Depolarization of hot photoluminescence of gallium arsenide crystals in a magnetic field. Determination of the energy relaxation times of hot electrons

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Oscillations due to successive emission of *LO* phonons by hot electrons were observed in the hot photoluminescence spectrum of gallium arsenide. The luminescence was polarized because of the orientation of the electron momentum. The application of a magnetic field caused depolarization of the hot photoluminescence and this was due to rotation of the electron momentum. An analysis of the experimental results yielded the time constant of the process of emission of an *LO* phonon by an electron τ_{p_0} and of the intervalley (Γ–L) transition time $\tau_{\Gamma-L}$. For an electron energy of $\varepsilon = 0.3$ eV the phonon emission time τ_{p_0} was 1×10^{-13} sec. The value of $\tau_{\Gamma-L}$ for $\varepsilon = 0.38$ eV was 2.5×10^{-13} sec, corresponding to the intervalley scattering interaction constant of 0.8×10^{9} eV/cm.

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§1. INTRODUCTION

Linear polarization of the hot photoluminescence of GaAs-type semiconductors was detected and investigated by Zemskiĭ *et al.*[1] This linear polarization is due to an anisotropic distribution (orientation) of the photoelectron momenta.[2] For example, excitation from the heavy-hole band creates electrons whose momenta are oriented mainly at right-angles to the electric vector of the exciting light. Such orientation is governed by the selection rules for interband transitions and it results, because of the same rules, in linear polarization of the recombination radiation. A sufficiently strong external magnetic field can rotate the anisotropic part of the electron momentum distribution function because of the cyclotron motion of electrons and this can be detected from the change in the polarization characteristics of the hot photoluminescence.[3,4] An effect of this kind has been observed in fields of ≈60 kG for a sample of p-type GaAs with an acceptor concentration of 1.2×10^{18} cm^{-3} (Ref. 3). An investigation of this effect makes it possible to determine directly the very short electron energy relaxation times. In particular, a time constant of $\tau = 0.5\times10^{-13}$ sec has been obtained[3] and attributed mainly to the impact ionization of acceptors by hot electrons.

We investigated in detail the change in the polarization characteristics of the hot photoluminescence in magnetic fields as a function of crystallographic orientation and we determined the characteristic time constants of the various energy relaxation mechanisms (more specifically, the time constants of the impact ionization of acceptors mentioned above, as well as of the emission of optical phonons and of intervalley transitions). In the samples with a low carrier density the dominant relaxation mechanism is the one associated with the emission of *LO* phonons, which was investigated by us most thoroughly. The experimental method is described in §2. The influence of corrugations of the valence band on the nature of the changes in the polarization characteristics of the luminescence are discussed in §3 for the (100) and (111) orientations. A theoretical analysis of the influence of magnetic fields on the polarization characteristics of the luminescence in the case of multistage transitions (for example, in the case of successive emission of long-wavelength optical phonons by electrons) is given in §4. Finally, §5 presents the results of a determination of the depolarization of the hot luminescence of heavily and moderately doped p-type GaAs crystals and of the energy relaxation times of hot electrons.

§2. MEASUREMENT METHOD

We investigated p-type GaAs single crystals doped with Zn and Cd acceptors whose concentrations were in the range $10^{17}-3\times10^{18}$ cm^{-3}. Measurements of the Hall effect at 300 and 77 °K in accordance with a method described in Ref. 5 were used to determine the acceptor concentration N_A and the compensating donor concentration N_D. These values, together with the difference $N_A - N_D$, are all listed in Table I.

The luminescence was excited by linearly polarized radiation generated by He–Ne ($\hbar\omega_{exc} = 1.96$ eV) and Kr^+ ($\hbar\omega_{exc} = 1.83$ and 1.65 eV) lasers. The spectral and polarization measurements were carried out using DFS-24 and DFS-42 double monochromators. A two-channel photon-counting system made it possible to determine the luminescence intensity normalized to the intensity of the exciting light.

A study of depolarization of the hot photoluminescence was made in the Faraday geometry (with the magnetic field parallel to the exciting light beam) using fields up to 70 kG. The magnetic field was generated in a superconducting solenoid whose internal aperture had a diameter of 20 mm. The cryostat shown in Fig. 1 was employed. A crystal 1 was located in a solenoid cavity 3. The exciting light was incident normally on the surface of a sample and the luminescence was collected by a spherical mirror 2. The maximum deviation of the luminescence rays collected by this mirror from the normal to the surface of the sample was about 20°. This deviation did not exceed 6° inside the crystal, as

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TABLE I. Properties of Samples

Sample No.	Type of acceptor	Plane	N_A (cm^{-3})	N_D (cm^{-3})	$N_A - N_D$ (cm^{-3})
631	Zn	(111)	$1.4 \cdot 10^{17}$	$0.5 \cdot 10^{17}$	$0.9 \cdot 10^{17}$
426	Cd	(111)	$5.0 \cdot 10^{17}$	$1.3 \cdot 10^{17}$	$3.7 \cdot 10^{17}$
100	Zn	(100)	–	–	$1.0 \cdot 10^{18}$
427	Zn	(111)	$1.9 \cdot 10^{18}$	$0.7 \cdot 10^{18}$	$1.2 \cdot 10^{18}$
667	Zn	(111)	$3.2 \cdot 10^{18}$	$1.8 \cdot 10^{18}$	$1.4 \cdot 10^{18}$

deduced from the refractive index of GaAs. The crystal was exposed either to helium vapor (when its temperature was about 30 °K) or to liquid helium which was continuously pumped ($T = 1.6$ °K). Since the scattered-light intensity was considerably less in the former case, in most measurements the crystal was exposed to helium vapor. Control experiments showed that the hot luminescence spectrum and the dependence of the degree of polarization on the magnetic field were the same in both cases (helium vapor and liquid). The Rayleigh scattering background was minimized also by cutoff and interference filters.

