HIGH-SPEED OPTOELECTRONIC EFFECTS ARISING UNDER INTENSIVE PICOSECOND STIMULATED EMISSION IN GaAs

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A number of optoelectronic threshold effects arising under intensive stimulated radiative recombination of hot dense electron-hole plasma (EHP) in a thin (~1μm) epitaxial layer of GaAs has been revealed. These effects' build-up and decay time intervals are of ~10 ps or less at room temperature (which makes it possible to modulate the optical and electrical properties of semiconductor heterostructures and devices with a frequency of ~ 100 GHz). These effects are observed when the stimulated recombination emission appears in picoseconds. The emission intensity can be as high as ~10^8 W/cm^2 and the EHP concentration can change several times by magnitude. The revealed class of optoelectronic effects has its origin in strong mutual influence between the stimulated emission and dynamical processes in dense EHP. The acquired knowledge of somewhat uncommon mechanism of changes of EHP concentration and temperature, of intensity and spectrum of stimulated emission, of the gain, transparency, band-gap width, etc. can be used for successful construction of semiconductor high-speed powerful optoelectronic devices (such as semiconductor lasers and superluminescence diodes, semiconductor light-wave converters, modulators of the optical transparency and photoconductivity).

We have found a number of the high-speed non-linear (threshold) effects, which control optical and electrical properties of GaAs. Our experiments have been carried out at room temperature. In the experiments we used excite-probe technique. The exciting and probing light pulses with duration 40 to 11 ps illuminated a GaAs thin (~1μm) layer almost perpendicular to the surface. The light wavelength and intensity were tuned for each pulse independently. The diameter of the photoexcited GaAs region was 200 μm and more. When the density of EHP, generated under interband absorption of powerful exciting pulse, exceeded approximately $1.4 \cdot 10^{18}$ cm^{-3}, the superluminescence appeared in picoseconds and propagated along the GaAs layer. By the term "superluminescence" we consider an amplified spontaneous emission in the systems without the optical cavity. The effects appearing due to the superluminescence are described below.

1. Under the superluminescence, the stimulated recombination of EHP provides relaxation with the characteristic time of ~ 10 ps (Fig.1 and below Fig.13) of EHP concentration and the corresponding GaAs bleaching down to a residual level. The bleaching, (i.e., an increase of transparency T) is described by the ratio $\log(T^1/T^0)$, where the indices 1 and 0 denote the presence and absence of excitation, respectively. In the presence of superluminescence, variations of the bleaching are more affected by variations of the EHP concentration than by the EHP temperature [1]. At a fixed diameter of the photoexcited GaAs region, the residual level of bleaching (and the corresponding EHP concentration) is independent of both the photon energy $\hbar\omega_{ex}$ and the integral energy W_{ex} of the exciting light pulse (Figs.2 and 3). When the residual level is reached, EHP temperature T_c becomes close to the room temperature, the superluminescence decays, and the energy distribution of EHP is approximately characterised by the conditions: (1) $n = p$ and (2) $\mu_e(n,T_c) - \mu_h(p,T_c) \approx E_g$,, where n and p stand for the concentrations of the electrons and holes, respectively; μ_e and μ_h are Fermi quasi-levels of the electrons and holes; and E_g is the band-gap width. Note that the energy distribution of EHP during the superluminescence can also be characterised by conditions (1) and (2), if we neglect that small part of EHP concentration, subtraction of which removes the population inversion of the charge carriers. These statements are confirmed by the agreement between the calculated (according to conditions (1) and (2)) and experimental spectra of the bleaching (Fig.2). When comparing the calculations with experimental data in Fig.2, we do not consider the range close to the absorption edge. Experimental results in this range are distorted by interference effects,

while the theoretical curves by the exciton effect, screened during the excitation and ignored in the calculations.

