Luminescence and Internal Quantum Efficiency of Deep UV Light Emitting Diodes

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***Abstract*—Deep ultraviolet (DUV) light emitting diodes (LED) made of Aluminium Gallium Nitride (AlGaN) are increasingly considered as light sources for medical as well as material processing applications. Recent research on AlGaN DUV LEDs focuses on the enhancement of the efficiency. The efficiency of AlGaN LEDs is limited by a low hole injection efficiency and TM-polarized emission requiring a careful design. In this context we are demonstrating the physics based modelling of AlGaN DUV LEDs by means of a self consistent simulation approach. The simulation model is validated and calibrated comparing experiment and simulation. We demonstrate that electron leakage presents a major contribution to the internal loss and analyse the impact of the active region design.**

I. Introduction

Efficient and compact deep ultraviolet (DUV) light sources are in high demand for application in the field of medical treatment, sterilization, and material processing. An emerging technology in this field are DUV AlGaN light emitting diodes (LED). However, the efficiency of AlGaN DUV LEDs still provides potential for optimization. The high acceptor activation energy in AlGaN [1] and the lack of suitable metals for p-contacts on large band gap AlGaN lead to a low hole injection efficiency which affects the internal quantum efficiency through electron leakage. Therefore DUV AlGaN LEDs have a p-side design with superlattices and gradually increasing Al content towards the active region [2]. Another critical aspect is the negative crystal field splitting in AlN which promotes the emission from the split-off hole band with TM-polarized emission perpendicular to the QW plane [3] mitigating the extraction efficiency.

The physical limitations imposed by the material properties of AlGaN require a careful design of the active region supported by physics based simulations. We analyse the impact of the active region design on the efficiency of AlGaN DUV LEDs by means of a carrier transport model [4] separating the continuum and quantum well (QW) carrier populations. This means that continuum and QW (bound) electrons and holes need not be in thermal equilibrium and their quasi Fermi levels might be different. The continuum and QW populations are coupled by dynamic scattering instead and generally all carriers are subject the global Poisson equation. A $\mathbf{k}\cdot\mathbf{p}$-Schrödinger model gives rise to the polarization resolved luminescence for each quantum well (QW). Self-consistency is achieved by a Gummel iteration. The model has been validated with experimental data showing good agreement. In the subsequent section we analyse the efficiency and light polarization of a 245nm DUV LED with three quantum wells.

II. Deep ultraviolet LED characteristics

The simulated DUV LED structure has been studied experimentally. The active region consists of three polar QWs with a width varying from 0.5nm to 2.8nm separated by 5nm wide Si-doped $Al_{0.825}Ga_{0.175}N$ barriers. Electron confinement is provided by an 8nm wide AlN EBL separated by a 5nm wide undoped $Al_{0.825}Ga_{0.175}N$ barrier from the p-side QW. The p-side starts with a 25nm wide Mg-doped $Al_{0.7}Ga_{0.3}N$ hole injection layer. The 150nm wide $Al_{0.42}Ga_{0.58}N/Al_{0.32}Ga_{0.68}N$ superlattice has been replaced by an effective AlGaN layer. The contact is placed on a final p-GaN layer. SRH recombination in the active region has been calculated for a threading dislocation density $N_{\mathrm{td}} = 2\cdot 10^{-9}\mathrm{cm}^{-2}$. Simulations have been carried out at $T = 300\mathrm{K}$ varying the bias voltage.

The QW Al mole fraction has been calibrated to match the emission wavelength of 245nm. The emission wavelength decreases with the QW width as illustrated in Fig. 1. The polarization degree reflects the relative contribution of TE- and TM-polarized emission according to $P = (I_{\mathrm{TE}} - I_{\mathrm{TM}})/(I_{\mathrm{TE}} + I_{\mathrm{TM}})$. The TM-polarized emission is only relevant in DUV LEDs and its contribution generally increases with decreasing wavelength. For the 0.5nm wide QW the TM polarized emission dominates while the wider QWs show largely TE polarized emission. The TM-polarized emission shows a lower transition energy than the TE-polarized emission in case of the 0.5nm wide QW but higher transition energy for the wider QWs as shown in Fig. 1. This suggests that in the 0.5nm QW the spin orbit split-off band is preferably filled because it has the lowest transition energy. Generally, the experimental values for the degree of polarization are well reproduced in the simulation. The decrease of the emission wavelength with the QW width is lower in the experiment, though. This effect can be explained with inhomogeneous broadening [5].

The internal quantum efficiency (IQE) and the contribution of electron leakage and Shockley-Read-Hall (SRH) recombination are illustrated in Fig. 2. The IQE for the investigated structure is around $\eta_{\mathrm{IQE}} \approx 0.02$ for the wider quantum wells. The low IQE can be attributed to the high contribution of the electron leakage which is an effect of the low hole injection efficiency. For the 0.5nm wide QW the IQE vanishes while the wider QWs do not show a strong dependence of the IQE on the width as shown in the inset of Fig. 2. In the LED with 2.2nm

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wide QWs bound and continuum electrons are not in thermal equilibrium for low currents as illustrated by the difference of the quasi Fermi levels in Fig 3. Thus, the QW electron density can increase with the current enabling a superlinear increase of radiative recombination contribution. The efficiency is rather limited by the low hole injection efficiency seen through the pronounced decrease of the hole quasi Fermi level in the p-side barrier. The efficiency of the device with 0.5nm wide QWs is limited by the electron injection into the QWs instead. In this device, the bound and continuum electron quasi Fermi levels are in thermal equilibrium even at low currents. The bound electron density is limited at a relatively low level so that radiative recombination almost vanishes. The vanishing IQE in the LED with 0.5nm side QWs and the low IQE variation in the devices with wider QWs has also been observed in the experiment.

