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Investigation of the Mole Fraction Effect for Wetting Layer on the Carrier Heating Phenomena in Quantum Dot Semiconductor Material

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Abstract: ***This research have included the studying of carrier heat phenomenon with the aid of transactions nonlinear gain coefficients, the influence mole fraction on the wetting layer had been studied , we has been observed that the increase in mole fraction lead to a change in the dynamics of carriers and determine the occupancy rate for each level, in addition to changing the energy gap for structure and this is leads to an increase in the heating effect on the semiconductor material.***

Keyword: Carrier heating, nonlinear gain coefficients, semiconductor optical amplifier and Quantum dot.

1. Introduction

Semiconductor optical amplifers (SOAs) have significant practical interest in data communication applications, because of their small size, high optical gain, low input power requirement, faster response time and large bandwidth [1,2]. A quantum dot (QD) nanostructure device shows excellent nonlinear properties and can be used to develop semiconductor devices when used in their active regions [3].

Carrier heating (CH) in semiconductor lasers and semiconductor optical amplifers (SOAs) refers to the phenomenon that the temperature of the carriers [electrons in the conduction band (CB) or holes in the valence band (VB)] is higher than the lattice temperature [4]. CH is one of the most important physical process that induce gain compression, which is crucial in determining the high speed modulation characteristics of semiconductor lasers and ultra-fast gain recovery of SOAs and has therefore been extensively investigated [5]. Due to the large effective mass of holes, the temperature change in the VB is relatively small and therefore the CH in the VB is usually neglected [4].

The major sources of heating effects in SOAs are carrier recombination, where the "cold carriers" which are close to the band edge are removed [6] and free carrier absorption (FCA) which includes the photon absorption by the interaction of free carrier with in the same b and [7]. Consequently, the temperature and energy of carrier will rise 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] . Several of researches studied the effect of carrier heating in bulk, Quantum Well and Quantum dot [9-11] to obtain perfect preference of device.

In this paper, we are introduced a theoretical model to decrease of carrier heating effect and investigate an influence of mole fraction of wetting layer on the nonlinear gain coefficients which are reflect the heating generated in SOA material.

2. Carriers Relaxation Times in QD SOA

We are treated with the rate equations for the electron transitions between the WL, GS, and ES used in [12], [13] and similar to [14] , [15] . the chosen rate equations are composed of the two energy levels in the conduction band are taken into account in this study. This system accounts for the fast transitions from WL to ES with the relaxation time τ_{WL}^{ES} □ 3 ps [11] , the fast transitions between ES and GS with the electron relaxation time from ES to GS , and the electron relaxation time from GS to ES τ_{ES}^{GS} □ 1.2 ps [11] , and the slow spontaneous transitions and electrons escape from ES back to WL with the spontaneous radiative time τ_{1R} □ 0.4 ns, the spontaneous radiative lifetime in WL τ_{WR} □ 1 ns, and the electron escape time τ_{2W} □ 1 ns. The balance between the WL and ES is determined by the shorter time τ_{2W} of QDs flling. ES level carriers relax quickly to the GS level serving as a carrier reservoir for the GS level [16].

The relation that relates carrier capture and carrier escape times is as follows [17]:

$$\tau_{xy}^{c(v)} = \tau_{yx}^{c(v)} \frac{D_y}{D_x} e^{\frac{\Delta E_{xy}^{c(v)}}{\kappa_\beta T}} \tag{1}$$

where $\Delta E_{xy}^{c(v)}$ is the energy difference between the state y and the state x in the conduction (valence) band and D is the degeneracy of the considered confined states,

3. Carrier Heating in QD SOA

The analysis are studied carrier heating in QD are collected between two theories, density matrix theory and wave-mixing theory, the density-matrix formalism are used to calculate the polarization induced by an electromagnetic field in a semiconductor medium. Wave-mixing condition satisfy by considering the case of copropagating pump and probe waves and assume the amplifier to be of the traveling-wave type. In the general case, nonlinearities in the semiconductor material lead to the generation of fields at the combination frequencies $\omega_j=\omega_0\pm j\delta$, $j=\pm1,\pm2,\ldots$, where $\delta=\omega_1-\omega_0$ is the detuning frequency. The electric field E(z,t) induces a nonlinear polarization in the active medium of the amplifier is given as [6]:

$$P(\omega_0,\omega_1,\omega_2)=\varepsilon_0 X_L(\omega_1)E_1+\varepsilon_0 X(\omega_1;\omega_0;\omega_1)E_1+\varepsilon_0 X(\omega_1;\omega_2;\omega_0)\frac{E_0^2}{|E_0|^2}E_2^* \qquad (2)$$

The most important contribution of the pump beam to the saturated susceptibility X with occupation probability, stems from the change of the carrier density induced by the pump, but X also has contributions from carrier heating and spectral-hole burning (SHB). The carrier density pulsation (CDP) and carrier heating effects enter through the Fermi function and spectral-hole burning enters through the term proportional to $\Delta\chi(\omega_0)$, which gives the spectral shape of the hole burned by the pump. The susceptibilities X, which account for coupling between the different field components mediated by beating with the pump can be decomposed into contributions from CDP, CH, and SHB [6]:

$$X=X^{CDP}+X^{CH}+X^{SHB} \qquad (3)$$

The susceptibility due CH contribution Which we are concern with studying is derived as [11]

$$X_x^{CH}=\frac{1}{(1-i\delta\tau_{SHB})}\frac{h_x^{-1}\tau_{in}}{(1-i\delta\tau_{in})}\left(-\frac{c\,n}{\omega}\frac{\partial g(\omega)}{\partial T_x}\left(\alpha_{T_x}(\omega)+i\right)\right)\cdot\left(\frac{2\varepsilon_0\,n\,c|E_0|^2}{\hbar\omega}\right)\left(\sigma_x\bar{N}_w\hbar\omega-g(\omega)E_{c,0}\right) \qquad (4)$$

where [11]

$$\tau_{in,x}=\left(\frac{1}{\tau_{SHB}}+\frac{1}{\tau_{CH}^x}-\frac{2\bar{\rho}_{ES}}{\tau_{21}}\right) \qquad (5)$$

