Effect of electric field on the optical orientation of 2D electrons

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(Submitted 29 June 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 4, 859–863 (25 August 1990)

In crystals with a linear in the momentum spin splitting of conduction bands the flow of current was found to be accompanied by the appearance of an effective magnetic field which affects the electron spin. This field was determined from the change in the optical orientation of the photo-excited carriers. The experimental study and the calculation were carried out for a heterostructure with isolated quantum wells.

A linear in the momentum spin splitting of the conduction band, which is permissible by the symmetry of uniaxially deformed crystals or crystals without an inversion center, grown in the form of heterostructures with quantum wells, and also of gyrotropic crystals leads to the appearance of several new effects. Thus, for example, the appearance of a photocurrent as a result of spin relaxation of optically oriented crystals in quantum wells was theoretically predicted in Ref. 1. The inverse effect—the polarization of carriers as a result of the current flow in gyrotropic crystals[2] and in deformed III–V crystals[3]—was considered in Refs. 2 and 3.

In the present letter we show that the flow of electric current in quantum-size structures of the type GaAs/AlGaAs is accompanied by the appearance of an effective magnetic field which affects the spins of the drifting electrons. We accordingly proposed that this field can be measured from the effect it produces on the optical orientation of the electrons in the external magnetic field.

This effect can be easily explained. The spin splitting of the conduction band, as we know,[4,5] affects the electron spin in the same way as the effective magnetic field $\mathbf{H}^*_{\rm eff}$, whose strength and direction are determined by the strength and direction of the electron momentum $\mathbf{p}$. In the 2D case, when the spin splitting is linear in the momentum, the field $\mathbf{H}^*_{\rm eff} \propto \mathbf{p}$ (Ref. 5). As a result of momentum scattering, this field varies randomly, which accounts at thermodynamic equilibrium for the absence of a regular field which affects the electron spin. The electron spin precession in a randomly varying magnetic field causes an additional spin relaxation of the electrons.[5] The passage of an electric current in the plane of the quantum well superimposes a regular drift with a momentum $\mathbf{p}_{\rm drift}$ on the random motion of electrons. This process causes the formation of a regular effective magnetic field $\mathbf{H}_{\rm eff} \propto \mathbf{p}_{\rm drift}$, in addition to the fluctuating part of $\mathbf{H}^*_{\rm eff}$, which accounts, as previously, for the spin relaxation. This field, which accounts for the precession of the average spin of the drifting electrons, can be determined from the change in the optical orientation of the photoexcited electrons.

We will show that a flow of current causes the average nonequilibrium spin $\mathbf{S}$ of the optically oriented 2D electrons to precess in an electric magnetic field $\mathbf{H}_{\rm eff}$. The

Hamiltonian $\mathscr{H}$ of the electrons in a symmetrical quantum well with a normal $z \| [001]$ in a magnetic field **H** directed in the plane of the quantum layer is

$$\mathcal{H} = \frac{\mathbf{p}^2}{2m} + \frac{1}{2}\hat{\boldsymbol{\sigma}}\hat{\epsilon}\mathbf{p} + \frac{1}{2}\mu_B g\hat{\boldsymbol{\sigma}}\mathbf{H}. \tag{1}$$

Here $\mathbf{p} = (p_x, p_y, 0)$ is the electron quasi-momentum (the x axis is parallel to [100]), m and g are the effective mass of electrons and the effective g-factor, and μ_B is the Bohr magnetron ($\mu_B > 0$). The pseudotensor of second rank is

$$\hat{\epsilon} = \frac{2\pi^2\gamma_c}{\hbar a^2} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

where γ_c is the cubic in **p** spin splitting of the conduction band in bulk GaAs, and a is the width of the well.

The precession of nonequilibrium **S** in an effective magnetic field is given by

$$\left(\frac{\partial \mathbf{S}}{\partial t}\right)_{\text{current}} = \frac{i}{\hbar} \sum_{\mathbf{p}} \mathrm{Tr}\left(\frac{1}{2}\hat{\boldsymbol{\sigma}}[\hat{\rho}, \frac{1}{2}\hat{\boldsymbol{\sigma}}\hat{\epsilon}\mathbf{p}]\right). \tag{2}$$

The density matrix $\hat{\rho}$ is comprised of an equilibrium part with respect to the momentum, $\hat{\rho}_0$, and a small nonequilibrium increment with respect to the momentum, $\vec{\rho}_1$. In the case of nondegenerate statistics we have[1] $\hat{\rho}_0 = \{0.5 + \hat{\sigma}\mathbf{S}, Z^{-1} \times \exp(-\mathscr{H}/kT)\}_{\text{sum}}$, where Z is a statistical sum.

