Investigation of Radiation Recombination Channels in Long-Wavelength InAs/InAsSb/InAsSbP LED Heterostructures

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Abstract. This work presents the results of the investigation of optical properties of long-wavelength (~5 µm at 300 K) InAs/InAsSb/InAsSbP LED heterostructures. These heterostructures are used in various applications in mid-wavelength infrared range, such as environmental monitoring, etc. Electroluminescence was used to study the optical characteristics of the structures in the temperature range 4.2–300 K. Various radiative recombination channels in LED heterostructures were considered, including those associated with the InAs substrate and those related to the active layer, the latter competing depending on the temperature. The obtained results can be useful when designing optoelectronic devices with weak temperature dependence of the emission wavelength.

1. INTRODUCTION

InAsSb solid solution is an indispensable material for the fabrication of optoelectronic devices that work in the technologically important mid-wavelength infrared (MWIR) spectral range (2–6 µm). MWIR light-emitting diodes (LEDs) are used in, e.g., environmental monitoring, industry and medical diagnostics [1,2]. In principle, by using $InAs_{1-y}Sb_y$ solid solution, one can cover a very wide spectral range, from 3.4 up to 11.0 µm [3,4]. An increase in the InSb mole fraction in the solution, however, which is necessary for moving to the longer-wavelength part of the MWIR range ($\lambda > 5$ µm), leads to a strong increase in the mismatch in the lattice parameters of the InAsSb epitaxial layer and a substrate (typically made of InAs, though GaSb substrates are also often used). This may lead to the appearance of numerous channels of radiative recombination, which may, in fact, be useful in relation to the operation of the LEDs [5], and thus, requires detailed investigations. In this paper, we present the results of the investigation of radiative recombination channels in *n*-InAs/*n*-InAsSb/*p*-InAsSbP LED heterostructures with the mole fraction y of InSb in the InAsSb active layer ranging from 0.075 to 0.16. The studies were carried out in the wide temperature range $T = 4.2$–300 K.

2. SAMPLES UNDER STUDY

The heterostructures were fabricated by metal-organic vapor-phase epitaxy (MOVPE) on undoped InAs(001) substrates with an electron concentration, caused by the presence of residual impurities, $n = 3 \times 10^{16}$ cm^{-3} ($T = 300$ K). The epitaxial deposition of InAsSb active layers and InAsSbP barrier layers was performed in a horizontal reactor with resistive heating under atmospheric pressure. The details of the growth of the heterostructures were reported elsewhere [6]. The thickness of the InAsSb active layers was ~3 µm, and that of the $InAs_{0.4}Sb_{0.2}P_{0.4}$ barrier layers ~1.2 µm. The material of the active region was undoped. Zinc was used as the acceptor dopant for the barrier layer. Heterostructure *A* had 0.075 InSb molar fraction in the active area; heterostructure *B* – 0.09; heterostructure *C* – 0.16.

The heterostructures were processed into LED chips, which were fabricated as 400×400 µm mesa

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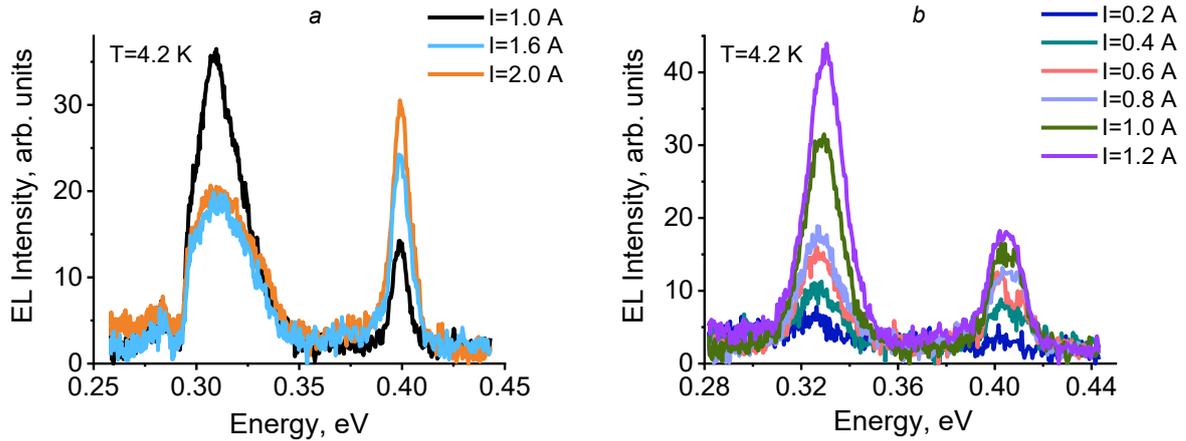Corresponding author: M.S. Ruzhevich, e-mail: max.ruzhevich@niuitmo.ru

