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Effect of Surface Density and Mean Size of Quantum Dot on Properties of GaInAsP/InP QDL System

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Abstract: *In this work, we studied the effects of surface density of quantum dots and the mean size of quantum dots (QDs) on dynamics of quantum dot laser (QDL). Here, detailed theoretical study of the parameters effect on some properties of GaInAsp/InP QDL system at 1.55 µm wavelength. It includes the following variables: the threshold current density, confined level occupancy, internal loss coefficient, optical confinement layer. In addition, it is diagnosed their role to determining the amount of the maximum temperature of laser. By studying a different control ranges of surface density and the mean size of QDs that identified optimum values for them. That gives better stability of the system's work near the room temperature compared to experimental results.*
Keywords - *Quantum dot lasers, Mean size of quantum dots, Surface density of QDs, GaInAsP/InP laser.*

I. Introduction

The Quantum Dot Laser (QDL) has distinctive characteristics in comparison to other semiconductor lasers. The most important features they have low threshold current, weak dependence on temperature and narrow spectrum [1]. The heterostructure semiconductor lasers was studied in comparison with QDL, so it was injected carriers in wetting layers in the Optical Confinement Layer (OCL), which is on both sides (n-p), created an approximate balance in the QDs system at room temperature. The occupancy of the upper levels of QD gap is an integral part of OCL accompanied by a clear census in both types of carriers in the OCL. These themselves carriers lead to the recombination radiation current, which depends on the temperature, while it did not contribute to the lasing [2,3]. This mechanism based on temperature is also present in the other semiconductor lasers, but its plays a key role in quantum dot laser [4]. There is a significant drop in the threshold current density of the double-heterostructure laser due to the presence of wide energy gap in cladding layers. Limit the effectiveness of the carriers in the active region and the coefficient of higher refractive effective area compared with wetting layers. It's been waveguide and confines the light emitted in the active region. The density definition of laser action power begins is threshold current density (j_{th}), so j_{th} decrease do increases in the optical output power at a certain injection current density [2].

The most important factors which are taken into consideration during the laser work are the internal optical losses that have negative role on the laser output. The optical losses in the laser output is desired, while the internal optical losses are one of the unwanted losses that occur in the laser cavity [5]. The internal losses of system QDL associated to the carrier occupation level in QD, as well as linked carrier intensity in the OCL. As a result of this association, which controlled by the threshold conditions, the density of free carriers are increases with the increased the temperature sensitivity. The increase in the amount of surface density reduces internal losses as a result of reducing the density of carriers in the OCL. Which act to determine the amount of internal losses that depend on the cross-section of influential of these carriers [3,6]. By adopting a theoretical model of QDL [5], we will study the effect of control parameters (surface density of QD and mean size of QDs) on each of: the carrier density in the optical confinement layer (OCL) , the confined level occupancy in QD , the intensity of the threshold current and the amount of internal loss coefficient . So we can define operation efficiency of the system within the limited range of the work temperature of the QDL tool.

II. Theoretical Model

The theoretical model based on the rate equations and it is simplified within the steady-state. Fig (1)a shows the schematic structure of QDL system and determine the shape of the optical confinement layer and quantum dots in the system. Fig. (1) b shows the energy band diagram of QD.

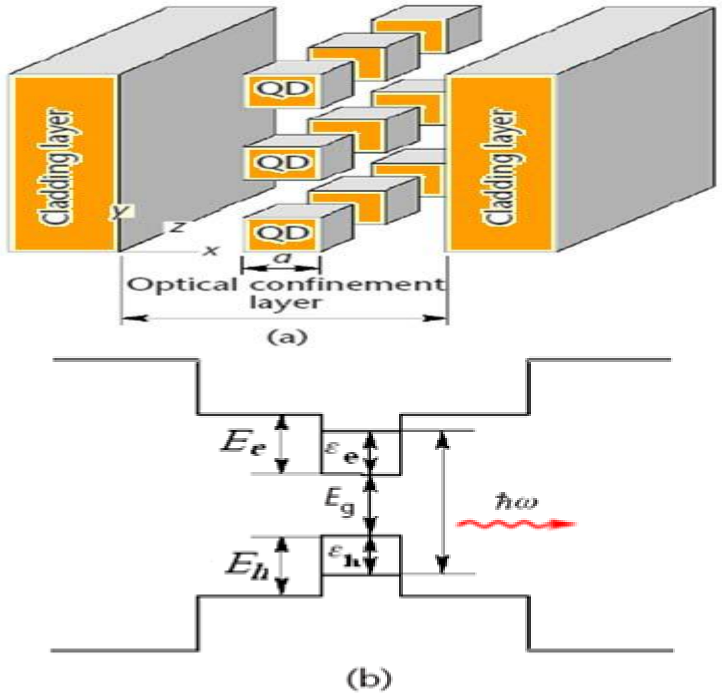


Fig (1): (a) Schematic structure and (b) energy band diagram of a QD [7].

