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Optical Confinement Factor of $Al_{0.7}Ga_{0.3}As/GaAs$ and $Al_{0.7}Ga_{0.3}N/GaN$ Quantum Wire Lasers

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Abstract: ***Recently, optical confinement factor has been established as an effective parameter for evaluating optimal performance by measuring threshold current and optical gain in the nano semiconductor laser diode. The effects of "well-width, wire-width, barrier-width and the quantum wire periodic"that are associated with the optical confinement factor of $Al_{0.7}Ga_{0.3}As/GaAs$and $Al_{0.7}Ga_{0.3}N/GaN$quantum wire structures were investigated.The active region of each one of these structures consisted multi-quantum well structures.Once of them (quantum wire structures) was consisting of five GaAs wells and four$Al_{0.7}Ga_{0.3}As$ barrier layers alternately and the cladding layer is AlAs, while for the other structure is consisting of five GaN wells and four$Al_{0.7}Ga_{0.3}N$ barrier layers alternately and the cladding layer is AlN. MATLAP software was used to the calculation. For both systems $Al_{0.7}Ga_{0.3}As/GaAs$ and$Al_{0.7}Ga_{0.3}N/GaN$, the optical confinement factor increases by increasing the well-width and wire-width.It has the highest value at the smallest barrier-width, 2nm. Also, the optical confinement factor decreases with increases quantum wire periodic. The values of optical confinement factor for $Al_{0.7}Ga_{0.3}As/GaAs$ less than $Al_{0.7}Ga_{0.3}N/GaN$ for the same values of well-width, wire-width and barrier-width.***

Keywords: Quantum Wire Lasers, Optical confinement factor, Multi-Quantum Well, QuantumWire, AlGaAs/GaAs, AlGaN/GaN

1. Introduction

Materials whose size is reduced to the nanoscale may suddenly exhibit unique properties very differently than those on the magnifying scale, resulting in unique applications that were not previously known [1]. For example, insulating materials are converted into conductive materials when shrinking to nanomaterial sizes [2]. Thus, size-dependent characteristics can be observed, where small size resultant the quantum confinement effect, due to demonstrate features on bandgap which increasing and accompanied by the quantization of the energy levels to discrete values [3]. The pursuit through nanotechnology is to possess the full ability to modify the mechanical, physical, and chemical properties of materials and their characteristics at the atomic and molecular levels to achieve high-efficiency material and desirable properties different from their bulk counterparts [4]. Especially semiconductor laser materials are affected by important factors such as the optical confinement factor (Γ), which is an important and effective factor for evaluating the performance of laser semiconductors. This factor is significantly affected by the volumetric scale of materials.In order to optimize a semiconductors laser performance for specific applicationsand to obtain optimal laser performance, the semiconductor laser materials must have a good characteristics including Γ and controlled. This makes the laser production process to be somewhat more complex than most conventional laser production methods.There is a strong correlation between the optimal laser performance of semiconductor and each of the threshold current and the active layer thickness. The optimal laser performance can be achieved through a low threshold current and reducing thickness of the active layer because of a direct link between them. This also, may be accomplished by the control on the scale of the active layer material which is greatly affecting Γ and thus affect the optimal performance of the laser materials [5]. For a good understanding to behavior of the optical confinement factor in the nanoscale materials we will focus on AlGaAs and AlGaN, The importance of AlGaAs and AlGaN over the past three decades as a result of the growing interest in these materials-based electronics can be largely attributed to the promising laser applications offered by low-dimensional these materials through the need to adjust its properties to improve performance for specific applications[6].

In the present work, comparative investigation to the importance of Γ and its related to the well-width, wire-width and barrier-width for the quantum wire structures (AlGaAs/GaAsand AlGaN/GaN). Where nanomaterials are expected to play a key role fundamentally important in explanation and understand how and why the threshold current and optical gain change with optical confinement factor and the active layer thickness as well as to provide model systems to demonstrate quantum size effects.

