We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Investigating the Role of Auger Recombination on the Performance of a Self-Assembled Quantum Dot Laser

Mahdi Razm-Pa and Farzin Emami

Abstract

We first examine the relaxation dynamics inside quantum dot structures. After presenting the rate equations model, we investigate the effect of some parameters introduced in the rate equation on the performance of quantum dot lasers. The effects of QDs coverage factor, inhomogeneous broadening, which its physical source is the size fluctuation of quantum dot in forming self-assembled quantum dots, as well as cavity length, on SAQD laser have been analyzed. Then, based on the rate equations, a circuit model will be introduced. Finally the effect of phonon bottleneck and Auger recombination on the performance of quantum dot lasing, are examined. It is shown that, there is more output power and quantum efficiency, and higher modulation bandwidths when Auger recombination is considered for these lasers.

Keywords: self-assembled quantum-dot laser (SAQDL), inhomogeneous broadening, phonon bottleneck, coverage factor, relaxation dynamic

1. Introduction

The reduction in dimensionality caused by confining electrons (or holes) to a thin semiconductor layer leads to a dramatic change in their behavior. This principle can be developed by further reducing the dimensionality of the electron's environment from a two-dimensional quantum well to a one-dimensional quantum wire and eventually to a zero-dimensional quantum dot. In this context, however, dimensionality refers to the degree of electron momentum freedom. In fact, within a quantum wire, unlike the quantum well where the electron is confined in just one dimension, it is confined in two dimensions and thus, the freedom degree is reduced to one. In a quantum dot, the electron is confined in all three-dimensions, hence reducing the degree of freedom to zero. Under certain growth conditions, when a thin semiconductor layer grows on a substrate having a completely different lattice constant, the thin layer is spontaneously arranged or changes into quantum dots through

self-assembles while attempting to minimize the total strain energy between the bonds. Microscopy can show quantum dots that are in the shapes of pyramids, square based, and tetrahedron [1]. The performance expected from quantum dot lasers is often due to the density of their quasi-atomic states. Using the quantum structures confined in some dimensions will reduce the momentum freedom of the carrier in a certain direction. Ideally, carriers are completely enclosed in quantum dots. Therefore, the density of quantum dot states, that is, the number of states per volume unit and per energy unit, is expressed by the delta function. The gain spectrum amplitude is determined only by homogeneous broadening due to intraband relaxation at the quantum dot. These gain properties are the basis of the features that give the quantum dot laser some advantages over conventional lasers [2, 3]. The effect of carrier dynamics on the performance of quantum dot laser and the possibility of bi-exciton lasing have been studied. Bi-excitons are achieved if the increase in ground state of the quantum dot reaches the laser threshold, and if the carrier relaxation is rapidly below 100 ps, the laser will be observed [4, 5]. Carrier relaxation in quantum dots (QDs) is studied widely when applications of these devices are reported for optical communications [6]. The problem of *phonon bottlenecks* in quantum dots has sparked heated debate over whether carrier relaxation in a discrete ground state is significantly slow due to the lack of phonons required to meet the conservation rule. Because of *phonon bottleneck* [7] problem in these types of lasers, it is found that some important parameters, such as threshold current density, quantum efficiency and modulation response, are deteriorated [8]. To overcome these problems, one can manage the level spacing of a QD to decrease the carrier relaxations which inherently may decrease the laser performance, since these long relaxation times are comparable to the semiconductor radiative and non-radiative lifetimes. To have fast relaxation, overcome the phonon bottleneck problem and to improve the threshold current, external quantum efficiency, and modulation response, Auger recombination effects may be considered [9]. The most useful and well-known method to study the statics and dynamics of the carrier and photon numbers in these lasers, is to solving the rate equations for them [10]. By using the rate equations in this article and taking the Auger effect into account, a new circuit model for InGaAs-GaAs self-assembled QD (SAQD) laser will be suggested. Indeed, the Auger effect on QD laser performance are considered.

2. Theoretical background

2.1 Carrier capture and relaxation dynamics into a quantum dots

The carrier relaxation process within quantum dots is actually two steps, as shown in the **Figure 1**.

One is the carrier relaxation from continuous energy levels within the discrete levels of the quantum dot (A, Red Color). Another is the relaxation between discrete levels within dots (B, Blue Color). In many light experiments, as well as in quantum dot lasers, carriers go through these two steps unless they are brought directly into discrete levels by excitation resonant or tunneling. Since the principle of energy conservation must be satisfied for the carrier to relax, relaxing carriers transfer the corresponding energy to other particles (such as phonons) and to other carriers in the bulk. Therefore, “the relaxation rate strongly depends on the density of final levels and on the number of particles other than the transition matrix elements” [4].

