Optical effects due to polarization of nuclei in semiconductors

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It is shown that the appreciable polarization of the lattice nuclei, which is produced by optical orientation of the electron spins in semiconductors, can strongly affect the depolarization of recombination radiation under conditions of the incomplete Hanle effect. This influence is due to action of the effective magnetic field of the polarized nuclei on the electron spin. In the investigated GaAs and $Ga_{0.7}Al_{0.3}As$ crystals, the nuclear field was as high as 3 kG. The method suggested here for observing nuclear polarization permits the use of optical means to investigate nuclear relaxation processes and to detect magnetic resonance in semiconductors.

1. INTRODUCTION

In earlier studies[1,2] we investigated the optical orientation in a system of electrons and lattice nuclei in semiconductors. It was shown that the spin-oriented electrons produced by circularly-polarized light, becoming localized on donor centers, give rise to a strong dynamic polarization of the nuclei of the crystal lattice proper. The polarized nuclei in turn, owing to the hyperfine interaction, produce a strong effective magnetic field that acts on the electron spin. This field can be of the order of 10 kG and can manifest itself in a number of effects in semiconductors.

In our earlier work[1,2] we investigated experimentally and theoretically one of the possibilities of the optical manifestation of such a nuclear field in weakly doped crystals, in which the rate of spin relaxation of localized electrons is strongly dependent on the intensity of the external longitudinal (relative to the electron-spin orientation) magnetic field. The magnetic field of the nuclei produced upon optical orientation, depending on its sign, either weakened or enhanced the action of the external field and by the same token influenced the rate of spin relaxation, and accordingly the degree of stationary orientation of the electrons. On the other hand, the degree of electron orientation and its changes can be easily detected optically, by determining the polarization of the recombination luminescence[3-5]. It was thus possible[1,6] to register nuclear polarization and its variation (in particular in NMR) by an optical method[1)].

In this paper we present the results of an investigation of a more general phenomenon, due to the nuclear field, which appears independently of the mechanism of the photoelectron spin relaxation.

The effective magnetic field of polarized nuclei acts on the electron spin in the same manner as an external magnetic field. It should therefore be manifest in all the spin effects that are sensitive to the magnetic field. The most universal of these effects is depolarization of the electron spin in a transverse magnetic field (the Hanle effect). In the usual geometry of observation of the Hanle effect, however, when the external field is perpendicular to the direction of the spin orientation of the electrons, polarization of the nuclei turns out to be practically impossible. Indeed, the electron transfers its orientation to the nuclei, and the external magnetic field, by flipping the nuclear spins, depolarizes the nuclei. Inasmuch as the depolarizing field is as a rule much weaker for nuclei than for electrons, the nuclei turn out to be fully depolarized even in a field too weak to effect the degree of orientation of the electrons.

This, however, will not take place if the angle between the external magnetic field and the orienting light beam differs from 90°. In this case the magnetic field will not destroy completely the nuclear polarization produced by the electrons, since the field influences only the transverse component of the spin, and the projection of the nuclear spin on the field direction remains the same. This gives rise to a nuclear field directed parallel or antiparallel to the external field and taking part in the depolarization of the electrons.

Thus, nuclear polarization is produced by the longitudinal components (relative to the external field) of the electron spin. The nuclear field produced thereby either helps or hinders the annihilation of a transverse component of the electron spin by the external field.

The present paper is devoted to an experimental and theoretical investigation of this phenomenon.

It should be noted that the dynamic polarization of the lattice nuclei (on the order of 10^{-4}%) by optically oriented electrons was observed earlier, as an independent phenomenon, by Lampel in silicon[8] and by Mayer et al. in anthracene[9]. The main feature of the phenomena investigated in the present paper (and also in[1,2,6]) is the strong reaction of the nuclear polarization of the electrons. This is what makes it possible to observe pronounced optical effects connected with ordering of nuclear spins[2)]. The nuclear field in our experiments reached several kilogauss.