2. Theoretical Model

The overlap between optical-mode pattern (or optically guided wave) and gain region (i.e. quantum well) of the laser is expressed by defining a confinement factor (Γ), and it is determined according to the formula: [7,8, 9]

$$\Gamma = \frac{\int_{-w/2}^{w/2} \varepsilon_o^2(x)dx}{\int_{-\infty}^{+\infty} \varepsilon_0^2(x)dx} \quad (1)$$

Where$\varepsilon_o(x)$ is the electrical field intensity of the first transverse mode (TE_o) generation in active layer.
The overlap of the optically guided wave with the single quantum well (SQW) described by the optical confinement factor, according to the following formula:[9,10]

$$\Gamma^{SQW} \cong \frac{T^2}{T^2+2} \quad (2)$$

Where T is the normalized thickness of active layer given by: $T = 2\pi\left(\frac{w}{\lambda}\right)\sqrt{(n_w^2 - n_c^2)}$, where, w is the active layer

width, $\lambda$is the emitted wavelength and n_c, n_w are the refractive indexes ofcladding and active layers respectively.
The refractive indices for $Al_xGa_{1-x}As$ and $Al_xGa_{1-x}N$ materials are n_1 and n_2 respectively which can be calculated from the following formulas: [11, 12]

$$n_1 = 3.59 - 0.71x + 0.091x^2 \qquad (3a)$$
$$n_2 = 2.5067 - 0.43x \qquad (3b)$$

The refractive index can vary significantly when using heterostructures. Thus, the optical confinement factor of the multi-quantum well (MQW) can be written as[13]:

$$\Gamma^{MQW} = \Gamma^{SQW} \frac{N_w\, w}{D} \qquad (4)$$

Where D is the average thickness of the active layer, and N_w and w are the numbers of wells and well width, respectively. Recognizing that the components being the wells number and the barrier layers number,N_B, are important for the considerations of the calculation of D in equation (4), we arrive at an equation which describes the average thickness of active layer: $D = N_w w + N_B B$. For the both two systems SQW and MQW, the values of the coefficient N_w and N_B can be defined as follow:

$$N_w = 1, \quad N_B = 0 \qquad \text{for SQW}$$
$$N_B = N_w - 1 \qquad \text{for MQW}$$

The structure of well layers with homogeneous cladding layers and average thickness of active layer with average index refraction ($\bar{n}_r$) can achieve equation (4) [14].

$$\bar{n}_r = \frac{N_w\, w\, n_w + N_B B\, n_B}{D} \qquad (5)$$

For optical confinement factor of MQW, using $\overline{T}$ instead of T in equation (2), which is given by:

$$\overline{T} = 2\pi\left(\frac{D}{\lambda}\right)\sqrt{\bar{n}_r^2 - n_c^2}$$

Well-known in quantum structures such as quantum-wells (QW) and quantum-wire (QWR), the confinement effects exhibit in one dimension for quantum wells and in two dimensions for the quantum wires [15].At the same time, the energy bands (conduction and valence) exhibit discrete instead of the continuous energy bands as in bulk structures depending on the dimensions of the confining area according to the following equations [15, 16]:

$$E_i = \frac{(i\pi\hbar)^2}{2m^* w^2} \qquad \text{for quantum well}$$
$$E_{i,j} = \frac{(i\pi\hbar)^2}{2m^* w^2} + \frac{(j\pi\hbar)^2}{2m^* W^2} \qquad \text{for quantum wire}$$

Where W is the wire width and i,j are principle quantum numbers($i, j = 1, 2, 3, \dots$).

As for the MQW structure, optical confinement factor, which relies heavily on the structure, is given in the following formula for multi-quantum wire (Γ^{MQWR})in a symmetrical waveguide for the TEM_{oo} mode is[17].

$$\Gamma^{MQWR} = \Gamma^{MQW} N_w F \qquad (6)$$

Where F is the in-plane space filling factor of the active layer which is connected to the quantum wire periodic (Λ) according to the following formula: F = W / Λ

3. Results and Discussion

The optical confinement factor is the important parameter for nanostructure laser device. In quantum wire, this parameter affected by well width (w), barrier width (B), number of well (N_w), wire width (W) and the period of quantum-wire (Λ). These parameters illustrates in figure 1.

