Study of Effect of Strain, Quantum Well Width, and Temperature on Optical Gain in Nano-Heterostructures

Swati Jha and Ashok Sihag

Abstract In the work discussed here, we evaluate the effect of change in strain, quantum well width variation, and temperature on the optical gain of two SQW (Single quantum well) nano-heterostructures. Both the heterostructures are SCH (Separate confinement heterostructures) with STIN (Step Index) profile. We have taken a quaternary semiconductor $Al_{0.15}In_{0.22}Ga_{0.63}As/GaAs$ and compared it with a ternary semiconductor heterostructure $In_{0.45}Ga_{0.55}As/InP$. This paper is an effort to compare the effect of change of strain on the optical gain of the two heterostructures. It also analyzes the behavior of quantum well width and temperature on the gain.

Keywords Heterostructures · Material gain · Strain · Temperature
Quantum well width

1 Introduction

InGaAlAs/InP heterostructures, in recent researches as in [1–3], have got special attention because of its lasing wavelength of 1.55 μm which dramatically coincides with the wavelength at which loss is minimum in optical fibers. In this work, we present the compositional details of the two different nano-heterostructures and investigate their comportment in terms of optical gain as against their lasing wavelengths. The effect of compressive and tensile strains is gauged on the two heterostructures along with the changes when the step index profiled well width of single quantum well is varied in steps on the material (optical) gain of the lasing herterostructures. Also, the influence of temperature variation is evaluated to figure out its impact on the gain.

S. Jha (✉) · A. Sihag
BML Munjal University, Gurgaon, India
e-mail: swati.jha@bml.edu.in

A. Sihag
e-mail: ashok.suhag@bml.edu.in

2   Heterostructures Compositional Details

The compositional details of the STIN SCH SQW quaternary semiconductor laser of $Al_{0.15}In_{0.22}Ga_{0.63}As$ on GaAs are presented in Table 1, while Table 2 envisages representation of the second ternary semiconductor lasing heterostructure, namely $In_{0.45}Ga_{0.55}As$ on InP substrate.

In the work presented in this paper, the researchers evaluate the effects of changing strain, well width modulation, and temperature variation on the optical gain. A comparative analysis of the two SQW heterostructures is also carried out to evaluate and understand their usage and effectiveness as lasing heterostructures. The differences studied here suggest the variability of their usage and suggest the predictability of their applications.
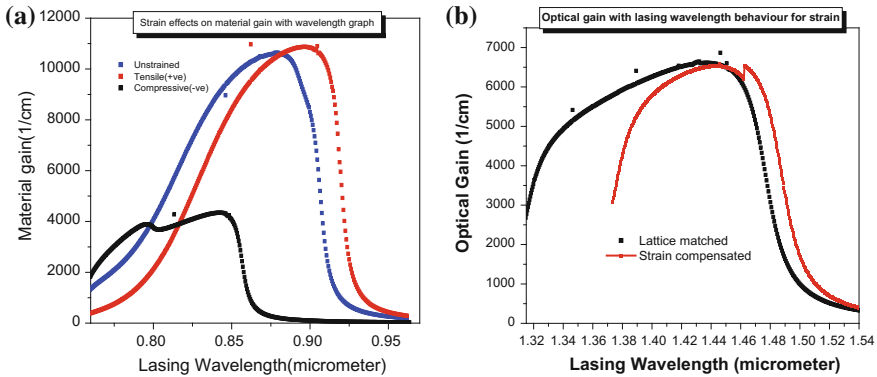
3   Effect of Strain

It is well-known fact that compressive strain splits the first light-hole and heavy-hole subbands [4]. When the QWs are strained compressively, the differential gain in lasers improves because of the reduction in density of states (DOS) of holes (which gets increased because of heavy-hole and light-hole subband mixing). When the QWs are heavily compressively strained, hole confinement increases leading to improved threshold, injection efficiency, and ultimately the gain.

Table 1 $Al_{0.15}In_{0.22}Ga_{0.63}As$ quantum well lasing heterostructure

Layer number	Name of the layer	Material used	Width (nm)	Conduction band offset (eV)	Valence band offset (eV)	Lattice constant (Å)
1	Cladding	$Al_{0.61}Ga_{0.39}As$	10	0.6084067	−0.2863090	5.815376
2	Barrier	$Al_{0.2}Ga_{0.8}As$	5	0.2405987	−0.1132229	5.970752
3	Quantum well	$Al_{0.15}In_{0.22}Ga_{0.63}As$	6	0.0964814	−0.048240	5.909987

