Carrier Transport Effects in Multi Layer Quantum Dot Lasers and SLDs

M. Rossetti[1], P. Bardella[1], M. Gioannini[1] and I. Montrosset[1]

[1] Dipartimento di Elettronica, Politecnico di Torino, Turin, Italy
mattia.rossetti@polito.it

Abstract. *Influence of carrier diffusion in the separate confinement heterostructure (SCH) region and carrier capture by each quantum dots layer (QDL) in quantum dot lasers and SLDs is studied with a modified rate equations model. We perform the static analysis of several Dots-in-a-Well lasers and SLDs with different numbers of QDLs.*

Introduction

In the last years, semiconductor Quantum Dots (QD) lasers and SLD have shown improved performances as compared with Quantum Well (QW) devices i.e. lower threshold currents and reduced temperature sensitivity.
Carrier transport effects in Multi-Quantum-Well (MQW) lasers have been widely studied in the past decade. The effect of transport and capture times on threshold current, quantum efficiency [1-2], modulation bandwidth [2-3] and large-signal responses [2] have been clearly demonstrated both experimentally and from simulations.
In QD based devices these effects are expected to be considerably greater. The presence of deeper localized QD states considerably reduces the escape rates from the confined states to the SCH bulk states, increasing therefore the non-uniformity between the carriers concentrations in each QDL. Inhomogeneous carrier distribution in the QDLs is expected to limit the performances of structures with a large number of QDLs.
We developed a time-domain rate-equation-model able to resolve carriers concentrations in each QDL and in the SCH region. The model considers carrier diffusion across SCH region, carriers relaxation in the confined states and thermionic emission from confined states. Three confined QD states (GS, ES1, ES2) are included.
In the following, a brief description of the model is given and then its application to the analysis of static properties of DWELL lasers with different number of QDLs is shown. Performances of multi layer SLDs when the number of QDL is changed are presented.

Description of the model

Carrier transport in QD lasers and SLD with an arbitrary number of QDLs is described via a rate equations based model, shown in figure 1.
In order to resolve carrier and photon densities variations along the waveguide in SLD structures, the cavity is divided in many slices in the propagation direction (z axis in figure 1) and a travelling wave (TW) method is applied.
Three populations of photons associated to GS, ES1 and ES2 transitions are considered. Each population is then subdivided in forward and backward propagating waves.
The spatial and temporal evolution of the photon number inside the cavity is therefore obtained as $S_k^{\pm}(z \pm \Delta z) = S_k^{\pm}(z) e^{\left(\sum_l \Gamma_{xy}^l g_k\left(\rho_k^l(z)\right) - \alpha_i - \alpha_{plasma}(z)\right)\Delta z} + S_{esp,k}(z)$, where subscript k represents GS, ES1 and ES2 photon populations; subscript l goes from 1 to the total

number of QDLs; S_k^+ and S_k^+ are forward and backward propagating photons associated to the k^{th} population; g_k is the material gain for the k^{th} population calculated via the carrier occupation probability in the k^{th} QD state, ρ_k; Γ_{xy}^{l} is the confinement factor in the l^{th} QDL; α_i and α_{plasma} are respectively internal and plasma losses; and $S_{esp,k}$ is the spontaneous emission rate in section z. Slice width Δz is related to the simulation time step Δt via the photons group velocity; Δt is chosen to be much smaller than the transition times involved in carrier rate equations in order to ensure a proper simulation accuracy.

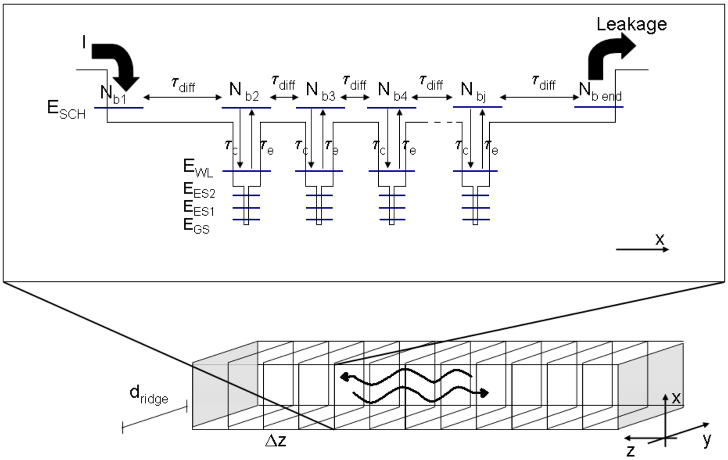


Figure 1 Schematic of the TW rate equation model: a 3D view of the optical cavity with forward and backward propagating waves is shown. The upper inset shows the energy level scheme in the direction perpendicular to the heterostructure (x axis) used to model carrier diffusion across the SCH [3]. Capture and escape times are reported. Wetting layer (WL) and QD states energies are shown. Intra-band transitions times between QD energy states, radiative and non-radiative recombination times are here omitted.

