Study of electroluminescence of InAs(Sb,P) LED heterostructures

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Abstract. Electroluminescence of InAs(Sb,P) heterostructures grown on InAs substrates was studied in the temperature range \( T = 4.2 \)–300 K. At low temperatures (\( T = 4.2 \)–50 K), stimulated emission was observed. This effect was due to optical resonator, which was formed between the lower face of the LED chip with the solid metal contact and the upper face with semiconductor/air interface. 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 results obtained show that structures based on InAs(Sb,P) are a promising material for fabrication of vertical-emitting mid-infrared lasers.

1. Introduction

It is known that characteristic optical absorption bands of many important chemicals (CH\(_4\), CO\(_2\), NO\(_2\), H\(_2\)S, CO, etc.) are located in the mid-infrared wavelength range (MWIR, wavelengths \( \lambda \) 2 to 6 μm) [1]. Sensors of these chemicals are of great demand in industry, in environmental control systems and in medicine. The most promising are MWIR sensors based on light-emitting diodes (LEDs) and semiconductor photodetectors, and it is worthwhile to fabricate light emitters and photodetectors on the basis of the same materials, as it greatly simplifies manufacturing processes.

To enhance the efficiency of optoelectronic devices, it is important to understand and control processes that govern absorption and/or emission of light in real structures. For that task, it is worth studying their operation not only at working temperatures, but also at lower temperatures. In this case, effects can be observed that may enable one to identify the mechanisms of physical processes in the devices in more detail. Within the frames of such an approach, we have studied electroluminescence (EL) of InAs(Sb,P) LED heterostructures in a wide temperature range, from 4.2 K up to 300 K.

2. Experimental details

The heterostructures were grown with the use of metal-organic chemical vapour deposition at Microsensor Technology, LLC, using synthesis method described elsewhere [2]. For all the heterostructures, a strongly sulphur-doped InAs substrate (\( n \)-type conductivity, electron concentration at 77 K \( n_{77} \approx (1-2) \times 10^{18} \) 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 \( n_{77} \approx 10^{16} \) cm\(^{-3}\); presumably due to background donors. A typical thickness of the active layer was 2 to 3 μm. On top of the active layer, a \( p \)-type InAsSbP barrier layer was grown. This layer was doped with zinc and had hole concentration at 77 K \( p_{77} \approx 2 \times 10^{18} \) cm\(^{-3}\). Parameters of the heterostructures are given in Table 1.
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$_{0.94}$Sb$_{0.06}$ | InAs$_{0.40}$Sb$_{0.20}$P$_{0.40}$ |
| C              | InAs$_{0.93}$Sb$_{0.07}$ | InAs$_{0.70}$Sb$_{0.10}$P$_{0.20}$ |
| D              | 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 ‘flip-chip’ technology was used, so 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, as the latter was transparent for the light emitted by the active layer due to the strong doping. 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) with the use of computer-controlled installation employing a grating monochromator and a lock-in amplifier. InSb photodiode was used as a detector.

3. Experimental results

Figure 1(a) shows normalized EL spectra of two heterostructures at $T=300$ K, which is a typical working temperature for this kind of LEDs. Figure 1(b) shows normalized EL spectra for three types of studied heterostructures at $T=4.2$ K at various driving currents $I$. The heterostructure of type A had the active region made of pure InAs. The heterostructure of type C had the active region made of InAsSb with InSb molar fraction 0.07 (see Table 1). In Fig. 1 (a) one can observe a red-shift of the maximum of the spectrum (curve 2 vs. curve 1) 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. The full-width at half-maximum (FWHM) of the spectrum at 300 K is 50 meV for the heterostructure of type C vs. 35 meV for the heterostructure of type A.

![Figure 1](image_url)

Figure 1. Normalized EL spectra of the heterostructures of type A (curve 1) and type C (curve 2) at $T=300$ K at driving current $I=1$ A (a), and spectra of the heterostructures of type C ($I=0.6$ A, curve 1), type B ($I=0.4$ A, curve 2) and type A ($I=1.2$ A, curve 3) at 4.2 K (b).

