The effect of strain on the spin relaxation of conduction electrons in III-V semiconductors

M. I. D'yakonov, V. A. Marushchak, V. I. Perel', and A. N. Titkov

A. F. Ioffe Physics and Engineering Institute, USSR Academy of Sciences

The spin relaxation of conduction electrons is investigated in uniaxially-strained crystals of GaSb, GaAs and p-type InP at moderate doping levels and temperatures $T \geqslant 77$ K. It is shown that under these conditions the primary mechanism for spin relaxation is a precession which is due to spin splitting of the conduction band. This splitting consists of two terms: a term present in the unstrained crystal proportional to the cube of the electron's quasimomentum, and an additional strain-related term which is linear in quasimomentum and strain. It is established that even for comparatively small values of the stress (15–20 kg/mm^2), the strain-induced splitting is the dominant term. In this case, the spin relaxation rate τ_S^{-1} is significantly increased and has an anisotropic character. Theoretical expressions are obtained which describe the growth in the relaxation rate as the applied stress P is increased. From a comparison of the experimental and theoretical dependences of $\tau_S^{-1}(P)$, we find a constant v which characterizes the strain-induced spin splitting of the conduction band in the compounds under study: $v = 3 \times 10^8$ cm s^{-1} in GaSb, $v = 8 \times 10^7$ cm s^{-1} in GaAs and $v = (4$–$5) \times 10^7$ cm s^{-1} in InP.

In semiconductors with zincblende structure, spin splitting occurs in the conduction band proportional to the cube of the electron quasimomentum p which is connected with the absence of a center of inversion. It has been shown both theoretically[1,2] and experimentally[3-6] that such a splitting leads to the appearance of a precession mechanism for spin relaxation of conduction electrons, which can be the dominant mechanism in pure and moderately doped crystals over a wide range of temperatures. In studying the influence of external perturbations on the effectiveness of this precession mechanism in GaAs, the authors of Refs. 7, 8 observed that uniaxial strain produced a sharp increase in the spin relaxation rate. The effect they observed was explained by the presence of an additional splitting of the conduction band in strained crystals, which was proportional to the first power of p.

In this work, we undertake a systematic study of how this strain-induced splitting of the conduction band influences the spin relaxation of photo-excited electrons in a number of III-V compounds: GaAs, GaSb and InP. We show that even for comparatively small stresses, i.e., 15–20 kg/mm^2, it is possible to detect the strain-induced splitting in moderately doped crystals: the spin relaxation rate increases significantly and develops an anisotropic character. In this case, the spin relaxation time decreases inversely as the square of the applied stress, and depends only weakly on temperature. We have observed this distinctive behavior of the electronic spin relaxation in strained crystals, and found it to be in full agreement with the results of our theoretical investigations. From a comparison of the experimental and theoretical dependences we have obtained, we determine certain constants which characterize the strain-induced splitting of the conduction band in the crystals under study.

THEORY

From symmetry considerations, we can write the correction V to the electron Hamiltonian which leads to the spin splitting in the conduction band of a strained crystal in the form[9]

$$V = \frac{\hbar}{2}[(\sigma\Omega_0)+(\sigma\Omega_d)+(\sigma\Omega_d')], \tag{1}$$

where σ are Pauli matrices and Ω_0, Ω_d and $\Omega_{d'}$, are vectors with components

$$
\begin{aligned}
\hbar\Omega_{0x} &= \alpha(2m^3E_g)^{-\frac{1}{2}}p_x(p_y^2-p_z^2), \\
\hbar\Omega_{dx} &= v(\varepsilon_{xy}p_y-\varepsilon_{xz}p_z), \\
\hbar\Omega_{dx}' &= v'p_x(\varepsilon_{yy}-\varepsilon_{zz}).
\end{aligned}
\tag{2}
$$

The remaining components of these vectors are obtained by cyclic permutation of the indices x, y, z. The coordinate axes correspond to the principal axes of the crystal. In these formulae, m is the electron effective mass, E_g is the width of the forbidden gap, ε_{ik} is the strain tensor, and α, v and v' are constants which determine the magnitude of the splitting. The first term in expression (1) characterizes the splitting which is present even in the unstressed crystal. The second and third terms described an additional splitting which appears in the presence of an applied strain.

If the strain axis coincides with the $\langle 100 \rangle$ direction, then $\Omega_d = 0$ and the strain-induced splitting is determined entirely by the last term in (1). The experimental data we will present below show that in this case the strain does not turn out to have much effect on the spin relaxation rate, whereas for other directions the effect of strain is large. From this it follows that the essential contribution to the strain-induced splitting of the conduction band comes from the second term of expression (1). This conclusion agrees

with the theoretical picture we have derived, in which the spin splitting $\hbar\Omega_d$ appears when we take into account the interaction between the conduction band and the nearest valence band Γ_{15}; the term $\hbar\Omega_d'$ is present only when the interaction with the higher-value conduction band Γ_{12} is included.[6] Therefore, in what follows we will set $\Omega_d' = 0$.

