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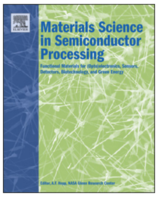

Strain-induced non-linear optical properties of straddling-type indium gallium aluminum arsenic/indium phosphide nanoscale-heterostructures

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Non-linear optical properties of indium gallium aluminum arsenic/indium phosphide (InGaAlAs/InP) material system based unstrained and strained lasing nano-heterostructures of straddled type (type-I) under TE (transverse electric) polarization mode have been studied. To produce the different states of strain at the heterointerfaces in the structure, the different layers of the active region of InGaAlAs (width ~6 nm) with different lattice constants (due to different mole fractions) have been assumed to be deposited in between the barriers of $In_{0.41}Ga_{0.34}Al_{0.25}As$ followed by claddings of $In_{0.52}Al_{0.48}As$. The entire nano-structure is a type of step SCH (separate confinement heterostructure) and has been assumed to grow over InP substrate. To study the strain induced non-linear optical properties of the structure, single effective mass and Kohn–Luttinger Hamiltonian equations have been solved to obtain quantum states and envelope wave functions in the heterostructure. In addition, the optical gain, differential gain, and the anti-guiding factor in order to support the gain calculation have been computed and reported. On behalf of simulation and previously reported experimental results, it has been suggested that either unstrained or compressive strained InGaAlAs/InP nano-heterostructures are more suitable for novel applications in the emerging areas of nano-opto-electronics due to the maximum gain occurring at lasing wavelength of 1.55 μm which is the wavelength of minimum optical attenuation.

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1. Introduction

Recently, step SCH (separate confinement heterostructure) type InGaAlAs/InP material system based single quantum well (SQW) lasing nano-heterostructures are widely used in an optical fiber communication system as light sources due to their interesting lasing wavelengths [1]. Quantum well (QW) lasing nano-heterostructure is seductive for research due to its physically and technology vital. In past few decades, for more semiconductors laser applications preferred the quantum well laser has been steadily grown until now. Recently, due to unusual properties of III–V semiconductors based quantum-size structures, they have drawn a very serious attention of researchers. Interestingly, formation of self-organized low-dimension semiconductor layers has drawn attention to the researchers due to the possibility of creating three-dimensional electron confinement in the uniform and coherent (non-dislocation) clusters. In the present era, quantum size-lasing heterostructures are very significant sources for fiber optic communications and are key components of applications such as optical data storage and remote sensing [2,3]. In quantum well based lasing heterostructures, it is desirable to lower the threshold

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current before lasing begins, that maximizes optical gain and minimizes the losses. Step index based SCHs (separate confinement heterostructures) play a promising role in this context. In the SCH based designs, the carriers get confined by heterostructure barriers so as to increase the carrier density in quantum well and therefore enhancing radiative recombination. As a result, a considerable amount of carriers is no more able to drift away to opposite electrode; they must recombine in the active or quantum region. The major benefits are continuous wave operation making them ideal for nano-optoelectronic applications. Further advantages include less heat generation and less power consumption.

Recently, InGaAlAs/InP material composition based lasing heterostructures have been more popular due to their lasing wavelength ~1.55 and 1.33 μm, the wavelengths of minimum attenuation [1]. For 1.55 μm wavelength, the multi-quantum wells (MQWs) based vertical cavity surface emitting lasers (VCSEL) of InGaAlAs/InP materials have been designed along with computation of their characteristics [4]. The bandwidth of such structures has been reported ~14.2 GHz that indicated a high speed performance for the application in optical fiber communications. A thoroughly analysis of the SCH designed for 1.5 μm InGaAlAs/InP multi-quantum-well (MQW) lasing heterostructures has been reported [5] and it has been proved that the enhancement rates of the threshold current and the slope efficiency of graded-index SCH (GRIN-SCH) decrease with increasing number of GRIN layers. In a recent research, thermal performance of 1.55 μm InGaAlAs/InP quantum well buried lasing heterostructures has been studied [6]. In this study, Sayid et al. have analyzed the temperature dependence of the threshold current and slope efficiency of 1.55 μm InGaAlAs/InP quantum well buried lasing heterostructures in terms of internal differential quantum efficiency, internal optical losses, radiative and non-radiative currents. They found that the carrier density is pinned in the lasing heterostructure effectively which suggests that the buried heterostructure has effective blocking. They have also confirmed the presence of Auger recombination which dominates under ambient conditions. Moreover, the uncooled InGaAlAs/InP based MQW buried lasing heterostructures have shown great promise for low power-consumption operation data communication links due to their low attenuation property [7]. In addition, InGaAlAs buried lasing heterostructures emitting 1.3 μm wavelength have also exhibited good temperature characteristics for uncooled operations [8].