Fig. 1. EL spectra of samples *B* (a) and *A* (b) at temperature *T* = 4.2 K for various injection currents.
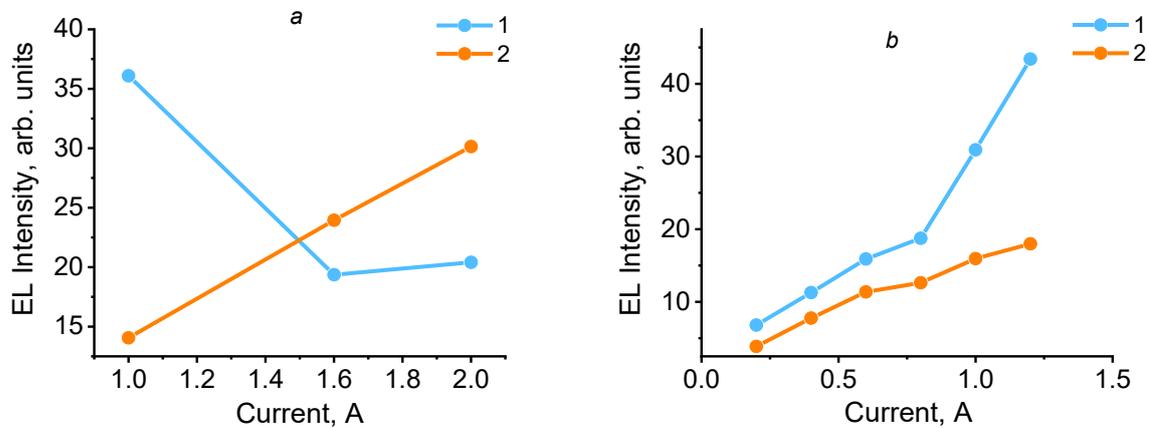

Fig. 2. EL intensity versus current for samples *B* (a) and *A* (b) at *T* = 4.2 K for the emission from the active layer (1) and from the substrate (2).

structures. The chips were mounted on TO-18 holders. For the studies, we recorded electroluminescence (EL) spectra under pulsed excitation at a frequency of 1 kHz and a pulse width of 2 μs with the use of MDR-23 grating monochromator. An InSb photodiode and a HgCdTe photoconductor served as detectors. Two to three LED chips from each heterostructure were subjected to investigations. All samples of the same type showed similar properties with slight variations.

3. RESULTS AND DISCUSSION

Figure 1 shows EL spectra for two of the studied heterostructures. The spectra were recorded at liquid helium temperature (*T* = 4.2 K) at various injection currents. As can be seen, both sets of spectra contain two major spectral lines. For spectrum of sample *B* one spectral line has the energy 0.32 eV, and the other one, 0.40 eV. The shape of the low-energy part of the 0.32 eV spectral lines in Fig. 1a is distorted with

absorption line of CO_2 gas present in the atmosphere. The values of full-width at half-maximum (FWHM) of these lines are about ~25 meV. These lines can be attributed to radiative recombination transitions related to the active layer of the heterostructure. The high-energy lines in the spectra are, most likely, associated with recombination in the InAs substrate, as reported previously [5]. Their FWHM values are of the order of 15 meV. Note the difference in the behavior of the intensity of the lines with changing the current. While in Fig. 1a (sample *B*), with the current increasing, the intensity of the low-energy line decreases and that of the high-energy line decreases, in Fig. 1b (sample *A*) one can see that with the injection current increasing, the intensity of both lines increases concurrently.

