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Electroluminescence of narrow-gap InAs/$InAs_{1-y}Sb_y$/InAsSbP heterostructures with y = 0.07–0.12

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Abstract. Electroluminescence of narrow-gap *n*-InAs/$InAs_{1-y}Sb_y$/*p*-InAsSbP heterostructures with the indium antimonide content in the active region y = 0.07–0.12 has been studied. A radiative recombination channel associated with the InAsSb/InAsSbP heterointerface has been discovered. The dependence of the type of this heterointerface on the actual composition of the barrier layer near the interface has been established.

Keywords: solid solutions, InAsSb, electroluminescence, heterostructures

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Материалы конференции
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Электролюминесценция узкозонных гетероструктур InAs/$InAs_{1-y}Sb_y$/InAsSbP с y = 0,07–0,12

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Аннотация. Исследована электролюминесценция узкозонных гетероструктур *n*-InAs/$InAs_{1-y}Sb_y$/*p*-InAsSbP с содержанием антимонида индия в активной области y = 0,07–0,12. Обнаружен канал интерфейсной излучательной рекомбинации, связанный с гетерограницей InAsSb/InAsSbP. Установлена зависимость типа этой гетерограницы от фактического состава барьерного слоя вблизи границы.

Ключевые слова: твердые растворы, InAsSb, электролюминесценция, гетероструктуры

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Introduction

Heterostructures (HSs) based on InAs(Sb,P) solid solutions are promising for creating emission sources operating in the mid-infrared (IR) spectral range. Light-emitting diodes (LEDs) based on these HSs are the main components in optoelectronic devices intended for spectroscopy of gases and molecules, environmental monitoring, medical diagnostics, etc. [1–3]. Changing the mole fraction y of InSb in the $InAs_{1-y}Sb_y$ solid solution used as the active region of these HSs makes it possible to cover a wide spectral range from 3.4 to 11.0 μm. However, shifting to the long-wavelength boundary of this range, which requires an increase in y, leads to an increase in the mismatch in the crystal lattice parameter of the InAsSb epitaxial layer relative to the binary InAs substrate and to the covering barrier layer. This hinders practical implementation of the HSs; however, the relative ease of their manufacture and low price compared to other types of mid-IR radiation sources continue to attract attention to this material.

This work presents results of studying electroluminescence (EL) of narrow-gap n-InAs/$InAs_{1-y}Sb_y$/p-InAsSbP HSs with y = 0.07–0.12, and compares these results with the features of the band diagram of the structures. Experimental studies were conducted in a wide temperature range T = 4.2–300 K.

Materials and Methods

HSs were grown by metal-organic vapor phase epitaxy (MOVPE) in a horizontal reactor at atmospheric pressure; details of the process were reported elsewhere [4]. Undoped (001)InAs wafers with the electron concentration $n = 3\cdot10^{16}$ cm^{-3} (T = 300 K) were used as substrates. The active region of HSs with the thickness of 3.0 μm represented an epitaxial layer of $InAs_{1-y}Sb_y$ with y = 0.07, 0.09, y = 0.10, or y = 0.12, and was not doped either. To create a 1.2 μm-thick covering barrier layer, a quaternary InAsSbP solid solution was used. The p-type conductivity in the barrier layer was obtained by doping the layer with zinc during the growth.

Based on the HSs, 400×400 μm LED chips were manufactured and mounted on TO-18-type housings. The emission was registered from the side of the barrier layer. EL spectra were recorded using a cooled InSb-based photodiode under pulsed excitation with a frequency 1 kHz and pulse duration 2 μs.

Results and Discussion

Figure 1 shows a full EL spectrum of the HS with y = 0.07, recorded at T = 4.2 K and injection current per pulse i = 1 A. At low temperatures, in the range from 4.2 to 150 K, in addition to the low-energy emission band with photon energy $h\nu$ ~ 0.3 eV, the EL spectra of all structures contained a high-energy band with a spectral maximum near $h\nu$ ~ 0.4 eV and a full width at half-maximum (FWHM) at T = 4.2 K, ~ 12 meV. We observed this feature earlier when studying EL of HSs with an active region based on $InAs_{1-y}Sb_y$ with $0.14 < y \le 0.16$. In particular, in Ref. [5], the results of the detailed studies of the nature of this EL band were presented and it was determined that this band was related to the recombination of donor-acceptor pairs in the InAs substrate. The low-energy band of the spectrum corresponds to the emission associated with the narrow-gap active region. In our studies, the spectra of this emission were recorded separately; the inset in Fig. 1 shows the spectrum for the sample with y = 0.07, recorded at T = 4.2 K and i = 4 A. The emission band has the maximum at 0.335 eV, a symmetrical Gaussian shape and a FWHM of 20 meV.

