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Stimulated emission from asymmetric InAs/InAsSb/InAsSbP LED heterostructures

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Abstract. Electroluminescent (EL) properties of asymmetrical InAs/InAs$_{1-y}$Sb$_y$/InAsSbP heterostructures with the $y = 0.09$ and $y = 0.11$ InSb content in the active layer were studied in wide temperature range $T = 4.2$–300 K. The stimulated emission in the spectral range 4.1–4.2 μm has been observed at low temperatures ($T < 30$ K). It was estimated that EL spectra were formed owing to different channels of radiative recombination depending on the ambient temperature. The influence of the quality of the type II InAsSb/InAsSbP heterojunction on radiative recombination transitions has been considered.

Keywords: light-emitting diodes, heterojunctions, InAs, antimonides, stimulated emission

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Стимулированное излучение в светодиодах на основе асимметричных гетероструктур InAs/InAsSb/InAsSbP

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Аннотация. Исследованы электролюминесцентные (ЭЛ) характеристики асимметричных гетероструктур InAs/InAs$_{1-y}$Sb$_y$/InAsSbP с мольной долей InSb в активной области $y = 0.09$ и $y = 0.11$ в диапазоне температур $T = 4.2$–300 K. При низких температурах ($T < 30$ K) наблюдалось стимулированное излучение в спектральной области 4.1–4.2 мкм. Установлено, что спектры ЭЛ формировались за счет различных каналов излучательной рекомбинации в зависимости от температуры окружающей среды. Рассмотрено влияние качества гетероперехода II типа InAsSb/InAsSbP на излучательные рекомбинационные переходы.

Ключевые слова: светодиоды, гетеропереходы, InAs, антимониды, стимулированное излучение

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Introduction

The unflagging interest in heterostructures based on narrow-gap $A^{III}B^{V}$ compounds is due to both their fundamental properties and a wide area of practical use for a broad range of optoelectronic devices operating in the mid-infrared (IR) spectral range (2–6 μm). Light-emitting diode (LED) heterostructures based on InAs(Sb, P) solid solutions are promising sources for environmental control systems and medical diagnostics [1, 2]. A challenge of enhancing the efficiency of mid-IR LEDs has found successful practical solutions [3]. However, optimization of the output characteristics of LEDs is often accompanied by a complication of the design of device structures. At the same time, identification of mechanisms of recombination processes occurring in narrow-gap semiconductor-based heterostructures can assist to discover new possibilities for the improvement in the efficiency of LEDs. The paper reports on getting a stimulated emission caused by interface-related radiative transitions in asymmetric heterostructures n-InAs/$InAs_{1-y}Sb_y$/p-InAsSbP with an ultimate molar fraction of InSb in the ternary solid solution of the active region ($y > 0.09$).

Materials and Methods

The InAs/$InAs_{1-y}Sb_y$/InAsSbP heterostructures were grown by the Metal-Organic Vapour-Phase Epitaxy (MOVPE) method on unintentionally doped InAs(001) substrates. The epitaxial deposition of the InAsSb and InAsSbP layers was performed under atmospheric pressure in a horizontal reactor with resistive heating. The active layer based on the InAsSb ternary solution was not intentionally doped during its deposition. Initial electron concentration in the n-type $InAs_{1-y}Sb_y$ layer was evaluated to be $n = 3 \times 10^{16}$ cm^{-3} ($T = 300$ K) and caused by the presence of residual impurities. The zinc-doped InAsSbP barrier layer was grown on top of the heterostructure studied and followed the active layer.

Two asymmetric heterostructures with a molar fraction of InSb in the ternary solid solution $y = 0.09$ (structure A) and $y = 0.11$ (structure B) were studied.

LED chips with round-shaped mesa with 300 μm diameter were fabricated using standard photolithography and wet chemical etching. The electroluminescence (EL) spectra were recorded in the temperature range $T = 4.2$–300 K under pulsed excitation at a frequency of 1 kHz and a pulse width of 2 μs. An InSb photodiode was used as a detector.

Results and Discussion

Fig. 1 presents EL properties of the structures under study. Fig. 1,*a* displays typical EL spectra at $T = 4.2$ K and the lowest injection current ($i = 0.2$ A) in our experiment. The spectra had the average full width at half maximum (FWHM) about 20–23 meV. The sharp low-energy edge in these spectra at $h\nu \sim 0.29$ eV is due to the absorption of the outcoming emission by molecules of carbon dioxide (CO_2) present in the ambient atmosphere. Fig. 1,*b* shows the temperature dependences of the spectral positions for the EL peaks of the heterostructures A and B, as well as the calculated temperature dependences of the energy gap (E_g) of the active layer for $InAs_{1-y}Sb_y$ solid solution with antimony content $y = 0.09$ and $y = 0.11$. The $E_g(T)$ dependences for $InAs_{1-y}Sb_y$ were obtained as a result of the Varshni approximation:

