Bias-Voltage Dependence on Thermoelectric Cooler Coefficient for $Al_{0.7}Ga_{0.3}As$ and $In_{0.2}Ga_{0.8}As$ SQW Laser Diode

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Abstract

The theoretical investigation of thermoelectric phenomena in single quantum well (SQW) laser diode was described in this work. Diode laser devices can be modeled by introducing a bias-dependent Peltier coefficient at interfaces that takes into account the variation of the carriers' average transport energy. The effective Peltier coefficient can vary as a function of applied bias voltage, and can give rise to interfacial thermoelectric cooling or heating depending on device parameters. The temperature dependences of the threshold current at different temperature are investigated for the laser diode, a record characteristic temperature T_0=110 K has been achieved for AlGaAs and T_0=50 K for InGaAs. The bias voltage dependent bipolar Peltier coefficient is modeled for SQW laser diodes, and the different regimes of bias voltage for which cooling is achieved are described. In this work two type of SQW laser diode were studied they are AlGaAs and InGaAs. The comparison of the theoretically calculated laser parameters; namely, confinement factor, threshold current density and the output power density of SQW GaAs/$Al_{0.7}Ga_{0.3}As$ and GaAs/$In_{0.2}Ga_{0.8}As$ laser showed that the confinement factor is a very important parameter for the performance of this quantum well laser.

Keywords: Thermoelectric cooler, confinement factor, SQW laser diode.

I. Introduction

Since laser diodes were developed, techniques have been developed to change their operating characteristics from their normal values to something that better suits a particular user, their production is driven by their use in the telecommunication industry [1]. Their low cost availability and ease of use often make performing such engineering feats preferable to pursuing other technologies. The heat management plays a crucial role in the performance and reliability of laser diode [2], [3]. Quantum well (QW) laser diodes (LDs) have been of interest for their applications such as recordable or rewritable optical disk systems [4]. Semiconductor lasers emitting near $0.98\mu m$ fabricated using InGaAs SQW structures are of considerable interest for application as pump lasers for erbium-doped glass fiber amplifier. Thus, in addition to high power output, high fiber coupling efficiency is an important parameter for the design of these lasers [5]. Such devices demand efficient heat management since their performance decreases drastically with increasing chip temperature. Heat management of the laser diode critically affects laser wavelength, output power, threshold current, slope efficiency, and operating lifetime [6]. For example, lasing wavelength shifts significantly with changes in junction temperature. The threshold current of a laser diode increases while the slope efficiency decreases exponentially with the junction temperature. In addition, junction temperature affects laser operation lifetime exponentially [7]. For all these reasons, heat management of the laser diode is crucial to the device performance. Attempts to manage heat sources at this size scale have met with limited success, although solid state cooling and power generation based on thermoelectric effects have been known since the Seebeck effect (for power generation) which was discovered in 1821. The thermoelectric cooling is associated exclusively with the Peltier effect which was discovered in 1834 by Peltier. Usually this effect is defined as absorption of heat or its evolution (in addition to the Joule heat) on the junction of two conductors through which a Dc electric current passes. The absorption of this heat or its evolution depends on the direction of the electric current [8]. Thermoelectric effects such as Peltier cooling occur when carriers move between regions in which their near-equilibrium energy distribution changes. In this process, heat energy is transported out of the device through the radiative recombination of thermally excited carriers whose energies are greater than the electrical bias energy. In these devices a high density of heat, on the order of kW/cm^2 is generated over a very small area which cause's a change in the device characteristics and emitted wavelength [1].

