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$In_xGa_{1-x}As_yP_{1-y}$–$In_zGa_{1-z}As$ optical transistor

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ABSTRACT

In this paper, we proposed, modeled and evaluated by numerical simulation of an InGaAsP–InGaAs optical transistor operating at optical communication wavelength of 1.55 μm. We numerically simulated the proposed structure and investigated the transient and steady-state characteristics by calculating the required microscopic parameters and solving the rate equations within the charge control model. The frequency response and bandwidth modulation of the proposed device are also calculated.

1. Introduction

The optical transistor (OT) is promising candidates for future optical computing schemes. They can provide ultrafast optical as well as electrical signals with high bandwidth and power. Transistor lasers (TL) first introduced by Holonyak and Feng in [1,2]. The TL or Heterojunction Bipolar junction transistor laser (HBTL) is fabricated by embedding a quantum-well (QW) in the base of a heterojunction bipolar junction transistor (HBT) that acts as an optical collector. The TL which operates as a transistor and a laser at the same time provides both a high impedance output with current gain at the base–collector junction and laser emission from stimulated base electron–hole recombination. It provides us with both optical and electrical gains simultaneously. Optical gain occurs when injected current into the base is sufficient to create population inversion. By making the opposite ends of the recombination region as reflective and creating a resonant cavity, we have a laser beam from recombination of carriers followed by population inversion. A schematic design of the transistor laser structure is shown in Fig. 1. Carrier dynamics in the TL is different from both conventional HBTs and laser diodes (LDs) and due to its unique carrier dynamics; the TL has the potential of high-speed direct modulation [2]. Semiconductor laser emitting at 1.55 μm is of interest for optical interconnections and long-distance optical fiber communications. TLs are one of the key components of a wide range of future photonic processors and light wave communication systems and their operation at optical communication wavelength is a subject of interest. To design such systems, it is necessary to predict and analyze the dynamic behaviors of the laser devices under specific operating conditions. For this purpose, computer-aided simulation techniques based on behavioral models of the TLs have been developed [2–6].

2. Mathematical modeling

In this section, we describe the theoretical framework we used in simulating the characteristics of the TL. To investigate the carrier dynamics in the Transistor lasers, we used a set of rate equations and a charge control model of the base charge in our numerical simulations [3]. Fig. 2 shows a schematic of the different processes in the base region of the TL under active bias conditions (B–E junction forward biased, B–C junction reverse biased).

The rate equations for the carrier density in the quantum well (n), the Base charge density ($Q_{b(t)}$) and the photon density in the optical cavity (N_p) can be written as,

$$\frac{dn(t)}{dt} = \frac{\nu Q_b}{\tau_{\text{cap}}} - \frac{n(t)}{\tau_{qw}} - \Omega(n(t) - n_{\text{nom}})N_p(t) \tag{1}$$

$$\frac{dN_p(t)}{dt} = \Omega(n(t) - n_{\text{nom}})N_p(t) - \frac{\theta N(t)}{\tau_{qw}} - \frac{N_p(t)}{\tau_p} \tag{2}$$

$$\frac{dQ_b}{dt} = \frac{J(t)}{q} - \frac{Q_b}{\tau_{rb}} \tag{3}$$

$$\frac{1}{\tau_{rb}} = \frac{1-\nu}{\tau_{rb0}} + \frac{\nu}{\tau_{\text{cap}}} \tag{4}$$

In the above mentioned coupled rate equations ν is a QW geometry factor that gives the fraction of the base charge captured in the QW, τ_{cap} is the electron capture time in the QW and τ_{qw} is the lifetime via spontaneous emission in the QW. We note that captured electrons recombine with holes in the QW region with an effective lifetime τ_{qw}^{eff} which varies significantly

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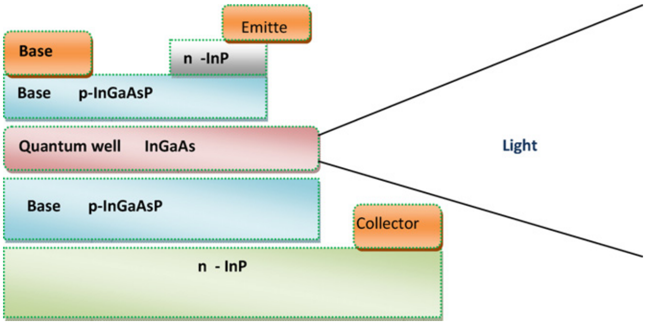

Fig. 1. Schematic design of the transistor laser we used for simulation.

