Spontaneous and stimulated emission in InAs-based LED heterostructures

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Abstract. Electroluminescence of ‘flip-chip’ LED heterostructures containing active layers made of InAs and barrier layers made of InAsSb(Ga,P) was studied experimentally and modelled. At the room temperature, spontaneous emission attributed to band-to-band recombination was observed. The shape of the EL band was strongly affected by absorption in the substrate. At low temperatures (T = 4.2 K and 77 K), stimulated emission was observed. Factors affecting the appearance and quenching of stimulated emission are discussed.

1. Introduction

Mid–wavelength infrared range (MWIR, 2-5 µm) is important for spectroscopy of gases and molecules, explosive detection systems, medical applications, and environmental monitoring tasks. Optical sensors used in these applications typically require a light emitter and a photodetector, and the efficiencies of both devices strongly depend on the processes of carrier recombination. This is why lately there has been much interest in the studies of recombination processes, both radiative and non-radiative, in the materials suitable for optoelectronic devices operating in the MWIR, that is, InAs-based materials with the addition of Sb, P, Ga and/or Al [1]. Recently, we have reported on the results of the studies of electroluminescence (EL) of light-emitting-diode (LED) heterostructures with active layer made of InAsSb [2]. In this paper, we report on the results of the studies of EL of LED heterostructures with the active layer made of pure InAs.

2. Experimental details

Heterostructures were grown with the use of metal-organic chemical vapour deposition (MOCVD) at Microsensor Technology, LLC, using a growth method described elsewhere [3]. For all heterostructures, commercially available sulphur-doped 500 µm-thick (001)InAs substrates with n-type conductivity were used. The active layer of the heterostructures was not intentionally doped and had electron concentration $n_e \approx 2 \times 10^{16}$ cm$^{-3}$, presumably due to background donor doping. The thickness of the active layer was ~2.5 µm. Barrier layers were made of InAsSb(Ga,P) with p-type conductivity. These layers were doped with zinc and had hole concentration $p_h \approx 2 \times 10^{18}$ cm$^{-3}$ at the temperature $T = 77$ K. Parameters of the heterostructures are listed in Table 1. Substrates with electron concentration $2 \times 10^{18}$ cm$^{-3}$ (structures A and B) were produced by Wafer Technology, Ltd, those with concentration $5 \times 10^{18}$ cm$^{-3}$ (structures C and D), by CrysTec GmbH.
LED chips with 380×380 µm size were fabricated with the use of standard photolithography and wet chemical etching. Electrical contacts were based on a multi-layer Cr–Au–Ni–Au composition. A non-transparent solid contact was placed on the top epitaxial layer, while a ring-type contact with 35 µm thickness and 200 µm internal diameter was placed on the InAs substrate. The emission was collected from the side of the substrate (‘flip-chip’ configuration) with the chips placed on TO-18 holders. EL spectra were recorded under pulse excitation. An InSb photodiode was used as a detector.

3. Experimental results
Figure 1(a) shows normalized EL spectra of the heterostructures at driving current \( I = 150 \text{ mA} \) (a typical working current for LEDs of this type) at \( T = 300 \text{ K} \). The spectrum of heterostructures of types A and B contained a symmetrical line centred at \( \approx -0.36 \text{ eV} \) with a full-width at half-maximum (FWHM) \( \approx 28 \text{ meV} \). The spectra of heterostructures of types C and D were broader and had more complex shape. This difference, as well as a seeming ‘shift’ of the maximum of EL spectra of heterostructures of types A and B in relation to that of heterostructures of types C and D was explained by the absorption of the part of radiation by the substrate, as in the latter structures the substrate was doped stronger and was more transparent to the outgoing radiation due to the Burstein-Moss effect. This is illustrated in figure 1(b), where optical transmission spectra of the two InAs substrates are shown along with the EL spectrum of heterostructure of type D. As can be seen in figure 1(b), as optical transmission spectrum of InAs substrate with \( n_\gamma = 2 \times 10^{18} \text{ cm}^{-3} \) is shifted towards lower energies, a substantial part of emission of the active layer is absorbed, so the spectrum of outgoing emission seems to be narrow and centred at 0.36 eV. On the other hand, optical transmission of InAs substrate with \( n_\gamma = 5 \times 10^{18} \text{ cm}^{-3} \) allows for the most part of the emission of the active layer passing through, while a small transmission spectrum feature at 0.42 eV results in the emission spectrum appearing as containing two bands. In reality, however, this emission spectrum had just one band as can be seen in figure 2, where emission spectra of the active InAs layer obtained with calculations and modelling are shown.

| Structure type | Substrate | Barrier layer |
|---------------|-----------|---------------|
| A             | \( n-\text{InAs}, n_\gamma=2 \times 10^{18} \text{ cm}^{-3} \) | \( p-\text{InAs}_{0.13}\text{Sb}_{0.87}\text{P}_{0.54} \) |
| B             | \( n-\text{InAs}, n_\gamma=2 \times 10^{18} \text{ cm}^{-3} \) | \( p-\text{InAs}_{0.21}\text{Sb}_{0.79}\text{P}_{0.57} \) |
| C             | \( n-\text{InAs}, n_\gamma=5 \times 10^{18} \text{ cm}^{-3} \) | \( p-\text{InAs}_{0.23}\text{Sb}_{0.77}\text{P}_{0.50} \) |
| D             | \( n-\text{InAs}, n_\gamma=5 \times 10^{18} \text{ cm}^{-3} \) | \( p-\text{In}_{0.76}\text{Ga}_{0.24}\text{As}_{0.80}\text{Sb}_{0.20} \) |

