Effect of Doping and Impurities on the Efficiency of III-Nitride Light Emitting Diodes

Friedhard Römer and Bernd Witzigmann
Computational Electronics and Photonics, University of Kassel, Wilhelmshöher Allee 71, D-34121 Kassel, Germany
Email: froemer@uni-kassel.de

***Abstract*—The doping of GaN based light emitting diodes (LEDs) is critical for achieving a high internal quantum efficiency. The high acceptor activation energy in GaN makes the acceptor doping a challenging task. Moreover, impurities might act as unintentional doping affecting the carrier injection. We analyze doping and impurity effects in III-nitride LEDs by means of physics based simulation. In the view of the high acceptor activation energy an enhanced impurity activation model has been devised integrating the effect of proximate doping sites and the Poole-Frenkel effect. We show by the simulation of a multi quantum well LED how the doping and shallow impurities affect the efficiency.**

I. Introduction

Recent thin film GaN/InGaN light emitting diodes (LEDs) for lighting applications achieve their maximum internal quantum efficiency (IQE) at driving current densities below 10A/cm^2. Increasing the current beyond this value results in a substantial decrease of the IQE. This effect is known as droop and can be explained by the Auger recombination and the direct carrier leakage which is mostly electron leakage [1]. The Auger recombination is a semiconductor process and thus cannot be affected by technological means on a large scale. In contrast, the direct carrier leakage is much affected by the design and doping of the p-region of the diode.

Particularly the acceptor doping has been found to be critical because acceptors in GaN or AlGaN are subject to a high activation energy. The activation energy limits the density of free carriers but is also subject to reduction by proximate dopant sites [2] as well as the electric field [3]. Both effects are present in GaN-based LEDs due to piezoelectric fields at the hetero interfaces and the high acceptor doping. This factor gives rise to an enhanced impurity emission model [4]. The model has been implemented in a physics based simulator designed for the simulation of semiconductor devices with quantum regions [5]. With this simulator we have performed model calculations to study the interaction of the doping and the piezoelectric polarization near the electron blocking layer (EBL). We are going to investigate the effect of impurities which have a large effect on the efficiency and I/V characteristics [6]. We demonstrate that the doping near the EBL strongly affects the direct carrier leakage.

II. Dopant Activation Model

The physical description of the dopant activation process considers the interaction of energetically shallow impurity sites with the nearest semiconductor band in thermal equilibrium. Their interaction with the respective band can be described by thermal emission subject to an activation energy. The activation energy primarily depends on the impurity species and the host material. For Mg acceptors in GaN experiments yield values of $E_A \approx 0.2\text{eV}$. However, it has been demonstrated that the activation energy depends on the impurity density [2]. The interaction of the Coulomb potentials of proximate ionized doping sites provides an explanation for this effect as illustrated in Fig. 1.

Another mechanism leading to an enhancement of the emission rate is the Poole-Frenkel effect which describes the dependence of the activation energy on the electric field in the vicinity of the impurity site. The model derived by Hartke [3] considers the interaction of an isolated impurity with the electric field. This effect cannot be regarded independent from the proximate dopant sites. With rising impurity density the emission enhancement due to the electric field only decreases as depicted in Fig. 1. Thus, the Poole-Frenkel effect is less significant for high doping than for the zero doping limit.

The model has been implemented in a multi scale semiconductor transport solver which solves the coupled transport problem for continuum and quantized carrier populations including quantization. The impurity activation model is fully coupled with the carrier transport equations and the Poisson equation [5]. The model parameters have been calibrated with the IQE characteristics of a single quantum well LED [7].

III. Effect of the Acceptor Doping Profile

The effect of the acceptor doping has been investigated for an MQW LED with five quantum wells emitting at 440nm [1]. The acceptor doping in the EBL has been varied considering constant and graded doping as illustrated in Fig. 2. Though a constant EBL doping is targeted a grading can result from unintentional dopant diffusion. Figure 2 illustrates that in the quasi neutral region the density of ionized acceptors N_A^- is significantly lower than the acceptor density N_A. This is primarily an effect of the high ionization energy. Above, the acceptor ionization strongly depends on the bias current.

