Carrier Transport in the Multi Quantum Well Region of III-Nitride Light Emitting Diodes

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***Abstract*—The carrier transport in the multi quantum well (MQW) region of III-nitride light emitting diodes is critical for their efficiency in the high current regime. The asymmetry of the electron and hole transport makes it difficult to achieve an equal distribution of the quantum well luminescence in order to decrease the droop. To study the luminescence distribution we have devised a carrier transport model accounting for the carrier quantization effects in an MQW active region. The detailed study of the carrier distribution in the MQW is supported by an equivalent circuit model. By means of this model we demonstrate that the re-distribution of the luminescence in the MQW with increasing bias current has an effect on the ideality factor.**

I. Introduction

The driving current of recent III-nitride light emitting diodes (LED) is limited by the decrease of the efficiency in the high current regime, the droop, which has been subject to intense theoretical as well as experimental studies in the past. A commonly accepted source of the droop is the Auger recombination [1]. This fundamental physical effect cannot be eliminated by technological means. Increasing the active volume by means of a multi quantum well (MQW) active region reduces the effect of the Auger recombination due to the lower average carrier density. The transport and scattering of electrons and holes in the MQW active region is critical because an unequal luminescence distribution voids the advantage of the MQW with respect to the droop.

To study the luminescence distribution in the MQW we use a drift-diffusion based carrier transport model with multiple carrier populations [2], [3]. Electrons and holes are subdivided into a continuum population and as much bound populations as there are quantum wells (QW) to realize a separation in the energy space. The continuum population is subject to drift-diffusion transport in all spatial directions. The bound populations are subject to the $\mathbf{k}\cdot\mathbf{p}$-Schrödinger equation in the direction perpendicular to the QW and drift-diffusion transport in the QW plane. The coupling of the continuum and bound populations is enabled by a dynamic scattering model [4].

II. MQW carrier transport

The continuum carrier transport is subject to corrections in active region. In the quantum wells, the continuum band edge is approximated by the minimum band of the proximate barriers as illustrated in Fig. 1 to enable the energetic discrimination of continuum and bound carriers in terms of the drift-diffusion transport. Quantum transport simulations [5] show this separation and also demonstrate that particularly electrons are able to tunnel the potential barriers created by the piezoelectric polarization. The effective reduction of the barrier potential is modeled with an effective potential correction for the continuum carrier transport [6].

The transport model has been validated with the spectra of multi color LEDs. In the experiment LEDs with four blue and one cyan QW have been characterized [7] varying the position of the cyan QW. The ratio of the blue to cyan emission shown in Fig. 2 demonstrates that the p-side QW dominates because the ratio steadily decreases while the position of the cyan QW moves from the n-side to the p-side. The simulations with the effective potential correction show the same result. Simulations without effective potential corrections show the opposite behavior demonstrating the relevance of this model.

III. Equivalent circuit model

The re-distribution of the luminescence has been investigated for a polar InGaN/GaN LED with two QWs and an electron blocking layer (EBL) emitting at 450nm. The analysis is supported by an equivalent circuit model. Since radiative as well as non-radiative recombination center on the quantum wells the current paths are well defined giving rise to the circuit elements illustrated in Fig. 3. The recombination in each QW is modeled with a diode. The MQW barriers present resistive elements in the current path of each species. Another resistive element originates from the coupling of the continuum and bound carriers. All resistive elements are described by a unitless normalized resistance which is proportional to the change of the quasi Fermi level distance with the current:

$$\eta = \frac{I}{k_b T}\frac{d\Delta E_F}{dI}.$$

This definition is compatible with the ideality factor.

The equivalent circuit depicted for the double quantum well (DQW) shown in Fig. 3 omits the scattering resistance of the holes because continuum and bound holes are nearly in thermal equilibrium [3]. The barrier resistance of the electrons is neglected because the continuum quasi Fermi level remains nearly constant over the whole MQW active region.

Figure 4 shows that with increasing current the luminescence re-distributes from the n-side to the p-side QW. Both QWs show a nearly identical ideality factor $\eta_{\mathrm{qw,n}}$ and $\eta_{\mathrm{qw,p}}$ in the low current regime. In the high current regime the ideality factor increases above 1.5 which is due to the phase space filling. The resistance of the MQW barriers vanishes for

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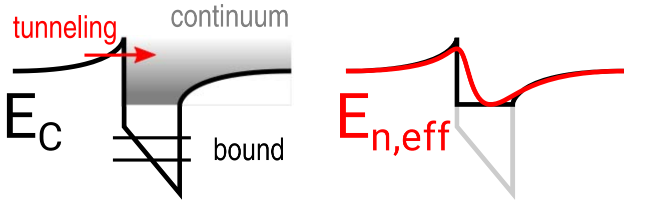

Fig. 1. Left figure: schematic of the conduction band edge E_C, continuum and bound states. Right figure: schematic of the continuum band edge approximation (black) and effective electron potential $E_{\mathrm{n,eff}}$ (red).

