

# OBSERVATION OF OPTICAL ORIENTATION OF EQUILIBRIUM ELECTRONS IN n-TYPE SEMI-CONDUCTORS

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The first experiments on optical orientation of free carriers in semiconductors were performed recently [1 - 5]. Since holes usually do not become oriented in the valence band, owing to rapid relaxation of their spins [6], most experiments were performed on p-type materials and the oriented carriers were the electrons propelled into the conduction band by circularly polarized light. Thus, only the spins of non-equilibrium carriers were oriented, a phenomenon analogous to the optical orientation of excited gas atoms [7].

However, we have previously observed [3] optical orientation also in n-type material. We show in the present paper that this phenomenon is due to optical orientation of equilibrium electrons, i.e., the orientation is realized in the ground state, in analogy with "optical pumping" of atoms [7].

The possibility of optical orientation of equilibrium electrons in n-type semiconductors was predicted in the theoretical paper of D'yakonov and Perel' [8]. This effect is determined by the following: circularly polarized light propels into the conduction band predominantly electrons with one spin direction, but the rate of electron recombination is independent of their spin. Obviously, this should lead to accumulation of oriented electrons in the conduction band. If the spin-relaxation time  $\tau_s$  is large compared with the lifetime  $\tau$  of the non-equilibrium electron, then an appreciable fraction of the equilibrium carriers can be transferred to the oriented state. Near the surface, the degree of stationary orientation of the electrons  $P$  ( $P = |(n_+ - n_-)/(n_+ + n_-)|$ , where  $n_{\pm}$  is the number of electrons with different spin orientations) will be determined by the relation [8]

$$P = P_0 I \tau_s (I \tau_s + n_0 L_s)^{-1}, \quad (1)$$

where  $P_0$  is the orientation of the electron during the instant of its production by the light ( $P_0 = 0.5$  for the  $\Gamma_8 - \Gamma_6$  interband transitions [6]),  $I$  is the excitation intensity,  $n_0$  the equilibrium electron density, and  $L_s$  the diffusion length, determined by the electron diffusion coefficient and by the time  $\tau_s$ .

An essential feature of this effect, as seen from (1), is the dependence of the degree of orientation on the excitation intensity. In the region of small orientations ( $I \tau_s \ll n_0 L_s$ ) the dependence will be approximately linear.

We note that this should not occur when the non-equilibrium carriers are oriented, since their number depends on the light intensity, but the degree of orientation does not depend on the intensity.

Our investigations were performed on n-Ga<sub>x</sub>Al<sub>1-x</sub>As ( $\leq 10^{16}$  cm<sup>-3</sup>) at 4.2°K. The electrons were oriented by circularly polarized He-Ne laser light, which yielded excitation intensities  $\leq 5 \times 10^{20}$  quanta/cm<sup>2</sup>sec. The composition of the crystals ( $x \approx 0.7$ ) was chosen such as to make the width of the forbidden band close to the quantum energy of the exciting light. The degree of electron orientation, as before [3, 4], was determined from the degree of circular polarization of the combination luminescence  $S$  ( $S = |(I_+ - I_-)/(I_+ + I_-)|$ , where  $I_{\pm}$  is the intensity of emission in circularly polarized light with right-hand and left-hand rotation). As shown by D'yakonov and Perel' [6], for transitions in which shallow impurities and excitons take place we have  $S = 0.5P$ .

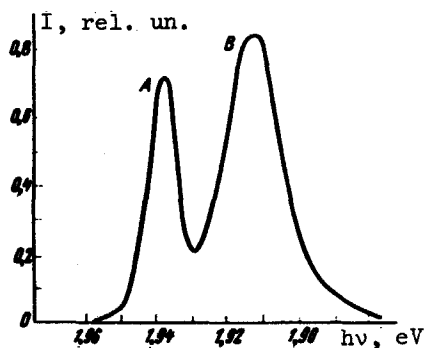


Fig. 1. Photoluminescence spectrum of  $n\text{-Ga}_x\text{Al}_{1-x}\text{As}$  crystal ( $x \approx 0.7$ ,  $n \approx 10^{16} \text{ cm}^{-3}$ ) at  $4.2^\circ\text{K}$ .

