Quantum dot laser optimization: selectively doped layers

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Abstract. Edge emitting quantum dot (QD) lasers are discussed. It has been recently proposed to use modulation p-doping of the layers that are adjacent to QD layers in order to control QD’s charge state. Experimentally it has been proven useful to enhance ground state lasing and suppress the onset of excited state lasing at high injection. These results have been also confirmed with numerical calculations involving solution of drift-diffusion equations. However, deep understanding of physical reasons for such behavior and laser optimization requires analytical approaches to the problem. In this paper, under a set of assumptions we provide an analytical model that explains major effects of selective p-doping. Capture rates of elections and holes can be calculated by solving Poisson equations for electrons and holes around the charged QD layer. The charge itself is ruled by capture rates and selective doping concentration. We analyzed this self-consistent set of equations and showed that it can be used to optimize QD laser performance and to explain underlying physics.

1. Introduction
Compact semiconductor lasers emitting near 1.2-1.3 µm are important light sources for a wide range of practical applications, from optical coherence tomography and aesthetic surgery to ultrafast data transmission and Raman amplifiers [1, 2]. The usage of InAs/InGaAs quantum dot (QD) lasers emitting via the ground-state (GS) optical transition allows one to overlap the required wavelength range with small room temperature threshold currents [3 – 4]. However, as the injection current increases, an additional short-wavelength spectral line associated with the first excited-state (ES) optical transition of QDs appears in the lasing spectra [5 – 18]. For example, if the GS transition is centered at 1.28 µm, the ES one appears near 1.2 µm. Further increase of injection current usually results in the GS-lasing quenching [11 – 17]. Because simultaneous lasing via the GS and ES transitions (so-called multi-state or two-state lasing) put obstacles in practical usage of such QD lasers, deep understanding of this phenomenon as well as finding its key parameters and possible methods of its suppression becomes important from both fundamental and practical points of view.

It has been found that p-doping of a thin, typically 10 nm, layer that is adjacent to QD layer enhance laser performance in a sense pointed above. Namely, p-doping enhances maximum power from GS and increases threshold current of ES lasing [13]. Therefore an explanation of this effect is required to understand experimental data and provide a basis for laser optimization. A few earlier works concerning GS/ES lasing were not quite consistent with details of the experiment.
and/or could not explain a serious impact of p-doping on competition between GS and ES lasing. For example the [5 – 8] papers are based on the system of rate equations formulated in terms of excitonic energy levels and excitonic exchange processes. However, this model is capable of explaining a saturation of the GS lasing transition rather than its quenching. Also it was suggested that laser self-heating in CW regime is the reason for the GS-lasing quenching [11, 12]. However, it has been experimentally demonstrated [13] that the GS-lasing quenching is observed even in pulsed regime, when a temperature increment is as small as 1K.

In our previous work [15], it has been demonstrated that the hole-to-electron capture rate ratio, which we denoted as the $h$-factor has a serious impact on a QD laser operation regime. In particular, if the $h$-factor is below a certain critical value, decline and complete suppression of the GS lasing is expected. Obviously, the capture rates are determined by the carrier concentration in the GaAs matrix surrounding QD layer. Concentration itself is depending on QD layer charge. This self-consistent problem could be solved numerically as we presented earlier [19]. The results obtained confirm the idea that p-doping change the hole capture rate (increase $h$-factor) and favors to GS lasing by this means. Therefore, up to date, phenomenological theory of QD laser operation with different capture rates of electrons and holes has been presented together with numerical modeling of $h$-factor. In this paper we would like to present an analytical approach to calculation of $h$-factor at high injection currents. This approach could be useful for laser optimization as well as for a deeper view on underlying physics. Though suggested approach can be applied to QD lasers based on various material systems, for the sake of simplicity, conventional InAs/InGaAs/GaAs QD laser [17] structure details and material parameters will be used in this paper.

2. Analytical approach

In this part we discuss GaAs volume that surrounds layer of quantum dots. A few assumptions have to be made in order to construct simple and clear theoretical model. Let us list them:

- The "flat band" assumption. The electric field in the volume of GaAs waveguide is zero except for the areas near QD layers. That means that all charges including the charge of matrix/emitter interface (GaAs/AlGaAs) are effectively screened. This screening is due to free carriers in the matrix. Strong screening could be achieved only when injection and carrier concentration is high enough. That is why only the case of high injection and high output power is discussed here.

- Carrier mobility in matrix is high enough so we can neglect the gradient of chemical potentials $F_n$ and $F_p$ inside the matrix. The steps of their spatial dependence are located near matrix/emitter barrier.

- The screening is strong enough so neighboring layers of QDs do not affect each other. In the case of single layer QD laser that assumption is the same as the first one.

- The doping layer and QD layer can be modeled like a zero width layers.