Figure 1.
Carrier relaxation in a quantum dot [1]. (A, Red Color) The relaxation from continuous levels. (B, Blue Color) The relaxation between discrete levels.

Figure 2.
Carrier capture and relaxation processes [4, 12]. (a) LO- and LA-phonons. (b) Auger processes.

Introducing the LO- and LA-phonons, it is possible to satisfy the energy conservation rule [11], is shown in **Figure 2a** [4, 12]. Such a two-phonon process decreases the lifetimes severely [4], but it cannot be adequate to relax back the carriers inside the dots deeply. Carrier trapping into the dot energy levels and hence energy conservation rule, are satisfied whenever the number of carriers outside the dots are increased. So, Auger process can be proper phenomenon due to increase of the captured carriers that occupy the QD energy levels [13]. Therefore, with more injected currents or equivalently more injected carriers, the relaxation lifetime increases and Auger process can be effective due to carrier relaxation into deep lower levels by a step-like energy decrement. Illustration of the carrier relaxation processes, considering the Auger effect, is shown in **Figure 2b**. Auger scattering is more important when the density of excited carriers is high. As illustrated in **Figure 2b**, one of the two electrons in the wetting layer (WL) is captured by the Auger mechanism in the excited state (ES) of QD, while the other electron is emitted upward in the WL or separate confinement heterostructure (SCH). Then, the electron which is captured in ES transfers its energy to the third electron of the barrier or even more probably to another electron in the excited state (ES) of QD and relaxes downward in the QD ground state (GS).

2.2 Rate equation model

Usually, the carrier and photon behaviors in SAQD semiconductor lasers are expressed by a set of coupled differential equations called rate equations [14].

In **Figure 3**, there is a simple energy band diagram to explain different levels, ground state (GS), excited state (ES), and wetting layer (WL) state, in these structures [14]. In this model, there are some injected carriers into a SCH barrier with a rate of I/e where I is the injected current and e is the electron charge.

They can either relax with a time of τ_s in the WL state or come back from the barrier with a time of τ_{qe} . These carriers can be captured by different dot sizes from the WL state. Assume that each dot has only two distinct energy states; GS and excited state (ES). In these levels, the captured carriers have a time of τ_c from WL to ES and relaxed carriers have a time of τ_d from ES to GS. They can come back in the reverse path at the times of τ_{eES} and τ_{eGS} , respectively. There are several radiative or non-radiative recombination times for carriers. τ_{sr} is carrier recombination in the SCH region and τ_{qr} is carrier recombination in the wetting layer (WL). τ_r is recombination in the QD. Assume that an excited emission is only due to an electron hole recombination in ES and GS. The photons emitted from the laser cavity have a rate of S/τ_p , where S is the number of photons and τ_p is the photon lifetime. The governing rate equations for various components of these carriers are explained as [14–16]:

$$\frac{dN_s}{dt} = \frac{I}{e} - \frac{N_s}{\tau_s} - \frac{N_s}{\tau_{sr}} + \frac{N_q}{\tau_{qe}}, \quad (1)$$

$$\frac{dN_q}{dt} = \frac{N_s}{\tau_s} + \frac{N_{ES}}{\tau_{eES}} - \frac{N_q}{\tau_{qr}} - \frac{N_q}{\tau_{qe}} - \frac{N_q}{\tau_c}, \quad (2)$$

$$\begin{aligned} \frac{dN_{ES}}{dt} = & \frac{N_q}{\tau_c} + \frac{N_{GS}(1 - P_{ES})}{\tau_{eGS}} - \frac{N_{ES}}{\tau_r} - \frac{N_{ES}}{\tau_{eES}} - \frac{N_{ES}}{\tau_d} \\ & - \frac{(c/n_r)g_{mES}\Gamma}{1 + \epsilon_{mES}\Gamma S/V_a} S, \end{aligned} \quad (3)$$

Figure 3.
A sample energy band diagram for a SADQ laser considering the excited state.

$$\frac{dN_{GS}}{dt} = \frac{N_{ES}}{\tau_d} - \frac{N_{GS}}{\tau_r} - \frac{N_{GS}(1 - P_{ES})}{\tau_{eGS}} - \frac{(c/n_r)g_{mGS}^{(1)}\Gamma}{1 + \epsilon_{mGS}\Gamma^S/V_a}S, \quad (4)$$

$$\frac{dS}{dt} = \frac{(c/n_r)g_{mES}^{(1)}\Gamma}{1 + \epsilon_{mES}\Gamma^S/V_a}S + \frac{(c/n_r)g_{mGS}^{(1)}\Gamma}{1 + \epsilon_{mGS}\Gamma^S/V_a}S - \frac{S}{\tau_p} + \frac{\beta N_{GS}}{\tau_r} + \frac{\beta N_{ES}}{\tau_r} \quad (5)$$

With the following parameters: N_s : number of carriers in the SCH layer, N_q : number of carriers in the WL layer, N_{ES} : number of carriers in the ES layer, and N_{GS} : number of carriers in the GS layer.

