Nitrogen Effect on the Frequency Shift in Indium-GaAsN Quantum Wells Laser

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Abstract. The GaAsN/GaAs material system has recently been investigated as material for the realization of high-performance laser diodes emitting at the optical fiber window. Nitrogen content in GaAsN has a great influence on the band gap in this semiconductor. The knowledge of influence of nitrogen on optical transition energies in GaAsN/GaAs 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. The purpose of this work is to solve the coupled nonlinear rate equations describing the complex electric field and the carrier density in a simple model of the GaN$_x$As$_{1-x}$ or (In)GaAsN semiconductor laser. The model is sufficient to account for many of the observed dynamics in a single mode semiconductor laser in response to a dynamic drive current, such as relaxation oscillations and frequency chirping.

1. Introduction

A semiconductor laser consists of an active region sandwiched between a p-n junctions made of a direct band gap material, the n-side contains an excess of electrons, while the p-side contains an excess of holes. Through this junction there is formed a potential barrier which prevents recombination between electrons and holes. Direct polarization of the junction reduces the barrier and facilitates the recombination of the carriers. If the forward bias is large, there is a population inversion which relates the gain required for lasing [1-3]. The interaction between the active region and the laser light is maximized by the use of a double heterostructure constituted by a combination of materials with different band gaps. This structure ensures the confinement of photons and charge carriers due to differences in refractive index and forbidden band widths, respectively. A low concentration of nitrogen in binary GaAs lattice generates a dramatic effect on electronic structure and optical properties of this compound. By replacing weak amounts (1%) of arsenic by nitrogen gives a ternary compound GaNAs and lead to reduce the band gap that reaches about 0.2 eV. GaN$_x$As$_{1-x}$, with “x” represented the proportion of nitrogen replacing the As element, is a very interest compound used as active region of semiconductor diode laser giving rise to a wavelengths laser between 1330 nm and 1555 nm which correspond to the optical fiber window very useful for optical telecommunications. [4-7]. The optical power emitted by the diode laser is proportional to the...
current supplied to the GaN_{x}As_{1-x} semiconductor heterojunction. The laser dynamics can be modeled by coupled rate equations which describe the relation between the carrier number, the photon density and the optical phase [4]. The purpose of this work is to solve the coupled nonlinear rate equations describing the complex electric field and the carrier density in a simple model of the GaN_{x}As_{1-x} semiconductor laser. The model is sufficient to account for many of the observed dynamic such as relaxation oscillations and frequency chirping [8, 9].

2. Experimental

Trimethyl gallium arsine AsH_3 and dimethylhydrazine (DMHy) were used to grow GaNAs of thickness 0.2μm on GaAs substrates. The vector gas N_2+H_2 with the ratio of 80-20% respectively. The compound surface GaNAs are characterized by AES and EELS using a hemispherical analyzer operating in direct mode N (E). Owing to the Auger Electron Spectroscopy; we give some results related to the effect of the temperature on GaAsN heated during its preparation process. The Auger signals N-KLL has been recorded as shown on fig. 1. Through the intensity of both peaks, we note that GaAsN heated at 730°C involves less nitrogen in comparison to GaAsN no heated. Hence, we conclude that the composition of nitrogen decreases as function of the temperature. This might be due to desorption of excess nitrogen from the GaAsN surface [10]. This heating process leads to give the GaAsN/GaAs stable. Such an aspect is confirmed by the Electron Energy Loss Spectroscopy (EELS) during the irradiation process by the electron beam as shown on fig.2. Fig.3a illustrate the variation of the energy band of a quantum well based (In) GaAsN showing the geant optical mode in the InGaAsN semiconductor laser cavity.

The analyzis of our samples by spectroscopic techniques such as AES and EELS aims to the realization of quantum wells. These samples will be then charactirized by photoluminescence PL to determine the emission wavelength and energy levels. Each quantum well is in itself a laser diode as shown in fig.3b. Waiting to perform this experiment by designing quantum wells and the realisation of ohmic contact we began first with a simulated study. The experimental investigation of QWs laser diodes will be published after.

