Electroluminescence of InAsSb-based mid-infrared LEDs in 4.2–300 K temperature range

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Abstract. Electroluminescence of mid-infrared LEDs with active layer made of InAs and InAsSb in a wide temperature range (4.2–300 K) was studied. At low temperatures ($T=4.2$–100 K), stimulated emission from the LEDs was observed. The emission became spontaneous at higher temperatures due to the effect of CHHS Auger recombination process, when the energy of a recombining electron-hole pair was transferred to another hole with the latter transitioning to the spin-orbit-splitted band. The spontaneous character of recombination held up to the room temperature due to the effect of other Auger processes. Still, the results obtained show that structures based on InAsSb are a promising material for fabrication of mid-infrared lasers.

1. Introduction
The mid–infrared wavelength range (MWIR, wavelengths $\lambda$ 2–6 $\mu$m) represents great interest for the development of optoelectronic devices with applications in optical gas sensing, environmental control, biomedical imaging, thermal imaging, etc. From the viewpoint of sensor technology, light-emitting diodes (LEDs) represent an almost ideal source of MWIR radiation, as they demonstrate reasonably wide emission band, room temperature operation, very high modulation rate, small size and low power consumption [1]. Their problem is low emissivity, which is mostly due to the specifics of the electronic structure of narrow-bandgap AIIIBV semiconductors, which serve as a basis for MWIR LED heterostructures.

To enhance the efficiency of optoelectronic devices, it is important to understand and control the processes of carrier recombination, which govern emission of light (or the lack of thereof). For that task, it is worth studying the operation of the devices not only at working temperatures, but also at lower temperatures. Within the frames of such an approach, we have studied electroluminescence (EL) of InAsSb-based LEDs in a temperature range, 4.2–300 K.

2. Experimental details
The LED heterostructures were grown with the use of metal-organic chemical vapour deposition at Microsensor Technology, LLC, using synthesis method described elsewhere [2]. For most of the heterostructures, a strongly sulphur-doped InAs substrate ($n$-type conductivity, electron concentration at 77 K $n_{77}=(1-2)\times10^{18}$ cm$^{-3}$) was used. An active layer of the heterostructures was made of InAs or InAsSb. This layer was not intentionally doped and had electron concentration $n_{77}=1\times10^{16}$ cm$^{-3}$,
presumably due to background donors. A typical thickness of the layer was 2 to 3 µm. On top of the active layer, a \( p \)-type InAsSb(P,Ga) barrier layer was grown, this layer was doped with zinc and had hole concentration at 77 K \( p_{77} \approx 2 \times 10^{18} \text{ cm}^{-3} \). Parameters of the heterostructures are given in Table 1. For the growth of structure of type \( D \), a \( p \)-type InAs substrate was used. On this substrate, an InAsSbP barrier layer was grown first \( (p_{77} \approx 2 \times 10^{18} \text{ cm}^{-3}) \) and only then, an \( n \)-type InAs active layer.

Table 1. Parameters of the studied heterostructures.

| Structure type | Active layer | Barrier layer |
|----------------|--------------|---------------|
| \( A \)        | InAs         | InAs\(_{0.15}\)Sb\(_{0.31}\)P\(_{0.54}\) |
| \( B \)        | InAs         | InAs\(_{0.25}\)Sb\(_{0.25}\)P\(_{0.50}\) |
| \( C \)        | InAs         | InAs\(_{0.85}\)Ga\(_{0.15}\)As\(_{0.72}\)Sb\(_{0.28}\) |
| \( D \)        | InAs         | InAs\(_{0.15}\)Sb\(_{0.31}\)P\(_{0.54}\) |
| \( E \)        | InAs\(_{0.94}\)Sb\(_{0.06}\) | InAs\(_{0.40}\)Sb\(_{0.20}\)P\(_{0.40}\) |
| \( F \)        | InAs\(_{0.90}\)Sb\(_{0.07}\) | InAs\(_{0.70}\)Sb\(_{0.10}\)P\(_{0.20}\) |
| \( G \)        | InAs\(_{0.91}\)Sb\(_{0.09}\) | InAs\(_{0.48}\)Sb\(_{0.18}\)P\(_{0.34}\) |

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. For the measurements, the chips were placed on TO-18 holders. EL spectra were recorded under pulse excitation (frequency 1 kHz, pulse duration 1 µs) and InSb photodiode was used as a detector.