The application of a magnetic field to GaAs-type crystals caused splitting of the quadruply degenerate acceptor state. At sufficiently low temperatures and in sufficiently strong fields this should result in a strong circular polarization of the luminescence and in distortion of the dependence of the linear polarization on the magnetic field of interest to us. The experimental results indicated a much weaker circular polarization. This was due to the fact that the scatter of the acceptor levels in the doped crystals exceeded the splitting of these levels in a magnetic field. The circular polarization of the hot photoluminescence of the samples with $N_A \sim 10^{18}$ cm^{-3} amounted to a few percent (in fields of ~40 kG) but it increased to 8–10% for samples with $N_A \sim 10^{17}$ cm^{-3}. In the latter case the samples were heated to a temperature at which the degree of the circular polarization did not exceed 4–5%. Such heating had practically no influence on the spectrum and linear polarization of the hot photoluminescence.

§3. STOKES PARAMETERS IN A MAGNETIC FIELD. EFFECTS OF CORRUGATIONS

The luminescence polarization can be described, as is known,[6] by three Stokes parameters: ξ_1, ξ_2, and ξ_3. The parameters ξ_1 and ξ_3 represent the linear polarization and ξ_2 is the degree of the circular polarization. We shall consider these parameters in a rectangular coordinate system $\mathbf{e}_1$, $\mathbf{e}_2$, and $\mathbf{e}_3$, where $\mathbf{e}_1$ coincides with the linear polarization vector of the exciting light $\mathbf{e}$, whereas $\mathbf{e}_3$ is parallel to the luminescence beam which in our case is practically parallel to the exciting beam. Then, $\xi_3 = l\cos 2\psi$ and $\xi_1 = l\sin 2\psi$, where l is the maximum linear polarization and ψ is the angle between the direction of this polarization and $\mathbf{e}_1$. The parameter ξ_3 is identical with the degree of polarization $\xi_3 = (I_\parallel - I_\perp)/(I_\parallel + I_\perp)$, where $I_\parallel$ and $I_\perp$ are the intensities of the luminescence polarized, respectively, parallel or perpendicular to the polarization of the exciting light. The parameter ξ_1 represents the degree of polarization defined by $(I_{\pi/4} - I_{-\pi/4})/(I_{\pi/4} + I_{-\pi/4})$, where $I_{\pm\pi/4}$ are the intensities of the luminescence polarized at the indicated angles relative to the polarization of the exciting light. As pointed out above, in our case the parameter ξ_2 does not exceed 0.04–0.05 and its influence can be ignored.

At the temperatures used in our investigation the luminescence spectrum is formed as a result of the conduction band–acceptor transitions. It has been shown[7] that the corrugations of the constant-energy surfaces of the valence band can give rise to a strong dependence of the degree of the linear polarization of the hot luminescence on the orientation of the polarization vector of the exciting light relative to the crystallographic axes. This is due to the fact that the wave function of a hole at an acceptor is composed, in the case of large values of the quasimomentum, mainly of the wave functions of the heavy-hole subband and it is strongly anisotropic, so that the main contribution comes from holes with the "diagonal" directions of the quasimomentum (⟨111⟩ directions).

Calculated diagrams of the dependence of the parameter ξ_3 on the orientation of the polarization vector of the exciting light $\mathbf{e}$ relative to the crystallographic axes are plotted in Fig. 2 for the cases when the exciting beam is perpendicular to the (100) plane (a) and to the (111) plane (b); the data are taken from Ref. 8. In the former (a) case the maximum polarization corresponds to $\mathbf{e} \parallel [011]$. The minimum polarization (equal to zero) corresponds to $\mathbf{e} \parallel [001]$, when—in spite of the anisotropy of the photoelectron distribution functions—all four diagonal directions in the momentum space are equally populated. In the latter case (b) the degree of polarization is isotropic and it is independent of the direction of the vector $\mathbf{e}$.

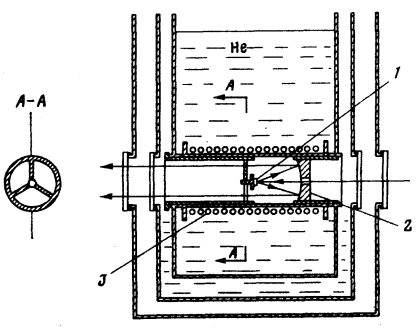

FIG. 1. Helium cryostat with a superconducting solenoid. A sample 1 and a spherical mirror 2 are exposed to helium vapor inside a solenoid 3. The beam path is indicated by arrows. $T = 1.6$°K.

