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DESIGN AND OPTICAL GAIN ANALYSIS OF NANO SCALE HETEROSTRUCTURE GAINP/ALGAINP RED LASER

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Abstract

Nowadays “laser diodes, LED’s, optical waveguides, directional couplers and photodetectors are widely used in telecommunication, for biomedical applications, pollution monitoring tools etc”. Lasers can be designed by using various semiconductor materials by changing their composition. In our work we have designed a nano scale heterostructure using semiconductor compounds GaInP/AlGaInP for generating a wavelength of 635nm having optical gain of order ~4000/cm at carrier injection of 5*1012/cm2 at room temperature. The calculation of wavefunctions, dipole moments and optical gain are done by using Luttinger Kohn 4*4 model. The optical gain computed for Ga0.46In0.54P/Al0.25Ga0.27In0.48P type-I quantum well heterostructure (varying well width 3nm-7nm) is further analyzed for external strain applied and at different temperatures in order to make the laser more suitable to be used for different purposes. “The effect of uniaxial strain [001] applied shows significant improvement in optical gain under z polarization whereas x and y polarizations are less effected by applied strain”. The designed heterostructure is analyzed under different temperature conditions for below and above room temperature. The reported results show that the designed laser can be used for a range of 600-650nm wavelength.

Keywords- Heterostructure, optical gain, uniaxial strain, Luttinger Kohn model.

1. Introduction

Optoelectronics, sometimes thought of as a sub-field of photonics, is the study and use of electronic devices and systems that detect and control light. This topic explores the dynamic interplay between electrical and optical processes. “LEDs (Light Emitting Diodes), LASERs (Light Amplification by Stimulated Emission of Radiation)”, photodiodes, and solar cells are all examples of important optoelectronic devices. In order to create LASERs, semiconductor compounds with a direct band gap are required. Researchers are looking at various heterostructures for use in LASER light production. Structures with many types of semiconductor layers on the same substrate are known as heterostructures. According to the band alignment that results in the discontinuity, they may be categorized as type-I, type-II, or type-III. For the treatment of skin cancer and other superficial skin disorders, red lasers have found widespread usage in biomedical applications[1]. They can be fabricated by using different semiconductor materials like nitrides and phosphides. Nitride based red laser are harmful and are expensive so an alternative to this is generation of red laser using non nitride semiconductor compounds [2]. The study of self consistent model is required for 635nm wavelength generation and its analysis is provided with cladding layers of AlGaInP with high Al content [3]. We have used quantum well of Ga0.46In0.54P with cladding and barrier layers of Al0.25Ga0.27In0.48P compounds in order to generate a wavelength of 635nm. The calculations of energy band gap and lattice constant are done by using designated formulae [4]. Our work provides us with a nano scale heterostructure design using GaInP/AlGaInP compounds operating at 635nm wavelength with optical gain of order ~4000/cm. The design is analyzed under external strain applied of order 3, 5 and 8 GPa and temperature dependency of optical gain is also obtained. “In the next section, design and theory of the Ga0.46In0.54P/ Al0.25Ga0.27In0.48P type-I QW heterostructure is presented following which the simulation results are discussed. Finally the inferences from the work are presented”.

2. Structure and Theory

The Al0.25Ga0.27In0.48P barrier layers are both n and p type, and they sandwich a Ga0.46In0.54P layer that makes up the single quantum well structure. To investigate the impact of well thickness on optical gain, the width of the quantum well is changed from 3 to 5 to 7 nm, while the width of the barrier layers remains constant at 10 nm. Figure 1 depicts the energy band structure, which includes the heavy hole sub band (HHB), the light hole sub band (LHB), and the split off band (SOB). On a GaAs substrate, a heterostructure of type I QWs is formed. Figure 1 shows that the split off sub band is located far below the heavy hole band, suggesting that it contributes little to optical gain. Type I structures have lighter and heavier hole sub bands that are physically closer together.

