Doping Effect on Quantum Dot Laser Dynamics

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Abstract: **In this paper, we study the effect of the doping processes on the wetting in quantum dot laser that it appeared on the concentrations of carriers of electrons (e) and holes (h) which lead to effect on the output power of quantum dot laser also this study was included the variation of time behaviors for the carriers in quantum dot laser at different values of current densities at fixed value of n- or p- doping in the wetting layer. The switch-on time is affected by the laser output by doped semiconductor QD laser.**

Keywords: Quantum dot laser, Doping, Laser dynamics.

1. INTRODUCTION

During the past decades, the performance of semiconductor lasers has been dramatically improved from a laboratory curiosity to a broadly used light source [1]. Owing to their small size and low costs, they can be found in many commercial applications ranging from their use in DVD players to optical communication networks. The rapid progress in epitaxial growth techniques allows to design complex semiconductor laser devices with nanostructured active regions and, therefore, interesting dynamical properties [3,4]. Future high-speed data communication applications demand devices that are insensitive to temperature variations and optical feedback effects, and provide features such as high modulation bandwidth and low chirp, as well as error-free operation. Currently, self-organized semiconductor quantum dot (QD) lasers are promising candidates for telecommunication applications [2].

Quantum dot (QD) heterostructures with size quantization of charged carriers in all three dimensions suitable for advanced research and applications were developed significantly later than layered quantum well (QW) heterostructures [5]. The latter represented essentially the mainstream double heterostructure (DHS) concept [3] complemented by the ultimate reduction of the thickness of a narrow bandgap layer. Nevertheless some trends in the evolution of both types of size-quantized structures are similar [6].

The two-dimensional layer structures were initially fabricated in non-coherent heterogeneous systems, such as ultrathin layers of metals or semi-metals on glass substrates [5]. In non-coherent systems each layer structure constituting the solid-state phase or material has its own lattice parameter and/or crystal orientation. Thus the crystal planes of the constituting materials (or phases of the same material) do not match. Consequently a lot of defects originate at the interface which hinder the realization of the intrinsic electric, optical, vibrational, etc properties that could be expected for ideally lattice- matched (or 'coherent') heterojunctions. In spite of some progress in the demonstration of the medications of electronic and optical properties [2], no serious proofs of strong advantages for device applications were presented**.** Quantum Dot Lasers (QDL) are now approaching a time in their development when they challenge current quantum well devices in terms of performance [7-9]. Many of the predicted advantages associated with QDL's, such as temperature insensitivity, large direct modulation bandwidth, wavelength tunability, reduced chirp and lower threshold current have been realized [10,11].

An area of interest where QDL's currently fall short of predicted performance is with regard to modulation bandwidth. The extension of this modulation bandwidth is of great interest to application of QDL's as optical transceivers [6]. The doping processes have a great important on the concentrations of carriers in quantum dot laser which lead to more effective on the output power of laser [8].

2. THEORY

The analytic and numeric investigations of the laser turn- on dynamics presented here are based on the model given in reference [7,8]. In the QD laser system the electrons are first injected into the WL before they are captured by the QDs.

The following nonlinear rate equations (1-3) for the charge carrier densities in the QDs n_b with b=e/h, the carrier densities in the wetting layer WL w_b , and the photon density n_{ph} determine the dynamics (e and h stands for electrons and holes, respectively) [7,8].

$$\dot{n}_b = -\frac{1}{\tau_b} n_b + S_b^{in} N^{QD} - R_{ind} - R_{sp} \qquad (1)$$

$$\dot{w}_b = \frac{j(t)}{e_o} + \frac{n_b}{\tau_b} \frac{N^{WL}}{N^{QD}} - S_b^{in} N^{WL} - \tilde{R}_{sp} \qquad (2)$$

$$\dot{n}_{ph} = -2\kappa n_{ph} + \Gamma R_{ind} + \beta R_{sp} \qquad (3)$$

The induced processes of absorption and emission are modulated by a linear gain

$R_{ind}(n_e, n_h, n_{ph}) = WA(n_e + n_h - N^{QD}) n_{ph}$.