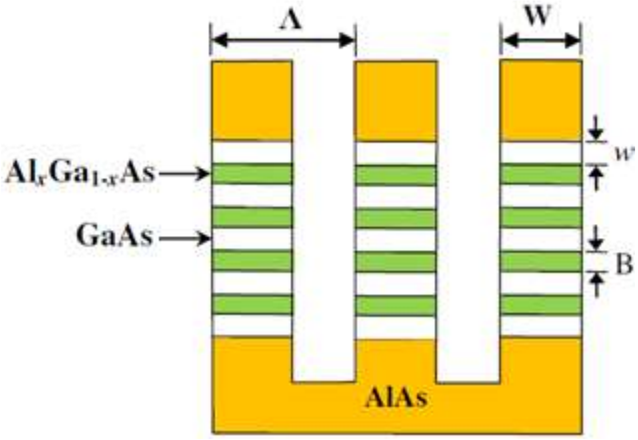
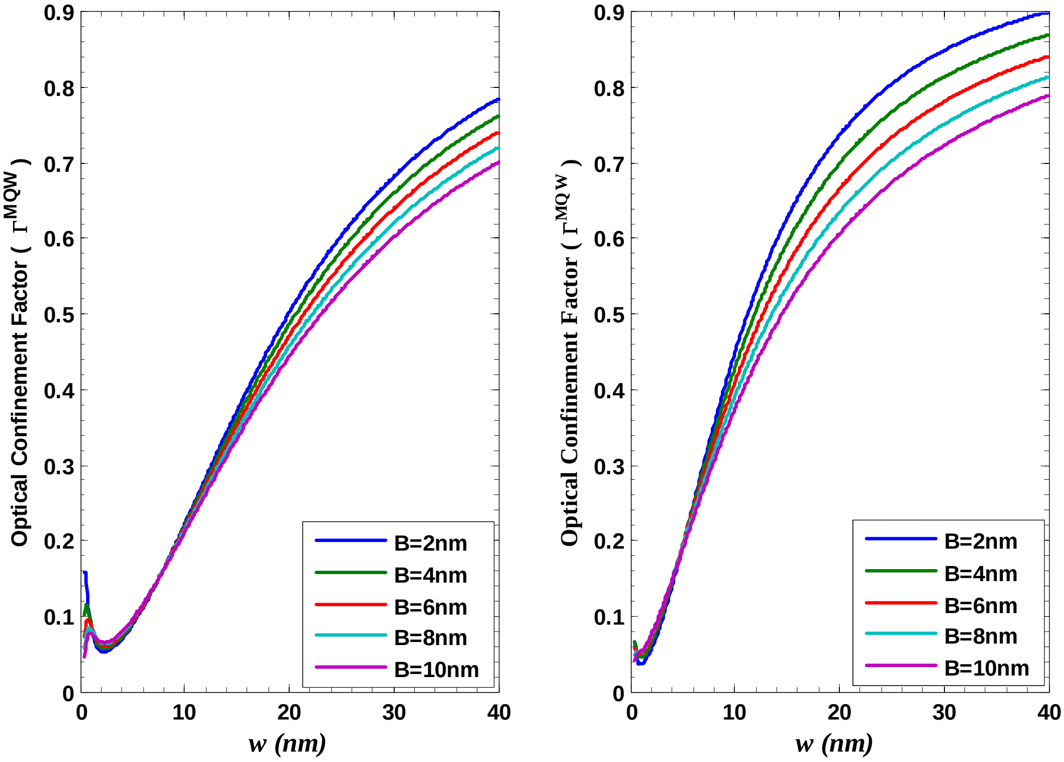


