Investigation of Carrier Transport in Nitride Based LED by Considering the Random Alloy Fluctuation

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***Abstract*—The past researches show that the alloy fluctuation dominates the carrier percolation transport and light emission behavior in light emitting diodes (LEDs). To further understand the carrier behavior with alloy fluctuations, we have systematically investigated the carrier transport in the n-i-n InGaN quantum wells (QWs) and how the different electron blocking layer (EBL) affects the current-voltage curve and internal quantum efficiency (IQE).**

***Keywords*—InGaN, AlGaN, random alloy fluctuation, EBL, LED**

I. Introduction

The carrier transport mechanism and the origin of efficiency droop have been the most popular issues for GaN LEDs. Many researchers have proposed numerical models to figure out the possible mechanism. However, it is noted that the conclusion is highly related to the model and the physical parameters. In the past, the traditional models assume the uniform distribution along InGaN QWs and use the reduced theoretical polarization value to fit the experiment data. However, the reduced polarization value results in a better electron-hole overlap, where a larger Auger coefficient is needed to fit the IQE curve. Such adjustments might mislead people to give the wrong conclusion. Recently, the atom probe tomography (APT) data shows that the ternary alloy of InGaN QWs and AlGaN EBL are fluctuated. Our past research [1] has modelled these nano-scale phenomenon and demonstrated the influence of the alloy disorder without any approximation. The inhomogeneous distribution of the bandgap and polarization potential attributed to the random alloy fluctuation affects the carrier confinement and injection greatly. To understand the carrier transport further in the random alloy system, this paper has systematically investigated the carrier transport with our 3D drift-diffusion solver and alloy fluctuation generator for different structures.

II. Methodology and Structure

To describe the alloy disorder of the InGaN/AlGaN properly, we have used in-house developed fully 3D model to analyze the electrical and optical properties. Firstly, we use the random alloy generator to produce the random alloy landscape. Then we combine the mesh file of the structures with the random alloy maps and produce the local input parameters (bandgap, polarization charge, effective mass,...) with linear interpolation according to the local composition. The alloy landscape and the corresponding conduction band profile are shown in Fig. 1. The algorithm detail can be found in Ref. [1]. Finally, the 3D solver can be applied and analyze the results.

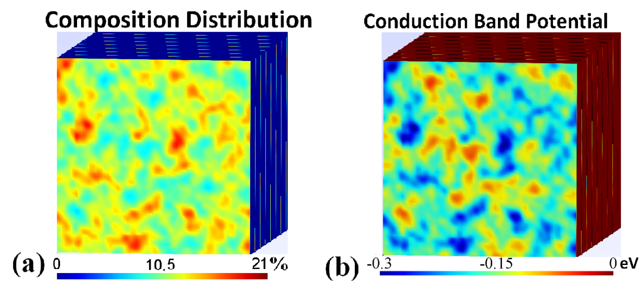

Fig. 1: (a) One of the random alloy landscape of the InGaN quantum wells. (b) The corresponding fluctuated conduction band potential in the InGaN quantum wells. The fluctuated indium composition leads to inhomogeneous distribution of potential.

III. Results And Discussion

This part has been divided by two parts. The first structure (Fig. 2(a)) is the n-GaN/i-InGaN/n-GaN without any recombination mechanism so that we can focus on the impact of different piezoelectric induced barrier for the pure electron transport. In the second part, we will discuss the influence of different EBL to the I-V and IQE curves for the p-n LED. We will make a comparison with experiment data.

A. Carrier Transport Analysis in n-GaN/ i-InGaN / n-GaN Structures

Brown et. al. [2] have done a series of experimental studies on the I-V behavior of the n-i-n $In_{0.14}Ga_{0.86}N$ structures. They found a clear rectifying I-V curve related to the quantum well thicknesses and numbers, and it is varying with temperature, which is likely dominated by the thermionic emission current. While we used the ideal QW model to fit the experiment results, a much higher forward voltage is obtained at the same current density. Therefore, the percolation transport through the random alloy might be a possible reason. As shown in Fig. 1(b), the fluctuated indium composition and polarization field lead to the fluctuation of conduction potential in the QW and QB. Electrons are much easily finding the smaller barrier site to percolate (Fig 2(b)). Figure 2(c) shows that the turn-on

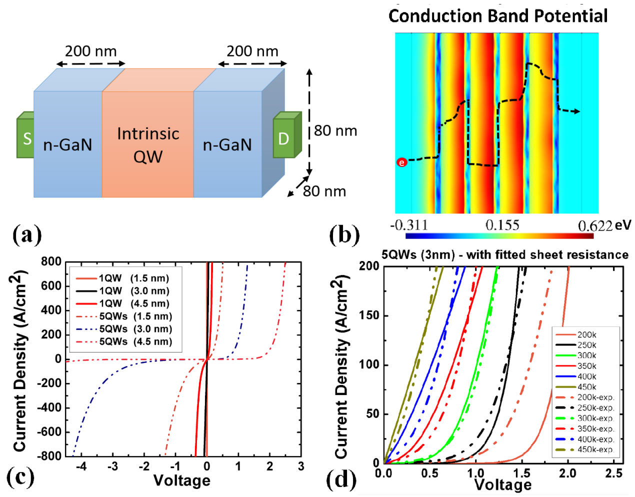

Fig. 2: (a) The configuration of the n-i-n structure. (b) The side view conduction band potential of the n-i-n InGaN quantum wells and the scheme of the carrier transport along the fluctuated barriers. (c) The I-V curve of various thicknesses of the fluctuated QWs. (d) The I-V curve with different temperature. The experiment data is form Ref. [2].