The presence of spin splitting in the conduction band is equivalent to the presence of a certain effective magnetic field directed along the vector $\boldsymbol{\Omega}_{\mathrm{eff}} = \boldsymbol{\Omega}_0 + \boldsymbol{\Omega}_d$. The precession of a spin in this effective field is also the cause of spin relaxation of conduction electrons. Since the direction of $\boldsymbol{\Omega}_{\mathrm{eff}}$ depend on the direction of the electron quasimomentum, the precession axis changes after each collision. For electrons which thermalize to near the bottom of the conduction band, when $\Omega_{\mathrm{eff}}\tau_p \ll 1$ (where τ_p is the momentum relaxation time), the angle of rotation of the spin in the time interval between collisions is small and gives rise to "dynamic averaging" of the effective field. The rate of spin relaxation under these conditions is in order of magnitude equal to $\Omega_0^2\tau_p + \Omega_d^2\tau_p$.[1] From this it follows that the strain-induced correction to the inverse spin relaxation time $\Omega_d^2\tau_p$ must be proportional to the square of the stress.

We remark that, as is clear from Eqs. (2), no matter what the direction of the quasimomentum, the strain-induced component of the effective magnetic field directed along $\boldsymbol{\Omega}_d$ lies in a certain plane whose position is determined by the strain tensor. The normal vector $\mathbf{N}$ to this plane has components

$$N_x = \varepsilon_{yz}, \quad N_y = \varepsilon_{zx}, \quad N_z = \varepsilon_{xy}. \tag{3}$$

Actually, it is not hard to verify that $\boldsymbol{\Omega}_d \cdot \mathbf{N} = 0$. For an isotropic momentum distribution of electrons, all directions of the strain-induced components of the effective field in this plane are equally probable. Thus, the spin relaxation including the strain must be characterized by a tensor, one of whose principal axes is directed along $\mathbf{N}$, while the other two lie in the plane perpendicular to it. The spin relaxation is produced only by the effective field components perpendicular to the spin. Therefore, relaxation of the spin projection along the direction of $\mathbf{N}$ due to strain is twice as fast as relaxation of the other two components.

Let us introduce the spin relaxation tensor Γ_{ij}. Then the equation describing the spin relaxation can be cast in the form

$$dS_i/dt = -\sum_j \Gamma_{ij}S_j - S_i/\tau_{s0}. \tag{4}$$

Here, $\mathbf{S}$ is the average electron spin and τ_{s0} is the isotropic spin relaxation time in the absence of strain, which is determined by the splitting $\hbar\Omega_0$. Using the methods employed in Ref. 2, we obtain

$$\Gamma_{ij} = \langle (\delta_{ij}\overline{\Omega_d^2} - \overline{\Omega_{di}\Omega_{dj}})\tau_p(\mathscr{E}) \rangle, \tag{5}$$

where $\tau_p(\varepsilon)$ is the momentum relaxation time for a given energy ε; the horizontal bars denote an average over the directions of the quasimomenta $\mathbf{p}$, while the angle brackets denote energy averages; thus, for an arbitrary function $f(\varepsilon)$,

$$\langle f(\mathscr{E}) \rangle = \frac{\displaystyle\int_0^\infty d\mathscr{E}\,\mathscr{E}^{1/2}f(\mathscr{E})\,\partial F/\partial\mathscr{E}}{\displaystyle\int_0^\infty d\mathscr{E}\,\mathscr{E}^{1/2}\,\partial F/\partial\mathscr{E}}, \tag{6}$$

where $F(\varepsilon)$, is the electronic energy distribution function. The angular averages give

$$\overline{\Omega_{di}\Omega_{dj}} = \frac{\Omega_d^2}{2}\left(\delta_{ij} - \frac{N_iN_j}{N^2}\right), \quad \Omega_d^2 = \frac{2v^2}{3\hbar^2}p^2N^2. \tag{7}$$

For nondegenerate electrons, we have $\langle p^2\tau_p(\mathscr{E}) \rangle = 3mkT\tau_p$, where k is the Boltzmann constant, T the temperature and τ_p the average relaxation time derived from the mobility. Then

$$\Gamma_{ij} = \frac{mv^2}{\hbar^2}\tau_p kT(N^2\delta_{ij} + N_iN_j). \tag{8}$$

Formula (8) allows us to write down at once the eigenvalues of the tensor Γ_{ij}, which we denote by $\tau_{d\parallel}^{-1}$ and $\tau_{d\perp}^{-1}$ for the axis parallel to the vector $\mathbf{N}$ and the two axes perpendicular to $\mathbf{N}$, respectively:

$$\frac{1}{\tau_{d\parallel}} = \frac{2}{\tau_{d\perp}} = \frac{2mv^2}{\hbar^2}kT\tau_pN^2. \tag{9}$$

Let us write the components of the strain tensor for the stress P using the formula

$$\varepsilon_{ij} = n_in_jP/2C_{44},$$

where $i \neq j$, C_{44} is the elasticity modulus, and n is a unit vector along the strain axis. The formula (9) can be case in the form

$$\frac{1}{\tau_{d\parallel}} = \frac{2}{\tau_{d\perp}} = A\frac{mv^2kT\tau_p}{2\hbar^2C_{44}^2}P^2. \tag{10}$$

Here, $A = n_x^2n_y^2 + n_x^2n_z^2 + n_y^2n_z^2$. Let us investigate the simplest special cases: 1) $\mathbf{n}\parallel \langle 111 \rangle$, then the vector $\mathbf{N}$ is also directed along $\langle 111 \rangle$ and $A = 1/3$; 2) $\mathbf{n}\parallel \langle 110 \rangle$, then the vector $\mathbf{N}$ is directed along $\langle 001 \rangle$ and $A = 1/4$; 3) $\mathbf{n}\parallel \langle 100 \rangle$, then $A = 0$ and, as we showed above, the strain has no effect on the spin relaxation.