Figure 1: $Al_xGa_{1-x}As$ quantum wire structure

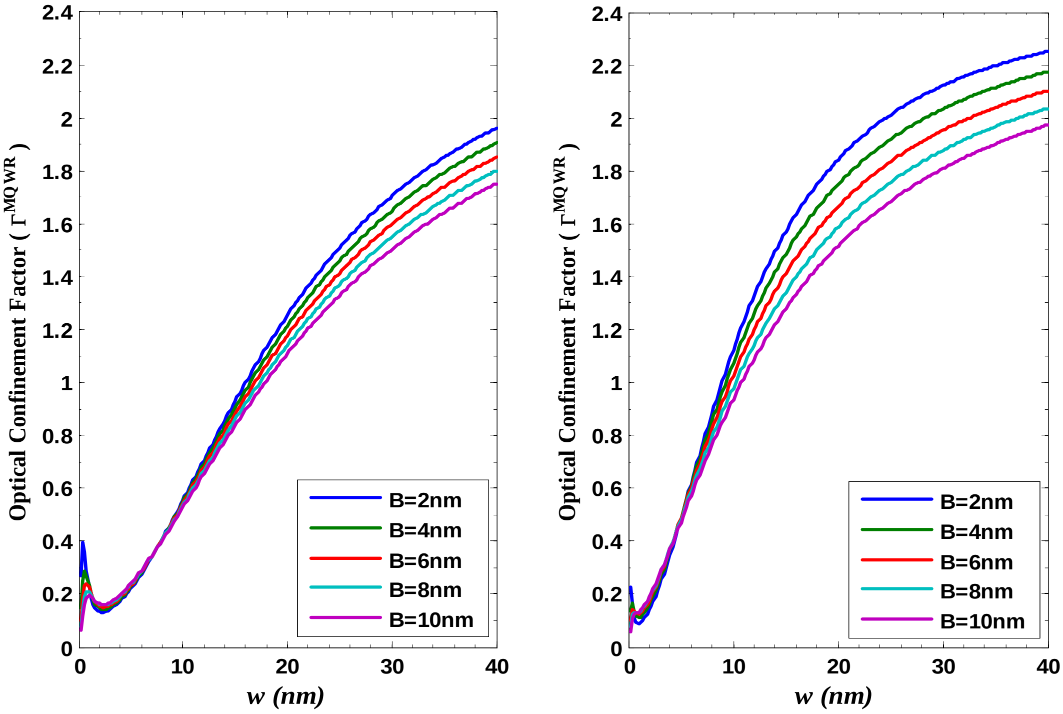
In this work used two quantum wire (QWR) structures. The active region of each one of these structures consisted multi-quantum well structures.Once of them (QWR) structures was consisting of five GaAs wells and four$Al_{0.7}Ga_{0.3}As$ barrier layers alternately and the cladding layer is AlAs, while for the other structure is consisting of five GaN wells and four$Al_{0.7}Ga_{0.3}N$ barrier layers alternately and the cladding layer is AlN. Multi quantum wells are considered due to their importance in different devices. MATLAPsoftware was used to the calculations.

The optical confinement factor ofmulti-quantum well(Γ^{MQW})for two structures ($\frac{Al_{0.7}Ga_{0.3}As}{GaAs}$and $Al_{0.7}Ga_{0.3}N/GaN$) were determined by using equations (2) and (4). Figure 2 shows that the (Γ^{MQW}) as a function of (w) for variation barrier widths (B) (2, 4, 6, 8, 10) nm. Figure 3 illustrates that the optical confinement factor of multi-quantum wire (Γ^{MQWR})versus (w) for different values of (B) which calculated by equation (6). It was drawn with 50nm of wire width and quantum wire periodic is 100nm.These curves in figures 2 and 3 intersect at the certain value of well width. At these values the optical confinement factors not change for any value of barrier width. However, at the values under the certain value for the well width, the changing rate of the optical confinement factor of the two nanostructures (MQW and MQWR) can be ignored with increased of barrier width (B). While the changing rate of optical confinement factor at values higher than that the certain value at the 2 nm barrier width be higher than the other barriers.