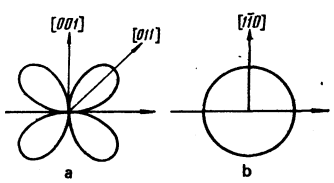

FIG. 2. Theoretical indicatrix of the degree of the linear polarization (Stokes parameter ξ_3) plotted as a function of the orientation of the electric vector of the exciting light relative to the crystallogrpahic axes[8]: a) (100) plane; b) (111) plane.

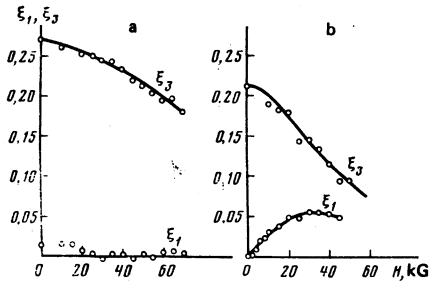

FIG. 3. Dependences of the Stokes parameters ξ_3 and ξ_1 on the magnetic field: a) sample No. 100, (100) plane; b) sample No. 631, (111) plane.

Rotation of the photoelectron momenta by a magnetic field in the case *a* leaves the vector of the maximum linear polarization directed along the [011] axis. Figure 3(a) shows the results of measurements of the Stokes parameters for the case a, when the polarization vector of the exciting light is directed along the [011] axis. The measurements were carried out using He–Ne laser radiation at the high-frequency edge of the luminescence spectrum (1.88 eV). The results indicated that whereas ξ_3 decreased in a magnetic field, the parameter ξ_1 remained practically zero. This indicated the absence of rotation of the maximum polarization vector, in agreement with the theoretical predictions.[4] In the case b we obtained the results shown in Fig. 3(b). In this case there was a reduction in ξ_3 and an increase in ξ_1. Rotation of the photoelectron momenta in a magnetic field in this experimental geometry resulted in rotation of the plane of polarization of the emitted luminescence.

The measurements (described below in §5) were carried out on samples whose surfaces were parallel to the (111) plane. As indicated above, the orientation of the electric vector of the exciting light was unimportant.

§4. DEPOLARIZATION OF THE LUMINESCENCE IN A MAGNETIC FIELD IN THE CASE OF MULTISTAGE TRANSITIONS

We shall consider the influence of a magnetic field on the distribution function of photoelectrons. We shall assume that the only relaxation mechanism is the emission of longitudinal optical phonons by electrons. In this case the electron energy distribution function is in the form of a series of discrete peaks representing electrons which have not emitted even one phonon (first peak), those which have emitted one phonon (second peak), two phonons (third peak), etc. We shall denote the distribution function of the directions of the electron momenta $\mathbf{p}$ corresponding to the n-th peak by $f_n(\mathbf{p})$. Then, we can define $f_n(\mathbf{p})$ by means of the transport equation

$$\omega_c \frac{\partial}{\partial \varphi} f_n(\mathbf{p}) + \frac{1}{\tau_n} f_n(\mathbf{p}) = \mathcal{F}_n(p, \vartheta, \varphi), \tag{1}$$

where $\omega_c = |e|H/mc$ represents the cyclotron frequency; ϑ and φ are the spherical angles of the vector $\mathbf{p}$ in a coordinate system in which the z axis is the direction of the magnetic field vector; τ_n is the time needed for the emission of an optical phonon by an electron corresponding to the peak whose number is n; $\mathcal{F}_n (n \neq 1)$ represents the arrival of an electron to the n-th peak from the $(n-1)$-th peak as a result of emission of an optical phonon; $\mathcal{F}_1$ represents the arrival of an electron in the first peak as a result of optical pumping. Then, for $n \neq 1$, we have

$$\mathcal{F}_n(\mathbf{p}) = \int W(\mathbf{p}', \mathbf{p}) f_{n-1}(\mathbf{p}') \frac{d^3p'}{(2\pi\hbar)^3}. \tag{2}$$

Here, $W(\mathbf{p}', \mathbf{p})$ is the probability of a transition (per unit time) of an electron from a state with a momentum $\mathbf{p}'$ to a state with a momentum $\mathbf{p}$, accompanied by the emission of a longitudinal optical phonon.

The solution of Eq. (1) is

$$f_n(p, \vartheta, \varphi) = \int_0^\infty e^{-t/\tau_n} \mathcal{F}_n(p, \vartheta, \varphi - \omega_c t)\, dt. \tag{3}$$

Expressing $\mathcal{F}_n$ in the form of an expansion in terms of spherical functions

$$\mathcal{F}_n(p, \vartheta, \varphi) = \sum_{lm} \mathcal{F}_{lm}^{(n)} Y_{lm}(\vartheta, \varphi), \tag{4}$$

we find from Eq. (3) that

$$f_n(p, \vartheta, \varphi) = \sum_{lm} f_{lm}^{(n)}(p) Y_{lm}(\vartheta, \varphi), \tag{5}$$

where

$$f_{lm}^{(n)}(p) = \frac{\tau_n}{1 + im\omega_c\tau_n} \mathcal{F}_{lm}^{(n)}(p). \tag{6}$$