2. THEORY

In an oblique magnetic field H, the stationary value S_z of the average electron spin projection on the excitation direction is given by

$$S_z(H)=S(0)\left[\frac{\sin^2\theta}{1+(g\mu_0 H\tau/\hbar)^2}+\cos^2\theta\right], \qquad (1)$$

where θ is the angle between the field and the orienting light beam (the z axis), S(0) is the stationary value of the average spin of the electrons in the absence of a magnetic field (directed along the beam), μ_0 is the Bohr magneton, g is the g factor of the electron, and τ is the time of vanishing of the electron orientation of the as a result of their recombination and spin relaxation. Formula (1) describes the incomplete Hanle effect, in which the electron-spin component transverse to H

decreases with increasing field in the usual manner, while the longitudinal component does not depend on the magnetic field. The $S_z(H)$ dependence determined by this formula is shown dashed in Fig. 1. This formula does not take into account the possible dependence of the electron-spin relaxation time on the magnetic field. Effects connected with this dependence were investigated in[1,2].

The magnetic field H acting on the electron spin consists of an external field H_0 and the effective magnetic field H_N of the polarized nuclei. The hyperfine interaction tends to polarize the nuclei along the direction of the average electron spin S. However, the nuclear-spin component that is transverse with respect to the external field H_0 is destroyed by this field and practically vanishes at $\mu_N H_0 T_2/\hbar \gg 1$ (μ_N is the magnetic moment of the nucleus and T_2 is the transverse time of the nuclear-spin relaxation). As applied to the conditions of our experiments, we assume that

$$\mu_N T_2 \ll \mu_0 g \tau. \qquad (2)$$

The nuclear-spin component transverse to H_0 vanishes already at so small an external field, which does not yet effect the electron polarization. As is well known[11], $T_2^{-1} \sim \mu_N H_L/\hbar$, where H_L is the characteristic local field due to the dipole-dipole interaction of the nucleon. Thus, with the exception of the region of small weak fields, $H_0 \lesssim H_L$, it can be assumed that H_0 and H_N are collinear

$$H = H_0 + H_N, \qquad (3)$$

In this case H_0 and H_N can have either equal or opposite signs.

Figure 1 shows the dependence of S_z on the external field H_0, which follows from formulas (1) and (3), under the condition that H_N does not depend on H_0 (solid line). The Hanle curve turns out to be simply shifted, so that the maximum orientation corresponds to the value $H_0 = -H_N$ at which the total field is H = 0. The assumption that H_N is independent of H_0 can be justified at $H_0 > H_L$. In fact, in this case the nuclei are polarized by the longitudinal component (relative to H_0) of the average electron spin S_H, which does not depend on the magnetic field: $S_H = S(0)\cos\theta$. The effective nuclear field H_N is proportional to S_H[2]:

$$H_N = bS(0)\cos\theta, \quad b = 4(3\mu_0 g)^{-1} \sum_\alpha A_\alpha I_\alpha (I_\alpha + 1) \frac{T_1}{T_1 + T_{1e}}, \qquad (4)$$

where I_α and A_α are the spin and the constant of the hyperfine interaction of the nucleus of sort α, the summation is over all the nuclei in the unit cell, T_{1e} is the time of polarization of the nuclei by the oriented electrons, and T_1 is the longitudinal nuclear-relaxation time. The quantity b could depend on H_0 via the leakage factor $T_1/(T_1 + T_{1e})$. However, if $T_{1e}/T_1 \ll 1$, there is no such dependence, and (4) yields then the limiting value of the nuclear field compatible with the given value of S_H.[3)]

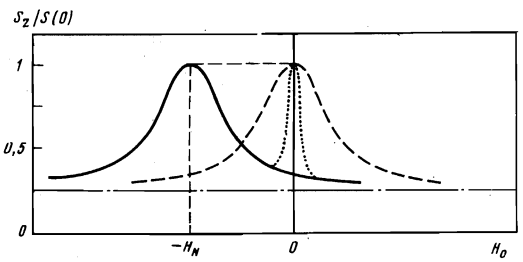

FIG. 1. Depolorization of electrons by an external magnetic field in the incomplete Hanle effect ($\theta = 60°$). The dashed line is constructed in accordance with formula (1) at $H = H_0$ (there is no nuclear field). The solid line was constructed from formulas (1) and (3), at H_N = const. The influence of the nuclear field is manifest in a leftward shift of the curve. The dashed line shows schematically the peaks expected in weak fields ($H_0 \lesssim H_L$) because the nuclear field in this region decreases abruptly.