The purpose of this paper is threefold. **(1)** To give a generalized description of the SQW laser diode structure and basic physical parameter of SQW laser. **(2)** To present a mathematical method for determining the amount of optical confinement factor, threshold current density, output power density, internal quantum efficiency and device sensitivity temperature. **(3)** To analyzing and comparing the basic parameter obtained for InGaAs with AlGaAs. The laser diode chosen for our investigation is single quantum well (AlGaAs and InGaAs) due to its important in communication system, well material is GaAs, barrier material is $Al_{0.7}Ga_{0.3}As$, AlAs as the cladding layer and $In_{0.2}Ga_{0.8}As$, InAs as the cladding layer. Its laser emission is in the near-infrared spectral region at wavelength of 870 nm for AlGaAs and 980 nm for InGaAs. MATLAB version 7.8 has been used for simulation and calculation. The paper is organized as follows: The next section II is dealing with the Peltier effect and optical confinement factor. The description of the theoretical investigation of the affecting parameters on the threshold current density follows in the section III. In Section IV the heat exchange at the junction will be presented and discussed in comparison for InGaAs with AlGaAs. Finally, Section V summarizes the conclusions.

II. Peltier Effect and Optical Confinement Factor

Diffusion in semiconductors occurs from hot regions to cold regions, making the Seebeck coefficient negative if the majority carriers are electrons and positive if the majority carriers are holes [9]. In doped semiconductor, carriers are constrained at a distance from the Fermi level and therefore transport more heat energy. This leads to a higher Seebeck coefficient than that of the metal [10]. It is well known that Seebeck effect is associated with the generation of a voltage along a conductor when it is subjected to a temperature difference. Charged carriers (electrons or holes) diffuse from the hot side to the cold side, creating an internal electric field that opposes further diffusion. The Seebeck coefficient is defined as the voltage generation per degree of temperature difference between two points [11]:

$$S = \frac{\Delta V}{\Delta T} \text{...............}(1)$$

where ΔV is the voltage gradient and ΔT is a temperature gradient

The Peltier effect reflects the fact that when carriers flow through a conductor, they also carry heat. The heat current *Q* is proportional to the charge current I [11]:

$$Q = \Pi \times I \text{...............}(2)$$

Π is called Peltier coefficient. When two materials are joined together, there will be an excess or deficiency in the energy at the junction because the two materials have different Peltier coefficients. The excess energy is released to the lattice at the junction, carrying heating while the deficiency in energy is supplied by the lattices creating cooling. The Seebeck and the Peltier coefficients are related through [11]:

$$\Pi = S \times T \text{..............}(3)$$

where T is the absolute temperature.

In the case of a semiconductor layer between two metal contacts, as shown in fig.(1a), the current is carried by majority carriers that are either electrons or holes depending on whether the semiconductor is doped with donors or acceptors respectively. Since electrons and holes have opposite charge, carriers in n-type and p-type regions flow in opposite directions for a given direction of current flux, and heat will be extracted/deposited at opposite junctions. If an array of n-type and p-type blocks are connected electrically in series but thermally in parallel, the applied current will cause a net transfer of heat from one side to the other, cooling one side of the array. This method of connecting an array of n-type and p-type materials with metal junctions is known as commercial or conventional Peltier cooler [1]. To motivate the thermoelectric effects to the case of bipolar devices such as diode, as shown in fig.(1b) more complicated thermoelectric description is needed. This complication is due to that the Seebeck coefficients for the diode's n-type and p-type regions (related to the average carrier transport energy) have components for both majority and minority carriers, and are also bias dependent due to the change in carrier concentration with injection [12].

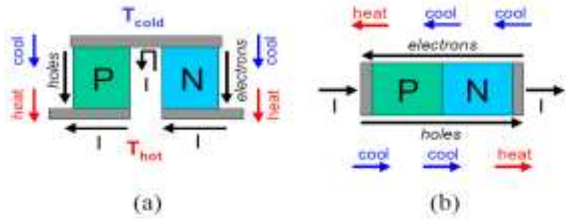

Fig.(1): (a)Conventional Peltier cooler. (b) Diode [1].