The formulas (2) and (6) represent a recurrence relationship between the distribution function for the n-th peak and the distribution function for the $(n-1)$-th peak. The distribution function for the first peak is governed by the optical pumping $\mathcal{F}_1(\mathbf{p})$:

$$f_{lm}^{(1)}(p) = \frac{\tau_1}{1 + im\omega_c\tau_1} \mathcal{F}_{lm}^{(1)}(p). \tag{7}$$

The coefficients in the expansion $\mathcal{F}_{lm}^{(1)}(p)$ are independent of the magnetic field if we ignore the quantization of states by the field. Therefore, Eq. (7) can be rewritten in the form

$$f_{lm}^{(1)}(p) = \frac{1}{1 + im\omega_c\tau_1} [f_{lm}^{(1)}(p)]_{H=0}. \tag{8}$$

Applying successively the recurrence relationships given by Eqs. (6) and (2), we obtain expressions linking the distribution functions of the various peaks in the presence of a magnetic field and in its absence:

$$f_{lm}^{(n)}(p) = \prod_{k=1}^{n} \frac{1}{1 + im\omega_c\tau_k} [f_{lm}^{(n)}(p)]_{H=0}. \tag{9}$$

It should be noted that the electron lifetime τ_k corresponding to the k-th peak generally depends on the electron energy ε_k in this peak.

The intensity of the recombination radiation with the polarization $\mathbf{e}_1$ is related to the distribution function as follows[2]:

$$I(\mathbf{e}_1) \sim \int [1 + \alpha_0 (3(\mathbf{e}_1\boldsymbol{\nu})^2 - 1)/2] f(\mathbf{p})\, d\Omega. \tag{10}$$

Here, $\boldsymbol{\nu}$ is a unit vector along $\mathbf{p}$ and $\alpha_0 = \pm 1$ applies to transitions from the light- and heavy-hole bands, re-

spectively. If the distribution function is written down in the form of Eq. (5), the intensity of the n-th peak with the polarization $\mathbf{e}_1$ is given by

$$I_n(\mathbf{e}_1) \propto (4\pi)^{1/2} f_{00}^{(n)} + \alpha_0 \frac{4\pi}{5} \sum_m Y_{2m}(\mathbf{e}_1) f_{2m}^{(n)}. \tag{11}$$

Equation (11) allows us to relate the Stokes parameters of the recombination radiation to the coefficients $f_{2m}^{(n)}$.

We shall now consider the case when the exciting beam, luminescence beam, and magnetic field are all parallel. Then, the parameter ξ_3 representing the degree of the linear polarization of the luminescence in terms of the $\mathbf{e}_1$ and $\mathbf{e}_2$ axes introduced in §3 is

$$\xi_3 = \left(\frac{3}{40}\right)^{1/2} \alpha_0 [f_{22}^{(n)} + f_{2,-2}^{(n)}] \Big/ \left[f_{00}^{(n)} - \frac{\alpha_0}{2\sqrt{5}} f_{20}^{(n)} \right]. \tag{12}$$

The parameter ξ_1 representing the degree of polarization in a system of axes rotated by 45° about the luminescence beam relative to the initial system $\mathbf{e}_1$, $\mathbf{e}_2$ is then

$$\xi_1 = i \left(\frac{3}{40}\right)^{1/2} \alpha_0 (f_{22}^{(n)} - f_{2,-2}^{(n)}) \Big/ \left[f_{00}^{(n)} - \frac{\alpha_0}{2\sqrt{5}} f_{20}^{(n)} \right]. \tag{13}$$

If linearly polarized light is used to excite the luminescence, we find that[2]

$$\mathcal{F}_1(\mathbf{p}) = F_0(p)\,[1+\alpha(3(\mathbf{ev})^2-1)/2]; \quad \alpha = \alpha_0.$$

The distribution functions of all the peaks have the same form (differing only in respect of the anisotropy parameter α) in the absence of a magnetic field. Then, in the selected coordinate system, we have

$$[f_{22}^{(n)}]_{H=0} = [f_{2,-2}^{(n)}]_{H=0}, \tag{14}$$

where the coefficients are real. This is a consequence of the symmetry of the distribution function relative to the $\mathbf{e}_2$, $\mathbf{e}_3$ plane. The relationship (14) makes it possible to express the Stokes parameters in terms of their values in zero magnetic field and this can be done with the aid of Eqs. (9), (12), and (3):

$$\left.\begin{aligned} \xi_3^{(n)} &= [\xi_3^{(n)}]_{H=0} \operatorname{Re} \prod_{k=1}^{n} \frac{1}{1+2i\omega_c\tau_k}, \\ \xi_1^{(n)} &= -[\xi_3^{(n)}]_{H=0} \operatorname{Im} \prod_{k=1}^{n} \frac{1}{1+2i\omega_c\tau_k}, \end{aligned}\right\} \tag{15}$$

where, according to Ref. 2,

$$[\xi_3^{(n)}]_{H=0} = 3\alpha_0\alpha_n/(20+\alpha_0\alpha_n),$$

and α_n is the anisotropy parameter of the distribution function for the n-th peak in zero magnetic field.