The quantities $\tau_{d\parallel}^{-1}$ and $\tau_{d\perp}^{-1}$ are the strain-induced contributions to the inverse relaxation time for spin components parallel and perpendicular to the vector $\mathbf{N}$. We recall that the full spin relaxation rate is the case where the precession mechanism is dominant is determined both by $\hbar\Omega_d$ and $\hbar\Omega_0$, and is described by an expression with two terms $\tau_s^{-1} = \tau_{d\parallel,\perp}^{-1} + \tau_{s0}^{-1}$, where[1]

$$\tau_{s0}^{-1} = q\alpha^2(kT)^3\tau_p/\hbar^2E_g. \tag{11}$$

Here q is a numerical factor which depends on the scattering mechanism. With increasing stress, as (10) shows, the strain-induced correction to τ_s^{-1} grows rapidly; beginning with a certain value of the stress P, τ_s^{-1} can be comparable or even larger than τ_{s0}^{-1}.

EXPERIMENTAL METHODS

The spin relaxation times for conduction electrons were measured using the method of optical orientation,[10] which is an extremely convenient technique for studying the unstrained crystal. Usually a measurement of the degree of circular polarization in the luminescence associated with recombination of conduction electrons is sufficient to determine the electronic lifetime τ along with τ_S:

$$\rho = \rho_0 (1 + \tau/\tau_s)^{-1}$$

together with its decrease in an external magnetic field B perpendicular to the beam of exciting light

$$\rho(B) = \rho(1 + \Omega^2 T_*^2)^{-1}$$

(the Henley effect). Here ρ_0 is the maximum possible degree of circular polarization in the absence of spin relaxation which is determined by selection rules; $T_* = (\tau^{-1} + \tau_S^{-1})^{-1}$ is the lifetime of the spin orientation, $\Omega = g\mu_0 B/\hbar$ is the Larmor precession frequency, g is the electronic g-factor, and μ_0 is the Bohr magneton. These expressions are independent of one another and allow us to find τ and τ_S from the well-known value of the degree of polarization of the luminescence in zero magnetic field and for values of the magnetic field for which the initial polarization has fallen by a factor of two, i.e., $\Delta B = \hbar(g\mu_0 T_*)^{-1}$ (this is the half-width of the Henley curve). In the strained crystal τ_S, and by implication T_*, are anistropic; consequently, the half-width of the Henley profile can be different for different orientations of the magnetic field.

Let us study in detail the Henley effect in the presence of anistropic spin relaxation. The equation for the average spin S in a magnetic field B under conditions of optical orientation takes the form

$$\frac{dS_i}{dt} = [\Omega S]_i - \frac{S_i}{\tau_{s0}} - \sum_j \Gamma_{ij} S_j - \frac{S_i - S_{0i}}{\tau}, \qquad (12)$$

where S_0 is the average electron spin which appears in the conduction band due to the light. We will assume as usual $B \perp S_0$, and introduce the system of coordinates x', y' and z', where the z'-axis is along S while the x'-axis is along B. We introduce the characteristic times $T_\parallel^{-1} = T_0^{-1} + \tau_{d\parallel}^{-1}$ and $T_\perp^{-1} = T_0^{-1} + \tau_{d\perp}^{-1}$, where $T_0^{-1} = \tau^{-1} + \tau_{s0}^{-1}$. Under steady-state conditions, we obtain from (12) the following values for the projection of the spin in the initial direction for three cases, differing in the direction of the vector N:

$$S_{z'} = \frac{S_0 T_\perp}{\tau} \frac{1}{1 + \Omega^2 T_\perp^2}; \qquad N \perp S_0, \quad B \parallel N, \qquad (13)$$

$$S_{z'} = \frac{S_0 T_\perp}{\tau} \frac{1}{1 + \Omega^2 T_\parallel T_\perp}; \qquad N \perp S_0, \quad B \perp N, \qquad (14)$$

$$S_{z'} = \frac{S_0 T_\parallel}{\tau} \frac{1}{1 + \Omega^2 T_\parallel T_\perp}; \qquad N \parallel S_0, \quad B \perp N. \qquad (15)$$

The expressions obtained by taking into account the direct coupling of the magnitudes of ρ and S ($\rho = -S_z$, see Ref. 1) describe the half-widths of all the Henley contours which can be created under experimental conditions. As a rule, in experiments which use the optical orientation technique in strained crystals, the vector S_0 is oriented along the optical excitation beam and perpendicular to the sample surface, while the magnetic field B and strain axis n lie in the plane which coincides with the sample surface, and are either parallel or perpendicular to one another. Expression (13), (14) and (15) make it possible to measure $\tau_{d\parallel}$ and $\tau_{d\perp}$ by measuring the half-width of the Henley profile for these two mutual orientations of B and n. The values of τ and τ_{S0} needed to do this are taken from measurements on the unstrained crystals.