At the interface of the EBL to the p-side barrier of the active region nearly full acceptor ionization can be observed. The positive polarization charge at this interface leads to a hole depletion resulting in a high acceptor ionization. In case of the constant doping the density of ionized acceptors is high enough to screen the positive polarization charge. As a result the electric field in the p-side barrier is positive as shown in

978-1-4799-8379-7/151$31.00 ©2015 IEEE

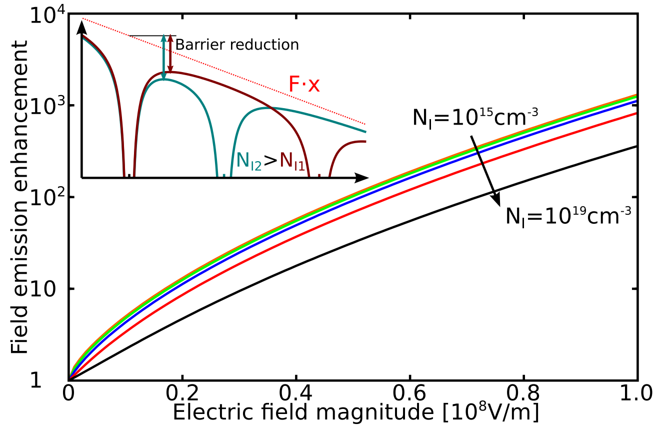

Fig. 1. Electric field related emission rate enhancement as a function of the electric field and the impurity density. The inset illustrates the barrier reduction at different impurity densities but the same electric field

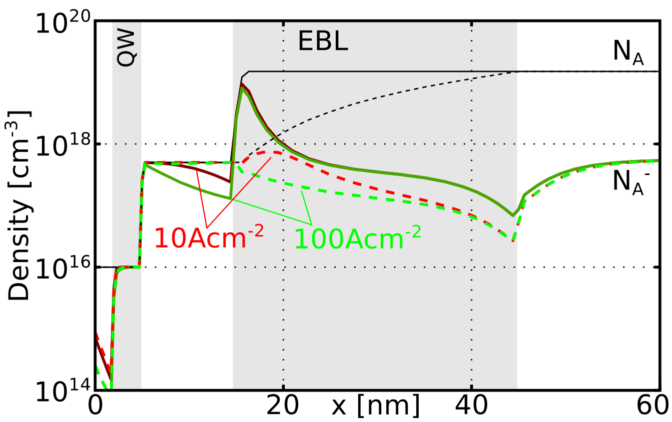

Fig. 2. Acceptor (N_A) and ionized acceptor density (N_A^-) for graded (dashed) and constant EBL doping (solid) at $j = 10\text{A/cm}^2$ and $j = 100\text{A/cm}^2$.

Fig. 3 driving electrons towards the p-side quantum well. The polarization charge is not fully screened with graded doping in the EBL so that the electric field in the last barrier is negative. In consequence electrons are attracted towards the EBL and leakage increases.

This effect is confirmed by the relative contribution of the recombination and leakage shown in Fig. 4. For constant EBL doping the direct carrier leakage is largely suppressed and does not dominate the droop unless the current density is higher than $j \approx 10^3\text{A/cm}^2$. The graded doping seems to promote the direct carrier leakage and so that it even contributes to the droop rollover.

In conclusion, the numerical study demonstrates the relevance of the acceptor doping for the efficiency of III-nitride LEDs. The efficiency is strongly affected by a tight interaction of the acceptor doping profile with the EBL, the p-side barrier and the p-side quantum well. Thus, the optimization of the doping profile depends strongly on the device as well as its operating conditions.

