Suppression by a longitudinal magnetic field of spin relaxation of conduction electrons in semiconductor crystals lacking an inversion center

V. A. Marushchak, M. N. Stepanova, and A. N. Titkov
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

(Submitted 1 March 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **37**, No. 7, 337–340 (5 April 1983)

Experiments have shown that the orbital motion of conduction electrons in a magnetic field effectively suppresses the spin relaxation of electrons caused by the spin-orbit splitting of the conduction band in crystals lacking an inversion center.

PACS numbers: 71.70.Ej, 75.80. + q, 61.50.Em

Recent experiments on the spin relaxation of conduction electrons in several $A^{\mathrm{III}}B^{\mathrm{V}}$ crystals[1–4] have shown that the primary spin-relaxation mechanism in sufficiently pure crystals is the D'yakonov-Perel' mechanism,[5,6] which involves a spin-induced splitting of the conduction band in crystals lacking an inversion center. This splitting is described by $\hbar\vec{\Omega} = \alpha(2m_e^{3/2}E_g^{1/2})^{-1}\vec{\kappa}$, where α is a dimensionless constant, m_e is the effective electron mass, E_g is the gap width, and the components of the vector $\vec{\kappa}$ are defined in terms of the components of the electron quasimomentum: $\kappa_x = p_x(p_y^2 - p_z^2)$, etc. The spin splitting of the conduction band is equivalent to the influence on the electron spin of an effective magnetic field whose strength and orientation are determined by the magnitude and orientation of the electron momentum. The precession of the electron spin in this equivalent field is responsible for the spin relaxation in the D'yakonov-Perel' mechanism. A rapid scattering of the electron momentum results in a frequent change in precession axis, which retards the relaxation.

Ivchenko recently suggested that it might be possible to suppress the D'yakonov-Perel' mechanism by an external magnetic field which is longitudinal with respect to the spin.[7] Two possible reasons for the effect were pointed out. One is the Larmor

0021-3640/83/070400-04$01.00

precession of the electron spin in a sufficiently strong external field B of frequency $\Omega_L = g\mu_B B/\hbar$, which suppresses precession in a randomly changing effective field. The effect of the external field should become appreciable when the electron spin can no longer keep up with the changes in the effective field, i.e., under the condition $\Omega_L > \tau_r^{-1}$, where τ_r is the scale time for the momentum straggling of the electron, which detemines the rate of change of the effective field.

The second possible cause of the weakening of the D'yakonov-Perel' mechanism was identified as the orbital motion of the electrons in the external magnetic field. The precession of the electron momentum around the direction of the field B with the cyclotron frequency $\Omega_C = eB/m_e c$ may be regarded as an additional mechanism for momentum straggling, so that it should weaken the D'yakonov-Perel' mechanism, as mentioned earlier. Attenuation of the spin relaxation should be observed in fields for which the change in the momentum orientation is determined primarily by the precession of the momentum in the field B, i.e., under the condition $\Omega_C > \tau_r^{-1}$.

In the present experiments we studied the effect of a longitudinal magnetic field on the spin relaxation rate of optically oriented photoelectrons in GaAs crystals with an acceptor concentration 4×10^{16} cm^{-3} at $T = 77$ K. Under these conditions the spin relaxation of the conduction electrons in GaAs is due entirely to the D'yakonov-Perel' mechanism.[3] Through the use of the method of Ref. 8 for optically orienting electron spins, and by analyzing the degree of circular polarization of the luminescence spectra and the change in this polarization in a transverse magnetic field, we were able to directly determine the spin relaxation time τ_S and also the lifetimes τ of the free electrons. These times turned out to lie in the respective intervals $(0.6\text{–}1.3)\times10^{-9}$ and

