Study of current-voltage characteristics of InAsSb-based LED heterostructures in 4.2 - 300 K temperature range

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Abstract. Current-voltage characteristics of light-emitting diode heterostructures based on InAsSb epitaxial films and a multi quantum-well structure were studied in the temperature range $T = 4.2 – 300$ K. It is shown that transport through the heterostructures is governed by the diffusion and recombination mechanisms at temperatures close to 300 K. The tunnelling effect appears in the temperature range 4.2 – 77 K. The presence of quantum wells in the active layer results in increased diode leakage currents due to tunnelling.

1. Introduction

Recently, there has been much interest in the study of narrow-bandgap materials and structures based on $A_3B_2$ compounds due to their potential applications in the mid-infrared light emitting diodes (LEDs) and photodiodes for systems of environmental control, gas sensing, and medical applications [1-3]. Currently, researchers are focused on developing the design of a heterostructure that would allow increasing the output power of LEDs. The first step towards improving the output characteristics of heterostructures is the study of their electrical properties, in particular, the measurement of current-voltage ($I-V$) characteristics. The study of $I-V$ characteristics at various temperatures provides important information on the quality of the $p-n$ junction. Since most studies are carried out in a narrow temperature range, transport mechanisms forming current–voltage characteristics of such LEDs at various temperatures are not clear yet [4–6]. At the same time, the study of various types of structures allows tracking the behavior of the characteristic when the active region of the structure changes with the same type and level of doping of the heterostructure layers. In this paper, we report on the studies of $I-V$ characteristics of mid-infrared (3.4–4.2 µm) LED heterostructures based on InAsSb epitaxial films and a multi quantum-well (MQW) structure in the temperature range 4.2–300 K.

2. Experimental

The heterostructures were grown by metal–organic chemical vapour deposition (MOCVD) at Microsensor Technology, LLC. For all the heterostructures, a sulphur-doped $n$-type InAs substrate (electron concentration $n \approx 2 \times 10^{18}$ cm$^{-3}$) was used. The active layer of the heterostructures was made of InAs$_{1-x}$Sb$_x$ epitaxial films or 108-QW InAs$_{0.88}$Sb$_{0.12}$/InAs. This layer was not intentionally doped and had electron concentration $n \approx (1–2) \times 10^{16}$ cm$^{-3}$, presumably due to background donor doping. A typical thickness of the active layer was $\sim 2.5$ 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 $p \approx 2 \times 10^{18} \text{ cm}^{-3}$. Parameters of the studied samples are given in Table 1.

Table 1. Parameters of the studied heterostructures.

| Sample | Active layer | Barrier layer |
|--------|--------------|---------------|
| $A$    | InAs         | InAs$_{0.15}$Sb$_{0.31}$P$_{0.54}$ |
| $B$    | InAs$_{0.93}$Sb$_{0.07}$ | InAs$_{0.70}$Sb$_{0.10}$P$_{0.20}$ |
| $C$    | 108-QW InAs$_{0.88}$Sb$_{0.12}$/InAs | InAs$_{0.70}$Sb$_{0.10}$P$_{0.20}$ |

LED chips $380 \times 380 \mu\text{m}$ in 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 a width of 35 µm and a 200 µm internal diameter was placed on the InAs substrate. The emission was collected from the side of the substrate. The chips were placed on TO-18 holders.

Recently, we have reported on the results of electroluminescence (EL) studies of these structures [7]. Figure 1 shows the corresponding EL spectra at the operating temperature of the LEDs $T = 300 \text{ K}$. The full-width at half-maxima of the spectra at 300 K are 0.32 µm, 0.56 µm, and 1.11 µm for samples $A$, $B$, and $C$, respectively. It can be seen that the emission spectrum shifts to the long-wavelength region with an increase in the InSb molar fraction in the active layer. The emission spectra of samples $B$ and $C$ are affected by the absorption band of carbon dioxide in the atmosphere.

![Figure 1](image)

Figure 1. Normalized EL spectra of the studied samples at $T = 300 \text{ K}$ and driving current 150 mA.