In the above equations, Γ is the optical confinement factor, Γ_0 is the inhomogeneous broadening of the optical gain, c is the speed of light, β is the spontaneous coupling efficiency, and the photon lifetime τ_p can be found from [17]:

$$\tau_p^{-1} = \left(\frac{c}{n_r}\right) \left\{ \alpha_i + \frac{\ln [1/(R_1 R_2)]}{2L} \right\} \quad (6)$$

Where R_1 and R_2 are the facet reflectivity of the laser cavity with a length of L and the internal loss of α_i , and n_r is the cavity refractive index. Where the nonlinear gain coefficient (ϵ_{mGS} and ϵ_{mES}) are defined as [4, 16, 18]:

$$\epsilon_{mGS} = \frac{e^2}{2n_r^2 \epsilon_0 m_0^2} \frac{|P_{c,v}^\sigma|^2}{E_{GS}} \frac{1}{\Gamma_{cv}\Gamma_{||}} \quad (7)$$

$$\epsilon_{mES} = \frac{e^2}{2n_r^2 \epsilon_0 m_0^2} \frac{|P_{c,v}^\sigma|^2}{E_{ES}} \frac{1}{\Gamma_{cv}\Gamma_{||}} \quad (8)$$

and $\Gamma_{||} \equiv 1/\tau_p$ is the longitudinal relaxation constant and Γ_{cv} is the scattering or polarization de-phasing rate. Based on the density matrix theory the linear optical gain of the active region, with a dot density of N_D , can be found as [10, 16, 19]:

$$g_{mGS}^{(1)} = \frac{2.35\sqrt{2\pi}e^2\hbar}{cn_r\epsilon_0 m_0^2} \frac{|P_{cv}^\sigma|^2}{E_{GS}} \frac{(2P_{GS} - 1)}{\Gamma_0} N_D D_{GS} \quad (9)$$

$$g_{mES}^{(1)} = \frac{2.35\sqrt{2\pi}e^2\hbar}{cn_r\epsilon_0 m_0^2} \frac{|P_{cv}^\sigma|^2}{E_{ES}} \frac{(2P_{ES} - 1)}{\Gamma_0} N_D D_{ES} \quad (10)$$

Parameters D_{GS} and D_{ES} in Eqs. (5) and (6), impose the GS and ES degeneracy which are considered to be 2 and 4, respectively [15]. $P_{c,v}^\sigma$ is a matrix element, related to the overlap integral $I_{c,v}^\sigma$ between the envelope functions of an electron and hole, defined as [19]:

$$|P_{c,v}^\sigma|^2 = |I_{c,v}|^2 M^2 \quad (11)$$

Where M^2 is the first-order K - P interaction between conduction and valence bands, with a separation of E_g and is equal to:

$$M^2 = \frac{m_0^2}{12m_e^*} \frac{E_g(E_g + \Delta)}{E_g + \frac{2\Delta}{3}} \quad (12)$$

In this relation, E_g is band gap, m_e^* is the effective mass for electrons and Δ is defined as the spin-orbit interaction energy for a QD material. Based on the Pauli's Exclusion Principle, the occupation probabilities at the ES and GS states of the QD are defined as [19]:

$$P_{GS} = \frac{N_{GS}}{2N_D V_a D_{GS}} \quad (13)$$

$$P_{ES} = \frac{N_{ES}}{2N_D V_a D_{ES}} \quad (14)$$

Where $V_a = LWd$ is the cavity volume with length L , width W and thickness d . Effects of the non-uniform dot size can be included in the relaxation, capture, and escape times with the following definitions [14–16, 18]:

$$\tau_c = \frac{\tau_{c0}}{(1 - P_{ES})} \quad (15)$$

$$\tau_d = \frac{\tau_{d0}}{(1 - P_{GS})} \quad (16)$$

Where τ_{c0} is the capture time from WL to ES and τ_{d0} is the relaxation time from EL to GS with the assumption of an empty final state. Without the stimulated emission and at room temperature, the system must converge to a quasi-thermal equilibrium based on a Fermi distribution. To have this condition, the carrier capture time, τ_{c0} , and relaxation time, τ_{d0} , and the carrier escape times, τ_{eGS} , τ_{eES} , should be satisfied by the following relations [14, 15]:

$$\tau_{eGS} = \tau_{d0} \left(\frac{D_{GS}}{D_{ES}} \right) e^{\frac{E_{ES} - E_{GS}}{kT}} \quad (17)$$

$$\tau_{eES} = \tau_{c0} \left(\frac{D_{ES} N_d}{\rho_{WL\text{eff}}} \right) e^{\frac{E_{WL} - E_{ES}}{kT}} \quad (18)$$

$$\rho_{WL\text{eff}} \equiv \left(\frac{m_{eWL} kT}{\pi \hbar^2} \right) \quad (19)$$

