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ELECTRONIC AND OPTICAL PROPERTIES OF SEMICONDUCTORS

Photoluminescence of Electron–Hole Plasma in Semi-Insulating Undoped GaAs

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Abstract—The dependence of the photoluminescence spectrum of electron–hole plasma in semi-insulating undoped GaAs on the concentration of the background carbon impurity N_C (3×10^{15} cm$^{-3} \le N_C \le 4 \times 10^{16}$ cm^{-3}) is studied at 77 K. It is established that the density of the electron–hole plasma, which is equal to $n_{e-h} \approx 1.1 \times 10^{16}$ cm^{-3} in crystals with the lowest impurity concentration at an excitation intensity of 6×10^{22} photons/(cm^2 s), decreases considerably as the value of N_C increases in the range mentioned above. A decrease in the density of the electron–hole plasma with increasing N_C is attributed to the effect of fluctuations in the carbon concentration N_C, which give rise to a nonuniform distribution of interacting charge carriers and to localization of holes in the tails of the density of states of the valence band. © *2004 MAIK "Nauka/Interperiodica".*

The photoluminescence (PL) of electron–hole plasma (EHP) and electron–hole drops in direct- and indirect-gap semiconductors, respectively, has been mainly studied in high-purity materials, so the conditions $N < n_{e-h}$ and $N < n_{ex}$ (N, n_{e-h}, and n_{ex} are the concentrations of the impurity, electron–hole pairs, and excitons, respectively) at high excitation levels were satisfied; as a result, collective interactions between nonequilibrium charge carriers appeared [1–6].

It is evident that an increase in N should enhance the screening effect of impurity atoms on the charge carriers and weaken the interaction between the charge carriers. It seems likely that the magnitude of this effect may depend on the electrical properties of the material, the degree of compensation, and the distribution of the impurity potential. However, the possible effect of these factors on the EHP in direct-gap semiconductors has been inadequately studied.

In this paper, we consider the dependence of the EHP PL intensity in semi-insulating undoped GaAs that includes impurity-potential fluctuations on the concentration of the background carbon impurity N_C. The electrical characteristics of the samples under study and the method for measuring the PL spectra were reported previously [7]. The excitation level J was changed from 3×10^{21} to 6×10^{22} photons/(cm^2 s) by varying the operation current of an Ar laser.

It was shown previously [7] that the edge-emission band in the PL spectra of semi-insulating undoped GaAs crystals that contain background carbon with the concentration N_C and are subjected to a low-intensity excitation ($J \le 3 \times 10^{21}$ photons/(cm^2 s)) is formed by the band-to-band transitions of interacting charge carriers at $N_C \le 1.4 \times 10^{16}$ cm^{-3}. At higher values of N_C, this band is related to recombination of free electrons with holes localized at the tails of the density of states of the valence band; these tails are caused by fluctuations in the doping-impurity concentration.

As the excitation-intensity increased ($J > 3 \times 10^{21}$ photons/(cm^2 s)), the spectrum of the edge-emission PL was modified. This modification is characteristic of radiative recombination in the EHP: the band peak (the energy corresponding to the peak $h\nu = h\nu_m$) shifted to longer wavelengths, and the band broadened and changed shape. In addition, the short-wavelength falloff of the PL intensity became less steep (Fig. 1), which was indicative of recombination of hot charge carriers whose temperature at the highest excitation intensity was estimated from the slope of the short-wavelength falloff and increased from 87 to 96 K as N_C increased in the range 3×10^{15} cm$^{-3} \le N_C \le 4 \times 10^{16}$ cm^{-3} under study.

The emission spectrum of some of the crystals at the highest excitation levels exhibited peaks (Fig. 1) that were evidently caused by the initiation of stimulated emission. The most substantial modification of the spectrum occurred in the crystals with the smallest values of N_C. As the carbon concentration increases, the spectrum modification is no longer observed at $N_C \approx 2.8 \times 10^{16}$ cm^{-3}, as follows from the extrapolation of the N_C dependences of the peak energy $h\nu_m(N_C)$ and the band width $W(N_C)$ at various excitation levels (Fig. 2).

In Fig. 3, we show the dependence of the EHP density n_{e-h} at $J = 6 \times 10^{22}$ photons/(cm^2 s) on the carbon concentration estimated from the effective-potential approximation using the formula [4]