3. Simulation of the diode laser GaNAs.

3.1 Band gap variation

The band gap of the relaxed unstrained alloy is known as:

\[ E_g(In_xGa_{1-x}N) = x E_g(InN) + (1-x) E_g(GaN) - bx(1-x) \]  

Where x is the proportion of Nitrogen injected into the alloy (In)GaAsN which compensate the (1-x) of arsenium of (In)GaAsN alloy, Eg is the energy band gap and “b” is the bowing parameter. Low Nitrogen content demonstrate large band gap bowing with only few % Nitrogen. Typical bowing coefficient for semiconductor alloys are on order of 0.1 eV and are fairly sensitive to the composition. However, bowing coefficients for GaAsN and (In)GaAsN alloys is considerably augmented, reached the values of 10eV and vary strongly with composition. Whence the band gap reduction is possible with 1% Nitrogen content or less as shown in Fig.4a. Fig.4b is related to the (In)GaAsN refractive index as function of the wavelengths and the composition x of indium. The best applications for these III-V materials are the lasers with wavelength in the 1.33 to 1.55 range that match with optic fiber windows.
**Figure 1**: AES N-KLL spectra of GaAsN compound before and after heating.

**Figure 2**: EELS spectra of GaNAs heating at 730°C for different exposure time.

**Figure 3a**: Current injection creating circulation of electrons and holes and generating inversion population giving rise to an optical laser mode.

**Figure 3b**: Diode laser conception showing the active region, the P-InGaAsN, the N-InGaAsN and the two cavity mirrors.

**Figure 4a**: Simulated variation of GaAsN with the nitrogen concentration.

**Figure 4b**: (In)GaAsN refractive index as a function of the wavelengths.
The optical power emitted by the diode laser is proportional to the current supplied to the GaNAs semiconductor heterojunction. The laser dynamics can be modeled by coupled rate equations which describe the relation between the carrier number, the photon density and the optical phase [14]. To use these models, values for the rate equations, parameters must be chosen appropriately in order to obtain agreement between simulated and measured results for system performance [1].

The purpose of this work is to solve the coupled nonlinear rate equations describing the complex electric field and the carrier density in a simple model of the semiconductor laser. The model is sufficient to account for many of the observed dynamics in a single mode semiconductor laser in response to a dynamic drive current, such as relaxation oscillations and frequency chirping [1, 15]. 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 [1, 16].

### 3.2 Rate equations: steady state

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 \( \phi(t) \). [1-6]

\[
\frac{dN_p(t)}{dt} = \frac{l(t)}{q} - \frac{N_p(t)}{\tau_n} - g(N,T) \frac{N_p(t) - N_0}{1 + \epsilon S_p(t)} S_p(t)
\]

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

\[
\frac{d\phi(t)}{dt} = \frac{\alpha_o}{2} g(N,T) [N_p(t) - N_0]
\]

\( N_0 \) 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, \( \epsilon \) 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, \( \alpha_o \) is the linewidth enhancement factor and \( q \) is the electron charge. The output power and the threshold current are given by: [1]. Where \( \eta \) is the quantum efficiency, \( h \) is the Planck constant and \( \nu \) is the radiation frequency.
The steady-state solution to the rate equations is to be obtained by setting all the time derivatives \( \frac{dN_p(t)}{dt} \) and \( \frac{dS_p(t)}{dt} \) 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. Hence, the couple rate equations (1) and (2) will be written as follow:

\[
\frac{I(t)}{q} - \frac{N_p(t)}{\tau_n}\frac{N_p(t) - N_0}{1 + \alpha S_p(t)} S_p(t) = 0
\]

\[
\Gamma g(N, T)\frac{N_p(t) - N_0}{1 + \alpha S_p(t)} S_p(t) - \frac{S_p(t)}{\tau_p} + i\frac{\beta N_p(t)}{\tau_n} = 0
\]

The carrier number \( N \) will be deduced as follow:

\[
N = \frac{\frac{l(t)}{q} - \frac{s_p(t)\tau_n}{\tau_p}}{\beta - 1}
\]

4. Photon density \( S(f) \) and Frequency Response of the Semiconductor Laser.

For laser with small signal, the expression of the photon density \( S(f) \) and transfer function \( R(f) \) above threshold are as follow \([1, 15]\).