For the first three peaks the formulas of Eq. (15) give

$$\left.\begin{aligned} \xi_3^{(1)} &= \frac{1}{1+4\omega_c^2\tau_1^2} [\xi_3^{(1)}]_{H=0}, \\ \xi_3^{(2)} &= \frac{1-4\omega_c^2\tau_1\tau_2}{(1+4\omega_c^2\tau_1^2)(1+4\omega_c^2\tau_2^2)} [\xi_3^{(2)}]_{H=0}, \\ \xi_3^{(3)} &= \frac{1-4\omega_c^2(\tau_1\tau_2+\tau_1\tau_3+\tau_2\tau_3)}{(1+4\omega_c^2\tau_1^2)(1+4\omega_c^2\tau_2^2)(1+4\omega_c^2\tau_3^2)} [\xi_3^{(3)}]_{H=0}. \end{aligned}\right\} \tag{16}$$

Similar formulas describe also the Hanle curves in the case of multistage transitions in atoms.[9] It should be noted that the formulas in Eqs. (15) and (16) remain valid if phonon emission is accompanied by other processes resulting in the transfer of electrons out of the n-th peak (such transfer may be due to, for example, intervalley transitions). Then, the quantity τ_n should be regarded as the effective loss time allowing for all such processes.

The polarization characteristics of the luminescence given above are derived in the approximation of a spherical model of the valence band. However, in reality (because of corrugations of the valence band) the photoelectron distribution is not characterized by spherical but by cubic harmonics.[8] We shall ignore the scatter of the electron energies at the moment of photoexcitation (i.e., we shall ignore the anisotropy of the reduced masses of electrons and heavy holes). Then, using the electron momentum distribution [Eq. (2) in Ref. 8] and assuming that only the "diagonal" holes contribute to the luminescence, we can substitute $n=1$ in Eq. (3) and obtain the expressions for the Stokes parameters of the recombination radiation near the short-wavelength edge subject to allowance for the valence-band corrugations. If the magnetic field is then directed along the [111] crystallographic axis, the expressions for the Stokes parameters in the Faraday geometry are

$$\left.\begin{aligned} \xi_3^{(1)}(H) &= \left[\frac{4}{9}(B-D) + \frac{4}{9}\frac{\gamma_3}{\gamma_2}(2B+D)\right] \Big/ \left[\frac{19}{2} - \frac{5}{6}\frac{\gamma_3}{\gamma_2}A\right], \\ \xi_1^{(1)}(H) &= \left[\frac{4}{9}(C+E) + \frac{4}{9}\frac{\gamma_3}{\gamma_2}(2C-E)\right] \Big/ \left[\frac{19}{2} - \frac{5}{6}\frac{\gamma_3}{\gamma_2}A\right]. \end{aligned}\right\} \tag{17}$$

In the formulas (17) the quantities γ_3 and γ_2 are the Luttinger parameters,[10] whereas the quantities A, B, C, D, and E are given by the expressions

$$A = \int_0^\infty \frac{1}{g} e^{-x}\,dx, \quad B = \int_0^\infty \frac{1}{g} \cos(2\omega_c\tau_1 x) e^{-x}\,dx,$$

$$C = \int_0^\infty \frac{1}{g} e^{-x} \sin(2\omega_c\tau_1 x)\,dx, \quad D = \int_0^\infty \frac{1}{g} e^{-x} \cos(\omega_c\tau_1 x)\,dx,$$

$$E = \int_0^\infty \frac{1}{g} e^{-x} \sin(\omega_c\tau_1 x)\,dx,$$

$$g = \left[1+\gamma\left(\frac{49}{81} + \frac{32}{81}\cos(3\omega_c\tau_1 x)\right)\right]^{1/2}, \quad \gamma = \frac{\gamma_3^2-\gamma_2^2}{\gamma_2^2}.$$

The dependence $\xi_3^{(1)}(H)$ in Fig. 4 represents the re-

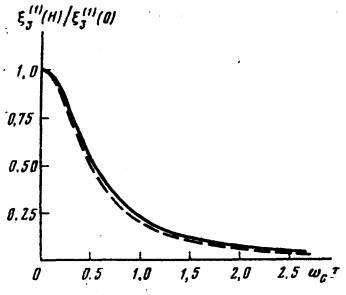

FIG. 4. Dependences of the Stokes parameter $\xi_3^{(1)}$ on $\omega_c\tau$. The dashed curve is the Lorentzian profile represented by Eq. (16) for $\xi_3^{(1)}$, whereas the continuous curve is calculated using Eq. (17).

sults of calculations based on Eq. (17) and it is compared there with the simple Lorentzian profile represented by Eq. (16) for $\xi_3^{(1)}$. We can see that allowance for the valence-band corrugations has practically no effect on the luminescence depolarization curve in the selected geometry. Therefore, we shall analyze the experimental results using Eqs. (15) and (16).

