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Electron spin relaxation in zinc-blende heterostructures

N. S. Averkiev†, *L. E. Golub*†‡ and M. Willander‡
† Ioffe Physico-Technical Institute, St Petersburg, Russia
‡ Physical Electronics and Photonics, Department of Microelectronics and Nanoscience, Chalmers University of Technology and Göteborg University, SE-412 96, Göteborg, Sweden

Abstract. 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].

Introduction

Spin relaxation processes have significant effect in optical and kinetic properties of semiconductors. They play important role in optical orientation of electrons and nuclei [1] and in anomalous magnetoresistance caused by weak localization [2]. Now, big interest to spin dynamics and relaxation exists due to a spin transistor creation attempts. 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.

This communication is devoted to an investigation of spin relaxation processes in real heterostructures 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 quantum well (QW).

1. 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:

$$H_1 = a_1(\sigma_x k_x - \sigma_y k_y)\,. \tag{1}$$

Here σ_i $(i = x, y)$ is the Pauli matrix, k_i is the wave vector component in the plane of the QW. a_1 is a constant which is determined by both bulk properties of the semiconductor and the value of k_z^2 averaged over the z-motion.

In asymmetrical heterostructures, there is a contribution to the Hamiltonian which is absent in the bulk [3]:

$$H_2 = a_2(\sigma_x k_y - \sigma_y k_x) , \tag{2}$$

where a_2 is the constant determined by heterointerface properties. It is equal to zero in a symmetrical structure and is proportional to the barrier height difference in an asymmetrical QW or to the electric field in a triangular QW. It is possible to change the value of a_2 by varying a gate voltage applied to the system or by another changing of the structure symmetry.

The relationship between the constants a_1 and a_2 may be different in different systems. a_1 may be much larger than a_2 [4], much less than a_2 [5] or they may be comparable [6].

The most interesting case realizes when the constants a_1 and a_2 are equal to each other by absolute value:

$$a_1 = \pm a_2 .$$

In this case, the total spin-orbit Hamiltonian is:

$$H' = H_1 + H_2 = a_1(\sigma_x \mp \sigma_y)(k_x \pm k_y) . \tag{3}$$

Therefore for electrons with the spin along [110] or [1$\bar{1}$0], $H' = 0$ for any value of the wave vector, **k**. It means that the spin relaxation time caused by both mechanisms, (1) and (2), is infinite. In other words, the spin relaxation mechanisms due to splittings (1) and (2) suppress each other totally.

In the general case, when a_1 and a_2 are arbitrary, we have obtained the following equations for spin dynamics [7]:

$$\dot{S}_z = -\frac{S_z}{\tau_z} , \qquad \dot{S}_x \pm \dot{S}_y = -\frac{S_x \pm S_y}{\tau_\pm} . \tag{4}$$

Here

$$\frac{1}{\tau_z} = C(a_1^2 + a_2^2) , \qquad \frac{1}{\tau_\pm} = \frac{C}{2}(a_1 \pm a_2)^2 , \tag{5}$$

and C is determined by properties of the scattering potential and electron distributons in spin sublevels. Note that the equation (4) is valid at times longer than the momentum relaxation time but shorter than the spin relaxation times [7].

2. Discussion

It is seen from Eq. (5), that if $a_1 = \pm a_2$, $\tau_\mp = \infty$, and the other time, $\tau_\pm$, is equal to τ_z. Besides, one can see the spin relaxation anisotropy even in the plane of the heterostructure. All three times, τ_+, τ_- and τ_z are different in the general case.

One can also see from (5) that at only one spin relaxation mechanism, when $a_1 = 0$ or $a_2 = 0$, spin relaxation is isotropic in the plane of a the heterostructure:

$$\tau_+ = \tau_- = 2\,\tau_z . \tag{6}$$

It means that, despite the cubic anisotropy included into the Hamiltonian H_1 or H_2, it averages and does not exibit itself in spin relaxation. In the presence of both spin relaxation mechanisms, on the contrary, the cubic anisotropy does lead to the difference between the spin relaxation times for spin lying in the plane of the heterostructure (see (5)).

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:

$$H'(u) = A_1\, u_{ii}\, (\sigma_{i+1}k_{i+1} - \sigma_{i+2}k_{i+2}) + A_2\, u_{ij}\, (\sigma_i k_j - \sigma_j k_i)\,. \tag{7}$$

Here $i, j = x, y, z$, $i + 3 \to i$, A_1 and A_2 are constants. Deriving the spin dynamics equations for this spin-orbit Hamiltonian, one can obtain three different spin relaxation times. It can be shown that the maximum anisotropy may be achieved if

$$A_1 u_{xx} = A_1 u_{yy} = -A_1 u_{zz}/2 = A_2 u_{xy}/3 \tag{8}$$

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 (8) may be obtained by applying two uni-axial strains along the axes [001] and [110] and they are not restricted to uni-axial strain along any axes.

3. Conclusion

The possibility for spin relaxation suppression was noted in Ref. [8] 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 Ref. [9] 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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