

Trap-assisted tunneling in InGaN/GaN LEDs: experiments and physics-based simulation

M. Mandurri^{1,*}, G. Verzellesi², M. Goano^{1,3}, M. E. Vallone¹, F. Bertazzi^{1,3},
G. Ghione¹, M. Meneghini⁴, G. Meneghesso⁴, and E. Zanoni⁴

¹Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy,

²Dipartimento di Scienze e Metodi dell'Ingegneria, Università di Modena e Reggio Emilia, 42122 Reggio Emilia, Italy,

³IEIIT-CNR, Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy

⁴Dipartimento di Ingegneria dell'Informazione, Università di Padova, Via Gradenigo 6/B, 35131 Padova, Italy

*E-mail: marco.mandurri@polito.it

Abstract—We present results from a combined experimental and numerical investigation of a blue InGaN/GaN LED test structure grown on a SiC substrate, confirming that tunneling represents a critical contribution to the sub-threshold forward-bias current and discussing the relative importance of different trap-assisted electron tunneling processes.

I. INTRODUCTION

Since sub-threshold forward-bias current is a sensitive indicator of growth quality as well as of device reliability and ESD robustness [1]–[4], the improvement of its physical understanding and the demonstration of reliable physics-based approaches for its simulation are important for LED technology optimization. The aim of this study is to investigate the relative relevance of several trap-assisted electron tunneling mechanisms in a single-quantum-well test structure manufactured by OSRAM Opto Semiconductors and characterized at room temperature at Università di Padova. The test LED

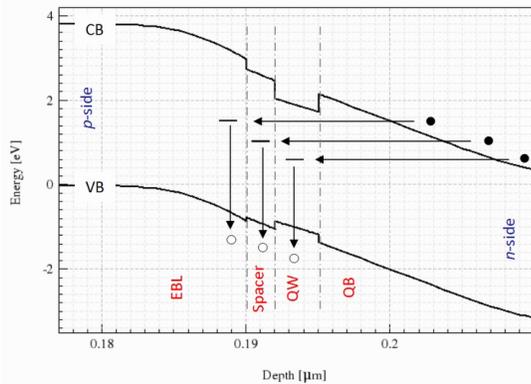


Fig. 1. Band diagram illustrating the processes considered in the present analysis, involving electrons tunneling from the n -GaN region towards trap levels located in the forbidden gap of EBL, spacer and QW.

structure, grown on a SiC substrate, includes a n -doped GaN buffer layer, a 10-nm GaN quantum barrier (QB), a 3-nm $\text{In}_{0.15}\text{Ga}_{0.85}\text{N}$ quantum-well (QW), a 2-nm GaN spacer, a 40-nm p -doped $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ electron-blocking layer (EBL) and a GaN p -cap region. All simulations have been carried out with Sentaurus Device [5], which allows the inclusion of user-defined microscopic descriptions of tunneling processes through its physical model interface.

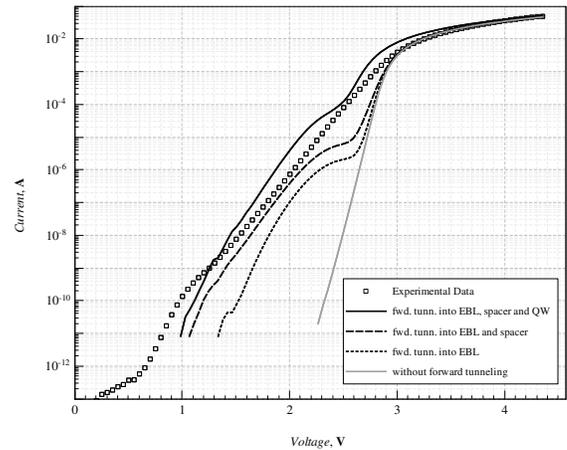


Fig. 2. Comparison between measured and simulated $I(V)$ characteristics, including different forward tunneling channels.

