

- [8] A.T. Berestov and S.P. Malysenko, Zh. Eksp. Teor. Fiz. 58, 2090 (1970) [Sov. Phys.-JETP 31, 1127 (1970)].
 [9] A.V. Voronel', V.G. Gorbunov, Yu.R. Chashkin, and V.V. Shchekochikhina, ibid. 50, 897 (1966) [23, 597 (1966)].
 [10] M.F. Sykes, J.E. Martin, and D.L. Hunter, Proc. Phys. Soc. 91, 671 (1967).

MEASUREMENT OF THE LIFETIME AND OF THE SPIN-RELAXATION TIME OF ELECTRONS IN SEMICONDUCTORS BY THE OPTICAL-ORIENTATION METHOD

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It was shown recently [1, 2] that in semiconducting crystals it is possible to attain an appreciable orientation of the spins of the non-equilibrium carriers as a result of interband transitions caused by absorption of polarized light. Observation of optical orientation makes it possible to extend to semiconductors the research methods widely used in atomic spectroscopy [3], and particularly to investigate relaxation processes in a crystal under stationary conditions.

In the present investigation we used the method of optical orientation to measure the temperature dependence of the lifetime and the spin-relaxation time of the non-equilibrium electrons in the interval 77 - 300°K using mixed p-type $Ga_xAl_{1-x}As$ crystals, for which a strong electron orientation was obtained earlier [2] at 77°K.

The orientation of the non-equilibrium electrons was produced by predominant population of one of the conductivity subbands with $m = 1/2$ or $m = -1/2$, with the electrons excited by circularly polarized light (σ^+ or σ^- , respectively) from the valence band to the conduction band. The degree of stationary orientation of the electron spins (P) in the presence of relaxation is determined by the relation [1 - 3]

$$P = \frac{P_0}{1 + \tau/T_1}, \quad (1)$$

where T_1 is the spin-relaxation time and τ is the lifetime of the non-equilibrium electron in the conduction band, P_0 is the orientation in the absence of relaxation, determined by the probabilities of the transitions to the state with $m = 1/2$ or $m = -1/2$ upon absorption of circularly polarized light. In our case $P_0 = 0.5$ for the interband transitions $\Gamma_{15.val}^{3/2} - \Gamma_{1.con}^{1/2}$ [1, 2].

The times τ and T_1 determine also the total lifetime of the oriented spin T_{1M} :

$$\frac{1}{T_{1M}} = \frac{1}{\tau} + \frac{1}{T_1}, \quad (2)$$

which can be measured from the decrease of the degree of orientation of the electrons in a transverse magnetic field (a phenomenon analogous to the Hanle effect in atomic spectroscopy [3]). The dependence of the degree of orientation on the magnetic field intensity (H) has in this case a Lorentz form:

$$P \sim \frac{1}{1 + (\omega_L g T_{1M})^2}. \quad (3)$$

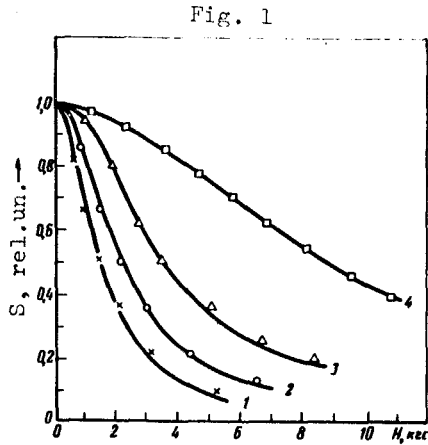


Fig. 1. Dependence of the degree of polarization of luminescence on the intensity of the transverse magnetic field in p-type $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}$ crystals at different temperatures: 1 - 77°K , 2 - 169°K , 3 - 220°K , 4 - 300°K . Unity for each temperature represents the degree of polarization at $H = 0$.

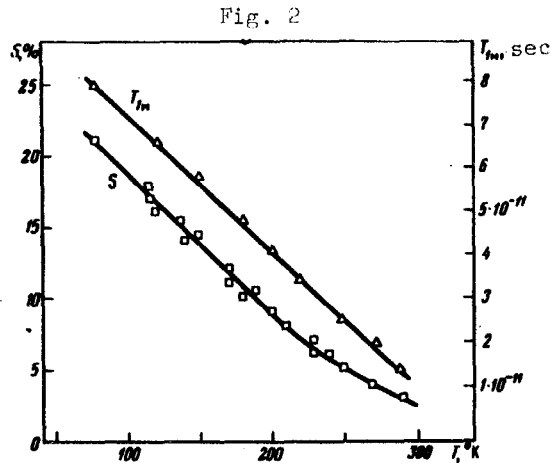


Fig. 2. Temperature dependence of the degree of polarization of luminescence S and of the time T_{LM} (obtained by measuring the depolarization of the luminescence in the magnetic field) for $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}$ crystals.

where $\omega_L = eH/2mc$ is the frequency of the classical Larmor precession, and g is the spectroscopic factor of the electron. In the investigated $\text{Ga}_x\text{Al}_{1-x}\text{As}$ crystals we can assume $g \approx 1$ [2].

