The Influence of Confined Energy on the Carrier Heating in Quantum Dot Semiconductor Optical Amplifiers

Dr. Ameen H. Al-Kursan [1] , Dr. Ahmed H. Flayyih[1] and Dr. Kareen H. Bardan [2]

[1]Nassiriya Nanotechnology Research Laboratory (NNRL), Physics,Department, Science College, Thi-Qar University, Nassiriya, Iraq.

[2]Science Department, Teachers College, Summer University, Nassiriya, Iraq.

Email: phy.lab2013@gmail.com

ABSTRACT

Research is involve the study of carriers heating phenomena in semiconductor materials for nano-structures. The relation between these structures and energy levels have been estimated by deriving the nonlinear gain coefficients. the theoretical results is shown that the effect of carrier hating is increase with increasing of dot size. This is agree with experiment results

Keywords : Quantum dot, Energy level, Energy density, Carrier heating effect, Nonlinear gain coefficient, Semiciconductor optical amplifiers.

1 INTRODUCTION

The development of semiconductor quantum dot (QD) lasers and amplifiers has brought about devices which have a zero-dimensional (0-D) or quasi-zero-dimensional density of states, and, theoretically, high differential gains and low threshold current densities. Additionally, the high degree of quantum confinement results in a density of states having discretized energy levels which can significantly modify the bulk carrier dynamics [1].

Semiconductor optical amplifiers (SOAs) are key devices in future telecommunication networks for applications such as signal regeneration and signal demultiplexing . The picosecond and subpicosecond dynamics of these devices have been intensively studied over recent years [2, 3].

It is well recognized that carrier heating affects the small-signal modulation response of semiconductor lasers as spectral hole burning. Both effects have been characterized by the nonlinear gain coefficient . However, the form of the nonlinear gain coefficient due to carrier heating is still a subject without any consensus [4].

The major sources of heating effects in SOAs are carrier injection, stimulated emission, Auger recombination and free carrier absorption (FCA). The injected carriers must release their access energy before reaching the lowest energy subbands. This energy will contribute to increase carrier temperature [5]. In stimulated emission the "cold carriers" which are close to the band edge are removed [6]. The FCA mechanism includes photon absorption by the interaction of free carriers within the same band [7]. This process transforms the carriers into higher energy states, and consequently the temperature and energy of the carriers will increase. As the temperature of the carriers is higher than that of the lattice, thermalization will occur where the carriers transfer their excess energies to the crystal lattice through interaction with phonons [8].

The experimental investigation for CH in QDs has been documented by Borri *et al.* [9]. Additionally, Zilkie et. al. [10] have studied CH dynamics in quantum well, quantum dash and QD SOAs. CH in light-emitting QD structures has also been studied [11], where the WL quantum well (QW) is modeled as an infinite QW while QD energy subbands are calculated using a simple harmonic oscillator model. This model is significant in describing the essential physics of these structures in a simple manner, but they are far from practical structures due to infinite potential of QW and the equidistant energy of the harmonic oscillator [12]. Uskov et. al. [13] presented a model for CH induced by Auger capture between WL and GS. However, the effect of CH on FWM in QD structures has not been modeled.

it is important to deal with the effect of CH on FWM in QD nanostructures. Accordingly, this study introduces a model for CH theory in QD SOAs for three-level rate equations system (WL, ES and GS) based on density matrix theory.

2. ENERGY LEVEL MODEL IN QD SOA

The disk model is One of the commonly used to study energy subbands of QDs. In this mode , it is suppose the shape of the QDs as disk of radius r_0 and height H. The Schrödinger equation for the electron wave-function and energy subbands is given by [14,15]

$$E\psi(\rho,\varphi,z)=\left(-\frac{\hbar^2}{2m^*}\left[\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\frac{\partial}{\partial\rho}\right)+\frac{1}{\rho^2}\frac{\partial^2}{\partial^2\varphi}+\frac{\partial^2}{\partial^2 z}\right]+V\right)\psi(\rho,\varphi,z) \qquad (1)$$

where m^* is effective mass and V is electric potential. The analytic solution is obtain by separating of wave function in the ($\rho-\phi$) plane and z-direction, so the total energy is sum of energy E_m for the two dimensional cylindrical QD in the ($\rho-\phi$) plane, and E_ℓ for a one-dimensional square potential in the z-direction [14],