voltage increases as the thickness or number of QWs increases. As we know, for the same polarization electric field, a thicker QW will cause a much larger potential band bending, making it harder for electrons to go across the junction. The turn-on voltage of a single QW is very low, because it has only one barrier to be overcome by applying the bias voltage. Even though the thickness of the QW is increased to 4.5 nm, the turn-on voltage is still less than 0.5V. When the number of QWs increases to five, the positive turn-on voltages for 1.5, 3, 4.5 nm at 20 A/cm^2 current density are 0.1, 0.68, and 1.73 V, respectively. Besides, the simulation (Fig 2(d)) including the indium fluctuation can well fit the experiment data over the room temperature. The dominated transport mechanism is the thermionic transport rather than tunneling effect, since the tunneling effect is temperature independent.

B. 3-D Vertical LED Structure

The second part is to examine the influence of different types of EBL. The structure is basically based on Ref. [3]. We mainly focus on how different EBLs influence the carrier injection by considering the random alloy fluctuations. Figure 3(a) shows the scheme of the structure. There will be three LEDs with the identical $In_{0.15}Ga_{0.85}N$ QW region and different EBL structure. The first one is the bulk EBL. The second one is the uniform multi-quantum barriers (UMQB) with four 5 nm GaN layers embedded between five 5 nm $Al_{0.15}Ga_{0.85}N$ layers, and the third one is chirped multi-quantum barriers (CMQB) with gradually thicker $Al_{0.15}Ga_{0.85}N$ layers (0.75, 3.375, 6.0, 8.625 and 11.25 nm, from n-side to p-side) intervaled with gradually thinner GaN layers (6.5625, 4.6875, 2.8125, and 0.9375 nm, from n-side to p-side). Figure 3(b) shows the forward voltages of the bulk EBL, UMQB, and CMQB LED at 20A/cm^2 are 3.20, 3.13, 3.11 V. The trend of the performance is basically coincident. The CMQB has the lower forward voltage because

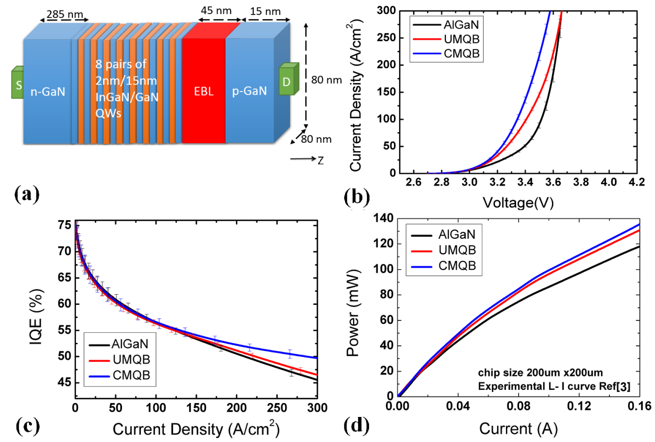

Fig. 3: (a) The configuration of the LED. (b) The I-V curve of the bulk EBL, UMQB, and CMQB LEDs. (c) The IQE curve of the bulk EBL, UMQB, and CMQB LEDs. (d) The reference experimental L-I data is obtained from Ref. [3].

of better hole injection through the gradual superlattice with alloy fluctuations, especially at the thinner AlGaN layers of CMQB LED. Reversely, lacking of hole injection and large driving voltage result in stronger leakage in the bulk LED over 3.5 V. However, the current density is already over 200 A/cm^2. The IQE droop (Fig. 3(c)) of the bulk EBL, UMQB, and CMQB LED between the peak value and the value at current density 300 A/cm^2 is 29.0, 27.5, 25.0%, respectively. The CMQB LED demonstrates the smaller droop effect among all the devices, because it provides a better hole injection ability. For the bulk EBL, the leakage current starts to happen in 3.5 V, which worsens the droop. The structures we modelled here are similar to the structure modelled by Piprek *et al.* [4]. Our model with alloy fluctuations has the smaller IQE difference among all the cases at the low current density, which is closer to L-I performance (Fig. 3(d)) in the Ref. [3].

IV. Conclusion

In conclusion, we have done a serious investigation of the carrier transport with alloy fluctuations for LED structures. The 3D drift diffusion model with alloy fluctuations can provide a more objective simulation results to examine the percolation transport in LEDs.

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