Carrier Transport in Multi Colour Deep Ultraviolet Light Emitting Diodes

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***Abstract*—Deep ultraviolet (DUV) light emitting diodes (LEDs) and lasers are enabled by high band gap Aluminium Gallium Nitride (AlGaN). The efficiency of recent multi quantum well (MQW) DUV emitters is still in the percent range which can be in part attributed to the hole injection. The hole injection and the carrier distribution in the high band gap AlGaN active region are not yet well understood. To support the experimental investigation of the current injection and distribution we have performed numerical simulations of a mixed MQW DUV LED series emitting at 233 nm and 250 nm. We demonstrate that particularly the emission of the 233 nm quantum well is very sensitive to the AlGaN material properties and inhomogeneous broadening. The numerical modelling enables a better interpretation of experimental data.**

I. Introduction

Aluminium Gallium Nitride (AlGaN) light emitting diodes (LEDs) and lasers are the enabling technology for compact deep ultraviolet (DUV) light sources in environmental, medical, and industrial applications. The low efficiency in the percent range impedes a wide deployment [1]. The efficiency enhancement of DUV emitters is therefore a contemporary research subject. Apart from the low light extraction efficiency, the low injection efficiency of holes has been identified as a major challenge. The low hole injection efficiency is related to the low free hole density and mobility in p-doped high band gap AlGaN layers. A better understanding of the hole injection and carrier transport in a multi quantum well (MQW) active region can be achieved by the spectral analysis of a mixed colour quantum well LED [2]. Here, the spectral signature of the marker quantum well (QW) is related to the asymmetry in the electron and hole transport. However, the spectral signature depends on the bias current and changes in the presence of defect recombination and inhomogeneous broadening.

To support the application of this method to the DUV MQW active regions we performed carrier transport simulations of a triple MQW with one QW emitting at 250 nm and two QWs emitting at 233 nm. The goal of the simulation study is to investigate the sensitivity of the spectral signature with respect to the inhomogeneous broadening amongst others. The numerical simulations were carried out with a multi scale carrier transport simulator incorporating a statistical model for the inhomogeneous broadening [3]. In the subsequent section we describe the simulation setup and analyse the effect of the inhomogeneous broadening (IHB) on the emission spectrum.

II. Mixed Quantum Well Modelling

The model structure of the mixed QW spectral signature is illustrated in Fig. 1. The 1.4 nm wide QWs are separated by 5 nm wide $Al_{0.835}Ga_{0.165}N$ barriers. The mole fraction of the QWs have been calibrated to match the emission peak at 233 nm and 250 nm, respectively. The n-side barrier is 40 nm wide. On the p-side, the 6 nm wide AlN electron blocking layer is followed by $Al_{0.75}Ga_{0.25}N$ hole injection layer. Since the p-side superlattice does not affect the carrier distribution in the active region immediately it has been replaced with an effective $Al_{0.285}Ga_{0.715}N$ layer. The acceptor doping concentration is $N_A = 10^{19}\,\mathrm{cm}^{-3}$. The donor doping is $N_D = 4 \cdot 10^{18}\,\mathrm{cm}^{-3}$. Both acceptors and donors are subject to incomplete ionization.

For studying the inter-QW transport emission spectra were simulated changing the position of the 250 nm QW successively from the n- side to the p-side without IHB and with an IHB energy σ =172 meV for the 250 nm QW and σ =104 meV for the 233 nm QWs. The spectrum in Fig. 2 shows that the 250 nm QW clearly dominates the emission no matter whether IHB is included or not. However, with IHB the emission of the 233 nm QWs is almost by two orders of magnitude stronger and the variation with the position of the 250 nm QW is rather weak.

The band structure and quasi Fermi levels for different currents in Fig. 1 provide an explanation for this behaviour. The multi scale model distinguishes continuum and QW carrier populations not enforcing thermal equilibrium. The 233 nm QWs are rather shallow so that the 2D and 3D quasi Fermi levels are near thermal equilibrium. This means that the bound electron density is limited and thus the radiative recombination. Electrons accumulate in the 250 nm QW with increasing current eventually screening the polarization potential. The bound (2D) quasi Fermi level is below the continuum (3D) quasi Fermi level. Thus, the electron current into the mid QW is not limited and its recombination dominates. The effect of the limited electron density is confirmed by the spectra without IHB in Fig. 2. Here, the 233 nm emission is enhanced if the 250 nm QW is near the p-side and thus cannot drain off the electron current.

