Temperature dependence of the optical and electrical properties of long-wavelength InAsSb-based LED heterostructures

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Abstract. Optical and electrical characteristics of asymmetrical InAs/InAsSb/InAsSbP LED heterostructures with the InSb content in the active layer of 0.15 and 0.16 were studied in the temperature range 4.2 - 300 K. At T < 150 K, radiative transitions involving donor-acceptor states in the InAs substrate were observed in electroluminescence spectra, and the presence of these states also showed up in the peculiarities of current-voltage characteristics. A strong effect of the quality of the InAsSb/InAsSbP heterointerface on the characteristics of the heterostructures was observed.

1. Introduction

The mid-infrared (wavelengths 2 - 6 µm) light-emitting diodes (LEDs) are promising emission sources for systems of environmental control and medical applications [1]. Today, one of the priorities is to optimize the design of heterostructures with the aim of increasing the efficiency and reliability of LEDs in the presence of external factors, such as temperature variations. Of special interest are wavelengths beyond 5 µm. This spectral range can be covered with devices based on InAsSb solid solutions grown on nearly latticed-matched InAs substrates. The design of structures for this spectral range requires an increase in the concentration of antimony atoms in the InAsSb active layer, which leads to an increase in the crystal lattice constant of the solid solution with respect to the corresponding parameter of the InAs substrate. At small mismatch values, the InAsSb epitaxial layers grow pseudomorphically undergoing elastic deformation. However, when a certain critical mismatch value is reached, plastic compression deformation occurs, which leads to the formation of a network of misfit dislocations at the interfaces between the constituent parts of the heterostructure [2].

Recently, we reported the results of electroluminescence (EL) studies of asymmetrical InAs/InAsSb/InAsSbP LED heterostructures with InSb content in the active layer 0.15 and 0.16. These LEDs emitted light with the wavelengths 5.02 and 5.10 µm, respectively, at 300 K. In this work, we shall focus on the discussion of temperature dependences of optical and electrical characteristics of these heterostructures.
2. Experimental

The heterostructures were grown by metal-organic vapour-phase epitaxy (MOVPE) in a horizontal resistively heated reactor at atmospheric pressure on undoped (001)InAs substrates with the electron concentration \( n = 3 \times 10^{16} \text{ cm}^{-3} \). Two heterostructures were studied with the InSb content in the InAsSb active layers equalling 0.15 and 0.16 for samples \( A \) and \( B \), respectively. The thicknesses of the active layers and of the wide-bandgap InAs\(_{0.41}\)Sb\(_{0.59}\)/P\(_{0.41}\) barrier layers were 3 \( \mu \text{m} \) and 1.2 \( \mu \text{m} \), respectively, for both structures. The barrier layers were doped with zinc using diethylzinc as a precursor. 400×400 \( \mu \text{m} \) LED chips were formed with the use of standard photolithography and wet chemical etching (sample \( A \)) and via the fabrication of a simple mesa-structure (sample \( B \)).

The upper (epitaxial-layer side) contact had the form of a ring with the width of 30 \( \mu \text{m} \) and the inner diameter of 200 \( \mu \text{m} \). A non-transparent solid contact was deposited on the substrate side. The chips were mounted on TO-18 packages. EL spectra were recorded under pulse excitation with the frequency of 1 kHz and the pulse duration of 2 \( \mu \text{s} \). An InSb photodiode and a HgCdTe photoconductor were used as detectors. The HgCdTe detector was applied for the additional studies of the long-wavelength parts of the spectra, which at higher temperatures fell outside the photosensitivity limit of the InSb detector. The spectra and the current-voltage (\( I-V \)) characteristics were studied in the temperature range 4.2 - 300 K.

3. Results and discussion

Figure 1(a) shows EL spectra of samples \( A \) and \( B \) recorded at the temperature \( T = 77 \text{ K} \). The spectra of both structures contain two pronounced emission bands: a broad band with a maximum at 0.29 eV (sample \( A \)) and 0.25 eV (sample \( B \)), and a narrow peak with a maximum at 0.39 eV. The latter was observed in the temperature range 4.2 - 150 K; with temperature increasing, only the low-energy EL band remained in the spectra of both structures. Figure 1(b) shows the temperature dependence of the positions of the high-energy EL peaks for both structures (symbols 5) and the low-energy EL peaks (symbols 3, 4) for samples \( A \) and \( B \), respectively. It also shows calculated temperature dependences of the bandgap (\( E_g(T) \)) of the active layer in samples \( A \) and \( B \) (curves 1 and 2, respectively). The \( E_g(T) \) dependences for InAs\(_{1-x}\)Sb\(_x\) solid solutions were calculated according to the expressions from reference [3]. The experimental temperature dependences of the EL peaks positions were obtained by approximating the spectra with the Gaussian distribution curve.