The assumption that H_N is constant is certainly incorrect in weak fields $H_0 < H_L$, where the longitudinal time of the spin relaxation of the nuclei is greatly decreased and approaches the time T_2 of the transverse relaxation. In weak external fields, as a rule, the nuclear field is therefore small and is not collinear with H_0. We can thus expect the electron orientation to have a sharp maximum near $H_0 = 0$. This maximum is shown in Fig. 1 by the dotted line.

The experimental data presented in the next section are in qualitatively good agreement with the simple theory developed above. Experiment indicates definitely, however, that the nuclear field H_N does not remain unchanged when the external field is increased. The possible reasons are discussed below.

3. EXPERIMENTAL RESULTS

The investigations were performed on epitaxial p-type $Ga_{1-x}Al_xAs$ and GaAs layers doped with S and Ge to concentrations 10^{18}—10^{19} cm^{-3}. In the case of GaAs we investigated also samples that were deliberately compensated by a tellurium impurity.

The spin-oriented nonequilibrium electrons were produced by excitation with an He-Ne laser ($\lambda = 0.63\ \mu$). The degree of nuclear orientation was measured optically, by determining the polarization of the recombination luminescence. According to the selection rules for the interband transitions in III-V compounds, the degree of polarization of the luminescence $P = |(J_+ - J_-)/(J_+ + J_-)|$ (where $J_\pm$ is the intensity of the luminescence with right- and left-circular polarization) is equal in magnitude to the projection of the average spin of the oriented electrons on the observation direction $P \equiv S_z$[12].

The experimental setup was analogous to that previously employed[1], but the circular polarization of the luminescence was effected not with a rotating $\lambda/4$ plate but with a photoelastic modulator[13,14] operating at 47 kHz. The luminescence was observed from the same crystal surface on which the exciting light was incident, in such a way that the angle between the exciting light beam and the observation direction was close to 0°.

The external magnetic field of intensity up to 4 kG could be oriented at any angle relative to the exciting-light beam. In all the investigated crystals, at longitudinal orientation of the magnetic field in the employed field intensity region, we observed either no increase or a weak increase (10—20%) of the electron orientation.

A. $Ga_{1-x}Al_xAs$. Incomplete Hanle Effect

The composition of the investigated solid solutions ($x \approx 0.3$) was chosen such that the width of the forbidden band of the crystal was somewhat smaller than the quantum energy of the He-Ne laser exciting light (1.96 eV). All the investigations were carried out at 4.2°K. At this temperature we observed in the spectrum of all the investigated crystals only one luminescence band,

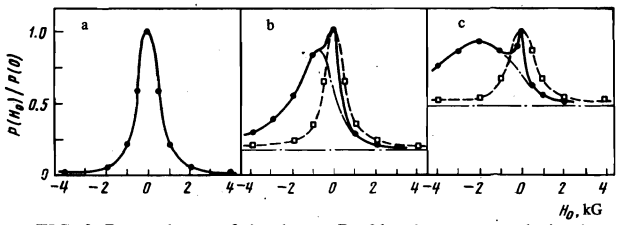

FIG. 2. Dependence of the degree P of luminescence polarization on the external magnetic field intensity. Crystal $Ga_{0.7}Al_{0.3}As$; $N_{Zn} \approx 9 \times 10^{18}$ cm^{-3}; T = 4.2° K. a) $\theta = 90°$, b) $\theta = 63°$, c) $\theta = 45°$. The black circles correspond to excitation of $\sigma+$ circularly polarized light, and the squares to excitation with light of alternating polarization (the polarization of the light was modulated between $\sigma+$ and σ^- at a frequency 47 kHz). The dashed line is a plot of formula (1) at $H = H_0$, and the parameters P(0) and τ were determined from curve a.

due to the transitions to the acceptor level. The degree of polarization of the luminescence was 8—10% and varied somewhat from sample to sample. The half-width of the Hanle line, depending on the doping level, fluctuated in the interval 500—800 G.