The contribution of the SRH recombination to the total current is subject to the threading dislocation density and higher than the contribution of the radiative recombination. The major SRH contribution originates from the QWs in the simulation. The SRH recombination in the metamorphically grown p-side might be arguably higher. Ultimately, it contributes to the electron leakage, so that increasing the SRH recombination in the p-side does not affect the efficiency.

III. Conclusion

In conclusion, we have demonstrated by physics based simulations that the quantum efficiency in DUV LEDs is limited by the low hole injection efficiency seen through dominant electron leakage. Another aspect which contributes to the low efficiency is that the DUV quantum wells are more easily saturated with electrons because of the inherently small difference of the barrier and QW band gap. Generally, the experimental figures show good agreement with the simulation confirming the validity of the model. It will be investigated how the doping of the active region and the inhomogeneous broadening affect the electron population of the QWs. Further investigations are required for optimizing the design of the p-side and thus the hole injection.

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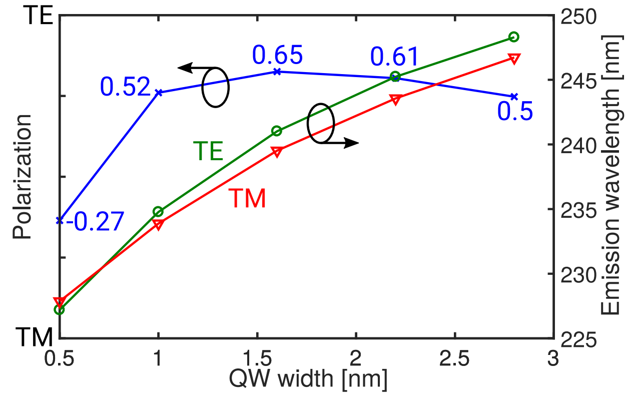

Fig. 1. Simulated light polarization and emission wavelength versus QW width at $j = 50\mathrm{Acm}^{-2}$. Only the 0.5nm QW shows dominant TM-polarization. Wider QWs show generally dominant TE-polarization.

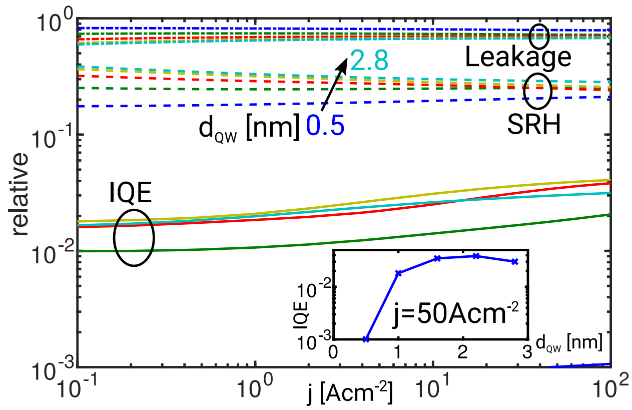

Fig. 2. IQE as well as relative contribution of the leakage current and Shockley-Read-Hall recombination to the total LED current. The inset shows the variation of the IQE with the QW width at $j = 50\mathrm{Acm}^{-2}$.

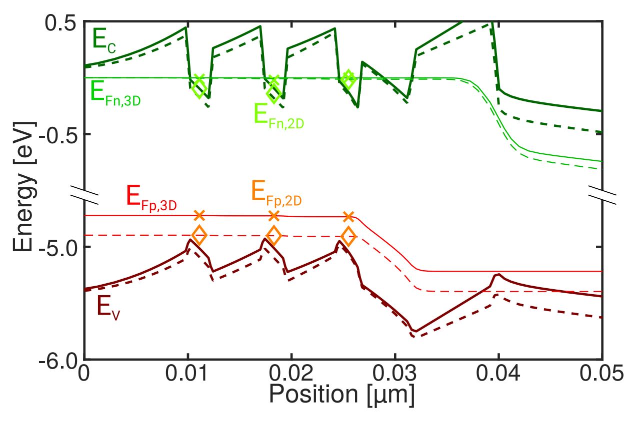

Fig. 3. Band structure of the DUV LED with 2.2nm wide QWs at $j = 0.5\mathrm{Acm}^{-2}$ (solid) and $j = 50\mathrm{Acm}^{-2}$ (dashed).

References

[1] K. B. Nam, M. L. Nakarmi, J. Li, J. Y. Lin, and H. X. Jiang, “Mg acceptor level in AlN probed by deep ultraviolet photoluminescence,” *Appl. Phys. Lett.*, vol. 83, no. 5, p. 878, 2003.

[2] M. Martens, C. Kuhn, E. Ziffer, T. Simoneit, V. Kueller, A. Knauer, J. Rass, T. Wernicke, S. Einfeldt, M. Weyers, and M. Kneissl, “Low absorption loss p-AlGaN superlattice cladding layer for current-injection deep ultraviolet laser diodes,” *Appl. Phys. Lett.*, vol. 108, no. 15, 2016.

[3] J. Zhang, H. Zhao, and N. Tansu, “Effect of crystal-field split-off hole and heavy-hole bands crossover on gain characteristics of high Al-content AlGaN quantum well lasers,” *Appl. Phys. Lett.*, vol. 97, no. 11, p. 111105, 2010.

[4] 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.

[5] F. Römer, B. Witzigmann, M. Guttmann, N. Susilo, T. Wernicke, and M. Kneissl, “Inhomogeneous spectral broadening in deep ultraviolet light emitting diodes,” *Proceedings of SPIE*, vol. 10912, p. 0D, 2019.