Impact of Temperature on Optical Properties of InGaAs/GaAsSb/InAlAs Nano-Scale Heterostructure

M. Imran Khan¹, Garima Bhardwaj², Sandhya Kattayat³, Sandeep Sharma⁴, P. A. Alvi¹,ᵃ)

¹Department of Physics, Banasthali Vidyapith, Banasthali-304022, Rajasthan (India)
²Department of Electronics & Communication Engineering, IIMT Engineering College, Meerut, 250001, UP, India
³Higher Colleges of Technology, Abu Dhabi, United Arab Emirates (UAE)
⁴Department of Physics, Shree Radheshyam R. Morarka Government College, Jhunjhunu- 333001, Rajasthan (India)

ᵃ)Corresponding author: drpaalvi@gmail.com

Abstract. The present article reports the impact of temperature on optical properties of InGaAs/GaAsSb/InAlAs nano-scale heterostructure which has been assumed to grow on GaAs substrate. For this heterostructure, the optical properties such as optical gain and transition wavelength have been simulated under the variable temperature with the help of 6 band k.p approach. The outcomes of the calculations inform that the increased temperature can reduce the optical gain appreciably with the red shift in wavelength in near infrared (NIR) region.

Keywords: InAlAs, GaAsSb, InGaAs, Optical gain, Heterostructure

1. INTRODUCTION

The heterostructures, particularly nano-scale heterostructures with the different band alignments, have been assumed as basic components for the optoelectronic devices [1-10]. Further, the nature of heterostructures is determined by the band alignment. Thus, the engineering of the band alignment can modify the function of the heterostructure based optoelectronic devices. In the recent times, several researchers have studied the two types (type-I and type-II) of band alignments based heterostructures and also studied their optical properties [11-19]. B. Chen has performed detailed calculations to study the optical properties of type-II InGaAs/GaAsSbBi quantum wells heterostructure grown on GaAs substrate and found the studied heterostructure suitable for 1550nm wavelength region working at room temperature [20]. In earlier research, the InP substrate based nano-heterostructures have been developed for 1550nm wavelength region laser application [21, 22]. So far, the most favorable and suitable heterostructure for the 1550 nm emission is based InGaAlAs/InP material system.

However, in the presented article, the calculations have been performed for the optical properties, especially the temperature dependent optical gain characteristics of type-II InGaAs/GaAsSb/InAlAs nano-scale heterostructure grown on GaAs substrate. This heterostructure has been found suitable for high optical gain at ~ 1650 nm.

2. HETEROSTRUCTURE DESIGN AND THEORY FOR SIMULATION

The structure InGaAs/GaAsSb/InAlAs is a symmetrical heterostructure which has type-II band alignment. In the type-II InGaAs/GaAsSb/InAlAs nano-scale heterostructure, the layer InGaAs (width ~ 40 nm) plays as a quantum well region, layer GaAsSb (20 nm) plays as a spacer, while the layer InAlAs (100 nm) is used for the barrier or cladding purpose.
In order to obtain the subband wavefunctions and the corresponding dispersed energy states, the complex calculations were carried out by solving the 6 band Hamiltonian. By knowing the associated wavefunctions, the dispersed energy states, following the calculations of the optical matrix elements, and momentum or transition matrix elements, the optical gain can be calculated with the help of formulation given below [23]:

$$G(\omega) = \frac{2 \pi e^2}{\hbar c \omega L^2} \sum_{\sigma} \sum_{n_{conf}} \int |(G, M_{nm}(k_z))|^2 \times \left( \frac{f_{n_\sigma}^0(k_z) - f_{n_m}^\sigma(k_z)}{E_{nm}(k_z) - \omega l} \right)^2 \frac{k_z d k_z}{2\pi}$$

In the abovementioned formulation, the detail of symbols used can be understood in the ref. [23-25].

### 3. RESULTS AND DISCUSSION

The primary calculations carried out were directed towards the solutions of the 6 band k.p Hamiltonian in terms of subband (electronic and hole subbands) wavefunctions. After getting the solutions i.e. the required wavefunctions, the dispersed electronic and holes energy states were calculated for the different temperatures (100, 150, 200, 250 and 300K). The dispersed electronic and holes energy states within the InGaAs/GaAsSb/InAlAs nano-scale heterostructure for temperature ranging from 100 K - 300K have been plotted in figure 1. The electronic energy dispersion has been shown by red color; while the hole’s energy dispersion has been shown by blue color. Figure 1 illustrate that the electronic energy reduces continuously with rising the temperature; while the hole’s energy is increased a little bit on rising the temperature. Thus, this behavior indicates the reduction in energy gap between the first electronic and first hole’s energy state. The reduced energy gap refers to red shift of the emitted wavelength. The red shift in wavelength with increase in temperature has been summarized in figure 2(a).

![Figure 1](image-url)

**FIGURE 1.** Impact of temperature on the dispersed energy states of conduction and valence band of the InGaAs/GaAsSb/InAlAs nano-scale heterostructure

Figure 2 (a) shows that the emitted wavelength enhances form 1540 to 1680 nm on increasing the temperature form 100K to 300K. Further, the temperature gradient wavelength has also been shown in figure 2(b). Figure 2(b) shows the temperature gradient wavelength (i.e. the rate of wavelength change with change in temperature) increases up to 250K and then decreases with further rising the temperature. The impact of temperature on the optical gain characteristics has also been studied and shown in figure 3. Figure 3 (a) predicts that the optical gain
reduced considerably with rise in temperature. At 100 K, the calculated optical gain is \( \sim 6000 \text{ cm}^{-1} \). It is reduced up to \( \sim 4500 \text{ cm}^{-1} \) at room temperature. This behavior shows that the optical gain can be controlled by increasing the temperature. The reason of reduction of gain with rise in temperature is based on the fact that the most probabilistic electronic energy states responsible for optical transitions becomes less populated with increase in temperature, as one can expect. However, the temperature gradient optical gain (i.e. rate of change in optical gain with change in temperature) has also been plotted in figure 3 (b), which shows that temperature gradient optical gain decrease with increase in temperature up to 300K and beyond to which it becomes saturated.

![Graphs showing temperature effect on transition wavelength and temperature gradient wavelength of InGaAs/GaAsSb/InAlAs nano-scale heterostructure](image1)

**FIGURE 2.** Temperature effect on (a) transition wavelength and (b) temperature gradient wavelength of InGaAs/GaAsSb/InAlAs nano-scale heterostructure

![Graphs showing temperature effect on optical gain and temperature gradient optical gain of InGaAs/GaAsSb/InAlAs nano-scale heterostructure](image2)

**FIGURE 3.** Temperature effect on (a) optical gain and (b) temperature gradient optical gain of InGaAs/GaAsSb/InAlAs nano-scale heterostructure
CONCLUSION

The optical properties such as optical gain and transition wavelength of InGaAs/GaAsSb/InAlAs nano-scale heterostructure have been studied with variable temperature by using the 6 band k.p approach. The calculation results suggest that the increased temperature can reduce the optical gain appreciably with the red shift in wavelength in NIR region.

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