$$E_g' = E_g - \frac{3e^2}{\pi\varepsilon}(3\pi^2 n_{e-h})^{1/3},$$

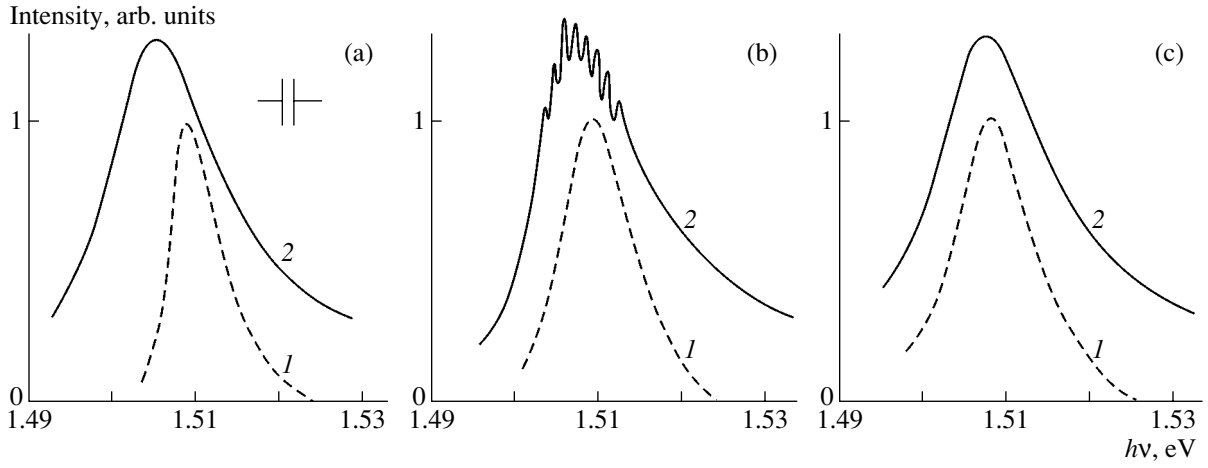

Fig. 1. Excitation-level dependences of the edge-PL spectra for GaAs crystals with different carbon concentrations N_C at $T = 77$ K. The excitation intensity was $J = (1)\ 3 \times 10^{21}$ and $(2)\ 6 \times 10^{22}$ photons/(cm^2 s). N_C = (a) 3.5×10^{15}, (b) 9×10^{15}, and (c) 2.1×10^{16} cm^{-3}. The spectra were normalized to unity and were shifted arbitrarily along the vertical axis.

where E_g' is the band gap narrowed as a result of collective electron–hole interaction, E_g is the unperturbed band gap, $\varepsilon = 12$ is the relative dielectric constant of GaAs, and e is the elementary charge. When estimating, we assumed that $E_g' = h\nu_m$ and we decreased the value of E_g at $N_C \geq 1.4 \times 10^{16}$ cm^{-3} by the depth of the percolation level for electrons and holes $\gamma' = (2/3)\gamma$ is the depth of potential wells formed by fluctuations in the carbon concentration).

As expected, the $n_{e-h}(N_C)$ dependence shown in Fig. 3 indicates that the EHP density decreases as N_C increases; this decrease is larger than that of electron–hole drops in Ge [8]. In our opinion, the main factor causing the substantial decrease in the EHP density as N_C increases is the presence of fluctuations in the doping-impurity concentration that give rise to a nonuniform distribution of interacting charge carriers. Localization of holes within the tails of the density of states of the valence band at $N_C \geq 1.4 \times 10^{16}$ cm^{-3} occurs in times that are shorter than the lifetimes of nonequilibrium charge carriers τ (according to our estimations, $\tau \leq 1.3 \times 10^{-11}$ s at the highest excitation intensity, which is

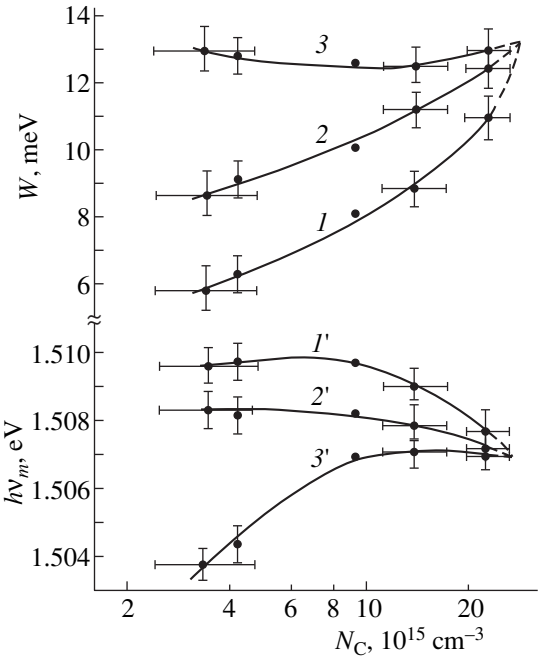

Fig. 2. Dependences of the (*1*–*3*) width W and (*1*'–*3*') the peak energy $h\nu_m$ of the edge-PL spectrum on the carbon concentration N_C at different excitation intensities J at $T = 77$ K. $J = (1, 1')\ 3 \times 10^{21}$, $(2, 2')\ 2 \times 10^{22}$, and $(3, 3')\ 6 \times 10^{22}$ photons/(cm^2 s).

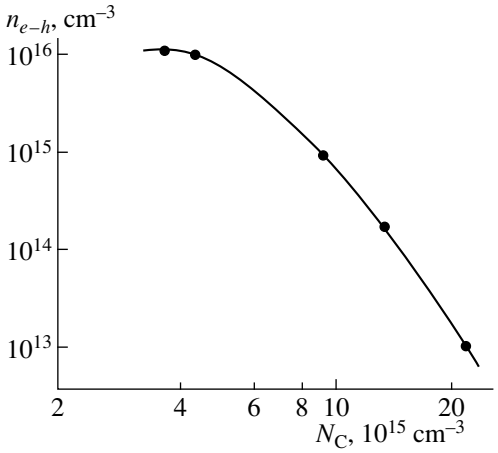

Fig. 3. Density of the electron–hole plasma as a function of the carbon concentration at the excitation intensity $J = 6 \times 10^{22}$ photons/(cm^2 s) and $T = 77$ K.

consistent with the values of τ in semi-insulating undoped GaAs, as reported previously [9]). This localization reduces the fraction of the charge carriers that are involved in the formation of the electron–hole plasma. The latter circumstance reduces the density of the electron–hole plasma even further.

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