Influences of Indium Fluctuation to the Carrier Transport, Auger Recombination, and Efficiency Droop

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***Abstract*—Our recent preliminary studies show that the nanoscale indium fluctuation in InGaN quantum well LED plays an important key role in carrier transport, radiative recombination, Auger, and droop effects. In this paper, we further examine the influence indium fluctuation for different degree of fluctuation, auger coefficients, and non-radiative lifetime. The influence of different AlGaN electronic blocking layer will be discussed in this paper. The commercial grade LED will be used for comparison to examine the model accuracy.**

I. INTRODUCTION

Nitride based white light emitting diodes (LED) have become emerging technologies in lighting market. Due to the quantum confined stark effect (QCSE) induced by the piezoelectric polarization field from the strong lattice mismatch, the carrier radiative lifetime is too long. Therefore, The efficiency droop effect has been observed which might be due to defect, Auger, and overflow. It is expected that the numerical modeling can play a key role in examining these effects. However, the issues are still unsolved for a long period due to the difficulties in predicting the LED behavior by a common numerical modeling tools. Traditionally, the LED device is simulated by assuming a perfect quantum well(QW) in the device. Due to the large potential barrier caused by the piezoelectric-related electric field, the drift-diffusion model often overestimates the forward voltage, Vf, (e.g., >> 4 V), which fails to match the experimental data where a Vf near 3 V is quite common in the commercial blue LEDs. Some studies use 40-50% polarization field to give a better prediction. But these treatments will lead to a much stronger radiative recombination and the overestimation of Auger coefficient [1]. Quantum ballistic transport or tunneling models are proposed to provide a possible reason for carriers to overcome the large piezoelectric potential barrier. But the tunneling transport behavior should be independent on temperature, which should be further examined by experiments.

Recently, three-dimensional (3D) atom probe maps of indium distribution within c-plane InGaN quantum wells [2] indicated that the indium composition fluctuates over a large range and might be the reason for the broadening of the emission spectrum in the InGaN QW. However, the impact of indium composition fluctuations on lateral and vertical carrier transport is poorly understood. Therefore, we first numerically demonstrated the influence of indium fluctuation to the efficiency droop, I-V curve, and Auger coefficient

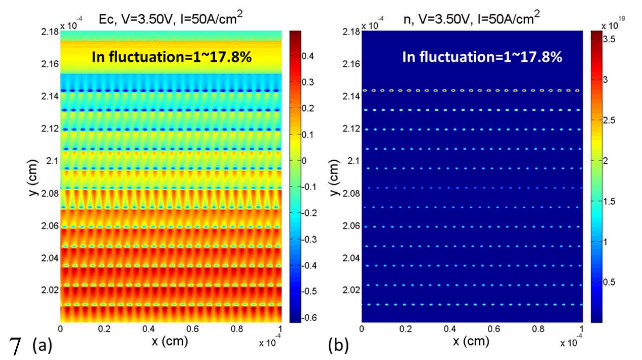

Fig. 1. (a) The conduction profile after using the indium fluctuation. (b) The electron density distribution when the indium fluctuation is considered. There are 12 QWs in this case.

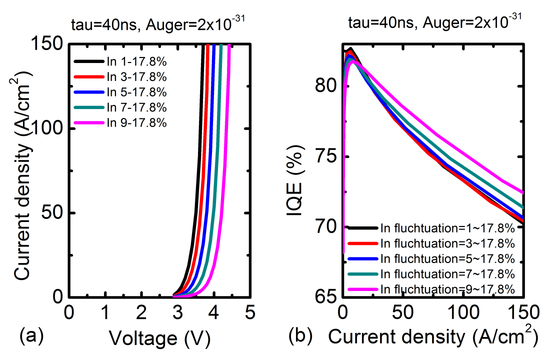

Fig. 2. (a) The I-V curve of the 12 QW InGaN quantum well with 15% AlGaN EBL for different degree of indium fluctuation. (b) The IQE versus current for different degree of the indium fluctuation.