Several mechanisms can contribute to the internal loss of the QD laser such as the free-carrier absorption in the OCL, scattering at rough surfaces and imperfections in the waveguide [6]. All these mechanisms can be conveniently grouped into two categories, one dependent on the carrier density in the OCL and the other is independent. The j_{th} which are associated with the recombination in QDs , j_{QD}, and in OCL, j_{OCL} , respectively, [7] can be written as:

$$j_{th} = j_{QD} + j_{OCL} \quad (1)$$

j_{OCL} is written as [8]:

$$j_{OCL} = ebR\rho^{n}_{ocl}\rho^{p}_{ocl} \quad (2)$$

Where $\rho^{n,p}_{ocl}$ are the free-electron / hole densities in the OCL at the lasing threshold respectively, b is the OCL thickness , R is the radiative constant for the OCL material and e is the electronic charge. j_{QD} can be written as [7]:

$$j_{QD} = \frac{eNs}{\tau_{QD}} f^{n}_{QD} f^{p}_{QD} \quad (3)$$

where $f^{n,p}_{QD}$ are the confined- carrier (electron or hole) level occupancies in QDs at the lasing threshold, Ns is the surface density of QDs and τ_{QD} is the spontaneous radiative recombination time in QDs.

The temperature-dependence of the free-carrier densities ($\rho^{n,p}_{ocl}$) acts as the major source of such dependence of j_{th} for which the carrier distribution below, and at the lasing threshold is described by the equilibrium statistics (relatively high T) [6, 8, 9]. $\rho^{n,p}_{ocl}$ are depend exponentially on T [10] as;

$$\rho^{n,p}_{ocl} = \rho^{n,p}_{ocl_0} \frac{f^{n,p}_{QD}}{1 - f^{n,p}_{QD}} \quad (4)$$

$$\rho^{n,p}_{ocl_0} = N^{ocl}_{n,p} \exp[-\frac{E_{n,p}}{T}] \quad (5)$$

$N^{ocl}_{n,p}$ is the effective density state in OCL, which can be written as [9]:

$$N_{n,p}^{ocl} = 2\left(\frac{m_{n,p}^{ocl}T}{2\pi\hbar^2}\right)^{\frac{3}{2}} \quad (6)$$

$m_{n,p}^{ocl}$ is the electron / hole effective masses in the energy unit and $\hbar$ is normalized Planck constant. The equality of the gain (g_{max}) to the loss (lasing threshold condition) can be written as [3]:

$$g_{max} = \frac{\beta + \alpha_{int}}{2 f_{QD}^{n,p} - 1} \quad (7)$$

where β is the cavity losses ($\beta = \frac{1}{L}\ln\left(\frac{1}{r}\right)$) [5] , *r* is the mirror facet reflectivity and *L* is the cavity length.

α_{int} is the internal losses coefficient that can be written as the sum of two components which are the overall internal loss coefficients, the first is constant (α_0) and the other increasing with the OCL electron density [8, 11]:

$$\alpha_{int} = \alpha_0 + \sigma\rho_{ocl}^{n,p} \quad (8)$$

where σ is effective cross section for the internal absorption loss processes. The expression of saturation gain condition, g_{max} , in OCL is [10], can be written as:

$$g_{max} = \frac{\xi}{4}\left(\frac{\lambda}{\sqrt{s_n}}\right)^2 \frac{1}{\tau_{QD}} \frac{\hbar}{\gamma} \frac{\Gamma}{a} Ns \quad (9)$$

where ξ is the QD-size distribution function ($\xi = \frac{1}{\sqrt{2\pi}}$) for the Gaussian distribution [7], $\hbar$ is normalized Planck constant, Γ is the optical confinement factor in the QD layer, λ is the wavelength and (a) is mean size of QDs. γ is homogenous line broading where [12];

$$\gamma = \varphi\left(q_n E_n + q_p E_p\right) \quad (10)$$

φ is the root mean square (RMS) of relative QD-size fluctuations, $E_{n,p}$ are the electron/hole quantized energy levels in a mean-sized QD and $q_{n,p}$ are the electron / hole quantized energy levels where ($q_{n,p} = \frac{\partial E_{n,p}}{\partial \ln a}$) , which is approximately constant to all modes.

One can write the QD confined-electron/hole level occupancies as [9];

$$f_{QD}^{n,p} = \frac{1}{2}\left(1 + f_{QD_0}^{n,p} - \frac{1}{2}\frac{\sigma\rho_{ocl}^{n,p}}{g_{max}}\right) - \sqrt{\frac{1}{4}\left(1 + f_{QD_0}^{n,p} - \frac{1}{2}\frac{\sigma\rho_{ocl}^{n,p}}{g_{max}}\right)^2 - f_{QD_0}^{n,p}} \quad (11)$$

From the temperature independent threshold condition, the electron density dependent internal loss makes couples to $f_{QD}^{n,p}$ as [9]:

$$f_{QD_0}^{n,p} = \frac{1}{2}\left(1 + \frac{\beta + \alpha_0}{g_{max}}\right) \quad (12)$$

III. Results And Discussion

There are many structure and control parameters plays influential roles in determining the characteristics of the quantum dot laser by controlling the concentration of semiconductor materials or manufacturing temperature. One can determine the concentration of the surface density (Ns) and the size of the quantum dots that will reflect on several properties in QDL system. We do carrying theoretical simulating of the theoretical expressions using Mathematic system that applied to GaInAs/InP heterostructure lasing near 1.55

μm. We'll examine some factors in determining the properties of this laser, which depending on the parameters listed in the Refs [2,3].

