GaN-Based Light-Emitting-Diode With a p-InGaN Layer

P. H. Chen, Cheng-Huang Kuo, W. C. Lai, Yu An Chen, L. C. Chang, and S. J. Chang, *Senior Member, IEEE*

***Abstract*—GaN-based LEDs with a p-InGaN layer was proposed and fabricated. By inserting the 50-nm-thick p-$In_{0.01}Ga_{0.99}N$ layer, it was found that we could reduce the 20 mA forward voltage from 3.34 to 2.99 V. It was found the inserted p-InGaN layer could also reduce the efficiency droop from 36.7% to 23.8%.**

***Index Terms*—Efficiency droop, light emitting diode (LED), p-InGaN.**

I. INTRODUCTION

OVER the past few decades, tremendous progress has been achieved in GaN-based blue, green and ultraviolet light emitting diodes (LEDs) [1], [2]. These LEDs have already been used extensively in traffic-light lamps and full-color displays. Nitride-based LEDs are also potentially useful for solid-state lighting and backlight of liquid-crystal display panels. For solid-state lighting, however, one needs to further improve both the internal quantum efficiency and (IQE) and light extraction efficiency (LEE) of the LEDs. It has been shown that techniques such as textured surfaces [3], highly transparent p-contact layer [4] and proper substrate design [5] can be used to enhance LEE of GaN-based LEDs. On the other hand, IQE is related to crystal quality [6], piezoelectric effect [7]–[12], localized state of InGaN layer [13], hole concentration in p-GaN layer [14] and electron overflow [15]–[17].

To reduce electron overflow, it is normally necessary to insert an electron blocking layer (EBL) on top of the mutiquantum well (MQW) active region. However, this EBL also results in a lower hole injection efficiency [15]. Very recently, Kuo *et al.* proposed to use an Mg-doped p-GaN layer to replace the undoped GaN last barrier layer used in conventional LEDs [19]. They found the p-GaN last barrier could simultaneously enhance the effective barrier height at barrier/EBL interface and hole injection efficiency. For practical devices, however, Mg-doped in the last barrier layer could diffuse easily into the well layers during the growth. By inserting a 25-nm-thick p-GaN layer between the undoped GaN last barrier and the AlGaN EBL, Chen *et al.* have achieved larger LED output power experimentally. Using APSYS simulation software, they concluded that the inserted p-GaN layer could push away the band bending of EBL [20]. In this letter, we report the fabrication of GaN-based LEDs with a p-InGaN layer inserted between the undoped GaN last barrier and the AlGaN EBL. The inserted p-InGaN layer will be prvided the the smaller bandgap energy and larger hole concentration of p-InGaN [21] which could further push away the band bending of EBL and thus enhance hole injection, as compared to conventional inserted p-GaN layer. Detailed fabrication process and the electro-optical properties of the fabricated LEDs will also be discussed.

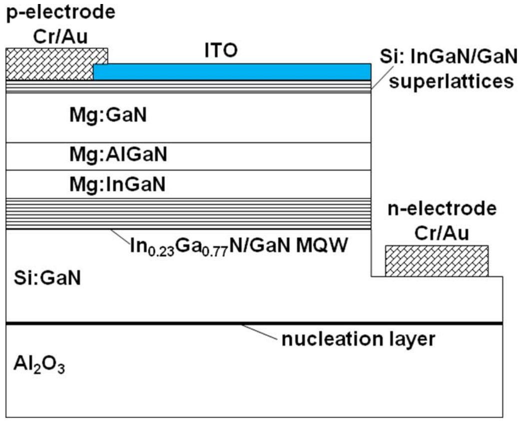

Fig. 1. Schematic diagram of the LED proposed in this study.

II. EXPERIMENT

The InGaN/GaN MQW LEDs used in this study were all grown on c-face 2-inch sapphire substrate by metalorganic chemical vapor deposition. Details of the growth procedures can be found elsewhere [3], [4], [6]. As shown in Fig. 1, the LED structure consists a 30-nm-thick GaN nucleation layer, a 4-μm-thick Si-doped n-GaN layer, an InGaN/GaN MQW active region, a 5-nm-thick p-$In_{0.01}Ga_{0.99}N$ layer, a 50-nm-thick Mg-doped p-$Al_{0.15}Ga_{0.85}N$ p-cladding layer, a 0.25-μm-thick Mg-doped p-GaN layer and a Si-doped n^+-InGaN/GaN (5 Å/5 Å) short period superlattice (SPS) tunnel contact structure. The MQW active region consists 10 periods of 3-nm-thick $In_{0.23}Ga_{0.77}N$ well layers and 15-nm-thick GaN barrier layers.

