Luminescence and carrier concentration in Sb-containing narrow bandgap quantum wells under optical excitation

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Abstract. We have experimentally studied the photoluminescence from InGaAsSb/AlGaAsSb quantum wells of different width under different levels of interband optical pumping. The dependences of photoluminescence intensity at spectral maxima on carrier concentration were theoretically calculated. This dependence was received using the rate equation taking into account the role of radiative and nonradiative recombination. Comparison of the theoretical and experimental results allowed to determine the nonequilibrium carrier concentration in quantum wells at certain experimental conditions.

1. Introduction
The InGaAsSb/AlGaAsSb quantum well (QW) nanostructures can serve as a basis of sufficiently powerful semiconductor injection lasers emitting in the wavelength range of 2–4 μm operating in continuous-wave mode. Lasers emitting in the mid-infrared range can be widely applied in the fields of spectroscopy of various substances, transmission of information via wireless communication lines, in security and fire control systems, in medical, military and other industries. The nonequilibrium carrier concentration and dependence of concentration upon pumping intensity are the important factors determining the operation of the laser. In this work, we present the method that helps to determine the nonequilibrium carrier concentration using the functional dependences of photoluminescence intensity on pumping intensity taken from experiment and theoretical calculations.

2. Samples and experimental setup
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2. Samples and experimental setup
The InGaAsSb/AlGaAsSb quantum well (QW) structures with different quantum well width (4, 5, 7 and 9 nm) were studied. Growth details and band structure calculations are given in Ref. [1]. The interband photoluminescence spectra were studied using a vacuum Fourier transform infrared spectrometer Bruker Vertex 80v. The samples were mounted into an optical cryostat cooled with liquid nitrogen (T = 77 K). Electron-hole pairs were excited directly in QWs by radiation of pulsed semiconductor laser with a photon energy of 1.17 eV. The duration of optical excitation pulses was Δt = 100 ns, the repetition frequency was 800 Hz, and the maximum average power was 2.4 mW. An InSb photodetector was used as a detector of radiation.

3. Results and discussions
The concentration of non-equilibrium charge carriers involved in radiative recombination can be obtained from analyzing the photoluminescence spectra at different levels of optical pumping. We
measured photoluminescence spectra at different pumping intensity $J_{PUMP}$ and experimentally obtained dependences of photoluminescence intensity at spectral maximum $J_{PL}$ on pumping intensity. Obviously, the spectral maximum corresponds to the effective bandgap. Dependence $J_{PL}(J_{PUMP})$ for the 9 nm wide QWs is presented in figure 1 by dots. Using the method described in Ref. [2], we received the theoretical dependences of photoluminescence intensity at spectral maxima on carrier concentration $N$ (see figure 2). For this purpose, we wrote down the number of photons emitted per unit volume per unit time, which is proportional to the derivative of Kane matrix element, overlap integral and Fermi-Dirac distribution function with $N$ as a parameter. It should be noted that non-equilibrium charge carriers in our experiments were excited directly in the quantum wells, i.e., the pump photon energy (1.17 eV) was less than the barrier band gap (1.72 eV). Under this type of excitation, the distance between the quantum confinement levels at which electrons and holes are produced in a quantum well is less than the pump photon energy value.

![Figure 1](image1.png)  
**Figure 1.** Experimental (dots) and theoretical (line) dependences of photoluminescence intensity at spectral maximum on pumping intensity for 9 nm wide QWs.

![Figure 2](image2.png)  
**Figure 2.** Theoretical dependence of photoluminescence intensity at the energy near effective bandgap versus carrier concentration for all structures at $T = 77$ K.

In order to find relation between carrier concentration and pumping intensity we used the rate equation:

$$\alpha L J_{PUMP} = AN + BN^2 + CN^3,$$

(1)

where $\alpha$ – absorption coefficient, $L$ – QWs width, $A = 0.5$ ns$^{-1}$ [1] – non-radiative Shockley-Read-Hall recombination rate, $B = 10^{-3}$ cm$^3$/s [2] – radiative recombination rate, $C = 10^{15}$ cm$^3$/s [1] – non-radiative Auger-recombination rate for 5 nm wide QW. The coefficient $C$ for other QWs was taken in two order of magnitude less. All this approximations are correct because samples have similar design and band parameters except the QW width. Quantum wells width affects only the energy spectrum and the condition of Auger recombination (see below).

The calculated dependence of $J_{PL}(\alpha J_{PUMP})$ for 9 nm wide QW is presented in figure 1 by line. By scaling the abscissa we have found the relation between experimental and theoretical value of pumping intensity. Using similar dependences $J_{PL}(\alpha J_{PUMP})$ for 4, 5, 7 and 9 nm wide QWs and the rate equation (1), we determined the dependences of carrier concentration $N$ on the pumping intensity. They are presented in figure 3.
Figure 3. Dependences of carrier concentrations on pumping intensity for structures with different QW widths.

The carrier concentration in 5 nm wide QW is lower because of more probable nonradiative processes. This approach is correct because samples differ only by QW width which causes the difference in the band structure. This does not influence the non-radiative Shockley-Read-Hall recombination rate, but could significantly influence the non-radiative Auger recombination [1, 3]. Band structure and energy levels were calculated using the Schrödinger equation and Kane’s model taking into account the nonparabolicity of the subbands. This approximation must be used, since the electron energy in subbands is of the order of the band gap value. The calculation shown that in 5 nm wide QWs the condition of resonant non-radiative Auger recombination is satisfied because the energy separation between the first heavy hole level and the spin-orbit split-off level is equal to the effective bandgap (see inset in figure 4):

\[ E(\text{hh}) - E(\text{sol}) \approx E(\text{e1}) - E(\text{hh}). \]  

(2)

So, in structure with 5 nm wide QW the concentration of carriers is less than in other samples due to satisfaction of resonant Auger condition. It should be noted that the resonant Auger recombination was early observed in the structure with 5 nm wide QWs when analyzing the photoluminescence dynamics measured by the up-conversion method [1]. Here we got the same results using another experimental method.

It is well-known that shortwave tail of photoluminescence spectra is determined with the distribution function of carriers and can give information about carrier heating. Using the method described in [4], we determined the carrier temperature for all structures at different pumping intensities. The carrier temperature increase (\( \Delta T_c \)) is approximately 10 K for 5 nm wide QWs for the maximum pump level. For other structures, \( \Delta T_c \approx 20 \) K (see figure 4). It is associated with more frequent electron-electron collisions and greater carrier concentration in structures without resonant nonradiative Auger recombination.
Figure 4. Dependences of carrier temperature on pumping intensity for structures with different QW widths. The inset shows the condition of resonant Auger recombination.

4. Conclusion
Finally, we presented the method allowing the determination of nonequilibrium carrier concentration dependence on optical pumping intensity in narrow-band nanostructures. Using this method, we found the carrier concentrations in InGaAsSb/AlGaAsSb nanostructures with different QW widths under certain experimental conditions.

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