Fig. (2)a show the carrier occupation level in QD that increases with increasing temperature . The effect of increasing Ns is effective in reducing the amount of the carrier occupation level in QD as a counterproductive relationship (see Fig. (2)b) . At the same time, it does increase T_{max} of QDL system. In Fig. (2)a there are two curve gropes: with the effect of internal optical losses by absorption σ ≠ 0 and without it σ ≈ 0.

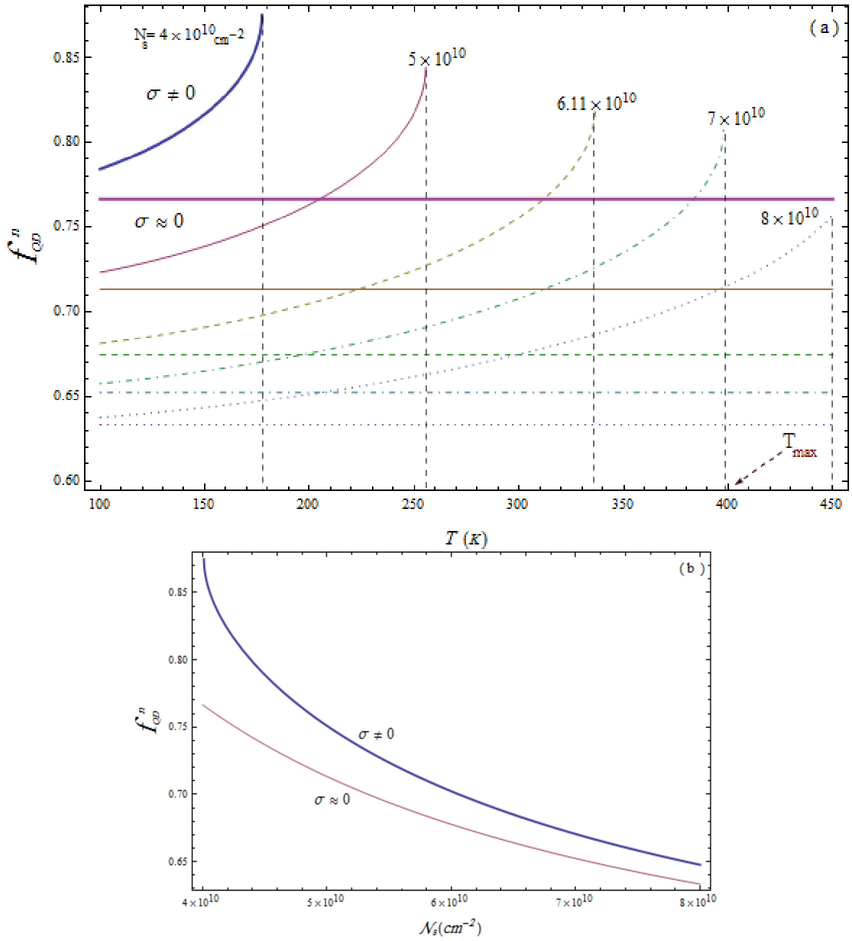


Fig. 2. (a) Carrier occupation level in QD, f^n_{QD}, vs. temperature, T, for different values of surface density of QDs; *Ns* ($\times10^{10}cm^{-2}$) = 4, 5, 6, 7 and 8. The curves are with the effect of internal optical losses by absorption and the lines are without the effect of these losses. (b)Carrier occupation level in QD, f^n_{QD}, vs. different values of surface density of QDs, *Ns*, The parameters used for GaInAsP/InP QDL are [3]: L= 1.628 mm, r= 0.32,λ= 1.55 μm, a = 150 Ao, E_n = 6. meV, ρ = 0.05, α_0 = 3. cm-1and σ =$2.67\times10^{-17}cm^2$, Γ = 0.06.

The case is different when increasing the mean size of QDs. Therefore, we note through Fig. (3), the increase of the parameter (a) will increase the amount of the carrier occupation level in QD, while this increase reduces the amount of T_{max}. So the mean size of QDs values must be selected close to 150 A0 so that the system works close to room temperature.