One may notice here that the first assumption is an exact opposite to one in [20] where screening is completely neglected. The "no screening" should work well at low injection. Actually, first three assumptions has been checked in numerical simulations (see [19]) and have been proven increasingly realistic with the rise of the injection current.

Due to screening there are no charges far from QD layer. That means electron concentration equals hole concentration that we denote as $n_0$. Let us note as $z$ the direction along a growth access and let $z = 0$ be the position of QD layer. Then we may write down the following:

$$n(z) = N_C \exp \left( \frac{F_n - E_C(z)}{T} \right) = N_C \exp \left( \frac{F_n - E_{C0}}{T} \right) \exp \left( \frac{q \phi(z)}{T} \right), \quad (1)$$

$$p(z) = N_V \exp \left( \frac{E_V(z) - F_p}{T} \right) = N_V \exp \left( \frac{E_{V0} - F_p}{T} \right) \exp \left( -\frac{q \phi(z)}{T} \right), \quad (2)$$
After in quantum dots and acceptors: field as $F$ potential

Let us charge: $\epsilon_0$ where $\phi$ is electrostatic potential, $F_n, F_p$ are constant Fermi levels for electrons and holes, $N_C, N_V$ are effective densities of states, $E_C^0, E_V^0$ are their values far from QD layer, $q$ is an absolute value of electron charge, $T$ is a temperature. Let us assume that $\phi = 0$ far from QD layer. Then one can note that

$$N_C \exp \left( \frac{F_n - E_C^0}{T} \right) = N_V \exp \left( \frac{E_V^0 - F_p}{T} \right) = n_0 .$$  (3)

After that we can write down carriers density in the matrix $\rho(z)$ and Poisson equation for potential $\phi$:

$$\rho(z) = -q n_0 \text{sh} \left( \frac{q\phi(z)}{T} \right) ;$$  (4)

$$\phi(z)'' = \frac{2q n_0}{\epsilon \epsilon_0} \text{sh} \left( \frac{q\phi(z)}{T} \right) ,$$  (5)

where $\epsilon$ is matrix dielectric permittivity and $\epsilon_0$ is a vacuum permittivity. If we denote electric field as $F \equiv -\phi'$ then $F(0)$ is connected with the total density charge $\sigma$ of the layer with quantum dots and acceptors:

$$|F(0)| = \frac{\sigma}{2\epsilon \epsilon_0} .$$  (6)

After integrating (5) we may achieve the relation between potential near the QD layer and its charge:

$$\frac{1}{2} F(z)^2 = \frac{2Tn_0}{\epsilon \epsilon_0} \text{ch} \left( \frac{q\phi(z)}{T} \right) + \text{const} ; F(\infty) = 0 ; \phi(\infty) = 0 ;$$  (7)

$$|F(0)|^2 = \frac{4n_0 T}{\epsilon \epsilon_0} \left( \text{ch} \left( \frac{q\phi(0)}{T} \right) - 1 \right) = \frac{\sigma^2}{4\epsilon \epsilon_0 T} .$$  (8)

Let us introduce parameter $x$

$$x = 1 + \frac{\sigma^2}{16n_0 T \epsilon \epsilon_0} ,$$  (9)

Figure 1. Scheme of energy bands and carrier concentration: screening of negatively charged QD layer

Figure 2. Calculated $h$ - factor versus $g_{he}/g_{ee}$ ration. See details in text. The square at the intersection of $h(h_x)$ dependence and $h = h_x$ line marks the solution of equation set. The solid gray line shows $Q$ dependence of $h_x$ for $Q_A = 0$ and $n_0 = 10^{14}$ cm$^{-3}$.
then carrier concentration near QD layer can be expressed as

\[ n(0) = n_0 \left( x \pm \sqrt{x^2 - 1} \right), \quad p(0) = p_0/\left( x \pm \sqrt{x^2 - 1} \right), \]

(10)

where sign ‘+’ is for \( \sigma > 0 \) and vice versa.

The suggested approach can be adopted to different models of quantum dots. Here, for example, we will use model that was successfully exploited in order to explain interplay between GS and ES lasing [15, 17]. In that model one need to know just two parameters about the environment of QD those are electrons and holes capture rates: \( g_{ec} \) and \( g_{hc} \). Those are the rates of carrier capture at the highest energy level of quantum dot when it is empty. All other parameters of quantum dot in a given laser structure can be calculated as a function of \( g_{ec}, g_{hc} \) (see details in [17]). For our consideration the charge of quantum dot is of major importance. So let us introduce function \( Q(g_{ec}, g_{hc}) \) that is the charge of QD at a given capture rates. The actual captures to ES for example are likely to come from 3rd excites state or 4th excited states. However, under an assumption that these (3rd or 4th) excited states are weakly populated it is easy to show that their population is proportional to the carrier concentration in the matrix. Finally we can write down:

\[ g_{ec} = V_e n(0), \quad g_{hc} = V_h p(0), \quad \sigma = N_S Q(g_{ec}, g_{hc}) - N_A h, \]

(11)

where \( V_e, V_h \) are capture constants (measured in \( s^{-1} cm^3 \)), \( N_S \) is surface QD density in one layer, \( N_A \) and \( h \) are concentration and thickness of an acceptor layer respectively. The set of equations (9 - 11) together with \( Q(g_{ec}, g_{hc}) \) function describe laser operation point. Below in the paper we will specify doping by convenient parameter \( Q_A = N_A h/(qN_S) \) that equals number of acceptors per one QD.