3. Experimental results and discussion

Figure 1 shows normalized EL spectra of four types of LEDs at \( T=300 \text{ K} \), which is a typical working temperature for the diodes employed in gas sensors (Fig. 1 (a)), and at \( T=4.2 \text{ K} \) (Fig. 1 (b)). In Fig. 1(a) one can observe a red-shift of the maximum of the spectrum due to the introduction of InSb, which has the energy bandgap value \( E_g \) smaller than that of InAs, and some broadening of the EL line typical of alloys as compared to binary compounds. Figure 1(b), in its turn, shows normalized EL spectra for three types of studied heterostructures at \( T=4.2 \text{ K} \) at various driving currents \( I \). As can be seen, these spectra drastically differ both in shape and full-width at half-maximum (FWHM) values from those recorded at 300 K. For example, for the structure of type \( A \), at the high-energy side of the barely visible wide emission band with FWHM 20 meV, there appeared a second narrow line with FWHM of 2 meV. For other structures at the temperatures close to 4.2 K we also observed quite narrow emission bands.

With temperature increasing, for all the structures we observed that the spectra with narrow EL peaks transformed back to broad bands. Temperature dependence of the calculated energy bandgap of some of the studied structures is presented in Fig. 2. This figure also shows experimental data. In the graph, for narrow emission lines (low temperature) we simply plotted out the position of the narrow peak of the EL spectrum. Though the position of this peak did not coincide with the maximum of the broad emission band (see Fig. 1(b)), it was not always possible to define the latter, as in most of the structures one could not distinguish the broad band with low intensity against the narrow peak with much higher intensity. For higher temperatures, when the EL spectra contained only broad bands, we derived the value of optical bandgap by calculating the EL spectrum and fitting its high-energy part to the experimental one with carrier concentration as a parameter. For the calculations, we took into account both electron–heavy hole and electron–light hole transitions and non-parabolic dependence of the conduction band and the valence band for light holes on energy, typical of narrow-bandgap semiconductors. The appropriate transition matrix element was calculated in Ref. [3]. The material
parameters necessary for calculations were taken from Ref. [4]. The calculated spectra (not shown) at \( T=77 \) K typically gave the best fit to the experimental ones at the values of carrier concentration under injection \( n=p=\left(3-5\right)\times10^{16} \text{cm}^{-3} \). The values of ‘optical’ bandgap were derived from the intercept formed by the low-energy part of calculated spectra on the abscissa axis. These values are shown in in Fig. 2 with empty symbols.

The appearance of the strong narrow peak in the EL spectra suggested that at low temperatures (from 4.2 up to 50–100 K, depending on the type of heterostructure), conditions for stimulated emission held true in the studied LEDs (see also Ref. [5]). For two structures of type \( F \) at temperatures, at which stimulated emission was still observed, we measured the light–current characteristics. With such measurements, if a pronounced “break” is observed in the recorded curve, a threshold current of stimulated emission \( I_{th} \) can be determined from the intercept formed by the characteristic on the abscissa axis. For the samples under study, it was possible to obtain a pronounced \( I_{th}(T) \) dependence in the temperature range 25–130 K (not shown). The experimental dependences appeared to be exponential (\( I_{th}\sim\exp(T/T_0) \), where \( T_0 \) is a characteristic temperature) in the portion ranging from 70 to 130 K. According to the known concepts about the temperature dependence of \( I_{th} \) of a semiconductor laser, this is indicative of the influence of Auger recombination [6]. The \( T_0 \) value was found to be \( 25\pm5 \) K for the 80–120 K range. No pronounced \( I_{th}(T) \) dependence was observed at low temperatures \( (T<70 \) K), which could be indicative of the predominance of Shockley–Read recombination.

