Modelling Electron Beam Induced Current in III-Nitride Light Emitting Diodes.

B. Utsch[†], F. Römer[†*], S. Faber[†], F. Bertram[‡], G. Schmidt[‡], P. Veit[‡], C. Berger[‡], A. Dadgar[‡], A. Strittmatter[‡], J. Christen[‡], and B. Witzigmann[†]

[†] Lehrstuhl für Optoelektronik, Department EEI, Friedrich-Alexander-Universität Erlangen-Nürnberg
Konrad-Zuse-Str. 3/5, D-91052 Erlangen, Germany

[‡] Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, D-39106 Magdeburg, Germany

[*] Email: friedhard.roemer@fau.de

***Abstract*—Electron beam induced current (EBIC) has been used as a tool in semiconductor analytics to determine the diffusion length of minority carriers in pn-junctions. Recent progess in controlling the electron beam and penetration has enabled the resolution of much finer structures, including the active region of multi quantum well (MQW) optoelectronic devices. The interpretation of the measured EBIC profiles is not straight forward, though. In this context we have devised and implemented an EBIC model and have simulated the EBIC in an indium gallium nitride (InGaN) MQW light emitting diode. The simulations demonstrate a combined effect of doping, band edges, and the polarization field on the EBIC. The simulations facilitate an isolation of these effects and therefore support the interpretation of the measured EBIC profiles. We demonstrate that the joint experimental and numerical EBIC analysis has the potential to reveal the structure of the III-nitride MQW active region.**

I. Introduction

The optimization of III-nitride multi quantum well (MQW) light emitting diodes and lasers is often impared by the vague structural data of realized devices. Analytical methods to reveal the structure such as secondary ion mass spectroscopy are expensive, destructive, and have a limited spatial resolution. Electron microscopy methods show the structure on the atomic scale but do not give account of the doping concentration and the composition of the material. For semiconductor junctions the electron beam induced current (EBIC) can be investigated in a scanning electron microscope in addition. The electron beam sweeping the device locally generates secondary electron hole pairs resulting in a short circuit current which varies with the beam target. In a pn-homojunction the current profile reflects the diffusion of minority electrons and holes in the quasi neutral regions giving rise to the diffusion length as well as the position and size of the space charge region (SCR) [1].

Recent advances in controlling the electron beam size and penetration enable the resolution of features in the MQW active region of III-nitride light emitters [2], [3]. However, in contrast to a simple pn-junction the EBIC profile of the targeted InGaN MQW light emitting diode (LED) with electron blocking layer (EBL) cannot be interpreted immediately because of the interplay of the hetero junction band offsets, the polarization charge, and the doping profile in the active region. This obstacle gives rise to the EBIC modelling reported in the work. We have been simulating the short circuit current in the MQW LED with Synopsys Sentaurus using the physical model interface of Sentaurus Device to implement the electron beam induced generation. Thus, a complete EBIC profile is generated in one quasistationary sweep. Subsequently, we identify the effect of the polarization charge and the EBL doping on the current providing guidelines for the interpretation of the EBIC characterization.

II. EBIC Simulation

For EBIC the electron beam penetrates the epitaxial stack parallel to the layers. The secondary electron hole pair generation profile is defined by the beam axis and entrance position. Generation is described by a Gaussian distribution perpendicular to the beam axis and by a Poisson distribution parallel to the axis [4]. The resulting generation profile is illustrated in Fig. 1 for an electron beam directed to the n-side of the MQW. Primary electrons typically generate a few hundred secondary electron hole pairs but do not contribute to the short circuit current to comply with charge neutrality and continuity. The secondary electron generation is considered like optical generation.

In short circuit the generation presents a local perturbation of the thermal equilibrium of electrons and holes. A short circuit current evolves only if electrons and holes are separated by a drift or diffusion force. In the MQW active region of a III-nitride light emitting diode the EBIC profile is less intuitive because of the interaction of doping, heterojunctions, and the polarization charge. The GaN/InGaN MQW LED under investigation has five quantum wells. The AlGaN EBL has an acceptor doping $N_A = 4 \cdot 10^{18}\,\mathrm{cm}^{-3}$. The p-side barrier has an acceptor doping as well. We consider a polarization charge screening about 50% [5] and complete ionization. The band structure in Fig. 2 illustrates that the SCR extends across the EBL because of the polarization charge.

