Investigation of InGaAsN for laser diode application

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Abstract. The knowledge of influence of nitrogen on optical transition energies in InGaAsN Quantum Wells (QWs) or Quantum Dots (QDs) structures is very important due to the possibility of adjustment of the optical transition energies to the telecommunication wavelength range when the system GaAsN is submitted to further indium elements giving rise to the quaternary alloys (In)GaAsN. We add a computational method in quantum mechanics to study the Schrödinger equation for one and many quantum wells configurations. The photoluminescence PL measurement obtained by simulated technique is used to predict the different lines and energy levels of our compound. The simulated results are followed by solving the coupled nonlinear rate equations describing the complex electric field and the carrier density in a simple model of the GaNₓAs₁₋ₓ or (In)GaAsN semiconductor laser.

1. Introduction

GaInNAs constitute actually a novel material system proposed and developed nowadays because of their physical properties and potential device especially in fiber devices applications. High performance and cheaper long wavelength (1300–1550 nm) emitting diode lasers with InGaAsN active region are essential components for optical fiber communication systems. Theoretical considerations and results on the effect of nitrogen incorporation on the oscillator strength of optical transitions in InGaNAs/GaAs quantum wells (QWs) are presented. The fundamental transition energy and its oscillator strength considering Quantum Wells configuration have been systematically investigated. Furthermore, the effect of the bandgap discontinuities and its variation with the concentration of nitrogen on the transitions intensity recorded in the Photoluminescence spectra has also been considered. Such structures are now realized and are emitting in the telecommunication wavelength range [1].

2. Theoretical model

The calculations of the related energy states in the QW region are obtained by solving the stationary Schrödinger equation assuming parabolic dispersion curves for the particles. The band gap is given by the band anticrossing (BAC) model which includes the influence of nitrogen and Indium on the band structure and estimates the effective band gap reduction [2]. The Schrödinger equation has a significant role in calculation of the parameters such as gain, effective barrier (SCH) height, energy levels of electron and hole in the well and consequently output wavelength which are directly or indirectly used in the rate equations.

\[
\left[-\frac{\hbar^2}{2m} \frac{d^2}{dz^2} + V(z)\right] \psi(z) = E \psi(z)
\]  

(1)
Where $\psi(z)$ is wave function of each particle (electron, light hole and heavy hole) in the well, $E$ is energy level of particle, $L_{QW}$ is well thickness and $V(z)$ is barrier height that is corresponding to $\Delta E_c$ for conduction band and $\Delta E_v$ for valence band. In addition, $m$ is particle mass that equals $m_w$ in the well and $m_b$ in the barrier regions. By assuming even solutions as the results, the wave functions are as following:

$$
\psi(z) = \begin{cases} 
u_0 & |z| = L_{QW}/2 \\ 0 & |z| < L_{QW}/2 \end{cases}
$$

$$
V(z) = \begin{cases} \nu_0 & |z| = L_{QW}/2 \\ 0 & |z| < L_{QW}/2 \end{cases}
$$

$$
\psi(z) = \begin{cases} A e^{-\alpha (|z| - L/2)} & |z| = L_{QW}/2 \\ B \cos kz & |z| < L_{QW}/2 \end{cases}
$$

$$
\kappa = \sqrt{2m_wE/\hbar} \text{ and } \alpha = \sqrt{2m_b(\nu_0 - E)/\hbar}
$$

The numerical solution of the Schrödinger equation for the configuration of one two and more quantum wells structures is given on figure 2.

**Figure 2a.** Shroedinger equation solution for one quantum well structure with fixed reflected and transmitted coefficients

**Figure 2b.** Shroedinger equation solution for two quantum wells structure with fixed reflected and transmitted coefficients

**Figure 2c.** Shroedinger equation solution for two quantum wells structures with fixed energy at 1.14 eV

**Figure 2d.** Shroedinger equation solution for five quantum wells structure with fixed energy at 1.08eV

The photoluminescence peak due to band-to-band transitions can be calculated for each band gap $E_g$ using the following formula:
We plot different curves corresponding to each concentration of nitrogen as follow:

$$I_{bb} = I_0 (\hbar \omega)^2 \left( \hbar \omega - E_g \right) \exp \left( - \frac{\hbar \omega - E_g}{K_b T} \right)^2$$

We plot different curves corresponding to each concentration of nitrogen as follow:

**Figure 3a.** Photoluminescence peak variation with nitrogen concentration (simulated curves)

**Figure 3b.** Photoluminescence peak variation with nitrogen concentration (experimental curves)

Fig.3a shows that the photoluminescence intensity diminishes and the bandwidth of the curves increases when the nitrogen concentration increases. Fig.3b is the similar curves variation with the nitrogen concentration obtained by experimental measurement [3,4].

