INTERCONNECTION BETWEEN THE PICOSECOND STIMULATED RECOMBINATION EMISSION AND THE KINETICS OF DENSE HOT ELECTRON-HOLE PLASMA IN GaAs

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High-speed optoelectronic effects, caused by interconnection between the picosecond stimulated emission and the kinetic processes in dense hot electron-hole plasma in GaAs, are briefly reviewed. The newest effect of this class is reported in detail. It deals with the band gap narrowing as a result of generation of multi-component plasma in GaAs. The plasma is generated by a picosecond light pulse and the picosecond stimulated emission is observed. In this situation, the total concentration of the pairs of photogenerated electrons and holes is experimentally proved to be the only parameter defining the electron distribution between Γ_6- and L_6-valleys and the corresponding narrowing of the band gap. This is explained by the fact that in the presence of the emission the temperature and concentration of the charge carriers are approximately bound.

Interconnection between the intensive stimulated recombination emission and the kinetic processes in dense hot electron-hole plasma (EHP) in GaAs can influence the performance of high-speed semiconductor elements employing ultrashort pulses of such an emission. The physical phenomena caused by the interconnection are the objects of our study.

All the experimental studies were carried out at room temperature. The stimulated recombination emission appeared in a thin (~1 μm) layer of GaAs during the dense EHP photogeneration by picosecond light pulse. The estimated emission intensity reached ~10^8 W·cm^{-2} and then decayed with the characteristic time ~10 ps with the decay of the excited pulse. It has been found that the kinetic processes in EHP were interconnected with the emission. Among these kinetic processes were: (1) different mechanisms of EHP heating (including intraband heating), (2) energy transport of charge carriers, (3) screening of electron-LO phonon interaction, (4) Raman light scattering with generation of elementary collective excitations (plasmons and *LO* phonons), etc. We found that interconnection between these processes and emission gave rise to ultrafast (in picosecond time scale) reversible variations of: (I) the concentration and temperature of charge carriers, band gap width, optical transparency, photoconductivity, etc.; (II) the width and shape of the spectrum of the stimulated emission, the position of the longer-wavelength edge of the spectrum; (III) the emission intensity; (IV) the carrier energy distribution (it may be converted into non quasi-equilibrium one, oscillating with energy). That is, new possibilities to modulate not only optical but also electrical properties of semiconductor heterostructures with the frequencies of ~ 100 GHz have been found.

The most up-to-date study was devoted to band gap narrowing as a result of altering the concentration (> 10^{18}cm^{-3}) and temperature (≥ 300 K) of the multi-component EHP. In application aspect, this problem is significant in particular because the narrowing causes a shift of the light amplification band in the active medium, etc. The dependence of the band gap width E_g on the concentration of charge carriers has been found to be too weak at large concentrations. It was explained as follows. In the case of intensive stimulated recombination emission (below referred to as the superluminescence) an increase of the concentration leads to an increase of the EHP temperature. Hence, a greater share of electrons appears in L_6-valley while the band gap narrowing is mostly determined by the electrons of Γ_6-valley. Comparison of experimental results and calculations of the band gap narrowing, caused by Coulomb interaction of carriers, confirmed this assumption.

Another consequence of the redistribution of electrons between the valleys is connected with peculiarities of the integral energy of picosecond superluminescence as a function of the exciting light photon energy [1]. The peculiarities were interpreted as the superluminescence amplification as a result of Raman scattering of exciting light on combined plasmon-phonon oscillations. The Raman scattering was stimulated by the superluminescence. Radiation of a quantum $h\omega_{op}$ of the combined oscillations increased the probability of electron transition from a state with the energy the electron had by excitation to the state from which the superluminescence originated. The energy $h\omega_{op}$, determined in experiment [1] under such an assumption was in agreement with calculations. In the calculations the character of the electron redistribution between the valleys was considered at the superluminescence.

The longer-wavelength edge $h\omega_s^e$ of emission spectrum was observed shifted to even longer wavelengths with increasing density D_s of the picosecond superluminescence energy, integrated over time and spectrum and averaged over the GaAs excited area cross-section. The change of $h\omega_s^e$ reflected the narrowing of the band gap E_g. With variation of the excite pulse parameters the energy $h\omega_s^e$ was found to vary approximately as the only function of the energy density D_s (Fig.1). In order to explain the revealed dependence of $h\omega_s^e(D_s)$, we made the following, rather natural assumption. The emission density D_s is approximately proportional to the concentration of photogenerated pairs of electrons and holes:

$$D_s \sim p = n = n_\Gamma + n_L, \qquad (1)$$

Here p is the total concentration of heavy and light holes; n, n_Γ and n_L are the electron concentrations, total and in Γ_6- and L_6-valleys, respectively. Then it is believed that the dependence $h\omega_s^e(D_s)$ reflects the shift of the superluminescence spectrum edge caused by the band gap narrowing with increasing EHP concentration.

