Effects of Number of Wells and Cavity Length in Limitation the Optimum Symmetric Multiple Quantum Well Laser

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Abstract

In this research several main parameters/factors that effect on each of structures of semi-conductor lasers have been investigated. This investigation depends mainly on two procedures: first one is classification for these parameters including each of threshold current density, injecting threshold carrier density, absolute threshold current density and their relations with each of number of wells and cavity length, and the second is simulation process for the previous parameters with variable values of number of wells and cavity length. Non ideal contribution to the total output current like Auger recombination, Interface recombination and Leakage recombination have also been estimated through the simulation process. In other words, this research is devoted to specify the optimum performance of multi-quantum well structure of semi-conductor laser.The calculations were performed for a representative separate confinement multiple quantum well laser structure in GaAs/AlGaAs system of: 7.5nm as a quantum well size, 250 nm as a thickness of the waveguide region and 8nm as a barrier size.

I. Introduction

Single Quantum Well (SQW) and Multiple Quantum Well (MQW) laser structures, are promising candidates for use in high speed integrated optics and optical communications field because of their significant superiority in performance over conventional double hetero-structures (DH) [1]. Quantum Well (QW) lasers posses [1, 2]: (1) the high potential of lower threshold current density with lower temperature sensitivity. (2) Higher differential quantum efficiency. (3) Improved coherency with reduced lasing line-width (i.e., small line-width enhancement factor because of the specific refractive index inside (QW) structure). (4) Superior mode stability. (5) Larger modulation band-width and reduced chirping during modulation process. As a matter of fact, the efficiency of (QW) laser structures can be improved by introducing a number of parameters that can determine the optimum design of this type of laser structures and the most important of these parameters are the number of the quantum well (υ_{QW}) and the cavity length (L), which can be affected by the values of threshold current density and carrier injection levels as will be discussed in this research [3].

II. Theory and Analysis

The parameters that effect on number of wells and cavity length values in symmetric multiple quantum well (MQW) lasers are ; threshold current density (J_{th}), injecting threshold carrier density (N_{th}) and absolute threshold current density (I_{th}). It should be mentioned that our numerical calculations were performed for a representative separate confinement MQW laser structure in (GaAs/AlGaAs) system with specific waveguide parameters as shown in Fig. (1) [4].

The total threshold current density can be obtained by adding all current contributions as shown in Eq. (1) [5,6]:

$$J_{th} = J_{r,th} + J_{S,th} + J_{A,th} + J_{lk,th}$$ ……………………………………….

Where:

(1)

$J_{r,th}$: is the radiative threshold current density.

$J_{S,th}$: is the interface threshold current density.

$J_{A,th}$: is Auger threshold current density.

$J_{lk,th}$: is leakage threshold current density.

The effects of parameters (J_{th}, N_{th} & I_{th}) will be classified according to three classifications as will be discussed below.

Figure (1) Representative Structure of GaAs/ALGaAs of MQW Laser.

A. The relationship between threshold current density (J_{th}), threshold carrier density (N_{th}) & number of the QW (υ_{QW}):

The radiative QW component of the current in MQW laser is calculated from the integral over the spontaneous emission spectrum of the QW_S [5]:

$$J_{r,th} = \upsilon_{QW} L_Z e \int_{E_{g,lh}}^{E_{g,b}} R_{SP}(E) dE \quad \text{……………………………………..} \quad (2)$$

L_Z is the size of well and the integration is taken over the transitions involving QW states only, with the lower cutoff at the effective band-gap ($E_{g,lh}$) of the QW and the upper cutoff at the band-gap ($E_{g,b}$) of the barrier. While R_{SP} represents the spontaneous emission and it can be calculated from the following equation:

$$R_{SP}(E) = r_0(E)|M_b|^2 \sum \rho_{r,jn}(E)[f_C(1-f_\upsilon)]_{E,jn} \quad \text{…………………………} \quad (3a)$$

Where:

r_0: is the spontaneous emission prefactor.