One of the parameters necessary for the accurate modeling of semiconductor lasers is the optical confinement factor. The optical confinement factor Γ, defined as the fraction of the energy of a particular waveguide mode confined to the active region, as the Γ increases as the active region thickness d increases [13]. It was also defined as the ratio of the light intensity within the active region to the sum of light intensity both within and outside the active region [14]. The analytical approximation for calculating the optical confinement factor Γ in a SQW is given by [15]

$$\Gamma = \frac{D^2}{D^2 + 2} \text{...............}(4)$$

$$D = 2\pi(\frac{w}{\lambda})\sqrt{(n_{r,w}^2 - n_{r,c}^2)} \text{...............}(5)$$

where w is the well width, λ is the vacuum wavelength at the lasing photon energy and D is the normalized thickness of the active region and $n_{r,w}$ and $n_{r,c}$ are the refractive indices of the active and cladding layers respectively.

Significantly higher differences of the refractive index can be achieved with heterostructures. The laser parameters and constants which will be used in the calculation needed in this paper are listed in table (1). For GaAs/$Al_{0.7}Ga_{0.3}As$ and GaAs/$In_{0.2}Ga_{0.8}As$ heterostructure the refractive index depending on the Al-content are calculated by using equations (6a,b). The difference between the refractive indices of GaAs/$Al_{0.7}Ga_{0.3}As$ and GaAs/$In_{0.2}Ga_{0.8}As$ depends on x is given by [16]:

$$n_r(GaAs) - n_r(Al_xGa_{1-x}As) = 0.62x \text{.....}(6a)$$

$$n_r(GaAs) - n_r(In_xGa_{1-x}As) = 0.62x \text{.....}(6b)$$

Table (1): Represents the list of constants that used in this paper:

Const.	$In_{0.2}Ga_{0.8}As$	$Al_{0.7}Ga_{0.3}As$	Unit	Ref. No.
η_{in}	80%	90%	none	[18]
g_o	1800	225	cm^{-1}	[18]
α	5	10	cm^{-1}	[14]
L	250	200	μm	[14]
k_B	1.3807×10^{-23}	1.3807×10^{-23}	J/K	[18]
H	6.626×10^{-34}	6.626×10^{-34}	J-s	[18]
n(*GaAs*)	3.59	3.59	none	[14]

III. Influence parameters on the threshold current density

I. Influence of the Confinement factor

The confinement factor of the fundamental mode was calculated using eq. (4) for both SQW AlGaAs and InGaAs. The results obtained are shown in fig.(1) in which the confinement factor Γ is drown as a function of well width. It is clear from this figure that Γ is increasing as the well width increases for all values of the barrier widths for both SQW laser diode structure. It was obtained that at maximum well width (w=30 nm) the confinement factor of InGaAs is approximately equal to Γ =0.0709 whereas for AlGaAs it's equal to Γ =0.0154. The confinement factor for AlGaAs is very small in comparison with InGaAs, because the gain may not equal or exceed the total losses in the waveguide region [19].

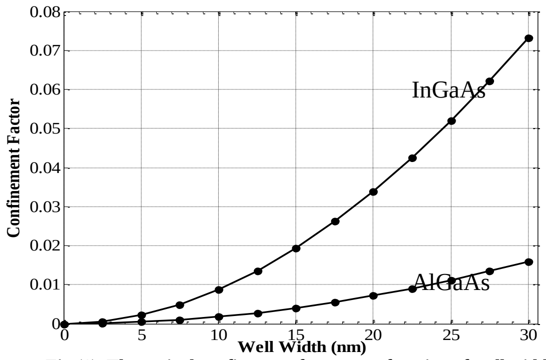

Fig.(1): The optical confinement factor as a function of well width for both SQW structure for different barrier width.

For strongly confined structures the threshold current density J_{th} for stimulated emission was calculated, taking care for the light confined within the active layer. The calculated threshold current density as a function of Γ for SQW lasers obtained by using equation:

$$J_{th} = \frac{J_o d}{\eta_{in}}\left\{1+\frac{1}{g_o\Gamma}\left[\alpha+\frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)\right]\right\} \quad \ldots\ldots\ldots\ldots(7)$$

Where η_{in} is internal quantum efficiency, J_o current density, g_o is the gain coefficient, Γ is the confinement factor, L is the cavity length, R_1R_2 are the reflectivity of the mirror, α is the loss coefficient and d is the active region thickness.

