Effect of the Hole Mobility on the Emission Spectrum of a Deep Ultraviolet Mixed Quantum Well Light Emitting Diode

F. Römer[§][*], G. Hofmann[§], J. Höpfner[†], M. Schilling[†], A. Muhin[†], T. Wernicke[†], M. Kneissl[†], and B. Witzigmann[§]
[§] Lehrstuhl für Optoelektronik, Department EEI, Friedrich-Alexander-Universität Erlangen-Nürnberg
Konrad-Zuse-Str. 3/5, D-91052 Erlangen, Germany
[†] Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstraße 36, D-10623 Berlin, Germany
[*] Email: friedhard.roemer@fau.de

Abstract—**Deep ultraviolet (DUV) light emitting diodes (LED) have matured in the past years but their efficiency still provides space for improvement. Below 265nm emission wavelength the quantum efficiency has been found to decrease almost exponentially. This is commonly attributed to the low light extraction efficiency and the small internal quantum efficiency. Increasing the internal quantum efficiency in this regime requires a deep understanding of the physical processes in the active region. To this end, we investigate the emission spectra of a mixed quantum well DUV LED emitting at 233nm and 250nm wavelength by means of physics based simulations. By comparing the simulations with measured spectra we estimate figures of physical properties entering the carrier transport. In particular we localize the hole mobility in the doped Aluminium Gallium Nitride barriers of the active region.**

I. INTRODUCTION

Compact deep ultraviolet (DUV) light emitting diodes (LED) and semiconductor lasers made of Aluminium Gallium Nitride (AlGaN) enable novel environmental and medical applications [1] that cannot be covered by incandescent and gas discharge sources of DUV radiation. While first high power LEDs emitting near 265nm wavelength have entered the market their quantum efficiency is still less than the efficiency of visible LEDs. With increasing photon energy the quantum efficiency drops below 1% [2]. In the wavelength regime below 265nm the light extraction efficiency decreases strongly due to absorption and the internal quantum efficiency (IQE) decays due to the hole injection efficiency. The optimization of the active region and the p-side electron barrier for high efficiency requires a deep understanding of the carrier transport processes there.

In this context, we have investigated the measured emission spectra of mixed quantum well (QW) DUV LEDs by physics based simulations. This LED has two QWs emitting near 233nm and one QW emitting at 250nm wavelength where the position of the latter is varied. Depending on the position the fraction of the 233nm and 250nm emission varies which is then used as a marker for calibrating the hole mobility in the active region amongst others. For the numerical analysis we use an in-house developed carrier transport simulator which employs a quantum corrected multi-population drift diffusion model as well as a microscopic model for calculating the QW luminescence. The luminescence calculation is subject to a statistical inhomogeneous broadening (IHB) model [3]. The significance of the transport modelling approach has been demonstrated with a visible multi color III-Nitride LED [4]. In the following section we present the simulations of the emission distribution amongst the 233nm and 250nm QWs and discuss the calibration of the hole mobility.

II. MIXED QUANTUM WELL EMISSION SPECTRUM

Figure 1 shows the active region and the p-side hole injection structure of the simulation model. The active region consists of three 1.4 nm wide QWs separated by 5 nm wide $\mathrm{Al_{0.835}Ga_{0.165}N}$ barriers and is followed by a 6 nm wide AlN electron blocking layer (EBL) and an $\mathrm{Al_{0.75}Ga_{0.25}N}$ hole injection layer (HIL) on the p-side. The donor concentration in the n-side and mid QW barriers is $N_D = 3 \cdot 10^{18}\,\mathrm{cm^{-3}}$. The acceptor doping concentration is $N_A = 10^{19}\,\mathrm{cm^{-3}}$. The EBL and the p-side barrier are undoped. Doping is subject to incomplete ionization. The active region setup matches the experimentally realized structure. Spectral calibration with the measured spectra yields an IHB of $\sigma_{\mathrm{IHB,250nm}}$ =81 meV for the 250nm QW and $\sigma_{\mathrm{IHB,233nm}}$ =110 meV for the 233nm QWs in addition to the homogeneous broadening. The calibrated QW mole fractions match the intended design values. The Auger and the QW scattering coefficients take the values calibrated for InGaN LEDs. [5].