M_b : is the transition matrix element.

$\rho_{r,jn}$: is the density of the energy states.

The spontaneous emission prefactor (r_0) is given by:

$$r_0(E) = e^2 n_g E / \pi m_0^2 \eta^2 c^3 \in_0 \quad \text{………………………………..} \quad (3b)$$

Here, (n_g) is the group index of the Q W material. It should be noted that the form of R_{SP} (E) is largely determined by the density of states function ($\rho_{r,jn}$) and Fermi-Dirac function (f_υ, f_c).

The interface recombination threshold current density ($J_{S,th}$) and by assuming identical interfaces in all of the structure, it could be simply given by [6] :

$$J_{S,th} = 2\upsilon_{QW} e N_{th} V_S \quad \text{……………………………………..} \quad (4)$$

V_S is the interface recombination velocity while the Auger threshold current density ($J_{A,th}$) is given by [6,7]:

$$J_{A,th} = \upsilon_{QW} L_z e C_A N_{th} \quad \text{…………………………………} \quad (5)$$

C_A is Auger coefficient but the Leakage recombination threshold current density ($J_{lk,th}$) is given by [7]:

$$J_{lk,th} = 2 d_g N_b / \tau_b \quad \text{…………………………………..} \quad (6)$$

N_b is leakage carrier concentration at the barrier material and τ_b is the life-time of the electron in the barrier. Leakage carrier concentration (N_b) can be given by:

$$N_b = N_{c,b} \exp[f_C - \Delta E_C) / K_B T] \quad \text{……………………………} \quad (7)$$

$N_{c,b}$ is the regular effective density of states in (Γ) conduction band of the barrier, i.e.($N_{C,b} = [m_{c,b} K_B T / 2\pi\eta^2]^{3/2}$),where $m_{c,b}$ is the effective mass of the electron in the barrier [6,7].

B. The relationship between threshold current density (J_{th}), threshold carrier density (N_{th}) and cavity length (L):

The threshold gain (g_{th}) is obtained from the local mode losses via the balance equation [8]:

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$$G_{th} = \Gamma g_{th} = [\alpha_i + \ln(1/R)/L]$$ ……………………………. (8)

Here, (G) is expressed in terms of the local gain coefficient (g) and gain confinement factor (Γ). The mode loss is modeled by a combination of mirror loss α_m (i.e. $\alpha_m = \ln(1/R)/L$), intrinsic loss (α_i), and R is the reflectivity parameter that is defined by the two mirrors reflectivity R_1 & R_2 ($R = \sqrt{R_1 R_2}$).By substitution, the value of the threshold mode gain can be given by [8]:

$G_{th} = \alpha_i + \alpha_m$ ……………………………….. (9)

A good approximation for a separate confinement MQW laser, is a linear relationship between Γ and υ_{QW} , which for our representative structure of Fig(1) is with L_Z =7.5nm. and d_g=250nm. and reads [4]:

$\Gamma = 0.023\ \upsilon_{QW}$ …………………………………………… (10)

Therefore, the relationship between (J_{th}) , (N_{th}) and cavity length (L) can be obtained by using Eqs. (1),(8),(9) and (10).

C. The effects of absolute threshold current (I_{th}) on optimum number of wells (υ_{QW}) and cavity length (L):

Besides injected carrier density N_{th} and threshold current density J_{th}, absolute threshold current density I_{th} is also an important operational parameter of semiconductor laser. For convenience, I_{th} has been normalized to 1μm of cavity width, which tends to decrease slightly toward smaller L (larger υ_{QW}). These minima are largely determined by the reflectivity parameter (R) through the relation [9]:

$$I_{th}^{min} = I_0 G_{th} L = I_0 [\ln(1/R) + \alpha_i L]$$ ………………………. (11)

The quantity I_o is essentially a function of the QW dimensions only, $I_o = J_o / G_o$, with $G_o = g_o \Gamma / \upsilon_{QW}$ where J_o and g_o are saturation parameters [9].

