Multi-species modeling of quantum dot lasers with microscopic treatment of Coulomb scattering

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***Abstract*—We present a spatially resolved semiclassical model for the simulation of semiconductor quantum-dot (QD) lasers including a multi-species description for the carriers along the optical active region. The model links microscopic determined quantities like scattering rates between the different species and dephasing times, that depend essentially on the carrier densities, with macroscopic transport equations and equations for the optical field.**

I. INTRODUCTION

Due to many advantages semiconductor quantum dot lasers have become increasingly interesting for telecom applications. A detailed understanding of the physics involved in these lasers and the need for optimization of such devices makes them subject for theoretical investigations, comprising modeling and numerical simulation. A suitable model used for the simulation of such devices is a complex multiscale problem and has to cover the most important physical effects.

On the coarsest scale, classical carrier transport through bulk part of the device can be described by a macroscopic model, which are the drift-diffusion equations in our case. Additionally, a semiclassical description of the optical field by Maxwell equations is required. Usually, by selfconsistently coupling of both the electronic and the optical model by the optical gain and by the rate of spontaneous and stimulated recombination, a consistent picture for the spatial distributions of the carriers and the field intensity [1] is achieved, c.f. Fig.1.

However, on the scale of the quantum dot active regions, processes like optical gain, scattering and recombination of carriers are needed to be described by a microscopic model. The dynamics of the laser will be strongly influenced by the scattering rates [2], as well as the spectrum of the optical gain by the dephasing time T_2 [3].

II. MULTI SPECIES MODEL

In our model we differ between bulk carriers, carriers confined in the wetting layer (WL) and carriers that are localized in the quantum dots. This is schematically shown in Fig. 2. This necessarily involves the Poisson equation for the electrostatic potential, where the sum over the the local distributions of the respective electron and hole species enters the net charge density, together with the doping profile. The bulk carriers are freely roaming through the layers in devices as depicted in Fig.1 and are described by classical drift-diffusion equations. The carriers confined in the wetting layer are described by modified drift-diffusion equations, whereas the occupation of the QD-states are described by rate equations. All these equations are coupled to each other by corresponding carrier-exchange rates. For the injection of the bulk carriers into the wetting layers, as depicted in Fig. 2, phenomenological capture-escape rates according to [4], [5] are used. For the capture-escape process from the wetting layer to the quantum dots we use scattering rates derived from a microscopic model for the dominating Auger-like processes at high carrier densities, which have their physical origin in Coulomb-scattering.

III. QUANTUM DOT ACTIVE REGION

The active region of our device under consideration comprises optically active QDs grown on a 2D wetting layer as shown in Fig 3. We restrict to QDs possessing only a single

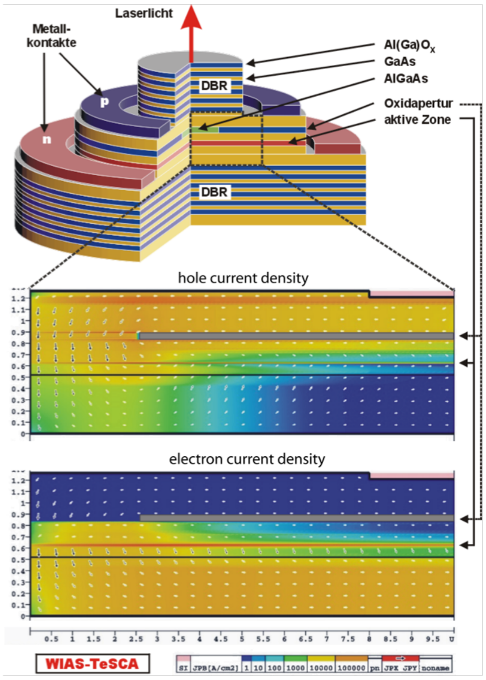

Fig. 1. Top: Scheme of a oxide confined VCSEL. Below: hole (upper) and electron (bottom) current density distribution in a 2D cross-section, calculated with WIAS-TeSCA.

