"Jumps" and undamped oscillations of the polarization in a system of optically-oriented electron and nuclear spins of a semiconductor

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(Submitted June 28, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 3, 158–162 (5 August 1977)

Conditions were realized in which a system of optically oriented electrons and nuclear spins of the semiconductor has two stable states. "Jumps" and undamped oscillations of the circular polarization of the luminescence were observed. The oscillation periods were the order of seconds.

PACS numbers: 78.20.Ls, 78.55.–m

We have previously[1] predicted the possibility of "jumplike" changes of the degree ρ of the circular polarization of the luminescence of a semiconductor when the spins of the nonequilibrium electrons are optically oriented. This effect follows from the results of calculation on the basis of the model of cooling of the nuclear spin system in the field of optically oriented electrons. It is connected with the presence of two stable states of the spin orientation of the electrons and of the nuclei in a certain range of values of the external magnetic field H perpendicular to the exciting-light beam.

In crystals of the GaAs type, the value of ρ for luminescence along the z axis is numerically equal to the projection of the average $\langle S_z \rangle$ of the oriented electrons on this axis. The value of $\langle S_z \rangle$ decreases with increasing transverse magnetic field directed along x. If the nuclear spin system is cooled, a considerable

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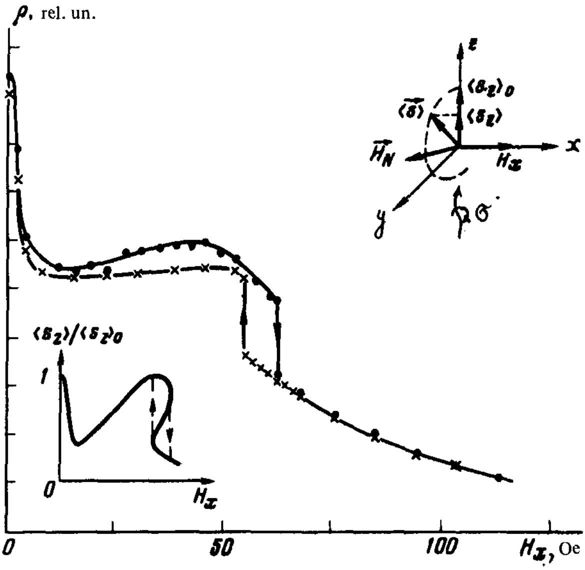

Fig. 1. Dependence of the degree ρ of the circular polarization of the luminescence on the external field H_x, perpendicular to the exciting-light beam at 77 K. The field H_x is directed along the [110] axis of the crystal p-$Al_{0.26}Ga_{0.74}As$. The exciting circularly polarized (σ) light propagates normally to the (100) plane along the z axis. In the lower left corner is shown the curve calculated from Eq. (1) subject to the condition (2). The arrows show the transitions between the two stable polarization states for oppositely directed changes of the field H_x.

orientation of the nuclei is produced in the external field H_x.[2] The electron spins are then acted upon, besides the field H_x, also by the effective nuclear field $\mathbf{H}_N$.[3,4] Since the nuclear spin temperature Θ depends on the average electron spin $\langle S\rangle$ and on the external field H_x, it follows that $\mathbf{H}_N$ is also a function of $\langle S\rangle$ and H_x. This leads to a complicated dependence of $\langle S_z\rangle$ on H_x and, under definite conditions, makes $\langle S_z\rangle$ multiply valued. Solution of the Bloch equation that describes the behavior of the average electron spin in a magnetic field, with allowance for the cooling of the spin system of the nuclei and their polarization, leads to the equation

$$(1-\chi)(1+b)^2 = ab\,\chi(1+b+\beta\chi)^2. \tag{1}$$

We have used here the dimensionless variables:

$$\chi = \langle S_z\rangle / \langle S_z\rangle_0 \quad \text{and} \quad b = H_x^2 / H_L^2 \;;$$

$\langle S_z\rangle_0$ corresponds to $\langle S_z\rangle$ at $H_x=0$, and H_L is the local field of the nuclei. The cooling of the nuclear spin system is characterized by a single parameter β. At $\beta=0$, Eq. (1) goes over into the ordinary Lorentzian. The parameter α characterizes its width at half height. In this case there is neither orientation of the nuclei nor the resultant field $\mathbf{H}_N$ acting on the electrons. The "jumps" of the luminescence polarization should be observed if the following condition is satisfied:

$$\alpha\,(\,|\,\beta\,|-1\,)>4\,. \qquad (2)$$

This condition is easiest to satisfy for crystals with a long lifetime T of the existence of the spin orientation ($\alpha \sim T^2$). In addition, it is necessary to produce sufficiently "deep" cooling (large values of β). It follows from (1) that the $\langle S_z\rangle$ (H_x) curve must include a narrow line near $H_x=0$, as well as additional maxima. These characteristic features were observed in the very first experiments.[1] Subsequent investigations have shown that by varying the orientation of the crystallographic axes relative to the external field H_x it is possible to realize the conditions necessary for the appearance of polarization "jumps." Figure 1 shows the experimental $\rho(H_x)$ dependence obtained with a $p-\mathrm{Al}_{0.26}\mathrm{Ga}_{0.74}\mathrm{As}$ crystal at 77 K. The optical orientation of the electrons was produced and observed along the z axis, perpendicular to the (100) plane. The crystal was rotated around the z axis until the [110] axis coincided with the direction of the external field H_x. The experimental curves of Fig. 1 demonstrate the dependence of the field at which the "jumps" are produced on the direction of the change of the field. The arrows marking the "jumplike" changes in the value of ρ delimit the region of the existence of two stable states of polarization. The solid line in the insert under the experimental curves is described by Eq. (1) when condition (2) is satisfied. It is seen that near the region of the "jumps" the calculated curve rises relative to the experimental curves. The height of this rise depends on the angle of rotation of the crystal around the z axis and reaches a maximum when the [100] axis coincides with the H_x direction. No "jumps" are observed in this case. The range of the angles ϕ between the [110] axis and the field H_x, within which "jumps" are observed, is ±4°. When the end of this range are approached, the heights of the "jumps" and the widths of the "hysteresis loop" decrease. Thus, although in general outline Eq. (1) provides a correct description of the behavior of $\langle S_z\rangle$ in a transverse magnetic field, it is obviously necessary to take anisotropy into account. This influence can be formally taken into account by treating the parameter β as a function of the angle ϕ. The angular dependence of $\beta(\phi)$ can reflect the dependence of the spin temperature on the orientation of the external field relative to the crystallographic axes.

Among the probable causes of this anisotropy we can point to the dependence of the nuclear spin relaxation time on the angle ϕ. The "leakage" factor, which enters as a multiplier in the quantity β, is in this case a function of ϕ. Another possible cause of the anisotropy is quadrupole interaction. In the investigated GaAlAs crystals, approximately one-quarter of the Ga atoms were replaced by Al, leading to violation of the cubic symmetry and to the onset of noticable electric-field gradients at the neighboring nuclei of the aluminum. D'yakonov and Perel' have called our attention to a possible manifestation of quadrupole effects when nuclei in solid solutions are optically oriented. The largest quadrupole moment is possessed by the ^{75}As nuclei which are closest to the aluminum. The electric field gradients are maximal in the direction of those body diagonals of the cube along which the Al—As bonds are located. NMR with all the singularities accompanying the presence of quadrupole splitting were optically observed on the ^{75}As nuclei. The resonance was detected by the change of the degree of polarization of the luminescence in the field H_x following application of a weak alternating field along the y axis. The plot of the resonance frequencies against

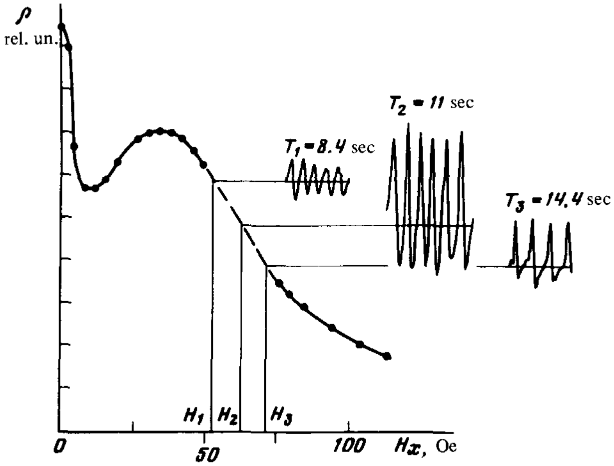

FIG. 2. Plot of $\rho(H_x)$ at 77 K. The angle between H_x and the [110] axis is 6°. The exciting-light propagation is normal to the (100) plane along the z axis. The dashed curve shows the region of existence of undamped polarization oscillations. The oscillations of ρ are shown in the same scale as the $\rho(H_x)$ plot. One can see the change in the profile and period of the oscillations for three values of the field, $H_x = 52$, 62, and 70 Oe, at an exciting light-flux intensity $\approx 5\times 10^{21}$ quanta/cm^{2}sec.

the angle ϕ has two branches corresponding to the influence of the gradients along the two pairs of the body diagonals of the cube which lie in the perpendicular planes. As a result of the influence of the quadrupole interaction, the field $\mathbf{H}_N$ can make a certain angle with the external field. Allowance for this effect results in modification of Eq. (1).

An interesting feature of the manifestation of the coupling of the oriented electron and nuclear spin systems are the undamped polarization oscillations. These oscillations are produced in the regions of the angles ϕ immediately adjacent to the region of the "jumps." The period of these oscillations depend on the intensity of the light and on the value of H_x, and are on the order of seconds (see Fig. 2). Prolonged undamped oscillations of the polarization with close values of the period were observed earlier in optical orientation of spins in analogous n-type crystals.[5] The possible cause of the experimentally observed slow oscillations of the circular polarization of the luminescence are the oscillations of the spin temperature of the nuclei. Starting from the balance equations that connect the reciprocal temperature with its time derivative, D'yakonov and Perel' have demonstrated the possible occurrence of relaxation oscillations of the spin temperature and of the electron orientation.[6] The problem was solved for the case of cooling in a magnetic field parallel to the exciting light beam. The period of the oscillations is determined by the large spin-lattice relaxation time. An analytic solution of the system of nonlinear equations that connect the average spins of the electrons and the nuclei in the case of optical orientation in a transverse magnetic field is difficult. It is probable that in this case, too, the slow oscillation of the circular polarization of the luminescence are manifestations of the oscillations of the spin temperature of the lattice nuclei. Just as in the case of a longitudinal external field, the positive "feedback" needed for the onset of oscillations is realized in the system of the electron and the nuclear spins near regions where $\langle S_z \rangle$ is multiply valued.

The authors thank B. P. Zakharchenya, M. I. D'yakonov, V. I. Perel', and I. A. Merkulov for discussions.

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