In this work we investigate crystals of GaAs grown by liquid-phase epitaxy with a 4×10^{16} cm^{-3} acceptor concentration of Ge, crystals of InP doped with Cd at 1×10^{17} cm^{-3}, and bulk crystals of GaSb with intrinsic acceptor concentrations of 2×10^{17} cm^{-3}. For these doping levels and $T \geqslant 77$ K, the spin relaxation of electrons in the unstressed crystal is entirely determined by the precession mechanism arising from the spin splitting of the conduction band.[6,11]

The spin relaxation times τ_S, $\tau_{d\parallel}$ and $\tau_{d\perp}$ are found by analyzing the circular polarization of the luminescence line which corresponds to recombination of electrons with holes located either on acceptors or in the valence band. The optical orientation experiment is carried out using standard apparatus[12,13]. Luminescence in crystals of GaAs ($E_g = 1.51$ eV at 77 K) was excited by a krypton laser with energy quanta $h\nu = 1.647$ eV. In the case of GaSb ($E_g = 0.803$ eV), a HeNe laser was used with $h\nu = 0.814$ eV. Because of the absence of a suitable source of monochromatic radiation for exciting InP ($E_g = 1.41$ eV), we used a flashlamp pump with two interference filters. The maximum transmission band of the filters corresponded to a wavelength of 8300 Å (1.49 eV), with a half-width of 150 Å for the excitation line. The excitation density was less than 5 W/cm for all of the experiments. Under such excitation conditions, and considering the 10^{-8}–10^{-9} s nonequilibrium lifetimes determined in this work, the nonequilibrium carrier concentration is found to be an order of magnitude or more larger than the intrinsic concentration of holes in the samples. The excitation direction and direction in which the luminescence is observed are opposite and perpendicular to the strain axis. A compressive strain was applied along the various crystallographic directions.

For all the applied loads, the ratios of the quantities $h\nu$ and E_g were such that excitation of electrons into the conduction band took place from both of the strain-split valence subbands. As for recombination, for 77 K and $P \geqslant 3$ kilobars the holes at the top of the split-off valence subband (light holes) are fully thermalized, and electrons recombine only with these light holes. We concluded this on the basis of the degree of linear polarization of the luminescence $(I_\parallel - I_\perp)/(I_\parallel + I_\perp) = 0.6$.[14]

EXPERIMENTAL RESULTS AND DISCUSSION

The influence of strain on the spin relaxation due to the precession mechanism is manifested by the degree of circular polarization in the luminescence ρ and the half-width ΔB of
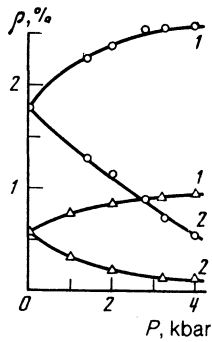
FIG. 1. Variation in the degree of circular polarization of luminescence ρ at 77 K in the crystals GaAs (○) and GaSb (△) as a function of the magnitude of uniaxial strain P applied along the $\langle 100 \rangle$ (curve 1) and $\langle 111 \rangle$ (curve 2) axes.

the Henley profile, which differ when the stress is applied along various crystal axes.

In Fig. 1 we show the experimental dependence of ρ on the magnitude and orientation of the uniaxial strain for crystals of GaAs and GaSb at 77 K. It is clear that for both compounds the circular polarization behaves in the same way. For an applied stress along the $\langle 100 \rangle$ axis the degree of circular polarization of the luminescence at first rises noticeably, and then reaches saturation. The value of ρ is observed to increase by a factor of approximately 1.5 for GaAs and 1.6 GaSb. This growth agrees with the anticipated increase of ρ to 1.6 ρ_0 because of the new selection rules in the strained crystals, i.e., electrons can only recombine light holes.[15] From this it follows that the ratio of the times τ/τ_S which enters into the expression for ρ does not change with strain along the $\langle 100 \rangle$ direction. At the same time, it turns out that in this case the half-width of the Henley profile also does not change, as is clear from the experimental data in Fig. 2a. The observed facts attest to the constancy in magnitude of τ and τ_S for an applied stress along the fourfold axis. In this geometry, the effect of strain can be related only to the splitting $\hbar\Omega'_d$, since the splitting $\hbar\Omega_d$ is absent on account of the vanishing of the non-diagonal components of the strain tensor. The independent of τ_S with pressure points up the smallness of $\hbar\Omega'_d$.