Table 2 $In_{0.45}Ga_{0.55}As$ quantum well lasing heterostructure

Layer number	Name of the layer	Material used	Width (nm)	Conduction band offset (eV)	Valence band offset (eV)	Lattice constant (Å)
1	Cladding	$Ga_{0.48}In_{0.52}As$	10	0.4844044	−0.1883795	5.863952
2	Barrier	$Al_{0.29}Ga_{0.17}In_{0.54}As$	5	0.1062417	−0.0413162	5.873997
3	Quantum well	$In_{0.45}Ga_{0.55}As$	6	−0.0283436	0.0141718	5.876105

(a)

(b)

Fig. 1 Effect of strain on material gain as a function of lasing wavelength for **a** $Al_{0.15}In_{0.22}Ga_{0.63}As/GaAs$ and **b** $In_{0.45}Ga_{0.55}As/InP$

However, this methodology works well only till 1% of the strain [5]. Beyond that, strains hardly have any effect on DOS because at higher values of strain, heavy-hole and light-hole subbands are already separated in energy. In Fig. 1a and b, we plot the strain effects on optical gain when they are plotted with respect to the lasing wavelength for the heterostructures and observe the effect of unstrained/lattice-matched and strain-compensated condition. From Fig. 1a it is observed that in $Al_{0.15}In_{0.22}Ga_{0.63}As/GaAs$ case, tensile strain (1.6×10^{-2}) gives the maximum gain; however, the lattice-matched condition is comparable. Nevertheless, if we consider the lattice-matched (unstrained) situation with the condition on application of strain (5.123×10^{-3}) for $In_{0.45}Ga_{0.55}As/InP$ in Fig. 1b, we observe a transition in the trend after the lasing wavelength of 1.449 µm at which the maximum gain of 6521.09 cm^{-1} in both cases is attained. We also find out that the peak material gain has a narrow spectrum in the strain compensated case.

4 Quantum Well Width Alteration Effects

Controlling the width of the quantum wells, the electron and hole wave functions can be transformed. This attribute leads to the modification of material parameters and not only improves the laser characteristics but also introduces new concepts to semiconductor optical devices. Here, in Fig. 2a, we investigate the effect of changing the well width from 60, 50, 40, and finally 30 Å on optical gain. Statistical data shows a staggering gain of 13,903.19 cm^{-1} at a lasing wavelength of 0.77 µm when the quantum well width is 40 Å. On increasing the well width from 30 Å to 50 Å and then to 60 Å, we observe a decrement in the gain values as well as the broadening of the gain spectra which may be attributed to the spectral hole burning.
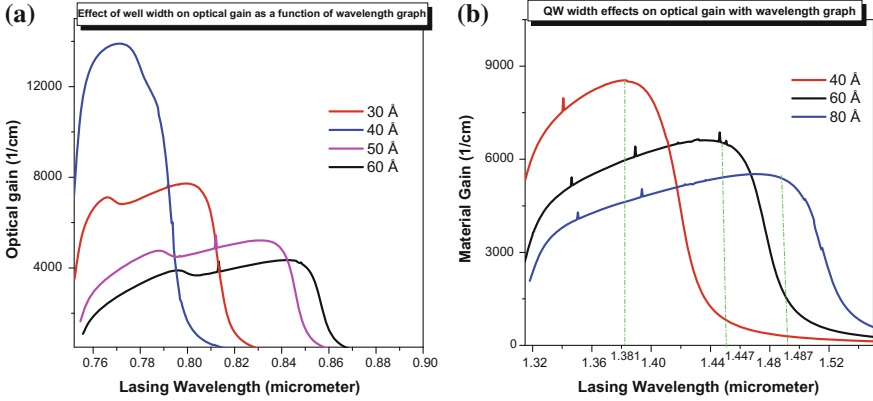
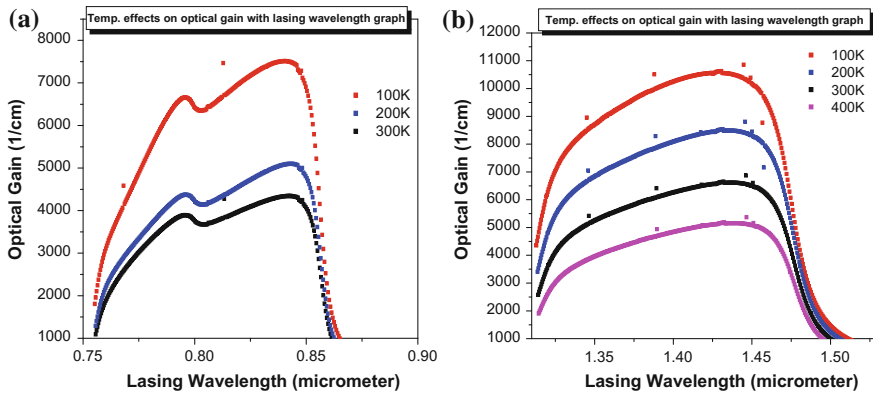**Fig. 2** Effect of QW width on material gain with lasing wavelength graph for **a** $Al_{0.15}In_{0.22}Ga_{0.63}As/GaAs$ and **b** $In_{0.45}Ga_{0.55}As/InP$