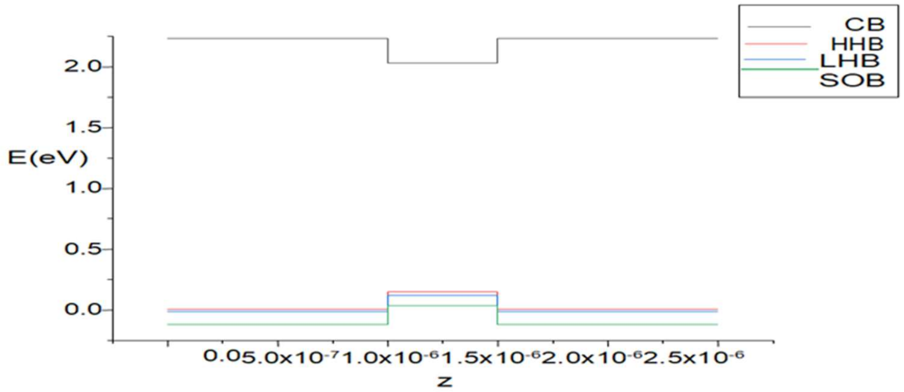

Figure 1. Energy band diagram for Ga0.46In0.54P/Al0.25Ga0.27In0.48P nano scale heterostructure

We have studied the theory of motion of electron and hole in periodic fields [5,6]. For the calculation of E-k dispersion curve which can be considered as the basis for the desired results Hamiltonian of the structure is to be obtained. “The six band k·p Hamiltonian matrix is utilized for the numerical calculation of electronic energy band and wavefunctions”. We have used 4*4 Luttinger Kohn model for the calculation and the matrix is provided below in equation 1.

$$H = \begin{bmatrix} H_{cc} & H_{cv} & H_{cs} \\ H_{vc} & H_{vv} & H_{vs} \end{bmatrix}$$

$$\begin{bmatrix} H_{sc} & H_{sv} & H_{ss} \end{bmatrix}$$

The matrix mentioned above consists of “ interband matrices Hcc, Hvv and Hss along the diagonal which describes the conduction band, heavy and light hole valence bands and split-off valence band respectively”. The Hcc matrix is

$$H_{cc}=\begin{pmatrix} E_g+\frac{\hbar^2 k^2}{2m_0}+A'k^2+a_c\varepsilon & 0 \\ 0 & E_g+\frac{\hbar^2 k^2}{2m_0}+A'k^2+a_c\varepsilon \end{pmatrix} \tag{1}$$

Where Eg is band gap, m0 is free electron mass, ac is deformation potential of the conduction band, Ɛ is a sum of diagonal elements of the strain tensor Ɛij, A’ describes the eight band Hamiltonian from other band. The Hvv matrix is

$$H_{vv}= H_k^{vv} + H_\varepsilon^{vv} + H_{kl}^{vv}+ H_{\varepsilon k}^{vv} \tag{2}$$

The terms H vv + H vv are Luttinger Kohn 4*4 terms and can be written as:

The terms H $_k^{vv}$ + H $_\varepsilon^{vv}$ are Luttinger Kohn 4*4 terms and can be written as:

$$H_k^{vv}=\begin{bmatrix} P+Q & S & -R & 0 \\ S^* & P-Q & 0 & -R \\ -R^* & 0 & P-Q & -S \\ 0 & -R^* & -S^* & P+Q \end{bmatrix}, \tag{3}$$

$$P\pm Q=-\frac{\hbar^2}{2m_0}[(\Upsilon_1\pm\Upsilon_2)(k_x^2+k_y^2)+(\Upsilon_1\mp 2\Upsilon_2)k_z^2]$$

$$R=-\sqrt{3}\,\frac{\hbar^2}{2m_0}[\Upsilon_2(k_x^2-k_y^2)-2i\Upsilon_3 k_x k_y], \tag{4}$$

$S = \sqrt{3}\,\frac{\hbar^2}{m_0}\Upsilon_3\,(k_x - ik_y)k_z$, and

$$H^{v}_{\varepsilon} = \begin{bmatrix} P_\varepsilon + Q_\varepsilon & -S_\varepsilon & -R_\varepsilon & 0 \\ -S^*_\varepsilon & P_\varepsilon - Q_\varepsilon & 0 & -R_\varepsilon \\ -R^*_\varepsilon & 0 & P_\varepsilon - Q_\varepsilon & -S_\varepsilon \\ 0 & -R^*_\varepsilon & -S^*_\varepsilon & P_\varepsilon + Q_\varepsilon \end{bmatrix}, \qquad (5)$$