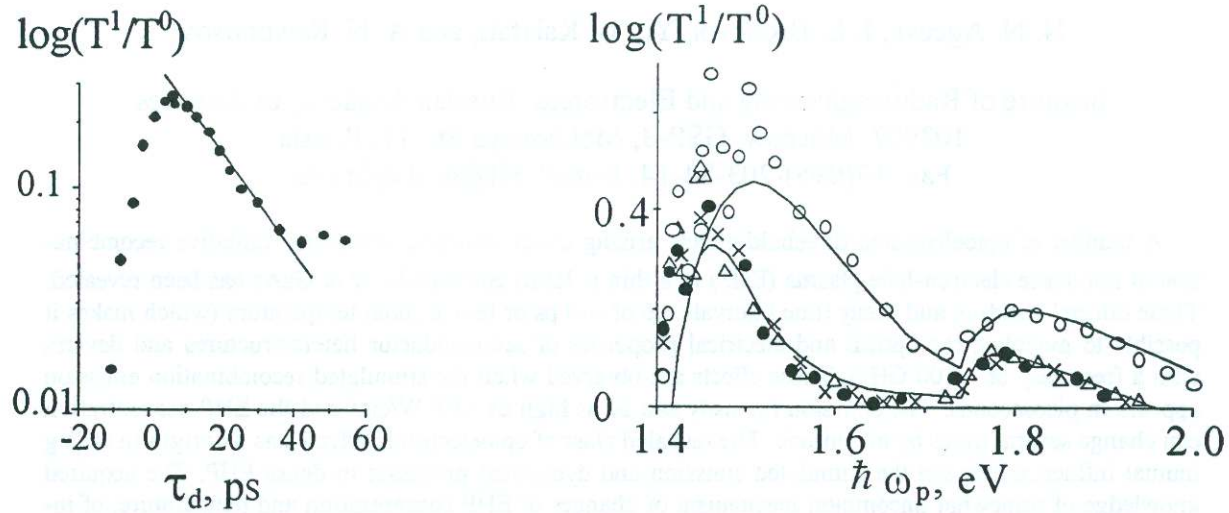


Fig. 1. GaAs bleaching as a function of time τ_d of the delay between the probe (p) and exciting (ex) pulses. $\hbar\omega_{ex}$ = 1.485 eV, $\hbar\omega_p$ = 1.568 eV, exciting light beam diameter F = 0.7 mm, the duration t_p of both exciting and probing light pulses is 14 ps.

Fig. 2. Bleaching spectrum, t_p = 40 ps. O - probing synhronous with excitation; Δ, ×, ● - after the exciting pulse. O, Δ - $\hbar\omega_{ex}$ = 1.52 eV; × - $\hbar\omega_{ex}$ = 1.67 eV, ● - $\hbar\omega_{ex}$ = 1.44 eV. Solid lines - calculations.

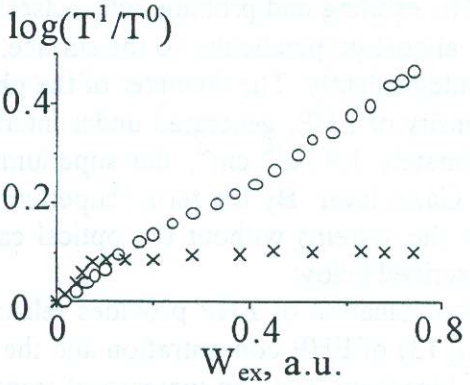


Fig 3. Bleaching of GaAs versus the energy W_{ex} of exciting pulse at $\hbar\omega_{ex}$ = 1.437 eV, $\hbar\omega_p$ = 1.562 eV, t_p= 30 ps. O - probing synhronous with excitation; × - after the exciting pulse.

