Mechanism of radiative recombination in strongly doped p-GaAs

L. P. Zverev, V. V. Kruzhaev, and S. A. Negashev

Ural State University
(Submitted June 3, 1974)
ZhETF Pis. Red. **20**, 52–56 (July 5, 1974)

We investigated the behavior of the photoluminescence (PL) spectra of strongly doped p-GaAs in a magnetic field, and analyzed the polarization of the recombination radiation in the Faraday configuration. The observed effects offer evidence in favor of the interband recombination mechanism.

In spite of the many investigations of the luminescence of strongly doped p-GaAs, there is still no unanimity concerning the nature of the states that take part in the recombination.[1,2]

It is known that to explain the recombination mechanism in strongly doped n-GaAs it was useful to investigate the photoluminescence (PL) spectra in a strong magnetic field.[3] We use here the method of[3] to investigate the PL of strongly doped p-GaAs, with separation of the σ^+ and σ^- polarizations (radiation directed along the field), and also without separation of the polarizations (summary spectra). Magnetic fields of intensity up to 330 kOe were used. The excitation intensity was 10^{22}–10^{23} photons/cm^2 sec. The σ^+ and σ^- spectra were investigated at $T = 77$ °K, and the summary spectra at 4.2, 77, and 300 °K. The samples were doped with zinc and had a carrier density 2×10^{18}–1×10^{20} cm^{-3}.

At $H = 0$, the edge-emission spectrum consists of a single line that broadens with doping and shifts towards lower energies, in agreement with the results of[1,2]. When a magnetic field is applied, no structure whatever is observed in the summary spectra. The line becomes somewhat narrower and its maximum shifts towards higher energies. The shift has a linear character in sufficiently strong fields, and a nonlinear-shift section, which increase with increasing degree of doping and with temperature (Fig. 1a), is observed in weak fields.

Separation of the polarizations has made it possible to resolve in the PL spectra of samples with $p \geqslant 6\times10^{18}$ cm^{-3} three lines: one in the σ^+spectrum ($1\sigma^+$) and two in the σ^- spectrum ($1\sigma^-$, $2\sigma^-$) (Fig. 2). The $1\sigma^+$ line is always somewhat more intense at higher energy than $1\sigma^-$. The $2\sigma^-$ line becomes manifest in the form of a step on the high-energy edge of the spectrum, and to separate it we subtracted the $1\sigma^+$ line from the σ^- spectrum (Fig. 2). This method is justified by the fact that in strong fields, when the $1\sigma^-$ and $2\sigma^-$ lines are separated, the $1\sigma^+$ and $1\sigma^-$ lines have practically the same shape. All three lines are shifted linearly with the magnetic field,

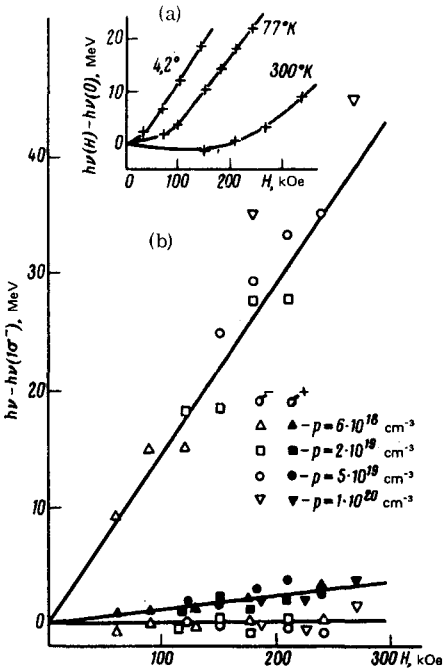

FIG. 1. a) Position of the maximum of the summary PL spectrum of the sample with $p = 5\times10^{19}$ cm^{-3} vs the magnetic field at different temperatures. b) Relative positions of the lines $1\sigma^-$, $2\sigma^-$, and $1\sigma^+$ in a magnetic field for different samples at $T = 77$ °K, and the corresponding distances between the Landau levels of the light and heavy holes (average for $m_s = \pm\frac{1}{2}$) calculated in accordance with[5] (solid line).

and their shifts can be extrapolated to one and the same energy E_0 at $H = 0$.

With increasing degree of doping, the energy E_0 decreases, together with the decrease of energy of the maximum of the line at $H = 0$. At the same time, the

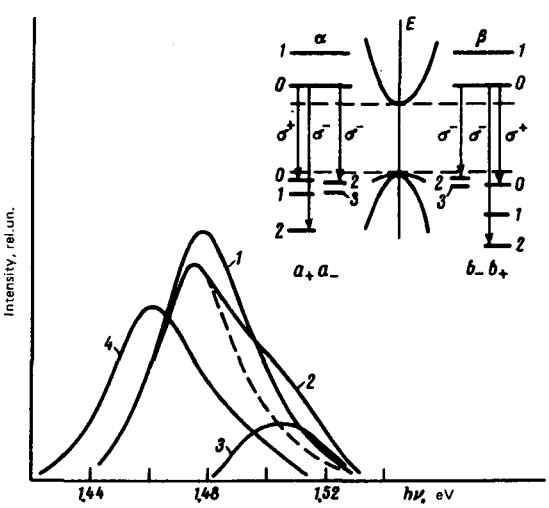

FIG. 2. Photoluminescence spectra of sample with $p = 5\times10^{19}$ cm^{-3} at $T = 77$ °K and $H = 180$ kOe: 1—σ^+, 2—σ^-, 3—$2\sigma^-$ line, 4—spectrum at $H = 0$. Scheme of allowed radiative transitions for the polarizations σ^+ and σ^- between the levels of the Landau conduction band (α,β) and the valence band (a_+, b_+—light holes, a_-, b_-—heavy holes). (α, a and β, b correspond to $m_s = +\frac{1}{2}$ and $-\frac{1}{2}$, respectively).[4]