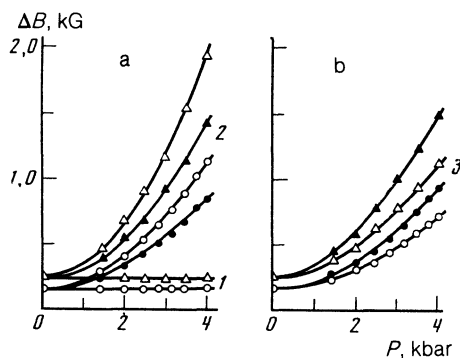Strain along the $\langle 111 \rangle$ axis, as is clear from Fig. 1, leads

FIG. 2. Dependence of the half-width of the Henley contour ΔB at 77 K in crystals of GaAs (●, ○) and GaSb (▲, △) on uniaxial strain P applied along the $\langle 100 \rangle$ (curves 1), $\langle 111 \rangle$ (curves 2) and $\langle 110 \rangle$ (curves 3) axes; dark points are for $\mathbf{B}\|\mathbf{n}$, light points for $\mathbf{B}\perp\mathbf{n}$.

to a rapid decrease in the degree of circular polarization of the luminescence, even though there is some growth of ρ_0 in this geometry. An analogous falloff in ρ with load is observed also for compression along the $\langle 110 \rangle$ axis. At the same time, in both cases there is a strong broadening in the depolarization curves for the luminescence in a transverse magnetic field (Fig. 2). Since the lifetime τ does not change with increasing stress, these results suggest a sharp acceleration in the spin relaxation for these orientations of the strain axes.

The resulting changes, shown in Fig. 2, indicate that in both compounds the half-width of the Henley profile is significantly different for orientations of the magnetic field along and transverse to the compression axis: $\Delta B_L \neq \Delta B_T$. For strain along the threefold axis, the half-width of the Henley profile in the $\mathbf{B}\perp\mathbf{n}$ geometry is larger than for $\mathbf{B}\|\mathbf{n}$. When the crystal is compressed along the twofold axis, and the luminescence is observed in a transverse direction which is also along a twofold axis, the opposite relation $\Delta B_L > \Delta B_T$ obtains. If, however, $\mathbf{n}\|\langle 110\rangle$, and the luminescence is recorded along the $\langle 001 \rangle$ axis, then ΔB_L and ΔB_T practically coincide with one another (this data is not reflected in Fig. 2). For large loads the observed differences between ΔB_L and ΔB_T reach 30–40%. All these peculiarities point to an anisotropic spin relaxation rate in the strained crystals. Their analysis allows us to say with confidence that the observed anisotropy in τ_S is connected with the strain-induced splitting of the conduction band. Actually, for a crystal strained along $\langle 111 \rangle$ the vector $\mathbf{N}$ is oriented along the strain axis $\mathbf{n}$, i.e., $\mathbf{N}\perp\mathbf{S}_0$, and from (13) and (14) the half-width of the Henley profile is determined by the expressions

$$\Delta B_L = \frac{\hbar}{g\mu_0} T_\perp^{-1}, \qquad \Delta B_T = \frac{\hbar}{g\mu_0}(T_\perp T_\|)^{-1/2}. \qquad (16)$$

As the stress is increased, the ratio $\Delta B_T/\Delta B_L$ approaches 1.4 (see the data in Fig. 2a), and consequently the value $T_\|^{-1}/T_\perp^{-1}$ goes to approximately 2. Since $T_\|^{-1}\approx\tau_{d\|}^{-1}$ and $T_\perp^{-1}\approx\tau_{d\perp}^{-1}$ for high stresses, this implies that $\tau_{d\|}^{-1}=2\tau_{d\perp}^{-1}$, as it should be in light of expression (10) for the case of strain-induced spin splitting of the conduction band.

When the stress is applied parallel to $\langle 110 \rangle$, the vector $\mathbf{N}$ is perpendicular to the strain axis and can have two possible orientations relative to the vector $\mathbf{S}$: $\mathbf{N}\|\mathbf{S}_0$ or $\mathbf{N}\perp\mathbf{S}_0$. The first case is realized for experiments which measure excitation luminescence along the $\langle 001 \rangle$ axis. In such an experimental geometry the magnetic field $\mathbf{B}$ is always perpendicular to the vector $\mathbf{N}$, since usually $\mathbf{B}\perp\mathbf{S}_0$. Then from (15) it follows that both for mutually parallel and perpendicular orientations of the vectors $\mathbf{B}$ and $\mathbf{n}$ the half-width of the Henley profiles should coincide:

$$\Delta B_L=\Delta B_T = \frac{\hbar}{g\mu_0}(T_\| T_\perp)^{-1/2}. \qquad (17)$$

The coincidence of the Henley profile half-widths in this geometry is precisely what is observed in experiment. In the case $\mathbf{N}\perp\mathbf{S}_0$, which occurs for excitation of luminescence along the $\langle 110 \rangle$ axis again according to (13) and (14) we have
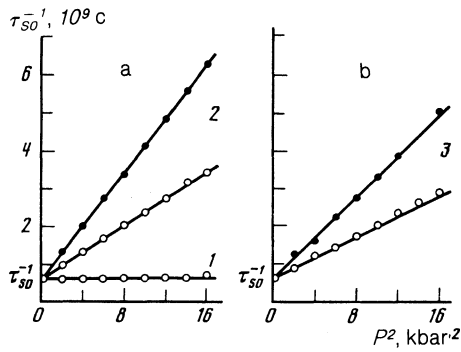
FIG. 3. Dependence of the spin relaxation rate $\tau_s^{-1} = \tau_{S0}^{-1} + \tau_{d\|,\perp}^{-1}$ at 77 K in crystals of GaAs on the square of the magnitude P of uniaxial strain applied along the $\langle 100 \rangle$ (curves 1), $\langle 111 \rangle$ (curves 2) and $\langle 110 \rangle$ (curves 3) axes. The continuous curves are used to determine the value of v from expression (10); ($\bullet$) is for $\mathbf{B}\|\mathbf{n}$, (O) is for $\mathbf{B}\perp\mathbf{n}$.

