Modulation doping of quantum dot laser active area and its impact on lasing performance

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Abstract. We present a theoretical study of modulation doping of active region in the quantum dot (QD) laser and corresponding issues of QD charge neutrality violation, a band diagram of the laser and charge carriers distribution in the structure. Modulation doping is discussed as a possible technique to control laser output characteristics. It was shown that modulation doping leads to an increase of threshold current of lasing through excited QD optical transition together with power emission from QD ground state.

1. Introduction
The GaAs/AlGaAs semiconductor laser with InAs QD has several advantages compared to quantum well laser such as low threshold current and better temperature stability. The reason of such improvements is δ-like density of states in QD. However, when the excited states (ES) of quantum dots are involved QD laser advantages become less pronounced. The major goal of this work is to study possibilities of suppression of ES lasing via modulation doping of thin layers near QD planes. It was shown earlier [1] that QDs charging plays an important role in lasing though high-power lasing regime and ES emission were not discussed. Later, an impact of charge redistribution between QDs and surrounding matrix was intensively discussed (see [2, 3] and reference wherein) on a phenomenological basis. The ratio of hole to electron capture rates (‘h-factor’) was suggested as a phenomenological parameter that is constant with respect to injection current. We present a thorough theoretical study of a laser band diagram in high injection regime in order to clarify the origin of the non-unity value of the h-factor, its dependence on laser design and injection current. Finally, we study L-I curves in modulation doped structures and compare them with known experimental results [4].

2. Model of the QD layer
In order to discuss the interplay between ground state (GS) and excited state lasing the 3-energy level model has been chosen to describe charge carriers in QDs. There are two levels for electrons (GS and ES) that are separated by ~ 60 meV energy gap and one effective level for holes. The idea of an effective hole level derives from small energy gap between 1st and 2nd hole energy states. Due to that, one can assume fast exchange of holes between ES and GS levels and almost
same values of filling factors $f_{12} \approx f_{h2} \equiv f_h$. The rate equations for carriers’ dynamics are:

$$\dot{f}_e = g_{en} (1 - f_e) - g_{en} f_e - g_{e12} f_e (1 - f_{e1}) + g_{e12} f_{e1} (1 - f_e) - \frac{P_2}{D_2},$$

$$\dot{f}_{e1} = \frac{D_2}{D_1} [g_{e12} f_e (1 - f_{e1}) - g_{e21} f_{e1} (1 - f_e)] - \frac{P_1}{D_1},$$

$$\dot{h} = g_{ep} (1 - f_h) - g_{ep} f_h - \frac{P_1 + P_2}{D_1 + D_2},$$

(1)

where $f_{e1,2}$ stands for GS and ES electron level filling respectively, $P_{1,2}$ are the stimulated emission rates from GS and ES optical transitions measured per one QD (s$^{-1}$), $D_{1,2}$ are the degree of degeneracy of GS, ES state (2 and 4, respectively), $g_{en}$, $g_{ep}$ are the capture rates of electrons and holes into empty QD from GaAs matrix, $g_{en}$, $g_{ep}$ are escape rates of electrons and holes from QD to the matrix, $g_{e12}$, $g_{e21}$ are the electron transfer rates from GS to ES and vice versa. It is assumed for electrons that only ES level is connected with the matrix.

The proposed model describes a few regimes of laser operation such as:

$$\begin{align*}
\text{(NL)} & \quad P_1 = 0, P_2 = 0 \quad (2) \\
\text{(GS)} & \quad f_{e1} + f_h - 1 = \gamma_1, P_2 = 0 \quad (3) \\
\text{(GS + ES)} & \quad f_{e1} + f_h - 1 = \gamma_1, f_{e2} + f_h - 1 = \gamma_2 \quad (4) \\
\text{(ES)} & \quad P_1 = 0, f_{e2} + f_h - 1 = \gamma_2, \quad (5)
\end{align*}$$