Where,

$$P_\varepsilon + Q_\varepsilon = a_v(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) \mp b\left[\varepsilon_{zz} - \frac{1}{2}(\varepsilon_{xx} + \varepsilon_{yy})\right],$$

$$R_\varepsilon = \frac{\sqrt{3}\,b}{2}(\varepsilon_{xx} - \varepsilon_{yy}) - id\varepsilon_{xy}, \qquad (6)$$

$S_\varepsilon = d\,(\varepsilon_{zx} - i\varepsilon_{yz})$

The gain coefficient may be thought of as the ratio of the number of photons emitted by the structure per unit volume per second to the number of photons injected per unit area per second. The optical gain coefficient of the designed QW heterostructure may be calculated using Fermi's Golden rule, as detailed in Refs. [7,8,9]. The calculations are done by using these parameters and energy band diagram is presented in figure 1. The next section consists of simulation results including wavefunction diagrams for different well thickness and table containing energy band value and lattice constants for the ternary and quaternary compounds used in the design. It also includes analysis result for different external strain applied and optical gain under different temperature conditions.

3. Simulation results

The Fermi Golden rule may be used to the analysis of optical features of a constructed heterostructure if the wavefunction is known, which is linked to the charge carriers (electrons and holes) and their “corresponding energy levels” [10]. The wavefunctions were calculated using a 44 Luttinger Kohn model. The energy levels of the conduction band and the valence band are calculated once the wavefunctions have been known. The calculation of energy gap and lattice constant is necessary in order to avoid lattice mismatch, table 3.1 presents the structural parameters for the layers used in heterostructure

Role of layer	**Specification of layer**	**Energy gap E_g in eVat 300 K**	**Lattice Constant Å**
Barrier layer	$Al_{0.25}Ga_{0.27}In_{0.48}P$	2.0487	5.600
Active Region	$Ga_{0.46}In_{0.54}P$	1.8130	5.676

Cladding	$Al_{0.25}Ga_{0.27}In_{0.48}P$	2.0487	5.600
Substrate	GaAs	1.43	5.653

Table 1. Structure parameters for GaInP/AlGaInP heterostructure.

The wavefunction diagram of designed Ga0.46In0.54P/Al0.25Ga0.27In0.48P type-I QW heterostructure is shown in Fig. 2.a to 2.c for different well thickness. It consists of various subbands of electron and holes. The transition is chosen between all these subbands for our calculation. From Fig. 2.b, we observe that "the electron density is more confined in the QW region for well thickness of 5nm" which shows high optical gain can be obtained for well thickness of 5nm. Further calculations for external strain and temperature conditions are done for well thickness of 5nm as high optical gain of order 4000/cm is obtained for this thickness.

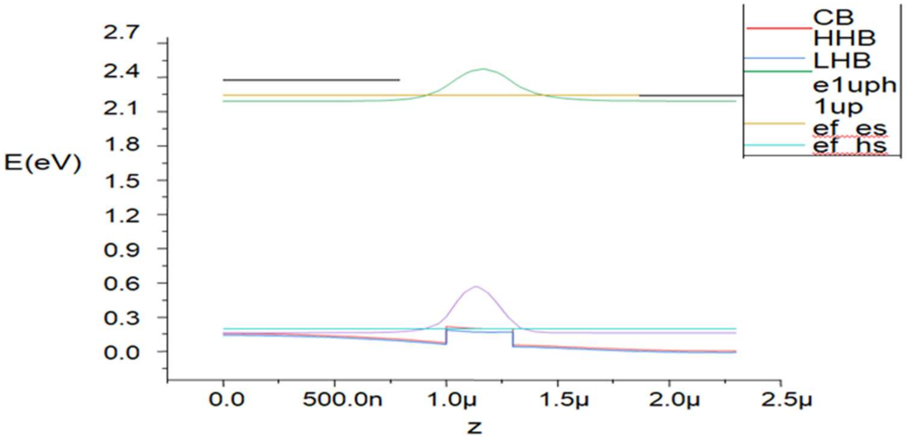

Fig.2.a Wavefunction diagram of Ga0.46In0.54P/Al0.25Ga0.27In0.48P heterostructure with the quantum well thickness 3nm.

