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Laser Processing For Nanoscale Size Quantum Wires of AlGaAs/GaAs

Ahlam H. Jaffer Ebtisam M-T. Salman Mohammed Hamad Jassam

University of Baghdad - College of Education for pure Science

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ABSTRACT

In this work we investigate and calculate theoretically the variation in a number of optoelectronic properties of AlGaAs/GaAs quantum wire laser, with emphasis on the effect of wire radius on the confinement factor, density of states and gain factor have been calculated. It is found that there exist a critical wire radius (rc) under which the confinement of carriers are very weak. Whereas, above rc the confinement factor and hence the gain increase with increasing the wire radius.

Introduction

In 2012, the semiconductor laser reaches 50 years old. Improvement of the performance such as high speed modulation toward theoretical limit, advanced application of wavelength and polarization and utilization of photonic integration is expected. Exciting challenge will be continued for the next breakthrough in photonic device technology [1].

The development of the physics and technology of semiconductor heterostructure has brought about tremendous changes in our every days lives [2] .

In recent years DH lasers have been fabricated with very thin active layers thickness of around 10 nm. The occupation states available for confined electrons and holes are no longer continuous but discrete [3].

Such a structure called quantum well (QW) laser. Fig.(1a) shows quantum well structure. with one active region which called single quantum well (SQW) laser , and those with multiple active region are called multi quantum well (MQW) lasers as shown in Fig.(1b)[4].

The ability to fabricate (SQW) and (MQW) devices[5] has given rise to a superior characteristics to laser diode, such as low threshold current ,high optical gain, and low temperature sensitivity [6].

* Corresponding author at: University of Baghdad - College of Education for pure Science. E-mail address:

The improved performance of (QW) laser diode with respect to equivalent bulk heterostructure devices led to the consideration of lower-dimensional structures, e.g, quantum wires (QWR) and quantum dots (QDs), as the natural evolution path toward the ultimate semiconductor laser device [7] .

The goal of this work is to quantify theoretically the Quantum wire laser parameters such as density of states, confinement factor, size effect, and optical gain.

$\Gamma_{QWR} = \Gamma_{Qw} . N_w . F$ (3)

Where n_a is the refractive indices of the active layer, n_c is the refractive indices of the cladding layer, w is the wire width, and D is the normalized waveguide thickness of the active region. (Γ_{Qw}), (Γ_{QwR}) is the confinement factor of quantum well and quantum wire respectively. Nw is the number of well. $F = \frac{w}{\Lambda}$, F is the in plane space filling factor of the active region , Λ is a period of quantum wire, F=1 for QW.

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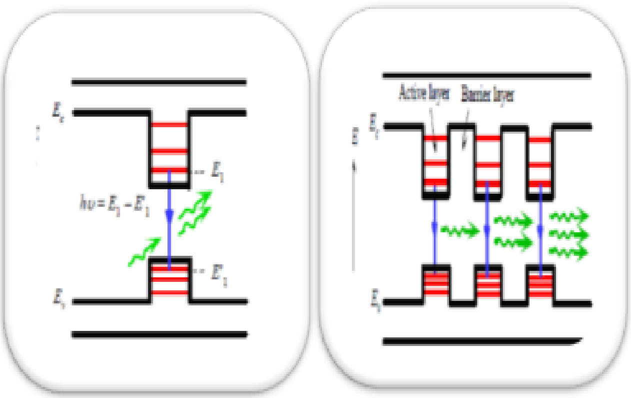

(a) (b)

Fig.(1) Quantum well structure band- gap diagram;
a) Single quantum well (SQWs) laser.
b) Multiple quantum well (MQWs) laser.[4]

Density of states

The density of states is a material property which quantifies the number of carriers that are permitted to occupy a given energy state of the semiconductor. Since most semiconductor lasers operate near the conduction band minimum, the density of states of a semiconductor material imposes an intrinsic limitation on the number of carriers that are allowed to contribute to the lasing performance at one time expression .In bulk materials, the parabolic shape of the density of states, Fig.(2), means that the electron density.