depending on injection current and model parameters. The $\gamma_{GS,ES} = \alpha/G_{GS,ES}$ are population inversion required for lasing through GS and ES respectively; $\alpha$ is modal losses and $G_{max,i}$ is maximum modal gain of QD layer. If the injection is low enough (NL) regime takes place and there is no stimulated emission. While injection, i.e. $g_{en}$ and $g_{ep}$, is increasing there are few possible scenarios: ‘(NL) → (GS) → (GS+ES)’, ‘(NL) → (GS) → (GS+ES) → (ES)’ or ‘(NL) → (ES)’. The first scenario at high injection results in simultaneous ES and GS lasing, the second one is called ‘damping of ground state lasing’ and the last one corresponds to lasing only through ES when GS modal gain is not high enough. The details are discussed in [3]. It was shown there that laser operation is sensitive to $g_{ep}/g_{en} \equiv h$ ratio. For example, any of three scenarios could unfold depending just on the value of $h$. The $h$ value itself depends on the electron and hole concentration in the matrix near QDs. The latter should be calculated by means of modeling of a band diagram of a working laser and is discussed in the next section.

3. Drift-diffusion model of semiconductor structure with δ-doped quantum dots

Previously [1] the band diagram was modeled on the assumption of negligible carrier concentration in the i-region of p-i-n laser structure. This assumption results in the absence of screening effects and constant electric field between the emitter/i-region boundary and QD layer. Moreover, it was assumed in [1] that the size of a potential curve near the AlGaAs/GaAs boundary is well below the $T$ (temperature in energy units). As one can see below both of these assumptions could be unfulfilled in the real QD laser. Hence, the method to model a laser band diagram that takes into account electric field of charges that are located in the i-area is required. In the paper the set of drift-diffusion equations (DDE) [6, 7] is used based on Boltzmann statistics of charge carriers:

$$n = n_{ir} e^{(\varphi + \psi_n - \phi_n)/T}; \quad p = n_{ir} e^{-(\varphi - \psi_p - \phi_p)/T},$$

(6)

where $n_{ir}$ - intrinsic concentration at reference location, $\varphi$ -electrostatic potential, $\phi_{n,p}$ - quasi-Fermi levels of electrons and holes respectively, $\psi_{n,p}$ - band parameters of modeling
heterostructure.

$$\frac{d}{dx} \left( \varepsilon \frac{d\varphi}{dx} \right) = -q (p - n + N_D^+ - N_A^-) - \rho_{QD} \tag{7}$$

$$\frac{dJ_n}{dx} = q R = -\frac{dJ_p}{dx} \tag{8}$$

$$J_n = -\mu_n n \frac{d}{dx} (\varphi + \psi_n) + T \mu_n \frac{dn}{dx} \tag{9}$$

$$J_p = -\mu_p p \frac{d}{dx} (\varphi - \psi_p) - T \mu_p \frac{dp}{dx} \tag{10}$$

$$q \psi_n = (\chi(x) - \chi_r) + T \ln \left( \frac{N_c(x)}{N_{cr}} \right) \tag{11}$$

$$q \psi_p = (\chi(x) - \chi_r) - (E_g(x) - E_{g_r}) + T \ln \left( \frac{N_n(x)}{N_{nr}} \right) \tag{12}$$

where \( q \) - electrical charge, \( \rho_{QD} \) - QD charge, \( n, p \) - concentration of electrons and holes, \( N_D^+, N_A^- \) - impurity concentration of donors and acceptors, \( J_{n,p} \) - current densities, \( \mu_{n,p} \) - carrier mobility, \( R \) - recombination rate, \( E_g \) - band gap energy, \( \chi \) - electron affinity, \( N_{C,V} \) - conduction and valence effective densities of states, subscript \( r \) refers to value at references material.