The calculated threshold current density as a function of Γ is illustrated in fig. (2a,b), the calculated J_{th} for active region thickness of maximum well width and Γ=0.0154 for AlGaAs is $J_{th}=0.38\times10^6$ A/cm^2 and Γ=0.0709 for InGaAs is $J_{th}=0.25\times10^6$ A/cm^2, this difference is principally due to a smaller confinement factor and also due to the inverse relation between threshold current density and confinement factor as shown in eq.(7).

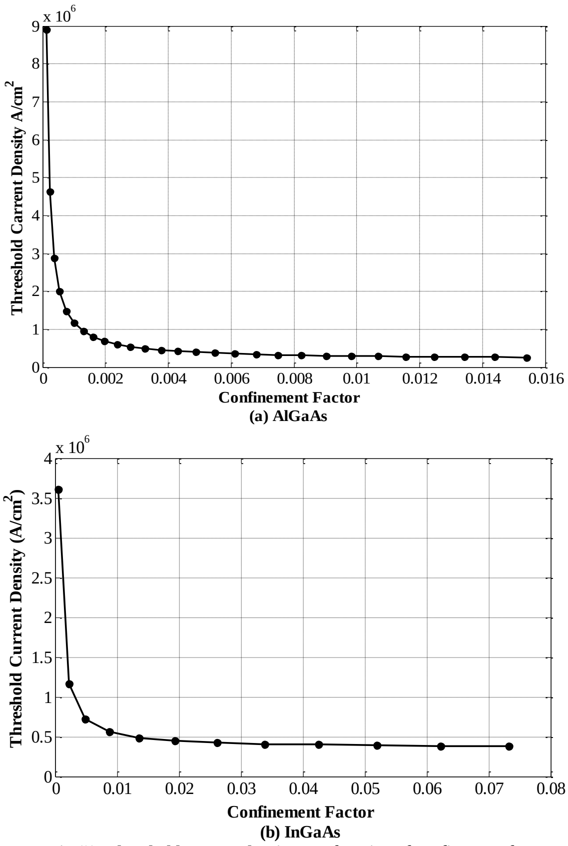

Fig.(2): Threshold current density as a function of confinement factor for both SQW structures.

The threshold current density as a function of temperature can be written as:

$J_{th} = J_o \exp(T/T_o)$……………(8)

Where T_o is an important factor which represent the sensitivity of the laser diode with changing temperature and it is also called the threshold temperature coefficient [20]. For AlGaAs devices, T_o is usually in the range 120 to 190 K, whereas for InGaAsP devices it is between 40 and 75 K [21]. This emphasizes the stronger temperature dependence of InGaAsP structures. Fig.(3) shows that $\ln(J_{th})$ increases linearly with increasing device temperature, from the fig.(3), T_o calculated for AlGaAs it was equal to (110K) and for InGaAs it was equal to (50K).

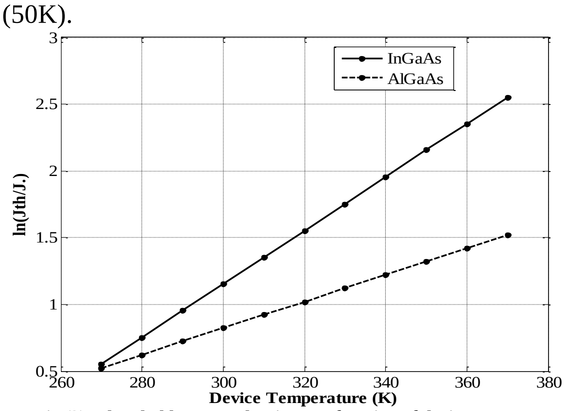

Fig.(3): Threshold current density as a function of device temperature for AlGaAs and InGaAs SQW structure.