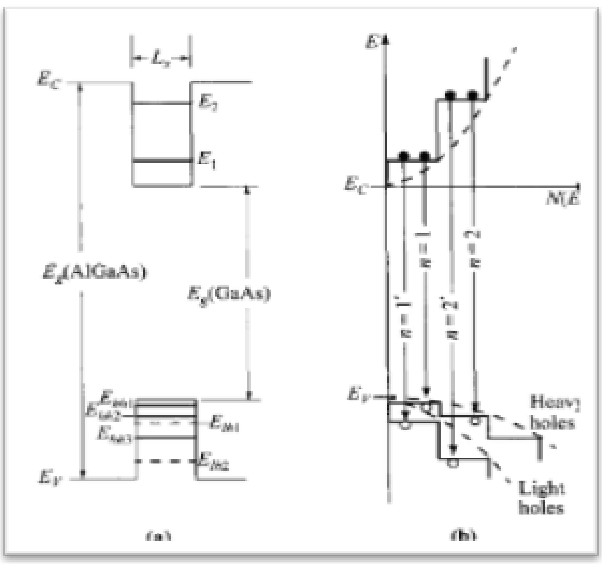

Fig.(2) (a) potential of quantum well and quantized levels. (b)density of states diagram and possible recombination [13].

Theoretical consideration

This section display the theoretical calculate of the parameters which need in this work of QWRs; optical confinement factor, density of states, size effect, and optical gain.

Optical Confinement Factor

The nanoscale confinement of matter to make nanomaterial for photonic devices involves various ways of confining the dimensions of matter to produce nanostructures [8]. The real confined systems, also called low – dimensional systems or nanostructures, are any three- dimensional quantum systems in which the carriers are free to move in only two, one or even zero dimensions [9]. Several forms of classifying the confined systems exist , the most universal considers the number of directions where the particle could move freely . For example, quasi-two dimensional systems (Q2D) have two directions for the free movement of the carriers and one confined spatial direction (QW), Fig.(1). The Q1D system has only one direction for free movement and two directions of confined movement where the carriers are compelled to move in a reduced space of quantum scale [9] as in case QWRs. .In the structure that two compound semiconductors with different band gaps pile up alternatively, electrons and holes are confined in the lower band gap layers [10].The confinement factor, defined as the fraction of the electromagnetic energy of the guided mode that exists within the active layer , is an important parameter representing the extent to the active layer for a fundamental modes approximately-,given[10]

$$\Gamma_{QW} = \frac{D^2}{D^2 + 2} \text{(SQW)} \quad (1)$$

$$D = 2\pi\left(\frac{w}{\lambda}\right).(n_a^2 - n_c^2)^{\frac{1}{2}} \quad (2)$$

The optical confinement factor of QWR laser can be calculated by [11]:

.

$$Dos_{1D}(E) = \frac{2m_e^*.m_h^*}{m_e^*+m_h^*} \cdot \frac{1}{\pi.\hbar.W_x.d} \cdot \frac{1}{(E_{cv}-E_{exy,l,m}-E_{hxy,l,m}-E_g)^{\frac{1}{2}}} \quad (8)$$

where Dos1D is the density of states of one-dimension QWRs , m*e and m*h are the effective mass of the electron and hole, respectively,Wx and d are the width and thickness of the quantum wires , respectively , Ecv is the transition energy between the conduction and valence band. ,Eg is the band gap energy, Eexy,l,m , Ehxy,l,m are the quantized energy level of the quantum wire in the conduction band and the valance band , respectively.

Size Effect of Quantum Wire

To obtain a lateral quantum confinement effect, it is necessary to consider the width and size distributions of QW dependence of optical gain. For this, it is important to investigate the possibility of a critical radius below which no bound states exist. If the QWR assumed to have a

cylindrical shape , so that the potential takes the simple from for cylindrical coordinates

$$V= V(r) = \begin{cases} 0 \text{ for } r < r_o \\ V_o \text{ for } r \geq r_o \end{cases}$$

For this potential the schroedinger equation is easily solved using Bessel function [14] and the energy is given by;

$$E=\frac{\hbar^2}{2m}\left(k_{vn}^2 + k_z^2\right) \quad ((9)$$

where the radial momentum Kvn is a discrete variable and the axial momentum $\mathcal{H}_z$ varies continuously. For the boundary at r = ro; schroedingr equation yield [15];

$$k_{vn}^2 + k_z^2 = \frac{2m}{\hbar^2}Vo \quad (10)$$

Surrounding the Fermi level is small [12] and also illustrates the added complexity of the quantum well and wire . The density of states for a quantum well is a step function with steps occurring at the energy of each quantized level, due to the carriers are free to move in the plane of the film. The case for the quantum wire is further complicated by the degeneracy of the energy level for instance two – fold degeneracy increases the density of states associated with that energy level by a factor of two. The density of states for QW and QWR can be written as:[12]

$$DOS_{2D}(E)=\frac{m}{\pi\hbar^2 L_x}\sum_l \Theta(E - E_l) \quad (4)$$

$$DOS_{1D} = \frac{2m^{\frac{1}{2}}}{\pi\hbar L_x L_y}\sum_{l,m}(E - E_{l,m})^{-\frac{1}{2}} \quad (5)$$