$$\Delta B_L = \frac{\hbar}{g\mu_0}\,(T_\| T_\perp)^{-\frac{1}{2}}, \qquad \Delta B_T = \frac{\hbar}{g\mu_0}\,T_\perp^{-1}. \qquad (18)$$

Now, even when the orientation is different from $n\|\langle 111\rangle$, ΔB_L should be larger than ΔB_T, and the difference between them for large loads should approach 40%, which is in good agreement with the trend of the experimental dependences in Fig. 2b.

Taking advantage of the relations (16) and (18), and the experimental values of ΔB_L and ΔB_T, we determined the spin relaxation rate in the strained crystals $\tau_s^{-1}(P) = \tau_{S0}^{-1} + \tau_{d\|\perp}^{-1}(P)$ for various experimental geometries. The results are presented in Fig. 3 for GaAs and Fig. 4 for GaSb. For $P = 0$, the strain-induced splitting $\hbar\Omega_d$ is absent, and the spin splitting is connected only with the term $\hbar\Omega_0$; the associated rate τ_{S0}^{-1} is determined by expression (11). For an applied stress along the $\langle 111\rangle$ or $\langle 110\rangle$ axis, we can trace out a quadratic growth in the strain-induced contribution to the spin relaxation rate, in agreement with theory; as follows from (10), we also have $\tau_{d\|}^{-1} = 2\tau_{d\perp}^{-1}$. A comparison of the magnitudes of $\tau_{d\|}^{-1}$ and $\tau_{d\perp}^{-1}$ for strains oriented along the $\langle 111\rangle$ and $\langle 110\rangle$ axis shows that their ratio is close to 1.3 in both compounds. This fact also agrees with the results of the theoretical investigation, as is clear from expression (10).
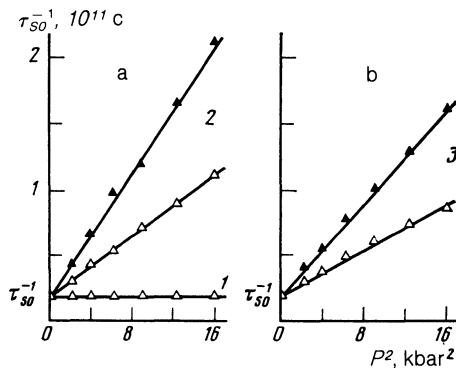

FIG. 4. Dependence of the spin relaxation rate $\tau_s^{-1} = \tau_{S0}^{-1} + \tau_{d\|,\perp}^{-1}$ at 77 K in crystals of GaSb on the square of the magnitude P of uniaxial strain applied along the $\langle 100 \rangle$ (curves 1), $\langle 111 \rangle$ (curves 2) and $\langle 110 \rangle$ (curves 3) axes. The continuous curves are used to determine the value of v from expression (10); ($\blacktriangle$) is for $\mathbf{B}\|\mathbf{n}$, ($\triangle$) is for $\mathbf{B}\perp\mathbf{n}$.
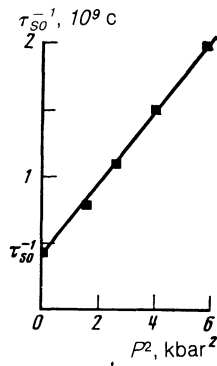

FIG. 5. The influence of strain on the spin relaxation rate $\tau_s^{-1} = \tau_{S0}^{-1} + \tau_{d\|}^{-1}$ at 77 K in crystals in InP. The strain was applied along the $\langle 110 \rangle$ axis while the luminescence is measured in the $\langle 001 \rangle$ direction. The continuous curves are drawn according to expression (10) for the values of v and τ_p presented in the text.

In experiments on InP, we limited ourselves to one geometry: $\mathbf{n}\| \langle 110\rangle$ and $\mathbf{S}_0\| \langle 001\rangle$. The values $\tau_s^{-1}(P)$ calculated for this compound are shown in Fig. 5 (see below). It is clear that the strain-induced contribution to the spin relaxation rate also depend quadratically on pressure. Since $\tau_{d\|,\perp}^{-1} \sim \Omega_d^2\tau_d$, the data presented in Figs. 3, 4 and 5 attest to the linear dependence of the splitting $\hbar\Omega_d$ on stress P for fixed temperature.