Since the lasing heterostructures operating at 1.55 μm wavelength are the most important and desired light sources for high speed optical transmission in the optical fiber based communication due to the minimum loss window region of silica-based fiber optics occurring around this wavelength [9], hence conventional InGaAsP/InP based quantum well lasing heterostructures are inefficient because their characteristics have relatively high temperature sensitivity at 1.55 and 1.3 μm wavelengths. Such lasing heterostructures, therefore, require the use of expensive cooling devices to stabilize the temperature for lasing operation [10]. Moreover, due to the larger potential conduction band offset ratio, the InGaAlAs/InP lasing heterostructures have shown very high electron confinement factor, reduced auger recombination and reduced threshold current [7,8,10–12].

In the following sections of the paper, the non-linear optical properties of unstrained and strained InGaAlAs/InP material system based lasing nano-heterostructures under TE (transverse electric) polarization mode have been studied. To study the non-linear optical properties of the structure, the behaviors of envelope functions along with quasi-Fermi levels in the respective bands have been reported. In addition, the anti-guiding factor being responsible for optical gain associated with the structure, the optical gain as a function of lasing wavelength and differential gain have been computed and reported. The simulated results have suggested that either unstrained or compressive strained nano-heterostructures are more suitable for novel applications in the emerging areas of nano-opto-electronics due to minimum optical attenuation.

2. Structural and theoretical detail

In this study, the nano-heterostructure utilized is a step SCH type-I, the most common configuration (straddled type). In this configuration, both conduction and valence bands of the narrow bandgap semiconductor lie completely within the bandgap of the wider bandgap semiconductor i.e. both the electrons and holes are spatially confined within the narrow bandgap material. The structure of the model has a single quantum well (SQW) sandwiched between the barriers followed by the claddings. The overall structure is assumed to be grown on InP substrate. InGaAlAs composition has been utilized as an active region (quantum region). The width of the active region is ~6 nm, while the barriers and claddings are of width ~5 and 10 nm, respectively, thereby creating a nano-heterostructure. The composition of active region is chosen such that its refractive index is higher than that of barriers while the band gap of active region is less than that of barriers. In case of GRIN structure, it is important to note that the refractive indices of the barriers sandwiching the quantum wells (quantum regions) are uniform while the refractive indices of the outer barriers decrease towards cladding gradually.

To evaluate the discrete energy levels within the semi parabolic conduction band, the single band effective mass equation can be used as follows [13]:

$$-\frac{\hbar^2}{2m_c^*}\nabla^2\psi+V_c\psi=E_c\psi \tag{1}$$

where ψ is envelope function, $\hbar$ is reduced Plank's constant divided by 2π, m_c^* is effective mass of electron in conduction band, V_c is potential of conduction band, and E_c is conduction band electron energy level. For a strained quantum well, the conduction band potential is

$$V_c=\begin{cases}\frac{2\delta_h}{3}, \text{Quantum well}\\ \Delta V_{bc}, \text{ Barrier}\\ \Delta V_{cc}, \text{ Cladding}\end{cases} \tag{2}$$

where δ_h is the hydrostatic potential and conduction band offsets of barrier and cladding layers are ΔV_{bc} and ΔV_{cc} respectively.

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