Where.

$$E_l = \frac{\pi^2\hbar^2 l^2}{2mL_x^2} + \frac{\hbar^2}{2m}\left(k_y^2 + k_z^2\right) \quad (6) \qquad E_{l,m} = \frac{\pi^2\hbar^2}{2m}\left(\frac{l^2}{L_x^2} + \frac{m^2}{L_y^2}\right) + \frac{\hbar^2}{2m}k_z^2 \quad (7)$$

Where.$l, m = 1,2,3, \ldots$ are quantum numbers of the energy levels due to carrier confinement in x,y and z directions , respectively ,kx,y,z are the wave vectors , and $\frac{\hbar^2 k_{x,y,z}^2}{2m}$ represent kinetic energies in the direction of unconfined dimensions . $\hbar = \frac{h}{2\pi}$, h is the plank's constant. As a consequence of one-dimensional movement, the density of states has $\frac{1}{E}$ dependence for each of the discrete pairs of states in the confined directions lastly as shown in Fig.(2) . By rearrangement of equations (4) and (5) resulting:

And valence bands, respectively,$|M^2|$ is the transition matrix element of the dipole moment, μ and ϵ are the magnetic susceptibility and the dielectric constant of the material respectively, f_c and f_v are the Fermi function for the conduction and valence bands, respectively, τ_i is the intraband relaxation time. (1(4)).

Result and discussion.

A single QWR laser of AlxGa1-xAs /GaAs is used for this investigation, due to its importance in communication. Mat lab, version 7.6 (2008) have been used for the calculation. The confinement factor of the fundamental mode was calculated using equ.(1), equ.(2), and equ.(3) for SQW and MQW. The result obtained is shown in Fig.(3) in which the confinement factor Γ_{QW} is drown as a function of well width, and Fig.(4) the confinement factor Γ_{QWR} is drown as a function of wire width for Al concentration x = 0.2. It is clear from the figure that(Γ_{SQW},Γ_{MQW}), and(Γ_{SQWR},Γ_{MQWR}) are increasing as the well width and wire width increases, Fig.(3) and Fig.(4).

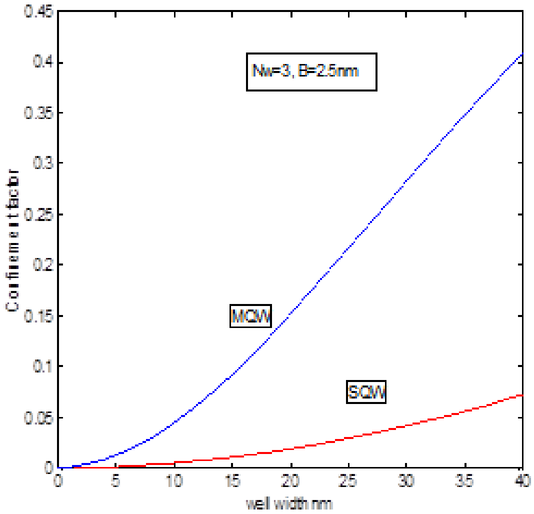

Fig.(3) The relation between confinement factor and well width of Al0.2Ga0.8As, x=0.2.

$\mathcal{H}$ is the eigen value . For small radius wires , zero Bessel function , J_o and zero modified Bessel function K_o are given by;

$$\mathbf{J_o = 1-\frac{1}{4}\,(kr)^2 + \dots\dots\dots} \quad (11)$$

$$\mathbf{K_o = -\ln \mathcal{H}r + \dots\dots\dots} \quad (12)$$

Applying continuity at r = r_o equation (11) and equation (12) gives

$$kr_o = \left[\frac{2}{\frac{1}{2}-\ln \mathcal{H}r_o}\right]^{\frac{1}{2}} \quad (13)$$

Optical Gain

The process of spontaneous emission occurs when a recombination of an electron– hole pair leads to the emission of a photon, random in direction, phase, and time. The second process is (stimulated) absorption; an electron hole pair is generated as the result of the absorption of an incoming photon. The third process is stimulated emission; a recombination of an electron–hole pair is stimulated by a photon, with a second photon generated simultaneously, which has the same direction and phase as the first photon.