depending on the base current being below or above the threshold value. When the base current is below the threshold, we have $\tau_{qw} = \tau_{qw}^{\text{eff}}$ and when it is above the threshold $\tau_{qw}^{\text{eff}} = (1/\tau_{qw} + 1/\tau_{sp})^{-1}$ where $\tau_{sp} = [\Omega N_p(t)]^{-1}$ represents the lifetime of the stimulated emission. Photon lifetime is determined by τ_p, where τ_{rb} and τ_{rb0} is base charge lifetime and base charge bulk lifetime respectively. Ω is differential gain factor and we assumed it varies as $g_0(1/1 + \in N_p(t))$, n_{nom} is transparency electron density, θ represents the fraction of spontaneous emission that is coupled to the cavity mode and J denotes the base current density. The first two equations describe electron–photon interaction in the QW region, Eq. (3) is the rate equation for the base charge and Eq. (4) gives the base charge loss rate by considering the recombination outside the QW and the QW capture process. First step in modeling the TL by solving the rate equations is to obtain needed microscopic parameters mentioned above such as spontaneous emission lifetime in the QW. Since these microscopic parameters in semiconductor nanostructures depend on the energy levels and related wave functions, we need to solve the Schrödinger equation numerically. Using the effective mass approximation, the Schrödinger equation can be written as:

$$\frac{-\hbar^2}{2}\frac{\partial}{\partial x}\left(\frac{1}{m(x)}\frac{\partial \psi}{\partial x}\right) + V(x)\psi = E\psi,$$

where $m(x)$ is the position-dependent effective mass of electrons, $V(x)$ is the electrostatic potential, ψ is the electron wave function and E is the electron energy. In this paper the Schrödinger equation has been solved by finite-difference method. We assume the QW is a two-level system and the carriers occupy single discrete levels in the bands. After calculating energy levels and wave functions, the rate of spontaneous emission can be calculated by Fermi's golden rule. The considered TL for simulation is a InGaAsP–InGaAs TL (Fig. 1) with 10 nm-thick $In_{0.53}Ga_{0.47}As$ QW. The base is 100 nm-thick $In_{0.81}Ga_{0.19}As_{0.41}P_{0.59}$ and the collector and emitter are InP. In this structure lasing occurs between the two energy levels of the QW at optical communication wavelength of 1.55 μm.

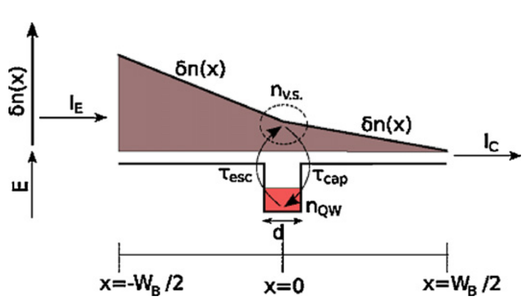

Fig. 2. Schematic band diagram of the transistor laser [4].

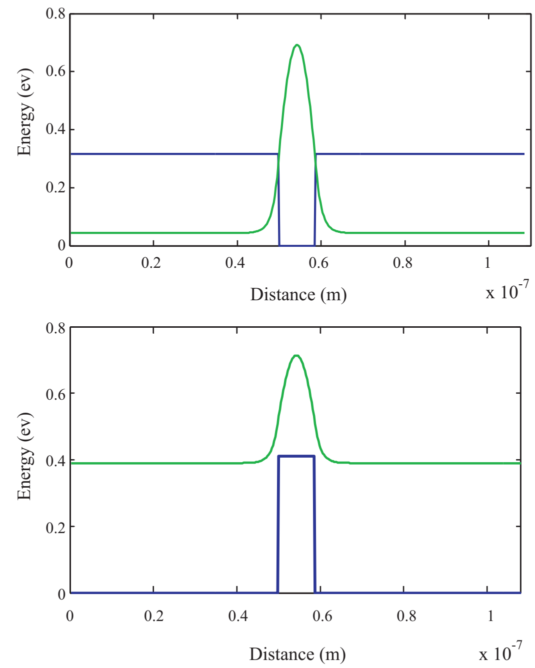

Fig. 3. Wave functions for the first valence and conduction bands energy levels of the 10 nm InGaAs well.

3. Simulation results

Solving the Schrödinger equation for the QW region gives us the energy levels and corresponding wave functions (Fig. 3) (Figs. 4–6).

Using these wave functions, spontaneous emission lifetime τ_{qw} is calculated.

3.1. DC analysis

By setting all time derivatives in the rate Eqs. (1)–(3) equal to zero, we obtain the steady-state solution of the electron and photon densities. Since one important parameter for semiconductor laser devices is lasing threshold current density, we investigate the behavior of this parameter in terms of electron capture time and spontaneous emission lifetime in the QW. As figure shows an increase in spontaneous emission lifetime reveals a decrease in threshold base current density, also increase in electron capture time reveals the same behavior. The obtained results are in good agreement with the experimental data available.

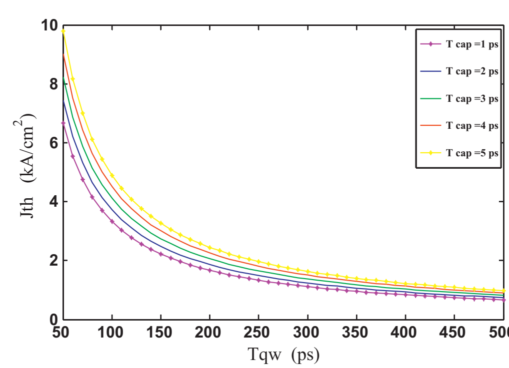

Fig. 4. Lasing threshold current density vs. spontaneous emission lifetime and electron capture time.