Therefore, the optimum number of QW can be obtained from:

$(\upsilon_{QW})^{opt} = Int (G_{th} / G_o)$ ………………………………… (12)

And the optimum cavity length at the minima I_{th} can be obtained from [9]:

$L^{(opt)} \approx \ln(1/R) / (\upsilon_{QW} G_o)$ ………………………………… (13)

III. Results and Discussions

By using Eqs. (1),(8), (9) and (10) and table (1)and (2) and as show in Figs.(2) and (3), the maximum number of QWs that can be accommodated with the chosen waveguide parameters is 16. One observes the expected general trend of increasing N_{th} with decreasing L and/or υ_{QW}. as a consequence of the QW gain saturation. The series of J_{th} curves for constant L exhibit minimum near $N_{th} \approx 3.5 \times 10^{18}$ cm^{-3}. Below N_{th} about 2.5×10^{18}cm^{-3}, J_{th} starts to increase rapidly approaching a vertical asymptote that corresponds to the transparency carrier density of $N_{tr} \approx 1.8 \times 10^{18}$ cm^{-3}. Also it should be mentioned that the interface recombination would become relatively more severe at these lower N_{th} values. So to keep N_{th} below about 3×10^{18} cm^{-3} (as a candidate operation range), one needs at least 16 QWs for L=30 μm, 8 QWs for L = 60 μm, 4 QWs for L =125μm, and 2 QWs for L=250 μm. For longer cavities the J_{th} minimum disappears. Obviously, less is to be gained by increasing υ_{QW} when the laser cavity is longer.
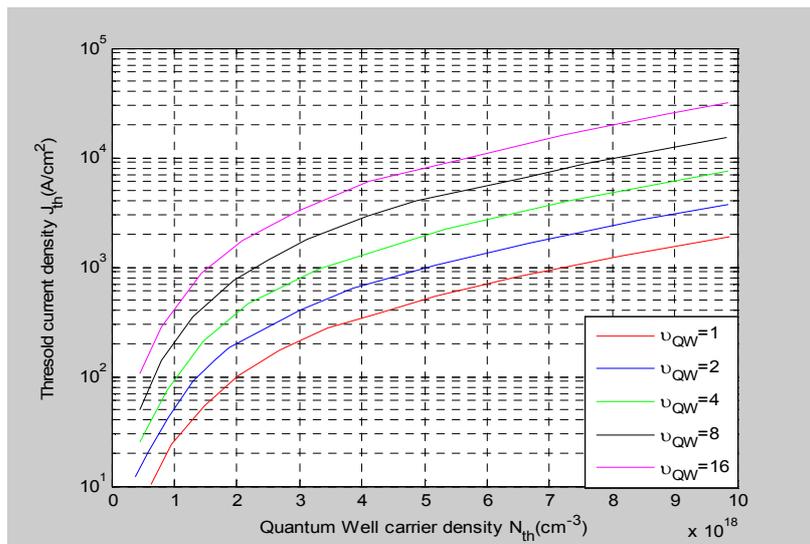