At thermodynamic equilibrium $\hat{\rho}_1 = 0$ and $(\partial \mathbf{S}/\partial t)_{\text{current}} = 0$. Upon switching on the current $\hat{\rho}_1 = \tau_p e\mathbf{E}\nabla_{\mathbf{p}}\hat{\rho}_0$ if there is a slight deviation from equilibrium, where τ_p is the momentum relaxation time, and **E** is the electric field strength. We then can write

$$\left(\frac{\partial \mathbf{S}}{\partial t}\right)_{\text{current}} = \frac{-1}{\hbar} \sum_{\mathbf{p}} \mathrm{Tr}\left(\hat{\rho}_1\left(\frac{1}{2}\hat{\boldsymbol{\sigma}} \times \hat{\epsilon}\mathbf{p}\right)\right) = \left(\frac{\hat{\epsilon}\mathbf{p}_{\text{drift}}}{\hbar}\right) \times \mathbf{S}. \tag{3}$$

It follows from (3) that when the current flows, there is an additional precession of the electron spins in an effective magnetic field:

$$\mathbf{H}_{\text{eff}} = \frac{\hat{\epsilon}\mathbf{p}_{\text{drift}}}{\mu_B g} = \frac{2\pi^2\gamma_c m}{\hbar a^2 \mu_B g}\mu_n \begin{pmatrix} E_x \\ -E_y \\ 0 \end{pmatrix}, \tag{4}$$

where $\mathbf{p}_{\text{drift}} = -m\mu_n\mathbf{E}$ is the drift momentum of the electrons, and μ_n is the electron mobility. We note that the field $\mathbf{H}_{\text{eff}}$ is directed in the plane of the quantum well, and that it is proportional to the electron mobility and to the electric field strength.

Let us estimate the effective field strength. For a well of width $a = 10^{-6}$ cm with $m = 0.066m_0$, $|g| = 0.44$, $\gamma_c = 2.45 \times 10^{-23}$ eV·cm^3 (Ref. 6), $\mu_n = 10^4$ cm^2/(V·s), and $E = 10$ V/cm, we find $H_{\text{eff}} = 1.1 \times 10^{-2}\mu_n E \approx 1$ kOe. A field of such magnitude is capable of producing a considerable depolarization of the optically oriented electrons, which manifests itself on the plot of their degree of polarization versus the external magnetic field strength.

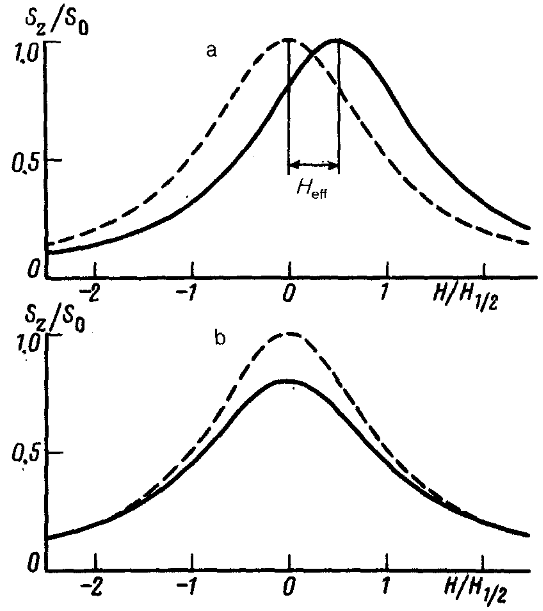

FIG. 1. The Hanle curves constructed from Eq. (5) for two orientations of the field $\mathbf{H}_{eff}$. Dashed curve—$H_{eff} = 0$; solid curve—$H_{eff} = -0.5H_{1/2}$. a—$\mathbf{H}_{eff} \| \mathbf{H}$, b—$\mathbf{H}_{eff} \perp \mathbf{H}$.

In the presence of an external magnetic field and a current the average spin **S** thus precesses in the combined magnetic field $\mathbf{H} + \mathbf{H}_{eff}$. In the standard expression which describes the Hanle effect, the field **H** in this case is replaced by $(\mathbf{H} + \mathbf{H}_{eff})$:

$$\frac{S_z}{S_0} = \frac{1}{1 + (\mathbf{H} + \mathbf{H}_{eff})^2/H_{1/2}^2}, \tag{5}$$

where $\mathbf{S}_0$ is the average electron spin in the absence of a magnetic field and current $(\mathbf{S}_0 \| z)$; the half-width of the Hanle curve is $H_{1/2} = \hbar/\mu_B |g| T_S$, where T_S is existence time of the optical orientation (the spin relaxation is assumed to be isotropic).