The large value of T_o for AlGaAs indicates low sensitivity of this device to temperature.

II. Output Power-Current Characteristics

The relation between the output power and the injection current is a fundamental characteristic of a laser diode. The expression for calculating output power can be given by eq.(9):

$$P = \eta_{in} E_g \left(\frac{\ln \frac{1}{R_1 R_2}}{2\alpha L + \ln \frac{1}{R_1 R_2}} \right) (J - J_{th}) \quad ....(9)$$

The results obtained for the power density as a function of the current density for both SQW structures is shown in fig.(4). We calculated J_{th} for SQW at room temperature. We observed that, InGaAs device is required high injection current for lasing, because of higher J_{th}. For small injection current density values, less than J_{th}, the device performance is a spontaneous emission. As the current density is increased and the gain of the active medium developed, stimulated emission is occurred, and output power start to increase with increasing injection current. At any value of the injected current density in fig.(4) ,($J=3.65\times10^6$ A/cm^2), the output power density for AlGaAs is about (3.5×10^5 W/cm^2) and for InGaAs is about (5.6×10^5 W/cm^2). The Slope efficiency or differential quantum efficiency defined as the increase in light output due to an increase in the current and are calculated by using eq.(10) and eq.(11). By using eq. (11) we calculated the slope efficiency and we get 89%, and also it was calculated through eq.(10) with the P-J characteristic curve of fig.(4) we got $\eta_s = 90\%$.

$$\eta_s = \frac{dP_{op}/hf}{dI/q} = \frac{dP_{op}}{dI(E_g)} \quad ....(10)$$

$$\eta_s = \eta_{in} \frac{\left(\ln \frac{1}{R_1 R_2} \right)}{\left(2\alpha L + \ln \frac{1}{R_1 R_2} \right)} \quad ....(11)$$

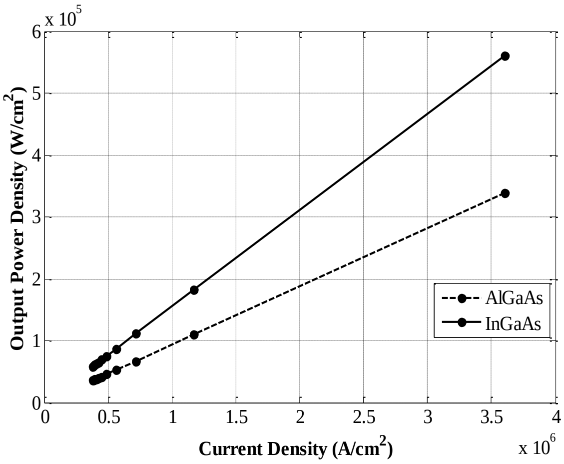

Fig.(4): Output power density as a function of injection current density for SQW structures.

IV. Heat exchange at the junction

The amount of the heat exchange at the junction associated with the Peltier coefficient can be calculated by referring to eq.(12). The results are depicted fig.(5) where heat exchange density at the junction Q_j and the current density are drawn as a function of bias voltage. According to eq.(13) and fig.(6), the bias current density is increasing linearly with the exponential of Junction voltage V_j.

$$Q_j = -J(V_{bi} - V_j) = JV \quad ....(12)$$

$$J = J_s\left(e^{qV_j/k_BT} - 1\right) \quad ....(13)$$

where J_s is the diode saturation current density and q is the electron charge.

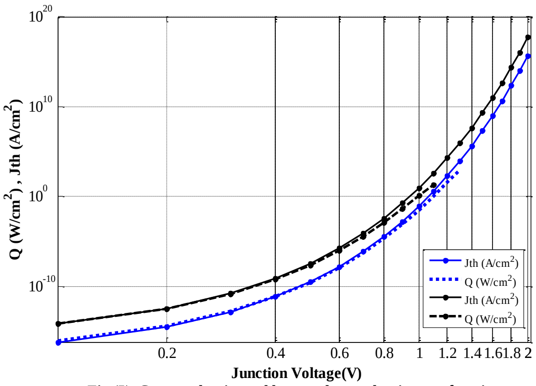

Fig.(5): Current density and heat exchange density as a function of junction voltage for both SQW laser diode structure.