Carrier dynamics is described with a complex set of rate equations. Charge neutrality in each QDL layer is assumed. We suppose the dynamics to be dominated by holes, having an effective mass much bigger than the electron one. This simplification allows us to considerably increase the computational efficiency of the model.

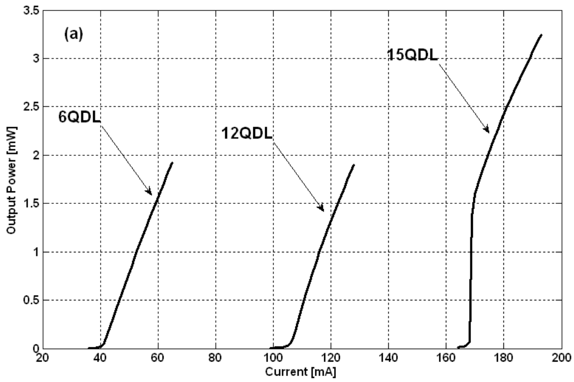
In order to model carrier diffusion across the SCH, we define a set of fictitious gateway states spatially distributed across the SCH [3] as shown in figure 1. Carrier diffusion between two adjacent gateways is modelled via an effective diffusion time $\tau_{diff} = \Delta x^2 / 2D_a$ where Δx is the barrier width and D_a is the diffusion coefficient. The diffusion rate between the i$^{\text{th}}$ and j$^{\text{th}}$ SCH state is calculated as $R_D^{ij} = \left(N_{b\,j} - N_{b\,i}\right) / \tau_{diff}^{ij}$.

Carrier relaxation in the two dimensional WL states is modelled via an effective capture time τ_c. The escape time τ_e is calculated from the capture time assuming no net transition rate at thermodynamic equilibrium.

Carrier dynamics in confined QD states in each QDL is described using a set of 4 rate equations (one for each confined state) for each QDL. This allows to resolve carrier distribution in each QDL. Intraband relaxation rates, non-radiative and Auger recombination as well as radiative recombinations are considered in each equation.

P-I characteristics of multi layer QD lasers

We apply the model to the P-I characteristic analysis of Dots-in-a-Well (DWELL) lasers with large SCH regions (about 1250 nm) and various number of QDLs. Figure 2a shows P-I curves obtained for structures with 6, 12 and 15 QDLs. An abrupt jump in the P-I characteristic of the 15 QDL structure appears just above threshold. This behaviour has been experimentally measured in many QD lasers with similar structure.



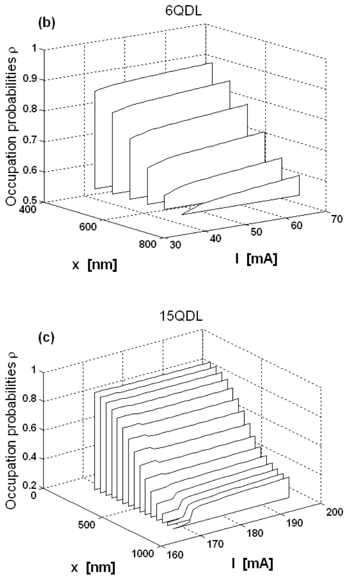


Figure 2 a) Calculated P-I characteristics for 6 QDL, 12 QDL and 15 QDL structures. All the devices are 3 mm-long. b-c) GS occupation probabilities versus current in the various layers (x axis is the direction perpendicular to the heterostructure growth plane) for 6 QDL and 15 QDL structures respectively. Above threshold, photons pumping in the QDL far from the carriers injection side is clearly shown in the 15 QDL structure.

The explanation of this effect can be obtained representing the occupation probabilities in the various QDL for the GS and the ESs. Figure 2b shows the GS occupation probability versus current in each QDL for the 6 QDL structure. The occupation increases in all the layers up to the threshold current (41 mA) and is significantly greater in the layers closer to the carrier injection side (p-side). These layers are almost saturated for the GS, while the last ones are just above transparency. Above threshold only a small change in the occupation probability takes place due to photons absorption in the last layers. In the case of the 15 QDL structure (figure 1c) the carrier density grows up to the threshold (around 168 mA) but strong carrier redistribution takes place among the layers just above threshold. In the layers far from the injection side, the GS is initially below transparency. However when the laser turns on, the photons generated by the more populated layers can pump the carriers of the last layers (photon pumping) which can reach the transparency. This behavior determines the slope discontinuity in the P-I characteristic.