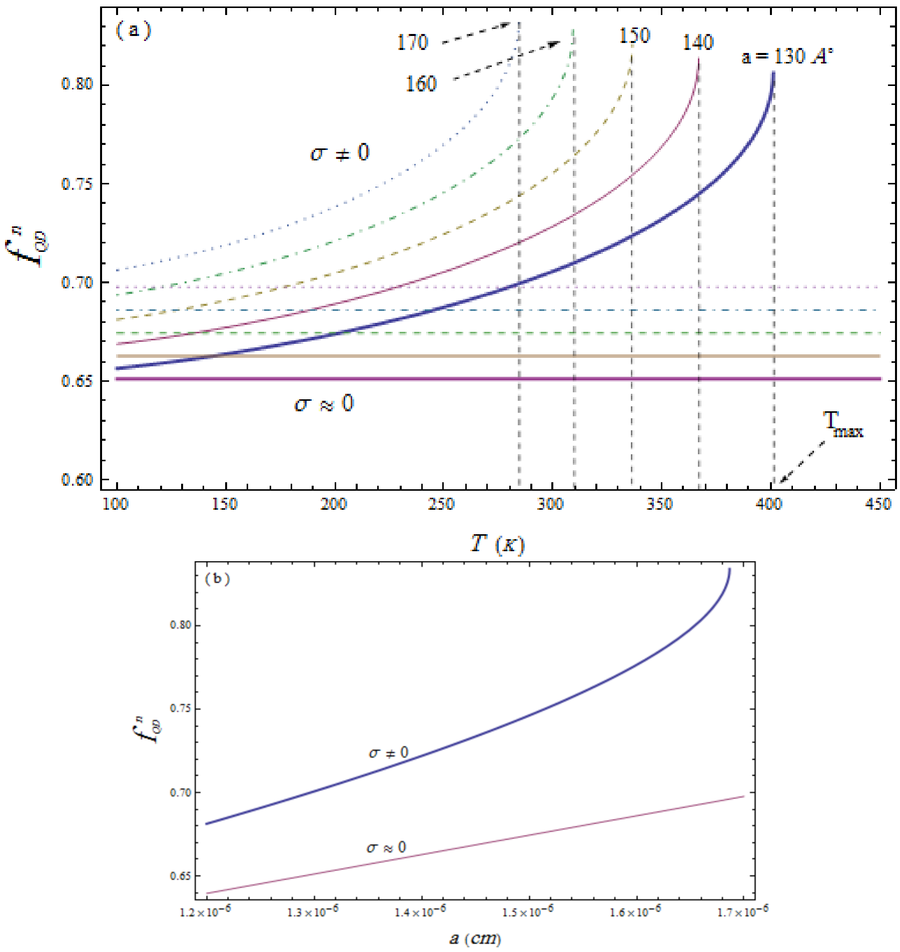


Fig. 3.(a) Carrier occupation level in QD, f_{QD}^{n}, vs. temperature, *T*, for different values of mean size of QDs, a (A^o) = 130, 140, 150, 160 and 170. (b) Carrier occupation level in QD, f_{QD}^{n}, vs. different values of mean size of QDs, a (A^o).

It can be noticed via Fig. 4(a), the increase of *Ns* parameter increases the temperature T_{max}, i.e., that has a positive role on T_{max}. While the effect of (a) parameter is shown in the Fig. 4(b), that impact be negative as it increases leads to a decrease of T_{max}

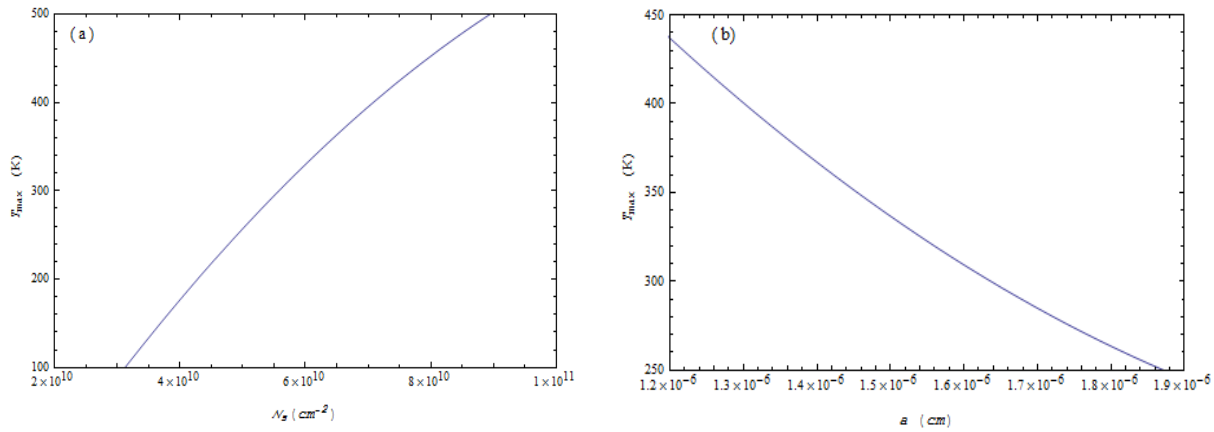
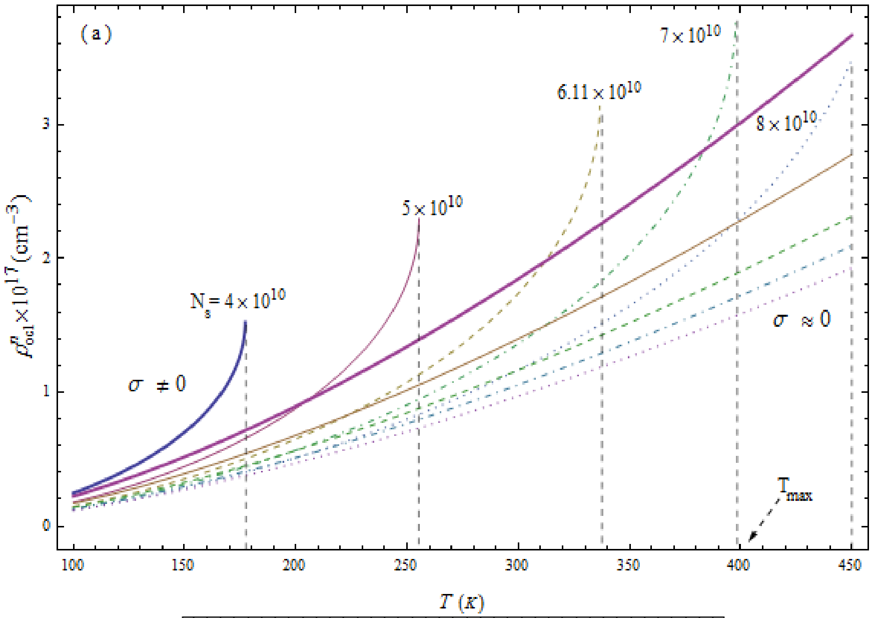