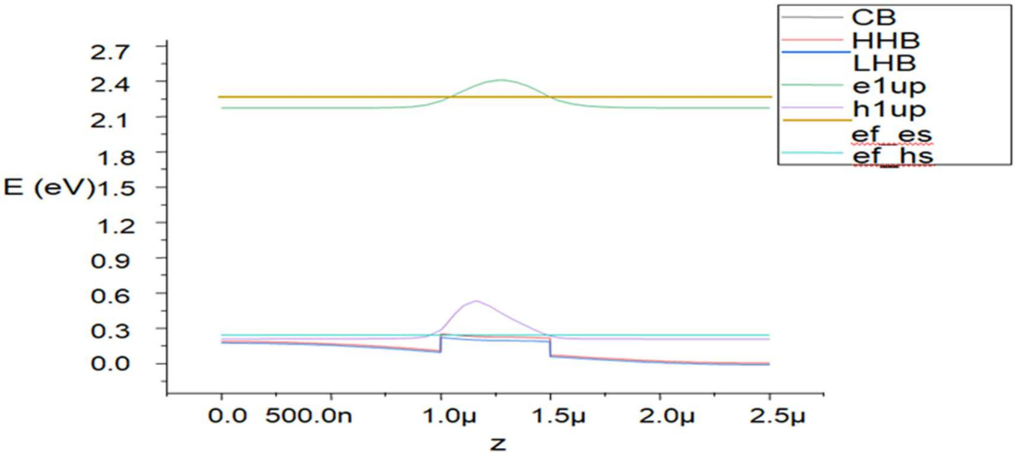

Fig. 2.b Wavefunction diagram of Ga0.46In0.54P/Al0.25Ga0.27In0.48P heterostructure with the quantum well thickness 5nm.

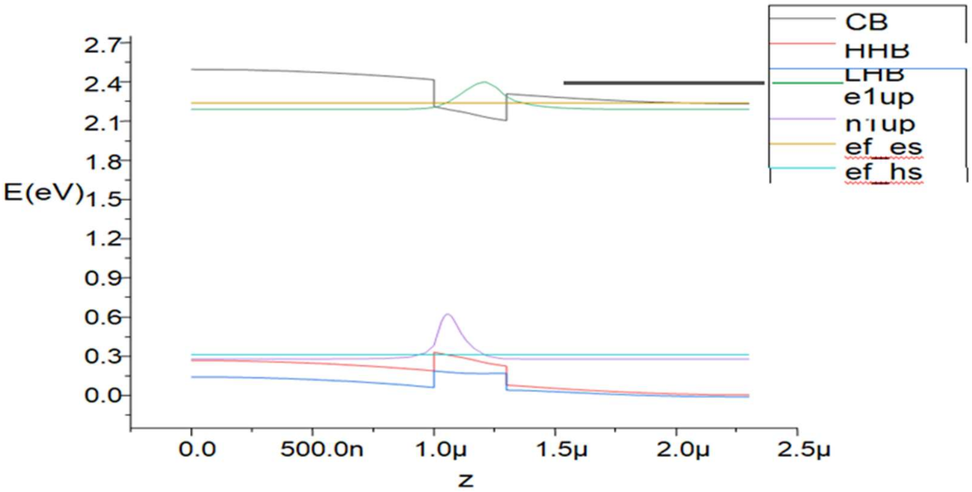

Fig. 2.c Wavefunction diagram of Ga0.46In0.54P/Al0.25Ga0.27In0.48P heterostructure with the quantum well thickness 7nm.

After considering these wavefunction diagrams we observe that 5nm well thickness is preferable as electron and holes are more confined for well region of thickness 5nm as compared to other thicknesses.

Effect of well thickness

We have observed that wavefunctions changes for different well thickness due to which optical gain is also affected. "The results presented in figure 3.a and 3.b" shows that optical gain decreases with increasing thickness of active region (quantum well) and lasing wavelength shifts to high value. The reason for varying optical gain and lasing wavelength is due to increasing well width, the density of states decreases which results in decreasing optical gain.