Figure 2 shows plots of the degree of luminescence polarization P on the external magnetic field intensity H_0 for several values of the angle between the direction of the magnetic field and the exciting light beam. As seen from the curve at $\theta = 90°$ the usual Hanle curve is observed: with increasing $|H_0|$ the polarization decreases to zero value and is approximated by a Lorentz curve. The maximum of the $P(H_0)$ curve is located at $H_0 = 0$. For other cases in Fig. 2 ($\theta \neq 90°$), the usual Hanle curve, recalculated for the given value of $\cos^2\theta$ from measurements at $\theta = 90°$, is shown by the dashed line. We see that at $\theta \neq 90°$ experiment yields entirely different dependences of the degree of stationary polarization in the magnetic field (solid line). If we discard the singularity at $H_0 = 0$, then we can assume that the Hanle line broadens and shifts, so that the polarization maximum is no longer at $H_0 = 0$.

These experimental data agree with the theory developed above (cf. Figs. 1, 2b, and 2c) and allow us to assume that the observed shift of the Hanle line is due to the strong magnetic field produced by the nuclei polarized as a result of the interaction with the oriented electrons produced by the light. The observed curves correspond to the Hanle effect in the summary field $H = H_0 + H_N$. The line shift is determined, naturally, by the absolute value of the nuclear field; the position of the maximum of the shifted line corresponds to the condition $H_0 = -H_N$ ($H = 0$). According to (4), H_N is proportional to $\cos\theta$. Accordingly, experiment reveals, with decreasing angle θ, a shift of the maximum of the $P(H_0)$ curve towards larger values of $|H_0|$ (cf. Figs. 2b and 2c).

The sign of H_N depends on the direction of the predominant polarization of the nuclei and is determined by the direction of the orientation of the electron spins. On the curves of Fig. 2, the Hanle line shifts towards negative values of H_0, which obviously corresponds to the case of positive H_N. The change of the circular polarization of the exciting light changes the orientation of the photoelectron spins, and accordingly a change takes place in the direction of the polarization of the nuclei and in the sign of the nuclear field. In the experiment, the direction of the Hanle-line shift (towards positive or negative H_0) was reversed when the sign of the circular polarization of the exciting light was reversed.

Many facts confirm that the observed shift of the Hanle line is indeed due to the action of the field of polarized nuclei. Thus, when the magnetic field is rapidly turned on ($\theta \neq 90°$), a stationary value of the luminescence polarization is established not instantaneously but after a certain time, on the order of one minute. Therefore, if the excitation is produced with light having alternating polarization, then the nuclear system will not manage to follow the rapidly alternating electron orientation produced by the light. In this case the nuclear polarization should be equal to zero and $H_N = 0$. The squares in Fig. 2 denote the obtained dependence of $P(H_0)$ following excitation by light whose polarization was modulated between σ^+ and σ^- at a frequency 47 kHz. A photoelastic modulator was placed in this case in the exciting-light beam, and the alternating intensity of the luminescence in the σ^+ and σ^- polarization was detected. We see that the values of $P(H_0)$ obtained by this method fit well the usual Hanle curve (dashed line) corresponding to the case $H = H_0$, i.e., $H_N = 0$.

Figure 3 shows, for constant excitation with definite polarization, the directly observed transient processes in the establishment of the stationary value of the polarization luminescent signal ($J_+ - J_-$), which is proportional to P, following rapid application of an external magnetic field. The experimental conditions (the values of the angle and the polarization of the exciting light) were chosen to be the same as in Fig. 2c. In the interpretation of the observed transient processes it must be recognized that, according to formula (1) the degree of luminescence polarization under the conditions of the Hanle effect depends only on the absolute value of the summary field, and decreases with increasing $|H|$.

