Effect of Inhomogeneous Broadening in Deep Ultraviolet Light Emitting Diodes

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***Abstract*—Due to their small dimensions deep ultraviolet (DUV) light emitting diodes (LED) are highly attractive light sources for environmental and medical applications. DUV LEDs generate light in active quantum wells (QW) made of Aluminium Gallium Nitride. The QWs are not lattice matched to the substrate and only few monolayers thick making them susceptible to compound fluctuations seen through inhomogeneous broadening (IHB). In this work we analyze by means of self consistent carrier transport and luminescence simulations how the IHB affects the electronic operation and emission polarization of DUV LEDs. We demonstrate that the IHB affects both the internal quantum efficiency and the current versus voltage curve of DUV LEDs.**

I. Introduction

Aluminium Gallium Nitride (AlGaN) light emitting diodes (LED) enable compact and robust deep ultraviolet (DUV) light sources for medical, environmental, and material processing applications. Current research focuses on the enhancement of the efficiency which is still limited by the low hole injection in the active region and dominant transversal magnetic (TM) over transversal electric (TE) emission due to the negative crystal field splitting in AlGaN with high Al content [1]. The light generation in the quantum wells (QW) of DUV LEDs has been observed to be subject to pronounced inhomogeneous broadening (IHB). The QWs in DUV LEDs are typically few monolayers thick and not lattice matched to the barrier compound promoting compound disorder which ultimately causes the IHB [2].

Compound disorder is seen though a random variation of the QW alloy in the lateral dimensions. For modelling carrier transport in its presence the localized landscape theory has been proposed [3]. Microscopic luminescence in the presence of alloy fluctuations can be modelled statistically introducing a distribution function for the band edge energy [2]. In the scope of model based LED design the statistical approach is advantageous because it is deterministic and enables the reduction of the carrier transport problem to one spatial dimension. In our approach we describe the subband energy fluctuations statistically to model the influence of the IHB on carrier transport and luminescence. We investigate the effect of the IHB on the electronic operation of DUV LEDs including the current versus voltage curve and the internal quantum efficiency (IQE). In the subsequent section we outline the modelling approach and analyze the effect of the IHB on a single quantum well LED.

II. Modelling Inhomogeneous Broadening

When modelling the effect of the IHB we focus on its influence on the QWs. Alloy fluctuation in the QWs is modeled by a Gaussian distribution of the subband energy levels. Fluctuations of the subband energy levels cause a broadening of the spectrum, but also alter the radiative recombination rate as well as the Fermi levels having an immediate influence on the electronic properties. Each conduction and valence subband is considered to be subject to a distinct broadening energy that governs the Gaussian distribution. The subband energy fluctuations are considered to be correlated because they are all caused by the same composition fluctuation. Therefore, we introduce a broadening energy σ which describes the band edge fluctuation. The distribution of σ between conduction and valence band is subject to the band offsets. Due to the large difference of the crystal field splitting energy between GaN and AlN [1] the broadening energy of the split off band is lower than the one of the heavy/light hole bands. This effect is considered in the model and explains the enhanced TE polarized emission of some DUV QWs.

We have implemented the statistical broadening model into the multi scale carrier transport simulator described in [4]. The Gaussian broadening function enters the microscopic luminescence and Fermi level calculation in the momentum space through the Fermi distribution. A seven point Gauss-Hermite quadrature rule has been found to provide sufficient accuracy making the implementation very efficient. For investigating the effect of the IHB on the carrier transport it is instructive to start with a simplified single quantum well (SQW) LED where non-radiative recombination and incomplete dopant ionization have been deliberately turned off. This makes carrier leakage the only loss term.

The band structure is illustrated in Fig. 1. The single 2.2nm wide polar AlGaN QW is embedded in 10nm wide undoped AlGaN barriers on an AlN substrate. An electron blocking has been omitted for simplicity. The doping density in the quasi neutral n- and p-regions is $N_D = N_A = 10^{18}\text{cm}^{-3}$, respectively. The QW compound is $\text{Al}_{0.71}\text{Ga}_{0.29}\text{N}$. The barriers and quasi neutral regions are made of $\text{Al}_{0.82}\text{Ga}_{0.18}\text{N}$. Without IHB

TM-polarized emission dominates. The subband broadening energy ratio is $\sigma_c = 2\sigma_{\text{hh}} = 2\sigma_{\text{lh}} = 4\sigma_{\text{so}}$.

With increasing IHB the density of states in the QW increases so that the 2D Fermi energy decreases and the density increases at a balanced level. The shift of the band edges between $\sigma = 25\text{meV}$ and $\sigma = 100\text{meV}$ in Fig. 1 is caused by an increase of the electron density in the QW which is not compensated by the increase of the hole density.