The recombination rate includes three terms, i.e. bimolecular recombination, Shockley-Reed-Hall recombination and recombination in quantum dots:

$$R = B n p + R_{SRH} + R_{QD} N_S \Phi(x) \tag{13}$$

$$R_{SRH} = \frac{pm - n_i^2}{\tau_n (p + n_i) + \tau_p (n + n_i)} \tag{14}$$

where \( B \) is the constant of bimolecular recombination, \( R_{QD} \) is the recombination rate in a single quantum dot, \( N_S \) is the total quantum dot surface density, and \( \tau_n, \tau_p \) are electron/hole lifetimes in the GaAs matrix. The \( \Phi(x) \) function is non-zero in the area where QDs are placed and should

Table 1. Table of models parameters. QD parameters [2], AlGaAs parameters[9], GaAs parameters [10], [11].

| QD model       | Drift-diffusion model               |
|----------------|------------------------------------|
| Electron capture rate, \( g_{en} \) | 219 ns\(^{-1} \) | Temperature, \( T \) | 300 K |
| Hole capture rate, \( g_{ep} \)       | 19 ns\(^{-1} \) | Active area width, \( b \) | 300 nm |
| Electron down-hopping rate, \( g_{e21} \) | 1250 ns\(^{-1} \) | n-emitter doping, \( N_D \) | \( 5 \cdot 10^{17} \) cm\(^{-3} \) |
| Electron up-hopping rate, \( g_{e12} \) | 125 ns\(^{-1} \) | p-emitter doping, \( N_A \) | \( 5 \cdot 10^{17} \) cm\(^{-3} \) |
| Internal losses, \( \alpha_{in} \)     | 1.5 cm\(^{-1} \) | Active layer doping, \( N_{act} \) | No doping |
| External losses, \( \alpha_{out} \)    | 3.1 cm\(^{-1} \) | QD surface density, \( N_S \) | \( 5 \cdot 10^{10} \) cm\(^{-2} \) |
| GS level degeneracy, \( D_1 \)         | 2 | \( Al \) mole fraction, \( x \) | 0.8 |
| ES level degeneracy, \( D_2 \)         | 4 | Band gap, \( E_g (AlGaAs) \) | 2.09 eV |
| Energy of GS optical transition, \( E_1 \) | 983 meV | Band gap, \( E_g (GaAs) \) | 1.42 eV |
| Energy of ES optical transition, \( E_2 \) | 1050 meV | Conductive band density, \( N_C \) | \( 1.6 \cdot 10^{19} \) cm\(^{-3} \) |
| GS maximum gain, \( G_{maxGS} \) | 6 cm\(^{-1} \) | Valence band density, \( N_V \) | \( 1.5 \cdot 10^{19} \) cm\(^{-3} \) |
| ES maximum gain, \( G_{maxES} \) | 12 cm\(^{-1} \) | SRH relaxation time, \( \tau_{n,p} \) | \( 10^{-8} \) s\(^{-1} \) |
| Localization energy of electron ES level, \( E_e \) | 0.16 eV | Bimolecular coefficient, \( B \) | \( 5 \cdot 10^{-11} \) s\(^{-1} \) cm\(^{-3} \) |
| Localization energy of hole level, \( E_h \) | 0.22 eV


be normalized to unity: \( \int \Phi(x) dx = 1 \). At the same time the charge density formed by a QD layer and included in (7) could be described as:

\[
\rho_{QD} = qQ_{QD}N_S \Phi(x),
\]

where \( Q_{QD} \) is the dimensionless charge of quantum dots.

