STIN InGaP/GaAs Nano-heterostructures

5.1 Introduction

InGaP/GaAs interface is getting attention of researchers and scientists for fabrication of optoelectronic devices. $\text{In}_{1-x}\text{Ga}_x\text{As}$ alloys, if fabricated as lattice matched on GaAs as substrate, have been proved to be a better alternate to AlGaAs/GaAs based structures. The reason being it can acquire any lattice parameter from GaP to InP provided convenient substrates are used [1]. Even tensile strained InGaP layers offer better characteristics for doped heterostructures with InGaAs channel as they have large conduction band offsets as compared to lattice matched ones [2]. An additional benefit is its large valence band offset and the aluminum free structure introduces deep levels that serve as recombination centers [3].

Depending on the nature of refractive index change across the barrier, nano heterostructures can be classified as STIN-SCH (Step Index Separate Confinement) heterostructures and GRIN-SCH (Graded Index Separate Confinement) heterostructures. In case of STIN-SCH, the refractive index across the barrier changes abruptly while in case of GRIN-SCH, the refractive index across the barrier changes gradually. This chapter is focused primarily on the optical characteristics of $\text{In}_{0.45}\text{Ga}_{0.55}\text{P}/\text{GaAs}$ based STIN-SCH single quantum well and STIN-SCH multiple quantum well heterostructures.

5.2 STIN SQW InGaP/GaAs Nano-heterostructure

The proposed lasing nano-heterostructure under study consists of a quantum well (60 Å thickness) of $\text{In}_{0.45}\text{Ga}_{0.55}\text{P}$ sandwiched between InGaAlP (barrier) followed by cladding of InAlP, as shown in Figure 1. The entire heterostructure has been considered to fabricate on GaAs substrate. For the heterostructure, GaAs has been chosen as a substrate because most of the desirable characteristics it possesses, for example, it has a high electron velocity, higher electron mobility, lower resistive device parasitic and less noise especially at higher frequencies. A well
known advantage of the material is its direct and wide band gap, making it to offer a good resistance to radiation damage thus considered as an excellent choice for high power optical applications. Its high dielectric constant combined with its resistive nature makes it a good electrical substrate thus providing natural isolation between devices and circuits.

![Energy Band Diagram](image)

**Figure 1.** (a) Energy band diagram and (b) Schematic layer structure for In\(_{0.45}\)Ga\(_{0.55}\)P/GaAs STIN-SQW heterostructure

(a) **Energy Levels and Envelope Functions**

The first step to engineer a quantum well based optoelectronic device is to have a thorough knowledge of allowed discrete energy states and the associated envelope functions in the active region. Schrödinger wave equation has been used to determine the energy levels and associated envelope functions in the conduction band while Kohn Luttinger Hamiltonian has been solved to get an exact insight into the allowed discrete energy states and the associated envelope functions in the heavy hole and light hole valence sub-bands. The calculated envelope functions for
conduction band, heavy hole and light hole sub-bands and band offsets as a function of the normalized width of the proposed structure are plotted in figures 2 and 3 (a, b) respectively.

**Figure 2.** Band offsets and envelope functions associated with electrons in conduction band for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure

**Figure 3.** Band offsets and envelope functions associated with (a) heavy holes and (b) light holes in valence band for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure.
(b) Quasi Fermi Levels

The knowledge of Quasi Fermi Levels is very essential for analyzing the gain spectrum of quantum well heterostructures. The injected carrier density and the magnitude of optical gain is largely dependent on the separation between quasi Fermi levels. As a matter of fact, to achieve a substantial gain in the device, the energy level separation between quasi Fermi levels has to be greater than the energy band gap of the material being employed in the active region. The behavior of quasi Fermi levels for electrons in the conduction band and holes in the valence band in the context of proposed In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure is shown in figure 4.

