Electroluminescent cooling using double diode structures

Toufik Sadi, Ivan Radevici, Pyry Kivisaari, Alberto Casado, and Jani Oksanen
Engineered Nanosystems Group, Department of Neuroscience and Biomedical Engineering, Aalto University,
P.O. Box 12200, FI-00076 AALTO, Finland
toufik.sadi@aalto.fi

***Abstract*—The progress in optical cooling in recent years is resulting in a renewed interest in electroluminescent (EL) cooling using conventional III-V semiconductor light emitting diodes (LEDs). In this work, we address the limiting factors for observing EL cooling in III-As intracavity double diode structures (DDSs), at high powers at and close to 300K, by using a combination of experimental characterization and physical device models. The studied DDSs incorporate optically-coupled III-As LED and p-n homojunction photodiode (PD) structures, integrated in a single device and providing a favourable environment for EL cooling observation. We employ a modelling framework coupling the drift-diffusion charge transport model to a photon transport model calibrated using measurements on real devices at different temperatures. Results suggest that the bulk properties of the III-V materials are already sufficient for EL cooling.**

I. INTRODUCTION

The last 20 years witnessed substantial research on planar optoelectronic devices based on new materials, such as III-N, at the expense of conventional III-V devices [1]. However, recent progress in optical cooling [2] is causing a renewed interest in III-As materials [3]–[5]. In this work, we analyze the feasibility of observing electroluminescent (EL) cooling using a very favourable experimental setup: an InGaP/III-As intracavity double diode structure (DDS) formed by a light emitting diode (LED) and a photodiode (PD). To this end, we employ a simulation framework, as calibrated with experiments, coupling the drift-diffusion (DD) formalism for electronic charge transport to a photon transport model.

Fig. 1 shows the studied device, enclosing a InGaP/III-As LED and a GaAs light absorbing PD in an intracavity DDS configuration. Light emission from the LED is guided towards the PD, and the direct measurement of the LED and PD currents allows detecting the amount of absorbed light [3]. The DDS eliminates the light extraction issues encountered in conventional setups, and allows direct measurement of the coupling quantum efficiency (CQE) defined as the ratio $\eta_{CQE} = I_2/I_1$ of the injected LED current I_1 and the photocurrent generated in the PD I_2 [3], [6]. EL cooling can be demonstrated if the condition for the power conversion efficiency (PCE) '$PCE = \eta_{CQE}\hbar\omega/U > 1$' is met, indicating that the LED emits an optical power $I_2\hbar\omega/q$ higher than the injected electrical power $I_1 U$, where U is the bias of the LED itself, and $\hbar\omega$ is the emitted photon energy ($\sim$ emitter bandgap $E_g = 1.42$eV). Here, $U = U_1 - R_e I_1$, where U_1 is the applied bias and R_e is the measurement probe resistance ($\sim 3.7\Omega$).

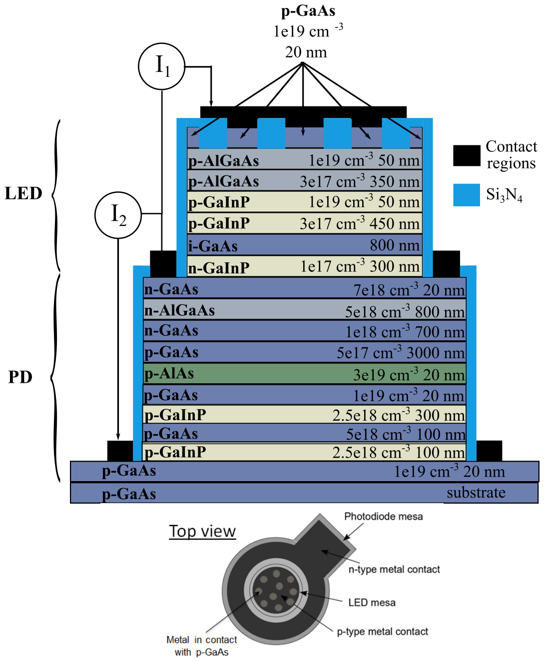

Fig. 1. The studied intracavity DDS, showing the layer arrangement including materials and doping concentrations (side view), and a top view of the full three-dimensional geometry. The top mesa diameter is 1mm.

