Improvement of carrier distribution by using thinner quantum well with different location

Sheng-Wen Wang[a], Da-Wei Lin[a], Chia-Yu Lee[a] ,Chien-Chung Lin[*b,] and Hao-Chung Kuo[*a]

[a] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan

[b] Institute of Photonic System, National Chiao Tung University, Tainan

* hckuo@faculty.nctu.edu.tw

ABSTRACT

We use thinner-quantum well to improve the droop behavior of GaN-base light emitting diode in simulation. Taking the advantage of that the thin quantum well will saturate easily, this characteristic of thin well will improve carrier distribution. Furthermore, this structure has more wave-function overlap than that of the thick well. This simulation result showed that decreasing the well thickness in specific position will not only improve the holes transport but also increase the quantum efficiency at high current density in the active region, and the efficiency droop behavior can be effectively suppressed. In this research, we designed three thin well structures by inserting different numbers of thin wells in the active region. We have compared them to the conventional LEDs, for which, the well thickness of 2.5 nm is used. The thin well structures have better droop behavior than conventional LED.

Keywords: Light-emitting diodes, quantum well

1. INTRODUCTION

GaN-base blue light emitting diodes (LEDs) are expected to replace the tradition lighting source due to many advantages of LEDs such as high efficiency, long lifetime, compact size.[1] At early stage, LEDs are used as background lighting source of displayer only and only operations under low current density are needed (about 20 A/cm2). However, if we want to replace the tradition illumination sources by LEDs, operations of LEDs under high current density will be applied. Unfortunately, researchers have discovered that the efficiency of LEDs will be reduced when it operate at high current density. The phenomenon is called "efficiency droop"[2] There are several mechanisms might lead to efficiency droop, for example poor hole transportation in multiple quantum wells (MQWs), electron leakage, and Auger recombination at high current density. The effective mass of holes is larger than that of electrons so that the mobility of holes is smaller than that of electrons. Therefore, significant amount of hole will be accumulated in the quantum wells near p-type layer which will increase the possibilities of electron leakage and Auger recombination at high carrier density.[3]

In our research, we replace some quantum wells adjacent to p-GaN with conventional thickness by thin wells. Although the thin quantum well will be saturated easily, this structure will lead to more overlap of wave-functions of electrons and holes than that of the thick well. Due to that the thin wells will be saturated easily, we can use this characteristic of thin well as a way to improve hole transportation. This simulation results show that by selecting appropriate wells to be replaced by thin wells, not only the holes transportation will be improved but also the quantum efficiency at high current density will be increased, and as a result, the efficiency droop behavior can be effectively suppressed. In this paper, we designed devices with three kinds of thin well structures and compared them to LEDs with conventional structure that all of the wells are with thickness of 2.5 nm. The devices with thin well structures have showed better droop behavior comparing to conventional LEDs.

2. SIMULATION MODELS

2.1 Simulation structure

The APSYS simulation software developed by Crosslight [4] was used to calculate band diagrams and carrier distributions. The LED structures constructed in simulation were composed of 100-μm-thick c-plane sapphire substrate, 4-μm-think n-type GaN layer (n-doping = 2×10^{18}cm^{-3}), six pairs of In$_{0.15}$Ga$_{0.85}$N/GaN MQWs with 2.5-nm-thick wells

