

# Photoluminescence in InGaAsSb/AlGaAsSb quantum wells: impact of nonradiative recombination

M Ya Vinnichenko<sup>1</sup>, I S Makhov<sup>1</sup>, A V Selivanov<sup>1</sup>, D A Firsov<sup>1</sup>, L E Vorobjev<sup>1</sup>, L Shterengas<sup>2</sup> and G Belenky<sup>2</sup>

<sup>1</sup> Peter the Great St. Petersburg Polytechnic University, 29 Polytechnicheskaya str., St. Petersburg 195251, Russia

<sup>2</sup> Department of Electrical and Computer Engineering, State University of New York at Stony Brook, New York, 11794 USA

e-mail: mvin@spbstu.ru

**Abstract.** The photoluminescence in nanostructures with InGaAsSb/AlGaAsSb quantum wells of different widths is investigated experimentally under different pumping levels and theoretically. The experimentally determined dependencies of photoluminescence intensity on the optical pumping level are compared with the calculated dependences of photoluminescence intensity on the nonequilibrium carrier concentration. The presence of resonant nonradiative Auger recombination in one of the investigated samples is proved by the comparison between experiment and calculations.

## 1. Introduction

The InGaAsSb/AlGaAsSb quantum well (QW) nanostructures can be used as a basis for injection laser diodes that emit radiation in the wavelength range between 2 and 3  $\mu\text{m}$  and above [1, 2]. Such laser diodes may be employed in many fields: infrared spectroscopy, safety systems, medicine, wireless communications, etc. Furthermore, the atmosphere is transparent in the spectral range 2 - 4  $\mu\text{m}$ , thus an applicability area of these lasers expands. However, some problems of the development of effective laser diodes operating in this spectral range are not completely solved.

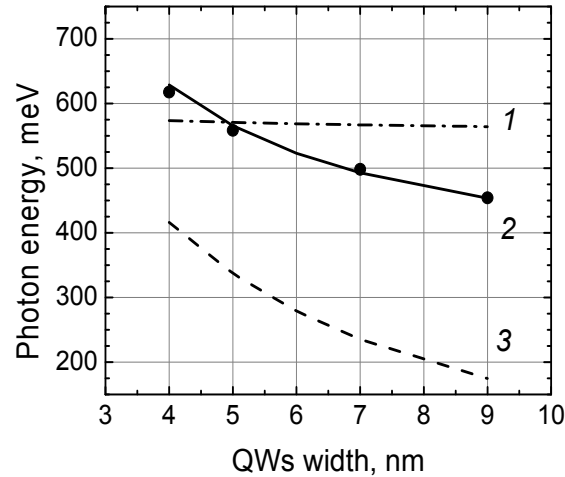
The efficiency and characteristics of the injection lasers are determined by the relation between radiative and nonradiative carrier lifetimes. It is well known, that at high injection levels the Auger recombination is one of the most important negative mechanisms of nonradiative recombination in QWs [3]. In some cases, Auger recombination can become resonant, which reduces the nonradiative lifetime by 2–3 orders of magnitude [4] and causes corresponding degradation of the laser parameters. For these reasons, the investigation of Auger recombination is undoubtedly of interest. The principal research method in our work is an analysis of interband photoluminescence spectra at different pump levels, which gives the essential information about the concentration and distribution function of the nonequilibrium charge carriers involved in the radiative recombination.

## 2. Sample and experiment

The structures for optical studies were MBE grown on GaSb substrates and contained ten InGaAsSb/AlGaAsSb QWs. The structures had different quantum well widths: 4, 5, 7 and 9 nm. The position of the energy levels in QWs was calculated in the context of Kane's model [5], in which the



nonparabolic shape of subbands was taken into account. This approximation must be used since the electron energy in subbands is of the order of the band gap value. We used material parameters taken from the paper [6]. Compressive strain in QWs decreases the density of states in the heavy hole subband. Therefore, in energy spectrum calculations we used the heavy hole masses less than in a bulk material. The calculated energy gaps between the first electron (*e1*) and heavy hole (*hh1*) subbands, the first (*e1*) and second (*e2*) electron subbands, the first heavy hole (*hh1*) and the first split off by spin-orbit interaction (*so1*) subbands for different QW widths are shown in figure 1.



**Figure 1.** Experimental positions of the photoluminescence peaks related to the transitions  $e1 \rightarrow hh1$  (circles) and calculated energy gaps (lines):  $E(hh1)-E(so1)$ ,  $E(e1)-E(hh1)$ ,  $E(e2)-E(e1)$  marked as (1), (2) and (3), respectively.  $T = 77$  K.