$$E_g = E_0 - \alpha \cdot T^2 \cdot (T + \beta)^{-1}, \qquad (1)$$

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with parameters $\alpha = 2.76 \times 10^{-4}$ eV/K and $\beta = 93$ K typical of the solid solution enriched with InAs [4]. The values of E_0 were calculated for the InAsSb solid solutions as an interpolation of the fractions of the binary compounds InAs and InSb in accordance with the expression [5]:

$$E_0 = E_{gInAs} \cdot (1 - y) + E_{gInSb} \cdot y - C_{InAsSb} \cdot y \cdot (1 - y), \qquad (2)$$

where $E_{gInAs} = 0.417$ eV, $E_{gInSb} = 0.235$ eV, and the bowing parameter $C_{InAsSb} = 0.61$ eV [6].

As we can see in Fig.1,*b*, an unusual behaviour of the spontaneous luminescence was observed for both structures. In the low temperature range ($T < 100$ K) a large discrepancy between experimental and calculated data was observed and a shift of the spectral position of the EL band maximum towards high energies of photon was revealed with temperature increasing. At high temperatures ($T > 200$ K) the spectral position of the EL band maximum was found to be close to the calculated curve corresponding to the temperature dependence of the energy gap of the ternary solid solution. It means that the temperature shift of the EL band for the structures under study to the low energy region corresponded to the narrowing of the band gap of $InAs_{1y}Sb_y$ epilayer. Moreover, there is a temperature range $100 < T < 200$ K where experimental data exhibited a trend in temperature dependence similar to the computed curve with some distance from the latter. The revealed energy distance was found to start from 15 meV and decreased to 0 at $T > 200$ K. The observed difference can be explained by the possible diffusion of Zn during growth or post-growth processing of the structures. Thus, it can be suggested that the spontaneous emission spectra in this temperature range were due to radiative recombination involving Zn acceptor states in the bulk of the active layer, as the activation energy of Zn shallow acceptor in InAs-related materials has similar value [6]. One can assume that there are two mechanisms of radiative recombination transitions which are switching from one to another near $T = 100$ K. This is indicative of the fact that with an increase in temperature to 300 K, band-to-band radiative recombination transitions in the active layer of the heterostructures became dominant in EL spectra, whereas the interface-related transitions could be responsible for the low-energy parts of the EL spectra.

As was shown in [7], the $InAs_{1-y}Sb_y$/InAsSbP heterojunction at $y > 0.09$ determines the type II alignment of the energy bands at the heterointerface. Owing to such band alignment, the energy gap between levels of localization for electrons and holes involved in radiative transitions can be smaller than the smallest bandgap of each alloy forming this heterojunction. Moreover, the value of this gap decreased with an increase in a molar fraction of InSb in the ternary solid solution $InAs_{1-y}Sb_y$ in the active region. A significant difference of 40–42 meV between the calculated bandgap of the InAsSb solid solution and the spectral position of the EL band maximum recorded at 4.2 K reveals that interface radiative recombination transitions occur across the $InAs_{1-y}Sb_y$/InAsSbP heteroboundary. As shown for a single type II heterostructure *n*-InGaAsSb/*p*-GaInAsSb, localization of electrons and holes in adjacent potential wells at the type II interface can result in obtaining a lasing mode based on indirect interface-assisted transitions [8].

a) *b*)

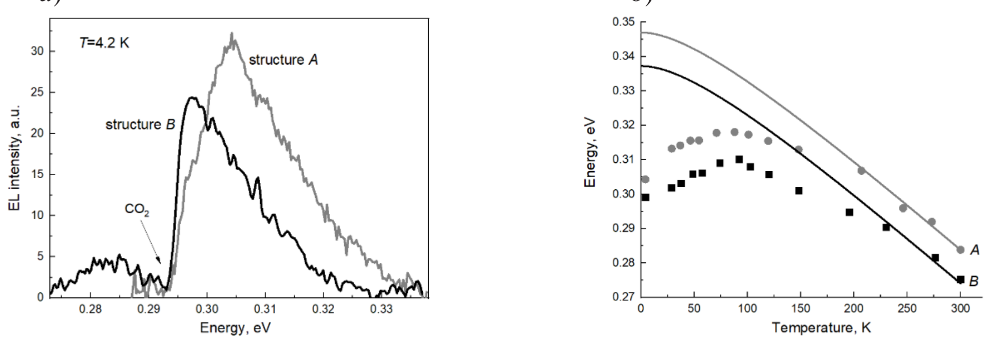

Fig. 1. EL spectra of spontaneous emission measured at $T = 4.2$ K and $i = 0.2$ A (*a*) and the temperature dependences of photon energy at the peak maximum of spontaneous emission (symbols) and calculated $E_g(T)$ dependences of $InAs_{0.91}Sb_{0.09}$ (structure *A*) and $InAs_{0.89}Sb_{0.11}$ (structure *B*) solid solution (curves) (*b*)