When a certain field H_0 is rapidly applied to a system with zero field in which all the nuclei are not polarized, we have at the first instant $H = H_0$. The subsequent change of the luminescence polarization is due to establishment of stationary polarization of the nuclei. Since the sign of the nuclear field is positive in all these experiments (it is determined by the choice of the exciting-light polarization), the observed effects are different for external fields with different signs. At positive H_0 the nuclear field is added to the external field, so that the net field increases and the luminescence polarization decreases as the nuclei become polarized after turning on the external field (Fig. 3a). At negative H_0, to the contrary, the nuclear field is subtracted from the external field, the value of the net field $|H|$ decreases, and an increase in the lumination polarization is observed after the external field is turned on (Figs. 3b and 3c). Interesting phenomena are observed in the region of small negative values of the external field, when $|H_0| H_N$, i.e., when the external field is smaller in magnitude and opposite in sign to the

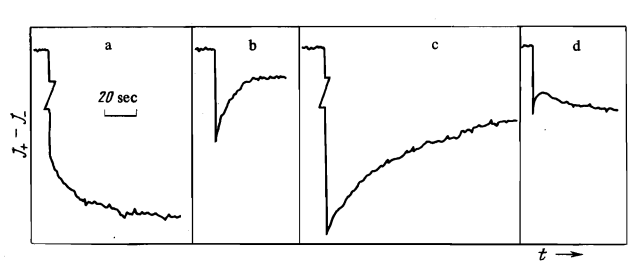

FIG. 3. Establishment of the stationary polarization luminescence signal ($J_+ - J_-$) following application of an external field [$\theta = 45°$ a) $H_0 = +1$ kG, b) - 2 kG, c) - 4 kG, d) - 0.75 kG.

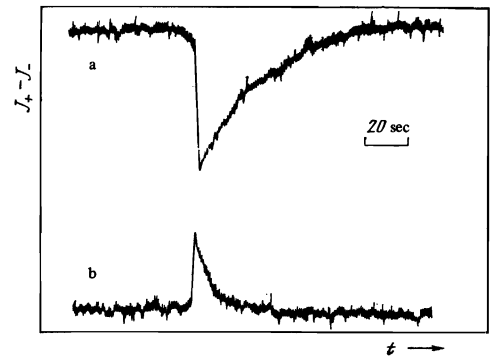

FIG. 4. Variation of polarization luminescence signal in adiabatic passage of resonances of all nuclei of the $Ga_{0.7}Al_{0.3}As$ crystal lattice; $\theta = 63°$. a) $H_0 = -1$ kG, b) + 1 kG.

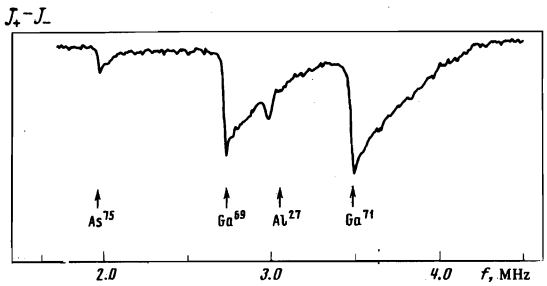

FIG. 5. NMR spectrum of $Ga_{0.7}Al_{0.3}As$ crystal, determined from the change of the luminescence polarization. $H_0 = -2.7$ kG, $\theta = 45°$.

produced nuclear field. In this case, the net field goes through zero during the transient process and reverses sign. On the other hand, the absolute value of H first decreases from $|H_0|$ to zero, and then increases again to $H_N - |H_0|$. The transient process in the luminescence (Fig. 3d) reflects this nonmonotonic variation of $|H|$.

Convincing proof of the nuclear nature of the field H_N, which causes the observed effect, is the observed change in the polarization of the luminescence under the influence of the radio-frequency field under conditions of nuclear magnetic resonance on the nuclei of the crystal lattice proper. The strongest change in the nuclear polarization is reached in adiabatic fast passage of the resonance, which reverses the nuclear magnetization, i.e., reverses the sign of the nuclear field[11]. Fig. 4 shows the observed changes of the signal ($J_+ - J_-$) with such a passage through the resonances (the RF field frequency was scanned). The sharp spike corresponds to passage of all the lattice nuclei through resonance, followed by relaxation of the nuclear magnetization to a stationary value. The character of the variation of the luminescence polarization (the decrease or increase of P) was different in external fields of different signs and was determined by the change in the absolute value of the net field following reversal of the nuclear magnetization. In these experiments, the nuclear field was first positive (the experimental conditions were the same as for Fig. 2c). Therefore at $H_0 > 0$ the reversal of the sign of H_0 from positive to negative as a result of passage through resonance caused a decrease of the net field, as against an increase for $H_0 < 0$.