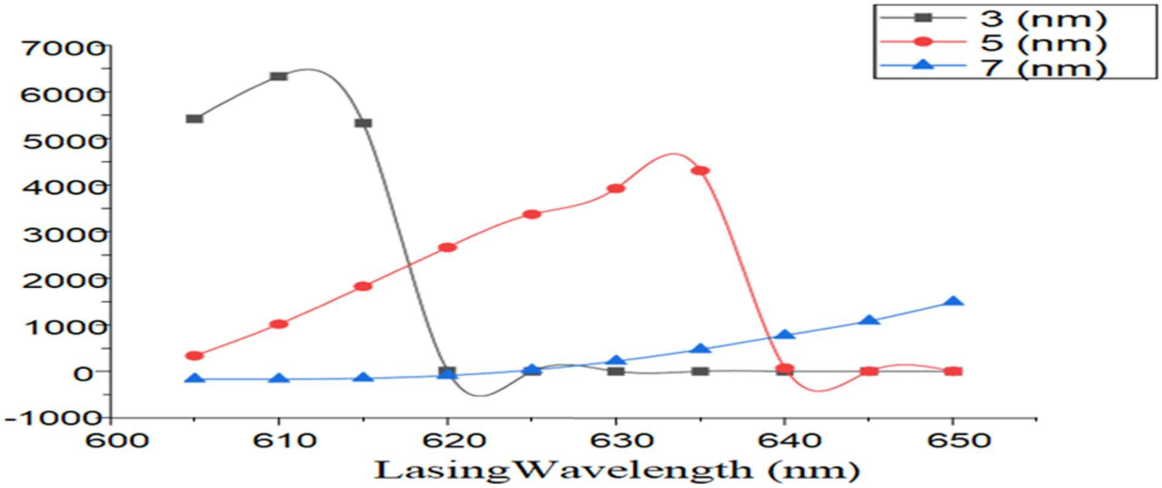

Fig. 3.a Gain spectra of Ga0.46In0.54P/Al0.25Ga0.27In0.48P nano scale heterostructure as well width variations for x and y polarizations.

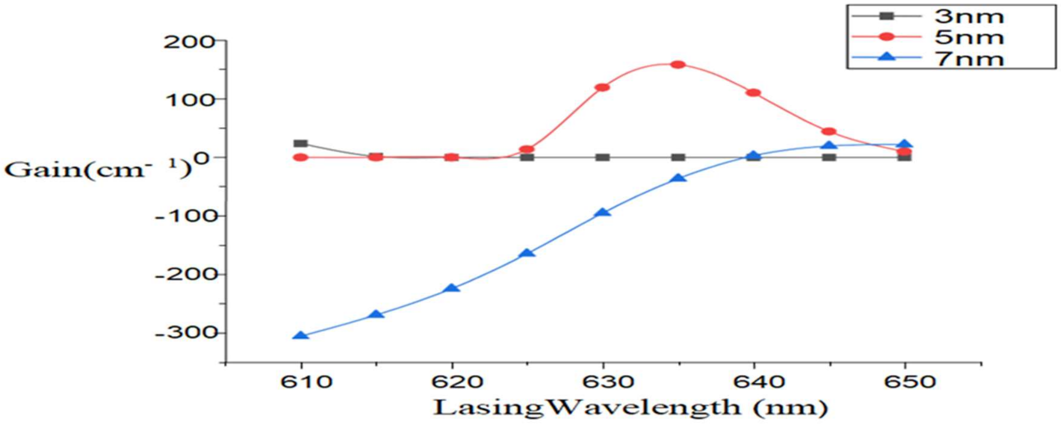

Fig. 3.b Gain spectra of Ga0.46In0.54P/Al0.25Ga0.27In0.48P nano scale heterostructure as well width variations for z polarization.

We conclude from here that 5nm thickness is efficient for high optical gain, further analysis of optical gain under strain and temperature dependency of optical gain is done on this well thickness. In the next section the optical gain results for external applied strain and changing temperature is provided.

Effect of strain on semiconductor

In our work we have done analysis for applied external uniaxial strain on our designed red laser heterostructures and observations are made for optical gain. The term uniaxial can be defined as strain occurring when only one component of the principal strains is nonzero. We have applied a uniaxial strain in [001]. Strain is generally used to enhance the performance of our heterostructure and as we observed that optical gain in z polarizations is very less so in order to make our laser to work more efficiently in z polarization as well we applied a strain in [001]. The optical gain values for different applied strain is presented in figure 4.a and 4.b for strain values of 3, 5 and 8 GPa. When the external strain is applied there are changes in bandgap, density of states changes and the wavefunctions changes or get mixed up due to these changes optical gain gets affected.