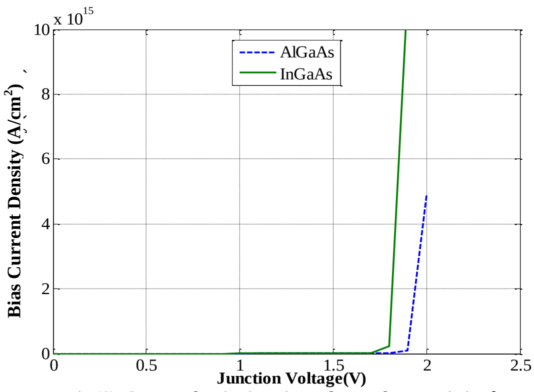

Fig.(6): Current density-junction voltage characteristics for both SQW laser diode structure at temperature 300K.

The amount of cooling Q_j is also increasing as the forward bias at the junction increases. However this behavior of Q_j changes when V_j approaches V_{bi} so that Q_j drops rapidly. We can see that the maximum value of the cooling power $Q_j = 2.452\times10^3$ W/cm^2 occurs when $V_{bi}-V_j = 1.392-1.366 = 0.026$V which is equivalent to the value of k_BT/q at room temperature. This verifies the condition appeared in eq.(14) for maximum Q_j and is a similar condition to heterobarrier cooler using thermionic emission [22]. Notice that the value of $V_{bi} = 1.392$V was calculated using eq.(15):

$$V_{bi} - V_j = \frac{K_B T}{q} \quad ....(14)$$

$$V_{bi} \cong \frac{k_B T}{q} \ln \frac{N_A N_D}{n_i^2} \quad ....(15)$$

Where N_D Donor concentration and N_A Acceptor concentration.

It is well known that heating in semiconductor lasers is detrimental to device performance and lifetime. The heat flows from an active medium of such structure is Q > 1000 W/cm^2 [23]. In this study a value of cooling power density at the level of $Q_j = 2.3\times10^3 W/cm^2$ is insured at the junction for AlGaAs and $Q_j = 4.8\times10^3 W/cm^2$ for InGaAs.

The calculated threshold current density and output power density versus cavity length for are shown in fig. (7a,b). The increase value of threshold current density and output power density as the cavity length is decreased are shown in this fig.(7a,b):

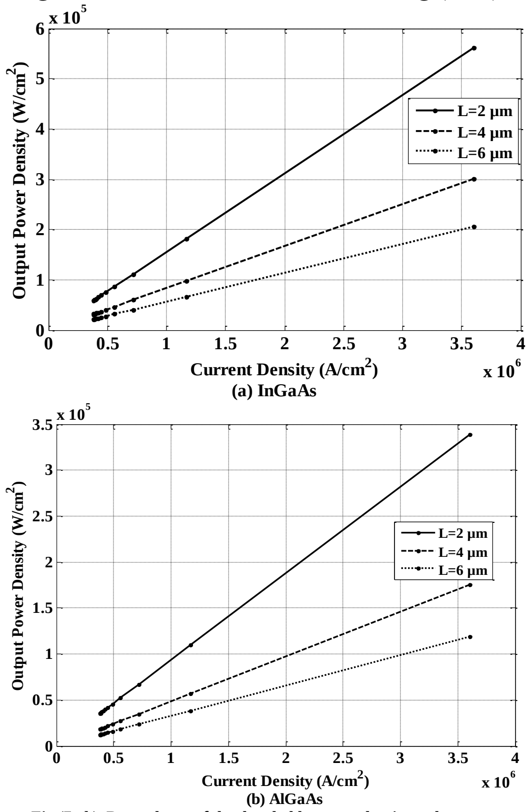

Fig.(7a,b): Dependence of the threshold current density and output power density on laser diode cavity length.