\[
R(f) = \frac{S_p(0)}{I(0)} = \frac{f_0^2}{f_0^2 - f^2 + i\Delta f d}
\]

\[
f_0 = \frac{1}{2\pi} \sqrt{\frac{gQ}{\tau_p} (1 - I_{th})}
\]

\[
f_d = \frac{\varepsilon g(1 - I_{th})}{2\pi \tau_p}
\]

\[
f_p = \sqrt{f_0^2 - \frac{f_d^2}{4}}
\]

Where \( R(f), f_0, f_d, \) and \( f_p \) are respectively the frequency response, the main frequency, the damping frequency and the frequency of peak response.
5. Numerical Simulation and Results.

5.1 Steady state solution

A desired modulated laser signal can be generated by direct injection of the laser diode by an electric signal. The carrier number \( N_p(t) \), the photon density or optical signal \( S_p(t) \) will carry the same information as the modulating electric signal \( I(t) \) does. Therefore, in the absence of current modulation, the laser diode emits a constant-power monochromatic light. The current modulation induces a variation of the power and frequency of the beam.

The deriving current of a modulated laser diode is the sum of two terms. [16]. Where is a time function format which describe the signal current. The first term represents the bias current, \( I_b \), which sets a value above the threshold level of the laser while the second term, which determines the modulation level, is noted \( I_m \). Both currents are adjusted to achieve the desired variable power.

In fig.5I and fig.5II we can see the simulated \( I(t) \) and the laser signal for different wavelength known in optical telecommunication using optical fiber. It becomes clear that the optical signal can carry the same information as the modulating electric signal does.

Fig.6a and fig.6b highlight the contribution of nitrogen on the displacement of the laser wavelength towards the red and shows a bandwidth narrower and more damped when the wavelength increases. Hence as cited above, the introduction of weak amount of nitrogen in GaAs compound allows great flexibility in terms of band gap energy and stress state. [19-25]

5.2. Amplitude modulation and frequency response

To obtain transient solutions to the rate equations we have to solve numerically the rate equations to obtain the optical power and the phase of the electrical field at the laser output. For this, we use a fourth-order Runge-Kutta algorithm; we proceed first by a number of simplifying assumptions such as:

1. The photon and electron distributions are spatially uniform
2. The refraction index is spatially uniform and the effect of its variations with time is neglected,
3. The optical confinement factor and the spontaneous emission factor are treated as constant. [1,12].

It will be possible to obtain very short optical pulses, suitable for high-speed light wave telecommunication systems, from a quasi-rectangular modulation current as shown in fig.7. 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 optical signal generated by the carriers. The frequency response of the semiconductor laser with the frequency response of the mount fixture is plotted on fig.8. We note that the bandwidth is mainly controlled by the resonance frequency. The damping due to the injected current variation is simulated and recorded, the latter being significantly influenced by parasitics and adiabatic phenomenon. We note also that the bandwidth increases when the bias current increases [1, 18].
Figure 6a: (In)GaNAs where nitrogen atom lead to a spectrum centered on $\lambda = 9000$ nm, $\Delta \lambda = 5$ nm.

Figure 6b: $\lambda = 1560$ nm with a bandwidth $\Delta \lambda = 1$ nm with less than 1% of Indium.

Figure 5.1: modulated laser derived by the current source $I(t) = 40$ mA for two wavelength $\lambda = 0.8898$ $\mu$m and $\lambda = 0.9000$ $\mu$m corresponding to InGaAs compound.

Figure 5.1I: modulated laser derived by the current source $I(t) = 30$ mA for two wavelength $\lambda = 1.3265$ $\mu$m (GaNAs) and $\lambda = 1.5540$ $\mu$m (InGaNAs).
Figure 7: Transient dynamics of carrier density and photon number for high-speed light wave telecommunication system

Figure 8: Variation of the frequency response intensity and the bandwidth with the bias current $I_b$: a) $I_b=30\mu\text{A}$; (b) $I_b=40\mu\text{A}$, (c) $I_b=50\mu\text{A}$, (d) $I_b=60\mu\text{A}$
6. Conclusion

We have studied the material GaN$_{x}$As$_{1-x}$ with sensitive spectroscopic methods as AES and EELS. We considered it as active region of a diode laser. The quantum well structure giving rise to diode lasers has been studied by varying the concentration in Nitrogen and by modulating the response of laser diode which emission is being possible 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 GaAs compound allows great flexibility in terms of band gap energy, appropriated wavelengths for telecommunication systems and stress state visibility.