One can see that quantum dots are characterized in the DDE by only two functions \( R_{QD}(n(x_0), p(x_0)) \) and \( Q_{QD}(n(x_0), p(x_0)) \), where \( n(x_0), p(x_0) \) are carriers concentrations at the point where QD layer is placed. These functions can be written down as

\[
Q_{QD} = (D_1 + D_2)f_h - D_2 f_e - D_1 f_{e1},
\]

\[
R_{QD} = (D_1 + D_2)\left(g_{cp}(1 - f_h) - g_{cp}f_h\right),
\]

where \( f_{e1,2} \) and \( f_h \) are the solution of (1) at the given rates of captures into empty QD \( g_{cp} \) and \( g_{cn} \). The rates themselves are obviously proportional to carrier concentration near a QD:

\[
g_{cn} = V_{cn}n(x_0); g_{cp} = V_{cp}p(x_0),
\]

and proportionality constants can be calculated with the detailed equilibrium principle:

\[
N_C V_{cn} \exp \left(-\frac{E_e}{T}\right) = \frac{1}{2} g_{cn}; N_V V_{cp} \exp \left(-\frac{E_h}{T}\right) = \frac{1}{2} g_{cp},
\]

where \( E_{e,h} \) are electron ES and hole localization energies in a QD, and \( N_{C,V} \) are effective state density in conductive and valence GaAs bands.

In order to numerically solve DDE system we used the method of [5] based on \( J_n, J_p \) effective approximation and Newton-Rapson iterative relaxation scheme [8].

4. Results and discussion

The band diagram near the threshold of GS lasing is shown in Figure 1.

![Figure 1. Band diagram of QD laser at the injection current just above the onset of GS lasing. The QD layer is placed in the middle of i-region. The n-emitter is at the left side of the figure. Quasi-Fermi levels for electron and holes are also shown.](image-url)

One can clearly notice a significant potential step on the emitter/i-region interface. The value of a potential rise in n-emitter is about 150 meV, which is much higher than \( T \), and should
be taken into account in any modeling approach. Also, the profile of the potential is clearly asymmetric with respect to the QD plane. This happens because of the significant drop of electric field while moving through the QD plane in positive direction. A possible explanation is following: due to higher electron mobility uncharged quantum dots attract more electrons than holes or, in other words, in the steady laser operation QDs tend to be negatively charged (see also [4]). This charging reveals itself as an electric field drop near the QD plane that results in boosted flow of holes from p-emitter to QDs that compensate higher electron mobility.

There are two widely used simplifications in modeling of light-emitting p-i-n structures: high Coulomb screening in the i-region and no-screening approach in the i-region. The first one refers to the idea that electron/hole concentration is so high in the i-region that no significant electric field could exist at the $T/qb$ scale, i.e. the free carriers screen fields of the charges in QD and emitters. That is often called ‘flat’ band theory. On the other hand, the second one assumes that charge carrier concentration is low enough to neglect any screening effects and, therefore, electric field is constant between emitters and QD layer [1]. We state that in the types of laser which have been studied both assumptions are not valid. As it can be seen from Figure 1 neither bands are flat nor screening can be neglected. That is why numerical modeling seems to be required in order to achieve quantitative results.

The dependence of h-factor on injection current and $\delta$-doping is shown in Figure 2a. The h-factor is well below unity which is in complete agreement with band diagram analysis i.e. negative charging of QDs and low hole concentration (depletion) in the QD region comparing with electrons (not shown in the current paper). One may also notice that the h-factor is growing with the injection current. Probably, this is due to increased boosting of holes current towards the QDs layer. The impact of $\delta$-doping on h-factor is quite obvious: p-doping increases h-factor and n-doping decreases it. In simplified terms p-doping, for example, leads to additional negative charge of acceptors near the QD plane, that clearly, increases holes flow and holes concentration.