The spontaneous emission in the QDs is approximated by $R_{sp}(n_e, n_h) = (W / N^{QD}) n_e n_h$. The spontaneous recombination rate inwhere isis given by $\tilde{R}_{sp}(w_e, w_h) = B^S w_e w_h$ where B^S is the band–band recombination coefficient in the WL. $\Gamma = \Gamma_g N^{QD} / N^{sum}$ is the optical confinement factor. Γ_g is the geometric confinement factor.

N^{sum} is twice the density of the total QD and N^{QD} denotes twice the QD density of the lasing subgroup (the factor 2 account for the spin degeneracy) . W is the Einstein coefficient and A is the wetting layer normalized area. β is the spontaneous emission coefficient , $j(t)$ is the injection current density, e_o is the electronic charge . 2κ is the optical intensity loss.

Nonradiative carrier–carrier scattering rates (nonlinear scattering rates) S_e^{in} and S_h^{in} for electron and hole capture into the QD levels, S_e^{out} and S_h^{out} for carrier escape from the QD levels.

Figure (1) represents an energy diagram of the band structure.

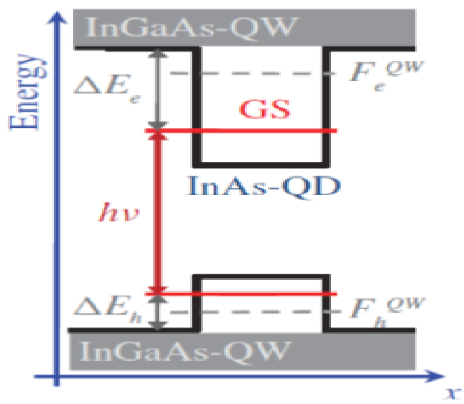


Figure (1): Energy diagram of the band structure across a QD. $h\nu$ labels the ground state (GS) losing energy. ΔE_e and ΔE_h mark the distance (in energy) of the GS from the QW band edge for electrons and holes, respectively [7].

Doped wetting layer (WL):

A doped WL can be implemented by choosing different initial conditions for electron and hole densities in the WL. Without doping, the following initial conditions $n_e^0 = 0$, $n_h^0 = 0$, $n_{ph}^0 = 0$, $w_e^0 = 10^{-2}\ \rho_e KT$, and $w_h^0 = 10^{-2}\ \rho_e KT$ have b the Boltzmann where K is Boltzmann constant and T is temperature. Note that charge conservation is contained in the five -variable rate equation system, thus leading to only four independent dynamic variables that are related by [8]:

$$N^{sum}(\dot{n}_e - \dot{n}_h) - N^{QD}(\dot{w}_h - \dot{w}_e) = 0$$

which can be integrated giving

$$N^{sum}(n_e - n_h) - N^{QD}(w_h - w_e) = N^{QD}(w_e^0 - w_h^0)$$

The microscopic calculations of the scattering rates would be doping the WL, since space charges will lead to band bending and deform the energy scheme; the relations of the scattering rates are given by researchers [9]. However, doping of the WL will also change the charge conservation condition [8].

3. RESULTS AND DISCUSSIONS

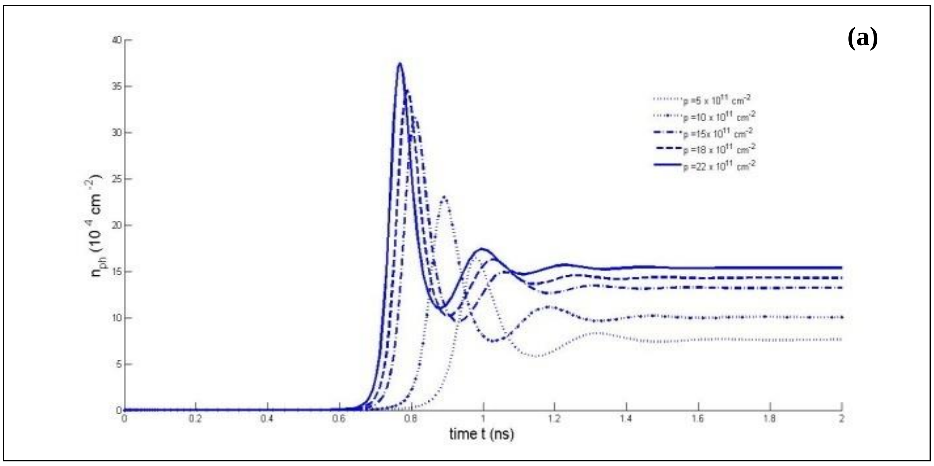
By increasing w_e^0 or w_h^0 and keeping the other at the small value of $10^{-2}\ \rho_e KT$ we are able to model *n*- or *p*-doping , respectively. Because the rate equation system treats 2D densities, also the doping concentrations $n \approx w^0{}_e$ and $p \approx w^0{}_h$ are given per area.