II. MODELLING METHODOLOGY

To model charge transport, we solve for the three-dimensional (3D) DD equations to calculate self-consistently the electrostatic potential, net recombination rates, densities and quasi-Fermi levels for electrons and holes [7], [8]. The recombination rates are included using the ABC parameterized formula for radiative, Shockley−Read−Hall (SRH), and Auger recombination [8]. Surface and interface non-radiative recombination rates are calculated as discussed in [7]. The DDS contacts are described by the Dirichlet boundary condition, biasing the LED in the customary manner while short-circuiting the PD. The total recombination in the LED (i-GaAs) active region is coupled to the total generation in the PD (GaAs) layers through an optical coupling constant (CC), with the generation profiles following the Beer-Lambert law in the PD [7]. The CC is determined by solving the radiative transfer equation [9] using a top-contact−cap-layer system reflectivity calculated from the transfer matrix method [10].

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III. RESULTS, DISCUSSION AND CONCLUSIONS

We calibrate the model and extract relevant parameters using data obtained from measuring the DDS in Fig. 1. Established values for the SRH ($3 \times 10^5 \mathrm{s}^{-1}$ [11]), radiative ($B \sim 2 \times 10^{-10} \mathrm{cm}^3\mathrm{s}^{-1}$ [3]) and Auger ($C \sim 10^{-30} \mathrm{cm}^6\mathrm{s}^{-1}$ [3]) recombination constants already provide a good fit for the experiments at 300K. Temperature dependence calibrations are under way and presently we use literature values. A surface recombination velocity $V_{sr} \sim 10^5$ cm/s is estimated at the emitter GaAs/air free surfaces (matching reported values [12]).

Fig. 2(a) shows the $I - U_1$ characteristics of the LED and photodiode, showing excellent agreement between simulations and measurements. The LED and PD ideality factors are 2 and 1, respectively. In this case, non-radiative surface recombination is the main mechanism driving LED current at low biases (<~1V). The PD currents confirm that the radiative recombination in the LED is of the bimolecular form. The PCE of the reference device and a surface passivated device, where surface recombination at mesa edges is removed, is shown in Fig. 2(b) as a function of the electrical input power. The PCE of the passivated structure exceeds unity for an input power range from 200μW to 0.1W, indicating cooling in this regime. Fig. 2(c) shows the experimental dependence of the CQE on temperature (for 250K, 300K and 350K), and the corresponding simulation at 300K, showing an increase in the peak CQE as temperature is decreased. While observing cooling can be facilitated by identifying the optimal temperatures, extensive modelling and theoretical work is ongoing to understand better the effect of temperature on the PCE.

To conclude, we couple a 3D DD formalism with an optical model to demonstrate the possibility of realizing EL cooling in III-As double diode structures, under high biases and at and close to 300K. The modelling framework is calibrated with measurements, and is used to show how suppressing surface recombination allows the PCE to exceed unity, corresponding to EL cooling. This observation indicates that the bulk properties of the DDS materials are sufficient for EL cooling. Additionally, it is expected that the PCE can be increased further by minimizing both the radiative recombination in the PD and the optical losses out of the structure, but also looking at temperature dependencies.

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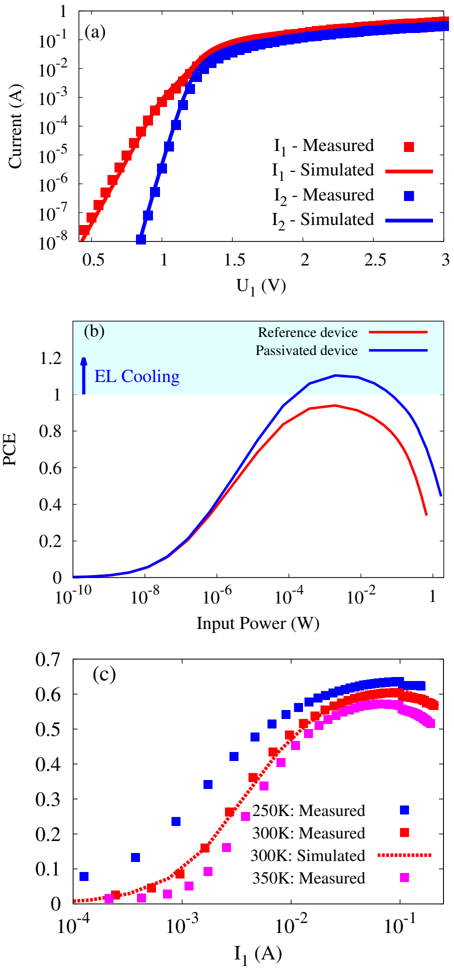

Fig. 2. (a) Experimental and simulated LED ($I_1 - U_1$) and photodiode ($I_2 - U_1$) characteristics, and (b) The corresponding PCE as a function of the input power, for a 1mm mesa diameter. (c) The measured and simulated CQE, as a function of LED current, for different temperatures, for a 200μm diameter.