Fig. 4. (a) Maximum temperature, T_{max}, vs. surface density of QDs; *Ns*. (b) Maximum temperature, T_{max}, vs. mean size of QDs, a.

On the free-carrier density in the OCL with dependent on temperature, the impacts of the two parameters are major source for the adoption of j_{th} on *T*. So it is responsible for the carrier's distribution in the laser threshold. One can observe through the figure, the increase in Ns will reduce ρ^n_{ocl} in both cases: when there are internal QD laser losses dependent absorption or absence of these losses part as it is in Fig. 5(b).



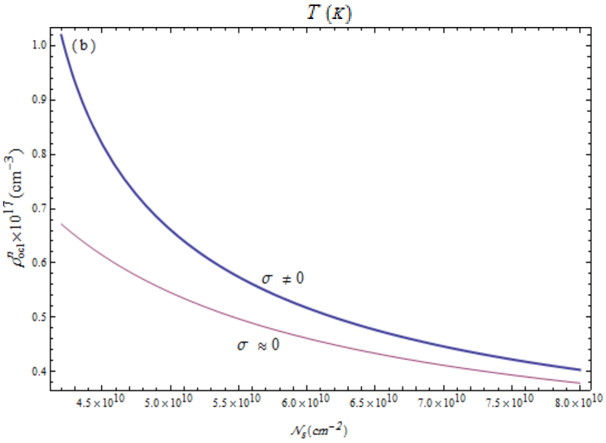


Fig. 5. (a) Free-carrier density in the OCL, ρ^n_{ocl} , vs. temperature, T, for different values of surface density of QDs; *Ns* ($\times10^{10}cm^{-2}$) = 4, 5, 6, 7 and 8. (b)Free-carrier density in the OCL, ρ^n_{ocl} , vs. Surface density of QDs; Ns.

The effect of the increase of mean size of QDs leads to increase ρ^n_{ocl} with decrease in T_{max}, where it is show that it is working on increases of ρ^n_{ocl} when with / without of internal absorption losses of laser system as shown in Fig. 6.