Where $\rho_{WL\text{eff}}$ is the effective density of states per unit area of the WL and N_d is the QD density per unit area. Both phonon- and Auger-assisted capture and relaxation are taken into account phenomenologically through the relation [16, 20, 21]:

$$\tau_{c0}^{-1} = \tau_{c01}^{-1} + C_W N_q \quad (20)$$

$$\tau_{d0}^{-1} = \tau_{d01}^{-1} + C_E N_q \quad (21)$$

Where τ_{c01}^{-1} , τ_{d01}^{-1} are characteristic rates of phonon-assisted capture and interlevel relaxation processes, respectively, and C_W and C_E are the coefficients for

Auger-assisted relaxation related to the WL and the ES, respectively. Assume that all of the carriers are injected into the WL layer or equivalently $\tau_{qe} = \tau_{sr} \rightarrow \infty$.

2.3 Effect of parameter variations

Section 2.3 covers investigation of the effects of some parameters expressed in the rate equations on the performance of quantum dot laser. This section is based on the results obtained the reference [22].

2.3.1 Inhomogeneous broadening Γ_0

Figure 4 shows the results of our simulations on the L - I curve of SAQD laser considering the effects of inhomogeneous broadening. Note that, the physical origin of this parameter is in the random size of the QDs [4]. As shown in the figure, for higher inhomogeneous broadening factor, more threshold current or equivalently more injection currents are needed but in this case, the external quantum efficiency does not have dominant changes. In other words, for higher Γ_0 the output power of the laser decreases. Physically speaking, for increased inhomogeneous broadening factors there is a higher occupation probabilities in the lasing action of the structure, so that the relaxation times increase and the output power decreases.

This effect can be studied in the dynamic response of a SAQD laser, too. The results of such variations for the frequency responses are plotted in **Figure 5**. The simulation results show that for higher inhomogeneous broadening factors the frequency responses of the laser deteriorates.

2.3.2 Carrier recombination time τ_{qr} in a WL

The effect of carrier recombination in WL, τ_{qr} which equals WL crystal quality, has been shown on L - I feature in **Figure 6**. As τ_{qr} degrades, the carriers would find more opportunities to recombine through non-radiative process out of the quantum dot which results in degradation of external quantum efficiency. The findings indicate that τ_{qr} degradation also increases the threshold current.

Figure 4. Effects of the inhomogeneous broadening variations on the L - I curve of SAQD laser considering the excited state with different values of the broadening parameter $\Gamma_0 = 5, 20$, and 40 meV.

Figure 5. Effects of the inhomogeneous broadening variations on the frequency response of SAQD laser with different values of $\Gamma_o = 5, 20, \text{ and } 40 \text{ meV}$.

Figure 6. The L - I curve of a SAQD laser for different values of carrier recombinations in WL.

The effect of carrier recombination in the WL state on the small-signal frequency response of laser is shown in **Figure 7**. As shown, the carrier recombination in the WL state has no considerable effect on modulation response.

2.3.3 Carrier recombination inside quantum dot, τ_r

Figure 8 shows the effect of carrier recombination inside quantum dot, τ_r , on the L - I curve. While the effect of τ_r on threshold current is significant, it does not have a considerable effect on external quantum efficiency.

Figure 7.
The modulation response of a SAQD laser for different values of carrier recombination in WL.

Figure 8.
The L-I curve of a SAQD laser for different values of carrier recombination inside quantum dot.

The effect of carrier recombination inside quantum dot on frequency response has been shown in **Figure 9**. What is important here is that, as τ_r decreases from 2.8 to 0.5 ns, the frequency response degrades. Therefore, to prevent the effect of phonon bottleneck on frequency response, the recombination lifetime within quantum dots τ_r must be much longer than the carrier relaxation time (the carrier relaxation time is about a few pico-seconds).

2.3.4 Carrier escape time from ground state to excited τ_{eGS} state and from excited state to WL state τ_{eES}

The effect of carrier escape time from ground state to excited state and from excited state to WL state on L-I feature has been shown in **Figure 10**. As the carrier

Figure 9.
The modulation response of a SAQD laser for different values of carrier recombination inside quantum dot.

Figure 10.
The L-I curve of a SAQD laser for different values of carrier escape time from ground state to excited state and from excited state to wetting layer.

escape time degrades, the number of carriers in WL states (N_q) increases. These carriers are generally used due to carrier non-radiative recombination (with τ_{qr} life-time) and this leads to the increase of the threshold current. Generally, for more decrement in τ_{qr} , there is more increment in the threshold current.