The IHB mitigates the imbalance between the 233 nm and 250 nm emission because it enables electronic states below

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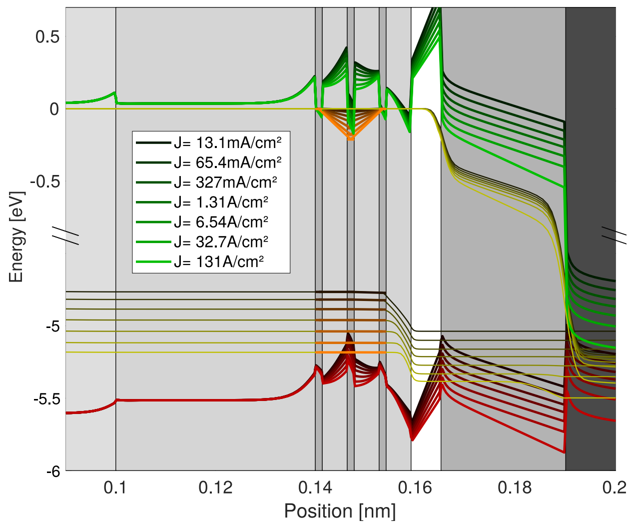

Fig. 1. Band structure for the mid 250 nm QW varying the bias current from $j = 13.1\,\mathrm{mAcm}^{-2}$ to $j = 131\,\mathrm{Acm}^{-2}$. Green and red shaded lines are the conduction and valence band, respectively. The olive shaded lines are the bulk (3D) quasi Fermi levels. The orange shaded lines are the QW (2D) quasi Fermi levels. IHB is enabled in the simulation.

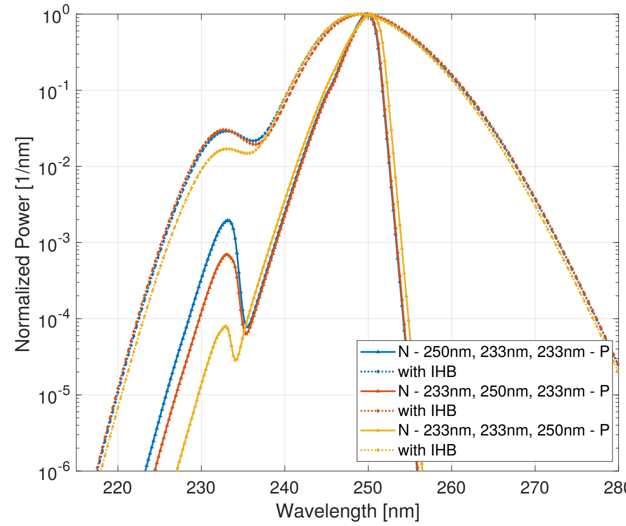

Fig. 2. Simulated spectra at $j = 13\,\mathrm{Acm}^{-2}$ without (solid) and with (dotted) inhomogeneous broadening varying the position of the 250 nm QW.

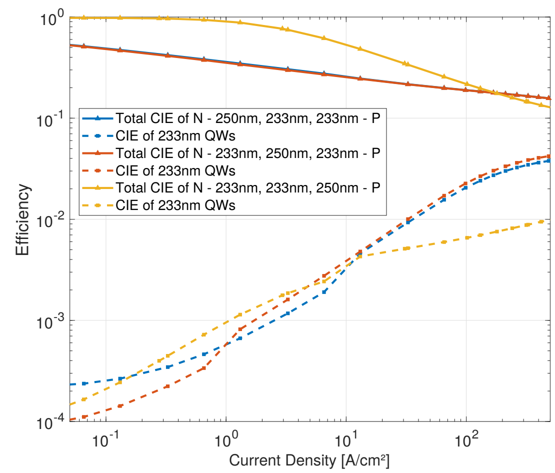

Fig. 3. Total CIE (solid) and CIE of the 233 nm QWs versus the current. IHB is enabled in the simulation.

the nominal band gap due to the Gaussian broadening of the subband energy levels [4]. This is also reflected in the spectra. With inhomogeneous broadening the hole injection becomes the limiting factor. This effect is confirmed by the current injection efficiency illustrated in Fig. 3. It is clear to see that the 250 nm QW on the p-side increases the current injection efficiency but impedes the hole injection into the 233 nm QWs, particularly in the high current regime. The electron accumulation in the 250 nm QW with rising current illustrated in Fig. 1 creates a minor penalty for the hole injection so that the injection into the 233 nm QWs increases with the current.

III. Conclusion

The numerical study demonstrates that the spectral signature of the mixed quantum well serves as a tool to analyse the carrier transport in the active region. However, the inhomogeneous broadening, the doping profile, and the heterostructure amongst others affect the current distribution in the multi quantum well which must be considered for a comparison with experimental results. Numerical carrier transport simulation can support the analysis of the experimental spectral signature. Future activities will focus on the effect of doping and the hole mobility as well as a detailed comparison with experimental data.

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