![Figure 1](image-url)  

**Figure 1.** EL spectra of samples \( A \) (1) and \( B \) (2) at \( T = 77 \text{ K} \) (a). Calculated \( E_g(T) \) dependence for InAs\(_{0.85}\)Sb\(_{0.15}\) (1) and InAs\(_{0.84}\)Sb\(_{0.16}\) (2); experimental data on the temperature dependence of the positions of high-energy EL peaks for both structures (5) and low-energy EL peaks for samples \( A \) and \( B \) (3 and 4, respectively) (b).

The nature of the low-energy EL bands was preliminary discussed elsewhere [4]. It was suggested that for the heterostructure with \( x_{\text{InSb}} = 0.16 \) the dominant channel of radiative recombination at \( T < 50 \) K was due to optical transitions at the InAsSb/InAsSbP heterointerface. However, at \( T > 80 \) K radiative
transitions in the bulk of the active layer became dominant. At the same time, it seemed that for the heterostructure with $x_{\text{InSb}} = 0.15$ radiative recombination was due to interband recombination in the active layer in the whole temperature range $4.2 – 300$ K. To verify these assumptions, additional studies were carried out and the results are presented in this work.

Let us consider formation of the high-energy EL bands. It was previously assumed that these bands were associated with the carrier recombination in the InAs substrate [4]. To verify this assumption, a study of EL from InAs$_{0.32}$Sb$_{0.26}$P$_{0.42}$/InAs$_{0.92}$Sb$_{0.08}$/InAs$_{0.32}$Sb$_{0.26}$P$_{0.42}$ heterostructure (sample C), grown on the same substrate, was carried out. The structure C consisted of an undoped (001)InAs substrates with the electron concentration $n = 3 \times 10^{16}$ cm$^{-3}$ which was overgrown first with a 0.6 µm-thick undoped InAs$_{0.32}$Sb$_{0.26}$P$_{0.42}$ barrier layer, then with a 1.5 µm-thick active undoped InAs$_{0.92}$Sb$_{0.08}$ layer, and finally with a 1.3 µm-thick $p$-InAs$_{0.32}$Sb$_{0.26}$P$_{0.42}$ barrier layer doped with zinc using diethylzinc as a precursor. Due to the peculiarities of the band structure of structure C (a strong electron confinement in the InAs substrate) the main EL signal was due to radiative transitions in the substrate [5]. Figure 2(a) shows EL spectra of sample C at driving current $I = 3$ A and at temperatures 4.2 and 63 K. It can be seen that at $T = 4.2$ K the spectrum contains single emission band with a maximum at 0.40 eV, the full width at half maximum (FWHM) of this band is 11 meV. However, as the temperature increased to 63 K, a second band appeared in the spectrum with a maximum at 0.41 eV. The overall FWHM of the spectrum increased to $\approx 31$ meV and the spectrum shifted towards lower energies. As the temperature increased further, this EL band became dominant. In the 148 – 300 K temperature range, the single band remained in the EL spectrum, with photon energy ranging from 0.389 to 0.357 eV. For EL spectra of samples A and B this effect was not observed. Figure 2(b) shows temperature dependences of the peaks of the high-energy EL bands for structures C (symbols 4), A and B (symbols 6) and those of the low-energy EL band for structure C (symbols 5), as well as calculated corresponding $E_\beta(T)$ dependences. Since, under said assumption the presence of these bands in the EL spectrum is determined by radiative recombination in the InAs substrate, the $E_\beta(T)$ dependence can be best described by the linear-quadratic relation proposed by Varshni [6]:

$$E_\beta = E_0 - \alpha T^2(T + \beta)^{-1}$$  \hspace{1cm} (1)

where $E_0 = E_\beta$ at $T = 0$ K (0.417 eV for InAs), $\alpha$ is the constant determining the temperature coefficient of the energy bandgap $dE_\beta/dT$, $\beta$ is the constant related to the Debye temperature $\theta$. The parameters of InAs for calculating $E_\beta(T)$ were taken from [7].