Such a sensitivity of the degree of electron orientation to changes of the nuclear magnetization makes it possible to detect optically, by means of the luminescence polarization, nuclear magnetic resonance at nuclei of the crystal lattice proper. Figure 5 shows the optically recorded NMR spectrum for all nuclei of the proper lattice of the investigated $Ga_{0.7}Al_{0.3}As$ crystals. The spikes correspond to the adiabatic fast passage through resonance, and are followed by relaxation of the magnetization to the stationary value.

The duration of the transient in the stationary nuclear magnetization is determined by the time of the longitudinal relaxation (T_{1e}) of the nuclei as a result of interaction with the oriented electrons. This relaxation turns out to depend strongly on the external field intensity[2], and as seen from Figs. 3b and 3c the time T_{1e} increases from 9 to 40 sec when H_0 is increased from 2 to 4 kG. The nuclear magnetization produced by the photoelectrons was preserved for a long time after the exciting light was turned off (approximately five minutes at $H_0 \geq 2$ kG). This time obviously characterizes the time of longitudinal nuclear relaxation in the absence of electrons produced by the light.

B. Dependence of the Nuclear Field on the External Field

The theoretical plot of $P(H_0)$ in the presence of nuclear polarization is shown in Fig. 1 for the case $H_N = \text{const}$. Such a constant nuclear field, independent of H_0, causes only a shift of the Hanle line, without changing its shape or the area under the curve. However, as seen from Fig. 2, the shifted Hanle lines observed experimentally under stationary conditions are significantly broader and their areas also exceed that of the usual Hanle line. In addition, the width of the maximum at $H_0 = 0$ greatly exceeds the local field ($H_L \sim 10$ G). These facts can be explained by assuming that the field H_N produced upon polarization is not the same for all values of the external field.

This assumption can be verified experimentally; namely, if H_N is constant and does not depend on H_0, then an abrupt change of the external field should cause immediate establishment of a stationary polarization. It is seen from Fig. 6, however, than when the field is changed (even at large values of H_0) a transient, is observed, and the stationary polarization is not established immediately. This obviously indicates that the stationary value of H_N is different in an external field of different intensity and the observed transient characterizes the change of the nuclear field H_{N1}, which adds up with the external field H_0, to a new stationary value H_{N2} in the field H_{02}.

These transients can be used to reconstruct the Hanle line shape corresponding to the nuclear field H_{N1}. Indeed, in an external field H_{01} the net field acting on the electron spin is $H_{01} + H_{N1}$. After switching H_0, the nuclear field does not change immediately, and at the first instant the luminescence polarization assumes the value corresponding to the net field $H = H_{02} + H_{N1}$.

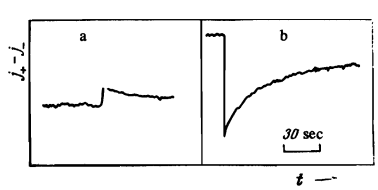

FIG. 6. Change of luminescence polarization following a rapid change of the external field. Crystal $Ga_{0.7}Al_{0.3}As$, $N_{Zn} \approx 2 \times 10^{18}$ cm^{-3}, $\theta = 45°$. The external field was switched over from - 1.0 to - 1.5 kG (a) and from - 2.0 to - 3 kG (b).

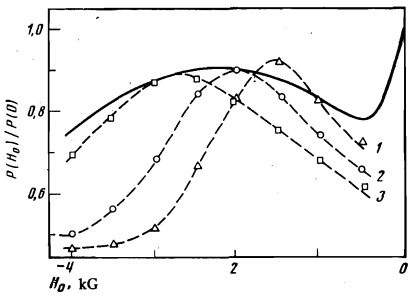

FIG. 7. Dependence of the degree P of luminescence polarization on the external field H_0. Crystal $Ga_{0.7}Al_{0.3}As$, $N_{Zn} \approx 2 \times 10^{18}$ cm^{-3}, $\theta = 45°$. The solid line corresponds to stationary polarization. The dashed lines correspond to the values of P′ (see the text); preliminary ionization of the nuclei was effected in a field H_{01} = 1 kG (1), - 2 kG (2), and - 3 kG (3).

