Heterostructures, superlattices, quantum wells

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Radiative recombination in InAs/InAsSb/InAsSbP heterostructures

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Abstract. Comprehensive studies of electroluminescence of InAs/InAsSb/InAsSbP heterostructures with different fractions of Sb in narrow-gap InAsSb layers were performed. Electroluminescent properties of the heterostructures were investigated in a wide range of both forward and reverse biases at temperature $T = 77$ K. It was found that in the different parts of the heterostructures, radiative recombination proceeds via interband and interface mechanisms, which manifests in the presence of two emission bands at different wavelengths in the electroluminescence spectra recorded under the forward bias. The recombination mechanisms were explained using schematic band diagrams of the heterostructures calculated for $T = 77$ K and both directions of the external bias.

Keywords: solid solutions, InAsSb, heterostructures, interface recombination, electroluminescence

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Излучательная рекомбинация в гетероструктурах InAs/InAsSb/InAsSbP

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Аннотация. Всесторонне исследована электролюминесценция гетероструктур InAs/InAsSb/InAsSbP с различным содержанием Sb в узкозонном слое InAsSb. Электролюминесцентные свойства гетероструктур исследовались при приложении смещения как в прямом, так и в обратном направлениях при температуре $T = 77$ K. Установлено, что в различных частях гетероструктур реализуются межзонный и интерфейсный механизмы излучательной рекомбинации, что проявляется в наличии двух полос излучения с разной длиной волны в спектрах электролюминесценции при прямом смещении. Механизмы рекомбинации объяснены с использованием зонных диаграмм гетероструктур, рассчитанных для $T = 77$ K и обоих направлений внешнего смещения.

Ключевые слова: твердые растворы, InAsSb, гетероструктуры, интерфейсная рекомбинация, электролюминесценция

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Introduction

Heterostructures (HS) featuring an active layer made of $InAs_{1-y}Sb_y$ solid solution are widely incorporated in optoelectronic devices operating in the mid-wavelength infrared (IR) spectrum. By adjusting the antimony content in this layer, it is possible to cover a spectral range from 3.4 μm to 11.0 μm. The above-mentioned IR optoelectronic devices mostly find applications in gas and molecule spectroscopy, environmental monitoring systems, industrial and safety solutions, and medical diagnosis [1 – 5]. However, the efficiency of InAsSb-based devices operating at near-room temperatures (T = 25 °C) is hindered by the dominance of non-radiative recombination. Consequently, the studies of fundamental recombination processes occurring via different mechanisms, particularly dominating spectral properties of HSs of various designs and active layer compositions, remain highly relevant. In order to investigate this effect, comprehensive studies of electroluminescence (EL) of n-InAs/n-$InAs_{1-y}Sb_y$/p-InAsSbP (y = 0.06–0.10) HSs under both forward and reverse bias at T = 77 K were carried out in this work.

Materials and Methods

HSs were grown by metal-organic vapor-phase epitaxy in a horizontal reactor at atmospheric pressure; the detailed growth procedure is discussed elsewhere [6]. Undoped (001)InAs wafers with the electron concentration $n = 3 \cdot 10^{16}$ cm^{-3} at T = 300 K were used as substrates. Epitaxial layers of the ternary $InAs_{1-y}Sb_y$ solid solution (y = 0.06–0.10) had the thickness of ~3.0 μm and were not doped intentionally, having n-type conductivity. The ~1.2 μm-thick barrier layers represented the quaternary $InAs_{1-x-y'}Sb_{y'}P_x$ solid solution with the composition set during the growth as y' = 0.22 and x = 0.47. P-type conductivity in the barrier layers was achieved by doping them with Zn during growth. The composition of the active layers in HSs is listed in Table.

Table

Studied heterostructures

#	Heterostructure design
1	n^0-InAs/n^0-$InAs_{0.94}Sb_{0.06}$/p^+-InAsSbP:Zn
2	n^0-InAs/n^0-$InAs_{0.91}Sb_{0.09}$/p^+-InAsSbP:Zn
3	n^0-InAs/n^0-$InAs_{0.90}Sb_{0..10}$/p^+-InAsSbP:Zn

Light-emitting diode chips were fabricated from the HSs and mounted substrate-side down onto TO-18 housings. EL studies were carried out under pulse excitation (f = 1 kHz, τ = 2 μs) and both forward and reverse bias at T = 77 K with the use of computer-controlled setup employing a grating monochromator MDR-23 (LOMO) and a lock-in amplifier. A cooled (T = 77 K) InSb photodiode was used as a detector.

