Incorporation of carrier capture and escape processes into a self-consistent cw model for Quantum Well lasers

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Abstract

We describe a one-dimensional model for the simulation of the cw properties of Quantum Well laser diodes, which incorporates self-consistently the carrier capture/escape processes into the complete semiconductor equations. The approach is applied to simulate some laser structures properties that can only be described considering carrier capture effects. We point out the importance of these processes in the performance of high power laser diodes operating under cw conditions.

Keywords: Quantum Well lasers; Carrier capture; Escape processes

1. Introduction

The carrier capture and escape processes are relevant to both the dynamic (determining the modulation bandwidth [1]) and the steady state properties of Quantum Well (QW) lasers. These processes will be extremely important for future generations of Quantum Dot lasers, and simple physical models are crucial for the development of simulation tools. Different approaches have been proposed to include these processes in those laser models solving the complete semiconductor drift-diffusion equations, with different levels of complexity, and relying on a number of external parameters [2,3].

We previously proposed a simple model for calculating the carrier capture and escape rates in QW lasers, with the advantage of using a single external parameter [4]. The model yielded good agreement with small signal experimental results for different laser structures, injection levels and temperatures. It is based on assuming elastic interaction between confined and unconfined carriers, neglecting the energy difference between the initial and final states.

In this work we extend our carrier capture/escape model and we include it into the complete drift-diffusion equations for semiconductor devices, with the goal of simulating some experimental features observed in QW lasers.

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2. Model description

The 1D model solves Poisson equation and continuity equations (electrons and holes) for the complete laser structure, together with a photon rate equation. The QW levels, band properties, and the optical mode vertical profile, are calculated out of the main self-consistent loop. Material gain spectra, spontaneous, Schockley–Read–Hall, and Auger recombination rates, are calculated using standard expressions. Free carrier absorption and band gap renormalization are included by means of empirical formulations.

Carrier capture and escape effects are incorporated by extending the model described in Ref. [4]. Unconfined and confined carriers are considered to coexist in real space in the QWs, without assuming *a priori* thermal equilibrium between them, but considering two different quasi-Fermi levels.

Our model includes an additional net capture rate term into the standard continuity equations for the unconfined carriers in the QW region, to account for the interaction between unconfined and confined carriers. The continuity equations for confined carriers can be expressed as:

$$R_{\mathrm{n}} = R^{(\mathrm{qw})} + R_{\mathrm{st}}$$

$$R_{\mathrm{p}} = R^{(\mathrm{qw})} + R_{\mathrm{st}}$$

The term $R^{(\mathrm{qw})}$ includes SRH, spontaneous and Auger recombination, whereas R_{n} is the net capture rate of electrons from the QW 3D states to the 2D states. The net capture rate is $R_n \equiv R_{cap} - R_{esc} \equiv n_{3d}/\tau_n^c - n_{2d}/\tau_n^e$, where τ_n^c and τ_n^e denote the electron capture and escape times. The latter is not a constant, but depends on the injection level and temperature. The model [4] relates τ_n^c and τ_n^e with a simple analytical expression, making thus possible to express the net capture rate in terms of only one time constant, τ_n^c in this case:

$$R_n = \frac{n_{3d}}{\tau_n^c}\left[1 - \exp\left(\frac{E_{Fn}^{(2d)} - E_{Fn}^{(3d)}}{kT}\right)\right]$$

A similar expression holds for the net hole capture rate.

All the equations are self-consistently solved by a Newton–Raphson method. Fig. 1 shows in more detail the implementation used to discretize the interaction of the confined and unconfined carriers. The mesh points for the 3D states extend along the whole laser structure (including the QW). Each of the points overlapping with the well region interact not only with the adjacent ones (unconfined), but also with confined carriers that are represented by a single point per QW. By this mechanism, carriers are 'captured' into the QW or 'escape' out of it. For this single point, the electrostatic potential used is the averaged value along the QW.

3. Application examples

The validity of the model is illustrated by simulating the diode differential resistance in QW lasers ($I\,dV/dI$ vs I). In bulk lasers, it shows a drop at the lasing threshold due to the pinning of the quasi-Fermi levels caused by stimulated emission [5]. However, QW lasers may show a very different behavior, due to carrier and escape processes [6]. A simple analysis based on rate equations indicates that the height of the step in the $I\,dV/dI$ characteristic depends on the ratio between the effective carrier lifetime and the escape time. This fact is related to the absence of quasi-Fermi level pinning for unconfined carriers in those laser structures with a small value of the carrier lifetime in comparison with the escape time, explaining the absence of the drop in the differential resistance of some samples.

