II. THEORY

In zinc-blende semiconductors, spin relaxation of electrons is well known to be due to spin-orbit splitting of conduction band. In a bulk crystal, the splitting is cubic in wave vector. In a QW structure, the corresponding Hamiltonian has to be averaged over the motion along the growth axis. We consider the QW grown along z direction parallel to [001] and choose x and y directions coinciding with crystallographic axes. At relatively small carrier concentrations, one can neglect cubic in 2D wave-vector terms and the Hamiltonian has the form

$$H_1 = a_1(\sigma_x k_x - \sigma_y k_y). \quad (1)$$

Here, σ_i ($i=x,y$) is the Pauli matrix, k_i is the wave vector component in the plane of the QW and a_1 is a constant.

In asymmetrical heterostructures, there is a contribution to the Hamiltonian, which is absent in the bulk:⁶

$$H_2 = a_2(\sigma_x k_y - \sigma_y k_x), \quad (2)$$

where a_2 is the constant determined by heterointerface properties.

To calculate spin relaxation times, one has to consider the dynamics of spin-density matrix, ρ :

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H, \rho], \quad (3)$$

where the total two-dimensional Hamiltonian is

$$H = \frac{\hbar^2 k^2}{2m} + V + H'. \quad (4)$$

Here m is an effective electron mass, $V(x,y)$ is a scattering potential and

$$H' = H_1 + H_2.$$

We assume that the scattering is elastic and independent on spin indices.

Since H' is a small perturbation, the spin relaxation times turn out to be much longer than isotropisation times of momentum distribution of electrons. For this reason it is convenient to represent the density matrix as a sum⁷

$$\rho = \bar{\rho} + \rho', \quad \bar{\rho}' = 0,$$

where the bar means averaging over the directions of \mathbf{k} . Here, $\bar{\rho}$ depends on $\varepsilon = \hbar^2 k^2 / 2m$ and the anisotropic part of the density matrix is due to H' only. Hence, ρ' is proportional to H' , i.e., ρ' is small in comparison to $\bar{\rho}$.

Then in the first order in H' , Eq. (3) has the form

$$\frac{\partial \rho'}{\partial t} = -\frac{i}{\hbar}[H', \bar{\rho}] - \sum_{\mathbf{k}'} W_{\mathbf{k}\mathbf{k}'}[\rho'(\mathbf{k}) - \rho'(\mathbf{k}')], \quad (5)$$

$$\frac{\partial \bar{\rho}}{\partial t} = -\frac{i}{\hbar}[H', \rho']. \quad (6)$$

Here, $W_{\mathbf{k}\mathbf{k}'}$ is the probability for scattering from the potential V from the state with \mathbf{k} to the state with \mathbf{k}' .

One can see from Eq. (5) that ρ' relaxes in the time, which is of order of momentum relaxation time, but $\bar{\rho}$ relaxes in the longer time, which is determined by H' —see Eq. (6). At these long times, Eq. (5) reduces to a quasistationary one

$$\sum_{\mathbf{k}'} W_{\mathbf{k}\mathbf{k}'}[\rho'(\mathbf{k}) - \rho'(\mathbf{k}')] = -\frac{i}{\hbar}[H', \bar{\rho}]. \quad (7)$$

Finding $\rho'(\mathbf{k})$ from here and substituting it to Eq. (6), one can obtain the closed equation for $\bar{\rho}$

$$\frac{\partial \bar{\rho}}{\partial t} = -\frac{1}{\hbar^2} \sum_n \tau_n [H'_{-n}, [H'_n, \bar{\rho}]]. \quad (8)$$

Here,

$$H'_n = \oint \frac{d\varphi_{\mathbf{k}}}{2\pi} H'(\mathbf{k}) \exp(-in\varphi_{\mathbf{k}}), \quad (9)$$

where $\varphi_{\mathbf{k}}$ is the angle between \mathbf{k} and x axis, and

$$\frac{1}{\tau_n} = \oint d\theta W_{\mathbf{k}\mathbf{k}'}(1 - \cos n\theta), \quad (10)$$

where $\theta = \varphi_{\mathbf{k}} - \varphi_{\mathbf{k}'}$. Equation (8) clearly demonstrates that it is spin-orbit interaction, which causes $\bar{\rho}$ relaxation.