and 10-nm-thick barriers, 20-nm-thick p-Al $_{0.15}$ Ga $_{0.85}$ N electron blocking layer (p-doping = 5 × 10^{17}cm^{-3}), and 200-nm-thick p-type GaN layer (p-doping=1×10^{18}cm^{-3}). In this study, three types of LEDs has been designed, hereby named as LED A , LED B and LED C. In LED A, only the last quantum well adjacent to p-GaN has been replaced with a thin well. In LED B, the last two quantum wells adjacent to p-GaN are replaced with thin wells. In LED C, all of the quantum wells are replaced with thin wells. All of the thin wells are with thickness of 1.25 nm. The simulation parameters used in this study were as following: The percentage of screening effect was set as 50%, Shockley-Read-Hall recombination lifetime was 1 ns, and Auger recombination coefficient in MQWs was 10^{-31}cm^6/s. The chip size of LED is 300 × 300 μm^2.
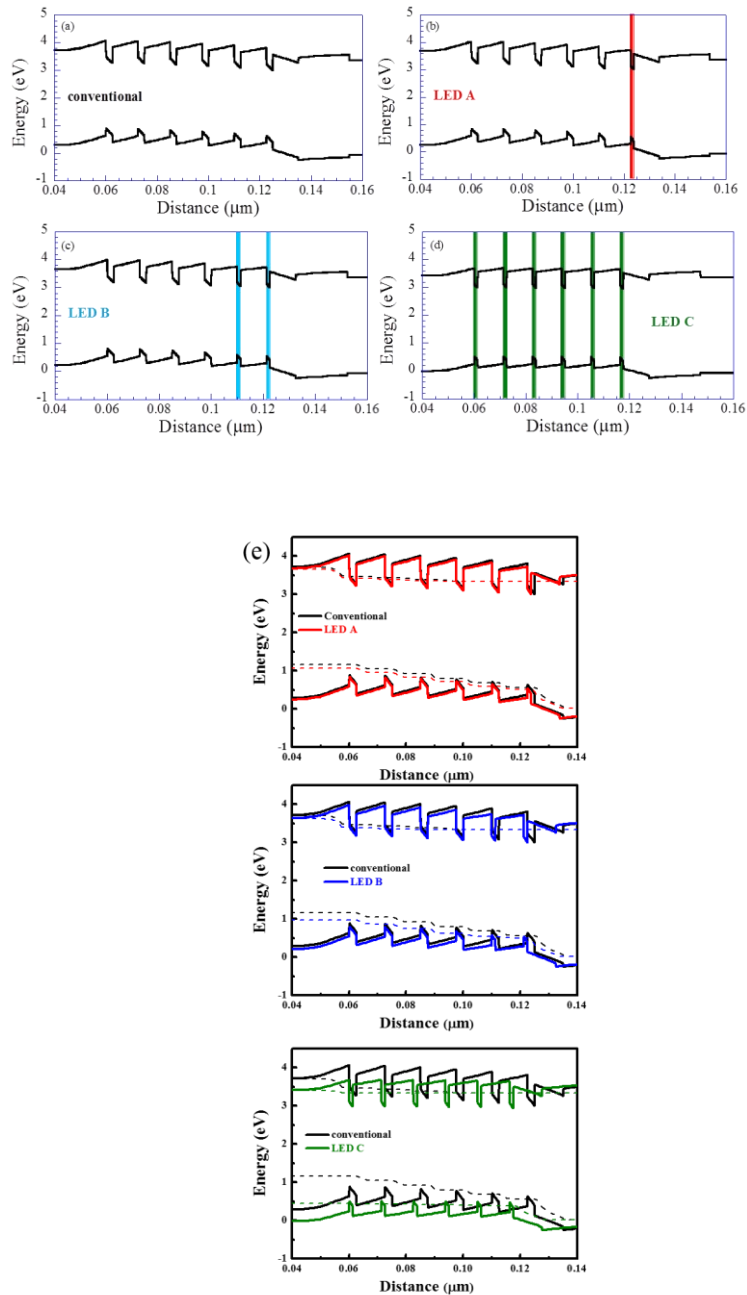

Figure 1. Calculated band diagram of (a) conventional and (b) LED A, (c) LED B, (d) LED C, (e) compare band diagram with conventional, LED A ,LED B, and LED C.

2.2 Simulation model

Figure 1 show the band diagram of conventional LED, LED A, LED B and LED C. For LED A, the thickness of the last quantum well (the sixth well) has been reduced from 2.5 nm to 1.25 nm as it is replaced by the designated thin well. The thin well will improve holes transportation from itself to the next quantum well. For LED B, the last two quantum wells are replaced by the thin well and the improved hole transportation has been pushed to the fourth well. For LED C, all of quantum wells are replaced by the thin well, and the thin wells structure has the most uniform holes distribution in active region.