Manuscript received October 12, 2013; revised November 26, 2013; accepted November 26, 2013. Date of publication December 06, 2013; date of current version February 11, 2014. This work was supported by the National Science Council of Taiwan under Grant NSC 101-2221-E-009-028-MY3 and Grant NSC-3113-P-009-007-CC2.

P. H. Chen is with the Institute of Electro-Optical Science and Engineering, National Cheng Kung University, Tainan 70101, Taiwan.

C.-H. Kuo, Y. A. Chen, and L. C. Chang are with the Institute of Lighting and Energy Photonics, National Chiao Tung University, Tainan 71150, Taiwan (e-mail: kuoch@mail.nctu.edu.tw).

W. C. Lai is with the Department of Photonics, National Cheng Kung University, Tainan 70101, Taiwan.

S. J. Chang is with the Department of Electrical Engineering, National Cheng Kung University, Tainan 70101, Taiwan.

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Digital Object Identifier 10.1109/JDT.2013.2293767

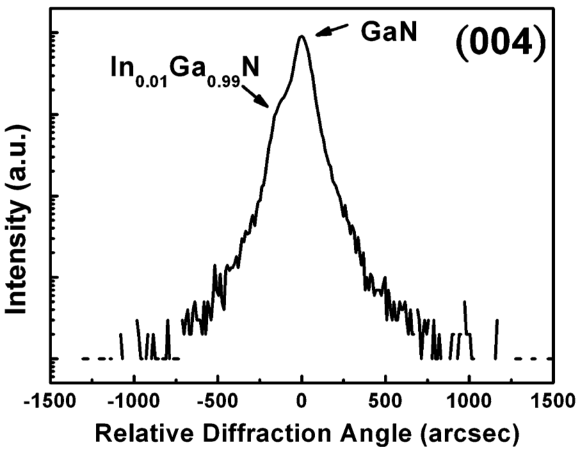

Fig. 2. DCXRD spectra of the bulk p-In$_{0.01}$Ga$_{0.99}$N layers.

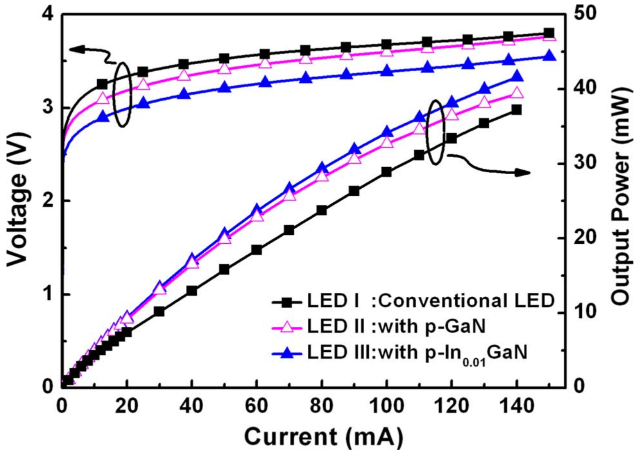

Fig. 3. L-I-V characteristics of the three fabricated LEDs.

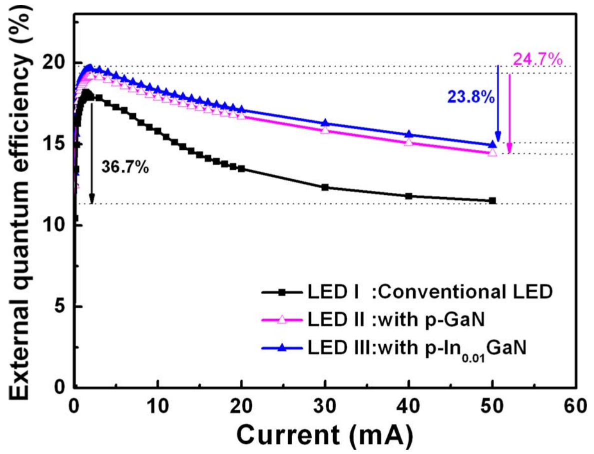

Fig. 4. EQE of the three fabricated LEDs.