Results and Discussion

EL spectra of structures *2* and *3* under forward bias contained two distinct emission bands (Fig. 1): a low-energy band ($h\nu_1$) related to radiative transitions involving the InAsSb/InAsSbP heterointerface and a high-energy band ($h\nu_2$) attributed to near-interband transitions with the assistance of impurity states in the substrate. The spectral position of the peak intensity of the $h\nu_1$ band varied with the change of Sb fraction in the active layer, while that of the $h\nu_2$ band remained constant ($h\nu_2$ = 0.393 eV) and close to the band gap energy of the bulk InAs at the same temperature ($E_{g,\,InAs}$ = 0.408 eV). The photon energy difference of ~15 meV allowed us to attribute this band to donor-acceptor recombination involving a shallow acceptor state, which is typical of the undoped InAs [7,8].

High-energy band $h\nu_2$ dominated independently of injection levels, and its intensity increased throughout the whole range of voltages, whereas the intensity of the $h\nu_1$ band gradually decreased with the injection level increasing. This phenomenon can be explained by the lowering of the potential barrier at the heterointerface between the ternary and quaternary solid solutions as the forward bias increased. Under these conditions, holes with increasing probability could overcome the barrier, reaching first the narrow-gap layer and then the n^0-InAs substrate. That redistribution of charge carriers led to increasing recombination probability in the substrate, resulting in the increase of the high-energy band intensity in the EL spectra.

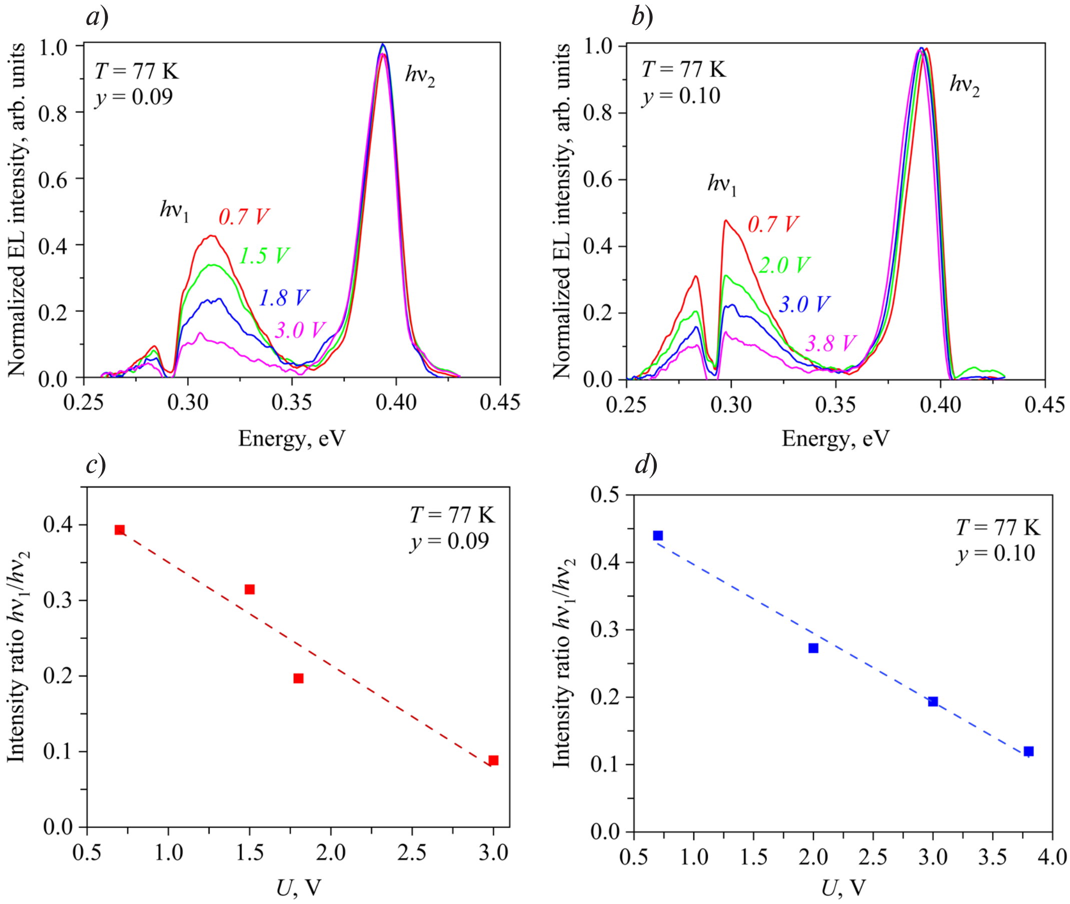

Fig. 1. Electroluminescence spectra under the forward bias applied to structures *2* (*a*) and *3* (*b*), and dependence of the ratio of EL band intensities $h\nu_1/h\nu_2$ on the applied bias (*c*, *d*)