This effect is clearly seen in Fig. 2, which shows the dependence of the intensities of the EL peaks on the injection current at *T* = 4.2 K. As can be seen in Fig. 2a, for sample *B*, with the current increasing from 1 to 2 A, the intensity of the high-energy ('substrate')
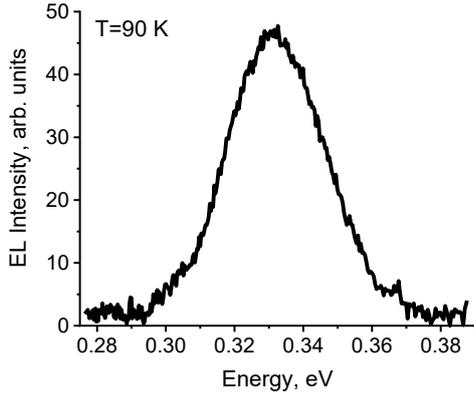
Fig. 3. EL spectrum of sample *A* at *T* = 90 K.

EL peak increases linearly, while the intensity of the low-energy peak decreases. At the same time, Fig. 2b shows that for sample *A*, with the current increasing from 0.4 to 1.2 A, the intensities of both peaks increase with very similar slopes. For the low-energy line, the intensity of the peak continues to grow with the current increasing up to 4 A (not shown).

The data presented in Figs. 1 and 2 are clearly indicative of the fact that at low temperatures the heterostructures under study contain at least two channels of radiative recombination, one of them being associated with the substrate, and the other one, with the active layer or the interface between the active layer and the barrier layer, where, according to the design of the heterostructure, the *p–n* junction should be located. Depending on the injection current, these channels obviously compete with each other.

With temperature increasing, the intensity of the high-energy EL lines decreases and eventually (at *T* ~ 80 K) these lines disappear, so only the low-energy

lines remain in the spectra. Figure 3 shows the EL spectrum of sample *A* at *T* = 90 K recorded at the injection current *I* = 0.8 A. The EL spectrum peak corresponds here to the energy 0.332 eV, with FWHM of the EL line equaling 33 meV.

Figure 4 shows the temperature dependences of the EL peaks position for samples *A* with composition of active layer *y* = 0.075 and *C* with composition of active layer *y* = 0.16. The solid lines in the figure show the calculated temperature dependences of the band gap of $InAs_{1-y}Sb_y$. These dependences were constructed for a solid solution using the Varshni expression [7] $E_g = E_0 - \alpha T^2 (T + \beta)^{-1}$. Here, $E_0 = 0.418$ eV (E_g at *T* = 0 K for InAs), and α and β are constants ($\alpha = 2.76 \times 10^{-4}$ eV/K, $\beta = 93$ K for InAs [8]).

The temperature dependences of the high-energy peaks follow the band gap dependence on the temperature. However, the energies of these peaks greatly exceed the value for E_g in the active layers, and therefore, as mentioned above, these peaks should be attributed to radiative recombination channel related to the InAs substrate. The energies of these peaks are ~15 meV smaller than the bandgap of InAs, and according to observations made earlier [5], these high-energy bands most probably originate in the recombination involving donor-acceptor pairs formed by residual impurities and defects in the substrate. According to Fig. 2, in the sample with larger InSb content, this channel becomes more dominant with increasing the current. Still, the channel can be considered parasitic as it obviously consumes considerable part of the injected carriers and thus, weakens emission from the active layer.