(a) (b)

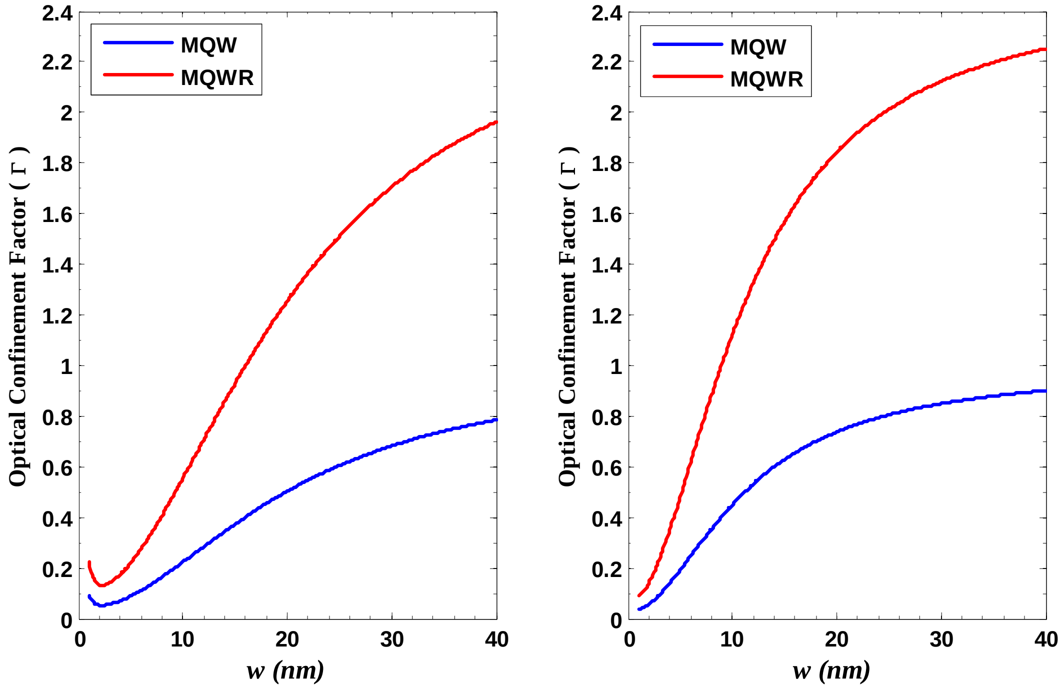
Figure 2: The various of optical confinement factor of quantum wellwith well width (*w*) for different barrier widths (B) for 5QWs (a) $Al_{0.7}Ga_{0.3}As/GaAs$ (b) $Al_{0.7}Ga_{0.3}N/GaN$



(a) (b)

Figure 3: The various of Γ^{MQWR} with well width (*w*) for different barrier widths (B) for 5QWs (a) $Al_{0.7}Ga_{0.3}As/GaAs$ (b) $Al_{0.7}Ga_{0.3}N/GaN$

For the muti-quantum well structure, the optical confinement factor is small in comparison with multi-quantum wireby 60% at each value of well width as illustrated in figure 4. From this figure, it is clear that the (Γ^{MQWR}) with w=15nm and B=2nm is 0.929 for $Al_{0.7}Ga_{0.3}As/GaAs$ and is 1.569 for $Al_{0.7}Ga_{0.3}N/GaN$, while for MQW structure is 0.372 for$Al_{0.7}Ga_{0.3}As/GaAs$ and is 0.628 for $Al_{0.7}Ga_{0.3}N/GaN$for the same value of *w*and B.because the quantum confinement effect in QWR structure is higher than it in QW structure, where the carriers confinement in two dimensions in QWR while this confinement occurs in QW at one dimension.



(a) (b)

Figure 4: The optical confinement factor versus well width for two structures (MQW and MQWR) for (a) $Al_{0.7}Ga_{0.3}As/GaAs$ (b) $Al_{0.7}Ga_{0.3}N/GaN$

Figure 5 illustrates that the (Γ^{MQWR}) as a function of (w) for two structures. This figure shows that the (Γ^{MQWR})increases with increasing well width,as well as the optical confinement factor for$Al_{0.7}Ga_{0.3}As/GaAs$structure is smaller than the optical confinement factor for $Al_{0.7}Ga_{0.3}N/$ GaNstructure.