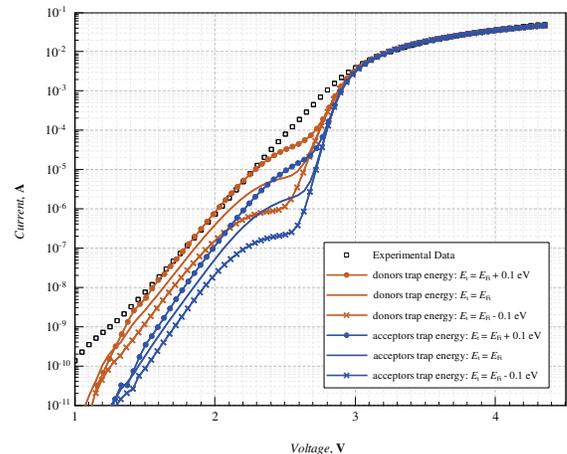


Fig. 3. Simulated $I(V)$ characteristics using donor- and acceptor-like traps with different energies compared with experiments.

II. SIMULATION RESULTS

In agreement with previous literature mainly focusing on GaN LEDs on sapphire substrates [6]–[9], our simulations

in the sub-threshold regime suggest that trap-assisted forward tunneling could be one of the most relevant contributions to the current flow [10]–[12]. Its impact on $I(V)$ curves depends on the number of layers affected by traps (Fig. 2). Trap levels closer to the edge of the conduction band (CB) are associated to higher forward currents (Fig. 3). In fact, when the energy level of the trap E_t is located closer to the CB edge, the tunneling path is shortened and the corresponding tunneling probability is increased. An increase of the trap density N_t also leads to larger forward currents. The different role of donor- and acceptor-like traps has been studied, for the information it can provide on the role played by extended (dislocation) or point defects. We have also observed (Fig. 4) that the $I(V)$

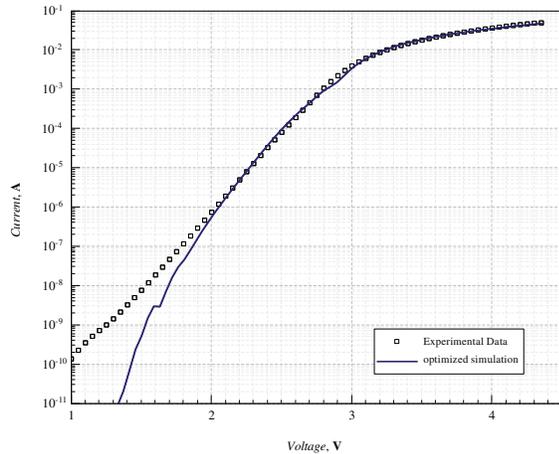


Fig. 4. Simulation reproducing the experimental characteristics above 2 V, obtained by tuning only the E_t and N_t trap-assisted tunneling parameters.

measurements above 2 V can be accurately reproduced (on a current range of about five orders of magnitude) by tuning only the two trap-assisted electron tunneling parameters E_t and N_t . Even if the agreement between simulation and experiments is encouraging, at low bias voltages there is still a significant discrepancy, and a more complete description of the physical processes involved in that range is needed. Fig. 5 illustrates some of the possible additional mechanisms involved, which include trap-assisted tunneling through and under the quantum well or between QB and EBL. The contribution of heavy-hole tunneling should also be included, since it is expected to have an impact in the intermediate voltage regime [9].

