GRIN InGaP/GaAs Nano-heterostructures

6.1 GRIN SQW InGaP/GaAs Nano-heterostructure

This chapter is focused primarily on the optical characteristics of In$_{0.45}$Ga$_{0.55}$P/GaAs based GRIN single quantum well and GRIN multiple quantum well heterostructures. As mentioned in chapter 4, the refractive index across the barrier changes gradually in case GRIN separate confinement heterostructures. The proposed lasing nano-heterostructure under study consists of a quantum well (60 Å thickness) of In$_{0.45}$Ga$_{0.55}$P sandwiched between InGaAlP (50 Å thick barrier with some grin steps) followed by cladding of InAlP (100 Å) as shown in Figure 1. Each graded index layer has different band gap and different refractive index in such a way that as we approach toward cladding region from quantum well, the refractive index decreases and the energy band gap increases.

![Figure 1](a) Energy band diagram and (b) Schematic layer structure for In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-SQW heterostructure.
(a) Energy Levels and Envelope Functions

In order to know the 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. Additionally, 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. It is clear from figure 1 that wave function associated with first allowed energy level CB1 in conduction band is symmetrically distributed across the centre of quantum well and provides the maximum confinement as compared to CB2 and CB3.

![Figure 2. Band offsets and envelope functions associated with electrons in conduction band for In\textsubscript{0.45}Ga\textsubscript{0.55}P/GaAs GRIN-SQW heterostructure](image-url)
6.1.1 Effect of Number of GRIN Steps

The effect of introducing uniformly graded barrier steps on the optical properties of proposed structure In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-SQW heterostructure has been observed.

6.1.1.1 Effect on Modal Gain

Figure 4 shows the plot of modal gain as a function of current density for step SCH and GRINSCH with the number of grin steps being taken as 3, 5 and 11. It can be observed that step SCH offers better gain spectra than the GRINSCH. Also modal gain decreases as the number of grin steps are increased in the structure. It has been observed that for STINSCH the maximum modal gain achieved is 58.33/cm and it goes on decreasing as the number of grin steps are increased in the structure. Recently P. A. Alvi et al. [1] have also theoretically investigated GRIN-InGaAlAs/InP lasing nano heterostructure and in this particular material system has also shown a reduction in modal gain with increase in the number of GRIN steps. The maximum modal gain achieved in In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-SQW employing 11 grin steps is found to be 52.11/cm.
6.1.1.2 Effect on Anti-guiding factor and Refractive Index Change

The value of anti-guiding factor is more in GRIN-SCH than step SCH as shown in figure 5 (a). Moreover the value of anti-guiding factor increases as the number of grin steps are increased in the structure. Figure 5(b) 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 as a function of carrier density decreases more rapidly as the number of GRIN steps are increased.

Figure 5. Behavior of (a) Anti-guiding factor and (b) Refractive Index Change with for In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-SQW heterostructure
6.1.2 Effect of polarization mode on G-J Characteristics

The modal gain spectrum for a particular number of quantum well in the heterostructure has been plotted and analyzed with in both TE and TM polarization modes as shown in figure 6 (a). Approximate value of threshold modal gain is 43.91/cm and 22.03/cm in TE and TM mode respectively at corresponding threshold current density being nearly 1956.77 A/cm². The value of modal gain is higher in TE mode than TM mode because most of the holes occupy the heavy hole energy sub-bands because of splitting of degeneracy of the valence band in the compressive strain induced in the quantum well region [2]. Similar results have also been reported by Pyare Lal. et al.[3] for GRIN based Al₀.₁₀Ga₀.₉₀As/GaAs lasing nano-heterostructure where gain obtained is more in TE mode than in TM mode. Due to microscopic selection rules being associated with unit cell wave functions, for TM polarization, transitions from heavy hole sub-bands to conduction band are forbidden. As a result entire absorption strength is contributed by transitions from light hole sub-bands to conduction band. In case of TE mode, transitions from heavy hole to conduction band accounts for the maximum gain. Therefore TE mode offers more optical gain than TM mode. On the other hand modal losses are also more in TE mode than TM mode as shown in figure 6 (b).