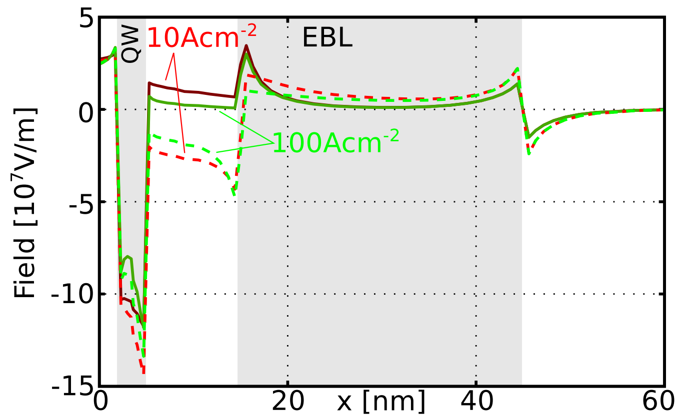

Fig. 3. Electric field in the vicinity of the EBL for graded (dashed) and constant EBL doping (solid) at $j = 10\text{A/cm}^2$ and $j = 100\text{A/cm}^2$.

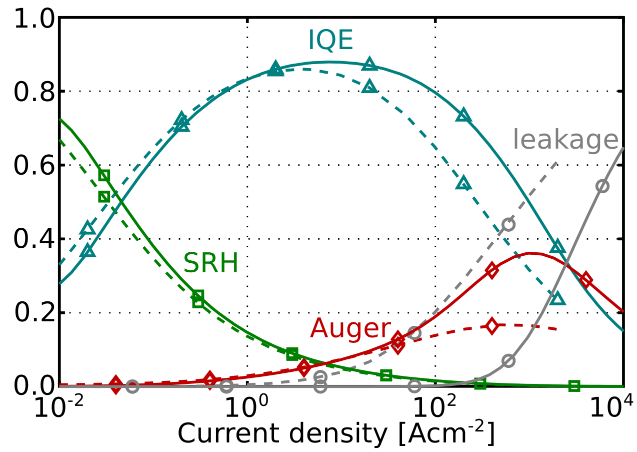

Fig. 4. Relative contribution of SRH (squares), radiative (triangles), and Auger recombination (diamonds) as well as leakage (circles) to the total current for graded (dashed) and constant EBL doping (solid).

REFERENCES

[1] F. Römer and B. Witzigmann, "Effect of Auger recombination and leakage on the droop in InGaN/GaN quantum well LEDs," *Optics Express*, vol. 22, no. S6, p. A1440, Sep. 2014.

[2] S. Brochen, J. Brault, S. Chenot, A. Dussaigne, M. Leroux, and B. Damilano, "Dependence of the Mg-related acceptor ionization energy with the acceptor concentration in p-type GaN layers grown by molecular beam epitaxy," *Applied Physics Letters*, vol. 103, no. 3, p. 032102, 2013.

[3] J. L. Hartke, "The Three-Dimensional Poole-Frenkel Effect," *Journal of Applied Physics*, vol. 39, no. 10, p. 4871, 1968.

[4] F. Römer and B. Witzigmann, "Acceptor activation model for III-nitride LEDs," *Journal of Computational Electronics*, 2015.

[5] F. Römer, M. Deppner, C. Range, and B. Witzigmann, "Auger recombination and leakage in InGaN/GaN quantum well LEDs," vol. 8986, Mar. 2014, p. 89861R.

[6] M. Auf der Maur, B. Galler, I. Pietzonka, M. Strassburg, H. Lugauer, and A. Di Carlo, "Trap-assisted tunneling in InGaN/GaN single-quantum-well light-emitting diodes," *Applied Physics Letters*, vol. 105, no. 13, p. 133504, 2014.

[7] B. Galler, P. Drechsel, R. Monnard, P. Rode, P. Stauss, S. Froehlich, W. Bergbauer, M. Binder, M. Sabathil, B. Hahn, and J. Wagner, "Influence of indium content and temperature on Auger-like recombination in InGaN quantum wells grown on (111) silicon substrates," *Applied Physics Letters*, vol. 101, no. 13, p. 131111, 2012.