![Figure 4. Behavior of quasi Fermi levels (a) conduction band and (b) valence band with carrier density for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure.](image)

(c) Optical Gain

The stimulated emission in a heterostructure results in optical gain. Optical gain is nothing but the growth ratio of intensity of light (density of photons) per unit length of propagation of light. The polarization modes dependent gain spectra of In$_{0.45}$Ga$_{0.55}$P/GaAs lasing nano-heterostructure have also been simulated and plotted. Figures 5(a) and 5(b) respectively show the behavior of material gain with respect to lasing wavelength and photonic energy within TE (Transverse Electric) and TM (Transverse Magnetic) polarization modes. For the proposed heterostructure,
the maximum material gain has been noticed at the lasing wavelength and corresponding required photonic energy for lasing action within TE mode rather than TM mode. The reason behind this fact may be the development of compressive strain induced in quantum well region. The induced strain causes the edges of valence bands to move resulting in top valence bands being pulled further apart which in turn increases the energy separation between light and heavy hole sub-bands. It may result in a situation that a higher density of holes can be retained in the top band alone prior to the time the next band is also populated. It would result in the lesser number of holes transit from light hole sub-band and split off band to the conduction band. As the TM polarization mode is mainly dependent on the hole transitions among these bands, so it is less prominent in a strained quantum well layer. On the other hand, in TE mode the effect is highly pronounced as the top heavy valence band is richly populated by holes. Thus TE mode contributes largely towards optical gain. On the other hand modal losses are also more in TE mode than TM mode. There is one more term associated with the gain of quantum well heterostructures i.e. modal gain. Modal gain is defined as the product of optical gain and confinement factor that depends on the geometry of active layer. The G-J characteristics (modal gain v/s current density) of the proposed lasing nano heterostructure are plotted in both TE and TM polarization modes as shown in figure 6. It can be analyzed from the graph that TE mode offers better modal gain as well as threshold gain at the same value of threshold current density.

![Figure 5. Polarization dependent gain characteristics as a function of (a) lasing wavelength and (b) photonic energy](image)

In $\text{In}_{0.45}\text{Ga}_{0.55}\text{P}/\text{GaAs}$ STIN-SQW heterostructure
(d) Differential Gain and Gain Compression

Differential gain is the optical gain per unit carrier density. Gain Compression is the compression in unit optical gain per unit photonic density. Differential gain can be calculated by differentiating material gain with respect to the injected carrier density. It is necessary to study the behavior of differential gain as it is responsible for finding the anti-guiding factor which plays a very important role in determining the lasing characteristics of nano-heterostructures. For the proposed In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW nano-heterostructure, both the differential gain and gain compression are found to decrease exponentially with the increase in carrier density as shown in the Figure 7. Also the value of differential gain decreases rapidly with the carrier injection above threshold carrier density, which is due to gain compression.
Figure 7. Behavior of (a) differential gain and (b) gain compression with carrier density for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure

(e) Refractive Index Change

In fact, the most important differences between the two dissimilar semiconductors forming heterojunctions are generally in the energy gap and the refractive index. In the lasing nano-heterostructures, the differences in energy gap allow spatial confinement of injected electrons and holes, while the change in refractive index is very important in order to form optical waveguides. Figure 8 (a) shows the behavior of refractive change with respect to carrier density for the proposed In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW nano-heterostructure. It is found that magnitude of refractive index change decreases with increase in carrier density.

Contrary to differential gain, the anti-guiding factor, being responsible for material gain associated with the heterostructure, has been observed to increase with increase in current density. The anti-guiding factor is proportional to the ratio of differential refractive index change and differential gain. Figure 8(b) shows that the behavior of anti-guiding factor for In$_{0.45}$Ga$_{0.55}$P /GaAs lasing nano-heterostructure, it increases linearly with the increase in current density.

Typical values of anti-guiding factor for lasing heterostructures at room temperature have been reported to vary from 2 to 6.22 However, in the design proposed, this value has been found to
vary in the range from 1 to 3 at room temperature conditions. Large values of anti-guiding factor can result in anti-guiding in narrow stripe lasing nano-heterostructures, self-focusing and filamentation in broad-area emitters. Mikulla et al. [4] have already demonstrated that epitaxial structures designed with a low optical confinement factor were less sensitive to filamentation. Numerical analysis of single pass tapered region amplifiers [5] and simple analytical models [6] have also confirmed this fact.

![Graph](image)

**Figure 8.** Behavior of (a) Refractive Index Change and (b) Anti-guiding factor for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure.