**Figure 2.** EL spectra of sample C at 4.2 K (1) and 63 K (2) (a). Calculated $E_\beta(T)$ dependence for InAs (1), Varshni approximation with $\alpha = 2.76 \times 10^{-4}$ eV·K$^{-1}$, $\beta = 93$ K (2), and with $\alpha = 3.1 \times 10^{-4}$ eV·K$^{-1}$, $\beta = 50$ K (3), experimental temperature dependence of the position of the high-energy EL peaks for samples C (4), A and B (6) and of the low-energy EL peaks for sample C (5) (b).
As can be seen in figure 2(b), the experimental high-energy EL peaks for sample C (symbols 4) demonstrate good agreement with the calculated $E_G(T)$ dependence for InAs (curve 1) within the whole temperature range. Thus, these peaks originate in interband radiative recombination in the InAs substrate. At the same time, the high-energy EL peaks for samples A and B (symbols 6) are in good agreement with the low-energy EL peaks for sample C (symbols 5). The position of EL maxima within the energy range 0.400 - 0.363 eV has a complex temperature dependence and cannot be described by a single curve. Using expression (1), a curve was calculated corresponding to the energy of radiative transitions to an acceptor level in bulk InAs with a depth of 18 meV (curve 2). Here, the corresponding constants $\alpha$ and $\beta$ were taken as for InAs: $\alpha = 2.76 \times 10^{-4}$ eV·K$^{-1}$, $\beta = 93$ K. It is seen that the experimental data are well described by calculated curve 2 in the temperature range 4.2 - 90 K. Hence, the radiative transitions involving acceptor states in the InAs substrate take place at low temperatures for the studied samples; most likely, these are donor-acceptor transitions typical of un-doped InAs crystals [8]. However, at temperatures from 90 to 148 K, the experimental data deviate from the calculated Varshni dependence for these radiative transitions in the InAs substrate (curve 2). It is seen that in this temperature range, the obtained experimental dependences are linear. The linearity of $E_G(T)$ dependence in the framework of Varshni formula can be explained as a decrease of the Debye temperature. In this case, $\alpha$ is close to the corresponding parameter for InAs and equals $3.1 \times 10^{-4}$ eV·K$^{-1}$, and $\beta$ turns out to be much smaller and equals 50 K (curve 3). Hence, a change in temperature from 4.2 to 300 K significantly affects the optical characteristics of the studied heterostructures.

Let us discuss the effect of temperature on the electrical properties of the samples. Figure 3(a) shows the current-voltage characteristics of sample A at various temperatures. At low temperatures (4.2 - 100 K), a characteristic kink in the direct branches of the $I$-$V$ characteristics is observed, which probably is due to the tunnelling through impurity states. As can be seen, increasing the temperature to 300 K leads to the generation of a considerable reverse current. Moreover, the current in the reverse branch tends to saturation starting from rather small voltages, which is typical of the diffusion mechanism [9].

![Figure 3](image_url)

**Figure 3.** Current-voltage characteristics of samples A (a) and B (b) at temperatures: 4.2 K (1), 77 K (2) and 300 K (3).

Figure 3(b) shows the $I$-$V$ characteristics of sample B. It is seen that a certain reverse current exists in this heterostructure in the whole temperature range studied. Moreover, this current substantially increases at 300 K and its value depends on the voltage, which contrasts this sample to sample A. This effect is probably related to the tunnelling through the InAsSb/InAsSbP heterointerface. The cut-off voltages were smaller than the corresponding bandgaps of the InAsSb active layers for both samples. For example, for sample B these values were 265 mV at $T = 4.2$ K and 18 mV at $T = 300$ K. This effect confirms the presence of leakage currents through the interface. As a result, for sample B, the contribution of optical transitions involving levels localized at the interface to radiative recombination
can become comparable to that of the interband radiative transitions in the bulk of InAsSb active layer and even prevail at low temperatures. This is exactly what is seen in the EL spectra (see figure 1).

Our results showed a strong effect of the temperature on the optical and electrical characteristics of the studied LED heterostructures. However, the design of the active region of the heterostructures determined the obtained results to a large extent. It was demonstrated that an increase in the InSb content in the InAsSb active layer up to 0.16 significantly changed the quality of the interface. It is possible to conclude that with InSb content in the InAsSb layer exceeding 0.15, the chemistry of the active layer surface, onto which the cap barrier layer InAsSbP will be grown, should be expected to change [10]. This can result in the formation of the type II heterojunction at the InAsSb/InAsSbP interface, which affected both optical and electrical characteristics of the samples. As and can be seen in figure 1(b), the predominance of the radiative transitions at the InAsSb/InAsSbP heterointerface at low temperatures and the interband transitions in the InAsSb bulk active layer at higher temperatures minimized the effect of the temperature on the wavelength of the LED.

4. Conclusion
Electroluminescence spectra and current-voltage characteristics of two asymmetrical InAs/InAsSb/InAsSbP LED heterostructures were studied. A significant change in their physical properties with temperature changing from 4.2 to 300 K and with InSb content in the InAsSb active layer changing from 0.15 to 0.16 was observed. At low temperatures ($T < 150$ K), radiative transitions due to recombination of donor-acceptor pairs in the InAs substrate were observed, and the existence of these impurity states was confirmed by the peculiarities observed in the current-voltage characteristics. At $T > 150$ K, radiative recombination was mainly determined by the interband transitions in the InAsSb active layers. However, for the heterostructure with the 0.16 InSb content, the radiative transitions at the InAsSb/InAsSbP heterointerface were making a great contribution to the radiative recombination, and the specifics of this heterointerface also affected the shape of $I$-$V$ characteristics. The existence of two radiative recombination channels in this heterostructure made it possible to reduce the effect of the temperature on the LED emission wavelength.

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