Figure 11 also shows that, as the carrier escape time degrades from ground state to excited state and from excited state to wetting layer, the frequency response degrades as well.

2.3.5 Coverage factor ξ

Figure 12 show the frequency response for different amounts of QDs coverage factor $\xi = 0.1, 0.2, 0.4$, relaxation time 100 ps and inhomogeneous broadening of $\Gamma_0 = 20$ meV. As shown in **Figure 12**, the increase in coverage factor due to the

Figure 11.
 The modulation response of a SAQD laser for different values of carrier escape time from ground state to excited state and from excited state to wetting layer.

Figure 12.
 Modulation response of a SAQD laser at different coverage factors; $\Gamma_0 = 20\text{ meV}$ and the relaxation time is 100 ps .

increase in the volumetric density of QDs (N_D) leads to the decrease in P_{GS} and P_{ES} , that is, filling probability of the GS and ES. As filling probability of the GS and ES decreases, the relaxation rate increases for the carrier inside the GS and ES, and this leads to the increase in 3 dB bandwidth.

Figure 13 shows the simulation results for the effects of coverage factor $\xi = 0.1, 0.2, 0.4$, inhomogeneous broadening $\Gamma_0 = 5\text{ meV}$ and relaxation time 1 ps on the frequency response band width. To achieve a high-speed modulation, higher than 10 GHz , not only the relaxation lifetime should be decreased to about 1 ps but also the QD coverage factor should also be increased and the inhomogeneous broadening should be decreased.

2.3.6 Cavity lengths L

Figure 14 shows the L - I characteristics for different cavity lengths. The increase in cavity length leads to loss degradation and output power increase.

Figure 13.
The modulation response of a SAQD laser for different values of coverage factor and $\Gamma_o = 5$ meV and relaxation time 1 ps.

Figure 14.
L-I curve of a SAQD laser at different cavity lengths.

2.3.7 QD height

Figure 15 shows the simulation results of modulation response for different quantities of QD height. As the QD height degrades, the modulation band width improves. The reason for modulation band width improvement while the QD height degrades can be caused by increasing carrier confinement within quantum dot in growth direction (z-) which leads to increase excited stimulated emission rate, respectively.

2.3.8 Stripe width of the laser cavity

Figure 16 shows the effect of stripe width of the laser cavity on frequency response. As the stripe width of the laser cavity degrades, the modulation band width improves. It is inferred from the figure that degradation of the stripe width of the laser

Figure 15.
Modulation response of a SAQD laser at different QD heights.

Figure 16.
Modulation response of a SAQD laser at different stripe widths of the laser cavity.

cavity and therefore the degradation of the active region can provide a higher total capture rate. Hence, it results in a greater modulation band width.

3. Circuit model implementation

To solve the rate equations of a SAQD laser, considering the excited state and Auger effect, a conceptual equivalent electrical circuit is proposed is shown in **Figure 17**. The aforementioned equations convert to some simple electrical circuit equations and then, the resulting circuit is simulated by a circuit simulator such as HSPICE [23]. The corresponding parameters for the equivalent circuit model of SAQD lasers are described in detail in Ref. [24].

4. Simulation results

In this simulation, typical parameters, which are shown in **Table 1**, are used.

Figure 17.
A modified equivalent circuit model of SAQD lasers, considering the Auger effect.

Quantity	Value
Inhomogeneous broadening, Γ_0	20 meV
Diffusion in SCH, τ_s	6 ns
SCH recombination, τ_{sr}	4.5 ns
WL recombination, τ_{qr}	3 ns
Capture from WL to ES, τ_{c0}	1 ps
Capture from ES to GS, τ_{d0}	7 ps
ES and GS recombination, τ_r	2.8 ns
Energy separation SCH and WL, state	84 meV
Average energy separation WL and ES	100 meV
Average energy separation ES and GS	80 meV
Average recombination energy from GS, EGS	0.96 eV
Average recombination energy from ES, EES	1.04 eV
Spin-orbit interaction energy of QD material, Δ	0.35 eV
Facet reflectivity, R_1 , and R_2	30%, 90%
Active region length, L_{ca}	900 μm
SCH thickness, H_b	90 nm
WL thickness, H_{WL}	1 nm
Active region width, w	10 μm
Active region volume, V_a	$2.2 \times 10^{-16} \text{ m}^3$
QD density of QD per layer, N_d	$5 \times 10^{10} \text{ cm}^{-2}$
QD density per unit volume, N_D	$6.3 \times 10^{22} \text{ m}^{-3}$
QD optical confinement factor, Γ	0.06
Intrinsic absorption coefficient, α_i	1 cm^{-1}

Quantity	Value
Spontaneous emission coupling efficiency, β	10^{-4}
Output power coupling coefficient, η_c	0.449
SCH, WL, and QD (GS, ES) diode ideality factors, $n_S = n_Q = n_{GS} = n_{ES}$	2

Table 1.
Typical parameters used in the simulation [14, 15, 23].