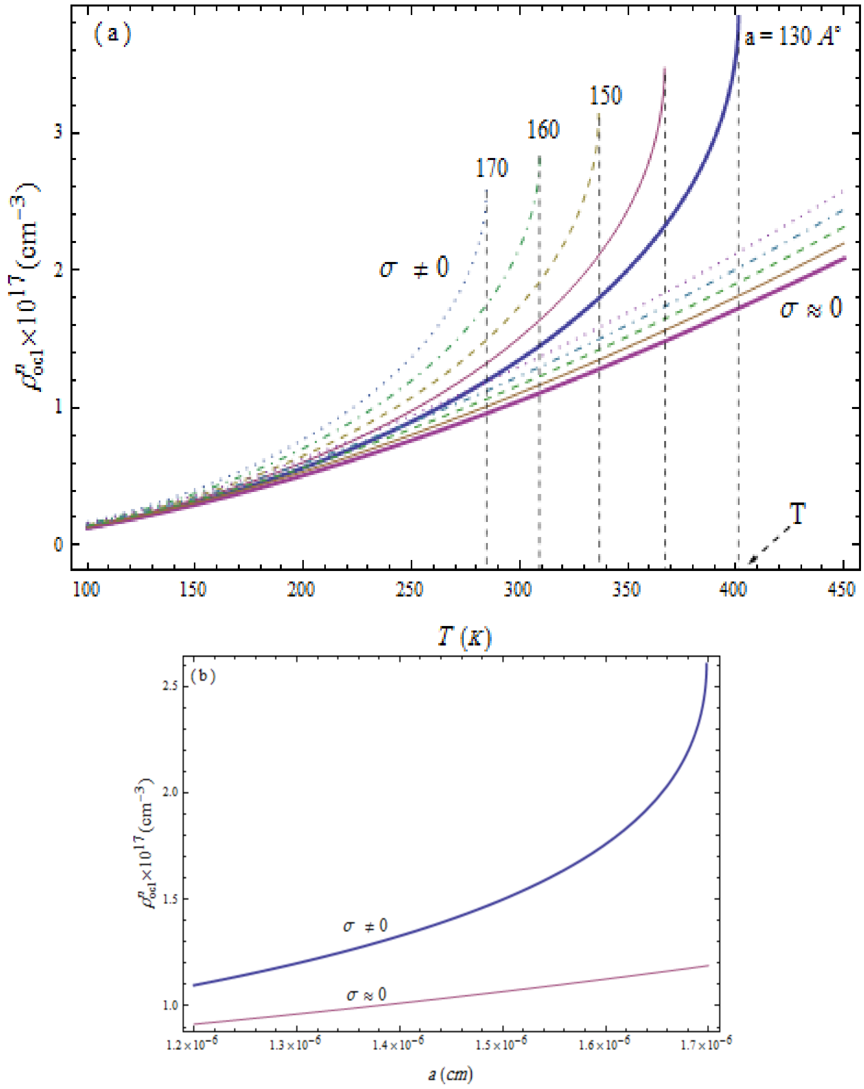


Fig. 6.(a) Free-carrier density in the OCL, ρ_{ocl}^{n}, vs. temperature, T, for different values of mean size of QDs, a (A^{o}) = 130, 140, 150, 160 and 170.(b) Free-carrier density in the OCL, ρ_{ocl}^{n}, vs. different values of mean size of QDs, a (A^{o}).

The results shows the influence of the control of the QDs surface density of the internal loss in QDL system, which connect carrier occupation level in QD, as well as with free-carrier density in the OCL. As a result of this association, this is depending on the threshold conditions with the increased of sensitivity to temperature and the carrier's density increases. In Fig. (7)a, the results show an increase in temperature will increase the internal losses almost linearly due to increased free-carrier density in the OCL. When a cross-section of the effective losses of internal absorption has much influential σ ≠0, so would negatively affect the working of the laser system. When σ≈ 0, can see an internal losses stable is act in the certain value. The result shows that the increase of *Ns* in the same temperature reduces internal losses, where the effect of Ns negative on the internal losses of QDL system (see Fig. (7)b). It also increases this parameter to increase T_{max} as shown in Fig. (7)a.

The relation between OCL free-electron density and temperature is given where as expected the former increases with an increasing of surface density of QDs as the straight solid line indicates. Finally, there are sensitive relation between the QD lowest excitation energy to the surface density of QDs for a variation of the constant loss coefficient, mean size of QDs and the mean size of QDs.

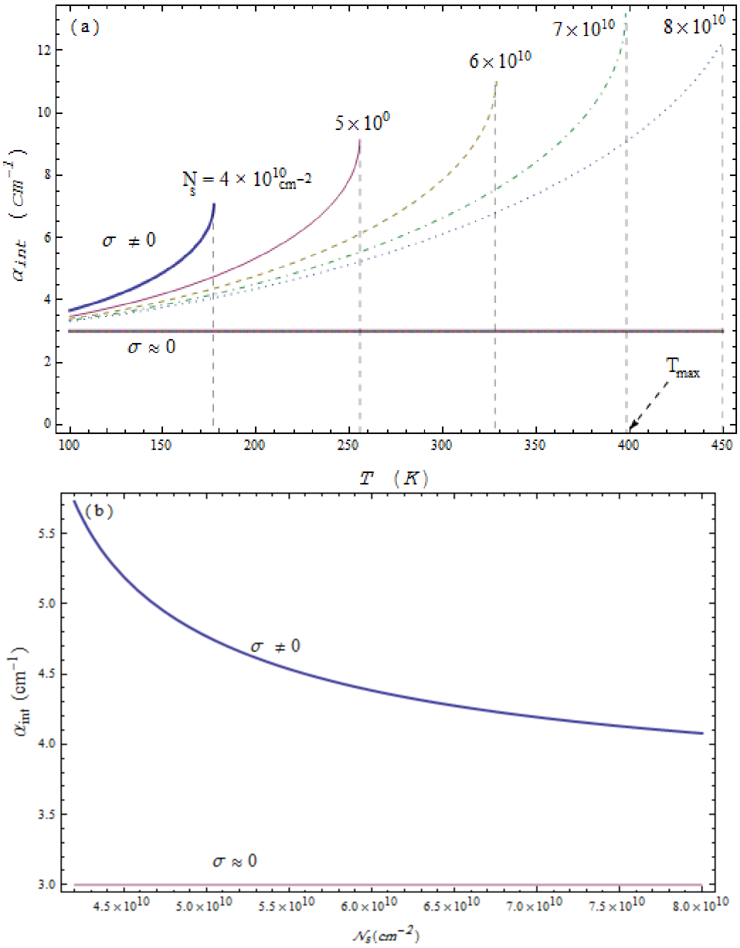
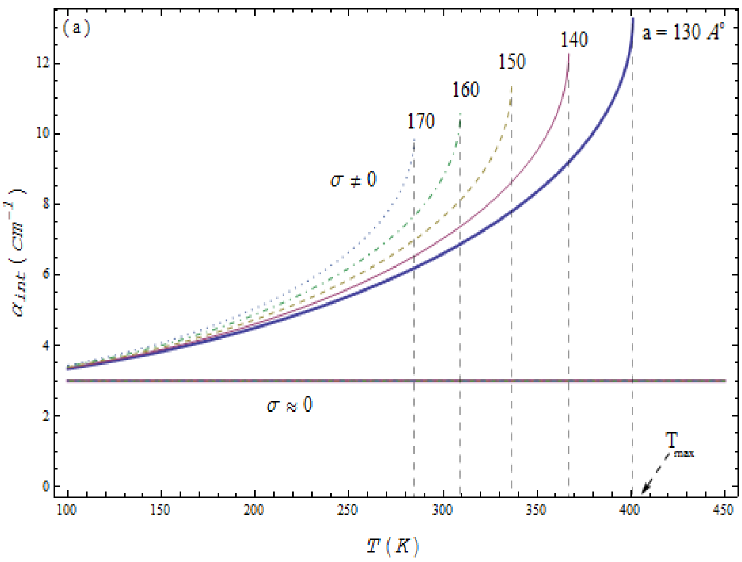