§5. EXPERIMENTAL RESULTS. DETERMINATION OF THE ENERGY RELAXATION TIMES

The luminescence depolarization in a magnetic field was studied for p-type GaAs samples with different acceptor concentrations (Table I). The experimental results for the high-frequency edge of the luminescence spectrum could be described well by Eq. (16) for $\xi_3^{(1)}$, which was also used to determine the electron lifetime τ_1 at the point of creation. The cyclotron frequency occurring in Eq. (16) was calculated allowing for the conduction band nonparabolicity. The cyclotron mass $m(\varepsilon)$ was deduced from the approximate formula for a Kane band[11]

$$m(\varepsilon)=m(0)\,(1+2\varepsilon/E_g)$$

assuming that $m(0)=0.067m_0$ and $E_g=1.52$ eV. In particular, in the case of excitation with He–Ne laser radiation ($\hbar\omega_{exc}=1.96$ eV) the energy of electrons at the moment of creation was $\varepsilon_0=0.38$ eV and their mass was $m=0.1m_0$.

The results of a determination of τ_1 for four samples as a function of the concentration of uncompensated acceptors N_A-N_D are presented in Fig. 5. They can be approximated by a straight line of the $\tau_1^{-1}=\tau_0^{-1}+C(N_A-N_D)$ type. The slope of the straight line gave $C=(0.9\pm0.3)\times10^{-6}$ cm^3/sec. Clearly, in the samples with high acceptor concentrations the main energy relaxation mechanism was the process of collisions of electrons with neutral acceptors accompanied by the excitation or ionization of the latter. A theoretical estimate of the total excitation and ionization cross section σ of neutral hydrogen-like atoms by fast electrons[12] for a medium with the permittivity of GaAs ($\approx$13) gave $\sigma v\approx0.5\times10^{-6}$ cm^3/sec for $v=10^8$ cm/sec. This was in satisfactory agreement with the above value of C. Extrapolation of the straight line in Fig. 5 to zero acceptor concentration gave $1/\tau_0=1.4\times10^{13}$ sec^{-1}.

We expected that at low impurity concentrations the main processes responsible for the energy relaxation of electrons would be the emission of long-wavelength LO phonons by the electrons accompanied by intervalley scattering (see below).[1)] In fact, for $N_A-N_D<5\times10^{17}$ cm^{-3} we found oscillations in the hot photoluminescence spectrum. Figure 6 shows the hot photoluminescence spectra of sample No. 631 obtained using excitation energies 1.96, 1.83, and 1.65 eV. We can see that the separation between the maxima in the spectra is 37 meV, which agrees with the energy of long-wavelength LO phonons in GaAs. We shall postulate that the first high-frequency maximum in each of the spectra I, II, and III (Fig. 6) is due to transitions to the acceptor levels of electrons excited from the heavy-hole band, which have not experienced energy relaxation. The second and third maxima correspond to the recombination of electrons which have emitted successively one and two optical phonons (the transition scheme is shown in the inset in Fig. 6). The rise of the intensity and the series of maxima in the spectra I and II are due to the participation in the recombination process also of the electrons excited from the light-hole subband. The widths of the maxima in the spectra is governed by a number of factors, in particular, by the scatter of the energies of the final states representing the acceptor levels and by the broadening of the initial electron energy distribution because of the valence-band corrugations. The broadening due to the last factor should decrease on reduction in the excitation energy, as found experimentally. The oscillations in the hot photoluminescence spectra are very pronounced for $N_A\sim3\times10^{17}$ cm^{-3} and their amplitude is not affected by a further reduction in N_A. It follows that the emission of phonons is the main electron energy relaxation mechanism at these acceptor concentrations.

In the series of maxima 1–2–3 in the spectrum I (Fig. 6) the linear polarization in the absence of a magnetic field decreases at each step by a factor of about 1.5, which is close to the theoretical result (1.6) obtained in Ref. 2 for the loss of polarization as a result of

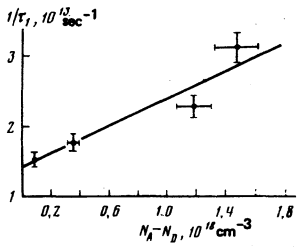

FIG. 5. Dependence of τ_1^{-1} on the concentration of uncompensated acceptors.

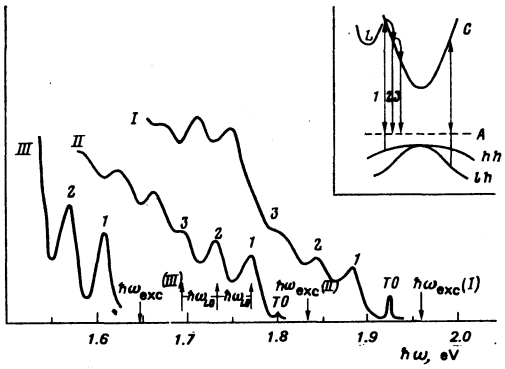

FIG. 6. Hot photoluminescence spectra obtained for different excitation energies: I) 1.96 eV; II) 1.833 eV; III) 1.648 eV. T = 30°K, sample No. 631. The excitation lines are identified by arrows. The peaks denoted by TO correspond to the Raman scattering of light on TO phonons (the scattering by LO phonons is forbidded in the experimental geometry employed here). The inset shows the transition scheme. The maxima 1, 2, and 3 in the spectrum correspond to the excitation from the heavy-hole subband (hh) and the recombination at the acceptor levels (A) of electrons arriving from the point of creation and to the recombination after the emission of one and two phonons, respectively.

