Modeling of Charge and Photon Transport in Coupled Intracavity Light Emitters

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***Abstract*— To enable a more detailed analysis of our recent studies of intracavity double diode structures (DDSs), new simulation tools are needed. Such simulation models must account for both charge and photon transport in the studied structures, consisting of optically coupled AlGaAs/GaAs double heterojunction light emitting diode (LED) and GaAs p-n-homojunction photodiode (PD) structure, enclosed within a single semiconductor cavity. We apply the drift-diffusion formalism for charge transport and an optical model coupling the LED and the PD, with the aim of complementing our experimental work on the efficiency of these devices to understand better their suitability for electroluminescence cooling [1], and shedding further light on electroluminescence and optical energy transfer in the structures.**

I. Introduction

In the last few decades, research on planar optoelectronic devices involved less studies on conventional III-V based devices, and focused much more on devices based on nitride and other emerging materials, e.g. antimonide and nanomaterials, by addressing the scientific and technological challenges introduced by these material systems [2], [3]. However, recent developments in optical cooling, light emission efficiency and information processing [4]-[6] provoked an interest in mature III-V materials, such as III-As. Despite substantial efforts, light confinement due to the large refractive index of typical semiconductors has remained one of the largest obstacles in demonstrating the optical cooling of semiconductors [7]. Our recent experiments [1] investigated the effects of enclosing a III-As light emitting diode (LED) and a light absorbing photodiode (PD) in an intracavity double diode structure (DDS) configuration, as shown in Fig. 1, which essentially eliminates the light extraction issues encountered in conventional setups. The presently studied intracavity approach can substantially relax the material requirements for reaching the high current electroluminescence (EL) cooling regime. In this work, we apply the drift-diffusion (DD) formalism for current transport, to understand further the behavior of the intracavity configuration, and discuss its suitability for EL cooling.

II. Simulation Method

We employ a numerical transport model based on the DD current and continuity equations for charge carriers, effectively coupling the partial differential equations for the electrostatic potential φ and the quasi-Fermi potentials φ_n and φ_p for electrons and holes, respectively, as given below:

$$\nabla \cdot (-\varepsilon \nabla \varphi) = q(p - n + N_d - N_a),$$

$$\nabla \cdot \mathbf{J}_n = \nabla \cdot (-q\mu_n n \nabla \varphi_n) = qR,$$

$$\nabla \cdot \mathbf{J}_p = \nabla \cdot (-q\mu_p p \nabla \varphi_p) = -qR,$$

where n is the electron density in the conduction band, p is the hole density in the valence band, N_d is the ionized donor density, N_a is ionized acceptor density, R is the recombination rate per unit volume, ε is the permittivity, q is the elementary charge, and μ_n and μ_p are the electron and hole mobilities, respectively. Further details about the model can be found in [8]-[10]. The recombination rate R is modeled using the well-known parametrized formula for radiative, Shockley–Read–Hall (SRH), and Auger recombination [8]. In contrast to typical LED models, our structure involves three terminals described by Dirichlet-form boundary conditions, biasing the LED in the customary manner, while short-circuiting the PD. In addition, the LED and the PD are optically coupled, as described below.

III. Simulated Structure

The studied DDS is shown in Fig. 1 [1]. It incorporates a double heterojunction (DHJ) GaAs/AlGaAs LED grown on top of a GaAs p-n-homojunction photodiode. Light emission from the LED is guided towards the photodiode either directly or after a single reflection from the top contact. Direct measurements of the current components (Fig. 1) allows detecting the amount of absorbed light [1]. In our mathematical model, the electron-hole (e-h) recombination term in the LED quantum well is coupled to an e-h generation term in the photodiode intrinsic layer, with a coupling constant extracted from these measurements.

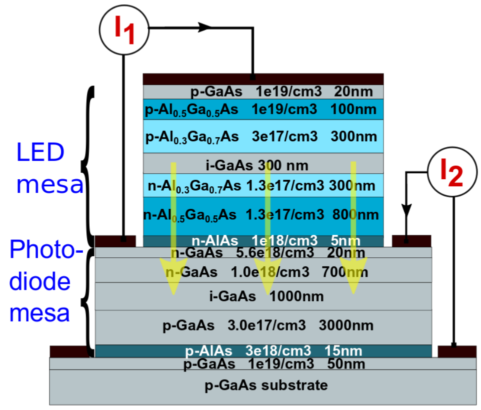

Fig. 1: Schematic illustration of the intracavity DDS configuration, incorporating a DHJ LED and a photodiode, showing each layer's doping density and thickness.

