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Optimization of high optical gain in type-II $In_{0.70}Ga_{0.30}As$/$GaAs_{0.40}Sb_{0.60}$ lasing nano-heterostructure for SWIR applications

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ABSTRACT

Most of the nano-heterostructures exhibiting lasing action in NIR (near infra-red) region that have been modeled and simulated are based on type-I category. The nano-scaled lasing heterostructures, however, of type-II category operating in SWIR (short wave infra-red) region have not been well studied. In this paper, for SWIR generation, an M-shaped type-II $In_{0.70}Ga_{0.30}As/GaAs_{0.40}Sb_{0.60}$ symmetric lasing nano-heterostructure has been designed. In order to simulate the optical gain, firstly the wave functions associated with conduction and valence sub-bands, carrier densities within the bands, energy band dispersion relations for the quantum well structure, optical matrix elements and finally optical gain have been studied by utilizing the six band **k.p** method. For the injected carrier concentration of $5 \times 10^{12}/cm^2$, the optimized optical gain within TE mode is as high as ~9000/cm at the wavelength of ~1.95 μm, thus providing a very important alternative material system for the generation of SWIR wavelength region.

1. Introduction

In the area of opto-electronics, type-II heterostructures have been very popular showing 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-infra-red (MIR and FIR) regions [1]. 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.

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 [2]. Moreover, B. Chen et al. [3] have designed strain compensated 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

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absorption of the 2–4 μm wavelengths. Recently, P. A. Alvi et al. [4] 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 [5,6]. However, there is still a requirement to design the simple heterostructures for better and high optical gain generation in SWIR region by approaching a 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 main goal of the work presented in this paper is to determine the important parameters in the designing of InGaAs/GaAsSb quantum well lasing nano-heterostructure and how to optimize them 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 (thickness ~ 4 nm) that is sandwiched in between two holes barriers (thickness ~ 2 nm) of $GaAs_{0.40}Sb_{0.60}$ material system. When the thickness of the active region becomes comparable to the de Broglie wavelength, quantum mechanical effects are expected to occur. These effects can be observed in the absorption and emission characteristics of the lasing heterostructures. 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 **k·p** Hamiltonian matrix, as [7];

$$H^{\nu}_{6\times 6}\text{ग}(k) = \begin{pmatrix} H^{U}_{3\times 3} & 0 \\ 0 & H^{L}_{3\times 3} \end{pmatrix}\text{ग} \tag{1}$$

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

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

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

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

$$P_\varepsilon = -a_\nu\left(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}\right) \tag{4}$$

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

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