Figure 2 shows that due to states below the nominal subband transition energy the mean photon energy decreases with increasing IHB [5]. Due to the different broadening of light/heavy hole and split off bands the TE polarized emission shows a more pronounced decrease of the mean photon energy and becomes the dominant contribution for $\sigma = 125\text{meV}$ as illustrated in Fig. 3. The increase of the photon energy in the high current regime is an effect of the phase space filling. It is noted that the bias voltage is generally lower than the photon energy. In this context it must be considered that leakage as the mostly dominated current contribution fixes the bias voltage. With decreasing photon energy the bias voltage decreases also slightly. While the mean photon energy decreases with increasing IHB the injection efficiency into the quantum well increases and the leakage decreases which is directly reflected in the IQE.

III. Conclusion

We have demonstrated that the inhomogeneous broadening (IHB) not only affects the emission spectrum of deep ultraviolet (DUV) light emitting diodes (LED) but also the electronic operation including the current versus voltage curve and the internal quantum efficiency. The effect is correlated with the reduction of the mean photon energy seen through increasing IHB but also with the increased ideality factor for bimolecular recombination in the presence of IHB [5]. The dominant TE emission from DUV LEDs can be explained with the IHB. The statistical model based on the Gaussian distribution of the subband energy levels integrates well with the multi scale carrier transport simulator. While the instructive example of the single quantum well LED has been presented here subsequent activities will focus on the effect of the IHB in realistic multi quantum well LEDs including non-radiative recombination as well as incomplete dopant ionization and the comparison of these simulations to experiments.

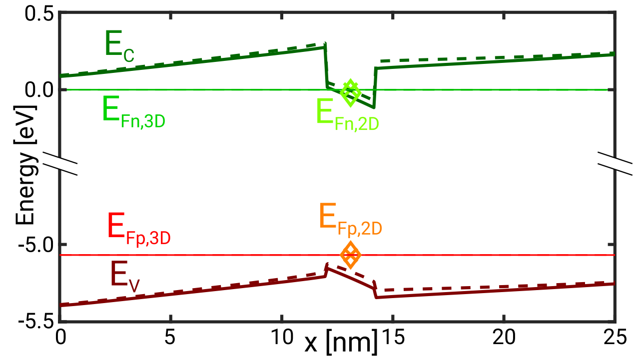

Fig. 1. Band edges and 3D/2D quasi Fermi levels at $j = 50\text{Acm}^{-2}$ for the broadening energy $\sigma = 25\text{meV}$ (solid/cross) and $\sigma = 100\text{meV}$ (dashed/diamond)

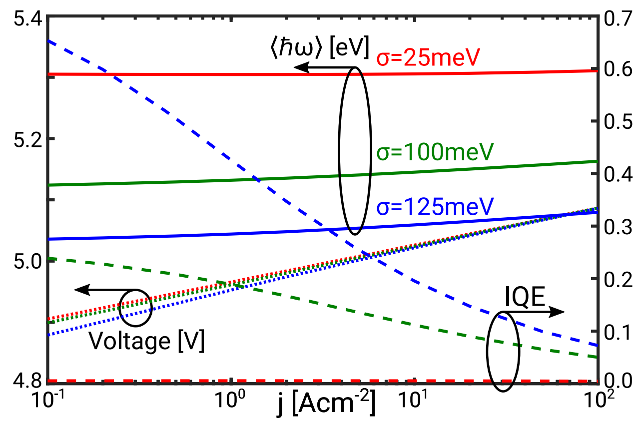

Fig. 2. Voltage, IQE, and mean photon energy $\langle\hbar\omega\rangle$ as function of the current varying the broadening energy σ.

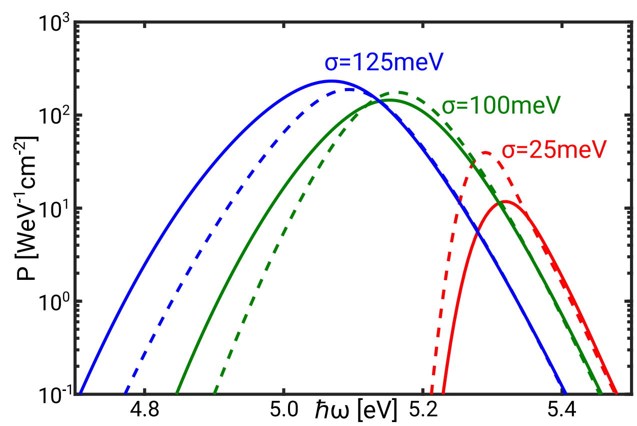

Fig. 3. b): TE (solid) and TM (dashed) emission spectrum as function of the broadening energy σ at $j = 50\text{Acm}^{-2}$.

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