Figure 18.
The L-I curve of a SAQD laser neglecting the Auger effect. (a) Various capture times $\tau_{c0} = 1, 10, 50, 100, 300$, and 500 ps at a fixed relaxation time of $\tau_{d0} = 7$ ps; (b) various relaxation times $\tau_{d0} = 1, 10, 50, 100, 300$, and 500 ps at a fixed capture time of $\tau_{c0} = 1$ ps.

Figure 18 illustrates the output power as a function of injected currents neglecting the Auger effect for $C_w = C_E = 0$, $\tau_r = 2.8$ ns and $\tau_{qr} = 0.5$ ns, when the carrier relaxation times τ_{d0} and capture times τ_{c0} , changes from 1 to 500 ps. As seen, there are more threshold currents for longer lifetimes. This is along with lower slopes for the output power curves which mean lower quantum efficiencies for increased lifetimes. Physically, such effect is due to the phonon bottleneck in QD lasers [4].

This phenomenon can be considered in dynamic response of the laser, too. Application of the proposed model to SAQD lasers considering this effect for dynamic response of the laser are shown in **Figure 19**. With higher relaxation times τ_{d0} and capture times τ_{c0} , the frequency response deteriorates and SAQD laser would have lower bandwidths.

Figure 20(a) and **(b)** illustrate the output power as a function of the injected currents considering the Auger effect for $C_W = 1 \times 10^{-14}$ m³/s, $C_E = 1 \times 10^{-12}$ m³/s, and $C_W = C_E = 0$ with $\tau_{C01} = \tau_{d01} = 100$ ps. Inhomogeneous broadening $\Gamma_0 = 20$ meV and recombination lifetimes of $\tau_r = 2.8$ ns, $\tau_{qr} = 3$ ns and $\tau_r = 2.8$ ns, $\tau_{qr} = 0.5$ ns, have been used for **Figure 20(a)** and **(b)**, respectively. It is obvious that the Auger process increases the efficiency, degrades the threshold current, and provides a high output power. This is because, by taking the Auger effect into account, the capture times and carrier relaxation lifetime decreases from WL to ES and from ES to GS. This means the degradation of phonon bottleneck effect. In other words, in QD elements

Figure 19.

Modulation response of a SAQD laser neglecting the Auger effect. (a) Various capture times $\tau_{c0} = 1, 10, 50, 100, 300$, and 500 ps at a fixed relaxation time of $\tau_{d0} = 7$ ps; (b) various relaxation times $\tau_{d0} = 1, 10, 50, 100, 300$, and 500 ps at a fixed capture time of $\tau_{c0} = 1$ ps.

Figure 20.

The L-I curve of a SAQD laser considering the Auger effect. Different values of recombination lifetimes (a) $\tau_r = 2.8$ ns, $\tau_{qr} = 3$ ns, $\Gamma_0 = 20$ meV; (b) $\tau_r = 2.8$ ns, $\tau_{qr} = 0.5$ ns, $\Gamma_0 = 20$ meV; and different values of inhomogeneous (c) $\Gamma_0 = 30$ meV; (d) $\Gamma_0 = 40$ meV.

with a low density of the carriers in wetting layer (N_q), both relaxation and capture processes are mainly phonon assisted. However, as the QD laser pumping increases, the density of the wetting layer increases, too. This process is first slow but then it

occurs in a more pronounced way. This is because, if the pumping increases from zero, most of the carriers get captured into the QDs. On the other hand, based on Pauli Exclusion Principle in QDs, the number of electron state in QD active layer, that is, GS and ES, has been limited. Therefore, if at first the GS and then the ES are filled with electrons, relaxation and capture in these states will get saturated as it is shown by factors $(1-P_{ES})$ and $(1-P_{GS})$ in Eqs. (11) and (12), respectively. Thus, the drain of carriers from the WL towards the dots slows down and this leads to the formation of the WL carrier reservoir. The carriers in the reservoir increase the Auger assisted capture speed as shown in Eqs. (16) and (17). On the other hand, by decreasing τ_{qr} from 3 to 0.5 ns, the carriers find more chances for recombining via non-radiative process outside the QDs. This results in the degradation of quantum efficiency and increase of threshold current simultaneously. **Figure 20(c) and (d)** illustrate the output power as a function of the injected currents for inhomogeneous broadenings $\Gamma_0 = 30$ meV and $\Gamma_0 = 40$ meV, respectively. As the inhomogeneous broadening increases, the optical gain decreases [see Eqs. (5) and (6)], and this results in larger occupation probabilities in leasing, and longer relaxation lifetime. Therefore, the quantum efficiency and output power decrease and threshold current increases.