Two cases can be singled out: $\mathbf{H}_{eff} \| \mathbf{H}$ and $\mathbf{H}_{eff} \perp \mathbf{H}$. In the first case, the field H_{eff} is combined with the external field or is subtracted from it, which leads to a shift of the original Hanle curve by an amount H_{eff} (Fig. 1a). In the second case, the field H_{eff} accelerates the electron depolarization at all values of the field H, leaving in this case the $S_Z(H)$ curve symmetrical with respect to the change in the sign of H (Fig. 1b).

The experiment, whose results are explained qualitatively by the theory discussed above, was carried out using a heterostructure which has grown in the [001] direction and which consists of 100 GaAs layers divided by $Al_{0.3}Ga_{0.7}As$ barriers 100 Å and 110 Å thick, respectively.[7] The quasi-two-dimensional electrons in the quantum wells were optically oriented by a σ light beam with $\lambda = 7525$ Å directed along the $z \| [001]$ axis. We measured the degree of circular polarization ρ of the luminescence, $\rho \sim S_Z$, using a light-polarization analyzer.[8] The electrical contacts of the GaAs layers were made by depositing gold with germanium on the surface of the crystal in the form of two narrow parallel strips and then brazing them to the crystal. The contacts were

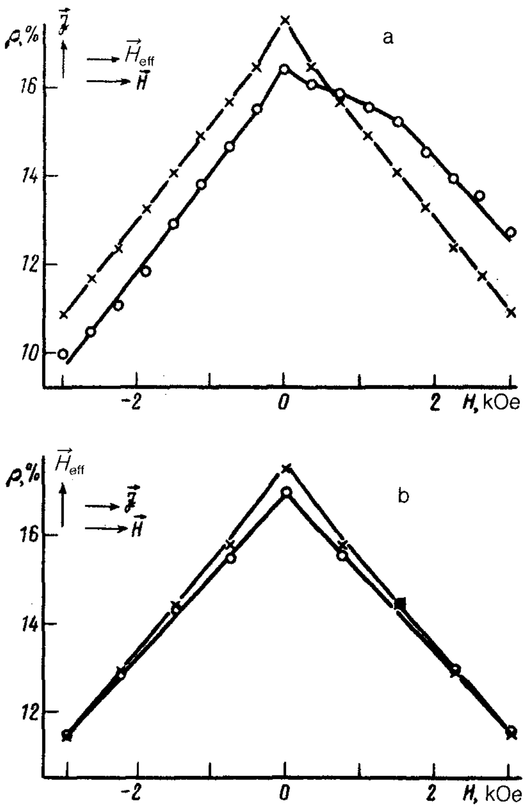

FIG. 2. Experimentally obtained Hanle curves for the case in which a current is flowing through the sample and during its absence for two orientations of the crystal $T = 77$ K. (At light intensity of 2 W/cm^2 and 77 K the photocurrent was higher than the dark current by a factor of more than 100.) *a*—$\mathbf{J}\perp\mathbf{H}$ ($\mathbf{H}_{eff}\|\mathbf{H}$), *b*—$\mathbf{J}\|\mathbf{H}$ ($\mathbf{H}_{eff}\perp\mathbf{H}$). ×—$J = 0$; O—$J = +150$ μA. The solid lines are drawn for clarity.

placed in such a way that the current J would flow along the [110] axis of the crystal. The applied magnetic field **H** was directed horizontally along the plane of the heterolayers.

In the experiment, we measured the Hanle curves when the current was flowing through the sample and without the current. Figure 2 shows the initial segments of the $\rho(H)$ curves obtained for two orientations of the crystal when the current $\mathbf{J}\perp\mathbf{H}$ and $\mathbf{J}\|\mathbf{H}$. These curves are strongly asymmetric with respect to the ordinate when $\mathbf{J}\perp\mathbf{H}$ (Fig. 2a) and match each other within the measurement error upon the reversal of the sign of H when $\mathbf{J}\|\mathbf{H}$ (Fig. 2b).