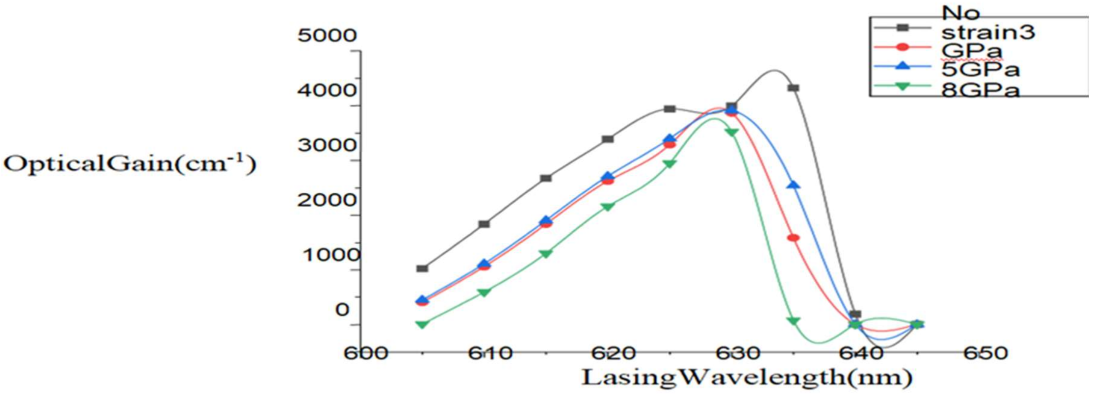

Fig. 4.a Interpretation of strain effects on total optical gain for GaInP/AlGaInP lasing nano-heterostructure x and y polarizations.

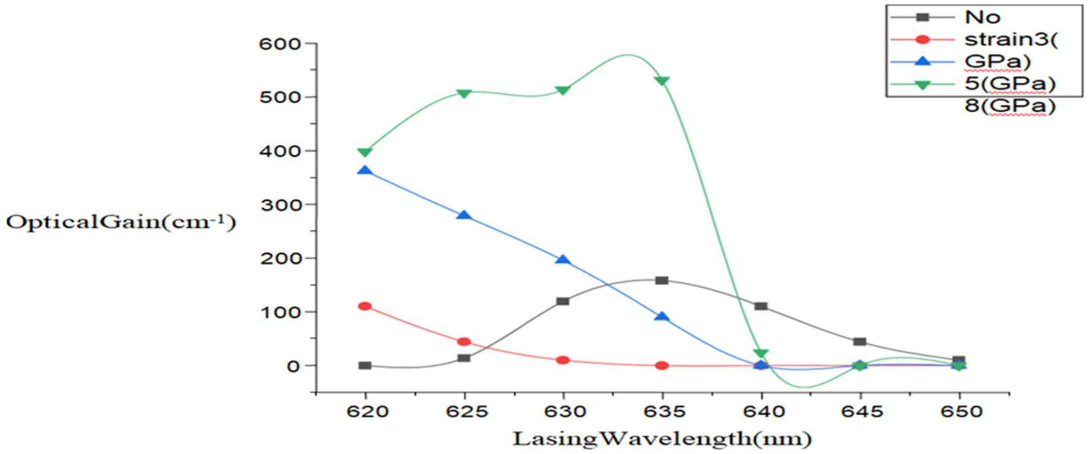

Fig. 4.b Interpretation of strain effects on total optical gain for GaInP/AlGaInP lasing nano-heterostructure z polarization.

Effect of temperature

As we know that every semiconductor compounds have its optical parameters which changes by changing in temperature. The above mentioned calculations are done under room temperature but the temperature can never be moderate as per our requirements, so an analysis for different temperature conditions is necessary. We have used GaInP and AlGaInP for our nano scale heterostructure design. These compounds also shows some changes in their structural parameters under temperature conditions, which effects the optical gain and it is presented in figure 5.a and 5.b for temperature below and above room temperature.