Fig. 2 shows a change in the position of the spectral maxima of the EL bands with temperature for four HSs, as well as the corresponding temperature dependences of the bandgap E_g of the active region material. For each HS, the EL spectra were recorded for several (2–3) experimental samples cut from different parts of the wafer, and the results were close. Calculation of the $E_g(T)$ dependence for the $InAs_{1-y}Sb_y$ solid solution was carried out according to the Varshni relation:

$$E_g = E^0 - \alpha \cdot T^2 \cdot (T + \beta)^{-1},$$

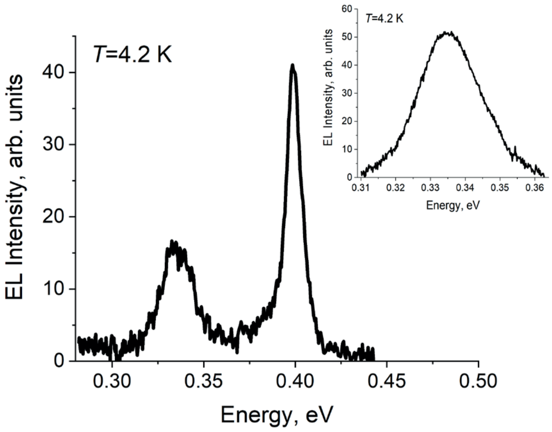

Fig. 1. EL spectrum of the HS with y = 0.07 at T = 4.2 K.
The inset shows the emission spectrum associated with the active region

Here, the band gap parameter for a solid solution, $E^0(y)$, was calculated at 0 K as

$$E^0(y) = (1-y)E^0_{InAs} + yE^0_{InSb} - y(1-y)C_{InAsSb},$$

where E^0_{InAs} = 0.417 eV, E^0_{InSb} = 0.24 eV, the bowing parameter C_{InAsSb} = 0.61 eV. The parameters α and β were taken as those for matrix material InAs: α = 2.76·10^{-4} eV/K and β = 93 K.

As can be seen in Fig. 2, in the low-temperature region (from 4.2 to ~ 140 K), there is a significant difference between the energies of the spectral maximum of the emission band and the calculated values of E_g of the active region material for all HSs. At 4.2 K, the energy discrepancy δE between the calculated values of E_g and the position of the spectral maximum mounted up to 50 meV. At temperatures above 200 K the energies of the spectral maximum approached the calculated values of E_g, and for all studied samples at the room temperature, the energy of the EL peak was close to E_g of the corresponding $InAs_{1-y}Sb_y$ solid solution. We observed a similar behavior of EL maxima earlier for HSs with 0.14 < y ≤ 0.16 [5]. At the same time, HSs of similar design with y = 0–0.09 grown by a different MOVPE technique demonstrated a good agreement between the energy of the spectral maximum and calculated E_g values of the active region material with δE ≈ 0 in the entire temperature range T = 4.2–300 K [6].

To interpret the results obtained in this work, the HS band diagrams were analyzed. Figs. 3, *a*, *b* show variants of the band diagram of the HS with y = 0.09 without electric bias. The diagram in Fig. 3, *a* was drawn under assumption that the chemical composition of the barrier layer corresponded to the technological parameters specified during its growth, i.e., x = 0.41 and y = 0.19 for $InAs_{1-x-y}Sb_yP_x$. As can be seen, in this case, an InAsSb/InAsSbP type I heterointerface and a classical heterojunction with asymmetric carrier confinement for electrons and holes at the opposite boundaries of the active region should be formed. However, as has been shown for HSs of various designs and with different InSb contents in the active region, the chemical composition of the InAsSbP quaternary solid solution deposited by MOVPE on a lattice-mismatched narrow-gap layer of the InAsSb ternary solid solution does not correspond to the specified composition near the heterointerface [7]. In particular, for a HS with y = 0.09, in the active region for the $InAs_{1-x-y}Sb_yP_x$ solid solution near the interface, interpolation of the data from [7] gives the values x = 0.375 and y = 0.21. The corresponding band diagram is shown in Fig. 3, *b*. As can be seen, in this case, an InAsSb/InAsSbP heterointerface of type II is formed. Fig. 3, *c* shows the same band diagram at a forward bias of 0.3 V. It can be seen that potential wells for electrons and holes are formed at the heterointerface; under these conditions, there is a high probability of interface recombination of electrons from the well at the side of the active layer with holes in the well at the side of the barrier layer.