After substituting $\bar{\rho}$ in a form

$$\bar{\rho} = f_0 + \frac{1}{2} \boldsymbol{\sigma} \cdot \boldsymbol{\alpha},$$

Eq. (8) reduces to following equations:

$$\dot{f}_0(\boldsymbol{\varepsilon}, t) = 0, \quad (11)$$

$$\dot{\boldsymbol{\alpha}}_i(\boldsymbol{\varepsilon}, t) = -\Gamma_{ij}(\boldsymbol{\varepsilon}) \boldsymbol{\alpha}_j(\boldsymbol{\varepsilon}, t), \quad (12)$$

where

$$\Gamma_{ij} = -\frac{1}{\hbar^2} Sp \left\{ \sum_n \tau_n [H'_{-n}, [H'_n, \sigma_j]] \sigma_i \right\}. \quad (13)$$

An initial condition may be derived considering the spin dynamics after the time τ_n , but before the spin relaxation time. In the time τ_n , the density matrix becomes isotropic but the spin relaxation processes do not start yet. Therefore,⁸

$$f_0(\boldsymbol{\varepsilon}) = \frac{1}{2} [F_+(\boldsymbol{\varepsilon}) + F_-(\boldsymbol{\varepsilon})], \quad (14)$$

$$\boldsymbol{\alpha}(\boldsymbol{\varepsilon}) = s [F_+(\boldsymbol{\varepsilon}) - F_-(\boldsymbol{\varepsilon})], \quad (15)$$

where s is the unit vector along the spin and $F_{\pm}(\boldsymbol{\varepsilon})$ are distribution functions of particles with the spin projection on s equal to $\pm 1/2$.

Taking into account that the spin density, $S(t)$, is the average of $\boldsymbol{\alpha}$ over $\boldsymbol{\varepsilon}$, one can obtain the kinetic equation for it at the time longer than τ_n :

$$\dot{S}_i = -\frac{S_j}{\tau_{ij}}, \quad (16)$$

where the tensor of reciprocal spin relaxation times is:

$$\frac{1}{\tau_{ij}} = \frac{\int d\boldsymbol{\varepsilon} [F_+(\boldsymbol{\varepsilon}) - F_-(\boldsymbol{\varepsilon})] \Gamma_{ij}(\boldsymbol{\varepsilon})}{\int d\boldsymbol{\varepsilon} [F_+(\boldsymbol{\varepsilon}) - F_-(\boldsymbol{\varepsilon})]}. \quad (17)$$

Equation (17) represents the extension of the results of Ref. 5 to the case of an arbitrary spin-orbit interaction H' and takes into account the anisotropy of scattering.

Substituting $H' = H_1 + H_2$ into Eq. (13) and then Γ_{ij} into Eq. (17) we have

$$\frac{1}{\tau_{zz}} = C(a_1^2 + a_2^2), \quad \frac{1}{\tau_{zx}} = \frac{1}{\tau_{zy}} = 0, \quad (18)$$

$$\frac{1}{\tau_{xx}} = \frac{1}{\tau_{yy}} = \frac{C}{2}(a_1^2 + a_2^2), \quad \frac{1}{\tau_{xy}} = -Ca_1a_2, \quad (19)$$

where

$$C = \frac{m}{\hbar^4} \frac{\int d\boldsymbol{\varepsilon} [F_+(\boldsymbol{\varepsilon}) - F_-(\boldsymbol{\varepsilon})] \tau_1(\boldsymbol{\varepsilon}) \boldsymbol{\varepsilon}}{\int d\boldsymbol{\varepsilon} [F_+(\boldsymbol{\varepsilon}) - F_-(\boldsymbol{\varepsilon})]}. \quad (20)$$

Equations (18)–(20) generalize the results^{3–5} for the case of two spin relaxation mechanisms.

III. DISCUSSION

It follows from Eq. (19) that because of the two mechanisms ($a_1 \cdot a_2 \neq 0$), the spin relaxation in the plane of the QW becomes anisotropic. It should be emphasized that if there is only one mechanism ($a_1 \cdot a_2 = 0$), then the spin relaxation is isotropic in spite of the cubic symmetry of the Hamiltonian H_1 or H_2 . Thus, the cubic anisotropy of the real QW structure manifests itself due to the interference of two spin relaxation mechanisms.

The system (16) may be rewritten as follows:

$$\dot{S}_x \pm \dot{S}_y = -\frac{S_x \pm S_y}{\tau_{\pm}}, \quad (21)$$

where

$$\frac{1}{\tau_{\pm}} = \frac{C}{2}(a_1 \pm a_2)^2. \quad (22)$$

The times τ_+ and τ_- describe the relaxation of the spin oriented along the directions $[110]$ and $[1\bar{1}0]$, respectively.