emission of an optical phonon by an electron in GaAs whose energy is about 0.40 eV. We investigated the dependence of the Stokes parameter ξ_3 on the magnetic field at the frequencies of the first, second, and third maxima in the spectrum I of Fig. 6 (the luminescence was excited with He–Ne laser radiation). The results are plotted in Fig. 7 together with the approximating curves calculated using the formulas in Eq. (16). These curves correspond to the following times: $\tau_1 = 0.7\times10^{-13}$ sec, $\tau_2 = 0.8\times10^{-13}$ sec, $\tau_3 = 1\times10^{-13}$ sec. The value of τ_1 corresponds to the electron lifetime at the point of creation with an energy $\varepsilon_0 \approx 0.38$ eV, the value of τ_2 corresponds to the lifetime at the point $\varepsilon_0 - \hbar\omega_{LO}$, and τ_3 corresponds to the lifetime at the point $\varepsilon_0 - 2\hbar\omega_{LO} \approx 0.31$ eV.

We shall show later that the difference between τ_1 and τ_3 is probably due to the role of the intervalley transitions. It is known that the conduction band of GaAs has the central Γ minimum as well as side minima at the points L and X of the Brillouin zone. According to the current ideas,[13] the lowest of these are the L minima (valleys) located at $\Delta E_{\Gamma L} \approx 0.31$ eV above the central minimum.[14] In the case of excitation of the luminescence by He–Ne laser radiation, the electrons at the point of creation have the energy $\varepsilon_0 = 0.38$ eV, i.e., they are above the bottom of the L valleys. Consequently, they may be scattered from the point of creation or remain inside the central minimum, $\Gamma \to \Gamma$, or they may undergo transitions to one of the L valleys emitting at the same time an "intervalley" phonon with $q \sim \pi/a$. Thus, the probability of the scattering of an electron from the point of its creation can be represented by

$$\tau_1^{-1} = \tau_{p_0}^{-1} + \tau_{\Gamma\to L}^{-1}, \qquad (18)$$

where $\tau_{p_0}^{-1}$ is the probability of emission of a long-wavelength optical phonon and $\tau_{\Gamma\to L}^{-1}$ is the probability of the scattering to the L valleys accompanied by the emission of a short-wavelength phonon.

The contributions of both electron scattering mechanisms were determined by finding the electron lifetime at the point of creation after excitation with $\hbar\omega_{exc} = 1.83$ eV photons, when the initial energy was $\varepsilon_0 = 0.26$ eV. This energy was less than $\Delta E_{\Gamma L}$ and, therefore, the scattering to the L valley was no longer possible. The dependence of ξ on the magnetic field for $\hbar\omega_{exc} = 1.83$ eV is shown in Fig. 8 together with a similar curve for $\hbar\omega_{exc} = 1.96$ eV. The times deduced from these curves are $(0.7\pm0.05)\times10^{-13}$ sec for $\varepsilon_0 = 0.38$ eV and $(1.0\pm0.05)\times10^{-13}$ sec for $\varepsilon_0 = 0.26$ eV. We shall identify the time $\tau_1 = 1.0\times10^{-13}$ sec with the time representing the process of scattering of electrons accompanied by the emission of a long-wavelength optical phonon, i.e., we shall identify it with τ_{p_0}. The value of τ_{p_0} can be compared with the calculated result. In the case of GaAs the parabolic approximation applied at $T = 0$°K for $\varepsilon = 0.3$ eV yields $\tau_{p_0} = 2\times10^{-13}$ sec (Ref. 15). Allowance for the conduction band nonparabolicity reduces somewhat (by 15–20%) the value of τ_{p_0} (Refs. 16 and 17).

Using $\tau_{p_0} = 1\times10^{-13}$ sec, we can determine the intervalley transition time for $\varepsilon_0 = 0.38$ eV by the application of Eq. (18). This gives $\tau_{\Gamma\to L} = (2.5\pm0.8)\times10^{-13}$ sec. We can assume that $\tau_{\Gamma\to L}^{-1} = B\sqrt{\varepsilon'}$, where ε' is the energy of the final state of an electron measured from the bottom of the L valley ($\varepsilon' = \varepsilon_0 - \Delta E_{\Gamma L} - \hbar\omega_{\Gamma L}$, where $\hbar\omega_{\Gamma L}$ is the energy of an intervalley phonon). Then, for $\hbar\omega_{\Gamma L} \approx 0.03$ eV, we obtain $B = 2\times10^{13}$ sec$^{-1}\cdot$eV$^{-1/2}$. This corresponds to the interaction constant for the scattering from the valley Γ to the valley L amounting to $D_{\Gamma L} = 0.8\times10^9$ eV/cm. The valley in question was calculated using the formula[15,16]

$$B = D_{\Gamma L}^2 m_L^{3/2}/\sqrt{2}\pi\hbar^3\rho\omega_{\Gamma L},$$

where ρ is the density of the investigated crystal (5.37 g/cm^3) and $m_L = 0.56m_0$ is the density-of-states mass in the L valley.[13]

Our results showed that an investigation of the hot photoluminescence of semiconductors yielded directly the energy relaxation times of hot electrons under intravalley and intervalley scattering conditions.