The optical gain in the semiconductor laser material depends on the density of states in the conduction and valence bands and the Fermi-Dirac statistics of the electrons and holes occupying them. The gain is given by [16];

$$Gth = \frac{1}{\Gamma_{QW}\,.\,N_w\,.F}\left(\alpha_{wG} + \frac{1}{L}\,\ln\frac{1}{R}\right) \quad (14)$$

(the gain can be obtained via expression as[17]

$$G(E)=\left(\frac{E}{\hbar}\right)\sqrt{\frac{\mu}{\epsilon}}\;|M^2|.\,Dos_{1D}(E)\,.\{f_c - f_v\} \quad (15)$$

Where Gth is the threshold gain , α_{wG} wave guide loss , L is the length of cavity , R the reflectivity , the subscripts c and v denote the conduction

From this figure it is clear that when the radius of the circle (red curve) is less than$\frac{1}{2}$, $\mathcal{H}$ becomes small, which indicates that there is no bound state. This gives weak confinement. Therefore we can define a quasi critical radius rc from equ. (10) so that;

$$r_c = \frac{1}{2}\sqrt{\frac{\hbar^2}{2mV_o}} \quad (16)$$

However, equ. (13) shows that when the curve points have imaginary values, which will be ignored, the curve goes back to the x- axis, (blue curve).

The density of states of QWR lasers was calculated by using equ.(8) , the results obtained are shown in Fig. (6) in which the density of states is drawn as a function of photon energy for x = 0.2 .

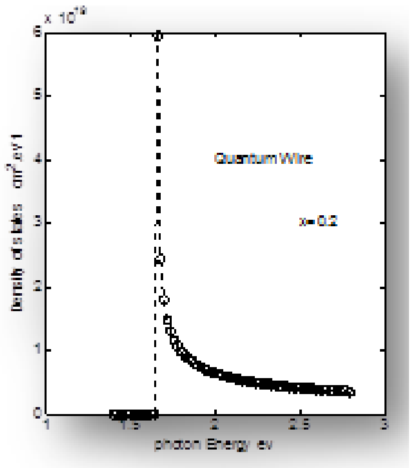

Fig.(6) The relation between DOS1D and photon Energy for x=0.2.

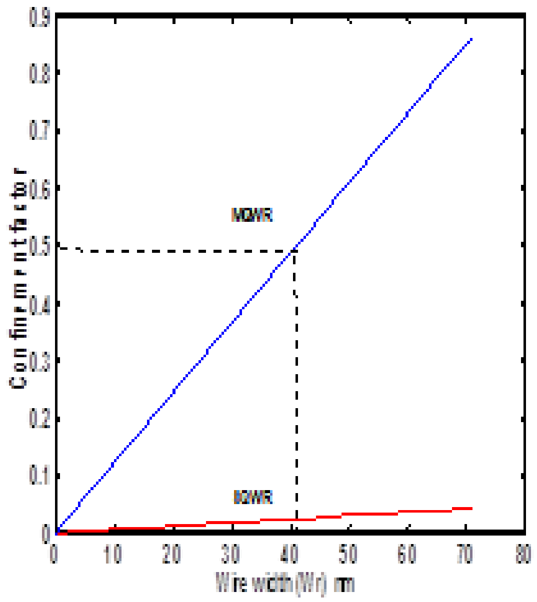

Fig.(4) The optical confinement factor as a function of the wire width for Al0.2Ga0.8As/ GaAs of MQWR structure.

By using equation (10) and equation (13), when the value of the wire width goes to zero Fig.(5) is plotted. At boundary condition r = ro equation (10) indicates that there exist two intersection points with the two axis (red curve),Where as the axial momentum Kr varies continuously to fill the energy spectrum.

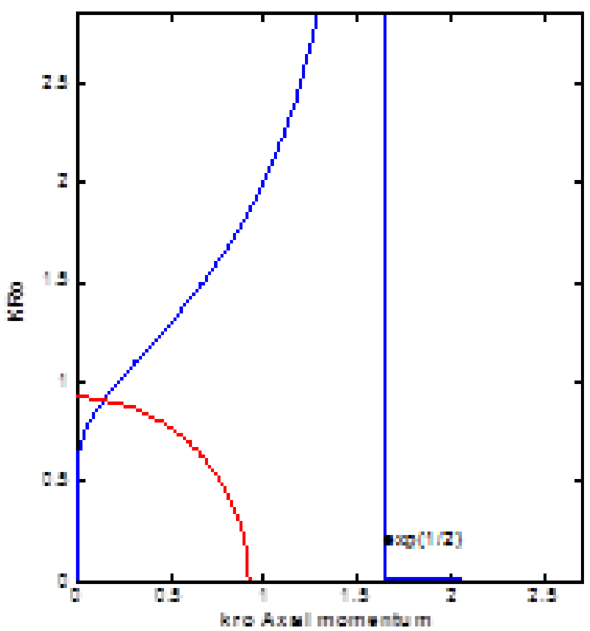

Fig.(5) The radius of the wire is reduced, the intersection moves toward the origin.