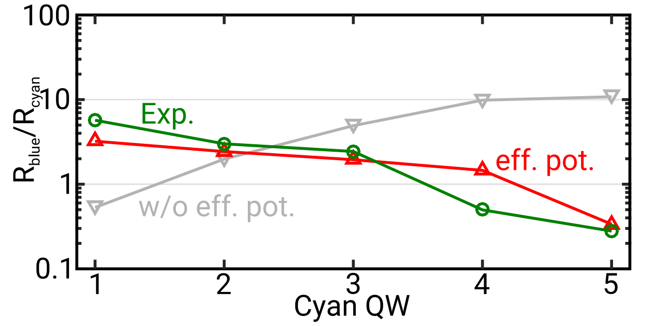

Fig. 2. Blue to cyan emission ratio at $j = 50\mathrm{Acm}^{-2}$ versus the position of the cyan QW. Pos. 1 is the n-side QW and Pos. 5 is the p-side QW. The simulation results are shown with (red) and without (gray) effective potential correction.

low currents and increases with the current as expected. The resistance of the p-side barrier $\eta_{\mathrm{bp,p}}$ is higher than the n-side barrier resistance $\eta_{\mathrm{bp,n}}$ because of the EBL. The scattering resistance of the n-side QW $\eta_{\mathrm{sc,n}}$ is significantly higher than the scattering resistance of the p-side QW $\eta_{\mathrm{sc,p}}$. This can be regarded as the main cause for the re-distribution.

With increasing current the scattering resistance decreases and even attains negative values in the high current regime. This means that the distance between the bound and continuum quasi Fermi level of the electrons decreases with increasing current. These quasi Fermi levels have a rather large distance so that the electron bound quasi Fermi level has a minor influence on the scattering rate. Thus, the scattering acts as a buffer which in part compensates for the effect of the phase space filling.

The ideality factor of the active region can be computed with the equivalent circuit elements and shows excellent agreement with the ideality factor obtained from the physical simulation. It is noted that the re-distribution causes a decrease of the ideality factor with increasing current which is eventually overcompensated by the phase space filling and the barrier resistance.

In conclusion, we have presented a model for simulating the carrier transport in the active region of MQW III-nitride LEDs and demonstrated its validity by comparing the simulation results with the experimental luminescence data of multi color LEDs. The luminescence re-distribution has been investigated with an equivalent circuit model. It has been found that the scattering between the continuum and bound electron states has a major influence on the re-distribution. The re-distribution leads to a decrease of the ideality factor.

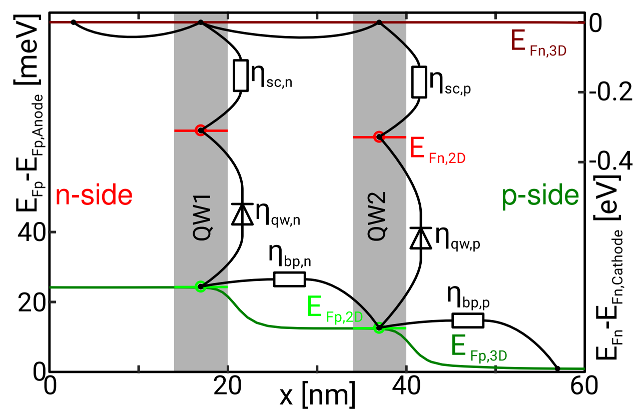

Fig. 3. Equivalent circuit elements in the active region of the DQW.

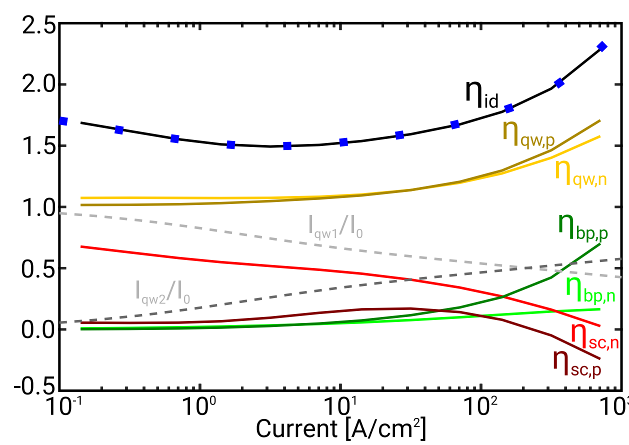

Fig. 4. Equivalent circuit element values in the active region of the DQW versus current. The black line and blue markers show the ideality factor obtained with the lumped model and the physical simulation, respectively.

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