Multi layer QD SLD

Multi layer QD SLDs with output power of several mW and about 100 nm optical bandwidth have been recently realized. In QD SLDs maximum modal gain is generally lower than in QW lasers, due to strong Pauli blocking effect in the QD states. In order to get considerable output powers, structures with a high number of QDLs must therefore be considered. It has been showed that increasing the number of QDLs up to 10, output powers can be considerably increased. In SLD structures with 10 QDLs, output power about 10 times greater than in an equivalent 5 QDLs structure has been obtained [4].

However carrier transport effects can represent a limit in the maximum number of QDLs useful to optimize SLD performances. Here we present a comparison between three 4.5 mm-long QD SLDs with 6, 12 and 15 QDLs respectively.

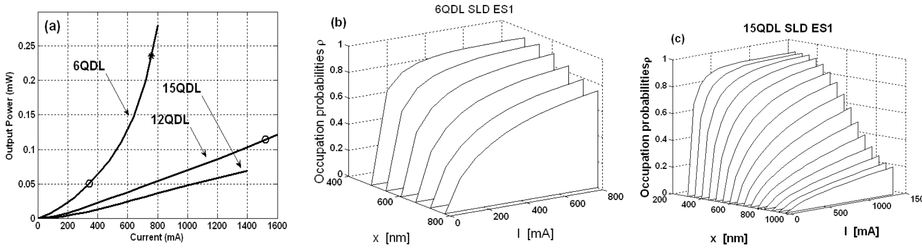


Figure 3 a) P-I characteristics for 4.5-mm-long SLDs with 6, 12 and 15 QDLs. b-c) ES1 occupation probabilities versus current in the various layers for 6 QDL and 15 QDL structures respectively.

Figure 3a shows the P-I characteristic of each structure. Circle and asterisk in the 6QDL SLD curve represent $P_{GS} = P_{ES1}$ and $P_{ES1} = P_{ES2}$ regimes.
In structures with 12 and 15 QDLs, the output power is considerably lower and a strong shift of the $P_{GS} = P_{ES1}$ regime occurs so that GS power is the main contribution to the total power for a wide range of currents. Figures 3b and 3c show ES1 occupation probabilities vs current in each layer for the 6 and 15 QDL SLDs. In the 15 QDL structure a strong non-uniformity between the ES1 occupation probabilities in the different layers occurs. Even if QDLs closer to the injection side are almost saturated, ES modal gain is quenched to very low values, considerably limiting the SLD output power.

Conclusions

Carrier transport effects in multi layer QD lasers and SLDs can be modeled with a travelling wave rate equation model; using this model static behavior of lasers and SLDs with different number of QDLs can be analyzed and performance limitations due to carrier transport effects can be underlined. Lasers with a high number of QDL (15) show abrupt jumps in the P-I characteristics at threshold and the differential efficiency is not considerably increased compared with 6 QDL lasers. Increasing the number of layers up to 15 in SLD structures the output power is considerably reduced due to the strong non-uniformity of carrier concentrations in each QDL.

This project was supported by the IST NanoUBSources European Project

References

[1] H. Hirayama, J. Yoshida, Y. Miyake and M. Asada, "Carrier capture time and its effect on the efficiency of quantum- well lasers", IEEE J. Quantum Electron., vol. 30, pp. 54-62, 1994.

[2] L.V.T. Nguyen, A.J. Lowery, P.C.R. Gurney and D. Novak, "A time-domain model for high-speed quantum-well lasers including carrier transport effects", IEEE J. Sel. Topics Quantum Electron., vol. 2, pp. 494-504, 1995.

[3] G. Rossi, R. Paoletti and M. Meliga, "SPICE simulations for analysis and design of fast 1.55 µm MQW laser diodes", J. Lightwave Technol., vol.16, pp. 1509-1516, 1998.

[4] M. Rossetti, L. Li, A. Markus, A. Fiore, L. Occhi, C. Vélez, S. Mikhrin, I. Krestnikov and A. Kovsh, "Characterization and modeling of broad spectrum InAs-GaAs quantum-dot superluminescent diodes emitting at 1.2-1.3 µm", IEEE J. Quantum Electron., vol. 43, pp. 676-686, 2007.