Of greater interest, however, is the temperature dependence of the low-energy EL peaks. As can be seen in Fig. 4, at low temperatures the energies of these
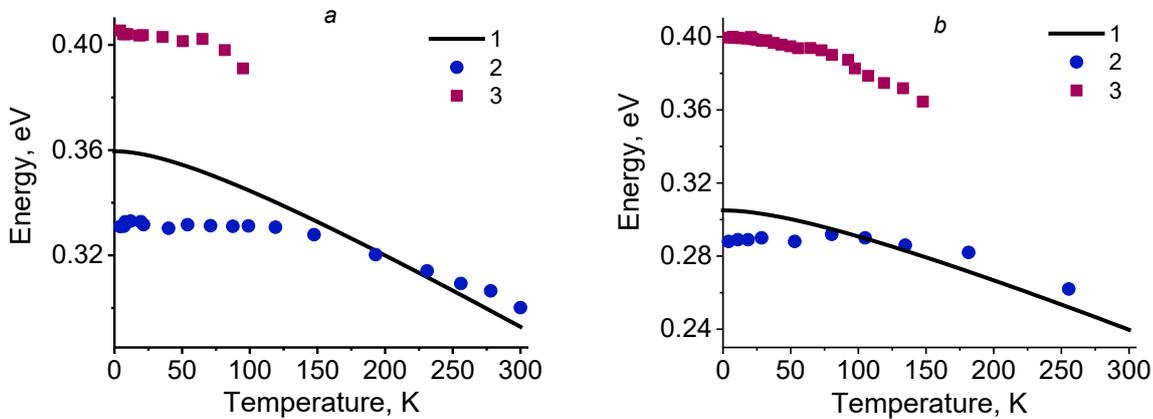
Fig. 4. Calculated temperature dependences of solid solution E_g (1) and EL peak positions for samples *A* (a) and *C* (b) for the emission from the active layer (2) and from the substrate (3).

peaks are noticeably smaller than the calculated E_g values of the active layers. This difference, depending on the sample, can reach a value of 50 meV.

In this regard, we can make an assumption about the formation of an interface radiative recombination channel near the type II heterointerface, which formed in the heterostructures under consideration. Indeed, it was shown in Ref. [9] that for narrow-gap InAsSb layer compositions, the $InAs_{1-y}Sb_y/InAsSbP$ heterojunction is a type II transition. When a forward bias is applied to the heterostructure, due to band bending at the n-InAsSb/p-InAsSbP heterointerface, potential wells for electrons and holes form in the conduction and valence band, respectively. Under the action of the external electric field, carriers are accumulated in potential wells. The conditions for indirect radiative transitions through the type-II heterointerface are established and the value of this indirect 'energy gap' involved in recombination can be smaller than the E_g value of the narrowest-gap solid solution forming a given heterojunction. Thus, the experimentally observed radiative transitions at $T = 4.2$ K with a photon energy much lower than the value of E_g of the active region should be due to carrier recombination near the InAsSb/InAsSbP heterointerface. For the structures whose data are shown in Fig. 4, the energy of the spectral maximum of the low-energy peak hardly changes in the temperature range $T = 4.2–150$ K and starts to follow calculated $E_g(T)$ dependence only at $T \sim 200$ K. In the temperature range $150 < T < 200$ K, for the studied structures, the change in the position of the EL peaks often follows the temperature narrowing of the band gap of $InAs_{1-y}Sb_y$ with some deviation towards lower energies relative to the calculated dependence $E_g(T)$. The energy deviation is 15 meV at $T = 150$ K and decreases to zero at $T > 200$ K. The value of 15 meV is close to the activation energy of the shallow Zn acceptor in InAs and related solid solutions [10]. Thus, it can be assumed that spontaneous luminescence in this temperature range is due to radiative recombination with the participation of Zn acceptor states in the bulk of the active region, which are formed as a result of zinc diffusion from the barrier layer to the active layer.

4. SUMMARY AND CONCLUSIONS

Thus, we have studied the channels of radiative recombination in n-InAs/$InAs_{1-y}Sb_y$/p-InAsSbP LED heterostructures with the composition of the active layer $y = 0.075–0.16$. EL spectra were obtained at various temperatures and various currents, which made it possible to observe radiative recombination channels associated with the active layers and the substrates.

