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POSSIBILITY OF ORIENTING ELECTRON SPINS WITH CURRENT

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It is known that if a polarized beam of electrons is scattered by an unpolarized target, then the spin-orbit interaction leads to scattering asymmetry about the plane containing the directions of the spin and of the initial momentum [1]. The so-called anomalous Hall effect is connected with this asymmetry [2 - 5]. In the scattering of an unpolarized beam by an unpolarized target, a spacial separation of electrons with different spin orientation is produced by the fact that the deflection is correlated with the spin [6]. A predominant deflection of electrons with opposite spins takes place in opposite directions.

When current flows through a conductor, the multiple scattering of the carriers should give rise to a spin flux perpendicular to the current and directed from the interior to the periphery of the conductor. We show in this paper that this leads to accumulation of spin orientation at the surface of the sample, limited by the spin relaxation. As a result there dhould exist at the surface of a current-carrying sample a layer in which the electron spins are oriented (spin layer). The spin-layer thickness is determined by the length of the spin diffusion.

From the phenomenological point of view the phenomenon can be described as follows: We introduce the spin-density vector $\vec{S}$ and the spin-flux density tensor $q_{\alpha\beta}$. The quantity $q_{\alpha\beta}$ gives the flux density of the β-component of the spin in the direction of α. The spin density $\vec{S}$ satisfies the continuity condition

$$\frac{\partial S_\beta}{\partial t} + \frac{\partial q_{\alpha\beta}}{\partial x_\alpha} + \frac{S_\beta}{\tau_s} = 0, \qquad (1)$$

where τ_s is the spin relaxation time. The expression for the spin flux density $q_{\alpha\beta}$ will be written in the form

$$q_{\alpha\beta} = - b_s E_\alpha S_\beta - d_s \frac{\partial S_\beta}{\partial x_\alpha} + \beta_s n \epsilon_{\alpha\beta\gamma} E_\gamma \quad , \qquad (2)$$

where $\epsilon_{\alpha\beta\gamma}$ is an antisymmetrical unit tensor of third rank, $\vec{E}$ the electric field intensity, and n the electron concentration. In expression (2) we confined ourselves to terms linear in the electric field, the spin density, and its first derivatives[1]. The first term in the right side of (2) describes the drift of the spin due to the electric field, the second describes the spin diffusion, and the third describes the occurrence of a spin flux in a direction perpendicular field, due to spin-orbit interaction. Consequently the coefficients b_s, d_s, and β_s can be called the spin mobility, the spin diffusion coefficient, and the spin-electric coefficient.

[1] It is possible to add to Eq. (2) also the terms due to the spin-orbit interaction, containing the expressions $E_\beta S_\alpha$, $\delta_{\alpha\beta}(\vec{E}\cdot\vec{S})$, $\partial S_\alpha/\partial x_\beta$, and $\delta_{\alpha\beta}\mathrm{div}\vec{S}$, which are compatible with the law of transformation of the tensor $q_{\alpha\beta}$. These terms, however, are of no significance in the effect under consideration, and have been omitted for simplicity.

The expression for the electron flux $\vec{q}$ can be written in the form

$$q = -bnE - \beta[E \times S] - \delta \operatorname{rot} S. \quad (3)$$

The first term here is the usual one (b is the mobility), the second term is responsible for the anomalous Hall effect, and the third describes a unique effect, wherein inhomogeneity of the spin density leads to the appearance of current. The last two terms of (3) are due to spin-orbit interaction.

The greek-letter coefficients β_s, β, and δ are proportional to the spin-orbit interaction. In a nondegenerate semiconductor the coefficients b_s and d_s coincide with the usual mobility b and diffusion coefficient D, and it can be shown that the coefficients β_s, β, and δ are connected by $\beta_s = \beta = e\delta/T$ (e is the electron charge and T is the temperature in energy units). We note that the coefficient β is connected with the coefficient R_M of the anomalous Hall effect by the relation $\beta = g\mu_0 eb^2n^2R_M$, where g and μ_0 are the g-factor and the Bohr magneton.

If the only cause of the spin orientation is the flow of current, then the spin density is proportional to the field and terms of the form (ES) can be neglected in (2) and (3). We then obtain for the stationary regime from (1) and (2) [2]

$$\Delta S = \frac{1}{L_s^2} S, \quad (4)$$

where $L_s = \sqrt{d_s \tau_s}$ is the spin diffusion length. This equation must be supplemented by boundary conditions denoting the vanishing of the spin flux through the surface. According to (2), we obtain

$$d_s \frac{\partial S}{\partial x_\nu} = \beta_s n [E \times \nu] \quad (5)$$

on the surface of the sample. Here $\vec{\nu}$ is a unit vector normal to the surface.

In the case of a round conductor of radius R, solution of (4) yields

$$S_\phi = S_0 I_1(r/L_s)/I_1(R/L_s), \quad S_r = S_z = 0, \quad (6)$$

where I_1 is a modified Bessel function of the first kind. The spin density S_0 on the surface is given by

$$S_0 = \frac{\beta_s \tau_s}{L_s} nEI_1(R/L_s)/I_1'(R/L_s). \quad (7)$$

For a thick conductor ($R \gg L_s$) we get

$$S_\phi = S_0 \exp(-x/L_s); \quad S_0 = \frac{\beta_s \tau_s}{L_s} nE. \quad (8)$$

Here $x = R - r$ is the distance from the surface. It is obvious that the formulas in (8) are valid near the surface of a bulky conductor of any form. When $R \ll L_s$ we have

$$S_\phi = S_0 r/R; \quad S_0 = \frac{\beta_s}{d_s} nER. \quad (9)$$

The maximum spin density is reached on the surface of a thick sample. It is remarkable that according to (8) the quantity S_0 does not contain a smallness connected with the spin-orbit interaction, since τ_s is inversely proportional to the square of this interaction. The degree of orientation $P = S/n$ in the spin layer can reach an order of magnitude of the ratio of the electron drift velocity to their random-motion velocity. In semiconductors this ratio can

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[1)] Inclusion of the terms mentioned in footnote 1 would lead to a small term proportional to grad div $\vec{S}$ in the left side of (4).

be appreciable, and P can exceed by many orders of magnitude the orientation produced by the magnetic field of the current.

We note that it follows from (3) that the current density is not uniform over the cross section of the conductor. In the spin layer it changes by a small amount of the order of $\delta S_0 L_s^{-1}$.

The orientation of the electrons in the spin layer can be detected by paramagnetic resonance, by the nuclear magnetization resulting from the Overhauser effect, and by the change produced in the surface impedance by the gyrotropy of the spin layer. In semiconductors the orientation can lead to circular polarization of the luminescence excited by the unpolarized light.

A magnetic field parallel to the current destroys the spin orientation if the period of the spin precession in the field is shorter than the spin relaxation time.

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