As can be seen in Fig. 1(b), the spectra recorded at 4.2 K differ in shape and 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, which would correspond to the narrowing of the initial bandwidth of 35 meV with the temperature decreasing, there appeared a second narrow line with FWHM of 2 meV. A study of the dependences of these bands on $I$ showed that with the latter
increasing from 0.1 up to 0.6 A, the intensity of the wide band increased insignificantly, while that of the narrow band increased substantially. For the structures of types B, C, and D at the temperatures close to 4.2 K, we also observed quite narrow emission bands. With increasing of the current, the integral EL intensity was increasing linearly, while the peak maximum was blue-shifting, presumably reflecting the filling of the conduction band and lifting of the Fermi quasi-level for electrons. EL spectra of the structures of type C at T=77 K previously demonstrated a clearly defined modal structure [3]. A similar structure of EL band was observed for some of the structures of type D at 4.2 K (not shown).

With temperature increasing, for all the structures we observed that narrow EL peaks transformed to broad ones: for example, for the structure of type C, the FWHM of the main emission peak increased from 7 meV to 400 meV. The exact transition point depended on the type of structure. Figure 2 shows the energy of the EL peaks $E_{EL}$ vs. temperature for structures of types A and C. All the spectra were recorded at the same driving current $I=0.6$ A. It is seen that for the structure of type A at $T\geq 70$ K the energy of the emission peak corresponds to the value of $E_g$ of the active layer calculated in accordance with the data presented by Vurgaftman et al. [4]. At lower temperatures, when the peak of EL was narrow, the energy of the peak was lower than $E_g$. Similar dependences of $E_{EL}$ on the temperature were observed for structures of type C. In this case, however, at higher temperatures (typically, at $T>120$ K) $E_{EL}$ values were larger than those of calculated $E_g$ by ~20 meV. At $T<100$ K, depending on the type of the heterostructure, the values of $E_{EL}$ were close to calculated $E_g$ or smaller.

4. Discussion

The analysis of the obtained results shows that at low temperatures (4.2–50 K), in the studied structures conditions for stimulated emission held true. It is worth noting that in LED structures with the active layer made of InAs, a similar effect was first reported on by Matveev et al. [5] (however, there, in contrast to the present work, double heterostructures were studied). Stimulated emission from structures with InAsSb-based active layer has been observed so far only in specially designed laser structures: in particular, one can mention strip-waveguide lasers based on double heterostructures with high symmetrical barriers [6–8]. In our case, resonators were not fabricated specially; the cleft edges of the LED chips were not mirror-like either. The inter-mode spacing in the EL spectra of 6 nm [3] allowed for assessing the length of the resonator as 280 μm using a simple method described by Grebenschikova et al. [8]. This value appeared to be much closer to the thickness of the LED chip (~300 μm) rather than to the distance between the cleft edges of the chip (380 μm). Also, it appeared that EL signal in the stimulated emission mode coming from the surface of the LED chips was much lower than that from the internal layers.
stronger than that collected from the chip edges. Thus, we concluded that in our structures the optical resonator was formed normal to the growth plane, most probably, between the surface of the chip with a gold Ohmic contact and the substrate, which was polished chemically in the process of making LEDs.

The experimental data showed that transition from stimulated to spontaneous emission occurred at different temperatures (50 to 100 K) for different types of heterostructures (see Figure 2). Table 2 shows that actually this transition was not related to a particular temperature, but rather, to the energy of the bandgap: the transition occurred when the energy of the ‘effective’ 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]). It was natural to suggest that 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-splitted band. With further temperature increasing and $E_g$ continuing to decrease, the resonance condition $E_g=\Delta_{SO}$, that was responsible for quenching of 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: likely, the dominating process was that with the participation of two electrons and a heavy hole with excitation of electron in more energetic state (CHCC), or that involving two heavy holes and an electron, with the conversion of a heavy hole into a light hole (CHHL).

| Structure type | $\Delta_{SO}$, eV | ‘Quenching’ energy, eV |
|----------------|-------------------|----------------------|
| $A$ (InAs)     | 0.37-0.41         | 0.41                 |
| $B$, $C$, $D$ (InAsSb) | 0.33-0.37       | 0.34                 |

5. Conclusion
When studying electroluminescence of InAs(Sb,P) heterostructures, at low temperatures (4.2–100 K), stimulated emission from the structures was observed. This effect, however, was quenched with the temperature increasing due to the resonant ‘switch-on’ of the CHHS Auger process. Despite this, it appears as InAs(Sb,P) heterostructures are promising for fabrication of the vertical-emitting MWIR lasers, since even under the influence of Auger recombination it is possible to obtain stimulated emission with minimum requirements for optical resonators. To increase the operating temperature of the devices, a different chemical composition of active layer may be used, which would allow to shift the $E_g=\Delta_{SO}$ resonance condition to higher temperatures.

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