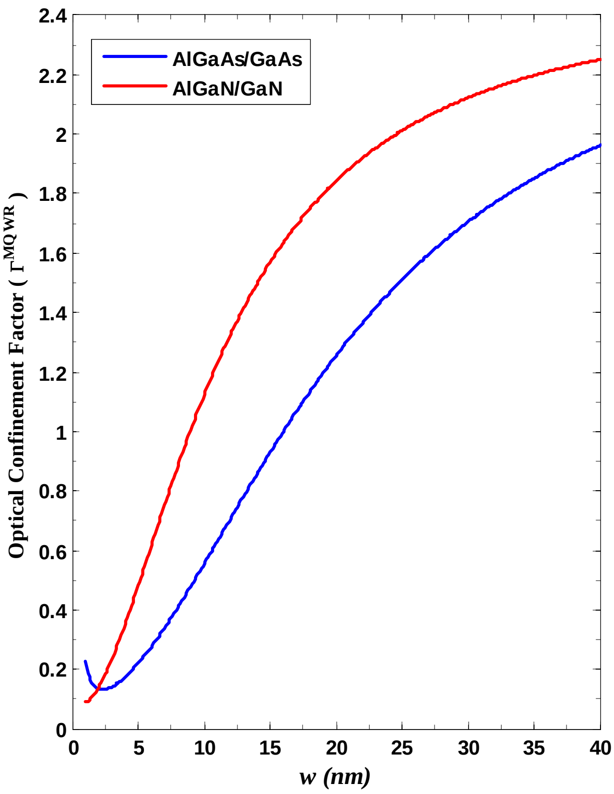
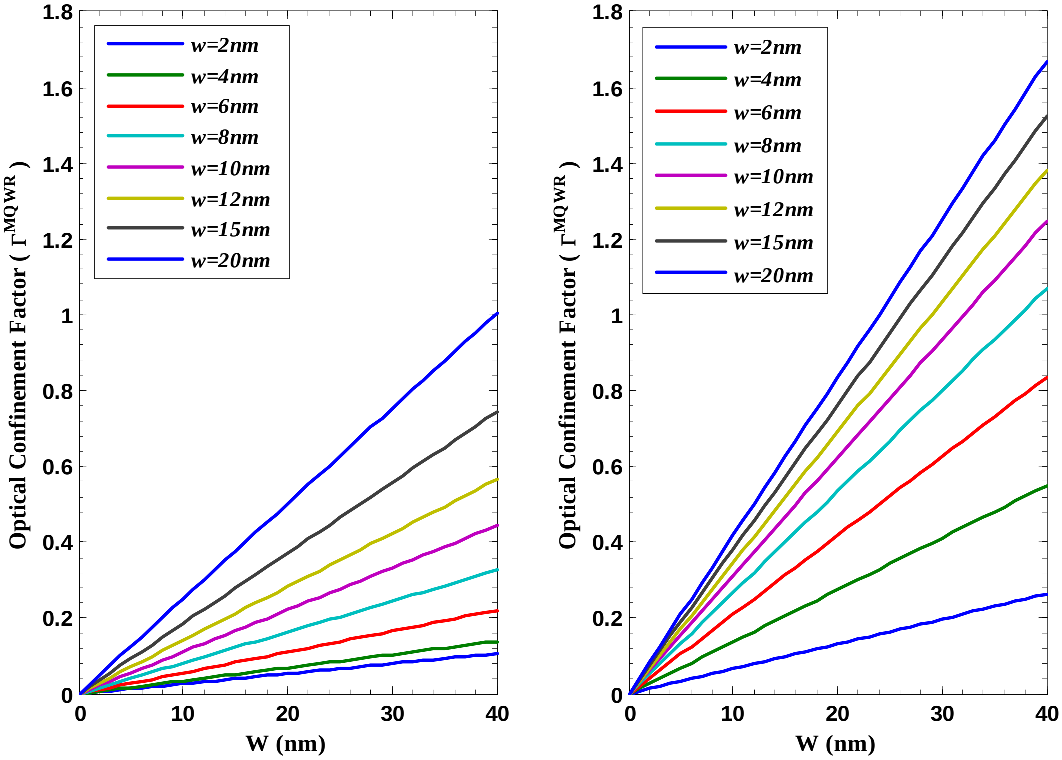


Figure 5: The Γ^{MQWR} as a function of well width for B=2nm for two MQWR structures.