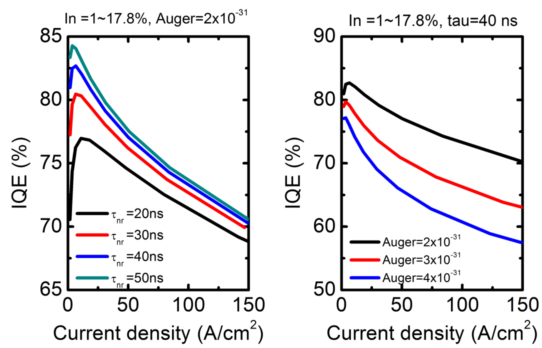

Fig. 3. (a) The influence of nonradiative lifetime to the IQE versus current curves. (b) The influence of Auger coefficient to the indium fluctuation

[1]. Our preliminary studies [1] showed that if the indium fluctuation is included the numerical modeling, we are able to provide new clues in explaining these droop effects and fitting well with the experimental results.

Therefore, in this study, we would like to demonstrate important physics by including the alloy fluctuation in the carrier transport model. In practice, modeling nanoscale composition fluctuations is challenging since the simulations are numerically intensive and require significant computer memory. A two dimensional (2D) finite element Poisson and drift-diffusion solver [3] developed by our lab was used in this study. A very fine mesh was employed by the solver to model the indium composition fluctuations laterally in the multiple quantum wells (MQW) and vertically through the QW. To model the indium fluctuation, we assumed a lateral sinusoidal indium fluctuation and the vertical variation in indium composition was modeled by a Gaussian. Therefore, the indium composition fluctuation is as shown in Fig. 1. 12 pairs of quantum wells and a $Al_{0.15}Ga_{0.85}N$ electron blocking layer are used in the simulation. The nonradiative lifetime is assumed to be 5.0×10^{-8} s and radiative recombination coefficient B is assumed to be 2.5×10^{-11} cm^3/s in the simulation.

Fig. 1(a) shows the conduction band potential fluctuation in the QW caused by bandgap and piezoelectric field fluctuation at 3.5 V, which is nearing the flatband condition. Fig. 1(b) shows the electron distribution in the QW where electrons are localized at the potential minimum. As follows, the carrier density is higher in regions of high indium content. The indium fluctuation leads to several interesting results: (1) At a fixed current density, the radiative recombination rate increases in the high indium region because of carrier screening of the piezoelectric field. (2) The electron overflow happens earlier because the high indium composition region occupies a small volume and the QW is much easier to fill, which may cause droop. (3) The influences of Auger C coefficient becomes significant even at smaller values because of higher local carrier density.

Fig. 2 shows the influences of indium fluctuation with different variation ranges. The piezoelectric polarization is assume to be 100% theoretical value and is changed with the indium fluctuation. As shown in Fig. 2(a), the Vf will change from 3.1V to 3.8V. With a larger indium fluctuation ranges, the forward voltage is more close to high quality commercial c-plane MQW blue LED devices. From the model IQE versus current curve as shown in Fig. 2(b), The peak IQE is higher with larger indium fluctuation due to carrier localization and the large indium fluctuation also leads to a much high local carrier density in the indium rich side, where the droop effect induced by Auger recombination or carrier overflow will be stronger.

Fig. 3(a) shows the IQE versus current with different nonradiative lifetime. The value of peak IQE will be affected by the nonradiative lifetime significantly especially when indium fluctuation is considered. Also, due to the high local carrier density, a much smaller Auger coefficient ranges from 2×10^{-31} cm^6/s to 4×10^{-31} cm^6/s is needed to present the droop effect as shown in Fig. 3(b), which is more close to the first principal theoretical calculation by including the phonon and defect assisted auger recombination. Our previous result [1] also shown that if we use 50% polarization and a normal QW, we will need a much larger Auger coefficient and very long nonradiative lifetime to see the droop effect, which is beyond any theoretical prediction and experimental evidences. Our result also shows that if the EBL is small. The overflow will dominate the system. However, if the EBL is higher enough to block the electron, the Auger recombination takes over immediately as the major reason of the droop effect.

We also applied our model in fitting the experimental result and it gave a very good fitting and prediction. Due to the length limitation, we didn't include these data here. In conclusion, our simulation results show that by considering the indium composition fluctuation in the QW, it is possible to explain the low forward voltage in the commercial blue LED diode. The influence of indium fluctuation to the IQE and carrier transport is very significant, which cannot be ignored in the device design and modeling. Of course, including the tunneling and ballistic transport with consideration of indium fluctuation will give the best prediction of device characteristics. This work is supported by National Science council in Taiwan by grant number NSC 99-2221-E-002-058-MY3, and NSC 100-2221-E-002-153-MY2, and the Solid State Lighting and Energy Center at UCSB.

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