$$E_d = E_m + E_\ell \qquad (2)$$

3 Carrier Heating in QD SOA

The time evolution of carriers in GS base on rate equations used by [16], is given by

$$\frac{d\rho_{GS,i}}{dt} = \frac{(\rho_{ES,i})[1-(\rho_{GS,i}-f_{GS,i})]}{\tau_{21}} - \frac{(\rho_{GS,i}-f_{GS,i})[1-\rho_{ES,i}]}{\tau_{12}}$$
$$-\frac{(\rho_{GS,i})}{\tau_{1r}} - \frac{(\rho_{GS,i})}{\tau^{c}_{CH}} - \frac{i}{\hbar}\mu_{cv,i}(\rho_{cv,i}-\rho_{vc,i})E(z,t) \qquad (1)$$

Where ρ_{GS}, ρ_{ES} are the occupation probability of carriers in GS and ES respectively, τ_{1r} is the spontaneous radiative lifetime in QDs, τ_{21} is the carrier relaxation time from the ES to GS, τ_{12} is the carrier escape from the GS to the ES. $f_{x,i}$ is the Fermi distribution where the carriers relaxes back to the equilibrium distribution. τ^{x}_{CH} is the CH time constant which is the time needed to cooling the carrier temperature toward the lattice temperature. *E(z,t)* is the electric field of the interacting light. $\rho_{cv,i}$ is the coherence term of the density-matrix which is given by [5]

$$\frac{d\rho_{cv,i}}{dt} = -(i\omega_i + \frac{1}{\tau_{cv}})\rho_{cv,i} - \frac{i}{\hbar}\mu_{cv,i}(\rho^{c}_{GS,i} - \rho^{v}_{GS,i} - 1)E(z,t) \qquad (2)$$

The total carrier density is unaffected with intraband process, so the steady-state ($\bar{\rho}_{ES}$) and small-signal ($\tilde{\rho}_{ES}$) occupation probabilities of ES are takes the same relations which are introduced in [17]. The influence of CH in QD SOA can be calculated by the concept of carriers energy density ($U_x = \frac{1}{V}\sum_i E_{x,i}\,\rho_{x,i} = \frac{1}{V}\sum_i E_{x,i}\, f_{x,i}$) [18], so the rate equation of energy density is simply estimate from Eq. (1), the result is [16]

$$\frac{dU_x}{dt} = \frac{\rho_h\left(\left\langle E^{GS}_x\right\rangle - \left(U_x - U_{f,x}\right)\right)}{\tau_{21}} - \frac{\left(U_x - U_{f,x}\right)\left(1-\rho_h\right)}{\tau_{12}} - \frac{U_x}{\tau_{1r}} - \frac{(U_x)}{\tau^{c}_{CH}}$$
$$+K_x\left\langle\left|E(z,t)\right|^2\right\rangle - \frac{i}{\hbar}\frac{1}{V}\sum_i E^{GS}_{x,i}\left|\mu_{cv}\right|\left(\rho_{cv,i}-\rho_{vc,i}\right)E(z,t) \qquad (22)$$

The fifth term ($K_x\left\langle\left|E(z,t)\right|^2\right\rangle$) is represent contribution of CH induced by free-carrier absorbtion (FCA), K_x ($=\varepsilon_0\, n\, n_g\, \upsilon_g \sigma_x N$) are coefficient that can be express by cross section σ_x for FCA in the conduction and valence band, H ere, $x = c$ or $x = v$ denote, respectively, the conduction or valence band [18], To determine the expression of temperature at small-signal, we use the expansions

$$\rho_x = \bar{\rho}_x + \tilde{\rho}_x\, e^{-i\delta t} + \tilde{\rho}^{*}_x\, e^{i\delta t}$$
$$f_x(t) = \bar{f}_x + \frac{\partial f_x}{\partial N}\tilde{N}\, e^{-i\delta t} + \frac{\partial f_x}{\partial T_x}\tilde{T}\, e^{-i\delta t} + c.c$$
$$U_x = \bar{U}_x + h_x\left(\tilde{T}\, e^{-i\delta t} + c.c\right)$$