3. Simulation of the diode laser InGaAsN.

The optical power emitted by the diode laser is proportional to the current supplied to the InGaAsN semiconductor heterojunction. The output of the solver is the time, injection current, and the transformed components of the state vector, computed at discrete time steps. The rate equations are integrated using the fourth order Runge-Kutta computation[9]. The laser dynamics can be modeled by coupled rate equations which describe the relation between the carrier number \(N_p(t)\), the photon density \(S_p(t)\) and the optical phase \(\varphi(t)\) [1-6].

\[
\frac{dN_p(t)}{dt} = \frac{I(t)}{q} - \frac{N_p(t)}{\tau_n} - g(N,T) \frac{N_p(t)-N_0}{1+\varepsilon S_p(t)} S_p(t) + \frac{\beta N_p(t)}{\tau_n} \quad (5)
\]

\[
\frac{dS_p(t)}{dt} = \Gamma g(N,T) \frac{N_p(t)-N_0}{1+\varepsilon S_p(t)} S_p(t) - \frac{S_p(t)}{\tau_n} + \Gamma \frac{\beta N_p(t)}{\tau_n} \quad (6)
\]

\[
\frac{d\varphi(t)}{dt} = \frac{\alpha_0}{2} g(N,T) \left[ N_p(t) - N_0 \right] \quad (7)
\]

\(N_0\) is the carrier number at transparency, \(\tau_p\) is the photon lifetime, \(\tau_n\) is the carrier lifetime, \(\Gamma\) is the optical confinement factor describing the confinement mode in the active region, \(\beta\) is the spontaneous emission factor, \(\varepsilon\) is the gain compression factor, \(g(N,T)\) is the optical gain coefficient dependent on the carrier density and the temperature function, \(I(t)\) is the injected current, \(\alpha_0\) is the linewidth enhancement factor and \(q\) is the electron charge, \(g\) is the quantum efficiency, \(h\) the Planck constant and \(\nu\) the radiation frequency. The steady-state solution to the rate equations is obtained by setting all the time derivatives to zero. The carrier concentration that satisfies a given steady-state injected current is obtained by iterative self-consistent solutions of the two coupled equations. The output power the threshold current and the carriers density are given respectively by the following expressions [1, 10-13].

\[P(t) = \frac{nh \nu}{q} (I - I_{th}) \quad (8)\]
\[ I_{th} = \frac{q}{\tau_n} \left( N_0 + \frac{1}{\rho_0 \tau_p} \right) \tag{9} \]
\[ N = \frac{I(t) \tau_n S_p}{q V \tau_p} \frac{1}{\beta - 1} \tag{10} \]

Figure 4a. Output laser power as function of the bias current at room temperature

Figure 4b. Laser threshold current temperature dependence (a) 20°C; (b) 40°C and (c) 60°C

4. Numerical Simulation and Results.

Fig. 5a records the variation of carrier and the photons generated by the injected current. Fig. 5b gives a single photon signal following the driver electrical signal when fig. 5c is a modulated optical signal used in telecommunication. We record in Fig. 5d the frequency signal modulation of the laser power centered on the wavelength \( \lambda = 1550 \) nm. In practice, optical modulation is a way to minimize the effects of electrical parasitics. Within the model, this is equivalent to adding an optical perturbation to the optical signal generated by the carriers.

Figure 5a. Transient dynamics of carrier density (a) and photon number (b)

Figure 5b. Transient dynamics of carrier density and photon number for a deterministic single mode
The damping due to the injected current variation is simulated and recorded in fig.5c, the latter being significantly influenced by parasitics and adiabatic phenomenon. Hence as cited above, the introduction of weak amount of nitrogen in InGaAs compound allows great flexibility in terms of band gap energy and stress state [1, 14].

5. Conclusion
Our material system InGaNxAs1-x was in its configuration as quantum wells. The numerical solution of the Schrödinger equation enables us to show the oscillation of the carriers in one, two and many quantum wells as well. Considering InGaNxAs1-x as active region of a diode laser, we determine the photoluminescence spectrum which shifts towards the red color when the nitrogen concentration increases. An efficiency computational program has been used to study the modulation response of laser diode emitting in different wavelengths following the concentration of the Nitrogen. The simulation program developed can be used to illustrate the performance of a waveguide laser diode as function of device parameters for all semiconductors electrically pumped laser diode. Adding of weak amount of nitrogen in InGaAs compound allows great flexibility in terms of band gap energy, appropriated wavelengths for telecommunication systems and stress state visibility.

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