Observation of a surface photocurrent caused by optical orientation of electrons in a semiconductor

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Experiments reveal that a photocurrent arises during the asymmetric scattering of spin-polarized electrons by charged impurity centers. The constant of the spin-orbit scattering is estimated.

The spin-orbit interaction is known to cause an asymmetry in the scattering of an electron by a charged center with respect to a plane passing through the spin and momentum vectors. In a semiconductor the spin-orbit interaction constant is several orders of magnitude greater than for a free electron, so that a relativistic effect may be manifested even at electron velocities in the thermal range.

The correlation of momenta with spins in scattering events can give rise to a current. This current should be seen extremely clearly during optical orientation of electrons in direct-band semiconductors, when the interband absorption of circularly polarized light gives rise to not only an orientation of the electron spins but also a diffusion spin flux away from the surface, because of a gradient in the spin density ($\mathbf{j}_s \sim \nabla n$). A flux of oriented electrons is accompanied under asymmetric-scattering conditions by the appearance of a current in the direction perpendicular to this flux and to the average electron spin. An external magnetic field can be used to rotate the electron spin to maximize the current. When light is incident normally on the surface of a crystal, the magnetic field should be applied along this surface in order to produce a component of the electron spin parallel to it. This experimental approach was proposed by Averkiev and D'yakonov.[1] The absence of an external electric field simplifies the problem of distinguishing the photocurrent caused exclusively by the orientation of the carriers. Furthermore, since the spin orientation can be controlled optically, it becomes possible to eliminate the contributions of all photovoltaic effects not related to this orientation.

The present experiments were carried out using n-type $\mathrm{Ga_{0.73}Al_{0.27}As}$ crystals grown on semi-insulating substrates at $T = 77$ K. Contacts were formed by brazing indium. The regions of the crystal near the contacts and edges were shielded from light. The crystals were illuminated by circularly polarized light from an LG-38 helium-neon laser. The degree and sign of the circular polarization were modulated at the frequency $\Omega = 30.256$ kHz by a piezoelectric quartz modulator, which caused a modulation of the light intensity at the frequency Ω amounting to less than 0.05% of the total intensity. The small change in the light intensity at the frequency Ω during modulation of the circular polarization at this frequency is an extremely important condition for observing the effect, since a modulation of the light intensity is accompa-

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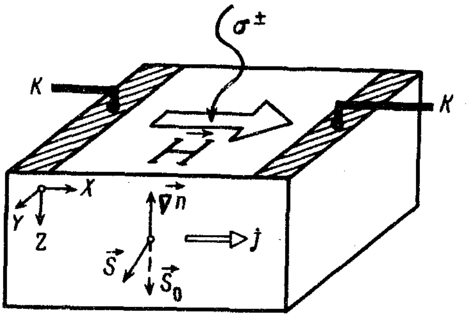

FIG. 1. Arrangement for observing the surface photocurrent during the optical orientation of electrons.

nied by strong parasitic signals at the frequency Ω (the Dember effect, the photomagnetic effect, etc.), which make it difficult to measure the signal. A static magnetic field **H** was applied along the axis connecting the contacts (the X axis) and lay in the plane of the surface of the crystal (Fig. 1). The signal from the sample was detected by synchronous detection at the frequency Ω. When strong parasitic signals were present, caused by a modulation of the light intensity during the modulation of the polarization, we also used a modulation of the static magnetic field at a low frequency ($\omega = 23$ Hz) and a second synchronous detection (at the frequency ω) in order to bring out the signal. In this case, we detected a signal proportional to the derivative of the signal shown in Fig. 2a. The results of these experiments are shown in Figs. 2a and 2b. Figure 2a shows the photo-emf which arises at the surface of the crystal during illumination by circularly polarized light versus the strength of the static magnetic field applied to the crystal. The resistance of the illuminated region of the crystal (a circular spot ~ 0.2 mm in diameter) is $\sim 250\ \Omega$. The current per unit length in the illuminated region at the surface of the crystal, which corresponds to the maximum signal, is therefore 0.01 μA/cm (at $H = 90$ Oe). As was shown in Ref. 1, the asymmetric-scattering current is determined by

$$I = e\,\delta n_0 S_y \ , \qquad (1)$$

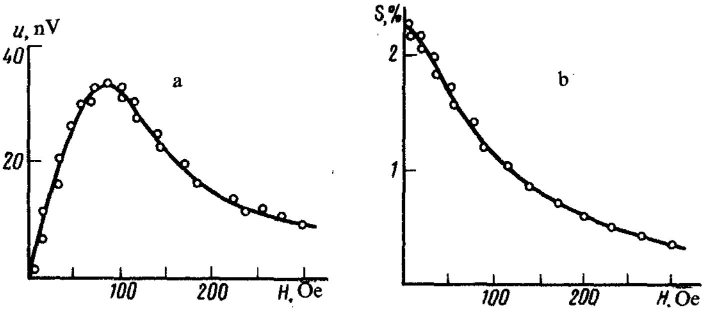

FIG. 2. a—Photo-emf that arises at the surface of the crystal versus the magnetic field; b—depolarization of optically oriented electrons in a transverse magnetic field (the Hanle effect).

where e is the magnitude of the electron charge, the coefficient δ is proportional to the spin-orbit interaction, n_0 is the surface density of photoexcited electrons (in our case, $n_0 = 5\times 10^{15}$ cm^{-3}), and S_y is the projection of the average electron spin onto the Y axis. For n-type semiconductors, we have $S_y = S_0/4$, where S_0 is the average electron spin in the absence of a magnetic field. From Fig. 2b we find $S_0 = 2.3\%$. From (1) we then find the estimate $\delta = 0.2\times 10^{-2}$ cm^2/s, in order-of-magnitude agreement with the result calculated in Ref. 2.

It should be noted that the coupling of the spin and momentum of conduction electrons caused by the impurity of valence-band states and the spin-orbit interaction may also give rise to a current, proportional to $[\mathbf{S}\times\mathbf{k}]$, where $\mathbf{k}$ is the electron wave vector. This current was estimated for an InSb crystal in Ref. 3, in a study of the anomalous Hall effect. A corresponding estimate for the $Ga_{0.73}Al_{0.27}$ crystal yields a value at least two orders of magnitude lower than that observed by us.

Figure 2b shows a curve of the depolarization of the optically oriented electrons in a transverse magnetic field (the Hanle effect), found from independent luminescence measurements, similar to those of Ref. 4, for the same crystal. We should point out that the lifetimes of the spin orientation found from the electrical and optical measurements are the same. This time is determined by the particular magnetic field $\mathbf{H}^*$ in which we observe the maximum of the signal in Fig. 2a, while in Fig. 2b it is determined by the field $\mathbf{H}$ at which $\mathbf{S}$ has decreased to half its value at $H = 0$. The fields H^* in Figs. 2a and 2b are essentially identical. The relaxation time of the magnetic moment of the minority charge carriers, $T = \hbar/g\mu_B H^*$, is 2×10^{-9} s, where g is the electron g-factor, μ_B is the Bohr magneton, and $\hbar$ is Planck's constant. The measured current is thus carried primarily by thermalized electrons, so that it is possible to distinguish the observed effect from the circular photovoltaic effect predicted in Ref. 5; that effect is due to an asymmetry of the scattering of nonthermalized electrons by a surface. We wish to emphasize that in the effect under discussion in the present letter the current flows only in a surface layer, in contrast with the bulk circular photovoltaic effect observed in gyrotropic crystals.[6]

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