Instability of polarization in a system of electron and nuclear spins of an *n*-type semiconductor under optical orientation in weak magnetic fields

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We observed instability in a system of optically oriented electron and nuclear spins of an *n*-type semiconductor; this instability leads to the onset of oscillations of the degree of polarization ρ of the luminescence, with a period that amounts to dozens of seconds. With weak influence of the nuclei, the electron depolarization takes place in fields $H < 10$ Oe. At a strong influence of the nuclei, a line of width ≈ 0.1 Oe is observed in the $\rho(H)$ spectrum.

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Absorption of circularly polarized light in semiconductors leads to orientation of the spins of the electrons and of the nuclei. The average nuclear spin **I** depends on the average electron spin **S**. In turn, **S** is a function of **I**, as is manifest, for example, in the depolarization of the luminescence in an oblique magnetic field.[1] If a situation corresponding to the presence of "positive feedback" is realized in the experiment, then jumplike changes of polarization become possible in the system of electron nuclear spins, and in particular self-polarization.[2] It can be assumed that the relation between **S** and **I** becomes more strongly pronounced if **S** is sensitive to weak magnetic fields **H**, and the light-induced effective fields $\mathbf{H}_N$ of the nuclei at the electrons are large (large **I**). Such nuclear fields are produced, for example, in GaAs crystals and in solid solutions on its basis. The hitherto known characteristic values of the fields that depolarize the luminescnec of these crystals amounts to hundreds and thousands of oersteds, corresponding to electron spin-orientation lifetimes $T_s < 10^{-8}$ sec. All the measurements of T_s for these crystals, with the exception of[3], were made on nonequilibrium electrons in *p*-type crystals. In *n*-type crystals there is a large background due to transitions with participation of nonoriented equilibrium electrons. However, it is precisely in such crystals that one can expect an increase in the sensitivity of **S** to **H**, since the channel of spin-relaxation by equilibrium holes is excluded. Observation of NMR on the equilibrium part of the nuclear polarization under optical pumping of an *n*-GaPAs crystal in a transverse field[4] became possible apparently because of the increased T_s in *n*-type crystals. Attempts to observe an analogous effect in *p*-type crystals were not successful.

The luminescence spectrum of the *n*-GaAlAs crystals selected by us, with donor concentration $\approx 10^{16}$ cm^{-3}, is analogous to that given in[3] and includes two emission bands, *A* and *B*. Band *B* is usually ascribed to inter-impurity recombination, and band *A* is correlated with a transition in which an exciton takes part. The maxima of bands *A* and *B* correspond to energies 1.80 and 1.78 V. Figure 1 shows a plot of $\rho(H)$ (the Hanle effect) at the maximum of the band *A* excited by the circularly-polarized radiation of an He-Ne laser at 4.2 °K. The measurements were carried out by the method of two-channel counting of photons with oppositely directed angular momenta. A block diagram of the setup is given in[5]. To weaken the influence of the field $\mathbf{H}_N$, a quartz modulator operating at 30.265 kHz was placed in the excitation channel. Thus, the circular polarization of the exciting light reversed sign ($\sigma^+ \rightleftarrows \sigma^-$) at this frequency.

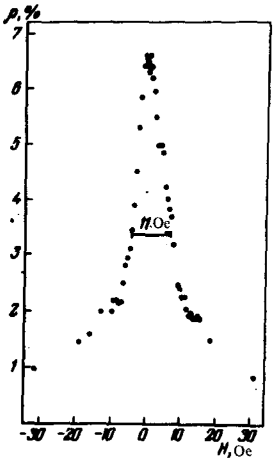

FIG. 1. Plot of $\rho(H)$ following excitation by circularly polarized light modulated at 30.265 kHz.

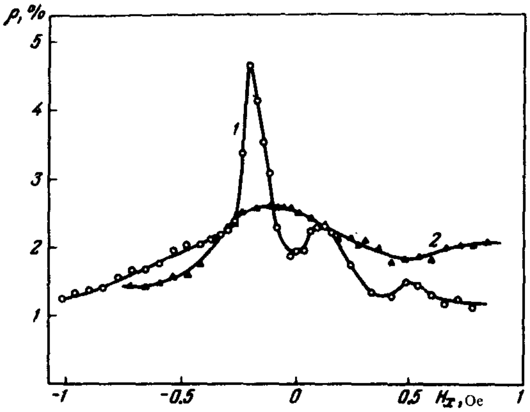

FIG. 2. Plot of $\rho(H)$ in the region of weak fields following excitation with light having a fixed sign of circular polarization. Curve 1 corresponds to optical orientation of an angle $\phi \approx 3°$ to the z axis, and curve 2 corresponds to rotation of the crystal to 5° ($\phi \approx 8°$).

