Electrically-injected III-V diodes for large-area optoelectronics

Antti Myllynen, Toufik Sadi, and Jani Oksanen
Engineered Nanosystems Group, Department of Neuroscience and Biomedical Engineering, Aalto University,
P.O. Box 12200, FI-00076 AALTO, Finland
antti.i.myllynen@aalto.fi

***Abstract*—The growing demand for high-power light-emitting diodes (LEDs) for large-area optoelectronic applications has lead to the development of the diffusion driven charge transport (DDCT) technique that provides an unconventional current injection method for planar LED devices. In this work, we have performed the first numerical simulations of an electrically-injected laterally doped heterojunction (LHJ) LED based on the conventional III-As compound semiconductors, utilizing the DDCT method. Our device consists of a GaAs/AlGaAs double heterojunction (DHJ) on a n-GaAs substrate where the lateral pn-junction can be fabricated by a selective area doping process. We employ a numerical model based on the drift-diffusion current and the continuity equations to model charge transport, and also develop fabrication methods for the devices. Our simulation results suggest that the proposed device can work as an ultra-efficient LED that can be used for large-area applications by repeating the simulated unit to form a multi-finger structure.**

I. Introduction

Practically, all current LED and solar cell designs are based on using a similar DHJ structure: the active layer (AL) is sandwiched between a pn-junction. Such a basic structure and the basic principle of current injection has remained essentially unchanged for decades. However, recent attempts to fabricate optoelectronic devices including nanoscale ALs near or at device surfaces have revealed several drawbacks in the conventional design: it does not allow current injection to active layers located very close (10s of nm) to surfaces, e.g. due to the formation of a depletion layer [1], and it presents a major challenge e.g. to fabricate transparent but low resistance top contacts for nanowire devices.

In this work, we elaborate the design of an efficient and low resistance current injection scheme for structures including large-area potential wells, which also provides an interesting current injection platform for nanowires, and plasmonic near-surface structures based on quantum wells, solar cells and lasers. The basic structure implementing diffusion driven charge transport (DDCT) current injection is illustrated in Fig. 1. Preliminary simulation and experimental work has been carried out on DDCT structures based on GaN [2], [3]. In this paper, we carry out insightful simulations on structures based on III-As compound semiconductors.

Fig. 1 shows one period of our studied device that consists of a GaAs/AlGaAs DHJ structure with a GaAs cap layer that has been removed between the contacts to avoid potential problems with the parasitic diode that would otherwise be formed. The lateral p-n junction can be formed with a selective

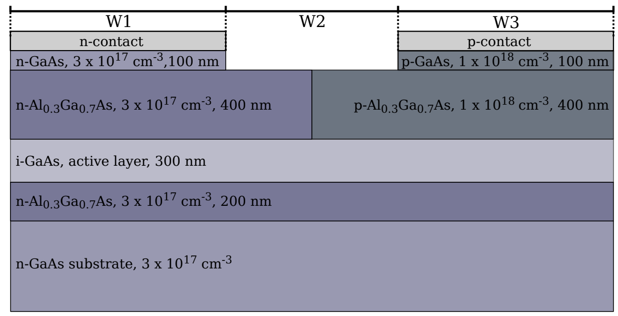

Fig. 1. Schematic structure of one period of the studied LHJ GaAs/AlGaAs DDCT LED.

p-doping process such as the diffusion doping methods we are presently testing [4] or ion-implantation. By utilizing the DDCT method [5], the injection of the charge carriers is possible from the same side of the AL which leaves other side of the device completely free of the contacts blocking light emission. Additionally, releasing the device layer from the substrate with an epitaxial lift-off process, could enable unconventional thin-film devices where the AL is located close to the device surface. This would leave the surface exposed and usable for further processing such as an anti-reflection or surface plasmon coatings [6] that could enhance light emission from the device.

II. Simulation model

We employ the standard numerical transport model based on the drift-diffusion current and the continuity equations for charge carriers, which couples the partial differential equations for the electrostatic potential and the quasi-Fermi levels for holes and electrons [7]. Recombination in the model (with a net rate R) includes Shockley-Read-Hall (SRH), radiative, and Auger recombination processes, modeled using the ABC model, but also non-radiative recombination at surfaces and interfaces, calculated as discussed in [7].

Our simulations are performed in two dimensions, assuming that the behavior of the device is unchanged along the third axis. The n- and p-contacts shown in Fig. 1 were assumed to be ohmic and lossless. The model parameter calibration against the ongoing experiments to account for the real properties of diffusion doped structures is under way. For the results presented here, we use the literature values for the pertinent

978-1-5386-5599-3/18/$31.00 ©2018 IEEE

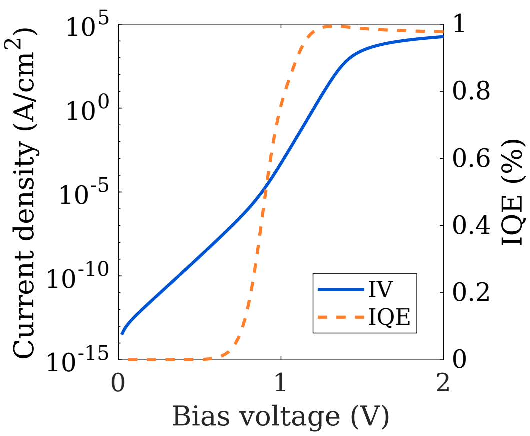

Fig. 2. The $I-V$ curve showing SRH and radiative recombination dominated regimes. The IQE of the device starts to increase as radiative recombination starts to dominate, and stays over 97 % at biases above 1.2 V.

materials and a relatively conservative SRH recombination parameter $A = 3\times10^5\ s^{-1}$. Further details about the modeling framework and parameters can be found in [7].