The(Γ^{MQWR})as a function of wire width for various valuesof well width whichshown in figure 6. It is clear that the (Γ^{MQWR})increases with increasing wire widthfor each value of well width and increases with increasing well width. Figure 7 shows that the(Γ^{MQWR})forthese two structures as a function of wire width (W) at well width (w)=15nm. It is clear that the (Γ^{MQWR})for$Al_{0.7}Ga_{0.3}As/GaAs$ structure is small for each value of wire width comparison with (Γ^{MQWR}) for$Al_{0.7}Ga_{0.3}N/GaN$ by 50%.



(a) (b)

Figure 6: The Γ^{MQWR} as a function of wire width for different well widths for 5QWs (a) $Al_{0.7}Ga_{0.3}As/GaAs$(b) $Al_{0.7}Ga_{0.3}N/GaN$

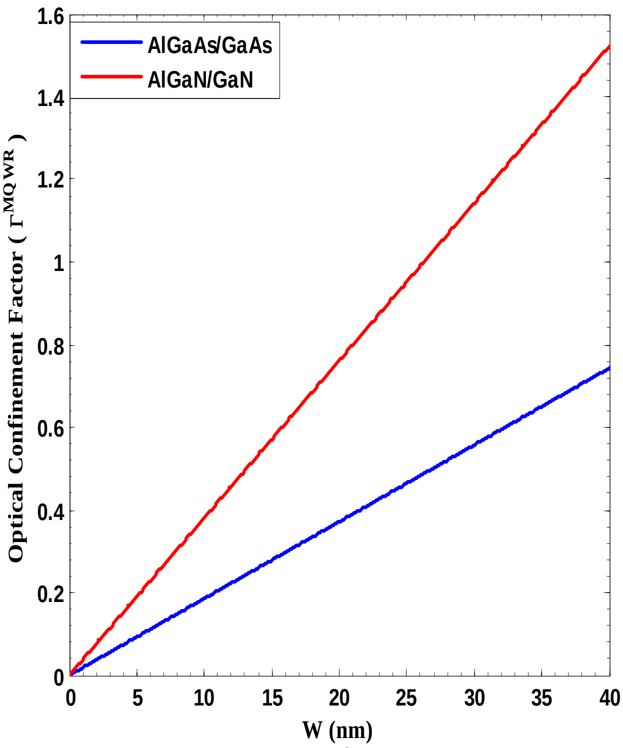


Figure 7: The various of Γ^{MQWR} with wire width for *w*=15nm for two structures.

The optical confinement factor versusthe periodic of quantum wire for different well width (5, 10, 15, 20, 25)nm shows in figure 8. It is clear that the (Γ^{MQWR})increases with increasing well number, and decreases with increasing the periodic of quantum wire. Where these increases of the periodic of quantum wireleads to increases the interval between the quantum wire and the next quantum wire. Figure 9 illustrates thatthe(Γ^{MQWR})for$Al_{0.7}Ga_{0.3}As/GaAs$ is smaller than (Γ^{MQWR}) for $Al_{0.7}Ga_{0.3}N/GaN$ for well width (*w*=15nm).