The interband photoluminescence spectra were studied using a vacuum Fourier transform infrared spectrometer Bruker Vertex 80v operating in a step-scan mode. For the experimental studies, the samples were mounted into an optical cryostat where the sample temperature can be varied from 80 K to 320 K. Electron-hole pairs were excited directly in QWs by a pulsed semiconductor laser with a photon energy of 1.17 eV. The optical excitation of the samples was obtained through a fused silica window. Photoluminescence emission of the samples was collected through a ZnSe window by an off-axis parabolic mirror of a spectrometer. A Ge filter was used in order to block the pumping light. An InSb photodetector was used as a detector of radiation.

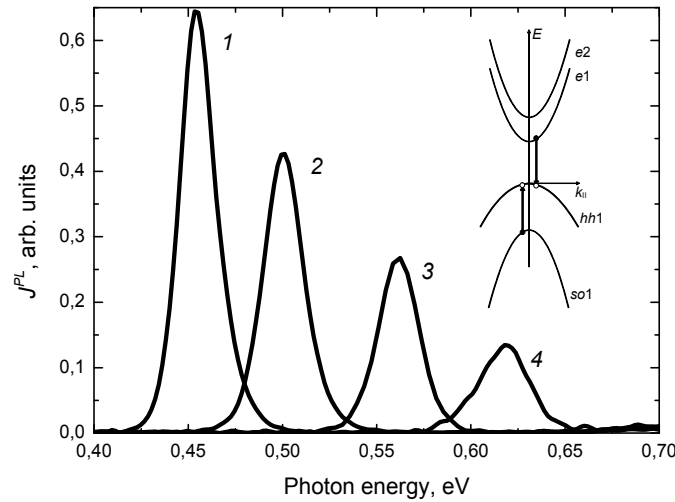
Our goal was to investigate the influence of Auger processes on the carrier concentration. The condition of the resonance Auger recombination is the equality of the effective band gap and the energy separation between the first heavy hole level and the spin-orbit split-off level [3, 4] (see inset in figure 2):

$$E(e1) - E(hh1) \cong E(hh1) - E(so1). \quad (1)$$

In our structures, this condition of resonant nonradiative Auger processes is satisfied only in the structure with 5 nm wide QWs at liquid nitrogen temperature ( $T = 77$  K). So, in this structure the concentration of carriers taking part in the radiative recombination should be less than in other samples. It should be noted that the resonant Auger recombination in the structure with 5 nm wide QWs was early observed [3] when analyzing the photoluminescence dynamics measured by the up-conversion method. Here we present another experimental method.

### 3. Results and discussions

The interband photoluminescence spectra are presented in figure 2 for the maximum pumping level for all structures at  $T = 77$  K. The spectral positions of the photoluminescence peaks for all structures are shown in figure 1 by solid circles. It is clear that photoluminescence intensity at the maximum of its spectral dependence ( $J_{\text{MAX}}^{\text{PL}}$ ) is determined by the optical electron transitions  $e1 \rightarrow hh1$ . So, one can see a good agreement between experiment and calculations.



**Figure 2.** Photoluminescence spectra for the maximum optical pump level. Curves 1, 2, 3, 4 correspond to the samples with QW widths of 9, 7, 5, 4 nm. The lattice temperature  $T = 77$  K. The inset shows the condition of resonant Auger recombination.