Dependences of EL intensity on the injection current for samples with compositions $y = 0.075$ and $y = 0.16$ were different, which confirmed the technological challenges associated with growing longer-wavelength MWIR structures. Various recombination channels have been established in the structures. In particular, a peak associated with the recombination in the substrate was discovered at low temperatures ($T < 100$ K), which effect can be considered parasitic. As to the active layer, at low temperatures ($T < 150$ K) the radiative recombination occurs at the heterointerface between the active and barrier layers, yet at higher temperatures it proceeds in the bulk of the active region. We believe that this feature can be useful in the design of devices with temperature-independent emission wavelength.

ACKNOWLEDGEMENTS

REFERENCES

[1] D. Ting, A. Soibel, A. Khoshakhlagh, S. Keo, B. Rafol, A. Fisher, B. Pepper, E. Luong, C. Hill and S. Guhapala, *Advances in III-V semiconductor infrared absorbers and detectors*, Inf. Phys. Technol., 2019, vol. 97, pp. 210–216. https://doi.org/10.1016/j.infrared.2018.12.034

[2] D. Jung, S. Bank, M.L. Lee and D. Wasserman, *Next-generation mid-infrared sources*, J. Opt., 2017, vol. 19, no. 12, art. no. 123001. https://doi.org/10.1088/2040-8986/aa939b

[3] S.P. Svensson, W.L. Sarney, D. Donetsky, G. Kipshidze, Y. Lin, L. Sheterngas, Y. Xu and G. Belenky, *Materials design parameters for infrared device applications based on III-V semiconductors*, Appl. Opt., 2017, vol. 56, no. 3, pp. B58–B62. http://dx.doi.org/10.1364/AO.56.000B58

[4] A. Rogalski, P. Martyniuk, M. Kopytko, P. Madejczyk and S. Krishna, *InAsSb-based infrared photodetectors: thirty years later on*, Sensors, 2020, vol. 20, no. 24, art. no. 7047. http://dx.doi.org/10.3390/s20247047

[5] A.A. Semakova, V.V. Romanov, N.L. Bazhenov, K.D. Mynbaev and K.D. Moiseev, *Suppressing the temperature dependence of the wavelength in heterostructures with a staggered type-II InAsSb/InAsSbP heterojunction*, Semiconductors, 2021, vol. 55, pp. 354–358, http://dx.doi.org/10.1134/S1063782621030155

[6] V.V. Romanov, E.V. Ivanov and K.D. Moiseev, *InAs$_{1-y}$Sb$_y$/InAsSbP narrow-gap heterostructures (y = 0.09–0.16) grown by metalorganic vapor phase epitaxy for the spectral range of 4–6 μm*, Phys. Solid State, 2019, vol. 61, no. 10, pp. 1699–1706. https://doi.org/10.1134/S1063783419100305

[7] Y.P. Varshni, *Temperature dependence of the energy gap in semiconductors*, Physica, 1967, vol. 34, no. 1, pp. 149–154. https://doi.org/10.1016/0031-8914(67)90062-6

[8] I. Vurgaftman, J.R. Meyer and L.R. Ram-Mohan, *Band parameters for III–V compound semiconductors and their alloys*, J. Appl. Phys., 2001, vol. 89, no. 11, pp. 5815–5875. https://doi.org/10.1063/1.1368156

[9] V.V. Romanov, E.V. Ivanov and K.D. Moiseev, *Forming a type-II heterojunction in the InAsSb/InAsSbP semiconductor structure*, Phys. Sol. State, 2020, vol. 62, pp. 2039–2044. https://doi.org/10.1134/S1063783420110244

[10] I. Melngailis and R.H. Rediker, *Properties of InAs lasers*, J. Appl. Phys., 1966, vol. 37, no. 2, pp. 899–910. https://doi.org/10.1063/1.1708280