In this work we also verify that the strain-induced spin splitting is proportional to the magnitude of the electron quasimomentum, which leads to a linear dependence of $\tau_{d\|,\perp}^{-1}$ on temperature. In order to do this, we measured the dependence of the times τ_S on strain in GaAs crystals at two temperatures, $T = 77$ K and $T = 155$ K. The results of measurement of $\tau_{S0}^{-1} + \tau_{d\perp}^{-1}(P)$ in the $\mathbf{n}\| \langle 110\rangle$ and $\mathbf{S}_0\| \langle 110\rangle$ geometries are presented in Fig. 6. Prior to studying the dependence of $\tau_{d\perp}^{-1}$ on temperature, it is necessary to include the variation of τ_p with temperature, which arises from the right-hand part of expression (10). This can be done with the help of data on the spin relaxation rate in unstrained crystals at the same temperatures. According to (11), the increase in τ_{S0}^{-1} should be proportional to T^3, i.e., in our case τ_{S0}^{-1} should increase by a factor of 8. However, the observed increase amounts at most to a factor of 6. The disagreement in these values reflect the decrease in the time τ_p by a factor
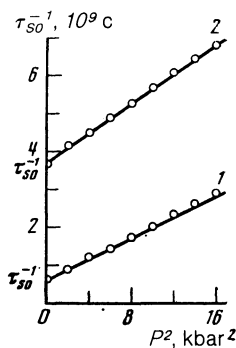

FIG. 6. Spin relaxation rate in strained crystals of GaAs at temperatures 77 K (curve 1) and 155 K (curve 2). The strain was applied along the $\langle 110 \rangle$ axis while the luminescence is excited along the $\langle 110 \rangle$ direction.

of 1.3, which is found to be in agreement with the temperature behavior of τ_p, which was studied earlier in Ref. 16. Folding this decrease of τ_p into the rate of change of τ_{d1}^{-1} with stress when the temperature is increased from 77 to 155 K, we now should have a growth not by a factor of (2), as follows for (10), but in all by a factor of 1.5. This conclusion is verified by the trends in the experimental dependences shown in Fig. 6. The strain-induced correction to the spin relaxation rate for the higher temperature increases with stress about 1.5 times faster.

The experimental dependences of $\tau_S^{-1}(P^2)$ we have measured, along with expression (10), allow us to determine the constant v for stain-induced spin splitting in the conduction band. Of course, it is true that in order to do this we require knowledge of not just relative but absolute values of the times τ_p. To determine them, we taken advantage of the suppression effect of the precession mechanism on the spin relaxation in an external magnetic field $\mathbf{B}$ oriented along the optical excitation beam.[17-19] The influence of the field consists in the following: the rotation of electron quasimomentum around the direction of $\mathbf{B}_n$ with cyclotron frequency Ω_c leads to dynamic averaging of the internal effective magnetic field acting on a spin. This slowing of the relaxation becomes noticeable in fields for which the change in direction of the momenta is determined essentially by cyclotron precession rather than collisions, when $\Omega_c > \tau_p^{-1}$. In Refs. 17–19 it is shown that the ratio of these two times $\tau_S^{-1}(B_n \neq 0)/\tau_S^{-1}$ $(B_n = 0)$, determines the degree of slowing down of the relaxation rate; this ratio can be deduced experimentally from the growth of the circular polarization of luminescence ρ with field.

In Fig. 7 we present the experimental dependence of $\tau_{S0}^{-1}(B_n \neq 0)/\tau_{S0}^{-1}(B_n = 0)$ on magnetic field, along with the same dependence calculated according to Refs. 6, 19, for GaAs (curve 1), GaSb (curve 3) and InP (curves 2, 2′). In
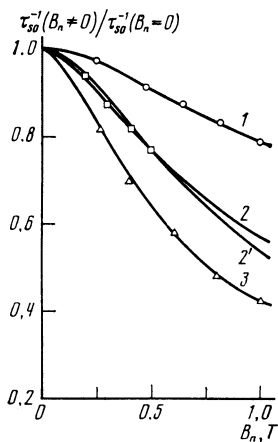
this calculation we included the fact that for the doping levels chosen and the temperature 77 K the electrons in GaAs and GaSb scatter predominantly off of charged impurities.[20,21] In the case of InP, as estimates show, it is also necessary to include scattering by neutral impurities, since Cd forms a rather deep acceptor level with an ionization energy of 50 meV[22] and the number of neutral centers at 77 K can be large. Since isolating the relative contributions to τ_p from scattering off of neutral and ionized impurities is difficult, we carried out calculations for each scattering mechanism separately: curve 2 is for ionized impurities, curve 2′ for neutral impurities. The best agreement between experimental and theoretical dependences was achieved for GaAs when $\tau_p = 1.9 \times 10^{-13}$ s, for GaSb when $\tau_p = 4.0 \times 10^{-13}$ s, and for InP when $\tau_p = 5.1 \times 10^{-13}$ s (ionized impurities) or $\tau_p = 3 \times 10^{-13}$ s (neutral impurities). The actual value of τ_p in InP should obviously lie in the interval between these two latter values.

By using these values of τ_p and those of m and C_{44},[22] along with the data from Figs. 3, 4 and 5, we found the constants for strain-induced spin splitting: $v = 3 \times 10^8$ cm s^{-1} for GaSb, 8×10^7 cm s^{-1} for GaAs and $(4-5) \times 10^7$ cm s^{-1} for InP. It is interesting to note that the decrease in the value of v from 3×10^8 cm s^{-1} in GaSb down to $(4-5) \times 10^7$ cm s^{-1} in InP correlate with the decrease in the spin-orbit interaction energy in these crystals from 0.8 eV to 0.11 eV.

