Photocurrent in structures with quantum wells with an optical orientation of free carriers

E. L. Ivchenko, Yu. B. Lyanda-Geller, and G. E. Pikus
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR

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In media without an inversion center the spin relaxation and Larmor spin precession of optically oriented, thermalized carriers induce a current which is proportional to the spin polarization. The magnitude of this effect in the semiconductor structures GaAs/AlGaAs is determined.

Exposure of gyrotropic crystals to a circularly polarized light is known to give rise to a circular photovoltaic effect (CPE), i.e., a generation of photocurrent which changes direction as a result of a change in the sign of the circular polarization of light.[1] In nongyrotropic crystals of class T_d, which lack an inversion center, the circular photovoltaic effect can be induced by an external magnetic field or a uniaxial deformation.[2] All of the CPE mechanisms which have so far been studied are linked with the asymmetry or anisotropy in the momentum distribution of the carriers which are excited in the optical transitions. After the removal of light the photocurrent produced in this manner decays in a time corresponding to the momentum relaxation (τ_p). In the present letter we will show that a circular photocurrent, which is proportional to the nonequilibrium spin polarization of thermalized photoelectrons, can be seen in media without an inversion center. The effect occurs as a result of the spin relaxation or the Larmor precession of the spins of optically oriented electrons, with allowance for the linear splitting, in the wave vector **k**, of the conduction band spin branches. After the removal of light the current therefore decays in a time corresponding to the directed spin, $T = \tau_l \tau_s / (\tau_l + \tau_s)$, where τ_l is the lifetime of an electron in the conduction band, and τ_s is its spin relaxation time.

We will calculate the photocurrent for a periodic heterojunction $GaAs/Al_xGa_{1-x}As$ (a quantum-well chain or a short-period superlattice). Such a structure is known to have an optical orientation of free carriers[3] and its symmetry admits linear terms in **k** in the electron energy spectrum.[4] In a symmetrical quantum well with a normal $z \| [001]$, for example, the effective Hamiltonian for electrons at the bottom of the lower subband contains, along with the parabolic term $E^0_{\mathbf{k}} = \hbar^2 (k_x^2 + k_y^2)/2m_c$, the term

$$\mathcal{H}^{(1)} = (\beta/2)(-\sigma_x k_x + \sigma_y k_y). \qquad (1)$$

The coefficient β is related to the coefficient γ_c, which determines the cubic splitting in **k** of the conduction band of a bulk GaAs, by the relation $\beta = 2\gamma_c \langle k_z^2 \rangle$ (if the difference in the values of γ_c in the composites GaAs and $Al_xGa_{1-x}As$ is ignored).

The current can be calculated from the formula

$$\mathbf{j} = -e\sum_{\mathbf{k}} \mathrm{Sp}\,(\mathbf{v_k}\,\rho_{\mathbf{k}}). \tag{2}$$

Here $\hat{v}_{\mathrm{k}} = \hat{v}_{\mathrm{k}}^{0} + \hbar^{-1}\nabla_{\mathrm{k}}\mathscr{H}^{(1)}$ (where $\hat{v}_{\mathrm{k}}^{0} = \hbar\mathbf{k}/m_c$) is the velocity operator, and ρ_{k} is a 2×3 electron-density spin matrix which satisfies the kinetic equation

$$\frac{\rho}{\tau_l} + \frac{i}{\hbar}[\mathcal{H}^{(1)} + \mathcal{H}_{\mathbf{B}},\ \rho] = G + \mathrm{St}\rho, \tag{3}$$

where $\mathscr{H}_{\mathbf{B}} = g\mu_0\mathbf{B}\vec{\sigma}/2$, μ_0 is the Bohr magneton, g is the g-factor of the electron, G is the optical-generation matrix, and $St\rho$ is the collision integral. We assume that the dominating spin-relaxation mechanism is the D'yakonov–Perel' mechanism which is associated with the term $[\mathscr{H}^{(1)},\rho]$ in (3) (Ref. 4). The collision integral for elastic scattering, for example, in this case is

$$\mathrm{St}\rho = \sum_{\mathbf{k'}} \frac{2\pi}{\hbar} N_i\,|V_{\mathbf{kk'}}|^2 \{\delta(E_{\mathbf{k}}^{(0)} + \mathcal{H}_{\mathbf{k}}^{(1)} - E_{\mathbf{k'}}^{(0)} - \mathcal{H}_{\mathbf{k'}}^{(1)}),\ \rho_{\mathbf{k'}} - \rho_{\mathbf{k}}\}, \tag{4}$$

where N_i is the concentration of defects, $\{AB\}_{\mathrm{sym}} = (AB + BA) = 2$, and the terms responsible for the spin flip are disregarded in the matrix elements of $V_{\mathbf{kk'}}$. The collision integral vanishes upon substitution of the matrix function

$$\rho_{\mathbf{k}}^{(0)} = \{\frac{1}{2} + \vec{\sigma}\mathbf{S},\ f(E^0 + \mathcal{H}^{(1)} + \mathcal{H}_{\mathbf{B}})\}_{\mathrm{sym}}, \tag{5}$$

where $f(E)$ is an equilibrium distribution function which is normalized to the concentration of the photoelectrons n, and the vector $\mathbf{S}$ does not depend on $\mathbf{k}$.

