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Carrier lifetime in InAs(Ga,Sb,P) heterostructures

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Abstract. Carrier lifetime limited by radiative and most probable non-radiative recombination processes was calculated for InAs(Ga,Sb,P) heterostructures under injection. At low temperatures (T<130 K), the carrier lifetime was mostly determined by radiative recombination. With temperature increasing, influence of Auger processes became crucial. Among these processes, the dominating role of CHHS process, in which the energy of a recombining electron-hole pair is transferred to a heavy hole transitioning to the spin-orbit-splitted band, was established at low temperatures.

1. Introduction

Devices based on infrared light sources are useful for medical and industry applications as well as for environmental monitoring. The most common infrared sources are thermal ones, but their efficiency is limited by the maximum temperature that materials can withstand without thermal degradation. In this regard, devices based on light-emitting diodes (LEDs) are very promising. One of the main disadvantages of middle-wavelength infrared (MWIR) LEDs is their low power. Therefore, study of recombination processes in such devices is very important, as the mechanisms of recombination determine the lifetime of charge carriers, and consequently, the efficiency of the devices. Recently, there has been much interest in theoretical calculations of carrier lifetime in materials for MWIR devices, including InAs-based materials. Currently, there exist different approaches to calculation of the carrier lifetime limited by non-radiative processes in such materials [1-3]. For the most rigorous calculations, it is important to consider the band structure of the semiconductor, in particular, the non-parabolicity of the electron and light hole bands, characteristic of narrow-bandgap materials. In this paper, we report on the results of calculations of carrier lifetime for InAsSb active layer of InAs(Ga,Sb,P) heterostructures limited by radiative and most probable non-radiative processes, which were performed within the frames of the Kane model. The calculations were based on the results of the recent study of electroluminescence of InAs(Ga,Sb,P) LED heterostructures as presented in Ref. [4], so the carrier concentrations considered varied from 1×1016 to 5×1016 cm⁻³.

2. Calculation of the carrier lifetime

The heterostructures were grown with the use of metal-organic chemical vapour deposition on InAs substrates at Microsensor Technology, LLC. An active layer of the heterostructures was made of InAs₁ₓSbx. A typical thickness of the active layer was 2–3 μm. On top of the active layer, an InAsSb(Ga,P) barrier layer was grown. Parameters of the heterostructures are given in Table 1.

Electroluminescence of the heterostructures was studied in the temperature range T=4.2–300 K. At low temperatures (4.2–50 K), stimulated emission was observed. With temperature increasing, the
radiation became spontaneous. This transition from stimulated to spontaneous emission occurred at different temperatures for structures with different content of InSb in the active layer [4]. To analyze these results in more detail, the necessity to calculate carrier lifetimes limited by various recombination mechanisms became apparent, and this was the task of the current work.

Table 1. Parameters of the studied heterostructures.

| Structure type | Active layer | Barrier layer |
|---------------|--------------|---------------|
| A             | InAs         | InGa$_{0.15}$As$_{0.57}$Sb$_{0.28}$ |
| 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$_{0.34}$ |

Table 1. Parameters of the studied heterostructures.

It is known that for semiconductors, in which the energy of spin-orbit-splitting is smaller or comparable to the width of the band gap, in general the most probable processes are the Auger process, in which the energy of a recombining electron-hole pair is transferred to a heavy hole transitioning to the spin-orbit-split band (CHHS), and the process with the participation of two electrons and a heavy hole with excitation of an electron to a more energetic state (CHCC) [5]. As mentioned above, there were several approaches to the calculation of the carrier lifetime limited by Auger processes. For example, in Ref. [1] in the calculation of Auger processes the matrix element was taken to be constant. However, expressions for the matrix element include the overlap integrals which should be calculated at the threshold values of momentum of the particles participating in the recombination. In Ref. [6], it was shown that it was necessary to take into account the behavior of the overlap integral near the Auger recombination threshold. As a result, the overlap integrals are not constant, but depend on temperature. Indeed, in Ref. [2] it was shown that for InAsSb materials the values of overlap integrals vary with temperature. Still, in lifetime calculations the overlap integrals in narrow-bandgap III–V semiconductors for simplicity are often assumed to be temperature-independent [3].

In our study, we performed calculation of the carrier lifetime limited by radiative and Auger processes within the framework of the Kane model [7,8]. This calculation appears to be the most accurate since the model considers both electron-heavy hole and electron-light hole transitions with an account for non-parabolic dependence of the energy of the conduction band and the valence band of light holes on the wave vector.

The detailed calculation of the carrier lifetime with an account for the CHCC and CHHS processes was performed in Ref. [7]. The lifetime defined by these processes was:

$$\tau_{CHCC} = \frac{1}{[R_{CHCC}(n+p)n]^{-1}}, \tau_{CHHS} = \frac{1}{[R_{CHHS}(n+p)p]^{-1}}.$$  

where $n$ and $p$ are concentrations of electrons and holes, respectively, $R_{CHCC}$ and $R_{CHHS}$ are corresponding recombination coefficients.