Figure 21 shows the effect of Auger coefficient increment on the small-signal frequency response of the laser for different values of $C_W = 1 \times 10^{-14}$ m³/s, $C_E = 7 \times 10^{-12}$ m³/s, and $C_W = C_E = 0$. The inhomogeneous broadening is $\Gamma_0 = 20$ meV. The recombination lifetimes of $\tau_r = 2.8$ ns and $\tau_{qr} = 3$ ns have been used. The simulation reveals that when the Auger coefficient increases, the relaxation lifetime decreases. It means that the phonon bottleneck effect is degraded and as a result, the modulation bandwidth increases. On the other hand, as Auger coefficient increases and carrier relaxation times τ_{d0} and capture times τ_{c0} decreases, the 3 dB frequency increases. What is important here is that, as τ_r decreases from 2.8 to 0.5 ns, the frequency response degrades. Therefore, to prevent the effect of phonon bottleneck on frequency response, the recombination lifetime within quantum dots τ_r must be much longer than the carrier relaxation time (the carrier relaxation time is about a few pico-seconds) [4]. Results obtained by using the presented circuit model are in good agreement with the results calculated by solving the rate equations numerically and also with experiments reported so far [4, 7].

Figure 21. Modulation response of a SAQD laser considering the Auger effect for different values of carrier recombination inside quantum dot (a) $\tau_r = 2.8$ ns and (b) $\tau_r = 0.5$ ns.

5. Conclusions

The Auger effect can be overcome in the phonon bottleneck problem in SAQD lasers propose a modified equivalent circuit for simulation of the rate equations, considering this effect for the first time. The static and dynamic behavior of these lasers were studied. It is found that, if we want to solve the rate equations of a SAQD laser, it is possible to compensate the effect of phonon bottleneck by introducing the Auger effect. This can decrease the threshold current and increase the quantum efficiency of the SAQD laser, so the output power can be raised. It is shown that the Auger effect can increase the modulation bandwidth of a SAQD laser. Quantum dot lasers have been more favored for applications in optical communications, silicon photonics, lightwave telecommunication systems, high power lasers, Q-switched or mode locked lasers for short pulse generation and broad band light sources. The future implications of quantum dot lasers are issues such as quantum dot lasers and integration with Si photonic integrated circuits and colloidal quantum dot lasers.

Author details

Mahdi Razm-Pa^{1*} and Farzin Emami²

1 Electronic Department of Charkhab Kian Electronic Devices Company, Borazjan, Bushehr, Iran

2 Optoelectronic Research Center, Electronic Department of Shiraz University of Technology, Shiraz, Iran

*Address all correspondence to: razmpa.mahdi@gmail.com

IntechOpen

© 2022 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

- [1] Harrison P. Quantum Wells, Wires and Dots: Theoretical and Computational Physics of Semiconductor Nanostructures. New Jersey, USA: Wiley, John Wiley & Sons, Inc; 2010. p. 564. DOI: 10.1002/0470010827
- [2] Steiner T. Semiconductor Nanostructures for Optoelectronic Applications. Bingley, United Kingdom: Artech House Publishers; 2004. p. 412. DOI: 10.1108/SR.2004.24.3.320.3
- [3] Grillot F, Norman JC, Duan J, Zhang Z, Dong B, Huang H, et al. Physics and applications of quantum dot lasers for silicon photonics. *Nanophotonics*. 2020;**9**(6):16. DOI: 10.1515/nanoph-2019-0570
- [4] Sugawara M. Self-assembled InGaAs/GaAs quantum dots. In: *Semiconductors and Semimetals*. Vol. 60. Washington, USA: Optical Publishing Group; 1999. p. 385. DOI: 10.1364/QO.1999.QMC4
- [5] Razm-Pa M, Emami F. Simulation of the effect of biexciton oscillator strength on performance of self-assembled quantum-dot laser. *Journal of Nanoelectronics and Optoelectronics*. 2018;**13**:493-500. DOI: 10.1166/jno.2018.2091
- [6] Morris D, Perret N, Fafard S. Carrier energy relaxation by means of Auger processes in InAs/GaAs self-assembled quantum dots. *Applied Physics Letters*. 1999;**75**(23):3593-3595. DOI: 10.1063/1.125398
- [7] Sugawara M, Mukai K, Shoji H. Effect of phonon bottleneck on quantum-dot laser performance. *Applied Physics Letters*. 1997;**71**(19):2791-2793. DOI: 10.1063/1.120135
- [8] Xin QL, Nakayama H, Arakawa Y. Phonon bottleneck in quantum dots: Role of lifetime of the confined optical phonons. *Physical Review B*. 1999;**59**(7):5069-5073. DOI: 10.1103/PhysRevB.59.5069
- [9] Magnusdottir I, Bischoff S, Uskov AV, Mork J. Geometry dependence of Auger carrier capture rates into cone-shaped self-assembled quantum dots. *Physical Review B*. 2003;**67**(20):205326/1-205326/5. DOI: 10.1103/PhysRevB.67.205326
- [10] Sugawara M, Mukai K, Nakata Y, Ishikawa H, Sakamoto A. Effect of homogeneous broadening of optical gain on lasing spectra in self-assembled In_xGa_{1-x}As/GaAs quantum dot lasers. *Physical Review B: Condensed Matter*. 2000;**61**(11):7595-7603. DOI: 10.1103/PhysRevB.61.7595
- [11] Feldmann J, Cundiff ST, Arzberger M, Bohm G, Abstreiter G. Carrier capture into InAs/GaAs quantum dots via multiple optical phonon emission. *Journal of Applied Physics*. 2001;**89**(2):1180-1183. DOI: 10.1063/1.1333718
- [12] Ohnesorge B, Albrecht M, Oshinowo J, Forchel A, Arakawa Y. Rapid carrier relaxation in self-assembled In_xGa_{1-x}As/GaAs quantum dots. *Physical Review B*. 1996;**54**:11532-11538. DOI: 10.1103/physrevb.54.11532
- [13] Narvaez GA, Bester G, Zunger A. Carrier relaxation mechanisms in self-assembled (In,Ga)As/GaAs quantum dots: Efficient P to S Auger relaxation of electrons. *Physical Review B*. 2006;**74**(7):075403/1-075403/7. DOI: 10.1103/PhysRevB.74.075403