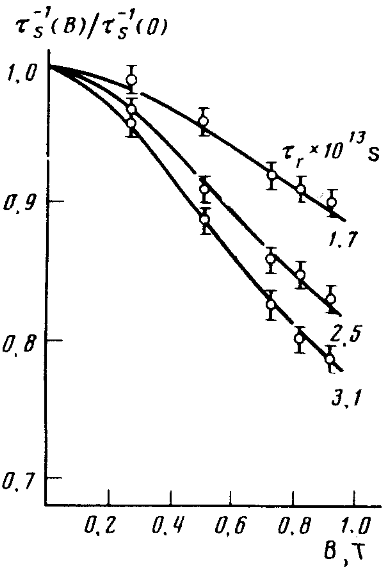

FIG. 1. Decrease in the spin relaxation rate of conduction electrons caused by a magnetic field in GaAs samples with various carrier mobilities. The curves are plotted from expression (1) with the values of τ_r specified. $B \parallel \langle 110 \rangle$.

$(0.5-1.5)\times 10^{-8}$ s for the particular samples studied. The effect of a longitudinal magnetic field on the spin relaxation rate τ_S^{-1} was studied by observing the field-induced change in the degree of circular polarization of the luminescence, which is given by[8] $\rho = 0.25/(1+\tau/\tau_S)$. It was assumed that τ was independent of the magnetic field. The values found for τ result from a competition between radiative and radiationless recombination.[9] If a field altered the effectiveness of these processes, the change would be seen in a change in the integrated luminescence intensity, but no such change was observed.

Figure 1 shows the effect of a longitudinal magnetic field on τ_S^{-1} in samples differing in compensation and in carrier mobility. As predicted by the theory of Ref. 7, a field slows the spin relaxation; the effect becomes more apparent as the electron mobility in the sample increases. Since we have[7] $\Omega_L/\Omega_C = 0.05$ in GaAs, we should assume that the attenuation of the spin relaxation results from the orbital motion of electrons. For a comparison of the experimental data with the theory we thus used the corresponding expression from Ref. 7 [Eq. (9) of that paper],[1)] which can be written as follows after an average is taken over the energy distribution of the thermalized electrons:

$$\tau_S^{-1}(B)/\tau_S^{-1}(0) = 1/8\,\{15(T_1-9T_2) + 5(1-4T_1+45T_2)F(y) + (17T_1-117T_2)F(4y) + 3(1-4T_1+9T_2)F(9y)\}\,, \tag{1}$$

$$F(y) = 1/120\int_0^{\infty} dx\,x^5(1+yx^3)^{-1}\exp(-x), \qquad y=\pi(\Omega_C\tau_r/48)^2$$

Here $T_1 = (h_x^2h_y^2 + h_x^2h_z^2 + h_y^2h_z^2)/h^4$ and $T_2 = (h_x^2h_y^2h_z^2)/h^6$, where $\mathbf{h}$ is a unit vec-

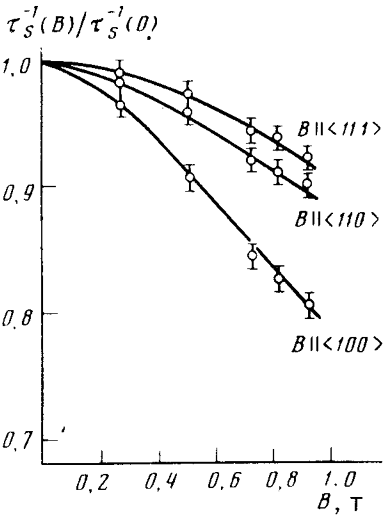

FIG. 2. Decrease in the spin relaxation rate of conduction electrons when the magnetic field B is oriented along various crystallographic axes in GaAs samples with identical carrier mobilities. The curves are plotted from expression (1) with $\tau_r = 1.7\times 10^{-13}$ s.