3. Results and Discussion

For the determination of transport mechanisms, we studied $I$–$V$ characteristics. Figure 2 shows the $I$–$V$ characteristics of sample $A$ in the temperature range 4.2–300 K. With diode temperature increasing, the height of the potential barrier decreases and the energy distribution of charge carriers changes. For these reasons, the direct current through the structure increases with temperature increasing at a constant forward voltage, which explains the shift of the $I$–$V$ characteristic to the left. This behaviour of the $I$–$V$ characteristic was also typical of the other two structures. The reverse characteristic is practically independent of temperature, which is indicative of the fact that a band-to-band tunnelling mechanism of the current prevails. It can be seen that the direct branch of the $I$–$V$ characteristics practically does not change with temperature increasing from 4.2 K to 77 K, which was typical of the other two structures as well. This is due to the weak dependence of the energy gap ($E_g$) on temperature.

Figure 3(a) shows the $I$–$V$ characteristics of samples $B$ and $C$ at 77 K and 300 K. These heterostructures had the same barrier layers and differed only in the design of the active region (see
Table 1). The reverse characteristics indicate that the diode leakage current has been greatly increased due to incorporation of MQWs to the active layer, which resulted in forming minibands [7].

Figure 2. Current-voltage characteristics of sample A in the temperature range 4.2 - 300 K.

Figure 3(b) shows the temperature dependence of the cut-off voltage in the forward $I-V$ characteristics for samples B and C. It is seen that for sample C with MQW in the active region, the cut-off voltage is lower than that for sample B, which is based on the bulk material. As expected, the cut-off voltage, which characterizes the potential barrier for carriers, linearly decreases with increasing temperature. This dependence is also characteristic of sample A (see figure 2). However, the cut-off voltages are smaller than the corresponding bandgaps of the materials of the active layers. The lower cut-off voltages are apparently caused by leakage currents through the interface, which significantly contribute to the current.

Figure 3. Current-voltage characteristics of samples B (straight curves) and C (symbols) at 77 K and 300 K (a), and the experimental temperature dependences of the cut-off voltage for samples B and C (b).

At low voltages $V < E_g/e$, the forward current usually can be described as $I \sim \exp\left(eV/\eta kT\right)$, where the value of the parameter $\eta$ reflects the mechanisms of the carrier transport. The diffusion current predominates if $\eta = 1$, and the current due to recombination in the space charge region, if $\eta = 2$ [8]. According to [9], at temperatures above 200 K in the $p-n$ junctions based on InAs and related solid solutions, the diffusion mechanism of the current prevails, i.e., in accordance with the Shockley theory, recombination in the $n$- and $p$-region of the $p-n$ junction determines the $I-V$ characteristics. In the studied heterostructures, $\eta$ was in the range from 1.03 to 1.45 at 300 K and various diode voltages,
which is indicative of a mixed charge transport mechanism with contributions made by both the diffusion and recombination components. For example, for sample B (see figure 4(a)), two portions can be distinguished in the $I$–$V$ characteristic at 300 K. The parameter $\eta$ equals 1.03 at low biases (up to 0.04 V), and 1.42 at biases of 0.06 V and higher. At low temperatures, higher values of the parameter $\eta$ were obtained. At $T = 77$ K, the parameter $\eta$ equaled 2.14, and at 4.2 K, $\eta = 9.75$. Figure 4(b) shows the temperature dependence of $\eta$ for sample B. It can be seen that $\eta$ increases sharply with decreasing temperature from 77 K to 4.2 K. This dependence was typical of the other two structures as well. The large values of $\eta$ indicate presence of additional leakage currents through the interface.

![Figure 4](image-url)

**Figure 4.** Current-voltage characteristics at 4.2 K and 300 K (a), and the calculated temperature dependence of the parameter $\eta$ (b) for sample B.

### 4. Conclusion

Current-voltage ($I$–$V$) characteristics of LED heterostructures based on InAsSb epitaxial films and a multi quantum-well structure were studied in the temperature range 4.2–300 K. The cut-off voltages linearly decrease with increasing temperature, but these values were smaller than the corresponding bandgaps of the active layers of heterostructures, which was probably due to the interface leakage currents. For all heterostructures, the transport was governed by the diffusion and recombination mechanisms at temperatures close to 300 K. The effect of tunnelling was observed in the temperature range 4.2–77 K.

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