This behavior of the Hanle curves can be explained by taking into account the effective field $\mathbf{H}_{eff}$. In the case of a current flow J ($\mathbf{J}\|\mathbf{p}_{drift}\|\mathbf{E}$) along the [110] axis, the field $\mathbf{H}_{eff}$, according to (4), is at right angles to J. Then $\mathbf{H}_{eff}\|\mathbf{H}$ when $\mathbf{J}\perp\mathbf{H}$, and $\mathbf{H}_{eff}\perp\mathbf{H}$ when $\mathbf{J}\|\mathbf{H}$. In the first case, the field $\mathbf{H}_{eff}$ retards the depolarization of electrons when $H > 0$ and accelerates it when $H < 0$, causing the $\rho(H)$ curve to become

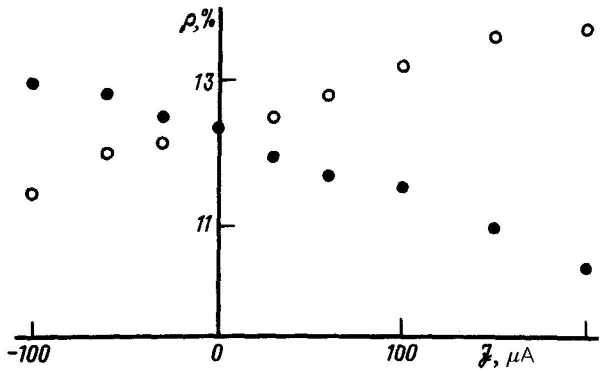

FIG. 3. The plot of ρ as a function of flow of the photocurrent through the sample for the case in which $\mathbf{J}\perp\mathbf{H}$ ($\mathbf{H}_{\rm eff}\|\mathbf{H}$). $T=77$ K. H: ○— + (2250 ± 2) Oe; ●— − (2250 ± 2) Oe.

asymmetrical (Fig. 2a). We note that the field $H_{\rm eff}$, estimated from the asymmetry of the $\rho(H)$ curves in Fig. 2a, is 0.6 ± 0.2 kOe. If $\mathbf{H}_{\rm eff}\perp\mathbf{H}$, the depolarizing effect of the field $\mathbf{H}_{\rm eff}$ depends on the direction of the field $\mathbf{H}$. The $\rho(H)$ curve in this case must remain symmetrical when the sign of H is reversed, as was observed experimentally (Fig. 2b).

Additional proof of the appearance of a field $\mathbf{H}_{\rm eff}$ comes from the plots of ρ as a function of the current flow through the sample. Such plots for the geometry $\mathbf{J}\perp\mathbf{H}$ in a field $H = +2.25$ kOe and $H = -2.25$ kOe are shown in Fig. 3. As can be seen in the figure, the variation of the polarization $\Delta\rho = \rho(+H) - \rho(-H)$ is a linear function of the current, where the sign is reversed when the sign of J is reversed. This behavior of ρ also is explained by the effect of the field $\mathbf{H}_{\rm eff}$. According to (4), the field $\mathbf{H}_{\rm eff}\|\mathbf{H}$ in such a geometry. This field, which is directly proportional to the current, changes its direction as the direction of the current is changed. The increase in the current will then shift the curve of $\rho(H)$ along the abscissa, which should be accompanied by a linear change of ρ on the linear part of the ρ-vs-H curve in the case of small (along the $H_{1/2}$ scale) values of $\mathbf{H}_{\rm eff}$; by an increase of ρ at $H>0$ and a decrease of ρ at $H<0$ for $J>0$, and vice versa by a decrease of ρ at $H>0$ and an increase of ρ at $H<0$ for $J<0$.

We see that since the field $H_{\rm eff}$ is proportional to the electron mobility [see Eq. (4)], the measurement of this field (for the known width of the quantum well and the known strength of the applied electric field) could also be the method by which the mobility of the carriers can be determined in quantum-size structures.

We note, in conclusion, that the effective field $\mathbf{H}_{\rm eff}$ can be determined not only from the change in the polarization of the light-oriented electrons. Thus, for example, a current-induced orientation of electrons in a deformed GaAs, which was predicted in Ref. 3, is in fact the result of the magnetization of electrons in a field $\mathbf{H}_{\rm eff}$. The degree of polarization of these electrons in this case is $\mathscr{P}_T \sim \mu_B g H_{\rm eff}/kT$. In addition, the field $H_{\rm eff}$ may lead to a shift of the ESR line of free electrons (the analog of the Overhauser shift) and correspondingly[2] to a rotation of the plane of linearly polarized light (the Faraday effect).

We wish to thank B. P. Zacharchenya and V. G. Fleisher for sustained interest in this work. We also thank G. E. Pikus, I. A. Merkulov, A. G. Aronov, and Yu. B. Landa-Geller for useful discussions, P. S. Kop'ev for furnishing the crystal, and I. R. Dainova for making the contacts for the sample.

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Translated by S. J. Amoretty