The SCR is reflected in the EBIC profile in Fig. 3, simulated at the temperature $T = 184\,\mathrm{K}$. In the quasi neutral n-region the EBIC reflects the hole diffusion as in a homojunction pn-diode. The low hole diffusion length $l_p \approx 60\,\mathrm{nm}$ can be attributed to the low hole mobility in doped GaN. The EBIC shows a strong decrease on the p-side of the diode which can be attributed to the EBL. The band diagram Fig. 2 shows that

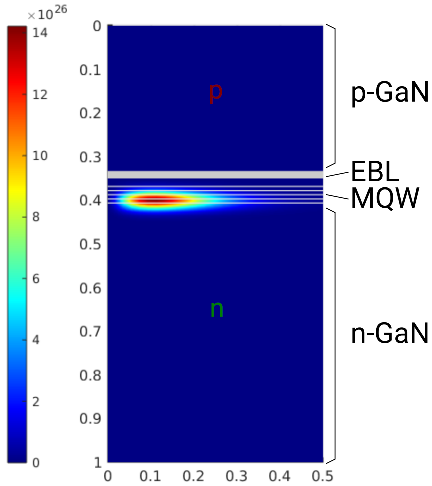

Fig. 1. Generation rate in $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ for an electron beam hitting the layer stack near the n-side of the MQW. Coordinates are in μm. The grey overlay illustrates the position of the EBL and the MQW.

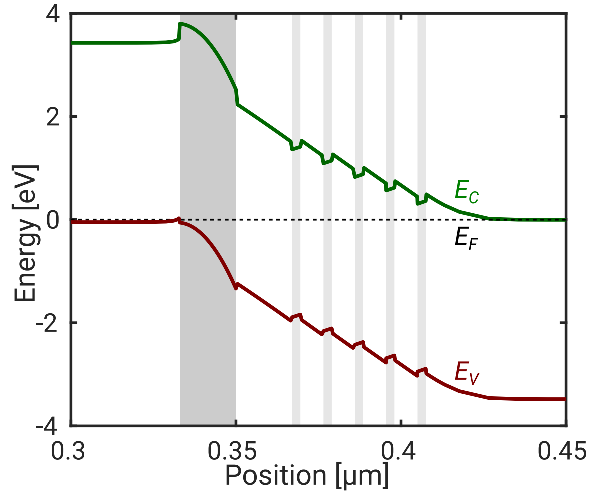

Fig. 2. Band structure of the MQW active region for $N_{\mathrm{A,EBL}} = 4 \cdot 10^{18}\,\mathrm{cm}^{-3}$ in thermal equilibrium. The grey areas illustrate the EBL and the MQW.

electrons are subject to a $\Delta E_C \approx 0.5\,\mathrm{eV}$ barrier from the p-side. Thus, electrons generated at the p-side are captured and recombine there rather than contributing to the short circuit current. Though polarization fields mitigate the barrier the screening by ionized dopants enhances it again. Therefore, the EBIC on the p-side reduces with the EBL acceptor doping.

The EBL polarization field and the global SCR field have the same sign but the built in voltage is determined by the contact quasi Fermi levels. Therefore, the doping related screening of the polarization field in the EBL enhances the global field in the MQW region. This supports the separation of electrons and holes which competes with the strong recombination in the quantum wells. Thus, the EBIC increases in the MQW with the EBL acceptor doping as shown in the inset of Fig. 3.

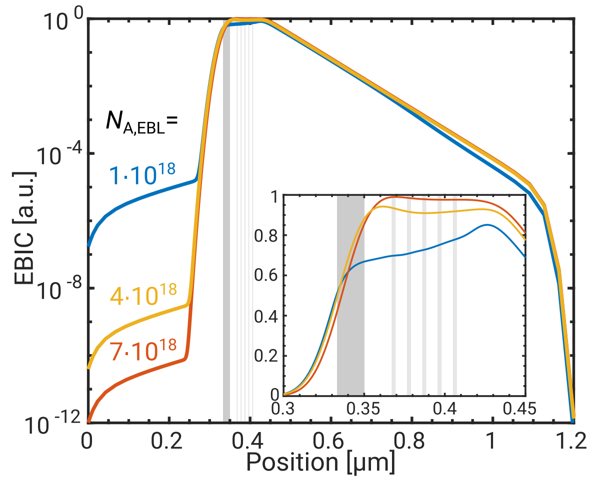

Fig. 3. Variation of the EBIC profiles with the EBL acceptor doping $N_{\mathrm{A,EBL}}$. The inset shows a magnification of the EBIC in the active region.

III. Conclusion

The EBIC characterization establishes a valuable tool in semiconductor analytics but in contrast to a pn-homojunction its interpretation for a III-nitride LED active region is more involved. Thus, we propose to complement experiments with EBIC simulation including drift-diffusion. The aspect discussed in this study, the EBL doping, already demonstrates the complexity of its effect on the EBIC signal but also that the modelling supports the interpretation of EBIC experiments. In an outlook we are going to analyze the influence of other design parameters, for instance the composition of the EBL and compare the simulation results to experimental EBIC data. It is planned to expand the model to full three dimensions.

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