EL under reverse bias was studied to determine whether the energy gaps alignment at the InAsSb/InAsSbP heterointerface was resulting from the specifics of chemical processes occurring during precursor decomposition at the stage of structure growth, or the offset forming the type-II heterojunction was caused just by the applied forward bias. EL spectra of structures *1* and *3* under the reverse bias $-U$ at $T = 77$ K are shown in Fig. 2. For comparison, Fig. 2 also shows corresponding EL spectra of the structures under the forward bias +U of the about the same value.

In the EL spectrum recorded with the reverse bias applied to structure *2*, both bands of luminescence were present, similarly to the situation under the forward bias. This observation is indicative of the fact that the energy band structure of InAsSb/InAsSbP heterojunction is not the result of an applied external bias, but an inherent feature of HS governed by the technological mode at the stage of fabrication (Fig. 2, *a*). In case of structure *3*, under both forward and reverse bias band $h\nu_2$ resulting from radiative recombination in the InAs substrate was observed, unlike band $h\nu_1$, which was solely present in EL spectra recorded under the forward bias. The latter observation is also indicative of the fact that the long-wavelength EL of HSs at low temperatures originates at the interface rather than in the 'bulk' of the active layer.

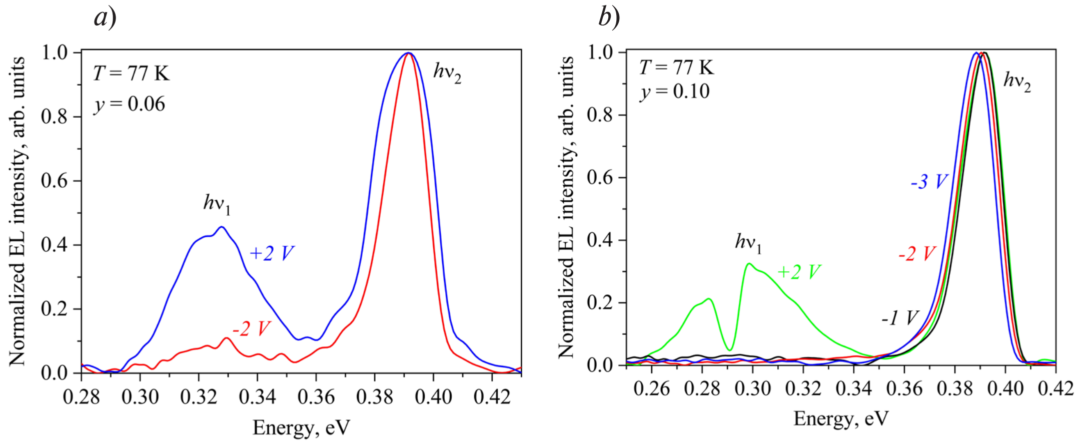

Fig. 2. Electroluminescence spectra under the reverse bias applied to structures *2* (*a*) and *3* (*b*) compared to that under the forward bias with close absolute value

The studied HSs featured noticeably high potential barriers for electrons in the conduction band at the InAsSb/InAsSbP heterointerface. The presence of such barriers strongly affects the electrical and luminescent properties of HSs. Fig. 3 (*a*, *d*) schematically shows band diagrams of structures *2* and *3* at T = 77 K, calculated in accordance to experimental data discussed in the work [9]. In that case, ternary and quaternary solid solutions form heterojunctions of type-II featuring high conduction band offsets ΔE_c and comparably low valence band offsets ΔE_v [10].

Under forward bias U = 0.35 V the potential barrier for electrons (holes) at the InAsSb/InAsSbP heterointerface was estimated to be ΔE_c = 0.19 eV (ΔE_v = 0.05 eV) and ΔE_c = 0.22 eV (ΔE_v = 0.08 eV) for structures *2* and *3*, respectively. An increase of free charge carriers concentration in the appropriate layers of the HSs results in localization of carriers in self-consistent potential wells formed on the opposite sides of the type-II heterointerface under the forward bias. This situation leads to an increase in the probability of radiative transitions at the interface (Fig. 3, *b*, *e*).