τ_{SHB} and τ_{CH}^x are the SHB and CH time constant, σ_x is the cross-section, $\bar{\rho}_{ES}$ is the occupation probability of ES at steady-state, $\bar{N}_w$ is the carrier density at steady-state, α_{T_x} is the line width enhancement factor for CH, $g(\omega)$ is the material gain, $E_{c,0}$ is the energy at ground state, c is the velocity of speed and n is the reflective index .Depending on the analytical solution of pulse propagation inside QD SOA , the nonlinear gain coefficient due CH is derived and it is given by [3]:

$$\kappa_{CH,x}=\left(\frac{\bar{N}_w E_{x,0}^2}{K_\beta T^2}\right)\left(\frac{h_x^{-1}\tau_{in}}{(\tau_{1r})(1-i\delta\tau_{in})}\right)\left(1-\frac{\sigma_x\bar{N}_w\hbar\omega}{g(\omega)E_{x,0}}\right) \qquad (6)$$

4. Results, Discussion and Conclusions

The aim of this study is introduce analytic model to simulate an influence of carrier heating phenomena in semiconductor material, CH nonlinear gain coefficients are support us important information about the heating generate inside material. This model described carrier dynamics between the wetting layer and dot, disk model is used to calculate energy levels for (GaAs/ InGaAs/InAs), the changing of mole fraction of this structure will be change the energy level and the energy splitting between GS, ES and WL levels. The our calculations for mole fraction (z=0.3, 0.35 and 0.4) versus energy level splitting is given by the following table

Table 1: show mole fraction versus energy splitting

Mole fraction	*Energy level*		
	ΔE_{ES}^{WL}	ΔE_{GS}^{ES}	ΔE_{GS}^{WL}
0.3	0.0188	0.1477	0.1665
0.35	0.0702	0.1472	0.2134
0.4	0.1159	0.1471	0.263

The change of energy splitting between levels is restrict of number of carriers in each levels as result of limitation of time relaxation for levels. Figures (1 and 2) show the influence of increase mole fraction for WL with CH nonlinear coefficients, the results refers to increase this parameter with increasing mole fraction. As we know, the mole refraction is related directly with energy gap, with increasing mole fraction (≥0.47) energy gap become indirect gap so that the impact of heating will be dominant, also the change of κ_{CH} with carrier density and detuning are agree with global research [10].

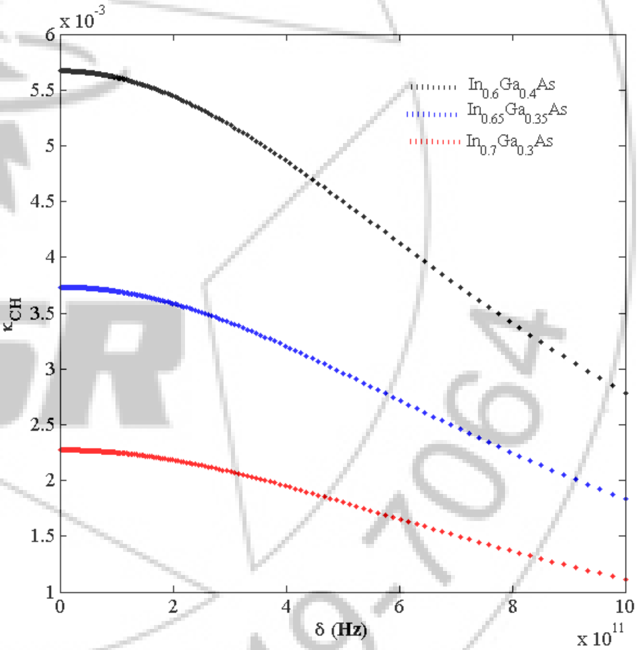

Figure 1: illustrated CH nonlinear gain coefficients versus detuning.

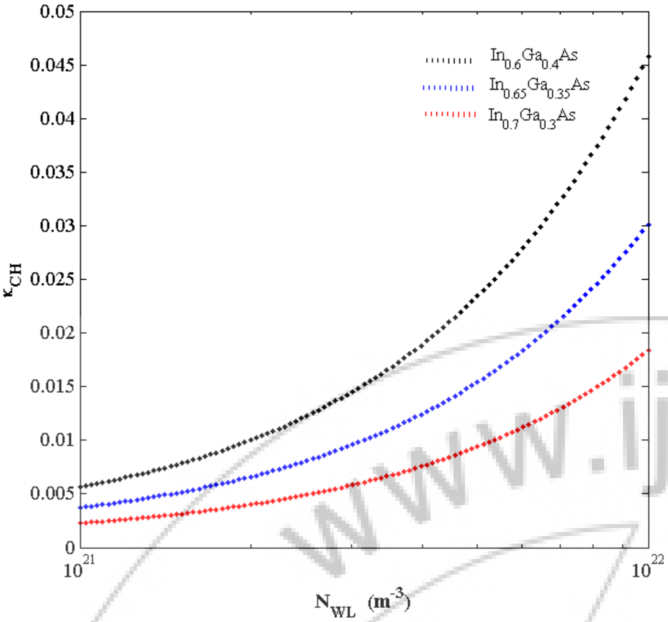

Figure 2: shown CH nonlinear gain coefficients versus Carrier density.

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Author Profile

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