IV. Results, Discussion and Conclusions

Fig. 2 shows the profiles of conduction and valence band edges, and the quasi-fermi levels (QFLs) for electrons and holes, for the LED at weak and strong injection conditions. While the QFLs for electrons and holes in the LED split as soon as bias is applied, QFLs in the PD start to split at around 0.6V when enough current is generated. The split becomes more visible at strong injection where LED photon emission results in the generation of a significant number of e-h pairs, giving rise to a large PD current. Fig. 3 shows the current density through the LED and the PD as a function of bias, and three figures of merit for the system: the coupling quantum efficiency I_2/I_1 (CQE), the PD internal quantum efficiency (IQE) I_2/I_{gen}, and the LED IQE I_{rad}/I_1. Here, I_1 is the LED current, I_2 is the PD current, I_{rad} is the current arising due to radiative recombination in the LED, and I_{gen} is the current due to carrier generation in the PD. These results qualitatively agree with experimental data published by the authors [1]. For the LED at strong injection, radiative recombination dominates. Non-radiative SRH recombination starts to dominate at weak injection, explaining the reduction in the CQE in this regime. CQE peaks at around 100A/cm^2 then falls again at strong injection, in agreement with Ref. [1].

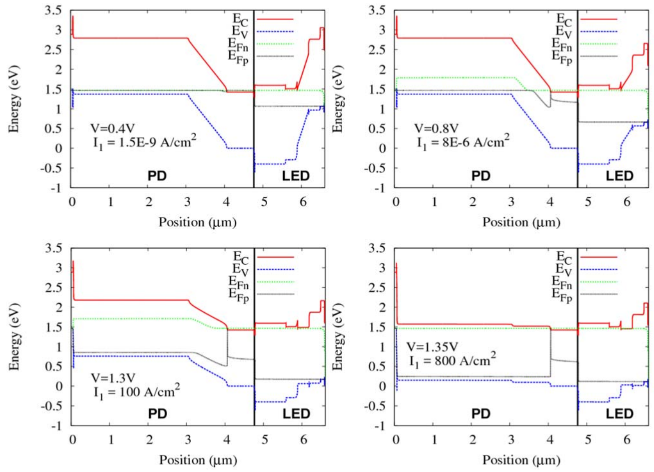

Fig. 2: The band diagrams at selected bias voltages.

To conclude, we used the DD formalism with first order optical coupling to study a LED-PD intracavity configuration with a strong potential in EL cooling. Our model will be used, as a starting point, to incorporate more detailed optical coupling models, and to explore further the effect of geometrical features and material properties, to optimize performance and demonstrate cooling. The model is also being extended to study more realistic three-dimensional structures, and will ultimately allow the self-consistent coupling of the electrical and optical device behavior; in this case, in-house optical models [11]-[13] will be used to extract directly the CQE. This will provide deeper insight into the physics and operation of the light emitters, allowing the design of efficient solid-state EL cooling devices.

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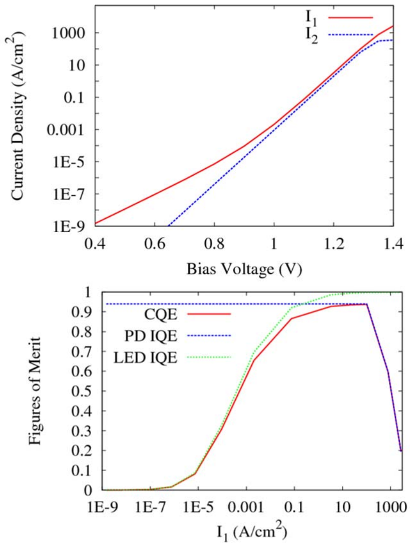

Fig. 3: (top) The current density through the LED and photodiode contacts, against bias. (bottom) The CQE of the DDS and the IQE of the LED and the PD.

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