Study on GaN-based light-emitting diodes with graded-thickness quantum barriers

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***Abstract*—GaN-based light emitting diodes (LEDs) with graded-thickness quantum barriers (GQB) is studied. Simulation results show that GaN-based LEDs with GQB has better performance than conventional GaN-based LEDs with uniform thickness barriers, the major physical cause is attributed to the superior hole distribution in the quantum wells due to the appropriate energy band diagram.**

I. INTRODUCTION

GaN-based light emitting diodes (LEDs) have been vigorously developed to take the place of traditional incandescent and fluorescent lamps, due to its high brightness and low power consumption. However, the optical performance of GaN-based LEDs is suffer from a significant decrease, especially at high injection current. Many possible mechanisms have been suggested to account for this efficiency droop situation, including polarization effect [1], Auger recombination, carrier overflow and poor hole injection efficiency [2]. Recently, some reports proposed the nonuniform distribution of holes due to the difficulty of hole transport into quantum wells from *p*-type region [3-5], maybe a main reason for the low radiative recombination rate. In order to improve the hole distribution, many approaches have been proposed, such as using *p*-type multiple quantum wells (MQWs) [6], InGaN barriers [3] and using GaN-InGaN-GaN multiple quantum barriers (MQBs) [4].

In this paper, we designed a LED structure with graded-thickness quantum barriers (GQB) to improve the hole distribution, is theoretically studied by applying the APSYS software [7] which has been successfully applied to simulate plenty of realistic devices [3-6].Comparing to conventional LED with uniform thickness barriers, better hole distribution in such GQBs structure, so better performance.

II. DEVICE STRUCTURE

The conventional GaN-based LED used as a reference was grown on a c-plane sapphire substrate by metal-organic chemical vapor deposition method. The device structure consists of a 3-μm-thick layer of *n*-type GaN (*n*-doping = $5\times10^{18}cm^{-3}$), followed by six periods of $In_{0.15}Ga_{0.85}N$/GaN MQWs, a 200-Å-thick layer of p-type (*n*-doping = $2\times10^{18}cm^{-3}$) $Al_{0.15}Ga_{0.85}N$ as electron-blocking layer (EBL), and a 0.3-μm-thick layer of p-type GaN (p-doping = $2\times10^{18}cm^{-3}$) cap layer. The thicknesses of quantum well and GaN quantum barrier are 2.5 and 10 nm, respectively. As for our designed GQB structure was similar except for that the thickness of GaN quantum barriers are 1.3, 1.2, 1.1, 1.0, 0.9, 0.8 and 0.7 nm along grown direction. Note that the total volumes of active region for the two structures are the same. The device geometry was designed with a rectangular shape of 300× 300μm^2.

III. RESULTS AND DISCUSSIONS

Fig. 1 illustrate the experimental and simulated current-voltage (*I-V*) and power-current (*L-I*) curves of the conventional LED, which shows good agreement between the experimental data and our simulated results.

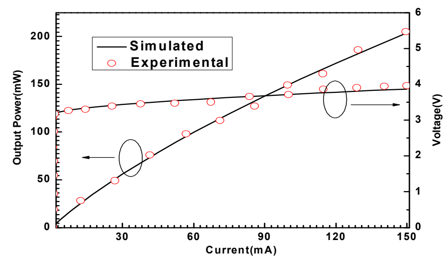

Fig. 1. Experimental and Simulated *I-V* curves and *L-I* curves of the conventional LED

Energy band diagrams of the two LEDs at 150 mA are plotted in Fig. 2. We can see that there is a severe band bending situation in the conventional LED [shown in Fig. 2 (a)] due to polarization charges which hinder carriers transport in the QWs freely, result in poor hole distribution in QWs. As we know, the holes in the GaN-based materials have a relatively high effective mass and the mobility is very low, so the holes is more difficult to inject into the QWs and transport in the active region under this situation, which cause the holes tend to accumulate in the QWs near the *p*-type region. And more near the *p*-type region, higher hole concentration. Thus the hole distribution is poor.