Fig. 7. (a) Internal losses of QDL, α_{int}, vs. temperature, *T*, for different values of surface density of QDs; *Ns* ($\times 10^{10}$cm^{-2}) = 4, 5, 6, 7 and 8. (b)Internal losses of QDL, α_{int}, vs. Surface density of QDs; *Ns*.

The opposite case when increasing mean size of QDs leads to high amount of internal losses in a constant temperature, and the increase of this parameter decrease the value of T_{max} as shown in the fig. (8).



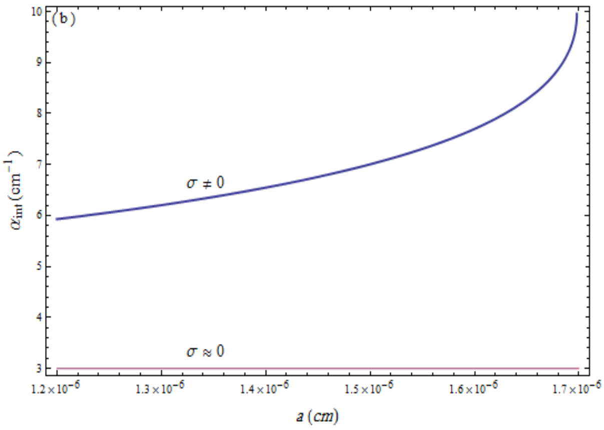


Fig. 8. (a) Internal losses of QDL , α_{int}, vs. temperature, *T*, for different values of RMS of relative QD-size fluctuations; a (A^{o}) = 130, 140, 150, 160 and 170.(b) losses of QDL, α_{int}, vs. mean size of QDs, a.

To control the *Ns* values having positive role in the amount of j_{th}, this role is achieved in both of its parts i,e., j_{QD} and j_{OCL}, as shown in Fig. (9). The effect of increasing the *Ns* work to reduce both j_{QD} and j_{OCL} and increase the amount of T_{max}.

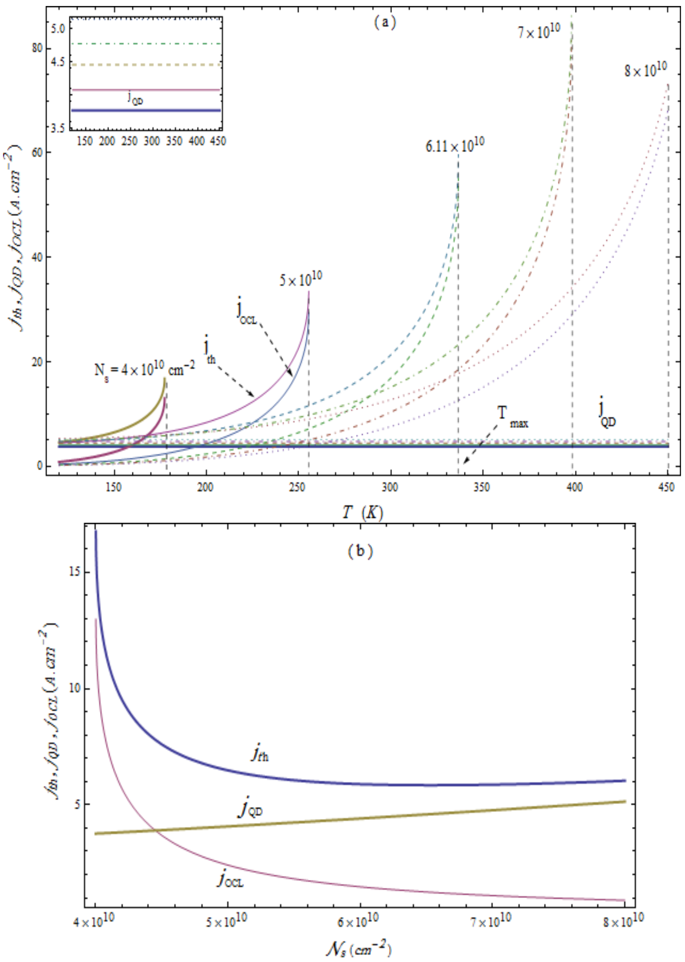


Fig. 9. (a) Threshold current j_{th} and its components j_{QD} & j_{OCL} vs. temperature, *T*, for different values of surface density of QDs; *Ns* (×10^{10}cm^{-2}) = 4, 5, 6, 7 and 8. Inset represent carves its of j_{QD} (b)Threshold current j_{th} and its components j_{QD} & j_{OCL} vs. Surface density of QDs, *Ns*.