![Modal Gain and Loss](image)

**Figure 6.** Polarization dependent (a) Modal Gain and (b) Modal Loss as a function of current density for In₀.₄₅Ga₀.₅₅P/GaAs GRIN-SQW heterostructure.
6.1.3 Effect of Strain

Introducing compressive strain (1.2%) in the structure resulted in decrease of material gain as a function of lasing wavelength, as shown in figure 7(a) while the modal gain as a function of current density increases in the compressively strained structure than lattice matched one as shown in figure 7(b).

![Figure 7](image-url)  
**Figure 7** (a) Material gain and (b) Modal gain under the effect of compressive strain in In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-SQW heterostructure.

6.2 GRIN MQW InGaP/GaAs Nano-heterostructure

In case of MQWs based heterostructures, more number of carriers can be associated with quantum well regions. In GRIN MQW heterostructures, the quantum well active region is sandwiched between the GRIN-SCH barriers of different refractive indices and band gaps. In such heterostructures the value of optical confinement factor varies as change in the number of grin steps so modal gain can be controlled by changing the number of grin steps. The effect of increasing the number of quantum wells in GRINSCH with 5 grin steps in the structure has been studied. With the help of Schrödinger wave equation and Kohn Luttinger Hamiltonian, the energy levels and associated wave functions have been calculated for electrons in conduction band, heavy holes and light holes in valence band as shown in figure 8 and figure 9 (a, b).
Figure 8. Band offsets and envelope functions associated with electrons in conduction band for In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-MQW heterostructure.

Figure 9. 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 GRIN-MQW heterostructure.
6.2.1 Effect of Number of Quantum Wells

6.2.1.1 Effect on Modal gain

Figure 10 (a) shows the variation of modal gain with current density. It is clear from the graph that the modal gain increases with increase in current density and it becomes almost constant at higher values of current density. The effect of increase in number of quantum wells on the modal gain was also estimated. The simulation studies reveal that the saturated modal gain at corresponding larger value of current density is increased with increase in number of quantum wells. For a single quantum well structure, at an optimum current density value of 30000 A/cm$^2$, the value of modal gain is 53.86/cm while introducing seven quantum wells in the structure make this value rise up to 119.2 /cm. The value of saturated peak modal gain versus number of quantum wells at an optimum current density value of 30000 A/cm$^2$ is also plotted in figure 10 (b). The increase in modal gain with increase in number of wells has also been very recently reported by Rashmi et al. [4] for GRIN based InGaAsP/InP nano heterostructures.

![Modal Gain with Current Density for different no. of QWs](image1)

![Modal Gain with increase in number of quantum wells](image2)

**Figure 10.** (a) Modal Gain as a function of current density and (b) Peak Modal Gain as a function of number of quantum wells with increasing number of wells in In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-MQW heterostructure
6.2.1.2 Effect on Modal Loss

There are certain factors affecting differential quantum efficiency like scattering losses, absorption of free carriers and inter valence band absorption which result in the overall modal losses in the structure [5, 6]. In addition, the optical losses in the structure have been simulated and plotted against current density as shown in figure 11(a). The behavior of optical loss with increasing number of quantum wells was also studied and was found to increase with increase in the number of quantum wells, as shown in figure 11(b).

![Figure 11. (a) Modal Loss as a function of current density and (b) Peak Modal Loss as a function of number of quantum wells with increasing number of wells in In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-MQW heterostructure](image)

6.2.1.3 Effect on Threshold current density and Transparent current density

As the number of quantum wells is increased in the structure, the value of threshold current density and transparent current density increases and threshold gain also increases. The reported values of threshold gain and threshold current density for In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-SQW heterostructure are 22.55 /cm and 686.18 A/cm$^2$ respectively whereas the same values for the structure with three quantum wells are 32.04/cm and 1756.63 A/cm$^2$ respectively. Figure 12
shows the variation in transparent current density as a function of increasing number of quantum wells.

Figure 12. Transparent current density as a function of number of quantum wells with increasing number of wells in In$_{0.45}$Ga$_{0.55}$P/GaAs GRIN-MQW heterostructure.

References