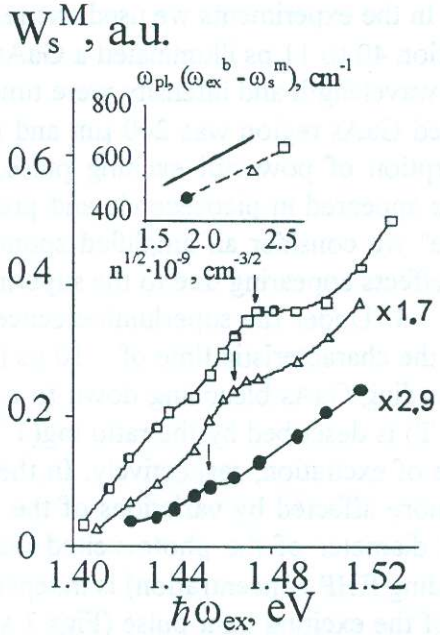


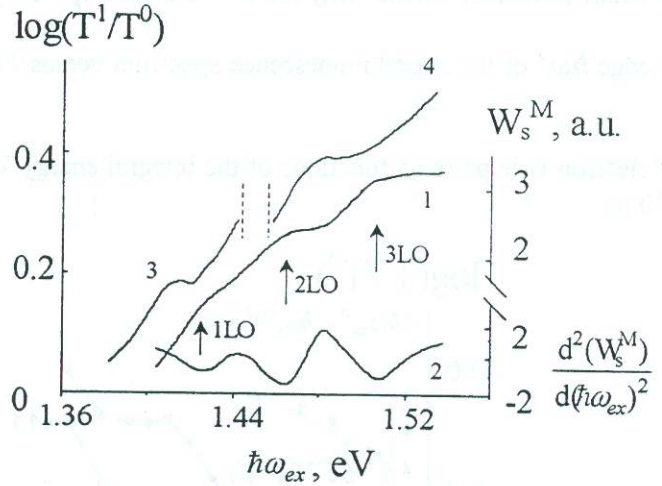
Fig. 4. The energy W_s^M at the maximum of the superluminescence spectrum versus $\hbar\omega_{ex}$ at t_p= 14 ps, F = 0.35 mm.: ● - W_{ex} = 0.1 a.u., Δ - W_{ex} = 0.3 a.u., □ - W_{ex} = 1.0 a.u. Solid lines are a guide for eye.

The insert shows the difference ω_{ex}^b - ω_s^m as a function of the electron concentration n. The positions of the maximum local enhancement of superluminescence, due to the exciting light Raman scattering, are indicated by the arrows. Here ω_{ex}^b is the frequency at which the maximum local enhancement of superluminescence is observed in $W_s^M(\hbar\omega_{ex})$ plots, ω_s^m is the frequency at the maximum of the superluminescence spectrum. Solid line is the theoretical dependence of plasmon frequency ω_{pl} on n.

2. An additional increase of the energy W_s^M at the maximum of the superluminescence spectrum, integrated in time domain, is produced by plasmon-assisted exciting light pulse Raman scattering [2] (Fig.4). An additional increase of W_s^M is also produced by energy transport of photogen-

erated electrons through LO phonon emission. The transport is going toward the bottom of the conduction band. The increase of W_s^M occurs when the spacing between the individual energy levels at which electrons are generated and the levels from which the undergo stimulated recombination is a multiple of the longitudinal optical (LO) phonon energy $\hbar\Omega$ (Fig.5). The graphs in Figs. 4–7,10,13 were measured using a sample with antireflection coating, to exclude the exciting or probe light interference. Note, that the above-mentioned both Raman scattering and electron energy transport are stimulated by the superluminescence.

The electron energy transport through LO phonon emission leads also to an appearance of the following oscillations with the period $\Delta = \hbar\Omega(1+m_e/m_h)$, here m_e and m_h are the masses of the electron and heavy hole, respectively. First, oscillations in the energy distribution of EHP and, correspondingly, in the transparency spectrum of GaAs (Fig.6) [3]. Second, oscillations in both the superluminescence spectrum width (FWHM) and the spectrum long-wavelength edge $\hbar\omega_s^e$ (correspondingly, the band gap width) as a function the exciting pulse photon energy $\hbar\omega_{ex}$ (Fig.7). The oscillations of $\hbar\omega_s^e$ as a function $\hbar\omega_{ex}$ occur, presumably, due to changes of the density of nonequilibrium LO phonons, emitted by the energy transport of electrons. An increase in the LO phonon density has the effect of narrowing the band gap E_g by virtue of the electron-phonon interaction [4].



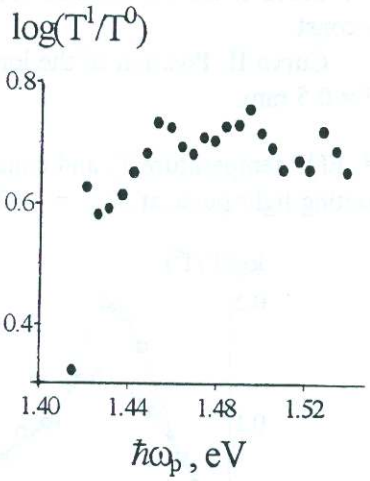


Fig. 5. Curve 1: the energy W_s^M as a function of the exciting pulse photon energy $\hbar\omega_{ex}$ at the diameter F = 0.5 mm, t_p= 14 ps. The positions of the maximum local enhancement of superluminescence, due to the transport of electrons through LO phonon emission, are indicated by the arrows. The number of LO phonons, emitted by this transport of one electron, is indicated adjacent to the arrows here and in Fig. 7.

