Simulating 1.30 μm Optical Gain in Type-I InGaAsN/GaAs Nano-Heterostructure

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Abstract. This paper reports theoretical simulation of optical gain achieved at 1.30 μm in the type-I InGaAsN/GaAs nano-scale heterostructure having active region of width ~ 40 Å. In addition, the modal gain, behaviour of differential gain and anti-guiding factor of the heterostructure is also simulated and reported. From simulation results, it is concluded that the proposed InGaAsN/GaAs heterostructure can produce the maximum optical gain ~2100/cm at 1.30 μm.

1. Introduction

The III-nitride based semiconductors, for examples: GaN, InN, AlN and their alloys, have been found to provide unique electrical, electronic, optical and mechanical properties which can be utilized for designing of future photonic and optoelectronic devices [1-3]. Since these semiconductors have wide band gap ranging from 1.9 eV to 6.2 eV, and therefore these materials can be utilized in the fabrication of optoelectronic devices operating in visible-to-ultraviolet regime. Examples are green, blue lasers and photo detectors. To date, III-nitrides based photodetectors operating in ultraviolet regime have exhibited promising output. In addition, III-nitrides based LEDs have been commercialized due to emission of super bright blue and green light. Moreover, these materials have some exceptional physical properties which make the devices ready for applications beyond the data storage and imaging [4]. These materials are also useful in high temperature electronics and space applications because these are physically and chemically strong. This property makes them ideal for operation in cruel environment.

For the application point of view, the III-nitride materials based devices are more beneficial in comparison to conventional semiconducting materials. For example, III-nitride materials based UV photodetectors are much sensitive to ultraviolet radiations while insensitive to infrared radiation. Thus, these devices are applicable in order to detect the ultraviolet radiations existing in the infrared and visible background [5]. Due to this, the III-nitride devices can be utilized in engine and furnace monitoring for automotive, flame detection, undersea communication, petroleum industry, and space-to-space communication, and in chemical analysis systems. One of the major advantages is that the III-nitride devices can be expected to work without optical filters due to their low dark currents and theoretical intrinsic solar blindness and, obviously, this behavior of these devices reduce the launch weight for space significantly.
2. Device Geometry and Theory

The geometry of device is very simple and consists of type-I double heterojunctions. The active region of the device is made of InGaAsN material, which is sandwiched between two barriers followed by claddings. The barriers and claddings are considered of GaAsN (with dilute N) material. The width of active region (quantum well region) is taken as 40 Å; while barriers are of width ~ 60 Å. The region behind the chosen of such size of active region is to have quantum confinement of the envelope function (or wave function) associated with the quantum well. The entire device is supposed to grow on GaAs substrate. This substrate is selected to have lattice matched condition of quantum well with the substrate in order to avoid unnecessary strain in the device. The unnecessary strain produced in the device may degrade the device performance.

The main object of this paper is to simulate the optical and modal gain. The optical gain for the heterostructure can be given as [6, 7]:

\[ G(h\omega) = \frac{2 me^2}{n_0 e_0 L m^2} \sum_{\sigma = u, d} \sum_{n,m} \int (\varepsilon \cdot M_{nm}^{\sigma}(k_t))^2 \times \frac{N_e^{\sigma}(k_t) - F_m^{\nu}(k_t))^{\frac{1}{2}}}{(E_{\nu}^{\sigma}(k_t) - \omega h)^2 + \gamma^2} \frac{dk_t}{2\pi} \]

Where \( f_n^{\nu}(k_t) \) and \( f_m^{\nu}(k_t) \) are quasi Fermi levels associated with conduction and valence band of the heterostructure respectively and can be given as:

\[ f_n^{\nu}(k_t) = \frac{1}{1 + \exp\left(\frac{E_n^{\sigma}(k_t) - F_n^{\nu}}{K_B T}\right)} \quad \text{and} \quad f_m^{\nu}(k_t) = \frac{1}{1 + \exp\left(\frac{E_m^{\sigma}(k_t) - F_m^{\nu}}{K_B T}\right)} \]

The details of symbols used in the above expressions can be seen in reference [7, 8].

3. Results and Discussion

Prior to optimize the optical gain of any heterostructure, it is essential to study the behavior of quasi Fermi levels associated with the conduction and valence bands of the heterostructure. Under the non equilibrium cases, these quasi Fermi levels play a very important role in specifying the carrier concentrations. The separation between quasi Fermi energy levels plays a critical role in understanding the optical behavior in the semiconducting heterostructure because of its relationship with the density of injected carriers and the intensity of optical gain [9]. Therefore, for the InGaAsN/GaAs nano heterostructure, the plot of quasi Fermi levels associated with the conduction and valence bands is shown in figure 1. In Figure 1, the behavior of quasi Fermi levels for electrons in the conduction and holes in the valence bands in the left (black) and right (blue) y-axes, respectively, is shown for In_{0.29}Ga_{0.71}As_{0.96}N_{0.04}/GaAs Straddled Heterostructures. This figure predicts that the quasi Fermi energies for both the conduction and valence bands are increased as increase in carrier density.

The optical gain is the fundamental characteristic of the quantum well heterostructures based lasers. The optical gain which depends on the confinement factor, GRIN (graded refractive index) layers and number of QWs (quantum wells) is termed as modal gain. For the InGaAsN/GaAs nano heterostructure, the behaviors of optical gain and modal gain with lasing wavelength are plotted in figure 2. In figure 2, the left (black) y-axis is chosen for optical gain; while the right (blue) y-axes is for modal gain. From figure 2, it is clear that the maximum optical of the heterostructure is found ~ 2100/cm at the wavelength of 1.30 μm. In the both spectra of optical gain and modal gain, two peaks are obtained. These two different peaks are due to different optical transitions which occur between different conduction and valence sub bands of the quantum well region of the heterostructure.
The differential gain for the In$_{0.29}$Ga$_{0.71}$As$_{0.99}$N$_{0.01}$/GaAs straddled heterostructure is also simulated and shown in figure 3. The differential gain is defined as first derivative of optical gain with respect to the carrier density. It is shown on the right (blue) y-axis. In addition, an interesting feature of the heterostructure, the anti-guiding factor is also calculated. The differential gain and anti-guiding factor are substantial parameters in the dynamics performance of quantum well heterostructures based lasers [10]. The anti-guiding factor plays a very crucial role in deciding the optical gain of lasing heterostructure and can be defined in terms of refractive index change and differential gain. Figure 3 shows the proportional and reciprocal behaviours of anti-guiding factor and differential gain, respectively as a function of carrier density.
Anti-Guiding Factor and Differential Gain with Carrier Density for InGaAsN/GaAs Straddled Heterostructure.

Conclusion
The gain spectra of type-I InGaAsN/GaAs nano-scale heterostructure has been simulated and reported successfully. Apart from this, the behavior of the modal gain, differential gain and anti-guiding factor of the heterostructure is also simulated and reported. According to the results, the InGaAsN/GaAs heterostructure can produce the maximum optical gain \( \sim 2100/cm \) at 1.30 \( \mu \)m.

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