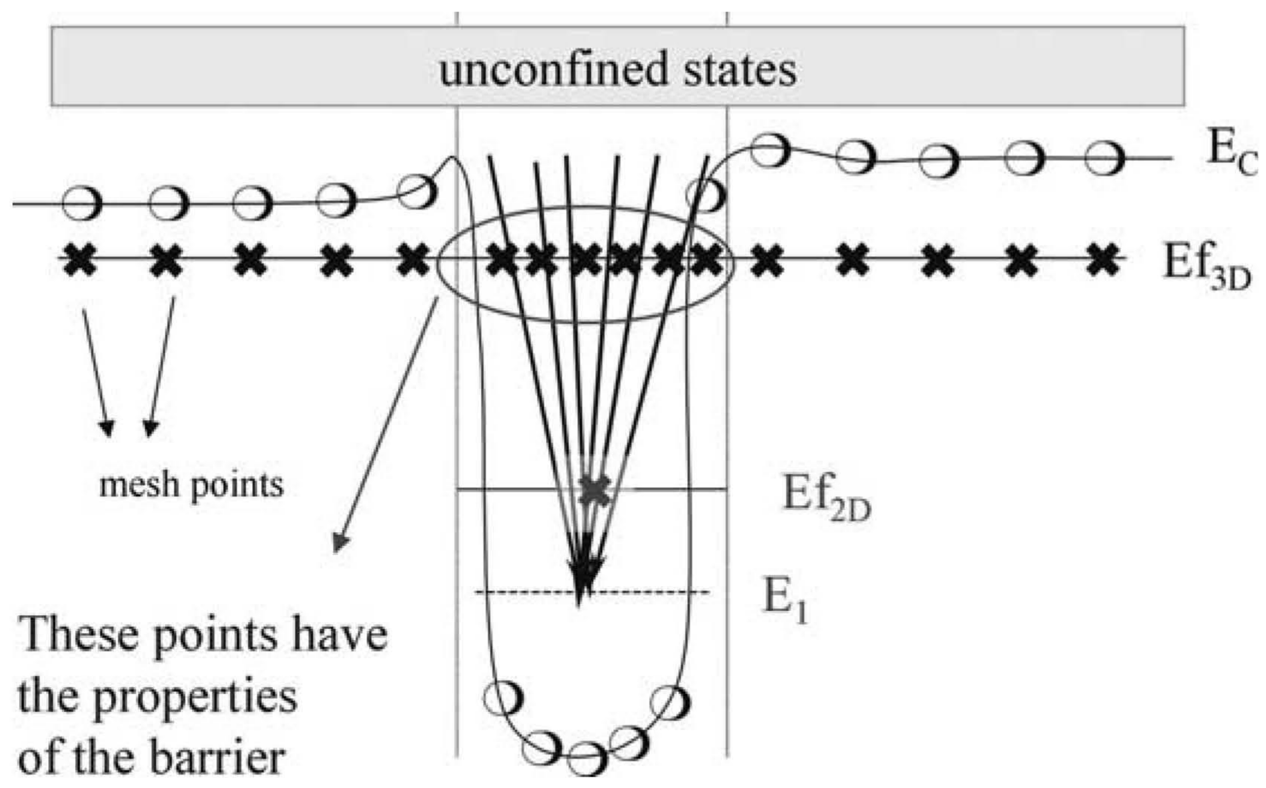

Fig. 1. Interaction between confined and unconfined carriers.