For comparison, LEDs with a 50-nm-thick p-GaN layer and conventional LEDs without any insertion layer were also prepared. In the following, we call the conventional LEDs, LEDs with the p-GaN layer and LEDs with the p-In$_{0.01}$Ga$_{0.99}$N layer as LEDI, LEDII and LEDIII, respectively. For the determine the In composition of p-InGaN, we first deposited a 30-nm-thick low temperature GaN nucleation layer at 560°C and a 2-μm-thick unintentionally doped GaN buffer layer at 1050°C. Bulk p-InGaN layer was then deposited on top of the GaN buffer at 890°C with a reactor pressure of 200 Torr. In composition of p-InGaN layer was then evaluated by double crystal X-ray diffraction (DCXRD). Fig. 2 shows DCXRD spectra of the bulk p-InGaN layers. From the peak positions, it was found that In composition in the bulk p-InGaN layer was around 1%.

For the fabrication of LEDs, we used an inductively coupled plasma (ICP) etcher to partially etch the sample surface until the n-GaN layer was exposed. We then deposited a 250-nm-thick indium-tin-oxide (ITO) film onto the un-etched sample surface by e-beam evaporation to serve as the p-contacts. We subsequently deposited Cr/Au onto the exposed n-GaN layer to serve as the n-type contact. The epitaxial wafers were then lapped down to about 90 μm. We then used scribe and break to complete the fabrication of 575 μm × 250 μm blue InGaN/GaN LED chips. Current-voltage (I-V) characteristics of the fabricated devices were then measured at room temperature by an HP4156 semiconductor parameter analyzer. These chips were subsequently packaged into lamps. Intensity-current (L-I) characteristics of the packaged lamps were subsequently measured using the molded LEDs with an integrated sphere detector.

III. RESULTS AND DISCUSSION

Fig. 3 shows I-V characteristics of the three fabricated LEDs. By inserting the p-GaN layer, it was found that we could reduce the 20 mA forward voltage from 3.34 V (i.e., LEDI) to 3.18 V (i.e., LEDII). This should be attributed the fact the band bending of EBL could be pushed away by the inserted p-GaN layer [20]. It was also found that 20 mA forward voltage could be further reduced to 2.99 V (i.e., LEDIII) when p-InGaN layer was inserted. This should be attributed to the smaller bandgap energy and larger hole concentration of p-InGaN [21]–[23] which could further push away the band bending of EBL and thus enhance hole injection. Similar to the charge asymmetry resonant tunnel (CART) structure [24], the inserted p-InGaN layer should also serve as a current spreading layer for holes. As a result, we achieved the smallest forward voltage from LEDIII. A detailed APSYS simulation results of the three fabricated LEDs is underway and the results will be reported separately.

L-I characteristics of these three LEDs were also plotted in Fig. 3. Under 20 mA current injection, it was found that output powers were 7.4, 9.1 and 9.4 mW for LEDI, LEDII and LEDIII, respectively. In other words, we can enhance the output power by 23.0% and 27.0% by inserting the p-GaN and p-InGaN barrier layer, respectively. Recently, Kuo *et al.* have shown the APSYS simulation result of LED with inserting the p-GaN and p-In$_{0.01}$GaN barrier layer, respectively. It has also been shown that effective barrier height at barrier/EBL interface of LED with p-In$_{0.01}$GaN barrier layer layer is higher than the other two LEDs [25]. As mentioned above, the enhance of output power should be attributed to the increased effective barrier height at barrier/EBL interface for enhancing the electron carrier confinement in the MQW region and hole injection efficiency by the inserted p-GaN. These values also indicate that output power enhancement was more significant when p-InGaN layer was inserted, as compared to p-GaN layer.

Knowing the L-I characteristics, we could thus determine the external quantum efficiencies (EQEs) of these three LEDs, as shown in Fig. 4. With 50 mA current injection, it can be seen that the EQEs for LEDI, LEDII and LEDIII dropped by 36.7%, 24.7% and 23.8%, respectively, when compared to their respective maximum EQEs. It should be noted that growth and processing parameters of these LEDs were all identical, except the inserted p-(In)GaN layer, Thus, LEE of these LEDs should be the same. Thus, the EQE decay observed in Fig. 4 should originate from the decay in IQE. This also suggests that we could reduce the efficiency droop from 36.7% to 23.8% by inserting a 5-nm-thick p-$In_{0.01}Ga_{0.99}N$ layer in between the undoped GaN last barrier and the AlGaN EBL.

IV. CONCLUSION

In summary, GaN-based LEDs with a p-InGaN layer was proposed and fabricated. By inserting the 5-nm-thick p-$In_{0.01}Ga_{0.99}N$ layer, it was found that we could reduce the 20 mA forward voltage from 3.34 V to 2.99 V. It was found the inserted p-InGaN layer could also reduce the efficiency droop from 36.7% to 23.8%.