The parameters \( V_e \) and \( V_h \) could be calculated from the experimental data, for example, from carrier escape times. The function \( Q \) depends on the parameters of laser structure such as ratio of losses to maximal gain and could be non-trivial [17]. In order to clarify nature of the solution of (9 - 11) set we provide here figure 2. At the fixed value of \( n_0 \) one can easily see that

\[ n(0)p(0) = n_0^2, \quad \text{and} \quad g_{ec}g_{hc} = V_e V_h n_0^2 \equiv G^2. \]

(12)

The last value is constant at a given \( n_0 \). Let us vary \( g_{ec} \) and \( g_{hc} \) keeping their product constant: \( g_{hc} = G\sqrt{V_e}, \quad g_{hc} = G/\sqrt{V_e} \). For any given \( h_x \) the charge \( Q \) can be calculated and then we get carriers concentration \( n(0) \) and \( p(0) \) (\( n_0 \) is already fixed). At figure 2 we plot
doping.

Figure 4. Dependence of output power on the injection current for different levels of doping.

\[ V_{b,p}(0)/(V_{c,n}(0)) \text{ versus } h_x. \] Obviously, the equality of these two values at certain \( h_x = h \) means the solution of the (9 - 11) system and determines the \( h \)-factor in the operation laser at a given injection. The \( QD \) parameters used in the calculations were generally taken from [15, 17]. The laser under consideration has 10 \( QD \) layers and stripe size 600x50 \( \mu m \). The laser operates at room temperature, measured internal losses in the laser are \( 1.6 \text{ cm}^{-1} \). Below in the paper all calculations are made with the same parameters. The rising dependence of \( Q(g_{ec}, g_{he}) \) on \( h_x \) is also shown in figure 2. The gray dotted line shows \( h \) dependence, when there is selective doping of one acceptor per one quantum dot (\( Q_A =1 \)). In that case due to negative charge of "empty" acceptor the electron concentration decreases and hole concentration increases. Both these factors leads to increasing of \( h \)-factor that favors GS lasing.

3. Results and discussions

First of all we would like to discuss dependence of \( h \)-factor on the injection and output power for the different doping levels. Such dependencies can be seen in figure 3. The \( h \) - factor is decreasing while injection rises. That could be easily explained with more effective screening by the higher carrier concentration in the matrix. In fact, the \( QD \) layer in conventional laser is negatively charged due to the slow hole captures. Therefore, screening would reduce hole’s flow towards \( QD \) layer and decrease \( h \)-factor. Square marks in the figure 3 show the onset of ES lasing. At higher powers when ES lasing is on the growth of \( n_0 \) with current become more steady due to more efficient captures in the ES state comparing with GS. That explains less decrease rate of \( h \) at higher currents. Just for illustration, the unpractical case of n-doping is also shown (\( Q_A = -0.5 \)). In that case \( h \)-factor is so low that GS lasing is almost totally suppressed.

Now we can directly discuss the interplay between GS and ES lasing. In the figure 4 laser output power from GS and ES are shown as a function of injection current. The power and injection current were calculated in the same way as in [17]. In figure 4 the data are shown for \( Q_A \) that equals 0, 1, 3 and 6. One can see that the laser characteristics are rather sensitive to \( Q_A \) and even moderate \( Q_A \) values significantly enhances the maximum power that can be generated at GS. Further increase of \( Q_A \) leads to higher internal losses that are of order of \( 0.06 \text{ cm}^{-1} \cdot Q_A \) for each \( QD \) layer. Obviously that suppress output power and overall laser efficiency. In this way the optimization could be performed depending on the preferred laser properties: \( Q_A \) should be high enough to take effects and low enough not to significantly rise the losses.
The modeling could be compared with experimental data shown on figure 5. The laser sample parameters were as in models. Despite we omit some processes in the laser such as non-radiative recombination there is fair agreement between experiment and theoretical modeling.

In conclusion, the analytical approach was suggested in order to describe effect of screening and selective doping in QD lasers. The results allow to optimize doping level according to preferable laser properties and clearly demonstrate positive effect of selective doping on laser performance.

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