In figure (2): Simulation result of the temporal variation of photon density n_{ph} for (a) different n-doping in the WL and (b) for different p-doping in the WL . Parameters as in Table 1; pump current density is *(j= 2.6 j_{th}).* The threshold injection current density is calculated by using the same parameters of the system which are given in Table.1($j_{th} = 2883\,A\ cm^{-2}$) [9].

Table 1: parameters used in the simulation [7]

symbol	value	symbol	value
W	$0.7\,ns^{-1}$	A	$4\times10^{-5}\,cm^2$
T	300 K	N^{QD}	$0.6\times10^{10}cm^{-2}$
2κ	$0.1\ ps^{-1}$	N^{sum}	$20\times10^{10}cm^{-2}$
Γ_g	0.075	N^{WL}	$2\times10^{13}cm^{-2}$
Γ	2.25×10^{-3}	B^S	$850\,ns^{-1}\,nm^2$
β	5×10^{-6}	$m_e\,(m_h)$	$0.043\,(0.45)\,m_0$

In figure (2) we find that the switch-on time is affected (decreased) by the doped semiconductor QD laser at constant value of injection current density.



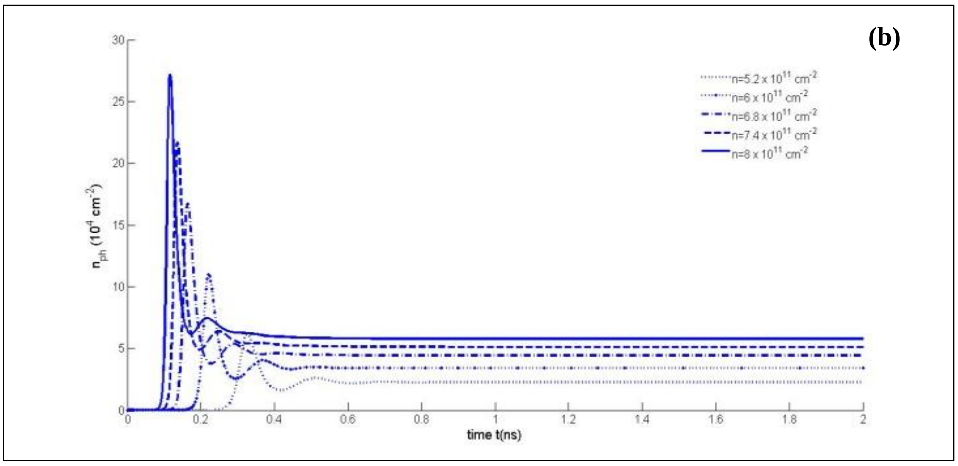


Figure (2): Simulation result of the temporal variation of photon density n_{ph} for (a) different n-doping in the WL and (b) for different p-doping in the WL . Parameters as in Table I; pump current is *(j= 2.6* j_{th} *).*

In figure (3): Simulation of the temporal variation of electrons and holes densities in the QD ((n_e , n_h)) for p-doping $p = 10x10^{11} cm^{-2}$ as shown (a,b) and in figure (4): n-doping ($n = 1.5x10^{11} cm^{-2}$) as shown (a,b)for different injection current density *j=(1.6,2.6,2.9,3.2,3.9)* j_{th}