The mechanism of diode thermoelectric cooling is especially relevant to semiconductor laser diodes, whose performance is strongly dependent on the junction temperature. The comparison of the theoretically calculated laser parameters; namely, confinement factor, threshold current density and the output power density for SQW GaAs/$Al_{0.7}Ga_{0.3}As$ and GaAs/$In_{0.2}Ga_{0.8}As$ laser showed that the confinement factor is a very important parameter for the performance of this quantum well laser. Measurements of the single quantum well AlGaAs and InGaAs lasers have been used to determine optical confinement factor. The quantum well sample measured gave a theoretical $\Gamma = 0.0154$ for AlGaAs and $\Gamma = 0.0709$ for InGaAs, the better agreement arising from the improved understanding of the growth of InGaAs and AlGaAs. The parameters of internal quantum efficiency, device temperature and threshold current density that describe the operating characteristics of laser diodes are calculated and compared for both AlGaAs and InGaAs, the result is (an internal quantum efficiency of 92% for AlGaAs and 81% for InGaAs, a value of cooling power density at the level of $Q_j = 2.3\times10^3 W/cm^2$ is insured at the junction for AlGaAs and $Q_j = 4.8\times10^3 W/cm^2$ for InGaAs. The temperature dependence of the current density of SQW laser structure investigated and measured. A large T_o value of up to (110K) was observed for AlGaAs and (50K) for InGaAs, that is mean InGaAs is more sensitive than AlGaAs to the temperature.

V. Conclusions

References

1- K. P. Pipe and R. J. Ram, "Bias-dependent Peltier coefficient and internal cooling in bipolar devices", Phys.Rev.,B 66, 125316 , (2002).

2- H. U. Pfeiffer *et al.*, "Reliability of 980 nm pump lasers for submarine, long-haul terrestrial, and low cost metro applications," in Proc. Conf. Optical Fiber Communication, Tech. Dig. Series, vol. 70, pp. 483–484, (2002).

3- K. L. Bacher, "High power 14xx nm pump laser modules for optical amplification systems," Proc. SPIE, vol. 4533, pp. 47–59, (2001).

4- Soohaeng Cho, Yongjo Park, and Youngmin Kim, "660-nm GaInP–AlGaInP Quantum-Well Laser Diode Structures with Reduced Vertical Beam Divergence Angle,"IEEE photonics technology letters, vol. 17, No. 3, (2005).

5- N. K. Dutta, J. Lopata, P. R. Berger, D. L. Sivco and A. Y. Cho," Performance Characteristics Of GalnAs/GaAs Large Optical Cavity Quantum Well Lasers" Electronics Letters, Vol. 27, (1991).

6- D. Schroder, Semiconductor Material and Device Characterization. New York: Wiley, (1990).

7- G. M. Smith, D. A. S. Loeber, and S. D. Solimine, "High power 980 nm pump lasers," in Proc. LEOS'00 13th Annu. Meeting, vol. 2, pp. 512–515, (2000).

8- Dallas Maxim semiconductor, "Thermoelectric Cooler (TEC) Control", (2004).