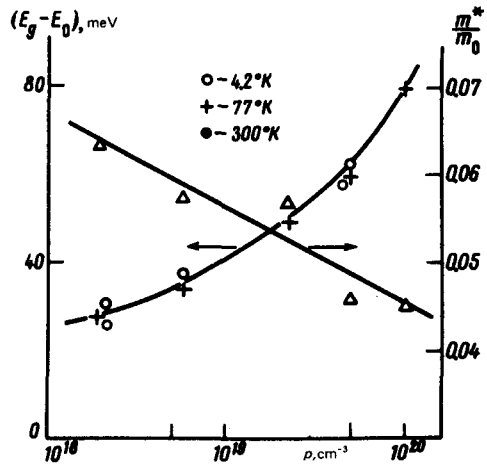

FIG. 3. Concentration dependence of the extrapolation energy E_0 at different temperatures, and of the coefficient, with dimension of mass, characterizing the rate of displacements of the maximum of the summary photoluminescence spectrum in a magnetic field at $T = 77$ °K.

rate of line shift in the magnetic field increases (Fig. 3).

Two fundamentally different recombination mechanisms in strongly doped p-GaAs are discussed in the literature: in the valence band[1] and in a band of shallow acceptors, which in accordance with the assumptions in[2] is preserved up to concentrations $p \sim 10^{20}$ cm^{-3}. It is difficult to explain the observed difference between the σ^+ and σ^- spectra by assuming recombination in the acceptor band. At the same time, all the described effects can be explained if it is assumed that in strongly doped p-GaAs the recombination is due to transitions from the conduction to the valence band. Indeed, at the employed excitation levels and at $T = 77$ °K, in fields $H > 50$ kOe, the electrons in the conduction band fill only the Landau levels with $n = 0$ and $m_s = \pm\frac{1}{2}$. (According to our estimates, the density of the nonequilibrium carriers does not exceed 10^{17} cm^{-3}.) At the same time, at $p \geqslant 6\times10^{18}$ cm^{-1}, the Fermi level of the holes lies 30—140 meV lower than the top of the valence band, and therefore, in accordance with the selection rules,[4] the six transitions shown in Fig. 2 can be realized in a wide range of fields. The transitions with $m_s = +\frac{1}{2}$ and $-\frac{1}{2}$ cannot be separated, owing to the smearing of the lines, and consequently the spectrum of σ^+ should consist of one line, while the spectrum of σ^- should consist of two, as is indeed observed in experiment. Since the initial states for these transitions are the same, the distances between the lines $1\sigma^-$, $2\sigma^-$, and $1\sigma^+$ are determined by the distances between the corresponding Laudau levels in the valence band. As seen from Fig. 1, for all the investigated samples these distances turned out to be close to the corresponding values for "pure" GaAs[5] (increasing somewhat with doping). The relative intensities of the lines ($I1\sigma^+/I1\sigma^- \approx 1.2$; $I1\sigma^-/I2\sigma^- \approx 3-5$) also agree with the theoretical estimates (~1.3 and ~3, respectively).[5] It should be noted that the recombination mechanism remains apparently unchanged in the entire temperature interval 4.2—300 °K, as is evidenced by the weak

change, with changing temperature, of the concentration dependence of the difference $E_g - E_0$ (Fig. 3), where E_g is the width of the forbidden band of the "pure" material.

Thus, the results agree with the known concept that a single energy spectrum of states, with a "band" character, is produced in a strongly doped semiconductor.[6] The influence of doping becomes manifest in a decrease of the forbidden-band width, which in our experiment can be characterized by the energy E_0 and by a decrease in the effective carrier mass.

The interband-transition model explains also the nonlinear line shift in weak fields. This effect is analogous to the nonlinear shift of the constant-intensity points in the photoluminescence spectra of n-GaAs, described in[3], and is caused by the electrons filling of the conduction-band Landau levels, which are broadened and overlap in these fields. When the magnetic field is increased to a certain value $H = H''$, all the electrons are quenched out at the Landau level $n = 0$, and the line shift acquires a linear character. With increasing degree of doping and with increasing temperature, the value of H'' increases and the nonlinear-shift sections increase.

[1]M. I. Nathan, G. Burns, S. E. Blum, and J. C. Marinace, Phys. Rev. **132**, 1482 (1963); D. A. Cusano, Sol. St. Comm. **2**, 253 (1964).

[2]J. I. Pankove, J. Phys. Soc. Japan **21**, Suppl., 298 (1966); D. N. Nasledov, V. V. Negreskul, and V. V. Tsarenkov, Fiz. Tekh. Poluprov. **3**, 1207 (1969) [Sov. Phys.-Semicond. **3**, 1012 (1970)].

[3]L. P. Zverev, G. M. Min'kov, and S. A. Negashev, *ibid.* **7**, 1585 (1973) [**7**, 1056 (1974)].

[4]L. M. Roth, B. Lax, and S. Zwerdling, Phys. Rev. **114**, 90 (1959).

[5]Q. H. F. Vrehen, J. Phys. Chem. Sol. **29**, 129 (1969).

[6]V. L. Bonch-Bruevich, Fizika tverdogo tela, (Solid State Physics), AN SSSR, 1965.