7. References
[1] A.Ouerdane, M.Bouslama, A. Abdellaoui, M.Ghaffour and Y. Al Douri 2013 Journal of Physics: Conference Series 435 012028
[2] J. lloyd Hughes, E. Castro-Camus, M.B. Johnston 2005 Solid State Communication 136.595-600
[3] Virginie Moreau 2009 Thèse de Doctorat Ecole Doctorale Sciences et Technologie de l’Information des Télécommunications et des Systèmes Université Paris-Sud11 Orsay France
[4] M.Geddo, M.Patrini, G.Guizzetti,M.Galli, R.Trotta, A.Polimeni, M.Capizzi,F.Martelli, and S.Rubini 2011 Journal of Applied Physics 109 123511
[5] Narjis Begum 2010 PhD CIIT/SP05_PPH-005/ISB COMSATS Institute of Information Technology Pakistan
[6] F. Maskuriy, M. S. Alias, S.M. Manaf 2011 Journal of Applied Optoelectronics and Advanced Materials 13 1213
[7] Arkadiusz Mika et al. 2013 Optica Applicata, XLIII, 1 53-60
[8] Ya Yan Lu Numerical Method For Differential equations Department of Mathemetic City University of Hon Gong , site: http://math.cityu.edu.hk/~mayylu/ma3514/3514.pdf
[9] S.Habermann, J.Hofeldt,R.Screiner,D.Schmitz,M.Heuken CS Mantech 2012 growth of InGaAs Conference April 23th-26th Boston Massachusetts USA
[10] A.Ouerdane, M.Bouslama, A. Abdellaoui, M.Ghaffour Y. Al-Douri, Study of InGaAsN/GaAs material for optoelectronic applications First International Conference on Innovative Materials and Techniques CIMT November 12-15,2012 Hammamet (Tunisia)
[11] A.Nouri, Z.Lounis, A.Ouerdane, M.Ghaffour, M.Bouadi, H.Dumont, L. Auvray, M.Bouslama 2007 The behaviour of ternary compounds InGaAs and GaAsN subjected to electron irradiation, Vacuum 81 979
[12] H. Baaziz , Z. Charifi , Ali Hussain Reshak , B. Hamad ,Y. Al-Douri 2012 Appl Phys A 106 687
[13] Babar Bachir, 2009 Electronics/Telecommunications University of Gävle Supelec 592 35
[14] R.A. Abdullah, K. Ibrahim 2010 Optoelectronics and Advanced Materials–Rapid Com. 4 568
[15] Jeffrey O. White et al. 2011 ARL-TN 1 0451
[16] Safwat W.Z. Mahmoud 2007 Egypt Journal Solids 30 277
[17] M. Aleshams 2009 Progress In Electromagnetic Research 8121
[18] H.K. Liang, S. F. Yu and H.Y. Yang 2010 Applied Physics letters 97 241107
[19] Vitezslav Jerabek, Ivan Huttel 2011 Radioengineering 20 486
[20] Krishna Myneni 2011 Semiconductor Laser Rate Equation Solver 44 1-37
[21] T. homas Erneux, Evgeny A.Viktorix and Paul Mandal 2007 Physical Review A76 0238
[22] Ovidio H. Anton, Dinesh Patle Carmen S. Menoni, Jeng-Ya Ych, T.T. Van Roy, L.J. Mawst, J.M.Pikal and Nelson Tansu 2005 Quantum Electronic 11 1079
[23] Sheng Chu, Guoping Wang , Weihang Zhou, Yuqing Kong, Lin Li, Jingjian Ren and Jianlin Liu 2011 Nature Technology 6 506
[24] H. A. McKay and R. M. Feenstra 2001, Journal Sci. B19 1644