then substituting in Eq. (2) one get

$$\tilde{T}_x = \frac{h_x^{-1}\tau_{in}\left(E^{*}_0 E_1 + E_0 E^{*}_2\right)}{\left(1-i\,\delta\tau_{in}\right)}\left(\frac{2\varepsilon_0\, n\, c}{\hbar\omega}\right)\left(\sigma_x \bar{N}\hbar\omega - g(\omega)E_{x,0}\right) \quad (3)$$

where

$$\tau_{in,x} = \left(\frac{1}{\tau_{SHB}} + \frac{1}{\tau^{x}_{CH}} - \frac{2\bar{\rho}_{ES}}{\tau_{21}}\right)^{-1} \qquad (4)$$

$\tau_{in,x}$ can be considered as the net of intraband relaxation time, τ^{x}_{CH} is the carrier heating time constant, τ_{SHB} is the SHB time constant, $\bar{\rho}_{ES}$ is the occupation probability of ES at steady-state, δ_{nm} is the pump-probe detuning, and g(ω) is the gain. The field $E(z,t)$ induces a polarization $P(z,t)$ in the active medium of the amplifier, the polarization is result of three contributions of a three mechanism, which are CDP, SHB and CH. The nonlinear gain coefficient is depend on the analytical solution of pulse propagation inside QD SOA [17]. For the four-wave mixing contribution we have; CDP, SHB and CH. In general, nonlinear gain coefficient due CDP is assumed to be equal to unity [5]. other nonlinear gain coefficients are calculated by the normalized nonlinear susceptibility. As we do with SHB coefficient [17], the nonlinear gain coefficient due CH is derived as

$$\kappa_{CH,x} = \left(\frac{\bar{N}_w E^2_{x,0}}{K_\beta T^2}\right)\left(\frac{h_x^{-1}\tau_{in}}{\left(\tau_{1r}\right)\left(1-i\,\delta\tau_{in}\right)}\right)\left(1 - \frac{\sigma_x \bar{N}_w\hbar\omega}{g(\omega)E_{x,0}}\right) \qquad (8)$$

$\bar{N}_w$ is the volume carrier density at steady-state and K_β is Boltzmann's constant

3. Calculations, Results, and Discussion

The QD structure chosen in this study is InAs grown on $In_{0.53}Ga_{0.47}As$ WL, while the substrate is GaAs. Many researches uses this structure to study different QD properties [19-22]. It is assumed here that the disk have a radius of (20 nm) and high of (5, 6, 7 and 8nm). The calculations of energy separation between GS. ES and WL for different size are given by Table (1)

The size effect reflects the degree of confined energy, the QD energy separations between interdot levels are approximately fix while they increase between QD levels and WL. The energy separation limits time relaxation of carriers between confined energy, therefore the influence of dot size is very important in studying heating effects. Fig.1 show 3-dimension plot ($\kappa_{CH} - \tau_{in} - \delta$) describing the effect of QD size. The nonlinear gain coefficient increase with increasing dot size, the rate of increasing at layer thickness equal (5 nm) is very interest where the interdot time relaxation and CH contribution is less than other size result.. The detuning effect and QD size on κ_{CH} involved in our study. CH is decrease with increasing the detuning between the pump and probe signals, the values of nonlinear gain at same detuning are also directly proportional with layer thickness. The SHB time and CH time constants versus CH effect have been studied in present the QD size. Figure (3) show the contribution of SHB process is more dominant in calculation of nonlinear gain the CH relation. Figure (4) reveal the comparison between the carrier heating contribution in this model with bulk model [18]. In QDs the carrier density is lower than bulk and QW devices, then CH is reduced, this result agree with some of global experimental measurements [18], [23].

5. Conclusions

We conclude The energy separation between QD levels and QW play important role in increasing of performance of semiconductor devices. The increasing of carrier heating effect with increasing of dot size is relate with energy separation between QD and WL, where the carrier relaxations are change.

Table (1) The calcuations of energy .