4. Discussion

The analysis of the obtained results indeed shows that at low temperatures (4.2–50 K), in the studied structures conditions for stimulated emission held true. Interestingly, this effect was observed not only for the LEDs with active layer sandwiched between the substrate and the barrier layer with wider bandgaps, but also for the structure of type \( D \) with active layer grown on top of the barrier layer. As it was shown that in LED structures of this type the optical resonator spontaneously forms normal to the growth plane, most probably, between the surface of the chip with a gold Ohmic contact and the substrate [5], the heterostructures look promising for fabrication of the vertical-emitting MWIR lasers, which are currently of great demand [7].

Figure 2 shows that transition from stimulated to spontaneous emission occurred at different temperatures (50 to 100 K) for different types of heterostructures. Our data showed that actually this transition occurred when the energy of the bandgap coincided with the energy of the spin-orbit splitting \( \Delta_{SO} \) in the material of the active layer (\( \Delta_{SO} \) was calculated on the basis of the data by Vurgaftman et al. [4]). With temperature increasing and \( E_g \) decreasing, we observed a resonant ‘switch-on’ of the CHHS Auger process, when the energy of recombining electron-hole pair was transferred to a hole transitioning to the spin-orbit-split band. With further temperature increasing and \( E_g \) continuing to decrease, the resonance condition \( E_g=\Delta_{SO} \), that was responsible for quenching of

Figure 1. Normalized EL spectra of the heterostructures of type \( C, F \) and \( G \) at \( T=300 \) K at driving current \( I=1 \text{ A} \) (a), and spectra of the heterostructures of type \( A \) (\( I=0.5 \text{ A} \)), \( C \) (\( I=0.6 \text{ A} \)), \( E \) (\( I=0.4 \text{ A} \)) and \( G \) (\( I=1.2 \text{ A} \)) at 4.2 K (b).
the effect of stimulated emission, disappeared, but the emission remained spontaneous. This was obviously due to the influence of Auger processes of other types, which suppressed amplification. We calculated temperature dependence of carrier lifetime limited by radiative recombination and two most likely Auger processes: the one with the participation of two electrons and a heavy hole with excitation of electron in more energetic state (CHCC) and the one involving two heavy holes and an electron, with the conversion of a heavy hole into a light hole (CHHL). For the se calculations, expressions derived in terms of the microscopic model for Auger recombination were used [8]; those describing radiative recombination were taken from Ref. [9]. The results of the calculation performed for structure of type C are presented in Fig. 3. It is seen that under the considered injection level ($n\approx p \approx 4\times10^{16}$ cm$^{-3}$, derived from the data used to fit the calculated spectra to experimental ones as discussed above and applied to the whole temperature range), the dominating Auger process is CHHL. Still, at $T<170$ K, radiative lifetime remains smaller than the one limited by Auger recombination.

![Figure 2](image1.png)  
*Figure 2. Calculated dependences $E_e(T)$ in the active layer of LEDs (lines), $E_{EL}$ of stimulated emission (filled symbols) and $E_f$ values derived from the emission spectra (empty symbols)*

![Figure 3](image2.png)  
*Figure 3. Calculated carrier lifetime limited by radiative recombination (1), CHCC (2), CHHL (3), and the sum of CHCC and CHHL (4)*

5. Conclusion
When studying electroluminescence of InAsSb–based mid-infrared LEDs in the temperature range 4.2–300 K, we were able to follow the effect of three recombination mechanisms on the properties of the LEDs: Shockley–Read recombination at $T<70$ K, CHHS Auger process at $70<T<130$ K and CHHL Auger process at $T>130$ K. Despite the influence of non-radiative recombination, however, stimulated emission from the structures was observed at $T<100$ K. This shows that InAsSb-based LED heterostructures are promising for fabrication of vertical-emitting MWIR lasers.

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