3. SIMULATION RESULTS AND DISCUSSION

3.1 Electric field at 100 A/cm^2

We can find that the quantum barrier which nearby the thin well structure is smoother than the quantum barrier which in conventional LED. Figure 2 shows the electric field of the active region, the electric field of barrier which nearby thin well is smaller than conventional of barrier, and this phenomenon will improve the holes transport. When the thickness of well become thinner, the thin well will be saturation easier. On the other hand, the current density is higher than normal thickness of well, and the thin well has more carriers at per unit of area. For active region of LED, inject the current into the quantum well. The screening effect will happen, so the barrier will become smooth. However, the thin well has higher carriers at per unit of area, and the screening effect will become stronger than normal thickness of well, so the band bend of quantum barrier will become smoother.
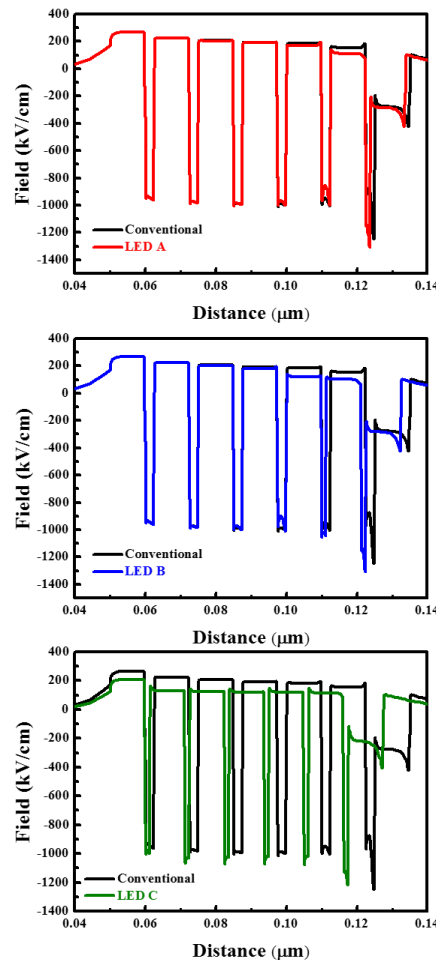

Figure 2. Simulated electrostatic fields of conventional, LED A, LED B, and LED C.

3.2 Carrier distribution at 100 A/cm^2

Figure 3 shows the calculated electron and hole distribution of the conventional LED, LED A , LED B and LED C at the current density of 100 A/cm^2. LED A has the thin well at last quantum well, so the holes can transport form last quantum well to fifth and fourth quantum well easily. The phenomenon will improve holes distribution at active region. LED B has two thin wells at fifth and sixth quantum well, so the holes can transport from last two quantum wells to fourth and third quantum wells easier than conventional LED and LED A. This structure of LED B has more uniform holes distribution than conventional LED and LED A. All of quantum wells in LED C are thin well, so that all of quantum wells have holes. Therefore, all of the quantum wells in LED C can emission photons.
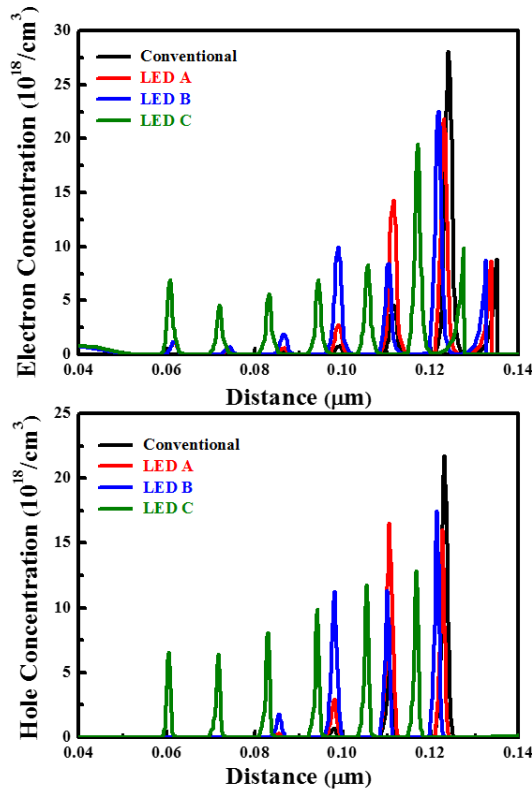
Figure 3. Calculated carrier concentration at current density of 100 A/cm^2 for (a) electron concentration and (b) hole concentration distribution.
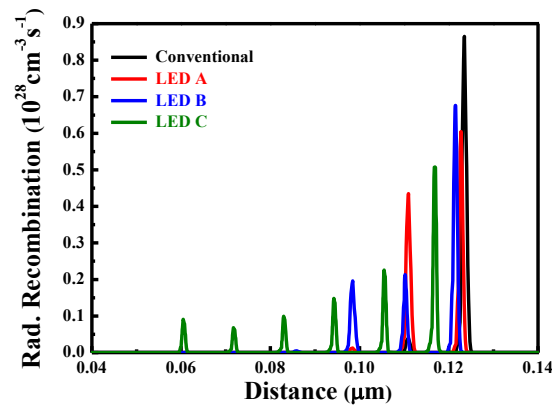
Figure 4. Radiative recombination distribution of conventional LED, LED A, LED B and LED C at 100A/cm^2.