If we perform this switching after polarizing the nuclei in the field H_{01}, vary the value of the final field H_{02}, and record each time the values of P′ after the switching, then the set of these values of P′ will yield the function $P(H_0 + H_{N1})$, i.e., the Hanle line shifted by an amount H_{N1}. Figure 7 shows the nonstationary Hanle line obtained in this manner following polarization of the nuclei in external fields with different intensities. We can conclude from these curves that, first, the nuclear polarization and the field H_N are not constant and increase with increasing external field, and second, that the nuclear field seems to be inhomogeneous in the crystal, thus causing a certain broadening of the Hanle line and a lowering of its maximum.

As noted in Sec. 2, the nuclear field H_N can depend on the value of the external magnetic field H_0 only via the leakage factor, i.e., via the dependence of the nuclear relaxation times T_1 and T_{1e} on the external magnetic field. It was observed experimentally, however, that the nuclear relaxation time following optical excitation and in darkness differ greatly, $T_{1\,dark} \gg T_{1e}$ (see Sec. 3A). Thus, the leakage factor $T_1/(T_1 + T_{1e})$ should have been close to unity and therefore independent of the magnetic field. This suggests that in the presence of illumination the time T_1, which determines the leakage of the nuclear polarization, does not equal the time measured in darkness. Illumination seems to produce additional nuclear-relaxation channels, which cause a significant decrease of the time T_1, so that in light the leakage factor is less than unity and depends on the external magnetic field.

This additional nuclear relaxation can be realized by means of nonequilibrium long-lived paramagnetic centers produced by optical excitation of the crystal. The possibility of formation of such long-lived paramagnetic centers by illuminating the crystal is well known, and was experimentally investigated in a number of semiconducting compounds[15].

C. GaAs. Influence of Compensation

The effects due to the production of a nuclear field were observed by us also in GaAs crystals, likewise excited with an He-Ne laser. In GaAs, however, the He-Ne laser radiation ($\hbar\nu$ = 1.96 eV) produces already transitions from the light and heavy hole bands, as well as from the valence sub-band that is split off by the spin-orbit interaction. The electrons excited by circularly polarized light from different valence sub-bands have opposite spin orientations, and the resultant degree of orientation of the electrons excited in this manner turns out to be much less than following excitation near the absorption edge[5,12,16,17]. We have therefore observed in the investigated GaAs crystals, with impurity concentration 10^{18}—10^{19} cm^{-3}, very small values of the average spin of the oriented electrons, 0.01, as against the value 0.08—0.10 in $Ga_{0.7}Al_{0.3}As$ crystals having the same impurity concentration, where the excitation was effected near the absorption edge.

Since the nuclear magnetization resulting from the interaction with the oriented electrons is proportional to the degree of orientation of the electrons, one should expect in GaAs a weaker manifestation of the effects due to the nuclear field. Indeed, in uncompensated crystals with impurity concentration $N_{Zn} \sim 10^{18}$—10^{19} cm^{-3}, we were unable to observe any manifestation of the nuclear field. At the same time, in deliberately compensated samples, we observed very strong effects due to the nuclear field. The optical properties of such compensated crystals were investigated in[18,19]. It was shown that the formation of the "tails" of the density of states in the forbidden band with increasing crystal concentration causes a strong shift of the luminescence band (from 1.48 all the way to 1.37 eV), and an appreciable increase in the electron lifetime.