Fig. 3 (*c*, *f*) shows energy band diagrams similar to that under reverse bias −0.22 V with voltage drops at the InAs/InAsSb and InAsSb/InAsSbP barriers taken as −0.02 V and −0.20 V,

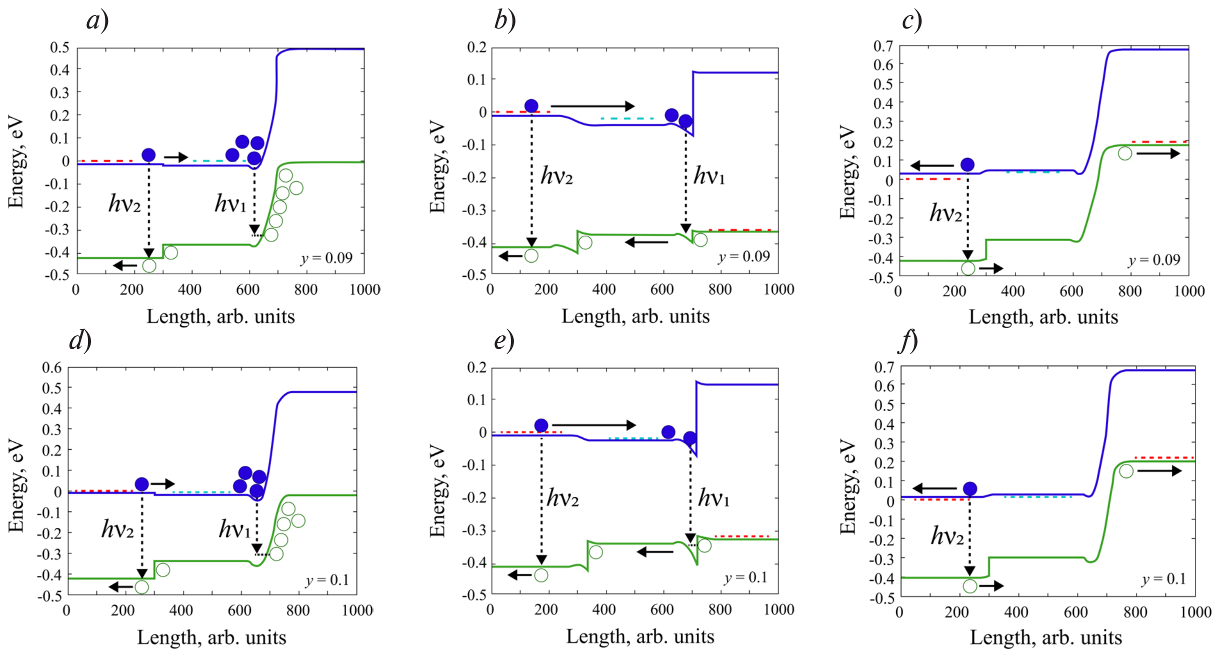

Fig. 3. Schematic band diagrams of structures *2* and *3*, respectively: under minimal forward bias (*a*, *d*); under forward bias of 0.35 V (*b*, *e*); under reverse bias of −0.22 V and corresponding voltage drops at the InAs/InAsSb and InAsSb/InAsSbP barriers estimated as −0.02 V and −0.20 V, respectively (*c*, *f*)

respectively. Since in this situation there are no potential barriers for charge carriers, they are free to move throughout the structure and radiative recombination occurs in the substrate, which corresponds to the EL spectra shown in Fig. 2. The interface EL band recorded under reverse bias applied to structure *1* ($y = 0.06$) is presumably associated with peculiarities of InAsSb / InAsSbP heterointerface of that particular structure. Note that for simplicity, transitions in the substrate are shown in Fig. 3 as interband ones; in reality they occur via shallow levels in the bandgap, as discussed above.

Conclusion

Our studies of electroluminescence at low temperature (T = 77 K) under both forward and reversed biases showed that in different parts of InAs / InAsSb / InAsSbP heterostructures radiative recombination occurs via interband or interface mechanisms. The intensity of the interface EL band decreases with the increase of the external bias in the forward direction due to the redistribution of charge carriers with decreasing of the potential barrier at the InAsSb/InAsSbP heterointerface. Observation of electroluminescence under a bias applied to the HSs in the reverse direction indicated that energy band alignment at the InAsSb/InAsSbP type II heterointerfaces is the result of epitaxial growth conditions rather than the applied bias.

The presence of two radiative recombination channels in the studied HSs and the dependence of the intensity ratio of the corresponding electroluminescence bands on the applied forward bias shows possibilities to control output wavelength via adjustment of the bias. These HSs are promising for development of differential detection devices used in optical spectroscopy.

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