LOW-TEMPERATURE PHOTOLUMINESCENCE OF GaAs UNDER CONDITIONS OF STRONG INTERACTION OF THE NON-EQUILIBRIUM CARRIERS

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At high excitation levels and at low temperatures, the excitons (or, as assumed by certain authors, the biexcitons) in the purest semiconductors, such as germanium and silicon, are condensed into electron-hole drops [1 - 3]. With further increase of the excitation level, practically the entire radiation of these semiconductors is determined by the recombination of the electrons and holes in the drops. Unlike Ge and Si, gallium arsenide is a semiconductor with allowed optical transitions, characterized by rapid relaxation of the concentration of the non-equilibrium carriers and excitons with times $\tau \lesssim 10^{-9}$ sec. Such free-exciton lifetimes in gallium arsenide may turn out to be shorter than the characteristic condensation times, which measurements on Ge and Si have shown to be $\gtrsim 10^{-8}$ sec [4, 5]. As a result, the existing notions concerning the condensation mechanism [6] can hardly be applied to gallium arsenide.

We present here experimental data which make it possible, nonetheless, to propose that a condensed phase with constant density is produced in gallium arsenide at low temperatures and high optical-excitation levels.

The experiments were performed on pure epitaxial gallium-arsenide films with parameters $n = 5 \times 10^{14}$ cm^{-3} and $\mu = 67 \times 10^{3}$ cm^{2}/v-sec at 77°K. The maximum excitation level, equal to 10^{22} cm^{-2}sec^{-1}, was obtained by sharp focusing of the radiation from a 0.15-W argon laser. The samples were placed in superfluid liquid helium at 1.5°K. Figure 1 shows the emission spectra obtained at different excitation levels. The emission intensities of the lines I_e, I_1, I_3, and I_4, which are due to excitons [7], and of the line I_2, which is due to recombination of an electron by a shallow donor with a hole in the valence band, vary in proportion to the optical-excitation level. At relatively high optical pumping density, a spectrally broad band I_c, whose maximum does not coincide with any of the observed narrow emission lines, appears in the emission spectrum. The integral density of I_c has a superlinear dependence on the excitation level ($\sim I^3$), as a result of which this band predominates completely in the spectrum at excitation levels exceeding 3×10^{21} cm^{-2}sec^{-1}.

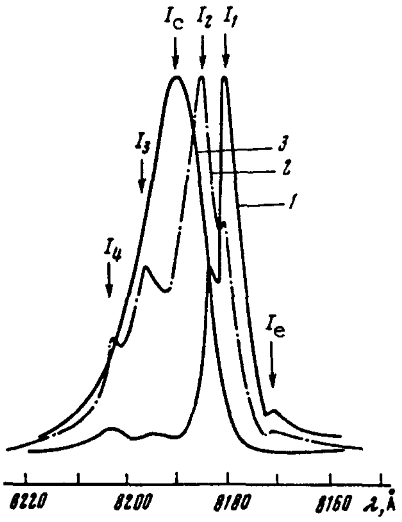

Fig. 1. Photoluminescence spectra of GaAs at T = 1.5°K and at different levels of optical excitation I: 1) $I = 5 \times 10^{19}$ cm^{-2}sec^{-1}, 2) $I = 2 \times 10^{21}$ cm^{-2}sec^{-1}, 3) $I = 5 \times 10^{21}$ cm^{-2}sec^{-1}.

An electric field leading to impact ionization of the free excitons and shallow donors[1] does not influence the main characteristics of the I_c radiation. When an electric field was present in the crystal, the I_c line was observed at relatively low excitation levels, whereas without a field the emission of the free and bound excitons predominated in the

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[1] According to the measurements, exciton ionization occurs in a field E = 1 V/cm, and impact ionization of the donors occurs at E = 3 V/cm.