The most bright manifestation of spin relaxation anisotropy occurs if $a_1 = \pm a_2$. In this case, one of the times τ_+ or τ_- becomes infinite. Therewith the other is equal to τ_{zz} .

Efficiency of the mechanisms depends on both the material and the shape of the QW. It was shown that in a rectangular GaAs/Al_xGa_{1-x}As QW, the mechanism (1) dominates,⁹ and in an asymmetrical In_xGa_{1-x}As/AlAs QW's the mechanism (2) is the most important¹⁰ or they are comparable.⁴

It is clear that if both a_1 and a_2 are not equal to zero, then the spin sublevels split. In the work¹¹ it is shown that a_1 and a_2 may be comparable in magnitude and, hence, the spin splitting is strongly anisotropic.

The spin relaxation anisotropy results from the initial T_d symmetry of the zinc-blende semiconductor. For this reason, the similar effect can take place in a strained bulk crystal. The corresponding Hamiltonian linear in 3D wave vector, \mathbf{k} , and components of an elastic strain tensor, u_{ij} , has the form:

$$H'(u) = A_1 u_{ii} (\sigma_{i+1} k_{i+1} - \sigma_{i+2} k_{i+2}) + A_2 u_{ij} (\sigma_i k_j - \sigma_j k_i). \quad (23)$$

Here, $i, j = x, y, z$, $i+3 \rightarrow i$, A_1 and A_2 are constants. Doing calculations for $1/\tau_{ij}$ in a way similar to Eq. (17), one can obtain three different spin relaxation times. It can be shown that the maximum anisotropy may be achieved if

$$A_1 u_{xx} = A_1 u_{yy} = -A_1 u_{zz}/2 = A_2 u_{xy}/3 \quad (24)$$

with the rest of $u_{ij} = 0$. Therewith two spin relaxation times are equal to each other and the third is infinite. Note that the tensor u_{ij} determined by Eq. (24) may be obtained by applying two uniaxial strains along the axes [001] and [110] and they are not restricted to uniaxial strain along any axes.

IV. CONCLUSION

The possibility for spin relaxation suppression was noted in Ref. 5 for a QW grown along [110] direction when the spin is oriented along the same axis. The present work shows that the spin relaxation rate also decreases for [110] direction, but in a QW grown in the symmetrical direction [001]. Therefore, this decrease takes place for the spin lying in the plane of the QW.

Analyzing weak localization effect, the authors of Refs. 3 and 4 showed that the mechanisms (1) and (2) suppress each other in anomalous magnetoresistance, but they are additive in spin relaxation. The present analysis shows that the suppression occurs in the spin relaxation also. Besides, we have found that spin relaxation is anisotropic even in the plane of the QW.

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¹ *Optical Orientation*, edited by F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam, 1984).

² S. Hikami, A. Larkin, and Y. Nagaoka, *Prog. Theor. Phys.* **63**, 707 (1980).

³ F. G. Pikus and G. E. Pikus, *Phys. Rev. B* **51**, 16 928 (1995).

⁴ W. Knap, C. Skierbiszewski, A. Zduniak, E. Litvin-Staszewska, D. Bertho, F. Kobbi, J. L. Robert, G. E. Pikus, F. G. Pikus, S. V. Iordanskii, V. Mosser, K. Zekenes, and Yu. B. Lyanda-Geller, *Phys. Rev. B* **53**, 3912 (1996).

⁵ M. I. Dyakonov and V. Yu. Kachorovskii, *Fiz. Techn. Poluprov.*

20, 178 (1986) [*Sov. Phys. Semicond.* **20**, 110 (1986)].

⁶ Yu. L. Bychkov and E. I. Rashba, *J. Phys. C* **17**, 6093 (1984).

⁷ G. E. Pikus and A. N. Titkov in Ref. 1.

⁸ M. I. Dyakonov and V. I. Perel', *Fiz. Tverd. Tela* **13**, 3581 (1971) [*Sov. Phys. Solid State* **13**, 3023 (1972)].

⁹ D. Stein, K. von Klitzing, and G. Weimann, *Phys. Rev. Lett.* **51**, 130 (1983).

¹⁰ A. M. Kreshchuk, S. V. Novikov, T. A. Polyanskaya, and I. G. Savel'ev, *Semicond. Sci. Technol.* **13**, 384 (1998).

¹¹ L. Wissinger, U. Rössler, R. Winkler, B. Jusserand, and D. Richards, *Phys. Rev. B* **58**, 15 375 (1998).