Variable-temperature luminescence studies of InAsSb-based LED heterostructures emitting beyond 5 µm

A A Semakova¹², V V Romanov³, K D Moiseev³, N L Bazhenov³ and K D Mynbaev¹²

¹ ITMO University, Saint-Petersburg 197101, Russia
² Ioffe Institute, Saint-Petersburg 194021, Russia

E-mail: antonina.semakova@itmo.ru

Abstract. Variable-temperature (4.2 - 300 K) electroluminescence (EL) studies were performed on two asymmetrical InAs/InAsSb/InAsSbP LED heterostructures emitting at 5.02 and 5.10 µm wavelengths at 300 K (with an InSb content in the active layer of 0.15 and 0.16, respectively). For the structure with the narrowest bandgap, a weak temperature dependence of the position of the EL peak was observed. Along with strong carrier localization in the active layer, which was provided by the design of the structure, this made the studied heterostructures promising for fabrication of LEDs with working wavelengths extending beyond 5 µm at 300 K.

1. Introduction

The mid–infrared (IR) wavelength range (2 - 6 µm) is often referred to as the ‘molecular fingerprint’ region of the spectrum, where the presence of various molecules can be detected via their unique spectral signatures; this enables many environmental, medical, industrial, security and defence sensing applications [1]. The 3 - 5 µm range can be easily covered with devices based on InAsSb solid solutions grown on nearly latticed-matched InAs or GaSb substrates. Lattice constants of InAsSb in the composition range providing emission/detection at wavelengths beyond 5 µm (required for detecting, e.g., nitrogen oxide with optical signature at 5.3 µm), however, do not match those of any binary substrates. This challenge can be met by the growth of InAsSb on metamorphic buffers [2], but this technique is complex and expensive. The development of metal-organic vapour-phase epitaxy (MOVPE) recently allowed producing heterostructures with high InSb content in the InAsSb active layer directly on InAs [3–5]. MOVPE also gives a possibility of growing InAsSbP isoperiodic to InAs over the entire composition range, which allows one to form potential barriers for both electrons and holes and thereby significantly improve carrier localization [4]. Recently, we reported on the growth and electroluminescence (EL) studies of asymmetrical InAs/InAsSb/InAsSbP heterostructures with an InSb content in the active layer achieving 0.16, which provided emission beyond 5 µm at 300 K [6]. The studies were performed at 300 K and 77 K and suggested the existence of a number of radiative recombination channels in the structures. To clarify this matter, we performed variable-temperature (T = 4.2 - 300 K) EL studies of heterostructures with an InSb contents of 0.15 and 0.16.

2. Experimental details

Heterostructures were grown in a horizontal MOVPE reactor with resistive heating under atmospheric pressure on un-doped commercial (001)InAs substrates (electron concentration n = 3×10¹⁶ cm⁻³).
InSb content in the active layers of samples \( A \) and \( B \) was 0.15 and 0.16, respectively; all other parameters of the structures were identical. The details of the growth were given elsewhere [6]. The thickness of the active layers in both samples equalled 3 \( \mu \text{m} \); that of the barrier layers, 1.2 \( \mu \text{m} \).

LED chips 400×400 \( \mu \text{m} \) in size were formed with photolithography. The upper (epitaxial-layer side) contact had the form of a ring with a width of 30 \( \mu \text{m} \) and an inner diameter of 200 \( \mu \text{m} \). A non-transparent solid contact was deposited on the substrate side. The chips were mounted on standard TO–18 packages. EL spectra were recorded under pulse excitation (frequency 1 kHz, pulse duration 2 \( \mu \text{s} \)) with the use of computer-controlled installation employing an MDR-23 grating monochromator and a lock-in amplifier. An InSb photodiode and a HgCdTe photoconductor were used as detectors.

3. Experimental results

Figure 1 shows the normalized EL spectra of the heterostructures recorded at a driving current \( I = 3 \text{ A} \) at \( T = 4.2 \text{ K} \). These spectra were recorded with the use of an InSb photodiode, and, as can be seen, the low-energy part of the spectrum of sample \( B \) is distorted due to the low cut-off wavelength of this detector. In further experiments, the EL spectra of sample \( B \) were recorded with the use of an HgCdTe photodetector. Both spectra presented in figure 1 consisted of two peaks. For sample \( A \), their maxima were located at 0.292 eV and 0.403 eV, respectively. For sample \( B \), the maxima were located at 0.263 eV and 0.400 eV, respectively. The full width at half maxima (FWHM) of the strong high-energy peaks at \( T = 4.2 \text{ K} \) equalled 10 - 12 meV. Low-energy peaks had much lower intensity and were much broader; their FWHM values at the same temperature equalled 50 - 60 meV.