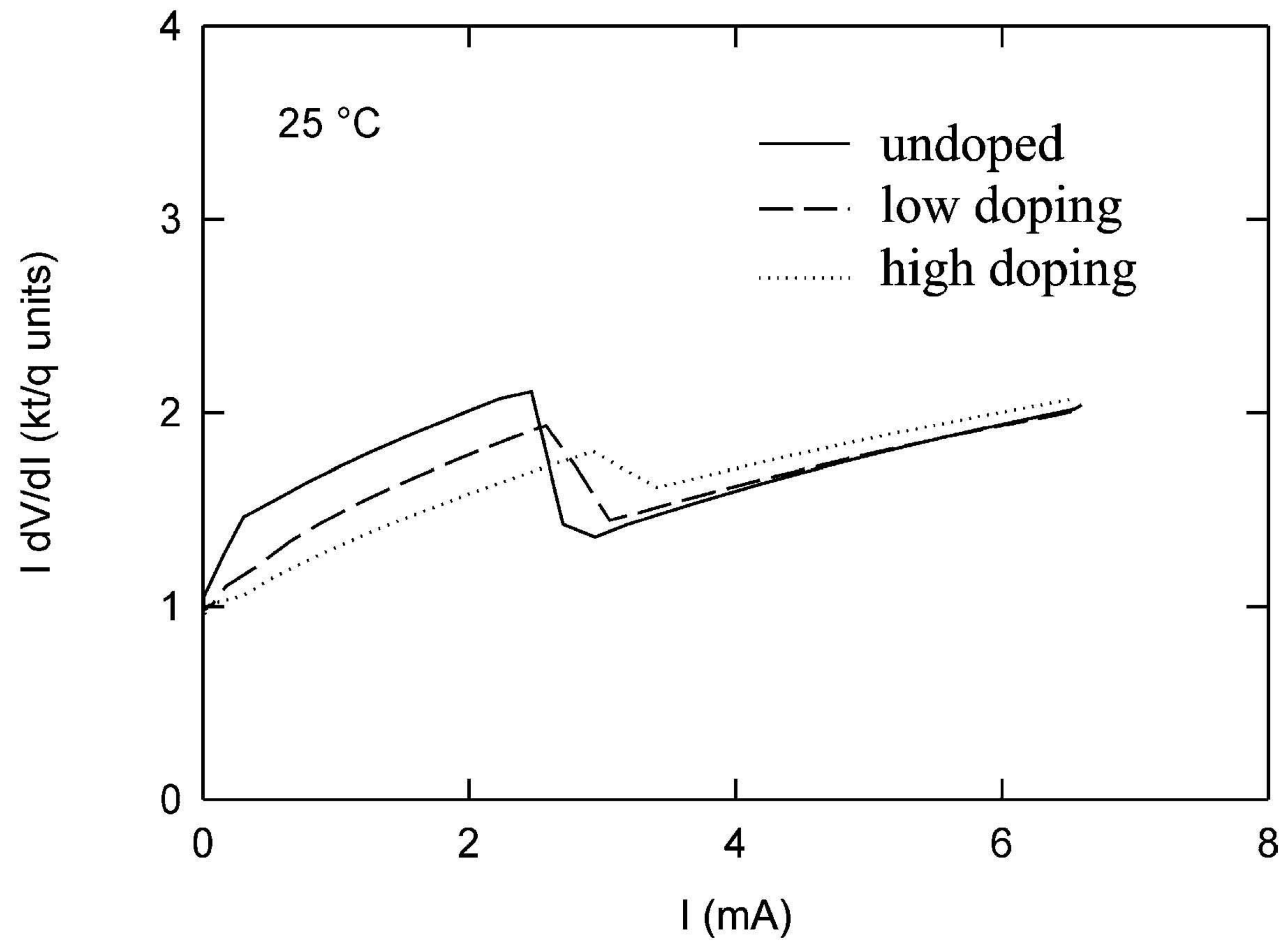

Fig. 2. $I\,dV/dI$ characteristic in InGaAs/GaAs QW lasers with different doping levels.

Different behaviors of the measured differential resistance for InGaAs/GaAs MQW lasers with different doping concentrations has been reported [7]. The higher the doping concentration, the lower the carrier lifetime/carrier escape time ratio, and therefore, the lower the height of the step in $I\,dV/dI$ characteristic. Simulations (Fig. 2) for those laser structures described in Ref. [7], using different capture times (and as a consequence of our model, different escape times), were carried out. A qualitatively good agreement with the experiments was obtained in the case of different doping concentrations.

Some laser structures with poor electron confinement present a deterioration of their performance due to the leakage of carriers over the heterojunction. The amount of this leakage depends on the carrier concentration in the confinement region, and hence, on the capture/escape processes. In a second example we demonstrate that our self-consistent model is properly accounting for these phenomena. Broad-area high power 808 nm InGaAsP lasers have been simulated to evaluate the impact of the capture time on the laser performance. The reference structure is a SQW device similar to that of Ref. [8]. A summary of the most important simulation results is shown in Table 1.