In conclusion, the investigations we have carried out show that the precession mechanism for spin relaxation in strained crystals of III-V compounds is due to large part to strain-induced splitting of the conduction bands. The rapid increase in the effectiveness of the precession mechanism with stress can eventually make it the dominant relaxation mechanism even for crystals which are more strongly doped than the p-type crystals investigated here, in which the conduction electron spin relaxation in the absence of strain is caused by their bulk interaction with free holes.[11]

FIG. 7. Decrease in the spin relaxation rate $\tau_{S0}^{-1}(B_n \neq 0)/\tau_{S0}^{-1}(B = 0)$ for 77 K in undeformed crystals of GaAs (O), GaSb (△) and InP (□) in a magnetic field oriented along the optical excitation beam. The continuous curves 1, 2 and 3 are theoretical dependences calculated according to Refs. 6, 19, for electrons scattering off of charged impurities for the values of τ_p presented in the text. Curve 2′ is a calculation for the case of neutral-impurity scattering.

[1]M. I. D'yakonov and V. I. Perel', Zh. Eksp. Teor. Fiz. **60**, 1954 (1971) [Sov. Phys. JETP **33**, 1053 (1971)].

[2]M. I. Dyakonov and V. I. Perel', Fiz. Tverd. Tela (Leningrad) **14**, 1452 (1972) [Sov. Phys. Solid State **14**, 1245 (1972)].

[3]A. I. Ekimov and V. I.Safarov, Pis'ma Zh. Eksp. Teor. Fiz. **13**, 700 (1971) [JETP Lett. **13**, 495 (1971)].

[4]D. Z. Garbuzov, P. I. Dzhioev, L. M. Kanskaya and V. G. Fleisher, Fiz. Tverd. Tela (Leningrad) **14**, 1720 (1972) [Sov. Phys. Solid State **14**, 1481 (1972)].

[5]V. A. Marushchak, M. N. Stepanova and A. N. Titkov, Fiz. Tverd. Tela (Leningrad) **25**, 3537 (1983) [Sov. Phys. Solid State **25**, 2035 (1983)].

[6]G. E. Pikus and A. N. Titkov, "Spin Relaxation under Optical Orientation in Semiconductors" in *Optical Orientation*, Eds. F. Meier and B. P. Zakharchenya (North-Holland, Amsterdam, 1984), ch. 2.

[7]M. I. D'yakonov, V.A. Marushchak, V. I. Perel', M. N. Stepanova and A. N. Titkov, Izv. Akad. Nauk SSSR, Ser. Fiz. **47**, 2311 (1983) [Bull. Acad. Sci. USSR, Phys. Ser. **47**(12), 23 (1983)].

[8]V. I. Safarov and A. N. Titkov, Physica **117B–118B**, 497 (1983); Proc. Intl. Conf. Phys. Semic., Montpellier (1982).

[9]G. L. Bir and G. E. Pikus, Fiz. Tverd. Tela (Leningrad) **3**, 3050 (1961) [Sov. Phys. Solid State **3**, 2221 (1962)].

[10]M. I. D'yakonov and V. I. Perel', "Theory of Optical Spin Orientation of Electrons and Nuclei in Semiconductors" in *Optical Orientation*, Eds. F. Meier and B. P. Zakharchenya (North-Holland Amsterdam, 1984), ch. 2.

[11]A. G. Aronov, G. E. Pikus and A. N. Titkov, Zh. Eksp. Teor. Fiz. **84**,

660   Sov. Phys. JETP **63** (3), March 1986

D'yakonov *et al.*   660

1170 (1983) [Sov. Phys. JETP **57**, 680 (1983)].

[12]R. R. Parsons, Can. J. Phys. **49**, 1850 (1971).

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

[14]G. L. Bir and G. E. Pikus, Simmetriya i Deformatsionnye Effekty v Poluprovodnikakh (Symmetry and Strain-Induced Effects in Semiconductors), Nauka, Moscow (1972), ch. 5.

[15]M. I. D'yakonov and V. I. Perel', Fiz. Tekh. Poluprovodn. **7**, 2335 (1973) [Sov. Phys. Semicond. **1**, 1551 (1974)].

[16]T. S. Lagunova, V. A. Marushchak, M. N. Stepanova and A. N. Titkov, Fiz. Tekh. Poluprovodn. **19**, 118 (1985) [Sov. Phys. Semicond. **19**, 71 (1985)].

[17]E. L. Ivchenko, Fiz. Tverd. Tela (Leningrad) **15**, 1566 (1973) [Sov. Phys. Solid State **15**, 1048 (1973)].

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

[19]V. A. Marushchak, M. N. Stepanova and A. N. Titkov, Pisma Zh. Eksp. Teor. Fiz. **37**, 337 (1983) [JETP Lett. **37**, 400 (1983)].

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

[21]P. C. Mathur, R. Shaym and Sushil Jain, Phys. Stat. Sol. (a), **50**, 11 (1978).

[22]Landolt-Bornstein, *Semiconductors*, v.17a, Ed. O. Madelung (Springer-Verlag, Berlin, 1982).

Translated by Frank J. Crowne