### 5.2.1 Effect of temperature on Optical properties of InGaP/GaAs Nano-heterostructure

#### 5.2.1.1 Effect on material gain

In this study, the gain spectra of InGaP/GaAs nano heterostructure was studied and simulated. The temperature dependent gain spectra of In$_{0.45}$Ga$_{0.55}$P/GaAs lasing nano-heterostructure have been simulated and plotted in Figure 9. The information elicited from the gain simulation studies indicate that with increase in temperature, the material gain as a function of lasing wavelength and photonic energy decreases. The reason can be that as the temperature is increased the more number of injected carriers move to elevated states and more holes occupy the separate confinement heterostructure region. In addition to it, the variation in the range of anti-guiding
factor with change in current density was also noticed at different temperature conditions and shown in figure 10. The simulation analysis shows that as the temperature is increased, the range of anti-guiding factor comes to a downscale which also supports the decrease in material gain. The inset graph in figure 10 shows the change in anti-guiding factor as a function of temperature.

![Graph](image)

**Figure 9.** Behavior of Material gain as a function of (a) lasing wavelength and (b) photon energy for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure.

![Graph](image)

**Figure 10.** Variation in anti-guiding factor as a function of current density for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructures
5.2.1.2 Effect on peak material gain and differential gain

The results obtained in figure 9 are summarized and plotted in figure 11(a) which shows the smooth downfall in peak material gain with increasing temperature at a particular carrier density of $10^{17}$/cm$^3$. Taking into account the effect of temperature over differential gain, the behavior of differential gain has also been predicted in figure 11(b). A significant change in the curvature of differential gain has been noticed, when plotted at increasing temperature conditions. Although an exponential decrease still holds good at the increasing temperatures, a downward shift has been observed in the value of peak differential gain with increase in temperature as shown in the inset graph in figure 11(b).

Figure 11. Temperature dependence of (a) Peak Material gain and (b) Differential gain for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure

5.2.1.3 Effect on G-J characteristics

Figures 12(a) and 12(b) respectively show the behavior of modal gain and modal loss as a function of current density with different temperatures ranging from 100 K to 500 K. It is observed that as the temperature increases, the modal gain as a function of current density decreases. Alternatively losses in the structure are increased as the temperature rises. The
decreasing values of peak modal gain at an optimum current density of 4000 A/cm$^2$ are plotted against temperature in figure 13.

Figure 12. Temperature dependence of (a) Modal Gain (b) Modal Loss as a function of current density In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure.

Figure 13. Peak Modal Gain as a function of temperature for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure.
5.2.1.4 Effect on Threshold current density and transparent current density

The values of threshold gain and threshold current density can be obtained by drawing a tangent passing through zero modal gain point in figure 12(a) (G-J curve). It can be analyzed that the value of threshold gain decreases while threshold current density increases as the temperature is increased as shown in figures 14(a) and 14(b) respectively. The current density at which modal gain becomes zero is termed as transparent current density. The transparent current density (at which modal gain becomes zero) increases as the temperature is increased as shown in figure 15.

(a) Threshold Gain with temperature for Step SCH SQW
(b) Threshold Current Density with temperature for Step SCH SQW

**Figure 14.** Temperature dependence of (a) Threshold Gain and (b) Threshold Current Density for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructures

(a) Transparent Current Density vs temperature for Step SCH with SQW

**Figure 15.** Temperature dependence of Transparent Current Density for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure
5.2.2 Effect of increasing carrier concentrations on Optical properties of InGaP/GaAs Nano-heterostructure

Figures 16(a) and 16(b) respectively show the variation in material gain with lasing wavelength and photonic energy at different carrier concentrations. Interestingly with varying carrier densities material gain shoots up retaining the same lasing wavelength and corresponding photonic energy as well. The results reveal that the maximum optical gain with value 2921.535 /cm is achieved at a lasing wavelength of 0.625 µm, the corresponding photonic energy is 1.98 eV at optimum carrier concentration of 2 x 10^{18} /cm^{3}. Figure 17 shows the increase in the value of peak material gain as a function of carrier density. The peak material gain is observed to increase exponentially with respect to carrier density.