9- J. J. Gu, M. W. Oh, H. Inui. And D. Zhang, "Anisotropy of mobility ratio between electron and hole along different orientations in $ReGe_x Si_{1.75-x}$ thermoelectric single crystals", Phys.Rev.,B, Vol. 71, 113201, (2005).
10- D. M. Rowe, CRC Handbook of Thermoelectric, CRC Press, New York, (1995).
11- G. Chen, M. S. Dreselhaus. G.Dresselhaus, J. P. Fleurial and T. Caillat, "Recent developments in thermoelectric materials", International Materials Reviews, Vol. 48, No. 1, (2003).
12- K. P. Pipe, R. J. Ram, and A. Shakhouri, "Bipolar Thermoelectric Devices", MIT Lincoln Lab., DARPA-university Opto Centers, RLE Progress Report 144, (2001).
13- M. J. Connelly, Semiconductor Optical Amplifiers, London, (2002).
14- Z. I. Kazi, T. Egawa, T. Jimbo, and M. Umeno, "Gain Coefficient, Quantum Efficiency, Transparency Current Density, and Internal Loss of the AlGaAs–GaAs-Based Lasers on Si Substrate", IEEE photonics technology letters, Vol. 11, (2004)
15- G. P. Agrawal, and N. K. Dutta, Long-Wavelength Semiconductor Lasers, Van Nostrand Reinhold, New York. 2nd edition, (1986).
16- M. Jaros, Physics and Applications of Semiconductor Microstructures, Clorendon Press-Oxford, (1989).
17- Goldberg Yu.A. M. Levinshtein, S. Rumyantsev and M. Shur, Handbook Series on Semiconductor Parameters, ed., World Scientific, London, vol.2, pp. 1-36, (1999).
18- S. M. Sze, Physics of Semiconductor Devices, 3ed, (2007).
19- M. Jain, J. Roberts, and C.N. Ironside, "Analysis of the gain distribution across the active region of InGaAs-InAs/GaAs multiple quantum well lasers", IEEE. Proc.-Optoelectronics, Vol. 152, No.4, pp. 209-214, (2005).
20- Bhattacharya, P., (semiconductor optoelectronic devices), Pearson education, Inc, 2nd ed., India, (1997).
21- J. M. Senior, Optical Fiber Communications, Prentice Hall series in Optoelectronics, 2nd edition, (1992).
22- A. Shakouri, E. Y. Lee, D. L. Smith, V. Norayanamurti, and J. E. Bowers, "Thermoelectric Effects in Submicron Heterostructure Barriers", Report USA. pp. 37-47, (1998).
23- V. V. Apollonov, A. N. Prokhorov, and A. H. Guenther, "Power Optics, Problems, Developments, and Opportunities", Laser Physics, Vol. 11, (2001).

اعتمادية فولتية الانحياز على معامل الكهروحراري لليزرات $Al_{0.7}Ga_{0.3}As$, $In_{0.2}Ga_{0.8}As$ ذات البئر المنفرد

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الملخص

الهدف من البحث هو التحقيق النظري لظاهرة التبريد الكهروحراري في ليزر دايود ذات بئر كمي منفرد (SQW)، حيث أستخدم نوعين من هذه الليزرات لغرض المقارنة النظرية من حيث عامل الحصر وهما $Al_{0.7}Ga_{0.3}As$ و $In_{0.2}Ga_{0.8}As$ ، أن معامل بلتير يعتمد اعتمادا شديداً على فولتية الانحياز ويمكن أن ينتج عنها تبريداً كهروحرارياً جيداً للسطوح البينية من خلال الاعتماد على عوامل النبيطة وأتضح أن اعتماد كثافة قدرة التبريد على كثافة تيار العتبة يرتبط الى حد كبير بعوامل تركيب الطبقات في المنطقة الفعالة ، وتمت دراسة أعتمادية التيار العتبة على درجة الحرارة ووجدت بأن T_0=110 K بالنسبة الى $Al_{0.7}Ga_{0.3}As$ و T_0=50 K بالنسبة الى $In_{0.2}Ga_{0.8}As$ و جرى تحليل أمثل لعوامل الثنائي الليزري المتمثلة في عامل الحصر و كثافة تيار العتبة و كثافة القدرة الخارجة لبئر كمي منفرد حيث أستخدم برنامج MATLAB إصدار ٧,٨ وذلك لتحليل و مقارنة النتائج. وقد ظهرت من خلال هذه البحث أن العامل الحصر هو معيار مهم لأجل أداء جيدا لهذه النوع من ليزر دايود ذات بئر كمي منفرد.