In the case under consideration, the energy of the photon emitted as a result of interface recombination at a type II heterointerface depends mainly on the valence band offset ΔE_V. Figure 3, *d* shows results of the calculations of ΔE_V for HSs under consideration; the calculations took into account the established changes in the composition of the InAsSbP quaternary solid solution isomorphous to the narrow-gap ternary InAsSb solid solution. As can be seen, with a

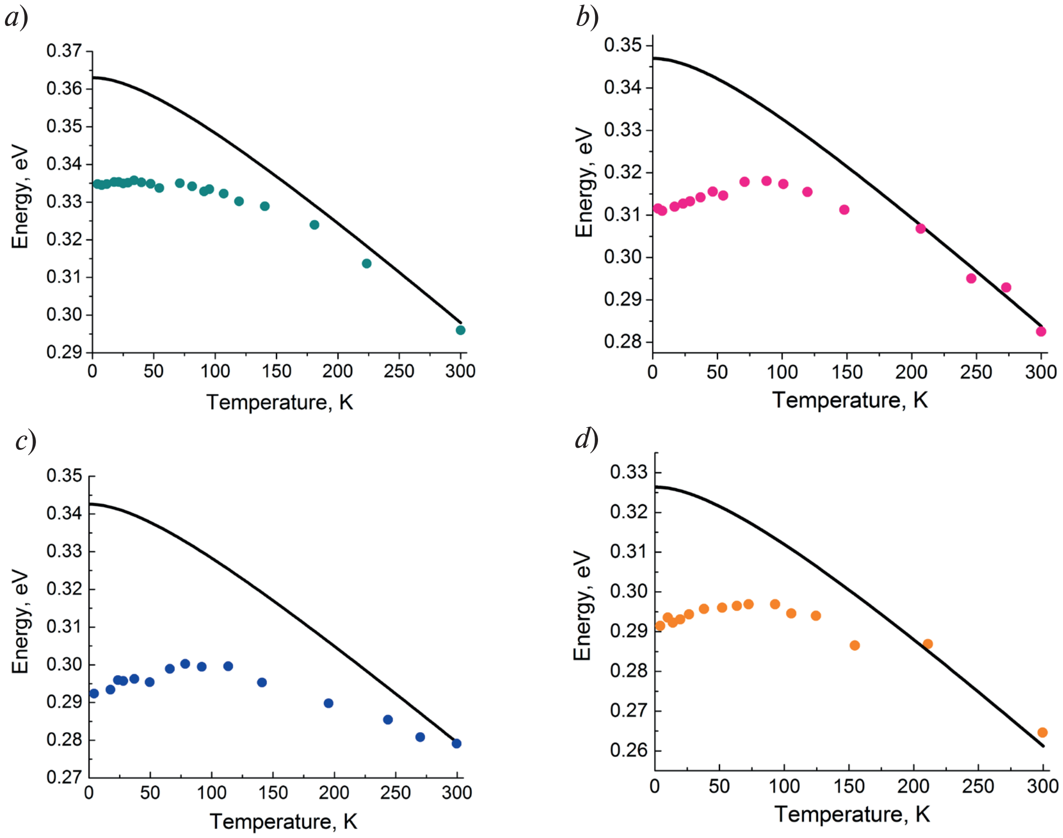

Fig. 2. Calculated temperature dependences of E_g for the active region of the HSs (solid lines) and experimental data of the positions of spectral maxima of EL (symbols): y = 0.07 (*a*); 0.09 (*b*), 0.10 (*c*), and 0.12 (*d*)

change in the composition of the active layer, the ΔE_V changes very little, which is explained by the "tuning" of the InAsSbP composition at the heterointerface in order to compensate for the mismatch of the crystal lattice parameter. The estimated average ΔE_V value 16 meV (shown in Fig. 3, *d* by dashed line) was obtained from calculations according to expressions from [7].

The values of δE obtained from the experiment, however, demonstrated a certain dependence on y in the active layer (Fig. 3, *d*) and were actually greater than the calculated values of ΔE_V. However, as was demonstrated in [8], structural defects in InAs-based compounds can generate deep acceptor states on the surface of the semiconductor. With increasing the InSb content in the solid solution, generation of surface states at the InAsSb/InAsSbP heterointerface should be expected as a result of the growth of internal strain in the epitaxial layer of the active region. Thus, we can suggest that at low temperatures, EL in the HSs was related to interface recombination near the type II InAsSb/InAsSbP heterointerface with the participation of the interface states. With temperature increasing, band-to-band transitions begin to dominate. This explains the temperature dependence of δE shown in Fig. 2. The extremum appearing on $\delta E(y)$ dependence at y = 0.10 in Fig. 3, *d* is caused by the relaxation of an epitaxial layer as a result of the generation of a grid of dislocations, as at this point, the lattice mismatch becomes greater than 1%.