tor along the magnetic field direction, and x,y,z are the principal symmetry axes of the crystal. The fact that the carriers are scattered by charged impurities was incorporated in the averaging method.[1)] It can be seen from Fig. 1 that expression (1), which contains a single adjustable parameter—the time τ_r—gives a good description of the field-induced decrease in τ_S^{-1}. Figure 1 also shows the values of τ_r which lead to the best agreement between experiment and theory. These values of τ_r are seen to be close to their theoretical predictions.[11] Analysis of (1) shows that the effect of the field should also depend strongly on its orientation with respect to the principal axes of the crystal. We accordingly studied the attenuation of spin relaxation in samples, with roughly equal carrier mobilities, in which the electron spins, were oriented along the three crystallographic axes $\langle 100\rangle$, $\langle 111\rangle$, and $\langle 110\rangle$. From the results (Fig. 2) we see that the field does not in fact have an anisotropic effect, which reaches a maximum at $B \parallel \langle 100\rangle$. These results are also described well by expression (1), with the same time, $\tau_r = 1.7\times 10^{-13}$ s, used for all the samples. We note that if the spin relaxation were suppressed by the Larmor precession of the electron spin, the effect of the field should not depend on its orientation.

In summary, these experiments with GaAs crystals have shown that the orbital motion of electrons in a magnetic field can effectively suppress the spin relaxation of electrons caused by the spin-orbit splitting of the conduction band. This effect should also occur for other $A^{\mathrm{III}}B^{\mathrm{V}}$ compounds, since a frequency ratio $\Omega_L/\Omega_C \ll 1$ is typical of crystals of this group.

We wish to thank E. L. Ivchenko for useful advice and G. E. Pikus and V. I. Safarov for useful discussions of the results.

[1)] In our case we have $\hbar\Omega_L, \hbar\Omega_C \ll kT$, and we have used the expression derived in the approximation of a classical magnetic field. The case of a quantizing magnetic field was examined in Ref. 10.

---

[1] A. H. Clark, R. D. Burnham, D. J. Chadi, and R. M. White, Solid State Commun. **20**, 385 (1976).

[2] V. I. Safarov and A. N. Titkov, Proceedings of the Fifteenth International Conference on Physics of Semiconductors, Kyoto, 1980; J. Phys. Soc. Jpn. **49**, Suppl. A, 623 (1980).

[3] M. I. D'yakonov, V. A. Marushchak, V. I. Perel', M. N. Stepanova, and A. N. Titkova, Trudy Vsesoyuznoĭ konferentsii po fizike poluprovodnikov (Proceedings of the All-Union Conference on the Physics of Semiconductors), Vol. 1, Baku, 1982, p. 165.

[4] A. G. Aronov, G. E. Pikus, and A. N. Titkov, Zh. Eksp. Teor. Fiz. **84**, 1170 (1983) [Sov. Phys. JETP (to be published)].

[5] M. I. D'yakonov and V. I. Perel', Zh. Eksp. Teor. Fiz. **60**, 1954 (1971).

[6] M. I. D'yakonov and V. I. Perel', Fiz. Tverd. Tela (Leningrad) **13**, 3581 (1971).

[7] E. L. Ivchenko, Fiz. Tverd. Tela (Leningrad) **15**, 1566 (1973).

[8] D. Z. Garbuzov, A. I. Ekimov, and V. I. Safarov, Pis'ma Zh. Eksp. Teor. Fiz. **13**, 36 (1971) [JETP Lett. **13**, 24 (1971)].

[9] D. Z. Garbuzov and V.B. Khalfin, Éffektivnost' i vremena izluchatel'nykh perekhodov v pryamozonnykh poluprovodnikakh tipa GaAs ("Efficiency and characteristic times for radiative transitions in direct-gap semiconductors of the GaAs type"), RTP LIYaF No. 652, Part 21, Leningrad, 1980.

[10] B. P. Zakharchenya, E. L. Ivchenko, and A. Ya. Ryskin, Fiz. Tverd. Tela (Leningrad) **18**, 230 (1976) [Sov. Phys. Solid State **18**, 132 (1976)].

[11] G. E. Stillman and C. M. Wolfe, Thin Solid Films **31**, 69 (1976).

Translated by Dave Parsons
Edited by S. J. Amoretty