Determination of the inter-band transition time in the valence band of gallium arsenide

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The lifetime τ_0 of holes in a spin-detached band in n-type gallium arsenide crystal (1.4×10^{18} cm^{-3}) is directly determined from luminescence depolarization in a transverse magnetic field. The measured value (1.3×10^{-13} sec) is determined by processes of transition between the spin-detached band and the band of light holes and is close to the calculated value of the relaxation time for such a transition with emission of an optical phonon.

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The intensity of a luminescence band arising in gallium arsenide crystals during transition between the conduction band Γ_6 and a sub-band of the valence band Γ_7, detached due to spin-orbital interaction, is 4–5 orders less than the intensity of the

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band for E_g[1] (Fig. 1 shows a diagram of the band structure and designations). Because the probabilities of excitation of electrons from sub-bands Γ_7 and Γ_8 are identical in terms of the order of the value, such a large difference in the intensities is related to the difference in the lifetimes of the holes in the degenerate band Γ_8 and the spin-detached band Γ_7. In the latter case, the lifetime is apparently determined by the transitions $\Gamma_7 - \Gamma_8$, which proceed with sufficiently high probability (Fig. 1). A high ($\sim$0.9) degree of circular polarization of luminescence was observed in the $E_g + \Delta$ band ($\Gamma_6 - \Gamma_7$ transitions) due to the short lifetime of holes in the detached band in experiments on optical orientation conducted in Ref. 1. Holes produced close to the edge of band Γ_7 do not succeed in losing the initial spin orientation, which can be produced during excitation by circularly-polarized light, during their lifetime. In other words, the lifetime of nonequilibrium holes τ_0 in band Γ_7 is distinctly less than the time of their spin relaxation τ_s.

This article presents preliminary results on the direct determination of life time τ_0. The effect of depolarization of luminescence in a transverse magnetic field during excitation by circularly-polarized light (the Hanle effect) was used to determine τ_0. Measurements were conducted in fields of up to 80 kG produced in a superconducting solenoid. The temperature of the sample was $\sim$2 K. Luminescence was excited by a He-Ne laser (1.96 eV). The energy of the holes produced in band Γ_7 was approximately 30 MeV.

Figure 2 shows the dependence of the degree of circular polarization of luminescence on the magnetic field for a sample of n-GaAs with a donor concentration of 1.4×10^{18} cm^{-3}. In the range of the change in magnetic fields which was studied, the experimental data in Fig. 2 are satisfactorily described by the Lorenz formula $\rho_H/\rho_0 = 1/[1 + (\omega_L T)^2]$, where ρ_H and ρ_0 are the degrees of circular polarization in the field and without the field, respectively, T is the spin lifetime ($T^{-1} = r_0^{-1} + r_s^{-1}$), ω_L is the Larmor frequency $\omega_L = g\mu_B H/\hbar$, where μ_B is the Bohr magneton, and g is the Lande factor, taken equal to 4 in accordance with the results of Refs. 2 and 3. The solid curve in Fig. 2 corresponds to $T = 1.3\times 10^{-13}$ sec. Ignoring, in view of what was stated above, r_s^{-1}, we identify T with the lifetime of holes at the peak of the valence band.[1)]

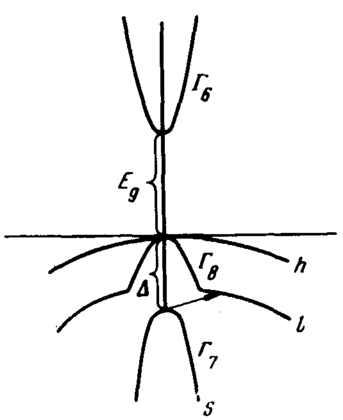

FIG. 1. Band structure of GaAs. The arrow indicates transitions between the spin-detached band and the band of light holes.