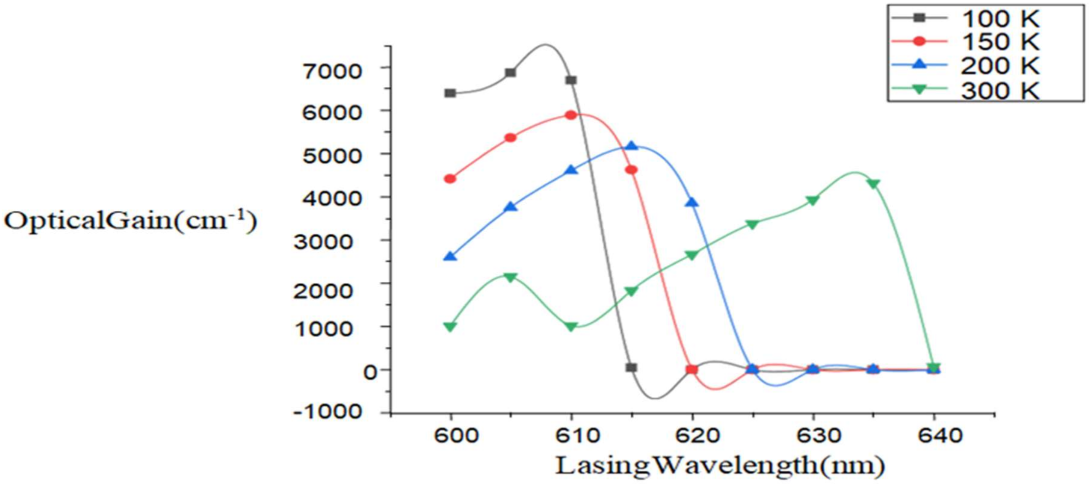

Fig. 5.a Effect of temperature on optical gain below room temperature.

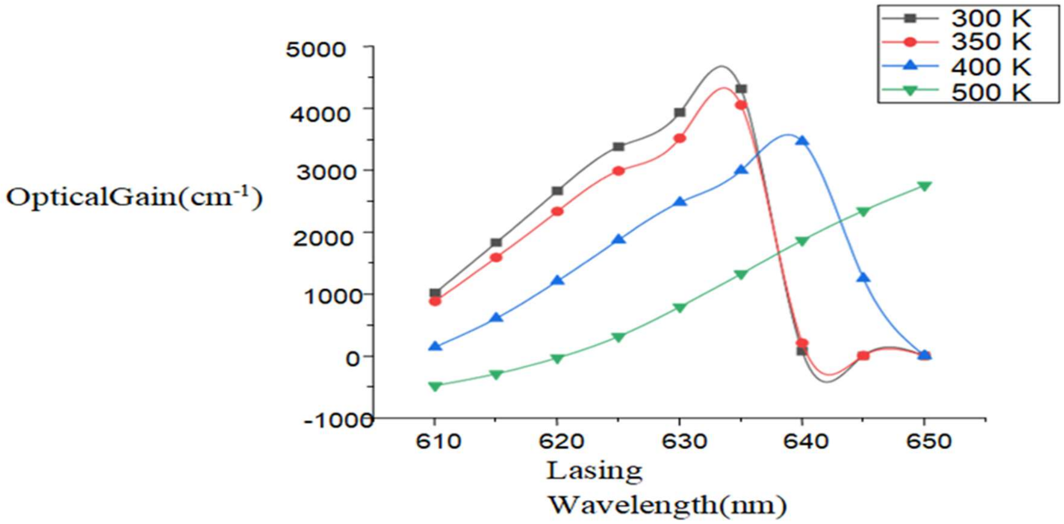

Fig. 5.b Effect of temperature on optical gain above room temperature.

We observe that optical gain is high for temperature below room temperature but the wavelength shifts to lesser value and for temperature above room temperature optical gain decreases and wavelength increases with increasing temperature.

4. Conclusion

We have done analysis for varying strain, changing well thickness and different temperature. We conclude here that the designed heterostructure can be used widely for generating a range of wavelengths 600-650nm by changing some basic specifications like thickness or providing strain. Our aim was to generate a wavelength of 635nm optical gain greater than 3000/cm and we have achieved our aim by obtaining a gain of order 4000/cm for well thickness 5nm and generating overall nano scale heterostructure of size 35nm.

5. References

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