**Table 1.** Parameters of the studied heterostructures.
Calculations of luminescence spectra were performed with the consideration of the non-parabolic dependence of the energy of electrons and light holes on the wavevector in accordance with Ref. [4]. Parameters of the material were taken from Ref. [5]. The results of the calculations for the heterostructure of type A are shown in figure 2(a) by curve 2. In these calculations, carrier concentration was taken as $4 \times 10^{16}$ cm$^{-3}$ in accordance with the data obtained under similar injection conditions for InAsSb-based heterostructures [2]. It is seen that the maximum of the calculated spectrum (curve 2) is indeed blue-shifted by $\sim$17 meV in relation to that of the experimental one (curve 1). Calculations placed the peak of the spectrum at 0.37 eV, which was indeed the position of the maximum of EL spectra of structures of type C and D, where the substrate was not hindering light output at the low-energy part of the emission spectrum. We also performed simulation of optical properties of our structures at 300 K with the use of COMSOL Multiphysics® software. For testing purposes, first, voltage-current characteristics of the structures were simulated and compared to the experimental ones (not shown). When a satisfactory agreement between the simulated and experimental characteristics was achieved, optical properties of the heterostructures were simulated. The result of the simulations for the structure of type A is presented in figure 2(a) by curve 3. Here, we assumed energy bandgap of InAs as 0.35 eV, that of InAs$_{0.15}$Sb$_{0.31}$P$_{0.54}$, 0.63 eV, applied bias, 100 mV. It can be seen that calculated and simulated spectra are in a very good agreement, which is indicative of almost negligible effect of non-parabolicity on the shape of the emission spectrum. Figure 2(b) shows the results of the simulations of the EL spectra at various biases. As expected, with the applied bias increasing, the intensity of EL increases and the peak gets blue-shifted.

Figure 2. EL at 300 K of heterostructure of type A: (a), experimental spectrum (curve 1), spectrum calculated in accordance to Ref. [4] (curve 2) and spectra simulated with COMSOL (curve 3); (b), simulated spectra at various applied biases: 1, 100 mV; 2, 150 mV; 3, 200 mV; 4, 250 mV; 5, 300 mV.

Figure 3(a) shows normalized experimental EL spectra for heterostructure of type D at $T=77$ K at three driving currents. At the smallest driving current studied, $I=0.024$ A, the peak of the spectrum (not shown) was located at 0.41 eV and had FWHM of 18 meV. With driving current increasing from 0.024 to 0.2 A, the peak experienced a small blue-shift with FWHM of the spectrum increasing (curve 1). At $I=0.4$ A, a narrow ‘side’ peak appeared at the broad spectrum (curve 2). At $I=0.8$ A, the narrow (FWHM $\sim 2$ meV) emission peak was dominating, and the broad emission band had rather low intensity as compared to that of the narrow peak (curve 3). Figure 3(b) shows normalized EL spectra for the same heterostructure at $T=4.2$ K. As can be seen, for all driving currents used, starting from $I=0.1$ A, the spectra represented a narrow (with FWHM from 0.5 meV at the lowest current) band.

In contrast to heterostructure of types C and D, in heterostructures of types A and B at 77 K and $I=0.8$ A, the emission line remained quite broad ($\sim 30$ meV) and transformed into a superposition of a wide ‘base’ and a narrow peak only at $I=2$ A. Similarly, at $T=4.2$ K, at $I=0.1$ A the emission line of these heterostructures remained broad and a distinctive narrow peak appeared only at $I=0.2$ A.
4. Discussion
The analysis of the acquired data showed that at low temperatures (4.2 and 77 K), conditions for stimulated emission held true in all the studied heterostructures. The effect of the appearance of stimulated emission at low temperatures was observed earlier in InAsSb-based LED heterostructures with similar design [2]. In LED structures with the active layer made of InAs, stimulated emission at low temperatures was first reported on by Matveev et al. [6]. In Ref. [6], in contrast to the present work, double heterostructures with high potential barriers on both sides of the active layer were studied, which should have helped carrier localization. In this work, we studied heterostructures with different barrier height, and it appeared that heterostructures with higher barriers (types A and B with the barrier energy gap of 0.63 eV and 0.62 eV at 300 K, respectively) at low temperatures required higher current density for showing stimulated emission than heterostructures of types C and D (barrier energy gaps 0.60 and 0.37 eV, respectively). Thus, carrier localization did not appear to be a crucial factor for the appearance of stimulated emission. As the quenching of the stimulated emission in our structures occurred at much lower temperatures than those corresponding to the point when the values of carrier lifetime limited by radiative recombination became comparable to that limited by the sum of non-radiative processes (T=230 K) [7], other factors contributing to the appearance and quenching of stimulated emission should be considered.

5. Conclusion
Electroluminescence (EL) of LED heterostructures with active layer made of InAs and barrier layers made of InAsSb(Ga,P) was studied at high (300 K) and low (4.2 and 77 K) temperatures. At the room temperature, EL spectrum represented a typical broad band, which could be attributed to band-to-band recombination. At low temperatures (4.2 and 77 K), stimulated emission was observed. Simulations of the emitting properties of the structures and theoretical calculations yielded results that agreed well with experimental observations, and this should help to increase the efficiency of MWIR light emitters by combining experimental and theoretical approaches.

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