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Tunability of optical gain (SWIR region) in type-II $In_{0.70}Ga_{0.30}As/GaAs_{0.40}Sb_{0.60}$ nano-heterostructure under high pressure

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ABSTRACT

The interest in applying an external pressure on a nano-heterostructure is to attempt to extract more information about the electronic structure through distortion of the electronic structure. This paper reports the tunability of the optical gain under the high pressure effect in M-shaped type-II $In_{0.70}Ga_{0.30}As/GaAs_{0.40}Sb_{0.60}$ symmetric lasing nano-heterostructure designed for SWIR generation. In order to simulate the optical gain, the heterostructure has been modeled with the help of six band k.p method. The 6×6 diagonalized k.p Hamiltonian has been solved to evaluate the valence sub-bands (i.e. light and heavy hole energies); and then optical matrix elements and optical gain within TE (Transverse Electric) mode has been calculated. For the injected carrier density of $5 \times 10^{12}/cm^2$, the optimized optical gain within TE mode is as high as $\sim$9000/cm at the wavelength of $\sim$1.95 μm, thus providing a very important alternative material system for the generation of SWIR wavelength region. The application of very high pressure (2, 5 and 8 GPa) on the structure along [110] direction shows that the gain as well as lasing wavelength both approach to higher values. Thus, the structure can be tuned externally by the application of high pressure within the SWIR region.

1. Introduction

In the last two decades, type-I heterostructures have been studied experimentally and theoretically in detail and these structures have been reported useful in optoelectronic devices such as lasers and LEDs and as well as in optical fiber based communications systems. But, the type-II based heterostructures have been utilized in photovoltaic applications such as photodetectors and solar cells. For example, the type-II heterostructures based core shell QDs (quantum dots) have been shown to have useful applications in solar cells indicating them ideal light-harvesting materials for solar energy conversion [1]. Type-II band alignment structure is coveted in the design of photovoltaic devices and detectors, since it is beneficial for the transport of photo generated carriers [2]. In a recent research, the type-II InAs/GaInSb superlattice structure is a relatively new alternative IR (infra red) material system and has great potential for LWIR (long wavelength infra red) spectral ranges with performance comparable to HgCdTe with the same cutoff wavelength. Moreover, heterostructures with type-II band alignment at source/channel heterointerface represent a steep p–n junction and have been investigated as TFET (tunnel field-effect transistor) performance boosters [3].

Recently, in the area of opto-electronics, type-II heterostructures have been very popular due to many important advantages. One of them is that their optical interband transition occurs at longer wavelengths as compare to those transitions that occur in type-I heterostructures and therefore such structures have been successfully utilized to make laser diodes and photodetectors operating in SWIR, mid-and far-infrared (MIR and FIR) regions [4]. Lasing heterostructures operating in the SWIR and MWIR regions are very desirable for many applications such as in pollution monitoring, molecular spectroscopy and trace-gas analysis.

So far, many researchers have worked theoretically and as well as experimentally to develop high performance optical devices such as lasing heterostructures and photodetectors based on type-I and type-II heterostructures. For example, S.-W. Ryu and P. D. Dapkus have characterized the optical properties of type-II InGaAs/GaAsSb quantum well (QW) heterostructure and observed strong photoluminescence at 1.3 μm at room temperature [5]. Moreover, Chen et al. [6] have designed strain compensated

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InGaAs/GaAsSb type-II quantum well heterostructures for the purpose of MIR detection and applied 4 band k.p theory in order to calculated the transition wavelength and have shown that these structures have the potential for absorption of the 2–4 μm wavelengths. Recently, Alvi et al. [7] have reported that type-I STIN and GRIN InGaAlAs/InP lasing heterostructures have high optical gain at 1.55 μm and 1.34 μm, respectively. In addition, for this structure, G–J characteristics along with the internal strain effects arising due to lattice mismatch have also been studied [8,9]. However, there is still a requirement to design the simple heterostructures for better and high optical gain generation in SWIR region by approaching new band gap engineering. As far as our knowledge is concerned, no one has achieved theoretically and experimentally such high optical gain in the InGaAs/GaAsSb material system based lasing nano-heterostructure.

The purpose of the work presented in this paper is to investigate the behavior of optical gain and corresponding variation in photonic wavelength under variable high pressure applied to the designed InGaAs/GaAsSb quantum well lasing nano-heterostructure and to optimize it for SWIR region. In the following sections of the paper, structure information of type-II InGaAs/GaAsSb heterostructure and theoretical background followed by results are discussed.

2. Structure information and theoretical background

The basic structure under simulation consists of a single $In_{0.70}Ga_{0.30}As$ electron QW (width ~4 nm) that is sandwiched in between two holes barriers (width ~2 nm) of $GaAs_{0.40}Sb_{0.60}$ material system. This picture is very clear from energy band diagram shown in Fig. 1. The entire structure is supposed to be grown pseudomorphically on InP substrate and look like M shape symmetric structure. An important and very interesting feature of InGaAs/GaAsSb type-II quantum well structure, which differentiates it from type-I heterostructure, is that the electrons are most probably confined in the conduction band of QW ($In_{0.70}Ga_{0.30}As$ layer), while holes are confined in the valence band of barriers ($GaAs_{0.40}Sb_{0.60}$). Due to this feature, there will be a smaller effective bandgap and hence longer wavelength emission.