Fig. 2 shows the EL spectra of the heterostructures under study at higher injection levels and low temperature (T = 4.2 K). The stimulated emission starts at the injection level of i > 0.2 A and demonstrates a narrow spectrum with FWHM ~ 2 meV. Increase in the injection level (i > 0.6 A) led to the formation of multi-mode spectrum which could be approximated with Lorentz distributions. The resulting intensity of EL spectra reached the saturation level at the injection current characteristic of the appearance of the third mode in the spectra. It should be noted that with an increase in the excitation level, the intensity of individual modes in the EL spectrum changed. The average inter-mode distance was Δλ ~ 1.2 nm corresponded to the cavity length L = 170 μm, which was determined mainly by the thickness of the InAs substrate.

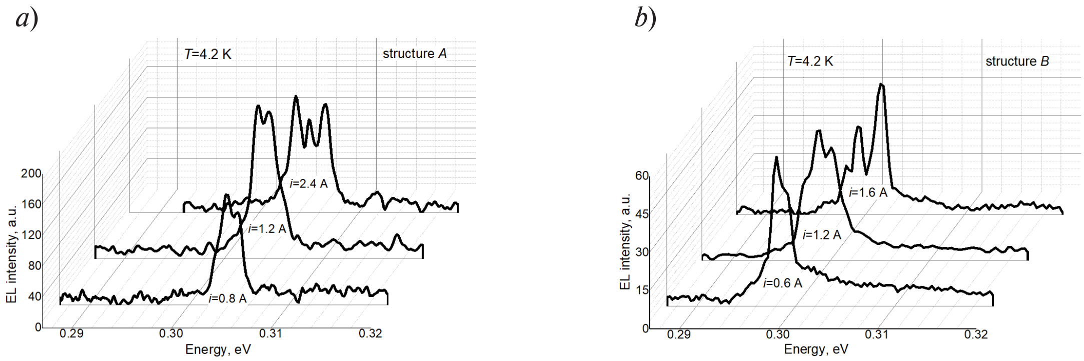

Fig. 2. EL spectra of stimulated emission for the heterostructures A (a) and B (b) measured at T = 4.2 K and different injection currents

As can be seen in Fig. 2, the stimulated emission was generated in the spectral region 0.29–0.31 eV depending on the studied heterostructure and that manifests a good agreement with spontaneous EL data at the given temperature. Therefore, the observed stimulated emission at low temperatures was caused by the interface radiative recombination of holes near the Fermi level with electrons localized in the potential well. The shift towards higher energy of photon with increasing of an injection level can be explained by a shift of localization level for electrons.

It should be noted that the stimulated emission was observed in the temperature range 4.2–30 K for both structures. The transition from stimulated to spontaneous emission occurred at T ~ 30 K (not shown in Fig. 1,b). The maximum temperature reached here is less than that reported for similar heterostructure based on the InAsSb active layer containing smaller antimony concentration [9]. The amazing fact manifested in this work is that the samples studied had the ultimate content of antimony in the active layer at which the crystalline structure of the layers of the heterostructure was not yet corrupted. It is well known that the crystalline perfection of ternary solid solutions grown on InAs substrates is in close association with a parameter of the lattice mismatch between epitaxial layer and substrate matrix. This parameter for $InAs_{1-y}Sb_y$ epitaxial layers at y = 0.09–0.11 does not exceed 1%, which is a critical value for thin layers. If the mismatch is greater, a near-surface network of dislocations can be generated, accompanied by an increase in the concentration of extended and point defects, etc., which leads to relaxation of the epitaxial system. Experiments carried out for samples with a higher content of antimony in the active region demonstrated suppression of stimulated emission in similar narrow-gap asymmetric heterostructures based on the InAsSb ternary solid solution.

Conclusion

Electroluminescence spectra of asymmetrical $InAs/InAs_{1-y}Sb_y/InAsSbP$ LED heterostructures with ultimate concentration of InSb in the active layer y = 0.09 and 0.11 were studied in the temperature range T = 4.2–300 K. The rearrangement of the contributions of three different mechanisms of radiative recombination was observed with temperature increasing. At low temperatures (T < 100 K) the spontaneous luminescence and the stimulated emission were caused by the interfacial radiative transitions at the type-II InAsSb/InAsSbP heterointerface. At higher temperatures (T > 100 K) radiative recombination transitions (solely spontaneous) involving zinc acceptor states in the active layer were dominant. At T > 200 K and up to 300 K the EL was determined by interband radiative transitions in the bulk of the active layer made of InAsSb ternary solid solution.

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