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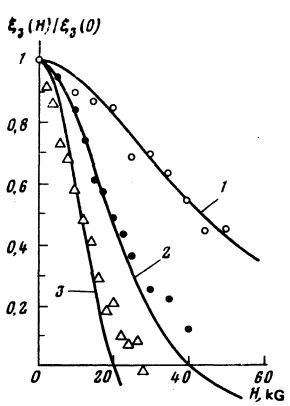

FIG. 7. Depolarization of the hot photoluminescence in a magnetic field: curves 1–3 correspond to measurements at the maxima 1–3 in spectrum I of Fig. 6 ($\hbar\omega_{exc} = 1.96$ eV). The points are the experimental results. The continuous curves represent approximation of the experimental results by means of Eq. (16).

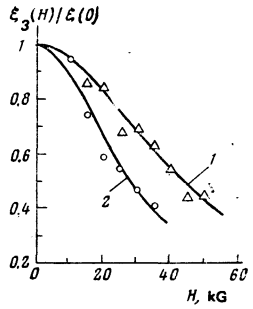

FIG. 8. Depolarization of the hot photoluminescence in a magnetic field for excitation energies of 1.96 eV(1) and 1.83 eV (2). The measurements were carried out at the maximum denoted by 1 in the spectra I and II in Fig. 6. Sample No. 63.

[1)]The contribution of the scattering by acoustic phonons can be justifiably neglected. Under our experimental conditions (low electron density) the electron—electron collisions also make a negligible contribution to the energy relaxation process (this is confirmed by separate estimates).

[1]V. I. Zemskiĭ, B. P. Zakharchenya, and D. N. Mirlin, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 96 (1976) [JETP Lett. **24**, 82 (1976)]; B. P. Zakharchenya, V. I. Zemskiĭ, and D. N. Mirlin, Fiz. Tverd. Tela (Leningrad) **19**, 1725 (1977) [Sov. Phys. Solid State **19**, 1006 (1977)].

[2]V. D. Dymnikov, M. I. D'yakonov, and V. I. Perel', Zh. Eksp. Teor. Fiz. **71**, 2373 (1976) [Sov. Phys. JETP **44**, 1252 (1976)].

[3]D. N. Mirlin, L. P. Nikitin, I. I. Reshina, and V. P. Sapega, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 419 [JETP Lett. **30**, 392 (1979)].

[4]V. D. Dymnikov, Zh. Eksp. Teor. Fiz. **77**, 1107 (1979) [Sov. Phys. JETP **50**, 559 (1979)].

[5]Sh. M. Gasanli, O. V. Emel'yanenko, V. K. Ergakov, F. P. Kesamanly, T. S. Lagunova, and D. N. Nasledov, Fiz. Tekh. Poluprovodn. **5**, 1888 (1971) [Sov. Phys. Semicond. **5**, 1641 (1972)].

[6]L. D. Landau and E. M. Lifshitz, Teoriya polya, Nauka, Moscow, 1967, p. 160 (The Classical Theory of Fields, 3rd ed., Pergamon Press, Oxford, 1971).

[7]V. D. Dymnikov, D. N. Mirlin, V. I. Perel', and I. I. Reshina, Fiz. Tverd. Tela (Leningrad) **20**, 2165 (1978) [Sov. Phys. Solid State **20**, 1250 (1978)].

[8]V. D. Dymnikov, Fiz. Tekh. Poluprovodn. **11**, 1478 (1977) [Sov. Phys. Semicond. **11**, 868 (1977)].

[9]M. P. Chaĭka, Interferentsiya vyrozhdennykh atomnykh sostoyaniĭ (Interference Between Degenerate Atomic States), Leningrad State University, 1975.

[10]J. M. Luttinger, Phys. Rev. **102**, 1030 (1956).

[11]I. M. Tsidil'kovskiĭ, Zonnaya struktura poluprovodnikov (Band Structure of Semiconductors), Nauka, Moscow, 1978, §4.3.

[12]L. D. Landau and E. M. Lifshitz, Kvantovaya mekhanika: nerelyativistskaya teoriya, Fizmatgiz, Moscow, 1963 (Quantum Mechanics: Non-Relativistic Theory, 2nd ed., Pergamon Press, Oxford, 1965), §145.

[13]D. E. Aspnes, Phys. Rev. B **14**, 5331 (1976).

[14]D. N. Mirlin, I. Ya. Karlik, L. P. Nikitin, I. I. Reshina, and V. F. Sapega, Pis'ma Zh. Eksp. Teor. Fiz. **32**, 34 (1980) [JETP Lett. **32**, 31 (1980)].

[15]E. M. Conwell, High Field Transport in Semiconductors, Suppl. 9 to Solid State Phys., Academic Press, New York, 1967 (Russ. Transl., Mir, Moscow, 1970, p. 218).

[16]E. M. Conwell and M. O. Vassell, Phys. Rev. **166**, 797 (1968).

[17]W. Fawcett, A. D. Boardman, and S. Swain, J. Phys. Chem. Solids, **31**, 1963 (1970).

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