Assuming that the energy equilibrium is established in a short time, $\tau_e \ll T$, we will solve Eq. (3) by means of an iteration over a small parameter $(\vec{\Omega}^{(1)} + \vec{\Omega}_{\mathbf{B}})\tau_{\mathrm{p}} \ll 1$, where $\vec{\Omega}^{(1)} = (\beta/\hbar)(-k_x, k_y, 0)$, and $\vec{\Omega}_{\mathbf{B}} = g\mu_0\mathbf{B}/\hbar$. We write ρ in the form $\rho^{(0)} + \rho^{(1)} + \rho^{(2)}$ and substitute in (5) the average electron spin $\mathbf{S}$ which satisfies the equation

$$\frac{\mathbf{S}_{\parallel}}{T_{\parallel}} + \frac{\mathbf{S}_{\perp}}{T_{\perp}} + \mathbf{S}\times\vec{\Omega}_{\mathbf{B}} = \frac{\mathbf{S}_0}{\tau_l}. \tag{6}$$

Here $T_{\parallel,\perp}^{-1} = \tau_l^{-1} + \tau_{s,\parallel,\perp}^{-1}$, $\tau_{s\perp} = 2\tau_{s\parallel} = \hbar^4(k_B T\tau_{\mathrm{p}}^{(1)}\beta^2 m_c)^{-1}$, $\mathbf{S}_{\parallel}$ is the component of the vector $\mathbf{S}$ parallel to the z axis, $\mathbf{S}_{\perp}$ is the component of the vector $\mathbf{S}$ perpendicular to the z axis, $\mathbf{S}_0$ is the average spin of the electrons which strike the bottom as a result of thermalization, T is the temperature, and k_B is the Boltzmann constant.

There is no electrical current in (5). The electron-spin precession, which is described by the second term in (3), disrupts the equilibrium energy distribution and induces a current

$$\mathbf{j} = \frac{e}{\hbar}\frac{n}{\tau_l}\tau_{\mathbf{p}}\nabla_{\mathbf{k}}(\vec{\Omega}^{(1)}, \mathbf{S}_0 - \mathbf{S}). \tag{7}$$

In the case of a normal incidence we have $\mathbf{S}_0 \| z$ and the photocurrent appears only in a transverse magnetic field $\mathbf{B}\perp z$:

$$j_\alpha = \pm e\frac{\beta}{\hbar} n \sim \frac{T_\parallel T_\perp}{\tau_l^2} \frac{\tau_p}{1+T_\parallel T_\perp \Omega_B^2} [\vec{\Omega}_B \times \mathbf{S}_0]_\alpha , \tag{8}$$

where $\alpha = x,y$; the upper sign corresponds to $\alpha = x$. Note that in asymmetric wells the Hamiltonian $\mathscr{H}^{(1)}$, in addition to the term (1), may contain the term $\mathscr{H}^{(1)} = C[\vec{\sigma}\mathbf{k}]_z$, where the constant C depends on the shape of the well. The current caused by this term is always parallel to **B**.

In the absence of a magnetic field the transverse component of the spin arises only in the case of oblique incidence of the light. In this case, according to (7),

$$j_\alpha = \mp \frac{e\beta}{\hbar} n \frac{\tau_p T_\perp}{\tau_{s\perp} \tau_l} S_{0\alpha} . \tag{9}$$

If the cubic terms in **k** are taken into account in (1), we will have an additional component of the current,

$$j_\alpha = \mp \frac{e\gamma_c}{\hbar^3} m_c k_B T \frac{\tau_p}{\tau_{s\perp}} n S_\alpha \theta . \tag{10}$$

Here $\theta = (\tau_2/\tau_1)[\langle E^2\tau_1^2\rangle/(k_B T)^2\tau_p^2]$, the angle brackets represent averaging over the energy, $\tau_p = \langle E\tau_1\rangle/k_B T$, and τ_l is the relaxation time of the polynomial $P_l(\mathbf{k})$ of the distribution function. In the configuration $S_0 \| z$ this component can be the dominant component if $\tau_s \ll \tau_l$.

Let us now determine the generated voltage. If the photoconductivity is greater than the dark conductivity, the voltage does not depend on the light intensity and at $S_z = 0.5$ and $\Omega_B^2 T_\parallel T_\perp = 1$, according to (8), is given by

$$e\mathscr{E} = \frac{j m_c}{e\tau_p n} \sim \frac{\pi^2}{2} \frac{m_c \gamma_c}{\hbar^2 d^2} \frac{\sqrt{T_\parallel T_\perp}}{\tau_l^2} .$$

At $\tau_s \gtrsim \tau_l = 10^{-9}$ s, $m_c = 0.066 m_0$, and $\gamma_c = 1.4\times 10^{-23}$ eV·cm^3 we have $\mathscr{E} = 4\times 10^{-3}$ V/cm for a well of width $d = 10^{-6}$ cm; i.e., for a transverse dimension $\sim(2;3)\times 10^{-2}$ cm the voltage across open-circuited contacts is $V = 10^{-4}$ V.

[1]E. L. Ivchenko and G. E. Pikus, *Problems of Modern Physics*, Nauka, Leningrad, 1980, p. 275; V. I. Belinicher and B. I. Sturman, Usp. Fiz. Nauk **130**, 415 (1980) [Sov. Phys. Usp. **23**, 199 (1980)].
[2]E. L. Ivchenko *et al.*, Solid State Commun. **69**, 663 (1989); Yu. B. Lyanda-Geller and G. E. Pikus, Fiz. Tverd. Tela **31** (1989) (in press).
[3]I. N. Uraltsev *et al.*, Phys. St. Sol. (b) **150**, 673 (1988).
[4]M. I. D'yakonov and V. Yu. Kachorovskiĭ, Fiz. Tekh. Poluprovodn. **20**, 275 (1986) [Sov. Phys. Semicond. **20**, 172 (1986)].

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