The dependence of lasing power through GS/ES optical transitions on the injection current is shown on Figure 2b. The major result is that p-doping increases both maximum power emitted through GS and threshold of ES lasing. These results are closely connected because after the

![Figure 2. a) h-factor dependence on current density for different samples: undoped (medium curve), n-doped (bottom curve) and p-doped (top curve). The onset of lasing through ES is also shown for undoped and p-doped samples. b) Dependence of the radiation power of the current at different modulation doping. Dash lines represents emission from ES, solid lines represents emission from GS.](image-url)
onset of ES lasing GS power stabilizes or decreases depending on laser parameters. The detailed explanation of the way higher value of h results in GS power rising was presented earlier [2]. We mention here simple qualitative picture: let us assume that QD charge should be equal -6q in order to balance the flows of electrons and holes toward the QD region, i.e. all electron levels should be filled and hole levels should be empty. In that case only transparent condition could fulfilled (no filling inversion) and no gain is possible. Otherwise, the charge neutrality of QDs, for example, when all electron and hole levels are filled, corresponds to maximum gain. As a result, charging of QDs suppresses QD gain and since the ES maximum gain is higher than GS one favors to the ES lasing.

In the end we should notice that performed calculations are also of significant importance for multimode or comb emission of QD laser. The multimode lasing is intrinsically connected with spacial-hole burning in active area that is ruled out by non-homogeneous distribution of light intensity and carrier diffusion along the direction of light propagation. The latter is described by the solution of DDE set studied in this paper. Thus, suggested approach to QD laser modeling can be discussed as a first step to accurate calculation of comb laser spectral properties, spatial hole burning and underlying physical effects.

5. Conclusion
It has been shown that h-factor is variable and depends on the carrier concentration near QD, doping and injection current. In the non-doped laser QDs become charged, ground electron state (GS) fully filled that suppress gain and lasing through GS in favor to ES emission. Our calculations demonstrate that p-type modulation layer leads to neutralization of QD and increases the ground state gain. That, in turn, leads to an increase of threshold current for lasing via ES and increases power radiated from ground state. On the other hand, n-type doping leads to decrease of threshold current and can completely suppress GS lasing.

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References
[1] L.V. Asryan, R.A. Suris. Charge Neutrality Violation in Quantum-Dot Lasers IEEE J. Sel. Top. Quant. Electron., vol. 3, no. 2, 1997
[2] V.V. Korenev, A.V. Savel'ev, A.E. Zhukov, A.V. Omelchenko, M.V. Maximov. Effect of carrier dynamics and temperature on two-state lasing in semiconductor quantum dot lasers, Semicond. 47 (10), 1397 (2013).
[3] V.V. Korenev, A.V. Savel'ev, A.E. Zhukov, A.V. Omelchenko, M.V. Maximov. Appl. Phys. Lett., 102, 112101 (2013).
[4] I. C. Sandall, P. M. Smowton, J. D. Thomson, T. Badcock, D. J. Mowbray, H.-Y Liu, and M. Hopkinson, Appl. Phys. Lett. 89, 151118 2006.
[5] Scharfetter, D.L., Gummel, H.K., Large signal analysis of a silicon Read diode. IEEE Trans. Electron Dev. 16, 6477 (1969)
[6] Lundstrom M.S., Schwartz J., Gray J.L. Transport equations for the analysis of heavily doped semiconductor devices Solid-Staft Electronics. 1981. Vol. 24. Pp. 683691.
[7] Lundstrom M.S., Schuelke R.J. Modeling semiconductor heterojunctions in equilibrium Solid-State Electronics. 1988. Vol. 25, no. 8. P. 683691.
[8] A. M. Ostrowski. Solution of Equations and Systems of Equations, Academic Press, New York, 1960
[9] Goldberg Yu.A. Handbook Series on Semiconductor Parameters, vol.2, M. Leı̂vinshtein, S. Rumyantsev and M. Shur, ed., World Scientific, London, 1999, pp. 1-36.
[10] Levinšhtein M.E., S.L. Rumyantsev Handbook Series on Semiconductor Parameters, vol.1, M. Levinštein, S. Rumyantsev and M. Shur, ed., World Scientific, London, 1996, pp. 77-103.
[11] Dargys A. and J. Kundrotas Handbook on Physical Properties of Ge, Si, GaAs and InP, Vilnius, Science and Encyclopedia Publishers, 1994

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