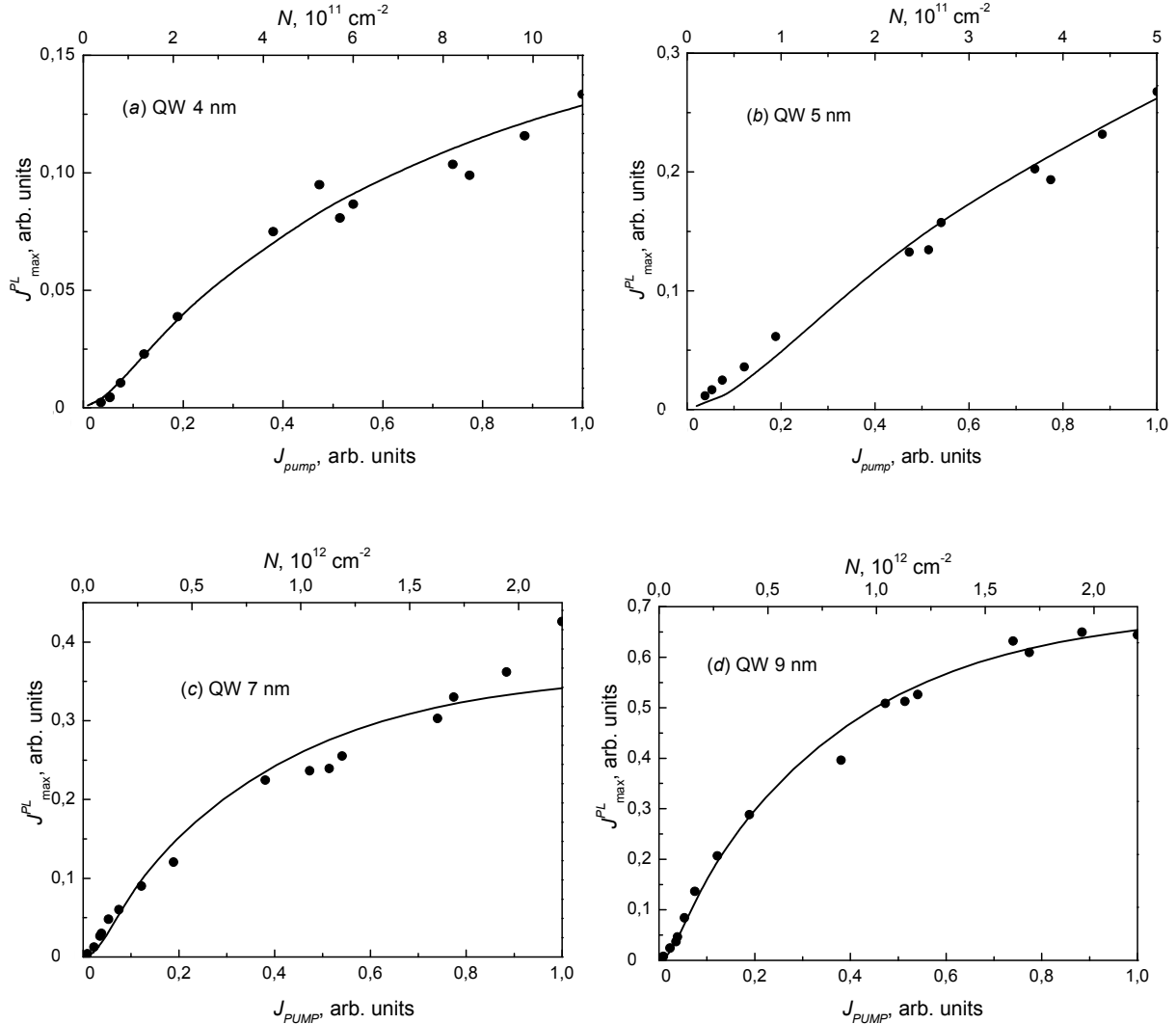
From the photoluminescence spectra measured at different pump levels, we received dependences of maximum photoluminescence intensity  $J_{\text{MAX}}^{\text{PL}}$  on the pump level  $J_{\text{PUMP}}$  (circles in figure 3). Concentration of excited charge carriers is proportional to the pump intensity. However, the photoluminescence intensity at a dedicated wavelength is not simply proportional to the concentration of carriers in the QWs. Using the method described in Ref. [7], we received the theoretical dependence of  $J_{\text{MAX}}^{\text{PL}}$  on carrier concentration (see lines in figure 3). For this purpose, we wrote down the number of photons  $dq_{sp}^{i \rightarrow j}$  emitted per unit volume per unit time in the photon energy range from  $h\nu$  to  $h\nu + d(h\nu)$  due to the optical electron transitions from the electron level  $i$  to the hole level  $j$ :

$$dq_{sp}^{i \rightarrow j} = \frac{2}{\pi} \frac{n}{\hbar} \frac{e^2}{m_0^2} \frac{m_{eh}}{L_{QW}} (h\nu) \frac{P^2}{c^3} I_{i \rightarrow j}(\mathbf{k}^2) f_e f_h d(h\nu), \quad (2)$$

where  $L_{QW}$  is the quantum well width,  $n$  is the refraction index,  $m_{eh}$  is the reduced effective mass,  $m_0$  is the free electron mass,  $c$  is the light velocity,  $\hbar$  is the reduced Planck's constant,  $I_{i \rightarrow j}$  is the overlap integrals for the selected quasi-momentum calculated in [8],  $\mathbf{k}$  is the wave vector,  $P$  is the Kane matrix element of the momentum operator written as for a bulk semiconductor:

$$P^2 = \frac{m_0}{2} \left( \frac{m_0}{m_e^*} - 1 \right) \frac{E_g (E_g + \Delta_{so})}{(E_g + \frac{2}{3} \Delta_{so})}, \quad (3)$$

$E_g$  is the bandgap energy,  $m_e^*$  is the electron effective mass,  $\Delta_{so}$  is the energy of level split off by spin-orbit interaction,  $f_e, f_h$  is the Fermi-Dirac distribution functions of electrons and holes.