![Figure 1. Normalized EL spectra of samples A (a) and B (b) recorded with an InSb photodiode. The dip at 0.29 eV is caused by absorption by CO\textsubscript{2} in the ambient atmosphere. The low-energy part of the spectrum in image (b) is distorted due to specifics of the sensitivity curve of the InSb photodetector.](image)

Due to the similarity in the position of high-energy peaks and their low FWHM values, which were typical of a material with high crystalline perfection, it was obvious that these peaks were related to the emission from the InAs substrates. The low-energy peaks could be related to the emission from the active layers. Variable-temperature luminescence studies revealed that the substrate-related EL signal could be traced up to \( \sim 150 \text{ K} \) and the FWHM of the corresponding peaks remained low (\( < 15 \text{ meV} \)). At that, the exact position of the peaks in the 4.2 - 150 K temperature range did not exactly correspond to the bandgap energy \( E_g \) of InAs, though followed its temperature dependence. As it was not clear whether the substrate-related EL signal was due to emission from the substrate itself or was caused by some interface-related phenomenon, a photoluminescence (PL) study of the substrate was conducted. This study was performed with the use of the same measurement set-up as described above with the PL signal excited by a semiconductor laser with a 1.03 \( \mu \text{m} \) wavelength. The PL spectrum of the substrate recorded at 85 K is presented in figure 2(a). It consists of two bands. The high-energy band had its maximum at 0.410 eV and its FWHM value equalled 13 meV. The low-energy band had its maximum at 0.390 eV; its FWHM value equalled 15 meV. At 300 K (spectrum not shown), the
maximum of the PL spectrum, which had only one band, was located at 0.360 eV. Figure 2(b) shows the temperature dependence of the maxima of high-energy EL peaks for sample B (symbols 1) and the $E_g(T)$ dependence for InAs, calculated according to the data from reference [7] (curve 4). Using the approach described in reference [8], we calculated experimental $E_g$ values of the studied material from the PL data at 85 K and 300 K and plotted them in figure 2(b) as symbols 3. As can be seen, these values fit very well the data of the empirical calculations of $E_g(T)$, so the high-energy peak in the PL spectrum was definitely related to inter-band transitions in the InAs substrate. At the same time, the position of the low-energy PL peak of the substrate at 85 K (symbol 2) agreed very well with that of the high-energy EL peaks of the heterostructures (symbols 1). This allowed us to conclude that the latter were due to impurity-related optical transitions in the substrate. On the basis of the data available in the literature, it could be suggested that those were transitions due to donor-acceptor pair recombination, which are often observed in un-doped InAs [6,9].

Figure 3 shows the results of variable-temperature studies of the position of low-energy EL peaks for both samples. In particular, shown are the experimental data on the temperature dependence of the positions of these peaks for sample A (symbols 1) and B (symbols 2), the data on the position of EL peaks for the same samples at 77 K and 300 K from reference [6] (symbols 3 and 4, respectively), and the $E_g(T)$ dependence for InAs$_{0.8}$Sb$_{0.15}$ and InAs$_{0.8}$Sb$_{0.16}$, calculated according to paper [7] (curves 5 and 6, respectively). As can be seen, at low temperatures, the energy of the maxima of EL peaks for sample A (symbols 1) was lower than that of $E_g$; this is typical of InAs-based solid solutions and again is explained by the dominance of recombination of donor-acceptor pairs. At $T > 77$ K, the energy of the peaks for sample A basically followed the $E_g(T)$ dependence of the corresponding solid solution. We earlier observed a similar effect for InAsSb-based LED heterostructures with an InSb content in the active layer of 0.06, 0.07 and 0.09 [8].

The temperature dependence of the positions of low-energy EL peaks for sample B (symbols 2) behaved differently. This dependence was weak and did not follow the calculated $E_g(T)$ relation (curve 6). At the same time, it agreed with the data from reference [6] (symbols 3 and 4), which also suggested a flat $E_g(T)$ curve for these samples.

The difference between the temperature dependences of the positions of low-energy EL peaks for samples A and B can be understood considering that with an InSb content in the InAsSb layer exceeding 0.15, the effect of a matrix surface on the following deposited layer (InAsSbP barrier layer) becomes crucial. In such samples, due to the enriching of the top surface of the InAsSb active layer with Sb, one can expect some changes in the composition of the barrier layer during the initial stages of the growth, until a new balance between P and Sb atoms in the crystal lattice is achieved.
This can result in the formation of the type II heterojunction at the InAsSb/InAsSbP interface in contrast to samples with lower InSb content in the active layer. It is well known that type II heterojunction provides formation of quantum wells at the opposite sides of the heterointerface [10], and that carrier scattering at the type II heteroboundary is strongly suppressed [11]. Thus, a large difference in photon energy between data (6) and (2) at $T < 50 \text{K}$ in figure 3 can reflect a contribution of the type II interface radiative transitions for sample B. At $T > 80 \text{K}$, due to the weakening of carrier localization at the heterointerface, radiative transitions in the bulk of the active layer become dominating. This effect gives the advantage of a very weak temperature dependence of the peak wavelength of the LED heterostructures. At the same time, the specific design of the considered InAs/InAsSb/InAsSbP heterostructure, which in thermodynamic equilibrium provides potential barriers for both electrons and holes, obviously ensures excellent carrier confinement. This allows room-temperature operation of long-wavelength (5.02 and 5.10 $\mu$m at 300 K for samples A and B, respectively) LED heterostructures.

4. Conclusion

Variable-temperature (4.2 - 300 K) electroluminescence (EL) studies were performed on two asymmetrical InAs/InAsSb/InAsSbP LED heterostructures emitting at 5.02 and 5.10 $\mu$m wavelengths at 300 K (with an InSb content in the active layer of 0.15 and 0.16, respectively). For the structure with a 0.16 InSb content, a very weak temperature dependence of the position of the EL peak was observed. Along with strong carrier localization in the active layer provided by the design of the heterostructures, this makes them really promising for fabrication of IR emitters with 300 K wavelengths extending beyond 5 $\mu$m.

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