An important role in recombination processes is played by the radiative recombination, which dominates at low temperatures. In this work, calculation of the carrier lifetime limited by radiative recombination was based on Ref. [8]. The lifetime of radiative recombination is related to the corresponding recombination coefficient $\gamma_{ph}$ as follows:

$$\tau_R = \frac{1}{[\gamma_{ph}(n+p)]^{-1}}.$$  

Parameters of the materials were taken from Ref. [9]. Values of carrier concentrations, which were used in the calculations, were determined in Ref. [4] by fitting calculated electroluminescence spectra to experimental ones with the Fermi level (carrier concentration) being the parameter. The carrier concentration under injection for all types of heterostructures varied from $3\times10^{16}$ cm$^{-3}$ up to $5\times10^{16}$ cm$^{-3}$. 


3. Results and Discussion

Figure 1(a) shows the results of calculations of the inverse lifetime limited by CHCC and CHHS Auger processes, and by radiative recombination for heterostructure of type A at carrier concentrations \( n_p=4\times10^{16} \text{ cm}^{-3} \). As can be seen, with the temperature increasing, the inverse lifetime limited by radiative recombination decreases and that limited by Auger recombination increases. At the considered injection level at \( T<210 \text{ K} \), the carrier lifetime is mostly determined by radiative recombination, and at \( T<170 \text{ K} \) the most intensive Auger process is CHHS. However, at \( T>170 \text{ K} \), the value of \( \tau^{-1} \) for the CHCC process becomes greater than that for CHHS recombination and increases with temperature. At \( T>80 \text{ K} \), the value of \( \tau^{-1} \) for CHHS recombination is practically constant. Figure 1(b) shows \( \tau^{-1} \) limited by the sum of non-radiative processes and by radiative recombination. As can be seen in Fig. 1(b), the “equi-rate temperature” \( T_{eq} \), i.e., the temperature where the value of \( \tau^{-1} \) of radiative recombination equals that of Auger recombination, is \( T_{eq}=210 \text{ K} \).

![Figure 1](image1.png)

Figure 1. Calculated temperature dependences of inverse lifetime limited by CHCC (1), CHHS (2) and radiative (3) processes \((a)\), and the sum of the two non-radiative (1) and the radiative (2) processes \((b)\) for the heterostructure of type A.

The results of calculations of the inverse lifetime for heterostructure of type D at carrier concentrations \( n_p=3\times10^{16} \text{ cm}^{-3} \) showed that the nature of studied processes was similar to that for the heterostructure of type A. At low temperatures \( (T<115 \text{ K}) \), the CHHS process still played the dominant role. For this heterostructure, \( T_{eq} \) equaled 150 K. Similar results were obtained for heterostructures of other types: CHHS process held the dominant role among the non-radiative processes at low temperatures. With temperature increasing, the CHCC process became more effective than CHHS.

Figure 2 shows the results of calculation of \( T_{eq} \) for various content of InSb \( x \) in the alloy at various carrier concentrations. We calculated \( \tau^{-1} \) for the set of \( x \) from 0 up to \( x=0.12 \), InAsSb alloy with this chemical composition is also widely used in fabrication of photodetectors and LEDs [10,11]. As can be seen, with \( x \) increasing, which corresponds to decrease of the bandgap of the active area, \( T_{eq} \) decreases. For example, increasing \( x \) from \( x=0 \) to \( x=0.12 \) leads to decrease of \( T_{eq} \) from 233 to 135 K at \( n_p=3\times10^{16} \text{ cm}^{-3} \). Also, our results show that with the carrier concentration increasing, non-radiative recombination becomes stronger than radiative one at lower temperatures: for \( x=0 \), changing carrier concentration from \( 1\times10^{16} \) to \( 5\times10^{16} \text{ cm}^{-3} \) decreases \( T_{eq} \) by 127 K.

The temperature of ‘quenching’ of stimulated radiation observed in the experiment in Ref. [4] appeared to be always lower than \( T_{eq} \) (for example, for heterostructure of type A at \( n_p=4\times10^{16} \text{ cm}^{-3} \), 80 K and 210 K, respectively, and for heterostructure of type D at \( n_p=3\times10^{16} \text{ cm}^{-3} \), 50 K and 150 K, respectively). Thus, contribution of other effects to the ‘quenching’ could be expected, which was natural as the studied LED heterostructures were not designed to be lasers. Still, the calculated lifetime relations obviously contributed to the ‘quenching’ of the stimulated emission in the experiment.
Figure 2. Calculated dependence of $T_{eq}$ on InSb content in InAsSb alloy at carrier concentrations: $n_p=5\times10^{16}$ cm$^{-3}$ (1), $n_p=3\times10^{16}$ cm$^{-3}$ (2) and $n_p=1\times10^{16}$ cm$^{-3}$ (3).

4. Conclusion

Carrier lifetime limited by radiative and most probable non-radiative processes for InAsSb active layer (with InSb content varying from 0 up to 0.012) in InAs(Ga,Sb,P) LED heterostructures under injection (carrier concentrations varying from $1\times10^{16}$ up to $5\times10^{16}$ cm$^{-3}$) was calculated. At low temperatures the lifetime was mostly determined by radiative recombination. As expected, with temperature increasing, influence of Auger processes increased. The dominating role of different Auger processes was established, with the CHHS process being crucial at low temperatures, and the CHCC process at higher temperatures. A strong effect of both InSb content and carrier concentration on the temperature where the value of lifetime of radiative recombination equals that of Auger recombination was found for the studied materials.

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