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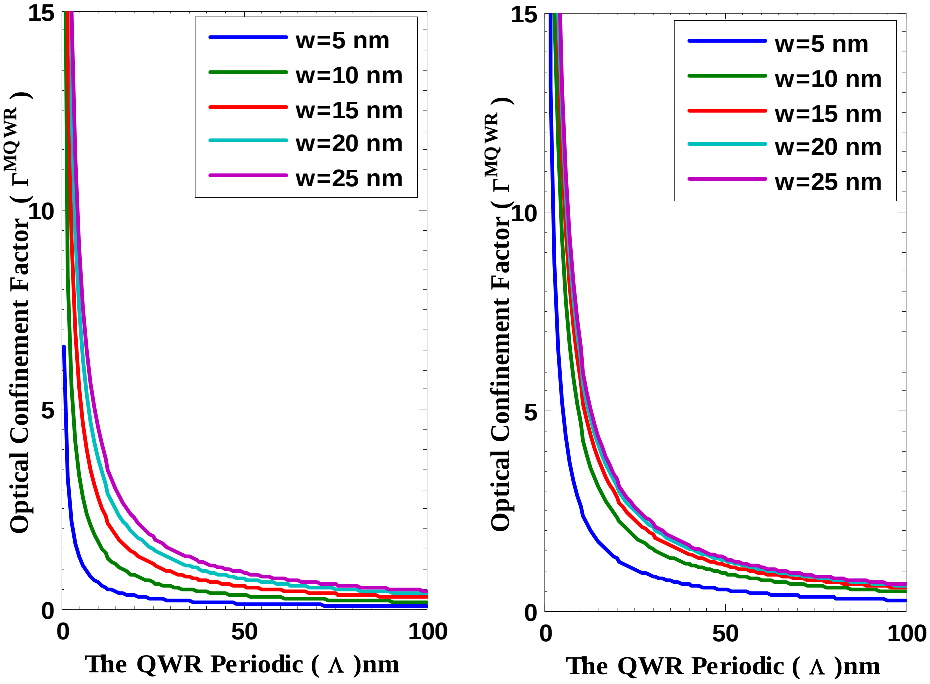

(a) (b)

Figure 8: The various of Γ^{MQWR} withthe quantum wire periodic for changed wire widths for 5QWs (a) $Al_{0.7}Ga_{0.3}As/GaAs$ (b) $Al_{0.7}Ga_{0.3}N/GaN$

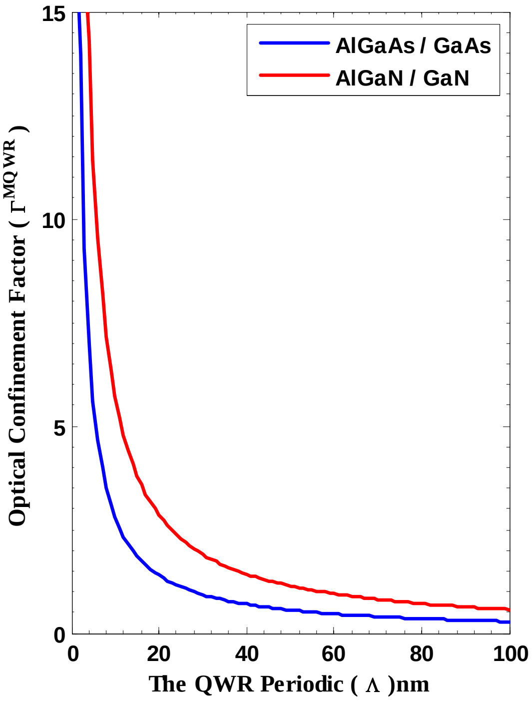

Figure 9: The optical confinement factor of quantum wire as a function of the quantum wire periodic for W=*w*=15nm for two structures

4. Conclusions

In conclusions, $Al_{0.7}Ga_{0.3}As/GaAs$ and $Al_{0.7}Ga_{0.3}N/GaN$ quantum wire laser systems emitted wavelength 872 nm in IR range and362 nm in UV range respectively. The optical confinement factor of these structures increases with increasing well widths and wire widths. It has highest (best) value for smallest barrier width (2nm). The optical confinement factor of quantum wire laser structure of $Al_{0.7}Ga_{0.3}As/GaAs$ is small comparison with $Al_{0.7}Ga_{0.3}N/GaN$ for the same well width, barrier widths andthe periodic of quantum wire.Also that the optical confinement factor of quantum wires of these two QWR laser structures$Al_{0.7}Ga_{0.3}As/GaAs$and $Al_{0.7}Ga_{0.3}N/GaN$ decreases with increasing the periodic of quantum wire.

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