- [14] Gioannini M, Sevega A, Montrosset I. Simulations of differential gain and linewidth enhancement factor of quantum dot semiconductor lasers. *Optical and Quantum Electronics*. 2006; **38**:381-394. DOI: 10.1007/s11082-006-0038-1
- [15] Gioannini M, Montrosset I. Numerical analysis of the frequency chirp in quantum-dot semiconductor lasers. *IEEE Journal of Quantum Electronics*. 2007; **43**:941-949. DOI: 10.1109/JQE.2007.904306
- [16] Grillot F, Veselinov K, Gioannini M, Montrosset I, Even J, Piron R, et al. Spectral analysis of 1.55- μm InAs-InP(113)B quantum-dot lasers based on a multipopulation rate equations model. *IEEE Journal of Quantum Electronics*. 2009; **45**(7):872-878. DOI: 10.1109/JQE.2009.2013174
- [17] Kashiri M, Asgari A. Modeling of carrier dynamics in InGaAs/GaAs self-assembled quantum dot lasers. *Applied Optics*. 2016; **55**(8):2042-2048. DOI: 10.1364/AO.55.002042
- [18] Grundmann M. *Nano-Optoelectronics, Concepts, Physics and Devices*. New York: Springer; 2002. p. 442. DOI: 10.1007/978-3-642-56149-8
- [19] Sugawara M, Hatori N, Ebe H, Ishida M. Modeling room temperature lasing spectra of 1.3- μm self-assembled InAs/GaAs quantum-dot lasers: Homogeneous broadening of optical gain under current injection. *Journal of Applied Physics*. 2005; **97**(4): 43523-43527. DOI: 10.1063/1.1849426
- [20] Sugawara M. Effect of carrier dynamics on quantum-dot laser performance and possibility of bi-exciton lasing. *Proceedings of SPIE*. 1998; **3283**:88-99. DOI: 10.1117/12.316640
- [21] Berg TW, Bischoff S, Magnusdottir I, Mørk J. Ultrafast gain recovery and modulation limitations in self-assembled quantum-dot devices. *IEEE Photonics Technology Letters*. 2001; **13**(6):541-543. DOI: 10.1109/68.924013
- [22] Razm-Pa M, Emami F. Effect of parameter variations on the static and dynamic behaviour of a self-assembled quantum dot laser using circuit-level modeling. *Quantum Electronics*. 2015; **45**(1):15-22. DOI: 10.1070/QE2015v045n01ABEH015264
- [23] Ahmadi V, Yavari MH. Circuit-level implementation of semiconductor self-assembled quantum dot laser. *IEEE Journal of Selected Topics in Quantum Electronics*. 2009; **15**(3):774-779. DOI: 10.1109/JSTQE.2008.2011997
- [24] Razm-Pa M, Emami F. Phonon bottleneck and auger recombination effect on the performance of a self-assembled quantum dot laser. *SILICON*. 2018; **10**:1513-1521. DOI: 10.1007/s12633-017-9634-x