Figure (2) Relationship Between Threshold Current Density and Threshold Carrier Density with Different Values of Number of Wells
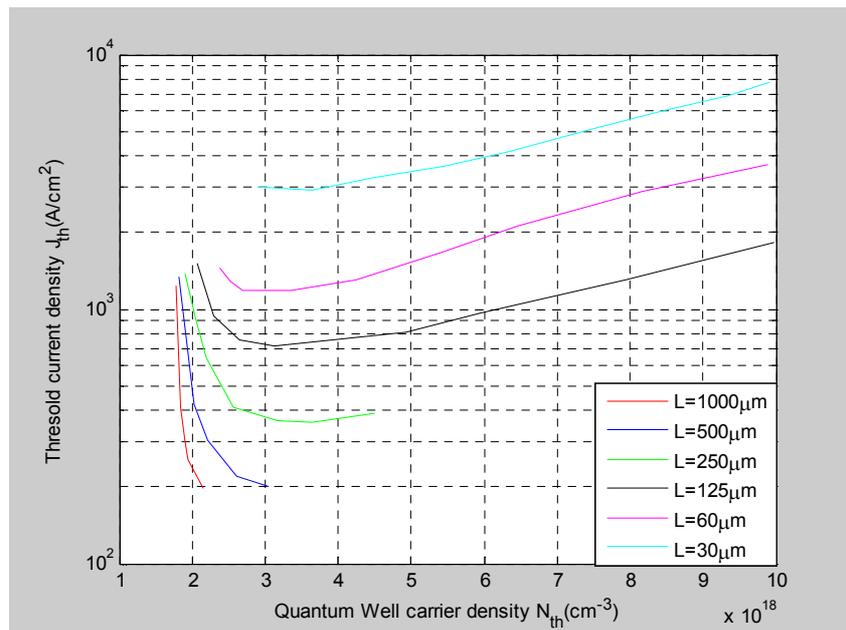
Figure (3) Relationship Between Threshold Current Density and Threshold Carrier Density with Value of Cavity Length.

Table (1)[4]
Densities of States and Fermi-Dirac Probability Function for Conduction and Valence Bands and Nc and N $_V$ Expressions

Parameter	Expression
Fermi-Dirac probability function for conduction band	$f_C(E_C) = \dfrac{n}{N_C} e^{(-\frac{E_C}{KT})}$
Fermi-Dirac probability function for valence band	$f_V(E_V) = \dfrac{P}{N_V} e^{(-\frac{E_V}{KT})}$
Density of State for conduction band	$\rho_C(E) = 4\pi (\dfrac{2m_C}{h^2})^{3/2} E^{1/2}$
Density of State for valence band (ρ_{Vj})	$P = \sum\limits_{i=l,h} \int \dfrac{\rho_{Vj}(E)dE}{1 + e^{\frac{E-E_V}{KT}}}$
N_C	$2(\dfrac{2\pi m_C KT}{h^2})^{3/2}$
N_V	$2(\dfrac{2\pi KT}{h^2})^{3/2} (m_{lh}^{3/2} + m_{hh}^{3/2})$

The alternate representation of I_{th} with cavity length L as a variable parameter is presented in Fig.(4) ,which was chosen for demonstrating the influence of interface recombination, Auger recombination, and carrier leakage respectively. In this figure, a SQW, 3-QW$_S$, and 6-QW$_S$ laser are compared with each other , which was determined in order to analyze the influence of these nonradiative and leakage mechanisms.

Fig.(4) shows a striking increase of I_{th} towards short cavity length, which is a direct consequence of the gain saturation in the QWs at high injection levels. With increasing QW number, the shifts will increase towards smaller L values. The position of the anomalous increasing might be affected by Auger recombination, leakage carrier, but only marginally by interface recombination.