Usually, different levels of heating are possible for electrons at a fixed total concentration n. In the presence of intensive superluminescence, the EHP temperature T and charge carrier concentration are bound. In this case the carrier energy distribution is close to the threshold one wherein the difference between quasi-Fermi levels of electrons μ_e and holes μ_h is equal to the band gap width E_g:

$$\mu_e(n,T) - \mu_h(p,T) = E_g. \qquad (2)$$

In this approximation the electroneutrality condition $n_\Gamma + n_L = p$ and the temperature dependence of the electron distribution between Γ_6- and L_6-valleys [2] allow us to define the electron concentrations n_Γ and n_L as functions of the EHP temperature (Fig.2).

The band gap narrowing ΔE_g originated from Coulomb interaction between the charge carriers. In terms of only the exchange energy (contribution of the correlation energy is small):

$$\Delta E_g = 4/3 \cdot (E_{ex}^e + E_{ex}^h), \qquad (3)$$

where E_{ex}^e and E_{ex}^h are exchange energies of electron (e) and hole (h) , respectively:

$$E_{ex}^e = -3e^2(3\pi^2 n_\Gamma)^{1/3}/4\pi\varepsilon\,, \qquad E_{ex}^h = -3e^2\eta(3\pi^2 p)^{1/3}/4\pi\varepsilon\,. \qquad (4)$$

Here e is the electron charge, ε =12.85 is the static dielectric constant, and η = 0.73 is the coefficient considering "engagement" of heavy and light holes.

The dependence $E_g = E_{g0} + \Delta E_g(n)$, calculated with expressions (3) and (4) with account of insignificant contribution of correlation energy, approximately coincided with the function $h\omega_s^e(D_s)$ in Fig.1. It confirmed the above interpretation of the experimental dependence $h\omega_s^e(D_s)$. We admitted that $E_g = h\omega_s^e$ = 1.382 eV at $n \approx 1.32 \cdot 10^{18}$ cm^{-3} in order to relate the experimental and calculated dependencies. Then E_{g0} = 1.407 eV, which agrees with the photon energy of the longer-wavelength edge of the spontaneous emission spectrum of "unexcited" GaAs. The agreement of the calculation and the experiment was reached without taking into account the exchange energy alteration with temperature. Apparently, it doesn't lead to essential errors in our conditions, when electrons are degenerated and the hole states are between degenerated and Boltcman ones.

Fig.1 demonstrates applicability of the EHP threshold state approximation at picosecond superluminescence. In such a state, the concentration, the temperature and the electron distribution on valleys become uniquely interconnected. However, systematic deviation of the experimental curve from the calculated dependence $E_g(n)$ originated after an increase of the excited spot diameter $F >$ 0.5 mm. The reason for the deviation needs additional study.

Applicability of the "threshold" state approximation in the case of superluminescence was proved by other means. As was mentioned in the introduction, earlier we revealed peculiar features in the dependence of the picosecond superluminescence energy on the pumping photon energy [1]. The features were interpreted as a consequence of the superluminescence amplification as a result of the exciting light Raman scattering. Raman scattering was stimulated by the superluminescence. The scattering occurred with radiation of quantum $h\omega_{op}$ (mentioned briefly as the plasmon) of the combined oscillations of optical plasmon and longitudinal optical (LO) phonon. From the condition $h\omega_s^e \approx E_g(n)$ we determined the concentration n at those exciting photon energy which resulted in the rise of the peculiarities. For the obtained n the plasmon energy $h\omega_{op}$, experimentally determined in [1], didn't contradict the calculated dependence $h\omega_{op}(n)$, Fig.3. The frequency ω_{op}:

$$\omega_{op}^2 = (\omega_L^2+\omega_p^2)/2 +[(\omega_L^2+\omega_p^2)^2 - 4\omega_p^2\omega_T^2]^{1/2}/2, \quad (5)$$
$$\omega_p^2=4\pi e^2(n_\Gamma/ m_e^\Gamma +n_L /m_e^L + p_h/m_{hh} + p_l /m_{lh})/\varepsilon,$$

where m_e^Γ, $m_e^L = 0.4m_0$, $m_{hh} = 0.62m_0$, $m_{lh} =0.075m_0$ are the effective masses of, respectively, electron in Γ_6-valley (see below), electron in L_6 -valley, heavy hole and light hole, m_0 – the rest-mass of electron, $\omega_L = 292$ cm^{-1} and $\omega_T =269$ cm^{-1} are the frequencies of the optical longitudinal and transverse phonons, respectively. We took into account the mass variation $m_e^\Gamma = 0.074 \div 0.088\ m_0$ with a change of n and T. The mentioned values of masses are realistic, but their precise definition is difficult due to dispersion of experimental results of different authors, due to the anisotropy of masses, non parabolic and corrugated energy bands, the anisotropy of the plasmon wave vector, etc.