For the GQB structure, the band bending situation is also exsit [Fig. 2(b)]. The interface polarization charge in the active regions is mainly influenced by the substrate material and the composition of the quantum wells and barriers. Thus the interface polarization charge is same in the two structures. However, the band bending level is graded because the quantum barriers thickness is graded in the GQB structure. And the band bending situation and polarization field is gradually alleviated from the *p*-type region to *n*-type region due to the barrier thickness is increased. So the holes can transport form *p*-type region to *n*-type region easier than conventional structure, and the hole distribution can be improved.

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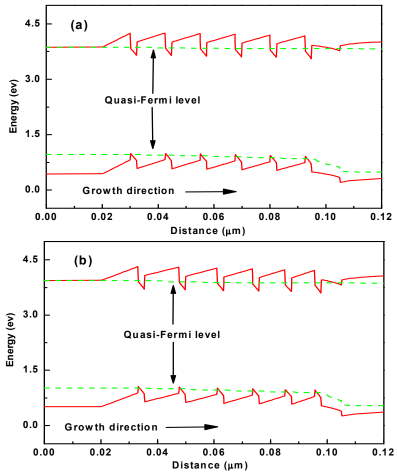

Fig. 2. (a) Energy band diagram of the conventional LED at 150mA (b) Energy band diagram of the GQB LED at 150mA

Figure 3 shows the hole distribution of two structures near the active region at 150mA. For conventional LED structure ,it can clearly seen that holes tend to accumulate in the QW near the *p*-type region, more near the *p*-type region, higher hole concentration, which is mainly attribute to the poor transportation of hole. But for the GQB LED structure, it can clearly seen the hole accumulation situation been improve greatly due to band bending situation is gradually alleviated as we have analysed before. From the QW near the *p*-type region to *n*-type region, the hole concentration decrease in the QW nearest *p*-type region (last QW) by about 5%, but increase in the first, second, third, fourth and fifth by 61%,14%,10%,12% and 9%, respectively, as compared with conventional LED structure.

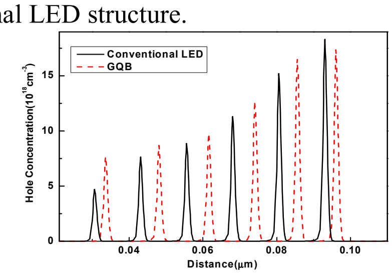

Fig.3. Hole concentrations of the two LED structures at 150mA

On the other hand, electrons distribution in the MQWs is relatively not being affected due to the relatively low effective mass and very high mobility. Therefore, the low radiative recombination rate can be improved, as illustrated the radiative recombination distribution in Fig. 4. For the GQB structures, it can clearly seen the radiative recombination rate just a little decrease in the last QW, but increase greatly in other QWs.

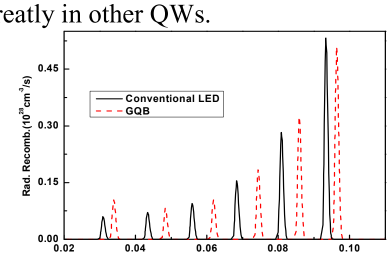

Fig. 4. Radiative recombination rate for the two LED structures at 150mA

Because of the superior hole distribution, the performance of the GQB LED is expected to be better than the conventional LED. Figure 5 shows the IQE and light output power as a function of current for the two LED structures under study, which indicates that the GQB LED has better lighting efficiency. It's worth noting here that the efficiency droop also be alleviated. If the droop ratio is defined as (Max_IQE – IQE@150mA)/Max_IQE, the droop ratio of the conventional LED is about 40%. However, the efficiency droop situation be improved and the droop ratio be reduced to 37%.

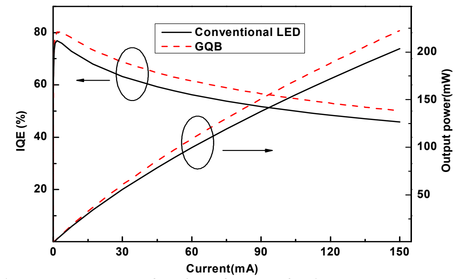

Fig. 5. IQE and light output power as a function of current for the two LED structures under study.

IV. CONCLUSIONS

In this paper, simulation work is made to compare a graded-thickness quantum barriers LED with conventional uniform thickness barriers LED. Simulation results show that the GQB LED improves hole distribution in the quantum wells greatly. Its significant advantage may help design LEDs with better performance.

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