![Figure 16](image)

**Figure 16.** Behavior of Material gain as a function of (a) lasing wavelength and (b) photon energy for increasing carrier concentrations in In_{0.45}Ga_{0.55}P/GaAs STIN-SQW heterostructure
Figure 17. Variation in Peak Material Gain with increasing carrier concentrations for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure

5.2.3 Effect of changing width of quantum well on Optical properties of InGaP/GaAs Nano-heterostructure

The thickness of quantum well is a significant parameter for determining quantum well properties. It is known that there always exists an optimum quantum well thickness which gives lowest threshold current at a particular optical gain. The gain spectrum of proposed structure was also analyzed by changing the width of quantum well in the range from 40 Å to 100 Å. Figure 18(a) shows that material gain as a function of lasing wavelength decreases as the width of quantum well is increased. Moreover a shift towards larger lasing wavelength is also observed as the width of active region increases. It is because as the well width increases, the separation between quasi Fermi levels decreases resulting in decrease in the separation between energy subbands. A quite similar observation can be drawn when material gain was plotted as a function of photon energy. A decrease in the value of material gain and shift in the value of photonic energy corresponding to maximum gain can be observed in figure 18(b).
Figure 18. Variation in Material gain as a function of (a) lasing wavelength and (b) photon energy for different quantum well widths in In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure

The summarized results from figure 18 are plotted in figure 19 where a clear downward shift in the value of peak material gain as a function of quantum well width is shown (refer figure 19(a)). Also the rising shift in lasing wavelength and declining shift in photonic energy as a function of width of quantum well can be clearly seen in figure 19 (b) and 19 (c) respectively.

Figure 20 (a) shows the behavior of differential gain as a function of carrier density for different widths of quantum well. It is observed to decrease exponentially with respect to carrier density. Moreover as the quantum well width is increased the value of peak differential gain is decreased as shown in inset graph of figure 20(a). The behavior of anti-guiding factor is observed to increase with increase in the width of quantum well as shown in figure 20(b). The inset graph of figure 20(b) shows the rising curve of anti-guiding factor with respect to quantum well width at an optimum current density of 8.023 A/cm$^2$. 
Figure 19. Variation in (a) Peak Material gain (b) lasing wavelength and (c) photon energy for increasing quantum well widths in In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure
Figure 20. Variation in (a) Differential gain and (b) Anti-guiding factor as a function of current density for increasing quantum well widths in In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-SQW heterostructure.

5.3 STIN MQW InGaP/GaAs Nano-heterostructure

Introducing multiple quantum wells in the proposed structure resulted in tremendous improvement in the gain characteristics. As mentioned in the very beginning of the chapter, by solving Schrodinger wave equation we have determined the energy levels and associated envelope functions in the conduction band as shown in figure 21. The electron density is highest in the central quantum well as compared to the adjacent quantum wells. This is a special feature of multiple quantum well structures and is responsible for improvement in modal gain. By using Kohn Luttinger Hamiltonian, allowed discrete energy states and the associated envelope functions in the heavy hole sub-bands and light hole sub-bands were determined as shown in figure 22.
Figure 21. Band offsets and envelope functions associated with electrons in conduction band for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-MQW heterostructure.

Figure 22. Band offsets and envelope functions associated with (a) heavy holes and (b) light holes in valence band for In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-MQW heterostructure.
Figure 23. Variation in (a) Modal Gain (b) Modal Loss as a function of current density for increasing number of QWs in $\text{In}_{0.45}\text{Ga}_{0.55}\text{P}/\text{GaAs}$ STIN-MQW heterostructure.

Figure 23(a) shows the increase in modal gain as a function of current density with increasing number of quantum wells in the structure. The associated losses in the structure are also increased with increase in the number of quantum wells as shown in figure 23(b). The discrete values of peak modal gain and loss in the structure are respectively plotted as inset graphs in figure 23(a) and figure 23(b) respectively. The associated values of threshold gain, threshold current density and transparent current density with respect to increase in the number of wells have been plotted in figure 24. It can be easily inferred from the graphs that threshold gain (refer figure 24(a)) threshold current density (refer figure 24(b)) as well as transparent current density (refer figure 24(c)) increases linearly with increase in the number of quantum wells.
Figure 24. Variation in (a) Threshold Gain (b) Threshold Current Density and (c) Transparent Current Density with increasing number of quantum wells in In$_{0.45}$Ga$_{0.55}$P/GaAs STIN-MQW heterostructure.
References