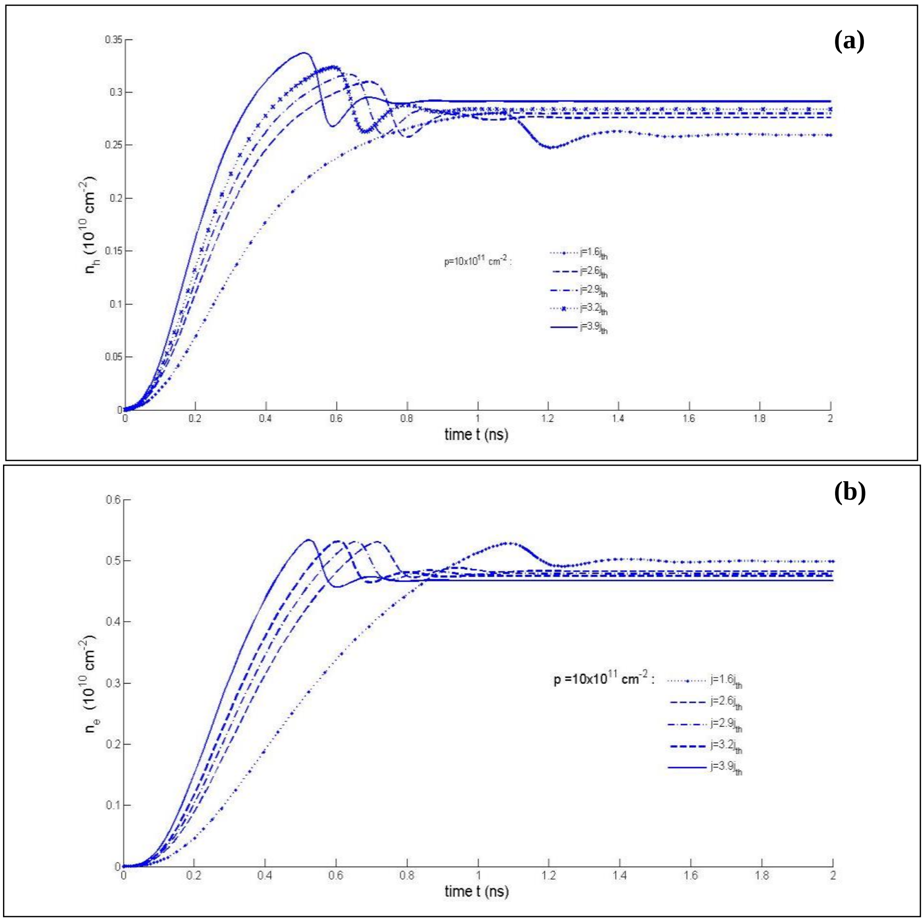


Figure (3): Simulation of the temporal variation of electrons and holes densities in the QD (n_e , n_h) for p-doping $p = 10x10^{11} cm^{-2}$ as shown (a,b) for different injection current density *j=(1.6,2.6,2.9,3.2,3.9)* j_{th} .