As we can observe in the light-current characteristics shown in Fig. 3, the slope efficiency decreases when the capture times are increased. This fact is explained as follows: as a consequence of the capture process, the 3D

Table 1
Capture time for electron and holes (input data, simultaneously changed), internal efficiency and characteristic temperature (results)

	τ_{cap} (n, ps)	τ_{cap} (p, ps)	η_{int} (%)	T_0 (K)
Standard	5	0.3	70.5	130
Test 1	50	3	42	68
Test 2	0.5	0.03	76.9	112.5

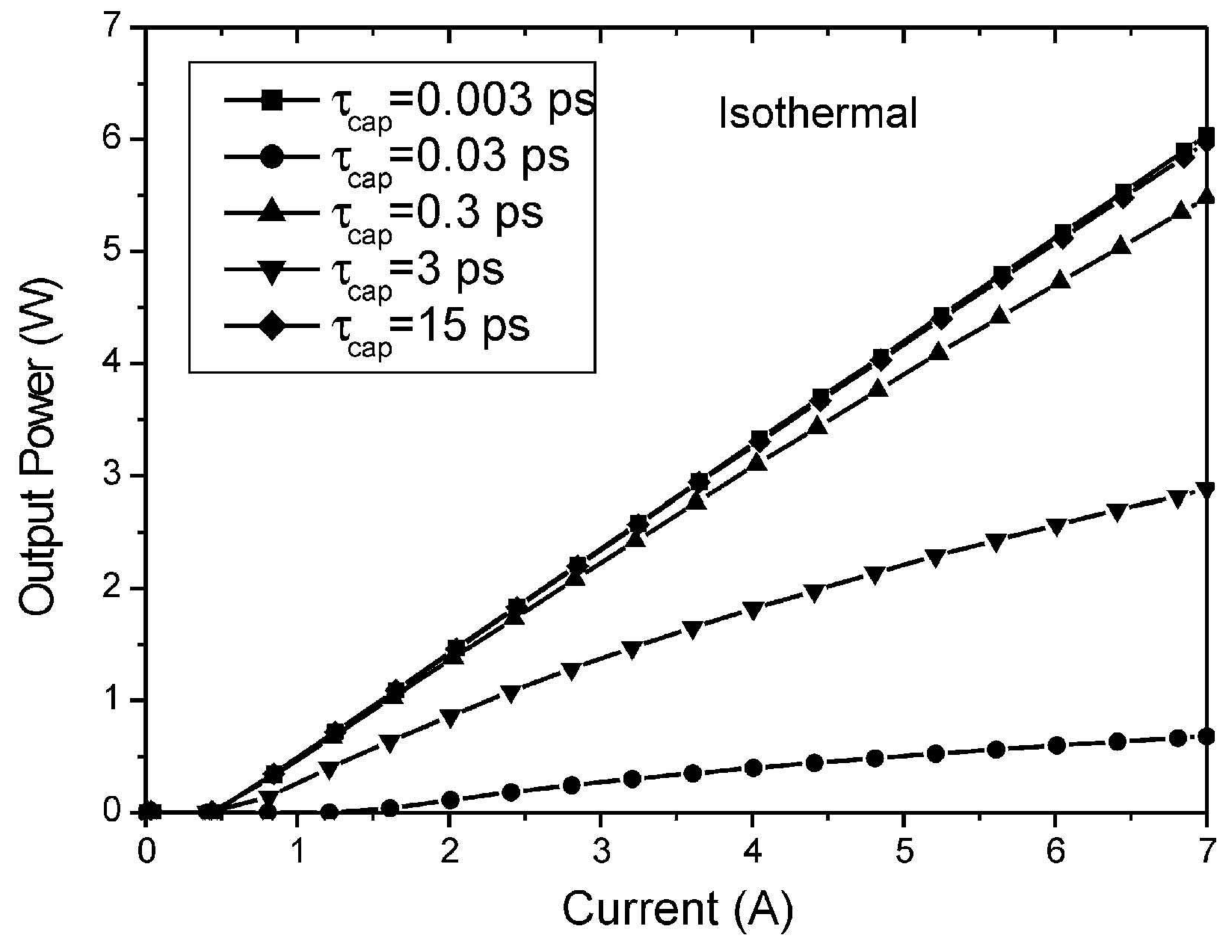

Fig. 3. Power–current characteristics as a function of the hole capture time.

carriers accumulate above threshold in the barrier region. The electron accumulation outside the well at high injection conditions, leads to their transport to the p-cladding region, where they recombine at the p-contact. A dramatic effect is observed when the electron capture time is higher than our standard value (5 ps). Simulations including self-heating stress even more the impact of this effect, as we can see in the dependence of the characteristic temperature (T_0) on the capture time.

4. Conclusions

A capture/escape model has been included into a cw simulation model for QW laser diodes. The results from the model reproduce quite well the experimental results in the differential resistance. The influence of carrier capture/escape processes on the optical performance of high-power lasers is demonstrated.

Acknowledgements

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