III. Results, Discussion and Conclusions

Fig. 2 shows the current density and the internal quantum efficiency (IQE) of the device as a function of the bias voltage. The $I-V$ curve shows that the device operates as a typical LED characterized by a SRH dominated region at low biases (<1 V) and a radiative recombination dominated region at higher voltages (between 1 V and 1.4 V). The current starts to saturate after 1.4 V, which is probably due to the internal resistance of the structure. The IQE has a maximum of 99.43 % at ∼1.33 V, which corresponds to a current density of ∼85 A/cm^2. Furthermore, the efficiency droop at high biases is very weak after the peak IQE. Fig. 3(a) illustrates the radiative and the total recombination rates, while Fig. 3(b) shows the charge carrier concentrations as a function of lateral position within the active layer of the LED, at a current density $J = 100$ A/cm^2. Fig. 3(a) shows that non-radiative recombination is negligible at all positions, and that the recombination rate is higher under the p-contact. The non-uniformity of the recombination rate is explained mostly by the lower hole concentration under the n-type contact as observed in Fig. 3(b), which is caused by the lower mobility of holes in GaAs and AlGaAs. Additional simulations (not shown here) suggest that the recombination profile can be made more homogeneous by minor modifications, such as decreasing the n-contact width $W1$ and optimizing the doping levels.

To conclude, we have performed insightful physical simulations of a GaAs/AlGaAs LHJ LED enabling the DDCT injection method, showing that very efficient electrical injection to the active layer is possible from the modeling point of view. Large-area LEDs can be realized by repeating our reference unit to form e.g. a multi-finger structure. By fully optimizing the dimensions and the doping levels of our structure, it could become a viable option for constructing large-area light emitters without the detrimental effect of surface recombination in the electroluminescent cooling experiments carried out in our group [8], [9].

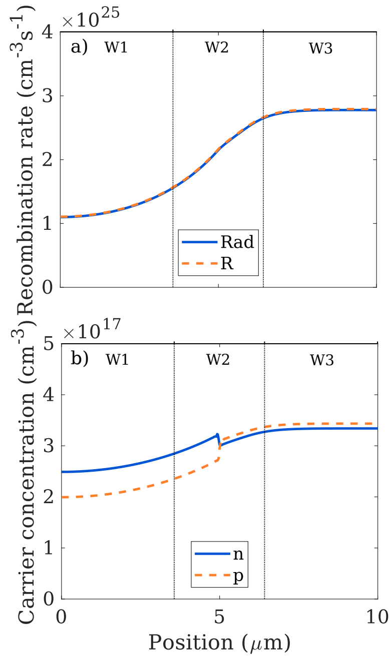

Fig. 3. (a) Radiative and total recombination rates and (b) the carrier concentrations within the AL as a function of lateral position at $J = 100$ A/cm^2.

Acknowledgment

We acknowledge funding from the Academy of Finland and the European Research Council under the Horizon 2020 research and innovation programme (grant agreement No 638173). The experimental work was undertaken at the Micronova Nanofabrication Centre of Aalto University.

References

[1] M.-K. Kwonn, J.-Y. Kim, B.-H. Kim, I.-K. Park, C.-Y. Cho, C. C. Byeon, and S.-J. Park, "Surface-Plasmon-Enhanced Light-Emitting Diodes," *Adv. Mater.*, vol. 20, p. 1253, 2008.

[2] P. Kivisaari, I. Kim, S. Suihkonen, and J. Oksanen, "Elimination of Lateral Resistance and Current Crowding in Large-Area LEDs by Composition Grading and Diffusion-Driven Charge Transport," *Advanced Electronic Materials*, vol. 3, p. 1700103, 2017.

[3] L. Riuttanen, P. Kivisaari, O. Svensk, J. Oksanen, and S. Suihkonen, "Electrical injection to contactless near-surface InGaN quantum well," *Applied Physics Letters*, vol. 107, p. 051106, 2015.

[4] A. Myllynen, "Laterally doped III-V diodes for large-area optoelectronics," Master's thesis, Aalto University, 2018.

[5] P. Kivisaari and J. Oksanen and J. Tulkki, "Current injection to free-standing III-N nanowires by bipolar diffusion", *Applied Physics Letters*, vol. 103, p. 031103, 2013.

[6] M. L. Brongersma and N. J. Halas and P. Nordlander, "Plasmon-induced hot carrier science and technology", *Nature nanotechnology*, vol. 10, p. 25–34, 2015.

[7] T. Sadi, P. Kivisaari, J. Tiira, I. Radevici, T. Haggren, and J. Oksanen, "Electroluminescent cooling in intracavity light emitters: modeling and experiments," *Opt. Quant. Elect.*, vol. 50, p. 18, 2018.

[8] I. Radevici, J. Tiira, T. Sadi, and J. Oksanen, "Influence of photo-generated carriers on current spreading in double diode structures for electroluminescent cooling," *Semi. Sci. Tech.*, vol. 33, p. 05LT01, 2018.

[9] J. Oksanen and J. Tulkki, "Thermophotonics: LEDs feed on waste heat", *Nature photon.*, vol. 9, p. 782-784, 2015.