Observation of the spin orientation of non-equilibrium electrons was based on the polarization of the conduction band - shallow acceptor recombination radiation. The connection between the degree of circular polarization of luminescence (S) and the degree of orientation of the spins was determined by the selection rules for the recombination transitions, and in this case $S = 0.5P$ [2].

Thus, as follows from the presented relations, it is possible to determine the values of the lifetime τ and the spin relaxation time T_1 of the non-equilibrium electrons from experimental measurements of the absolute value of S and the depolarization of the luminescence in a transverse magnetic field.

We measured S and T_{LM} in $\text{Ga}_{0.7}\text{Al}_{0.3}\text{As}$ crystals in the temperature interval $77 - 300^\circ\text{K}$. Figure 1 shows the dependence of the degree of polarization and luminescence on the magnetic field intensity at different temperatures. We see that the half-width of the polarization curve, which determines the time T_{LM} (3), increases strongly with increasing temperature. The temperature dependence of the time T_{LM} , obtained from these curves, is shown in Fig. 2, which shows also the measured dependence of the degree of polarization S (at $H = 0$) on the temperature. With increasing temperature, the degree of polarization drops from $S = 0.21 \pm 0.02$ at 77°K to $S = 0.03 \pm 0.01$ at 300°K . From the measured values of S and T_{LM} we calculated the values of τ and T_1 at different temperatures. These results are shown in Fig. 3. We see that the lifetime $\tau \approx 10^{-10}$ sec is practically independent of the temperature in the interval $77 - 300^\circ\text{K}$. On the other hand, the spin-relaxation time T_1 in the same temperature interval decreases by a factor of approximately 60.

The strong dependence of the spin-relaxation time on the temperature is a characteristic of the interaction between the spin and the lattice

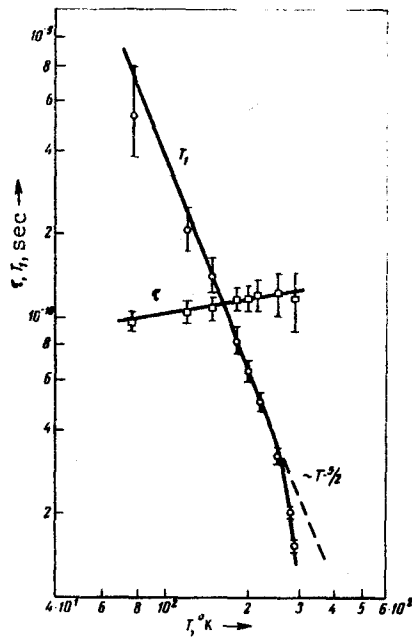


Fig. 3. Temperature dependence of the lifetime τ and of the spin-relaxation time T_1 on the non-equilibrium electrons, obtained from the data of Fig. 2.

vibrations. For relaxation on acoustic oscillations at $T < \theta_D$ (θ_D is the Debye temperature) the theory predicts a power-law dependence of the relaxation time on the temperature: $T_1^{-1} \sim (T^\circ\text{K})^{5/2}$ [4]. It is seen from Fig. 3 that in the region 77 - 240°K¹⁾ the observed T_1 dependence agrees quite well with the $T^{5/2}$ law. The deviation from this law in the region of higher temperatures is apparently due to the contribution of the optical oscillations, which cannot be neglected at these temperatures.

The lifetime τ changed insignificantly from $\tau = 0.9 \times 10^{-10}$ sec at 77°K to $\tau = 1.2 \times 10^{-10}$ sec at 300°K. However, the luminescence intensity decreased in this case by approximately one order of magnitude. A comparison of these facts makes it possible to conclude that in this case the lifetime of the electrons with respect to radiative transitions is at least 5 - 6 times larger than the total lifetime of the non-equilibrium carriers. The total lifetime is determined apparently by the nonradiative recombination via deep levels, and in this case, as is well known [6], it may remain constant when the temperature varies in a wide range. As shown by estimates, the increase of the radiative lifetime with increasing temperature may be due to a decrease in the number of neutral acceptors ($E_1 \approx 0.03$ eV) with which the nonradiative recombination takes place.

In conclusion, we note that our measurements of the total lifetime in conjunction with measurements of the quantum yield make it possible to determine the absolute value of the radiative lifetime.

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- [1] R.R. Parsons, Phys. Rev. Lett. 23, 1152 (1969).
- [2] A.I. Ekimov and V.I. Safarov, ZhETF Pis. Red. 12, 293 (1970) [JETP Lett. 12, 198 (1970)].
- [3] C. Cohen-Tannoudji and A. Kastler, Progress in Optics, 5, 33 (1966).
- [4] S.T. Pavlov, Fiz. Tverd. Tela 8, 900 (1966) [Sov. Phys.-Solid State 8, 719 (1966)].
- [5] M. Ilegems and G.L. Pearson, Phys. Rev. 1B, 1576 (1970).
- [6] S.M. Ryvkin, Fotoelektricheskie yavleniya v poluprovodnikakh (Photoelectric Phenomena in Semiconductors), Fizmatgiz, 1963.

¹⁾ From data on the IR spectra of the $\text{Ga}_x\text{Al}_{1-x}\text{As}$ crystals [5] we can estimate that $\theta_D \approx 400^\circ\text{K}$ for $x = 0.7$