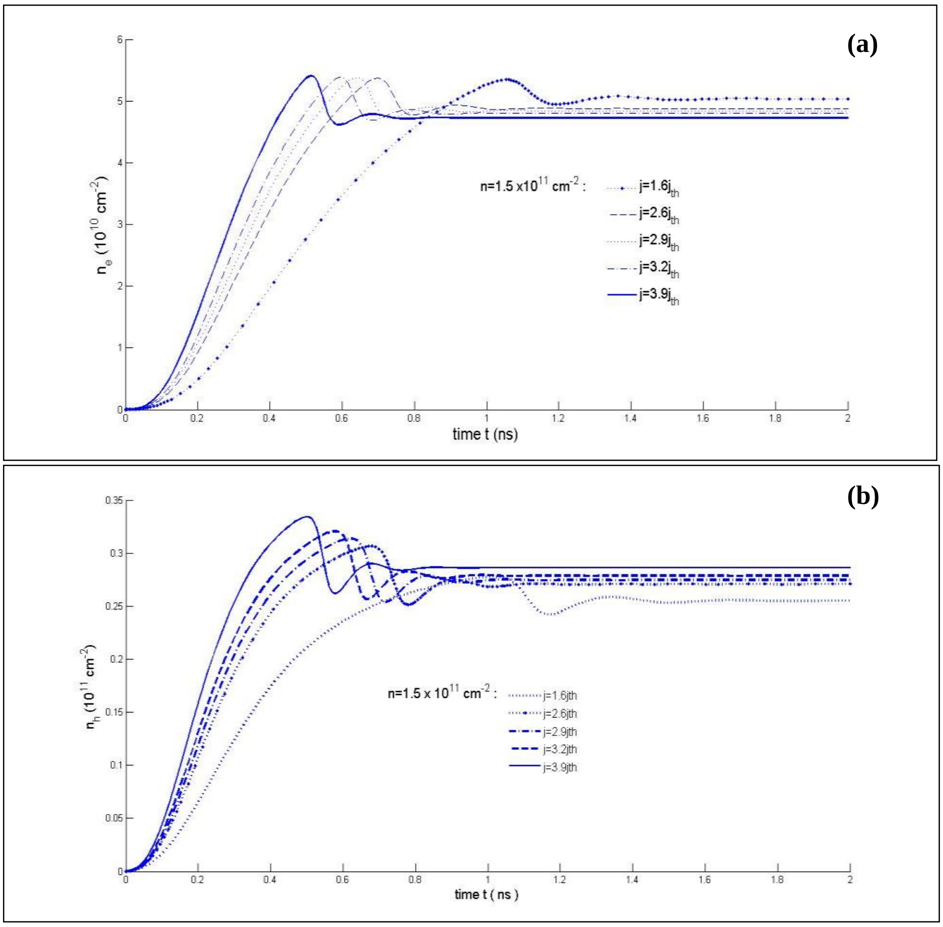


Figure (4): Simulation of the temporal variation of electrons and holes densities in the QD (n_e , n_h) for n-doping($n = 1.5x10^{11}cm^{-2}$)as shown (a,b) for different injection current density *j=(1.6,2.6,2.9,3.2,3.9)* j_{th} .

4. CONCLUSIONS

From the results we find that the carriers of the system are affected by doping the wetting layer regions which lead to change the output intensity (or number of photons per unit of area). This effect can be appeared and related with the current injection density because the doping processes is enhanced the carriers on the wetting layer that lead to change the carriers in the active layer of quantum dot laser. Doping in quantum dot laser is important in the many applications such as increasing the activity of carriers in the lasing processes, i.e. improving the output power of laser.

Thus, QD Laser with Doped Carrier Reservoir is a way of changing the confinement energies that lead to these effects on the laser output and we note that the switch-on time is affected (decreased) in the laser output by doped semiconductor QD laser.

REFERENCES

[1] Alferov Z I, The history and future of semiconductor heterostructures Semiconductors, 32 1–14, 1998.
[2] T.Steiner, "Semiconductor nanostructures for optoelectronic applications", Artech House, Inc., 2004.
[3] D. Bimberg, Quantum dots for lasers, amplifers and computing, J. Phys. D: Appl. Phys.,38, 2055 -2058, 2005.
[4] V.R. Vukkalam ,"Spatial Profiling of Quantum Dot Lasers", Waterford Institute of Technology, Ireland, 2012.
[5] S.Krishna, Optoelectronic properties of self-assembled InAs/InGaAs quantum dots, Center for High Technology Materials, Electrical and Computer Engineering Department, University of New Mexico, 1313 Goddard SE, Albuquerque, NM 87106.
[6] P. Michler, "Single quantum dots: Fundamentals, applications and new concepts", Springer, 2003.
[7] E. Malic´, M. J. P. Bormann, P. Hövel, M. Kuntz, D. Bimberg, A. Knorr, and E. Schöll, "Coulomb damped relaxation oscillations in semiconductor quantum dot lasers," IEEE J. Sel. Topics Quantum Electron., 13, 1242– 1248, (2007).
[8] K.Ludge and E. Scholl, Nonlinear dynamics of doped semiconductor quantum dot laser Eur. Phys. J. D 58,167–174, 2010.
[9] K. Lüdge, M. J. P. Bormann, E. Malic´, P. Hövel, M.Kuntz, D. Bimberg,A. Knorr, and E. Schöll, "Turn-on dynamics and modulation response in semiconductor quantum dot lasers," Phys. Rev. B, 78, 035316-1–03531611, (2008).
[10] W. W. Chow and S. W. Koch, Theory of semiconductor quantum – dot laser dynamics, IEEE J. Quantum Electron, 41,495-505, 2005.
[11] E. Kapon,"Semiconductor Lasers Fundamentals", Academic Press, 1999.