To calculate the wave functions confined with conduction band of InGaAs QW and valence band of GaAsSb barriers, and as well as to model the electron and hole energy levels at Γ-valley, the effective-mass approximation is used. Here, the energy of conduction band electrons is assumed to be parabolic. For strained semiconductor, the six bands Hamiltonian includes the energy levels from light hole (lh), heavy hole (hh), and spin–orbit split-off (so) bands. Taking into account the valence band mixing, and strain effects, the energy of valence subbands (hole energy band) is computed via 6×6 diagonal $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian matrix, as [10];

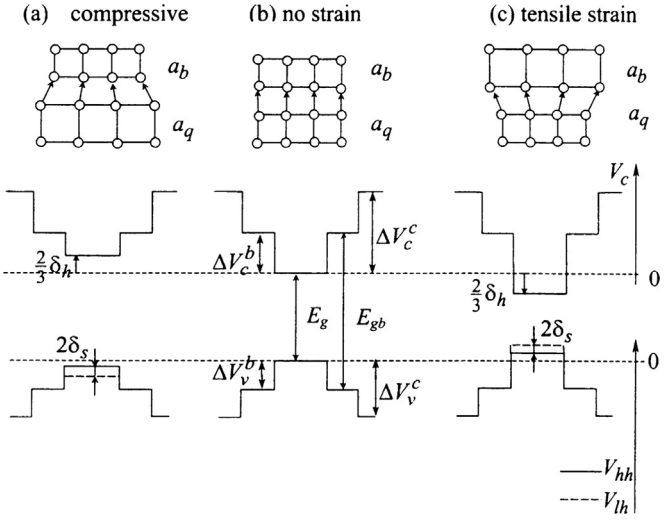

Fig. 1. Effect of strain on conduction and valance bands in quantum well structure.

$$H^{v}_{6\times6}(k) = \begin{pmatrix} H^{U}_{3\times3} & 0 \\ 0 & H^{L}_{3\times3} \end{pmatrix} \tag{1}$$

where $H^{U}_{3\times3}$ and $H^{L}_{3\times3}$ can be expressed as;

$$H^{\sigma}_{3\times3} = -\begin{pmatrix} P+Q-V_h(Z) & R_k \pm iS_k & \sqrt{2}R_K \pm \frac{i}{\sqrt{2}}S_k \\ R_K \pm iS_k & P-Q-V_h(Z) & \sqrt{2}Q \pm i\sqrt{\frac{3}{2}}S_k \\ \sqrt{2}Q \mp i\sqrt{\frac{3}{2}}S_k & \sqrt{2}R_k \pm \frac{i}{\sqrt{2}}S_k & P+\Delta-V_h(Z) \end{pmatrix} \tag{2}$$

And **σ** is equal to U or L.

In the above matrix, Δ(z) is the spin–orbit split-off energy, V_h (z) is the unstrained valance band edge, $P = P_k+P_\varepsilon$, and $Q = Q_k+Q_\varepsilon$.

where

$$P_k = \left(\frac{\hbar^2}{2m}\right)\gamma_1\left(k_t^2 + k_z^2\right), \tag{3}$$

$$P_\varepsilon = -a_v(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}) \tag{4}$$

$$Q_k = \left(\frac{\hbar^2}{2m}\right)\gamma_2\left(k_t^2 - 2k_z^2\right) \tag{5}$$

$$Q_\varepsilon = -\frac{b}{2}\left(\varepsilon_{xx}+\varepsilon_{yy}-2\varepsilon_{zz}\right) \tag{6}$$

$$\text{Nextparameters,}\quad S_k = \left(\frac{\hbar^2}{2m}\right)\sqrt{3}\left(\frac{\gamma_2+\gamma_3}{2}\right)k_t^2 \text{ and } R_k = \left(\frac{\hbar^2}{2m}\right)2\sqrt{3}\gamma_3 K_t K_z \tag{7}$$

where $k_t^2=k_x^2+k_y^2$, ε_{xx}, ε_{yy}, ε_{zz} are normal strain components and γ_1, γ_2 and γ_3 are the Luttinger parameters.

In the above expressions, a_v and b are the Bir-Pikus deformation potentials. The parameters used in the calculations such as the conduction and valence band offsets, elastic constants and energy band gaps, are taken from theoretical and experimental data given in the references [11,12].

The simulation of optical gain existing in the quantum well heterostructure is derived with the help of Fermi's golden rule as [10]:

$$G(\hbar\omega) = \frac{\pi e^2}{nc\epsilon\omega Lm^2}\sum_{\eta=\uparrow,\downarrow}\sum_{\sigma=U,L}\sum_{n,m}\int\left|\left(\hat{e}.M^{\eta\sigma}_{nm}(k_t)\right)\right|^2 \times \frac{\left(f_n^c(k_t)-f_{\sigma m}^v(k_t)\right)\left(\frac{\gamma}{\pi}\right)}{\left(E^{c,v}_{\eta,\sigma nm}(k_t)-\omega\hbar\right)^2+\gamma^2}\frac{k_t dk_t}{2\pi} \tag{8}$$

where

$$f_n^c(k_t) = \frac{1}{1+\exp\left(\frac{E_n^c(k_t)-F_c}{K_BT}\right)} \tag{9}$$