As shown by Fig. (10), the effect of increasing mean size of QDs work to increase the amount of the threshold current components, j_{QD} & j_{OCL} and it decrease T_{max} at the same time.

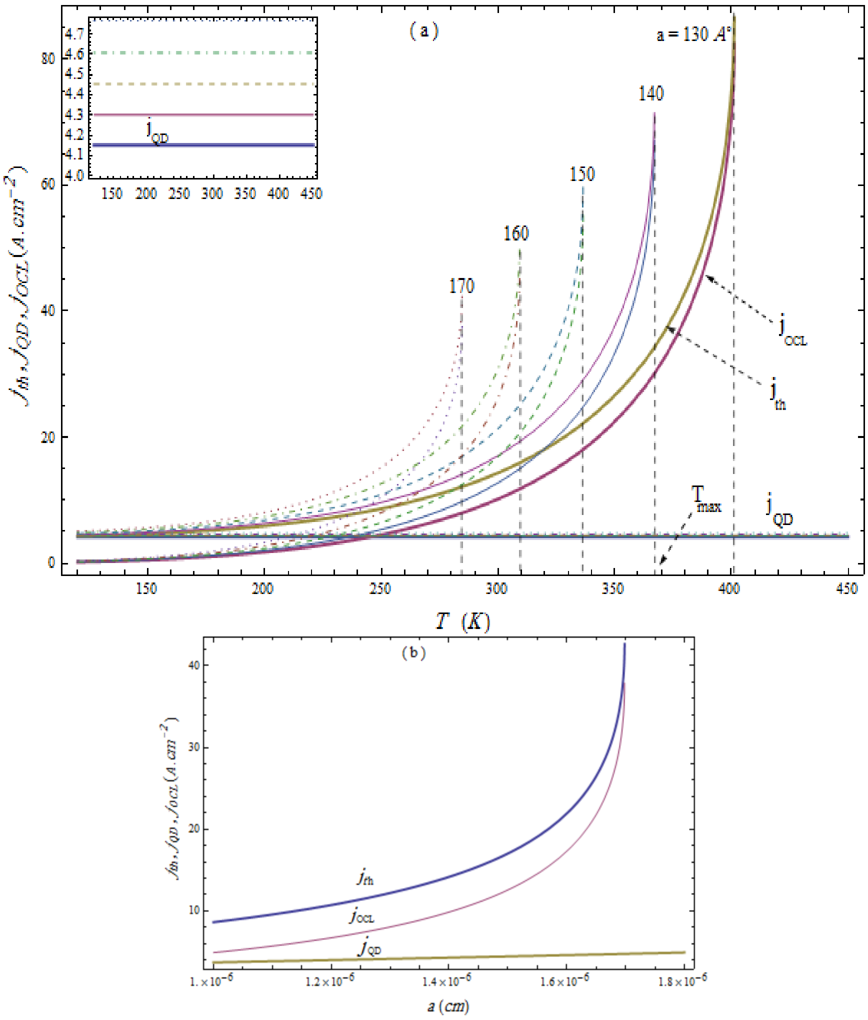


Fig. 10. (a) Threshold current j_{th} and its components j_{QD} & j_{OCL} vs. temperature, *T*, for different values of RMS of relative QD-size fluctuations; a (A°) = 130, 140, 150, 160 and 170. Inset represent carves its j_{QD} (b) Threshold current j_{th} and its components j_{QD} & j_{OCL} vs. mean size of QDs, a.

This would be the case if the overall injection went into QDs, and the recombination current in QDs would be temperature-independent. In actual QDLs, the carriers are first injected from the cladding layers into the optical confinement layer OCL (which includes the wetting layer), then captured into the QDs. The presence of carriers in the OCL results in the recombination therein. Hence the recombination processes both in QDs and in the OCL control j_{th} and its T-dependence.

IV. Conclusion

Based on the results of the simulation of the theoretical model introduced earlier, it is noticed that increasing of surface density of QDs of GalnAsP/InP laser system, which has instrumental effect in reducing the carrier occupation level in QD with an increase in the amount of maximum temperature (T_{max}). It also wills reduces free-carrier density in the OCL and reduce the amount of internal losses. So it would be useful to increase the surface density of QDs within the limits to keeps the stability of the system. At the parameters values of the laser under study, the optimum amount of surface density of QDs is up to $Ns_{(0pt)} \approx 5\times10^{10}$ cm^{-2} to ensure stable operating point at a room temperature. While the effect of mean size of QDs, it would be contrary to the studied QDL characteristics. It shows through the results that an increase of this parameter will increase f_{QD}^{n} and reduce T_{max}, ρ_{ocl}^{n} , α_{int} and j_{th}. So, most maintain the relative QD-size of small values have positive impact. Note that the optimum value of this parameter (of the QDL type under study) has limits of $a_{opt} \approx 150\ A^0$ to achieve better efficiency.

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