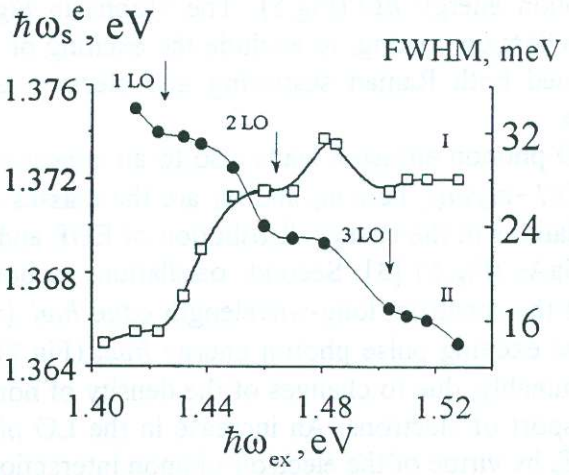
Curve 2: $d^2(W_s^M)/d(\hbar\omega_{ex})^2$ as a function of $\hbar\omega_{ex}$, used to determine the positions of the maximum local enhancement in curve 1.

Curves 3 and 4: bleaching of GaAs versus $\hbar\omega_{ex}$ at $\hbar\omega_p$ = 1.557eV. (3) – τ_d = 6 ps, F = 0.56 mm; (4)- τ_d = 0, F = 0.5 mm. All curves were measured at a fixed density of the exciting pulse energy, averaged over the beam cross section.

Fig. 6. Bleaching of GaAs as a function of the photon energy $\hbar\omega_p$ of the probing pulse at $\hbar\omega_{ex}$=1.558 eV, t_p= 14 ps, W_{ex} = const., τ_d= -3 ps.

3. The EHP concentration increases or decreases according to whether the temperature T_c of the EHP increases or decreases (Fig.8). It comes from the fact that the EHP concentration is controlled by recombination superluminescence and approximately satisfies condition (2). Consequently, a change of T_c due to the intraband light absorption, generation of LO-phonons or plasmons, etc., when combined with the recombination superluminescence, begins to control the changes of both EHP concentration and the transparency spectrum of GaAs (Figs. 5,9,10). It is also true for the EHP heating due to superluminescence, explained in item 5. The characteristic time of relaxation of the temperature as well as of EHP concentration down to a residual level is of ~10 ps

(see item 5). The photoconductivity (as well as the refractive index) has to follow the change of the concentration. So, the described phenomena can be used to create picosecond modulators of optical transparency and photoconductivity.



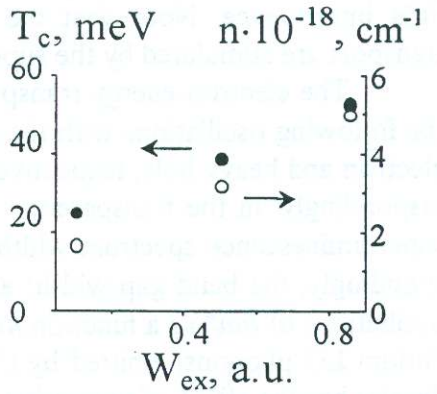


Fig. 7. Curve I: the superluminescence spectrum width (FWHM) versus $\hbar\omega_{ex}$ for F = 0.5 mm, t_p= 14 ps, W_{ex}= const.

Curve II: Position of the long-wavelength edge $\hbar\omega_s^e$ of the superluminescence spectrum versus $\hbar\omega_{ex}$ for F = 0.5 mm.

Fig.8. EHP temperature T_c and concentration n of electron-hole pairs as functions of the integral energy W_{ex} of exciting light pulse at $\hbar\omega_{ex}$ = 1.437 eV and t_p=30 ps.

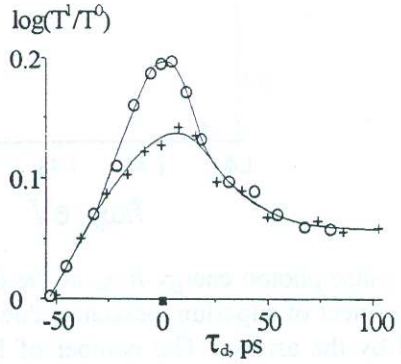


Fig. 9. Bleaching of GaAs as a function of delay time for $\hbar\omega_p$ = 1.56 eV, F = 0.6 mm, and t_p= 30 ps under irradiation by: + - exciting pulse only; O - exciting pulse and synhronous pulse (h) just heating EHP due to the intraband light absorption; ■ - heating pulse only; $\hbar\omega_{ex}$= 1.437 eV, $\hbar\omega_h$= 0.95 eV.