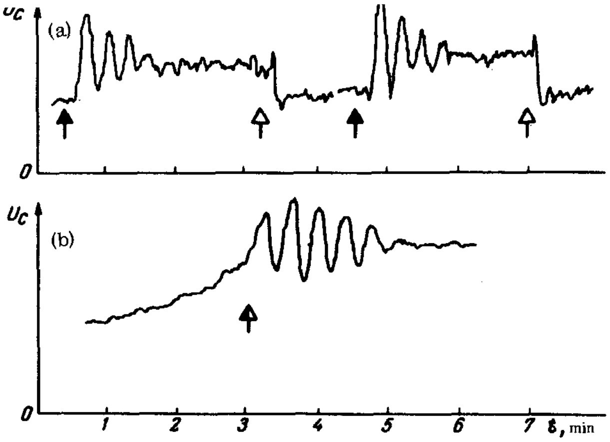

FIG. 3. Oscillations of the polarization signal U_c: a—after turning on the field $H_x = 0.1$ Oe, b—after slow passage through the section of H_x near the narrow line (see curve 1 of Fig. 2).

The angle θ between the vector **H** and the x axis was ~5°, and the optical orientation was produced along the z axis. In this case the accumulation of large nuclear polarization is difficult. As seen in Fig. 1, the half-width of the $\rho(H)$ curve amounts to several oersteds. A similar curve (with width 8.8 Oe at half-height) was obtained for the band B. In the working range of variation of the intensity, ρ increases with increasing intensity for both bands.

At constant excitation of the crystal by light with fixed circular polarization, the influence of $\mathbf{H}_N$ becomes very strong. Small changes of θ lead to considerable changes in the form of the $\rho(H)$ curve. Thus, when θ changes from 5 to 15° the half-width of the $\rho(H)$ curve decreases from 120 to ~10 Oe, and a steep front whose position depends on the direction of passage of the field **H** is observed on one side (hysteresis). Thus, the half-width of the $\rho(H)$ curve cannot be used to determine T_s directly without excluding the influence of the field H_N.

A very interesting picture is observed in the region of fields smaller than one oersted. Curve 1 in Fig. 2 corresponds to the band A at a field $H_z = 0.1$ Oe and to optical orientation along an axis inclined at an angle $\phi \approx 3°$ to z. The z axis is perpendicular to the sample surface. The polarization of the radiation along z is analyzed. The field **H** is directed along x. The earth's field is cancelled out. The width and position of the narrow line depend on the magnitude and sign of H_z, and also on the angle ϕ. No narrow line is observed when the sign of H_z is reversed and the sign of σ is unchanged. Curve 2 in Fig. 2 corresponds to rotation of the crystal and to an increase of ϕ by 5°. The function $\rho(\sigma, H_x, H_z)$ is odd with respect to the simultaneous reversal of the signs of σ, H_x, and H_z. The narrow region of the fields H_x obtained at increased values of ρ seems to correspond to "turning off" the depolarizing influence of the field $\mathbf{H}_N$. The strong mutual dependence of the electron and nuclear polarizations in the region weak fields is accompanied by the onset of instabilities. Very small changes of the magnetic field within definite regions are accompanied by prolonged oscillatory changes of the polarization. The period of the oscillations and the damping depend on the signs of σ and H_z. By way of example, Fig. 3 shows the changes of the polarization signal U_c at the output of a synchronous detector tuned to the frequency of the quartz modulator. Figure 3a illustrates the time variation of the luminescence polarization after turning on a field $H_x = 0.1$ Oe (dark arrows) and with the field turned off (light arrows). The zero level corresponds to excitation of the luminescence by linearly polarized light.

Figure 3b shows the variation of U_c in slow passage through the region of fields H_x to the left of the narrow line, corresponding to curve 1 of Fig. 2. The rate of passage was 0.15 Oe/min. When fields corresponding to the line maximum are reached, an instability arises and oscillations appear. The subsequent change of the field was then stopped. In the case corresponding to curve 2 of Fig. 3, a slow transition (lasting ~1.15 min) was observed, in the range of fields $H_x \approx 0.4$ Oe, from one stable state to the other without oscillations. Together with the relatively rapidly damped oscillations shown in Fig. 3, prolonged oscillating changes of the polarization were observed at other combinations of the fields H_x and H_z. Narrow lines were also observed on the $\rho(H)$ curves in the case of band B.

[1] M. I. D'yakonov, V. I. Perel', V. L. Berkovets, and V. I. Safarov, Zh. Eksp. Teor. Fiz. 67, 1912 (1974) [Sov. Phys.-JETP 40, No. 5 (1975)].

[2] M. I. D'yakonov and V. I. Perel', ZhETF Pis. Red. 16, 563 (1972) [JETP Lett. 16, 398 (1972)].

[3] A. I. Ekimov and V. I. Safarov, ZhETF Pis. Red. 12, 293 (1970); 13, 251 (1971) [JETP Lett. 12, 198 (1970); 13, 177 (1971)].

[4] B. P. Zakharchenya, M. E. Kompan, and V. G. Fleĭsher, ZhETF Pis. Red. 19, 734 (1974) [JETP Lett. 19, 378 (1974)].

[5] V. L. Vekua, R. I. Dzhioev, B. P. Zakharchenya, E. L. Ivchenko, and V. G. Fleĭsher, Fiz. Tverd. Tela 17, 1096 (1975) [Sov. Phys.-Solid State 17, No. 4 (1975).