Figure 8 shows a plot of $P(H_0)$ for a crystal with $N_{Zn} \approx 2 \times 10^{18}$ cm^{-1}, which is strongly compensated (the emission band lies in the region of 1.42 eV, corresponding to $N_D/N_A \sim 0.5$[19]). We see that in this crystal, at an average electron spin S = 0.008, the nuclear-field effect was the same, if not larger, than in the uncompensated $Ga_{0.7}Al_{0.3}As$ with a close value of the acceptor concentration, in which the electron orientation was higher by one order of magnitude, S = 0.08 (cf. Figs. 8a and 2b). Similar effects were observed also for crystals doped with Ge to concentration 6×10^{18} cm^{-3} and compensated with Te. For strongly compensated samples, certain effects became manifest also at 77°K (Fig. 8b), something that could not be observed in uncompensated samples of mixed crystals.

Such a patent dependence on the compensation is apparently determined by the conditions for the localization of the nonequilibrium photoelectron, since it is precisely the localized electrons which cause the effective polarization of the nuclei[2]. In the case of p-type crystals, the free electrons produced by the light can be localized only if the crystal contains, simultaneously with the acceptor impurities, also donor impurities, i.e., if the crystal is compensated. In the case of strongly doped and compensated materials, the electron is captured not by an oscillated donor center, but in a potential "well": the presence of randomly distributed ionized impurities produces in the compensated crystal fluctuations of the electrostatic potential, and it is the minima of this potential that the nonequilibrium electron can become localized.

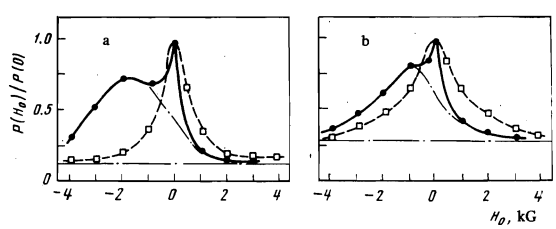

FIG. 8. Dependence of the degree of luminescence polarization P on the external magnetic field in the case of the incomplete Hanle effects in crystals GaAs, $N_{Zn} \approx 2 \cdot 10^{18}$ cm^{-3}, $N_D/N_A \approx 0{,}5$; a) T=4,2 K, b) T=77 K

Even without specially introducing donor impurities, p-GaAs is always slightly compensated. However, at such a low compensation level there exist only electrostatic-potential fluctuations that are shallow in dimension and in magnitude. The electron is therefore weakly localized in the shallow potential wells and can readily tunnel or hop over from one well to another. In the case of strong compensation, the widths and depths of the "wells" increase abruptly (up to several dozen meV), causing now a strong localization of the electron[20]. This is accompanied by a shift of the maximum of the luminescence band towards lower energies and by an increase in the lifetime of the nonequilibrium electron[18,19]. It is precisely in such strongly doped samples that the conditions are produced for effective polarization of the nuclei and for a clear cut manifestation of the nuclear field. At sufficiently strong compensation, the depth of the potential "wells" is such that the electron still remains localized even at 77°K, and this has made it possible to polarize the nuclei at this temperature.

In the investigated compensated crystals, we have also registered optically nuclear magnetic resonance and observed the transient process involved in the establishment of stationary nuclear magnetization.

4. CONCLUSION

The results of the present paper, together with the results of our earlier work[1,2] show that in the case of optical orientation of the electrons in semiconductors there is produced an appreciable polarization of the nuclei of the principal lattice, which produces a strong reaction on the orientation of the electrons and by the same token on the luminescence polarization. This influence reduces to the action of an effective magnetic field of the polarized nuclei on the electron spins. A free electron or an electron localized in a shallow impurity center interacts in the crystal with a temendous number of nuclei of the principal lattice. Therefore the action of all these nuclei on the electron spin averages out and turns out to be equivalent to the macroscopic magnetic field. This leads to a significant difference between the phenomena investigated here and the effects produced in optical pumping of gas atoms or deep impurity centers in crystals.

[1)]Optical observation of NMR was realized recently on F centers in alkali-halide crystals [7].

[2)]This makes possible in principle optical observation of self-polarization of nuclei, which was predicted earlier [10]. This effect has not yet been observed.

[3)]The linear connection between H_N and S_0, given by formula (4), is actually valid only at sufficiently small values of S_H [2] ($S_H < 0.2$). This was always satisfied in our experiments.

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