Disk dimension		InAs QD energy levels (eV)	
High (nm)	Radius (nm)	CB (electron)	VB (heavy-Hole)
5	20	0.8227 0.8965 1.0261	-0.0194 -0.0247 -0.0343 -0.0481 -0.0661 -0.0718
6	20	0.8077 0.8814 1.0110	-0.0153 -0.0206 -0.0302 -0.0440 -0.0619
7	20	0.7958 0.8696 0.9992	-0.0124 -0.0177 -0.0273 -0.0411 -0.0590
8	20	0.7871 0.8608 0.9904	-0.0103 -0.0156 -0.0252
InGaAs WL energy levels (eV)			
Thickness of WL (nm)		CB (electron)	VB (heavy-Hole)
20		1.2488	-0.1959

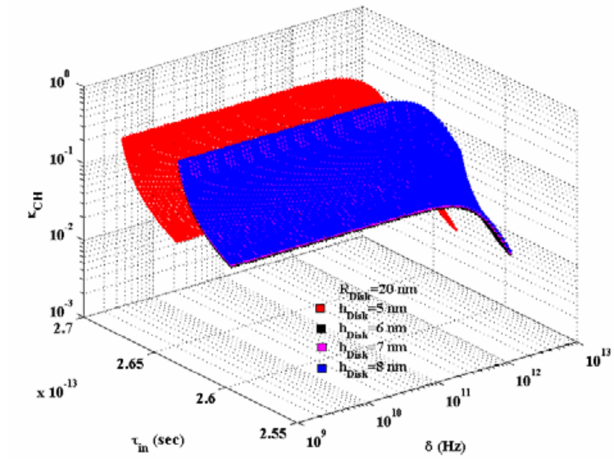

Fig. 1. Show 3-dimension plot $\left(\kappa_{CH} - \tau_{in} - \delta\right)$

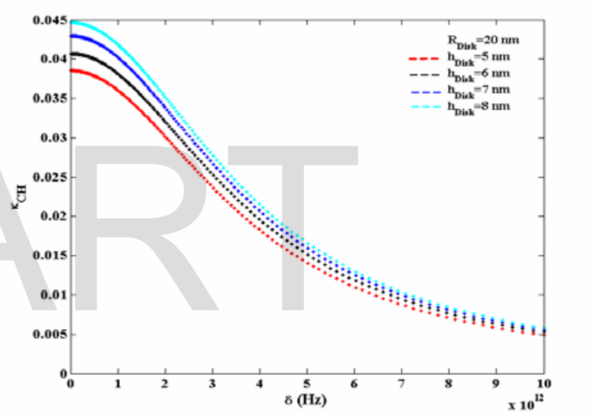

Fig. 2. Show κ_{CH} versus δ for many of layer thickness

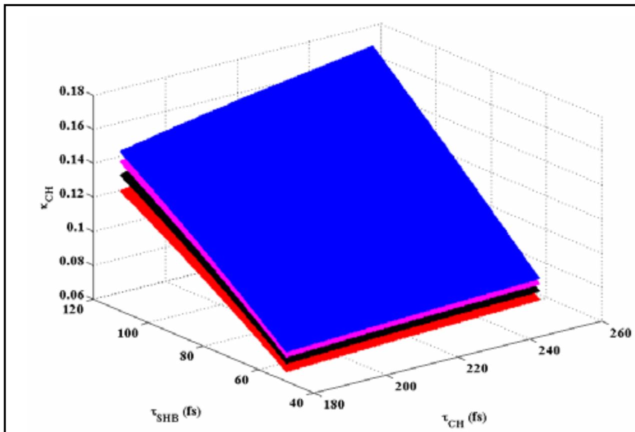

Fig.3. The influence of nonlinear relaxation process on the CH contribution.

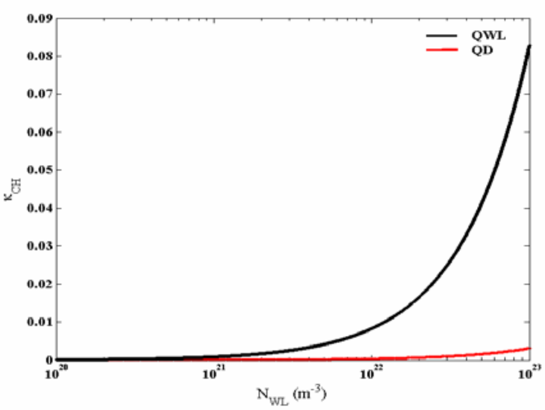

Fig.4 Illustrate the compression between the QD and bulk model

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