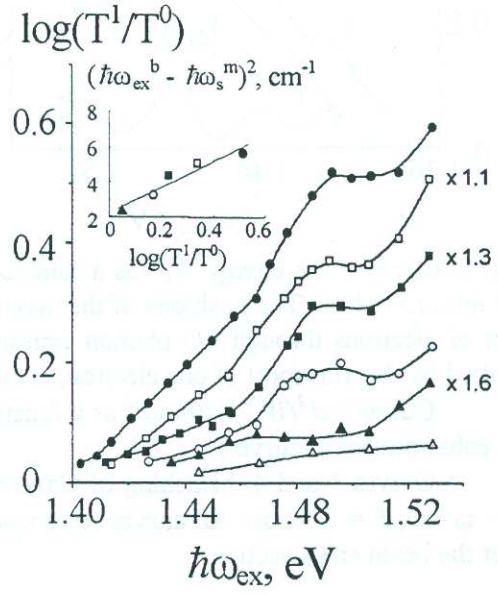


Fig. 10. GaAs bleaching as a function of $\hbar\omega_{ex}$ at $\hbar\omega_p$ = 1.557 eV, F =0.5 mm, t_p= 14 ps. •-W_{ex}=1.0 a.u., τ_d= -1 ps; □ - W_{ex} = 1.0 a.u., τ_d = -7 ps; ■ - W_{ex} = 0.5 a.u., τ_d = -1 ps; O - W_{ex} = 0.135 a.u., τ_d = -1 ps; ▲ - W_{ex} = 0.044 a.u., τ_d = -1 ps; Δ - W_{ex} = 0.02 a.u., τ_d = 18 ps.

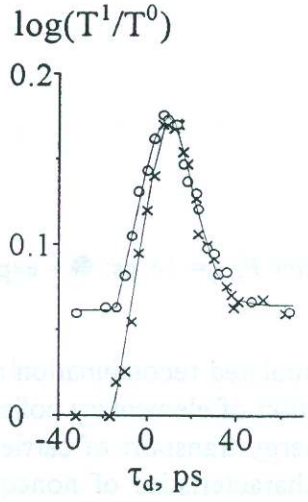
The insert shows the magnitude of $(\hbar\omega_{ex}^b - \hbar\omega_s^m)^2$ as a function of the bleaching $log(T^1/T^0)$ that was measured at $\hbar\omega_{ex} = \hbar\omega_{ex}^b$. Here $\hbar\omega_{ex}^b$ is the exciting photon energy at which the maximum local enhancement of the bleaching (by the exciting light Raman scattering) is observed in the dependencies of $log(T^1/T^0)=f(\hbar\omega_{ex})$; $\hbar\omega_s^m$ is the photon energy at the maximum of the superluminescence spectrum.

Note, that if the energy of the excitation pulse is sufficient by itself to create the bleaching above the residual level, the presence of the prebleaching virtually does not influence the amount of

the bleaching (Fig.11). This means that the bleaching (and the corresponding EHP concentration) within the range of reversible (in picosecond time scale) alterations is determined by the excitation pulse intensity at the given moment of time and is practically independent of its prehistory.

4. The superluminescence spectrum width becomes narrower with increasing universal parameter, which is the product of the beam diameter F by the average density D_{ex} of the picosecond exciting pulse energy. The measured spectra narrowed no more than by a factor of ~3 in agreement with calculations in [5]. The superluminescence spectrum also shifts toward longer wavelength area with increasing diameter F. That is caused by the EHP heating due to superluminescence [6].

The following correlation occurs between the time-integrated energy W_s of superluminescence with certain photon energy $\hbar\omega_s$ and time delay τ between two light pulses, excited GaAs. The dependence $W_s(\tau)$ has a minimum at $\tau = 0$ (Fig.12), which is due to the non-linear dependence of the energy W_s on the exciting pulse energy.