The key figure to be investigated is the ratio of the 233nm emission power to the 250nm emission power $R_\lambda = P_{\mathrm{233nm}}/P_{\mathrm{250nm}}$. In the characterization R_λ is calculated from the emission spectra and therefore subject to the spectrally varying light extraction efficiency (LEE). At room temperature and $j = 13\,\mathrm{Acm^{-2}}$ the characterization yields $R_{\lambda,\mathrm{n}} \approx 0.07$ for the n-side 250nm QW and $R_{\lambda,\mathrm{m}} \approx 0.03$ for the mid 250nm QW. For the p-side 250nm QW the 233nm emission vanishes both in the experiment and the simulation as illustrated in Fig. 2. These values are very sensitive to the temperature and the bias current. At room temperature the 250nm emission dominates.

Simulations to resemble the characterization focus on the QW scattering coefficient and the hole mobility. These values have a major effect on the carrier transport and are not yet as well determined in AlGaN as the electron mobility, for instance. However, the effect of the QW scattering coefficient is limited to the rather deep 250nm QW where the bound electron population is not in thermal equilibrium with the continuum as shown in Fig. 1. Simulations show that $R_{\lambda,\mathrm{n}}$ and $R_{\lambda,\mathrm{m}}$ change with the QW scattering coefficient almost by the same factor.

The hole mobility in the EBL and p-side barrier has been set to $\mu_{\mathrm{h,ebl}} = 1\,\mathrm{cm}^2/(\mathrm{Vs})$. The hole mobility in the other barriers is lower because of the donor doping. The IQE is hardly affected by the barrier hole mobility as shown in Figure 3 but very sensitive to the hole mobility in the p-side barrier and EBL. The variation of R_λ with the hole mobility in Fig. 3 shows that for $R_{\lambda,\mathrm{n}} > R_{\lambda,\mathrm{m}}$ the barrier hole mobility must be less than $\mu_{\mathrm{h,bar}} < 1\,\mathrm{cm}^2/(\mathrm{Vs})$. Only the variation of the barrier mobility shows this turning point behaviour. The QW scattering coefficient as well as the temperature have a large effect on R_λ but their effect on the relation of $R_{\lambda,\mathrm{n}}$ to $R_{\lambda,\mathrm{m}}$ is rather low. The emission spectra in Fig. 2 calculated for $\mu_{\mathrm{h,bar}} = 0.2\,\mathrm{cm}^2/(\mathrm{Vs})$ include the LEE and show good agreement with the characterization.

III. CONCLUSION

This study demonstrates that combining specialized experiments and physics based simulation enables the investigation of the otherwise opaque physics of AlGaN multi quantum wells by means of the macroscopic characteristics. Here, the emission spectrum of a mixed QW LED serves as a marker for analyzing the carrier transport in the active region. Analyzing the effect of the hole mobility, the scattering coefficient, and the temperature on the emission spectrum we conclude that the characterization results can only be explained by a low hole mobility in the active region. These findings enter the physical model calibration enabling the hole injection efficiency optimization of DUV AlGaN LEDs by physical modelling.

ACKNOWLEDGMENT

Funding by the Leibniz Association joint project UVSimTech under the contract K415/2021 is gratefully acknowledged.

REFERENCES

[1] M. Kneissl, T.-Y. Seong, J. Han, and H. Amano, "The emergence and prospects of deep-ultraviolet light-emitting diode technologies," *Nat. Photonics*, vol. 13, no. 4, pp. 233–244, 2019.

[2] H. Amano *et al.*, "The 2020 UV emitter roadmap," *Journal of Physics D: Applied Physics*, vol. 53, no. 50, p. 503001, 2020.