We explain the difference between the data obtained in this work and the data in [6] by the difference in the types of InAsSb/InAsSbP heterointerfaces. Barrier layers with significantly lower Sb and P contents were used in [6]. Band diagrams calculated for HSs used in [6] were of type I even when calculations were performed with consideration for possible variations in the P and Sb content in the barrier layer due to the changes in its chemical composition as a result of lattice mismatch. Thus, in the HSs studied in [6], the EL spectra in the entire temperature range T = 4.2–300 K were related to interband transitions in the active region. The switching of recombination mechanisms with changes in the temperature, as was observed in this work, makes it possible to suppress the temperature dependence of the HS emission wavelength, which is very important for the operation of mid-IR radiation sources [1,2].

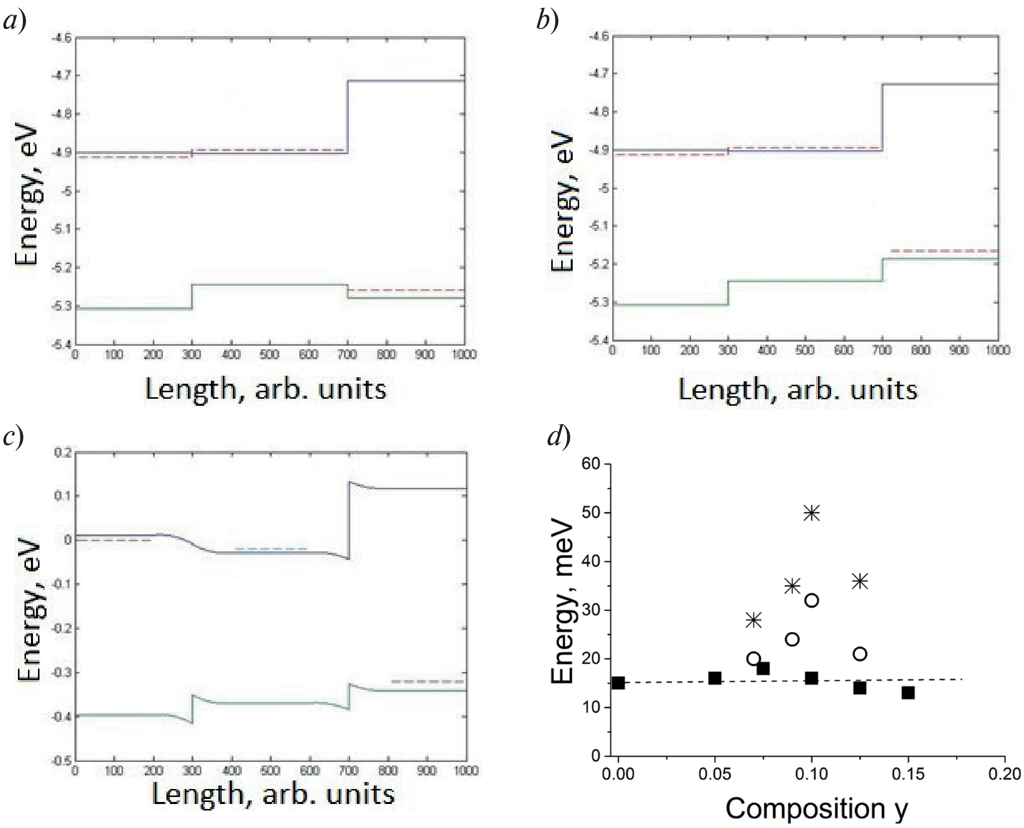

Fig. 3. Band diagram of n-InAs/InAs$_{1-y}$Sb$_y$/p-InAsSbP HS with y = 0.09 for calculated (*a*) and actual (*b*) compositions of the barrier layer without bias and at a forward bias of 0.3 V (*c*). Fig. 3, *d* shows δE values observed at T = 4.2 K (stars) and T = 77 K (circles) and the results of calculating ΔE_V at the heterointerface for various y taking into account changes in the composition of the InAsSbP solid solution (squares)

Conclusion

The paper presents the results of the study of electroluminescence of narrow-gap n-InAs/InAs$_{1-y}$Sb$_y$/p-InAsSbP heterostructures with y = 0.07–0.12 in the temperature range 4.2–300 K. It is shown that from 4.2 to ~ 140 K, interface radiative recombination at the InAsSb/InAsSbP heterointerface dominates. This is due to the formation of a type II heterointerface, caused by the change in the chemical composition of the InAsSbP quaternary solid solution that is deposited on a layer of a lattice-mismatched InAsSb ternary solid solution, which leads to a difference between the specified and actual composition of the InAsSbP barrier layer. An increase in the temperature above 140 K leads to switching of the recombination channel to the interband one in the active region. The resulting weak temperature dependence of the emission wavelength of the heterostructures can be used in practical applications.

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