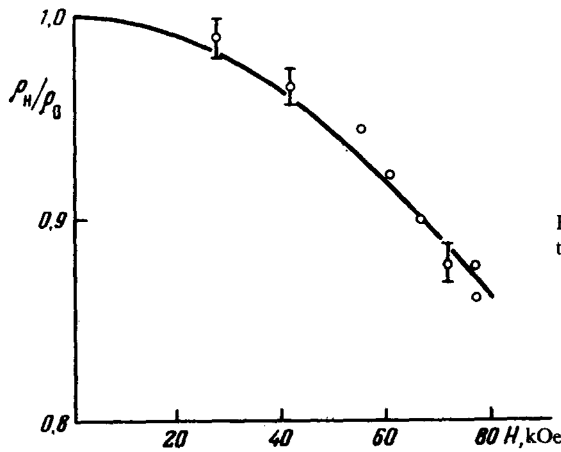

FIG. 2. Depolarization of luminescence in a transverse magnetic field.

There are various scattering mechanism which lead to the $\Gamma_7 - \Gamma_8$ transition of holes and which thereby determine their lifetime: a) transitions with emission of an optical phonon, b) impurity scattering, c) hole-electron scattering, and d) acoustic scattering. As estimations show, transitions with emission of an optical photon are the most probable.

The corresponding expression for the condition $\Delta - 3\hbar\omega_0 \gg (m_s/m_h)^{1/2}\Delta$ is as follows:

$$1/\tau_{op} = \frac{4}{3}\alpha_h \omega_o \left(\frac{\hbar\omega_o}{\Delta/3 - \hbar\omega_o}\right)^{1/2}. \tag{1}$$

Here α_h is the constant for the interaction of heavy holes with optical phonons of frequency ω_0 and m_h and m_s are the effective masses in the band of heavy holes and in the spin-detached band, respectively. We note that expression (1) corresponds to the transitions of holes from Γ_7 to the sub-band of light holes (transitions to the heavy-hole sub-band are forbidden by the selection rules), while the fact that the interaction constant α_h occurs in Eq. (1) is the result of the strong non-parabolic nature of the light-hole sub-band close to energies $\epsilon \sim \Delta$. For GaAs, $\Delta = 0.34$ eV; for a mean mass of heavy holes $m_h = 0.55$ and $\omega_0 = 5.5 \times 10^{13}$ sec^{-1}, $\alpha_h = 0.22$. Then, in accordance with Eq. (1), $\tau_{op} = 1.1 \times 10^{-13}$ sec. In gallium arsenide, the condition of applicability (1) presented above is poorly satisfied. However, the precise expression for $1/\tau_{op}$, obtained without any assumptions of the relationship between the masses (we do not present it here in view of its cumbersomeness), leads to a value $\tau_{op} = 2 \times 10^{-13}$ sec, which does not differ substantially, and which is close to the measured value τ_0.

In estimating the transition time for impurity scattering, it must be remembered that, because transitions $\Gamma_7 - \Gamma_8$ proceed with large momentum transfers electron screening is insignificant and scattering proceeds on ionized impurities even at low temperatures for all practical purposes. The corresponding time of transition for the impurity concentration 10^{18} cm^{-3} is an order greater than τ_{op}. The relaxation time during scattering on electrons is of the same order as for impurity scattering, while the relaxation time with emission of acoustic phonons is even greater and amounts to approximately 10^{-11} sec. Consequently, the measured value of the lifetime of holes in band Γ_7 is determined basically by τ_{op}. Thus, measurement of the Hanle effect has made it possible to directly determine the probability of emission of an optical phonon during inter-band transition. It can be hoped that similar measurements in less doped crystals as well as during an increase in initial energy of the holes will make it possible to determine the times of intra-band processes of energy relaxation as well.

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[1)]In substantialy doped specimens ($n > 10^{18}$ cm^{-3}), the time of intra-band energetic relaxation of holes τ_1 due to hole-electron interaction, is estimated to be smaller than 10^{-13} sec. Therefore, in the analysis of experimental data we do not take into consideration the spin reversal of holes by an angle $\omega_L\ \tau_1$, which occurs during that time. In the general case, depolarization of luminescence also occurs at this "intra-band" stage.

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