[3] F. Römer, M. Guttmann, T. Wernicke, M. Kneissl, and B. Witzigmann, "Effect of Inhomogeneous Broadening in Ultraviolet III-Nitride Light-Emitting Diodes," *Materials*, vol. 14, no. 24, p. 7890, 2021.

[4] F. Römer and B. Witzigmann, "Signature of the ideality factor in III-nitride multi quantum well light emitting diodes," *Opt. Quantum Electron.*, vol. 50, no. 11, p. 425, 2018.

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

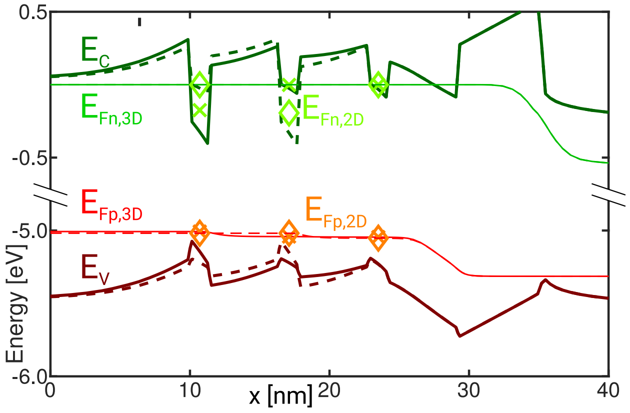

Fig. 1. N-side (solid) and mid (dashed) 250nm QW band structure. The current density is $j = 13\,\mathrm{Acm}^{-2}$. The thin lines show the continuum quasi Fermi levels. The cross and diamond markers illustrate the bound carrier quasi Fermi levels in the QWs. The bound electrons in the 250nm QW are not in thermal equilibrium with the continuum electrons.

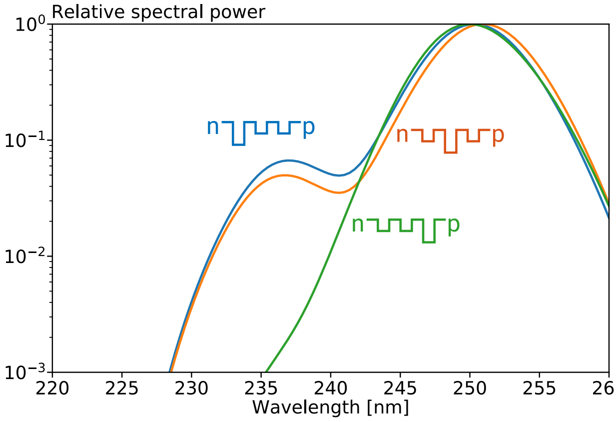

Fig. 2. Simulated spectra at $j = 13\,\mathrm{Acm}^{-2}$ changing the position of the 250nm QW. The barrier hole mobility is $\mu_{\mathrm{h,bar}} = 0.2\,\mathrm{cm}^2/(\mathrm{Vs})$.

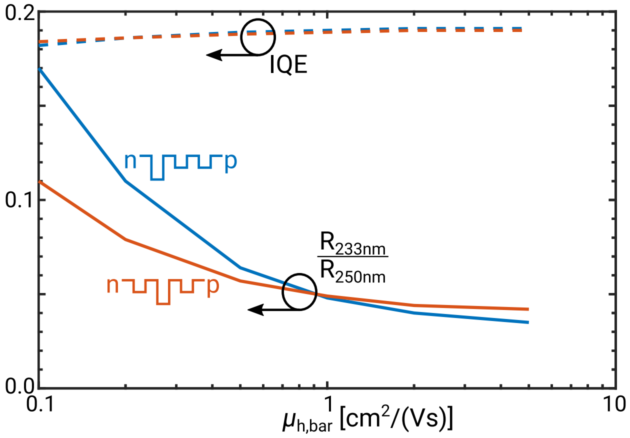

Fig. 3. Ratio of the 233nm radiative recombination rate to the 250nm QW radiative recombination rate and IQE as a function of the barrier hole mobility for the n-side and mid 250nm QW structure. The current density is $j = 13\,\mathrm{Acm}^{-2}$.