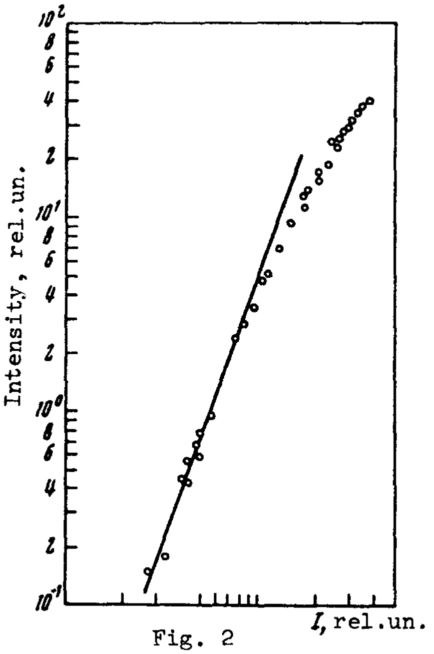

Fig. 2

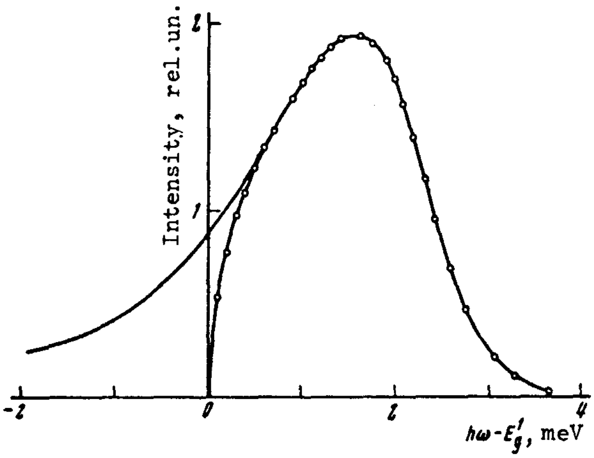

Fig. 3

Fig. 2. Dependence of the emission intensity I_c on the optical-excitation level I at E = 4 V/cm.

Fig. 3. Photoluminescence spectra of GaAs: 1) experimental curve ($I = 10^{22}$ $cm^{-2}sec^{-1}$, T = 1.5°K), 2) calculated curve (formula (1) at $n_0 = P_0 = 1.1 \times 10^{16}$ cm^{-3}, T = 3.8°K).

spectrum. The position of the I_c line in the spectrum and its shape remain unchanged in comparison with the corresponding characteristics at maximum excitation levels. This circumstance has made it possible to obtain the dependence of the integral intensity of the I_c radiation on the optical-excitation level in a wider range of variation of the pumping (Fig. 2). The experimental points were obtained with a field E = 4 V/cm, which excluded completely the contribution made to the registered radiation by processes in which free and localized excitons participate. The aggregate of the available experimental data gives grounds for assuming that the appearance of the I_c line may be due to "metallic" electron-hole drops. What is condensed in gallium arsenide, however, unlike in germanium and silicon, are free electrons and holes, as is evidenced by measurements performed in the presence of an electric field. To determine the density of the condensate, we calculated from the experimental data the emission line shape of a degenerate electron-hole plasma in semiconductors with direct allowed transitions. The calculation was based on the formula

$$I(\hbar\omega - \epsilon_g') \sim \frac{(\hbar\omega - \epsilon_g')^{1/2}}{\left[\exp\dfrac{(\hbar\omega - \epsilon_g')\dfrac{\mu}{m_e} - F_e}{kT} + 1\right]\left[\exp\dfrac{(\hbar\omega - \epsilon_g')\dfrac{\mu}{m_h} - F_h}{kT} + 1\right]},$$

where ε_g' is the width of the forbidden band for the carriers recombining into drops, μ is the reduced mass of the electron and the hole, $\mu = m_e m_h/(m_e + m_h)$, F_e is the Fermi energy of the electrons, and F_h is the Fermi energy of the holes.

The calculated and experimental plots were aligned to make their maxima congruent. The best agreement between theory and experiment took place at an equilibrium concentration $n_0 = P_0 = 1.1 \times 10^{16}$ cm^{-3} and $T = 3.8$°K (Fig. 3).

Estimates of the principal characteristics of the electron-hole drops in gallium arsenide, similar to those carried out in [1], yield $n_0 = P_0 = 3 \times 10^{16}$ cm^{-3}. The deviation from the value obtained from an analysis of the spectral curve is due to the existence of "indirect" transitions connected with Auger recombination of the electrons and holes in the drops. The latter undoubtedly takes place, as is evidenced by the long-wave tail of the experimental curve (Fig. 3).

The calculated local change of the width of the forbidden band, due to the correlation and exchange interaction of the carriers, is 7.6 meV. The potential-well depth determined from the radiation, 8.7 meV, is in satisfactory agreement with the calculated value. The slight discrepancy is not unexpected, since the numerical estimates of the condensate energy disregarded the correction due to the correlation interaction between carriers of opposite sign.

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MAIN FACTORS CONTROLLING AN INCLUSIVE PROCESS IN THE ENERGY INTERVAL 20 - 1500 GeV

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We have shown in [1] that the correlations between the longitudinal and transverse momenta in multiple generation at 400 GeV[1] are the consequence of phase space, the uniform filling of which is distorted only by the smallness of the transverse momenta. To approximate different distributions connected with this simplest condition, we used a spectrum of the form

$$\frac{d^2\sigma}{dp_t\,dp_\ell} = \frac{p_t}{\exp\sqrt{\left(\frac{p_t}{T_t}\right)^2 + \left(\frac{p_\ell}{T_\ell}\right)^2 + \frac{m^2}{T_t T_\ell}} - 1}. \tag{1}$$

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[1] The data at 400 GeV were obtained with the aid of Tkhra-Tskaro installations, which consists of a cloud chamber in a magnetic field and an ionization calorimeter. The installation registers interactions of nuclear-active particles of cosmic radiation with nuclei of a polyethylene target located over the cloud chamber.