Thus, the study of the integral spectrum of picosecond stimulated emission, including the analysis in the case of Raman scattering with plasmon participation, experimentally proved the following. In the case of picosecond superluminescence in GaAs it is possible to use the threshold state approximation of the multi-component EHP. Under this approximation the total concentration of electron and hole pairs, the temperature of charge carriers and the distribution of electrons between valleys become uniquely bound. Correspondingly, the band gap narrowing, caused by Coulomb interaction of carriers, is uniquely determined by the total concentration of electron and hole pairs.

The proved opportunity to use the approximation of the threshold state of dense hot multi-component EHP can have a practical value. It may be used in calculations of: (a) the mobility of charge carriers, (b) the optical transparency increase, induced by EHP, (c) the position of the longer-wavelength edge of light gain band in GaAs, (d) the amplification of the stimulated recombination emission by means of applying the Raman scattering of the exciting light, etc.

Finally, note that evolution of high-speed semiconductor optoelectronics needs the development of the kinetic theory of both the ultrashort intensive stimulated recombination emission and ultrafast processes, stimulated by the emission, in hot dense EHP. Further investigation of the interconnection between the emission and kinetic processes in the EHP can be useful in achieving this aim.

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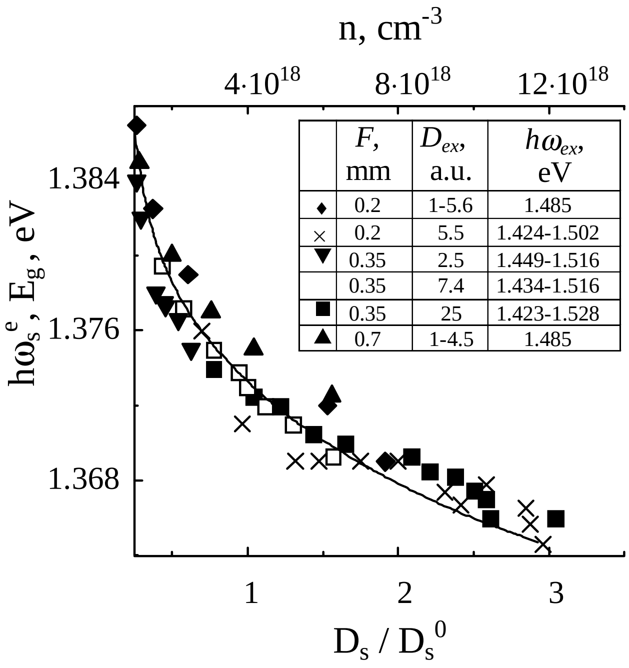

Fig.1. Photon energy $h\omega_s^e$ as a function of superluminescence energy density D_s. D_s^0 is normalized superluminescence energy density. The exciting light pulse parameters - the beam diameter (*F*), energy density (D_{ex}), photon energy ($h\omega_{ex}$). – are given in the legend. The calculated band gap E_g as a function of total concentration *n* of electron and hole pairs is shown by the solid line.

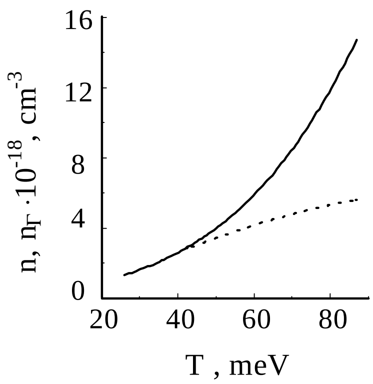

Fig.2. Total electron concentration *n* (solid line) and concentration n_Γ of electrons in Γ_6-valley (dashed line) as a functions of the temperature *T*.

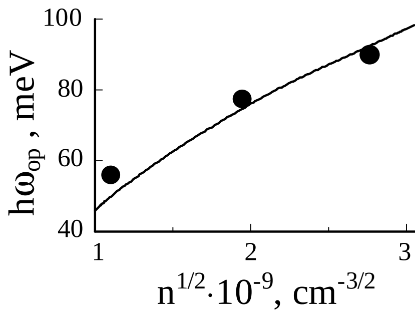

Fig.3. Quantum of energy $h\omega_{op}$ of the plasmon-phonon oscillations as a function of electron and hole pair concentration n. Spots-experiment, solid line–calculation.