Table(2)[4]
Some Parameters Values of GaAs/AlGaAs Multiquantum Well Laser

| Parameter	Symbol	Value
Operating wave length	Λ	$1.3\mu m$
Group velocity	c/μ_g	$3\times10^8/5$
Group refractive index	μ_g	5
Interface recombination group velocity	v_s	$100cm/s$
Effective mass of electron /Rest mass of electron	$\dfrac{m_C}{m_0}$	0.35
Effective mass of electron /Rest mass of electron	$\dfrac{m_{C,b}}{m_0}$	0.11
lifetime in the barrier	τ_b	1ns
Waveguide region of thickness	d_g	250nm
Linear current density saturation parameter	J_0	$220A/cm^2$
Linear gain saturation parameter	g_o	$1250cm^{-1}$
Intrinsic loss	α_i	$5cm^{-1}$
Reflectivity	R	0.3
Auger coefficient	C_A	$5\times10^{-30}cm^6/s$
Matrix element/Rest mass of electron	$\dfrac{\left|M_b\right|^2}{m_0}$	19.7+5.6y x=0.47y for $In_{1-x}Ga_xAs_yP_{1-y}$
Effective mass of heavy hole/Rest mass of electron	$\dfrac{m_{hh}}{m_0}$	0.62+0.05x
Effective mass of light hole/Rest mass of electron	$\dfrac{m_{lh}}{m_0}$	0.11+0.03x
energy gap of light hole band	$E_{g,hl}$	0.94ev
energy gap of barrier	$E_{g,b}$	1.2ev
Band offset	$\Delta E_c(eV)=0.34(1-x)+0.371x$	
Quantum well size	L_z	7.5nm
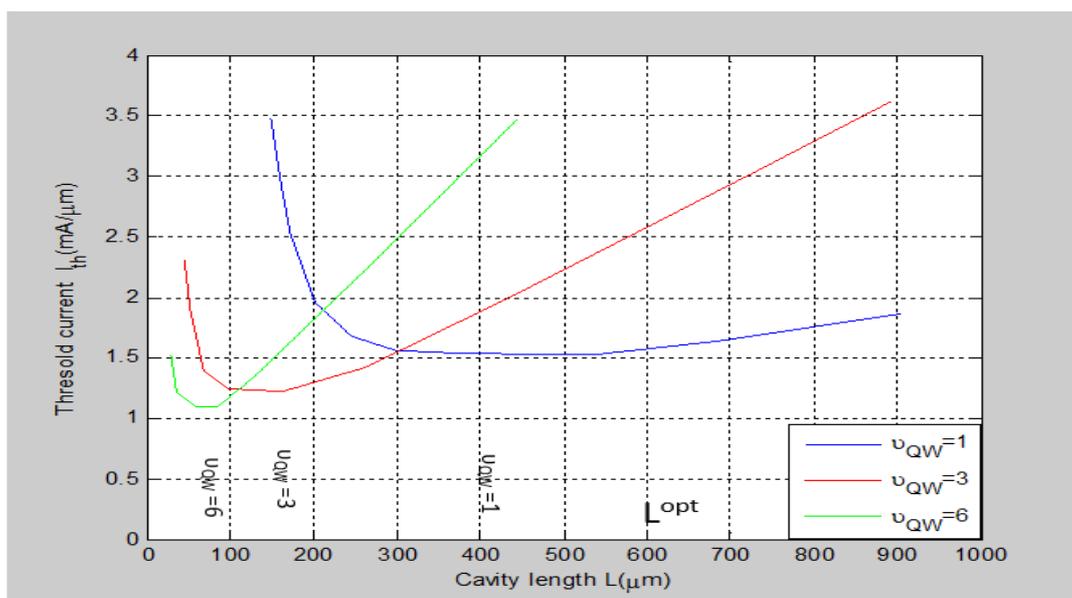
Figure (4) Relationship between Threshold Current and Cavity Length with Different Values of Number of Wells.

V. Conclusions

From the previous results, it can be concluded that our representative system of GaAs/AlGaAs has a dominant effect at longer cavity lengths, including the flat threshold current minimum, where the contributions of the non-ideal non-radiative transitions become small.

The system has determined the maximum number of the QW_S that can be accommodated with the chosen waveguide parameters to be 16, and the maximum cavity length to be in the range of ($250\mu m$).Higher cavity length values might cause J_{th} disappearing.

The intermediate range of N_{th} between (2.5-3) 10^{18} /cm^3 , can be considered as optimal for all practical purposes. So for operation in this favorable injection regime of N_{th} , one can choose either long cavities or large number of wells (QW_S) in order to avoid carrier losses, which demonstrates the preference of MQW over SQW laser structure.

In Fig.(4), there is an anomalous increasing of I_{th} with increasing υ_{QW} and towards short cavity length L.This anomalous region has been estimated to be caused essentially by Auger recombination and carrier leakage. Finally, and as shown in Fig.(4) , the optimum cavity length at minimum I_{th} can be specified.

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