REFERENCES

- [1] S.-K. Jeon, J.-G. Lee, E.-H. Park, J. Jang, J.-G. Lim, S.-K. Kim, and J.-S. Park, “The effect of the internal capacitance of InGaN-light emitting diode on the electrostatic discharge properties,” *Appl. Phys. Lett.*, vol. 94, no. 13, p. 131106, 2009.
- [2] J. Kim, Y. Tak, J. Kim, S. Chae, J.-Y. Kim, and Y. Park, “Analysis of forward tunneling current in InGaN/GaN multiple quantum well light-emitting diodes grown on Si (111) substrate,” *J. Appl. Phys.*, vol. 114, no. 1, p. 013101, 2013.
- [3] L. Liu, J. Yang, D. Teng, S. Qi, and G. Wang, “An explanation for invalidity of working currents’ derating on improving light-emitting diode devices’ reliability,” *J. Appl. Phys.*, vol. 114, no. 2, p. 023102, 2013.
- [4] G. Verzellesi, D. Saguatti, M. Meneghini, F. Bertazzi, M. Goano, G. Meneghesso, and E. Zanoni, “Efficiency droop in InGaN/GaN blue light-emitting diodes: Physical mechanisms and remedies,” *J. Appl. Phys.*, vol. 114, no. 7, p. 071101, Aug. 2013.

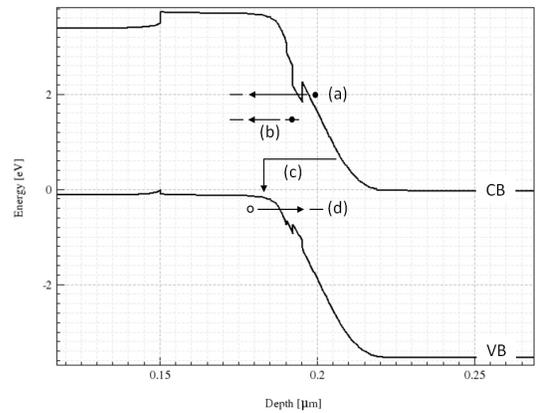


Fig. 5. Possible additional sources of forward current flow in a SQW LED: (a) trap-assisted tunneling through the QW; (b) trap-to-trap tunneling under the QW; (c) trap-assisted tunneling between n -type QB and p -type EBL; (d) trap-assisted hole tunneling.

- [5] *Sentaurus Device User Guide. Version I-2013.12*, Synopsys, Inc., Mountain View, CA, Dec. 2013.
- [6] X. A. Cao, E. B. Stokes, P. M. Sandvik, S. F. LeBoeuf, J. Kretschmer, and D. Walker, “Diffusion and tunneling currents in GaN/InGaN multiple quantum well light-emitting diodes,” *IEEE Electron Device Lett.*, vol. 23, no. 9, pp. 535–537, 2002.
- [7] X. A. Cao, J. M. Teetsov, M. P. D’Evelyn, D. W. Merfeld, and C. H. Yan, “Electrical characteristics of InGaN/GaN light-emitting diodes grown on GaN and sapphire substrates,” *Appl. Phys. Lett.*, vol. 85, no. 1, pp. 7–9, 2004.
- [8] C. L. Reynolds and A. Patel, “Tunneling entity in different injection regimes of InGaN light emitting diodes,” *J. Appl. Phys.*, vol. 103, no. 8, p. 086102, 2008.
- [9] D. Yan, H. Lu, D. Chen, R. Zhang, and Y. Zheng, “Forward tunneling current in GaN-based blue light-emitting diodes,” *Appl. Phys. Lett.*, vol. 96, no. 8, p. 083504, 2010.
- [10] J. A. del Alamo and R. M. Swanson, “Forward-bias tunneling: A limitation to bipolar device scaling,” *IEEE Electron Device Lett.*, vol. 7, no. 11, pp. 629–631, 1986.
- [11] N. I. Bochkareva, E. A. Zhirmov, A. A. Efremov, Y. T. Rebane, R. I. Gorbunov, and Y. G. Shreter, “Tunnel-recombination currents and electroluminescence efficiency in InGaN/GaN LEDs,” *Semicond.*, vol. 39, no. 5, pp. 627–632, 2005.
- [12] N. I. Bochkareva, V. V. Voronenkov, R. I. Gorbunov, A. S. Zubrilov, Y. S. Lelikov, P. E. Latyshev, Y. T. Rebane, A. I. Tsyuk, and Y. G. Shreter, “Defect-related tunneling mechanism of efficiency droop in III-nitride light-emitting diodes,” *Appl. Phys. Lett.*, vol. 96, no. 13, p. 133502, 2010.