**Figure 3.** Dependencies of photoluminescence intensity measured at the maximum of spectra on the pump level (circles) and on the electron concentration (solid lines, calculations) for the samples with different QW widths at  $T = 77$  K.

The theoretical results of the photoluminescence intensity maximum dependencies on the carrier concentration  $N$  for the samples with different QW widths are shown in figure 3 by circles. These results are in good agreement with the experimental dependencies of the photoluminescence intensity maximums on the pump level for all our samples (see figure 3). Comparison of theoretical and experimental dependencies gives us the information about the concentration of carriers taking part in the radioactive recombination. The different shapes of these curves can be explained by the following. At a low pump level, the photoluminescence intensity is proportional to the product of nonequilibrium electron and hole concentrations (we have neglected the equilibrium concentration). At a medium pump level, the electron gas becomes degenerated while holes are still non-degenerated due to the different effective masses of electrons and holes. As a result, the  $J_{MAX}^{PL}$  depends only on the

concentration of excited holes. At a high pump level, the concentrations of electrons and holes become constant and  $J_{\text{MAX}}^{\text{PL}}$  tends to the saturation. One can see that the concentration of carriers taking part in the radiative recombination is lower for the structure with 5 nm wide QWs (see the absence of saturation in figure 3 (b)).

A low carrier concentration in the 5 nm wide QW structure as compared to other structures with close parameters can be explained by the presence of an additional recombination channel. Based on the fulfillment of condition (1) for this structure, we suppose that this channel is related to resonant Auger recombination in accordance with the rate equation:

$$\frac{dN}{dt} = -AN - BN^2 - CN^3, \quad (3)$$

where the first term describes the Shockley–Read–Hall recombination, the second term describes the radiative recombination, and the third term describes the Auger recombination. The coefficient  $C$  reaches the maximum value in the 5 nm wide QW structure. In all structures except the 5 nm wide QWs, the concentration of carriers taking part in the radiative recombination is higher, that can be explained by the lack of resonant Auger recombination. These results confirm the assumption that the condition of resonant Auger recombination (1) can be satisfied only in the samples with 5 nm wide QWs. Similar findings were obtained in our previous study [3].

The shortwave tail of photoluminescence spectra describes the distribution function of carriers and can give information about carrier heating. Using the method described in [9], we determined the carrier temperature for all structures at different pump levels. 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. It is associated with more frequent electron-electron collisions in structures without resonant nonradiative Auger recombination.

#### 4. Conclusion

In the present work, the dependencies of the photoluminescence intensity at the maximum of the spectra on the pumping intensity and carrier concentration were experimentally and theoretically investigated in the nanostructures with different InGaAsSb/AlGaAsSb QW widths. The nonequilibrium carrier concentrations for the samples with 9, 7, 4 nm wide QWs are approximately the same, whereas the carrier concentration for the sample with 5 nm wide QWs is significantly less. This result can be explained by the mechanism of the resonant nonradiative Auger recombination, that is significant for this sample. The hot carrier temperature was estimated for all structures.

#### Acknowledgments

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#### References

- [1] Belenky G, Shterengas L, Kipshidze G and Hosoda T 2011 *IEEE J Sel Top Quantum Electron* **17** 1426
- [2] Shterengas L, Belenky G, Hosoda T, Kipshidze G and Suchalkin 2008 *S Appl Phys Lett* **93** 011103
- [3] Vinnichenko M Y, Firsov D A, Vorobjev L E, Mashko M O, Shterengas L and Belenky G 2013 *Semiconductors* **47** 146
- [4] Danilov L V and Zegrya G G 2008 *Semiconductors* **42** 550
- [5] Kane E 1957 *Journal of Physics and Chemistry of Solids, Elsevier* **1** 249
- [6] Vurgaftman I, Meyer J R and Ram-Mohan L R 2001 *Journal of Applied Physics* **89** 5815

- [7] Vorob'ev L E, Zerova V L, Borshchev K S, Sokolova Z N, Tarasov I S and Belenky G 2008 *Semiconductors* **42** 737
- [8] Sokolova Z N and Khalfin V B 1989 *Soviet physics semiconductors – USSR* **23** 1117
- [9] Vorobjev L E, Vinnichenko M Ya, Firsov D A, Zerova V L, Panevin V Yu, Sofronov A N, Thumrongsilapa P, Ustinov V M, Zhukov A E, Vasiljev A P, Shterengas L, Kipshidze G, Hosoda T and Belenky G 2010 *Semiconductors* **44** 1402