Investigating the effect of quantum well width variations from 60 to 40 Å, and finally to 80 Å on the optical gain for $In_{0.45}Ga_{0.55}As/InP$ illustrates that the maximum gain of 8550.24 cm^{-1} is achieved at a lasing wavelength of 1.38 µm for 40 Å. For 60 Å, a maximum gain of 6566.08 cm^{-1} is achieved at a lasing wavelength of 1.44 µm while for 80 Å, a maximum gain of 5373.29 cm^{-1} is achieved at a lasing wavelength of 1.48 µm as evident from Fig. 2b. It is indeed noteworthy that in both cases, at 40 Å, we have the maximum optical gain and also the gain spectrum is sharpest which indicates that it is the most suitable well width as far as gain is concerned because it offers maximum confinement. This observation reiterates the fact that maintaining a proper well width is very crucial for a better lasing characteristic.

5 Role of Temperature

Temperature has a big role to play in the lasing phenomena as it affects the injection efficiency, threshold current, and surely the gain. Hence, we now plot the effects of change in temperature on optical gain when it is changed from 100 to 300 K in steps of 100 K in Fig. 3a for $Al_{0.15}In_{0.22}Ga_{0.63}As/GaAs$.

Data from the graph indicates that at the same lasing wavelength of 0.84 µm we attain a maximum gain of 7494.40 cm^{-1} at 100 K, whereas at 200 K the gain is only 5096.12 cm^{-1} and the least value of gain (4321.95 cm^{-1}) is observed at 300 K. Exploring the effects of change in temperature on the material gain when it is varied from 100 to 300 K and finally 400 K in Fig. 3b for $In_{0.45}Ga_{0.55}As/InP$, we observe a regular trend of decrease in the material gain as we keep on increasing the temperature. This behavior of gain with temperature is similar in the two heterostructures.

Fig. 3 Effect of temperature on material gain with lasing wavelength graph for **a** $Al_{0.15}In_{0.22}Ga_{0.63}As/GaAs$ and **b** $In_{0.45}Ga_{0.55}As/InP$

6   Conclusion

On comparing the two STIN SCH SQW nano-heterostructures, we observe that the effect of strain, in $Al_{0.15}In_{0.22}Ga_{0.63}As/GaAs$ case tensile strain (1.6×10^{-2}), gives the maximum gain; however, the lattice-matched condition is comparable. Nevertheless, if we consider the lattice-matched (unstrained) situation with the condition on application of strain (5.123×10^{-3}) for $In_{0.45}Ga_{0.55}As/InP$, we observe a transition in the trend after the lasing wavelength of 1.449 μm at which the maximum gain of 6521.09 cm^{-1} in both cases is attained. It is also observed that the peak material gain has a narrow spectrum in the strain compensated case. Investigating the well width variations yield, 40 Å, as the most suitable well width as far as gain is concerned for both cases, we not only have the maximum optical gain at this well width but also the gain spectrum is sharpest which indicates that it offers maximum confinement. This observation reiterates the fact that maintaining a proper well width is very crucial for a better lasing characteristic. On exploring the effects of changes in temperature on the material gain, we observe a regular trend of decrease in the material gain as we keep on increasing the temperature. This behavior of gain with temperature is similar in the two heterostructures.

References

1. Alvi PA, Lal P, Dalela S, Siddiqui MJ (2012) An extensive study on simple and GRIN SCH-based In0.71Ga0.21Al0.08As/InP lasing heterostructures. Phys Scr 85:035402
2. Alvi PA, Lal P, Yadav R, Dixit S, Dalela S (2013) Modal gain characteristics of GRIN-InGaAlAs/InP lasing nano-heterostructures. Superlattices Microstructures 61:1–12
3. Lal P, Yadav R, Rahman F, Alvi PA (2013) Carrier Induced Gain Simulation of InGaAlAs/InP Nano-Heterostructure. Adv Sci Eng Med 5:918–925

4. Vahala KJ, Newkirk MA (1989) Parasitic-free modulation of semiconductor lasers. IEEE J Quantum Electron 25:1393–1398
5. Ishikawa M, Nagarajan R, Fukushima T, Wasserbauer J, Bowers J (1992) Long wavelength high-speed semiconductor laser with carrier transport effects. IEEE J Quantum Electron 28:2230–2241