Figure 4 shows the radiative recombination of conventional LED, LED A, LED B and LED C. For conventional LED, because of more holes accumulate at last two quantum wells, it just two quantum wells have recombination in the conventional LED. For LED A, due to the last quantum well is thin well, the holes can transport from last two quantum wells to fourth quantum well, and this structure has more radiative recombination area than conventional LED. For LED B, last two quantum wells are thin well, so the holes can transport to third quantum well. Then the LED B has more uniform holes distribution and radiative recombination region than conventional LED and LED A. For LED C, all of quantum wells are thin well, so that all of quantum wells can emission photons, and this structure is most uniform radiative recombination distribution. However, the most radiative recombination distribution has not the best light output power. Although, LED C has most uniform holes distribution, but every region of quantum wells are small than the origin thickness of well. The thinner well is saturation easy, and can't confirm more carriers in the quantum well. Therefore, we can find that the LED C has much more thin quantum wells than the others, but the efficiency of LED C is not most batter. However, the LED A and LED B have nice efficiency behavior compare with conventional LED, show in Figure 5, so we have to select the quantum to change the thickness of the well, and find the suitable number of the quantum well.
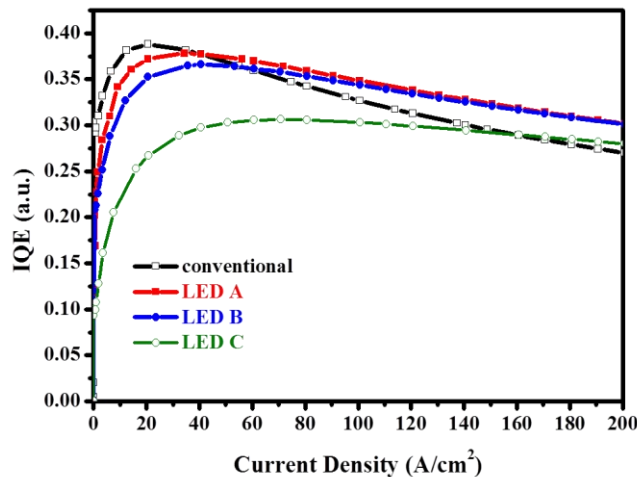
3.3 Efficiency

Figure 5. Simulated IQE as functions of current density for conventional LED, LED A, LED B and LED C.

The Figure 5 shows the external quantum efficiency (EQE) as a function of current density for the LEDs with various the number of thinner quantum wells. The efficiency droop behaviors, defined as (EQE peak－EQE 200A/cm^2)/ EQE peak , are 30.5% in conventional LED, 20.5% in LED A ,17.8% in LED B and 8.7% in LED C. However, LED C has lower EQE at standard-operation current density than the others. This result indicates that the thinner well can improve the holes transport and recombination rate, and then it will have most batter droop behaviors. All of efficiency will decrease because of emission region less than origin thickness of quantum well. Therefore, we chose one or two quantum wells to become thinner wells. This method will sacrifice the efficiency at lower current density, because most of holes will accumulate in last two quantum wells at lower current density, and the well is smaller than origin structure, so the emission region is less than normal quantum well.

4. CONCLUSION

In summary, we use two characteristics of thinner well which are higher wave-function overlap and carriers transport to next the quantum well easier than origin thickness of the quantum well. The simulation results show that when we inject current into the device, the electric field of the quantum barrier nearby thin well structure will be decreased. Due to the current density of the thin wells greater than normal thickness of the quantum well so that the carriers can screen the electric field of the quantum barrier easier than convention structure the phenomenon will let the band bend to become smooth and it will improve the carriers transport in active region. However, the thickness of the wells become

thinner in active region is not good ideal for LED device. Because of the thin well is easier saturation, on the other hand, the carriers in the well is less than origin and recombination region will be decreased. Finally, all of wells are thin well structure has more uniform carriers distribution in active region, but the efficiency is not batter than the others. Therefore, we have to choose some quantum wells to become thin wells, and we create two new structure which the last quantum well become thin well and the last two quantum wells become thin wells ,LED A and LED B represent. When we choose some wells become thin well, the holes transport will be improved. Even the efficiency decrease at lower current density, but it increase at high current density. Therefor the efficiency droop behavior is better than conventional LED, 30.5% in conventional LED, 20.5% in LED A , 17.8% in LED B and 8.7% in LED C.

ACKNOWLEDGMENTS

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