ACKNOWLEDGMENT

The authors would like to acknowledge the gas purification systems support from Entegris Inc.

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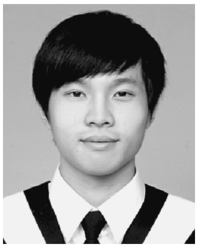
P. H. Chen was born in Taiwan in 1984. He received the B.S. degree in the Department of Electrical Engineering from the Chang-Gung University, Taiwan, in 2006, and the M.S. degrees in the Institute of Electro-Optical Science and Engineering from the National Cheng Kung University (NCKU), Tainan, Taiwan, in 2008. Currently, he is working toward the Ph.D. degree in nitride-based compound semiconductors and optoelectronic devices at the Institute of Electro-Optical Science and Engineering, NCKU.

Cheng-Huang Kuo was born in Tainan, Taiwan,in 1976. He received the M.S. degree from theDepartment of Physics, National Central University (NCU), Jhongli, Taiwan, in 2001, and the Ph.D. degree from the Institute of Microelectronics, National Cheng Kung University, Tainan, Taiwan, in 2004.

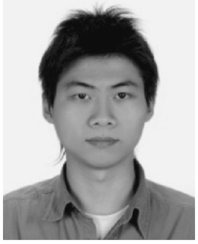
He is currently an Associate Professor with the Institute of Lighting and Energy Photonics, National Chiao Tung University (NCTU), Tainan, Taiwan. His current research interests include semiconductor physics and optoelectronic devices.

W. C. Lai was born in Taiwan, in 1970. He received the B.S. degree in electrical engineering from Feng Chia University, Taichung, Taiwan, in 1993, and the M.S. and Ph.D. degrees in electrical engineering from the National Cheng Kung University (NCKU), Tainan, Taiwan, in 1995 ns 2001, respectively.

He became a Postdoctoral Associate with the Department of Electrical Engineering, NCKU in 2001. He is currently with Department of Photonics, NCKU, as an Associate Professor. His research interests include the growth and characterization of III-V nitride semiconductors and devices.



Yu An Chen was born in Taiwan in 1989. He received the B.S. degree in Department of Electrical Engineering from the National Central University (NCU), Taoyuan, Taiwan. He is currently working toward the Ph.D. degree in nitride-based compound semiconductors and optoelectronic devices at the Institute of Lighting and Energy Photonics, National Chiao Tung University (NCTU), Tainan, Taiwan.



L. C. Chang was born in I-Lan, Taiwan, in 1985. He received the B.S. degree in department of Electrical Engineering from Yuan Ze University (YZU), Jung-Li, Taiwan, and the M.S. degree in Optical Sciences from the National Central University (NCU), Jung-Li, Taiwan, in 2007 and 2009, respectively. He is currently working toward the Ph.D. degree at the Institute of Lighting and Energy Photonics, National Chiao Tung University (NCTU), Tainan, Taiwan.

S. J. Chang (M'06–SM'10) was born in Taipei, Taiwan, on January 17, 1961. He received the B.S.E.E. degree from the National Cheng Kung University (NCKU), Tainan, Taiwan, in 1983, the M.S.E.E. degree from the State University of New York, Stony Brook, in 1985, and the Ph.D.E.E. degree from the University of California, Los Angeles, in 1989. He was a Research Scientist with NTT Basic Research Laboratories, Musashino, Japan, from 1989 to 1992. He became an Associate Professor with the Department of Electrical Engineering, NCKU, in 1992, and was promoted to Full Professor in 1998. Currently, he also serves as the Director of the Institute of Microelectronics, Deputy Director of the Center for Micro/Nano Science and Technology, and Deputy Director of the Advanced Optoelectronic Technology Center, NCKU. He was a Royal Society Visiting Scholar with the University of Wales, Swansea, U.K., from January 1999 to March 1999, a Visiting Scholar with the Research Center for Advanced Science and Technology, University of Tokyo, Japan, from July 1999 to February 2000, a Visiting Scholar with the Institute of Microstructural Science, National Research Council, Canada, from August 2001 to September 2001, a Visiting Scholar with the Institute of Physics, Stuttgart University, Germany, from August 2002 to September 2002, and a Visiting Scholar with the Faculty of Engineering, Waseda University, Japan, from July 2005 to September 2005. He is also an Honorary Professor of the Changchun University of Science and Technology, China. His current research interests include semiconductor physics, optoelectronic devices, and nanotechnology.

Prof. Chang received the Outstanding Research Award from the National Science Council, Taiwan, in 2004.