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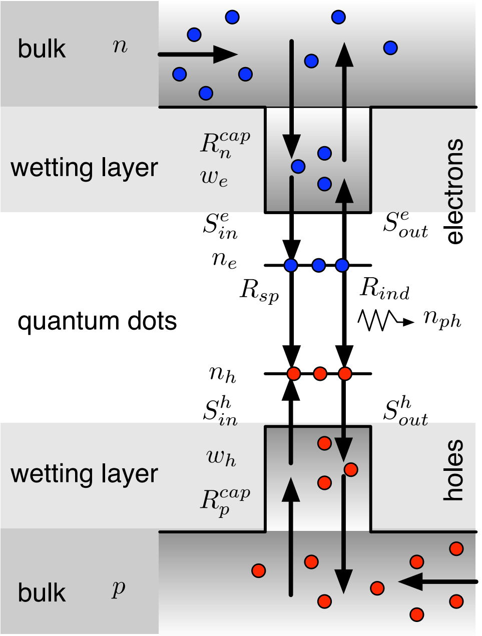

Fig. 2. Scheme of scattering and recombination processes in the quantum dot active region described by the multi-species model. After carriers from the bulk are injected into the wetting layers, they enter the quantum dots by Coulomb scattering. From there they contribute to the stimulated emission.

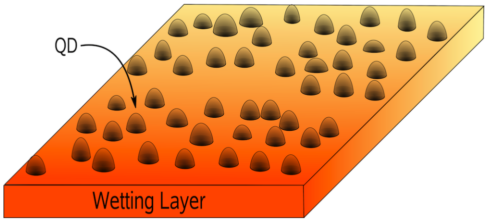

Fig. 3. Scheme of the active region, consisting of an ensemble of quantum dots, differing in size and shape, that are grown on a wetting layer.

electron and only a single hole (ground-) state, see Fig. 2. The optical transitions between the QD electron and hole states result in the optical gain. The Coulomb scattering causes non-radiative, Auger-like transitions between the QD and wetting layer states. Coulomb scattering is known to arise from carrier-carrier scattering as well as from carrier-phonon scattering. The latter process dominates at low carrier densities, whereas carrier-carrier scattering becomes increasingly important at higher carrier densities [6]. Aiming on high carrier densities at (and above) laser threshold, we will restrict our discussion on Coulomb scattering between the carriers and neglect any phonon scattering.

IV. COULOMB SCATTERING BETWEEN QUANTUM DOT AND WETTING LAYER STATES

The calculation of the scattering rates, as well as of the dephasing time T_2 of the resonant QD transition, has been treated by density matrix theory in the limit of the second order Born-Markov-approximation. This results in a non linear behavior of these scattering rates and of the T_2 time, making them especially depended on the WL carrier density [6]–[9]. For precise calculations several scattering channels between the QD and WL have to be included, as in particular pure dephasing processes for the calculation of T_2 [3]. The dephasing time determines the homogeneous line width of the emitted light. Therefore it is also of major importance for the gain.

V. CONCLUSION

A semiclassical, spatially resolved, multi-species model for the simulation of semiconductor quantum-dot (QD) lasers has been presented. It is is suited to be applied on VCSEL devices containing QD active regions. The electronic model comprises the carriers in the bulk, in the wetting layer and in the QDs with specifically suited continuity equations along the optical active region. In particular the coupling between the equations for the wetting layer densities and the equations for the QD densities are determined by microscopically calculated scattering rates between these species. This electronic model is selfconsistently coupled to equations for the optical field, where in addition microscopically determined dephasing times enter. In effect these microscopically calculated quantities become depended on the carrier densities in a nonlinear way. This particular nonlinear behavior is expected to influence the dynamic properties of the devices, as e.g. their modulation response [9].

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