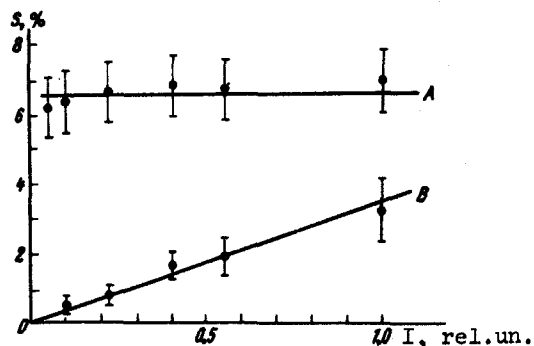


Fig. 2. Degree of circular polarization  $S$  of the luminescence bands A and B vs. the intensity of circularly polarized pump light  $I$  for  $n\text{-Ga}_{0.7}\text{Al}_{0.3}\text{As}$  crystals at  $4.2^\circ\text{K}$ .

Figure 1 shows a typical photoluminescence spectrum of the crystals at  $4.2^\circ\text{K}$ . It can be shown<sup>1)</sup> that the bands appearing in the spectrum are due to radiative transitions from the donor to the acceptor (band B) and to recombination of an exciton (free or bound, band A). Figure 2 shows the observed dependence of the degree of polarization of these luminescence bands on the excitation intensity<sup>2)</sup>. We see that these plots are significantly different: the polarization of band A is practically constant ( $S \approx 7\%$ ), but for band B the polarization varies linearly with the light intensity.

The observed relations can be explained by recognizing that at sufficiently low temperatures practically all the equilibrium electrons are frozen at the donor levels. Under these conditions, only the non-equilibrium carriers take part in the exciton production<sup>3)</sup>, and their degree of orientation does not depend on the excitation intensity. This obviously determines the constancy of the polarization of the exciton line A.

Line B is due to transitions from the donor level. In such transitions, the equilibrium and non-equilibrium electrons on the donors participate to an equal degree, and this should lead, as already mentioned, to accumulation of oriented carriers, i.e., to orientation of the equilibrium electrons. The observed linear dependence of the degree of luminescence polarization on the pump light intensity shows directly that the equilibrium carriers at the impurity levels are indeed oriented in this case<sup>4)</sup>. The slope of curve B in Fig. 2

<sup>1)</sup>This circumstance will be considered in greater detail in an article by Zh.I. Alferov, D.Z. Garbuzov, et al. in *Fiz. Tekh. Poluprov.* 5, No. 6 (1971).

<sup>2)</sup>The degree of polarization was constant along the contour of each luminescence band (at fixed excitation).

<sup>3)</sup>This is evidenced also by the superlinear, near-quadratic dependence of the brightness of band A on the pump-light intensity.

<sup>4)</sup>In some samples, the intensity of line B ( $I_B$ ) had an essentially non-linear (sublinear) dependence on the pump intensity ( $I$ ). The dependence of  $S$  on  $I_B$ , however, was always linear, for it was precisely the electron recombination rate (and the associated luminescence brightness) which determines the rate of accumulation of the oriented electrons at the donor level.

differs somewhat for different samples, and this may be due, in particular, to differences in  $n_0$  (see Formula (1)).

Measurements of luminescence polarization in a transverse magnetic field gave the following lifetimes of the oriented spin [2 - 4]:  $\approx 5 \times 10^{-10}$  sec for the exciton (band A), and  $1.2 \times 10^{-9}$  sec for the donor (band B). Obviously, this time is determined in either case mainly by the spin-relaxation time. One can thus conclude that the spin relaxation differs for an electron bound at a donor or in an exciton.

The maximum degree of polarization of band B was  $\approx 0.03$ . This corresponds to an orientation of  $\approx 6\%$  of all electrons at the donors. From Formula (1) we can estimate the penetration depth  $L_s$  of the orientation. In our case  $L_s \approx 1.0 \mu$ , making the estimated electron mobility at 4.2°K of the order of (or lower than)  $10^3$  V-cm<sup>2</sup>/sec.

The experiments have shown that in n-type semiconductors it is possible to obtain a noticeable orientation of the electrons at the donor levels even at excitation intensities such that the density of the non-equilibrium carriers is smaller than the density of the equilibrium electrons.

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#### COHERENT RADIATION OF CHARGED PARTICLES CHANNELLED IN A CRYSTAL

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It is known that coherent photon radiation is produced when a charged particle moves on a straight line in a medium having a dielectric constant that varies periodically in space. This radiation is similar to Cerenkov radiation [1] and its frequencies constitute a set of approximately integer harmonics. We consider in this paper this radiation, which is sometimes called resonant, in the case of charged particles moving in single crystals. We show that, unlike Cerenkov radiation and resonant radiation in media with a macroscopic variation of  $\epsilon$ , the intensity of resonant radiation in single crystals has a strong temperature dependence and decreases with increasing crystal temperature, while the intensities of the higher harmonics are strongly suppressed compared with the intensity of the first harmonic.

The most favorable conditions for resonant radiation occur when a charged particle is channelled (self-trapped) in a crystal [2]. We shall consider