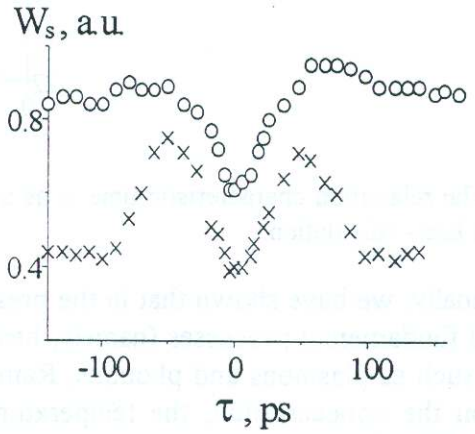


Fig. 11. GaAs bleaching versus delay time τ_d at $\hbar\omega_p$ = 1.558 eV, $\hbar\omega_{ex}$ = 1.436 eV, t_p= 11 ps: (×) - without sample prebleaching, (O) - with prebleaching.

Fig. 12. Energy of the superluminescence emission with $\hbar\omega_s$ = 1.395 eV from a sample excited by two pulses, with $\hbar\omega_{ex}$ = 1.494 eV and 1.483 eV, t_p= 20 ps, F = 0.6 mm, as a function of the delay time τ between the exciting pulses. × - W_{s1} = 0.21 a.u., O - W_{s1} = 0.54 a.u. (W_{s1} is the energy of the emission from the sample for each separate excitation pulse).

5. The negative feedback between the temperature of dense EHP and the intensity of powerful stimulated recombination emission appears due to EHP heating caused by the superluminescence. As a result of this feedback, the EHP temperature and concentration and GaAs transparency exponentially relax with a common characteristic time of ~ 10 ps (Fig. 1). An unusual feature of this picosecond relaxation is that the relaxation of EHP concentration and, correspondingly, of the transparency decelerates with increasing diameter F of the active (i.e., generating the superluminescence) GaAs region, although the intensity of the superluminescence emission increases. As is illustrated in Fig.13, this dependence is approximately described by the relation [6,7]:

$$\tau_r = 2/3(BT_c^{1/2}E_g/c(\gamma+F^{-1}) + A)\tau_h \qquad (3)$$

Here, τ_r is the characteristic time of relaxation of both EHP concentration and GaAs bleaching. The first term in the sum accounts for the relaxation deceleration due to EHP heating caused by the intraband absorption of the superluminescence. The second term corresponds to EHP heating caused by the fact that the energy of the charge carriers participating in the superluminescence is less than the average energy of the carriers in EHP (see also [1]). The parameters A and B were set at A = 8.5 and B = 0.57 in order to best fit the experimental data, and differ a little from the theo-

retical values of $A = 6.2$ and $B = 0.34$; c stands for the light speed in the medium and $\tau_h = 0.8$ ps is the EHP cooling time due to LO-phonon emission. The values of $T_c = 400$ K and $n = 2.8 \cdot 10^{18}$ cm^{-3}, averaged over the time of the bleaching relaxation to the residual level, were determined from the dependencies of the bleaching on T_c and n. The intraband light absorption $\gamma = 54$ cm^{-1} was determined from concentration n according to [8]. The time variables in relation (3) were measured in picoseconds, T_c in K, and E_g in eV.

The above-mentioned feedback mechanism will control the relaxation of stimulated emission in powerful high-speed semiconductor lasers and superluminescence diodes.

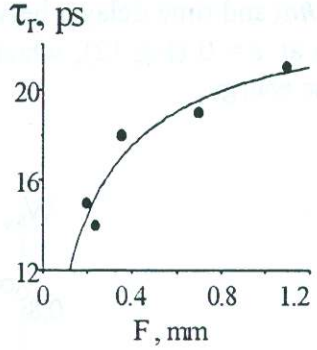


Fig. 13. The relaxation characteristic time τ_r as a function of the diameter F, $t_p = 14$ ps: ● - experimental data, solid line - calculation.

Finally, we have shown that in the presence of intensive stimulated recombination emission, individual fundamental processes (namely, heating of EHP, generation of elementary collective excitations such as plasmons and phonons, Raman scattering, the energy transport of carriers) influence upon the concentration, the temperature and some other characteristics of nonequilibrium dense hot EHP in a qualitatively unusual way. The processes in EHP induced by stimulated emission, in turn, make effect on the emission itself (namely on the spectrum, emission intensity, times of build-up and decay, etc.). That strong mutual influence between the stimulated emission and dynamical processes in dense EHP manifests itself in above described number of optoelectronic effects and might essentially affect on the performance of semiconductor high-speed optoelectronic devices with high emission intensity.

We hope that the outlined results of our fundamental studies will find their place in applications of high speed powerful optoelectronics based on GaAs. With this aim in view we are ready to cooperate with the specialists in this field of optoelectronics.

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