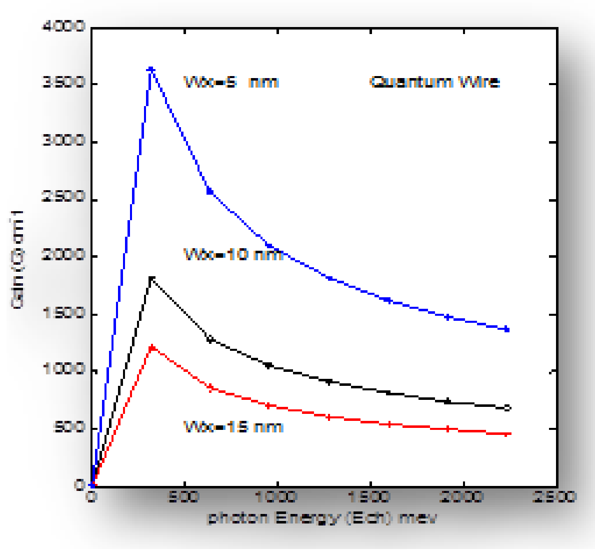

Fig.(7) The relation between the gain and photon Energy.

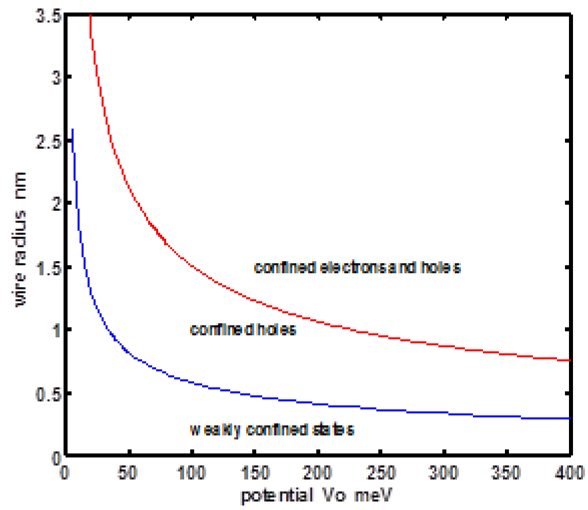

Fig.(8) Quasi-critical as a function of the band gap. Electrons and holes in quantum wires which are smaller than the quasi-critical radius are bound by the potential but are only weakly confined.

Equation (15) is plotted in Fig.(7) where, the gain is plotted as a function of the photon energy. This figure shows that the gain for a wire width of 5nm is larger than that of 15 nm by a factor of three. The material gain is proportional directly to the Dos_{1D}, therefore, any decrease of wire width resulting an increasing in the maximum of the gain value.

Equ. (16) is plotted in Fig. (8) which shows the variant of the wire radius with Vo , in which it is appear that there is a weekly confined states for the region where the wire radius is less than 1nm. The best confinement range is for r> 1.0 nm as it is shown in Fig.(8).

Conclusions

1-From the optimization of the quantum wire width it was found that there is a critical value for the quantum wire width $r_{c\ =1\ nm}$ below which the confinement of the carriers is weak.

2-The optimization of the structure and optoelectronic properties is very important for studying the QWR laser parameters i.e confinement factor, density of states, the optical gain, and the threshold current density .

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عملية الليزر للمقاس النانوي في الاسلاك الكمية لـAlGaAs/GaAs

احلام حسين جعفر ابتسام محمد تقي سلمان محمد حمد جسام

الخلاصة

في هذا العمل تم التحقق بالحساب النظري للتغيير في عدد من الخواص الالكتروبصرية لليزر السلك الكمي ل(AlGaAs/GaAs)، وقد تم التاكيد على حساب تاثير نصف قطر السلك على عامل الحصر ، كثافة الحالات، وعامل الكسب. لقد وجدنا ان هناك قيمة حرجة (r_c) لنصف قطر السلك ، يكون تحتها حصر الحاملات ضعيف جدا. في حين، عندما تكون القيمة اعلى منها يزداد عامل الحصر وبذلك يزداد الكسب مع زيادة نصف قطر السلك.