Comparison between standing transparent mirrorless packaging and planar-mounted packaging for GaN-on-GaN LEDs

E A Alias¹, M E A Samsudin¹, N Zainal¹*, M Iza², A I Alhassan², S P DenBaars²,³, J S Speck² and S Nakamura²

¹Institute of Nano Optoelectronics Research and Technology (INOR), Universiti Sains Malaysia, 11800 Malaysia
²Materials Department, University of California, Santa Barbara, CA 93106, USA
³Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106 USA

*norzaini@usm.my

Abstract. This work demonstrates that standing transparent mirrorless LED packaging as an attractive alternative configuration to increase the light extraction of LED on GaN substrate rather than standard planar-mounted packaging. From comparison study, it was found that the external quantum efficiency and the wall-plug efficiency of the standing transparent mirrorless LED is improved by 7% with respect to the planar-packed LED at a standard operating current of 20 A/cm². The extraction of light of the LED with the standing transparent mirrorless packaging is contributed from all sides of the LED. In contrast, the light extraction for the LED with the planar-mounted packaging is only coming from the top and the sidewalls of the LED as well as having a longer path length for the photon to escape from LED and might increasing the possibility of light absorption in the GaN substrate.

1. Introduction

It is well-accepted that highly efficient of white LEDs based on GaN are the most promising solid-state devices to replace conventional lighting e.g. incandescent bulb and fluorescent lamp for reducing energy consumption. GaN LEDs are typically grown heteroepitaxially on sapphire by MOCVD. However, full potential of GaN LEDs technology on sapphire is limited by a high threading dislocation density of $10^8 - 10^{10}$ cm$^{-2}$ arising from large different in lattice structure and thermal expansion coefficient [1-2]. Therefore, growing the LEDs on GaN substrate will be the answer towards the ultimate LED technology [3-4]. A reported free-standing bulk GaN has a low threading dislocation density of $10^5$ cm$^{-2}$ [5-6]. Despite of this, poor light extraction efficiency of the LEDs is the major issue that needs serious attention. This is because of large difference in the refractive index between the GaN material and air, which allows only 4% of light can be extracted [7]. At this point, various attempts have been demonstrated to enhance the light extraction e.g.; flip chip [8], chip shaping [4] and backside GaN substrate roughening [9]. Nonetheless, these methods entail a complex fabrication and processing steps. One should be concerned that, they are less effective to extract the light because the GaN substrate is bonded to the package through planar mounting configuration, causing more light loss along the optical path [10].
Alternatively, standing transparent mirrorless packaging of the LED would be a possible solution to reduce optical loss and the loss of the backside mirror [1]. Conceptually such packaging has a configuration to allow the light extraction from all sides. In this work, we will compare the light extraction of GaN-on-GaN LED with standing transparent mirrorless packaging and the one with planar-mounted packaging by focusing on optical-electrical properties of both LEDs.

2. Experimental procedures
In this work, GaN-on-GaN LED was grown using two-flow metal-organic chemical vapour deposition (MOCVD). The dislocations density of the GaN substrate was found to be $2 \times 10^6$ cm$^{-2}$. Prior to the MOCVD growth, the N-face on the backside of the GaN substrate was roughened using a mixed solution of NH$_4$OH (25%), H$_2$O$_2$ (30%) and DI water with ratio of 1: 1: 5 for 30 minutes. The purpose of the roughening is to further enhance the light extraction from the LED. Trimethylgallium (TMGa), trimethylaluminium (TMAI), trimethylindium (TMIn), and ammonia (NH$_3$) were used as the precursors for Ga, Al, In and N, respectively. For doping, bicyclopentadienyl-magnesium (Cp$_2$Mg) was used for p-type Mg doping and disilane (Si$_2$H$_6$) for n-type Si doping. The LED structure was initially grown by a 2 μm thick Si-doped GaN followed by 20 periods of InGaN/GaN superlattices, 8 periods of multi-quantum wells (MQWs) which consists of alternating layer of 3 nm thick InGaN quantum well and 11 nm thick GaN quantum barrier; 10 nm thick p-AlGaN electron blocking layer, 110 nm thick p-GaN ending with 20 nm high doped p-GaN contact layer.

After the growth, the LEDs was fabricated into functional devices with a dimension of 0.1 mm$^2$. The chips were diced, and they were packaged individually using standing transparent mirrorless and planar-mounted configurations. See figure 1 for details. For standing transparent mirrorless packaging, the LED chip was attached on a patterned sapphire substrate. Both packaged-LEDs were encapsulated using trapezium-encapsulation of YAG: Ce$^{3+}$ yellow phosphor to obtain white light. Next, integrating sphere measurement under a direct current was conducted to determine the light output power, external quantum efficiency (EQE), wall-plug efficiency (WPE) and luminous efficacy for both LEDs.

![Figure 1. Schematic illustration of GaN-on-GaN LED packaged with (left) standing transparent mirrorless, and (right) planar-mounted configurations.](image)

3. Results and discussions
The optical power of the GaN-on-GaN LEDs with the standing transparent mirrorless packaging and planar-mounted packaging is shown in figure 2. Apparently, the optical power for both LEDs is identical, and this indicates that different configuration of the packaging does not influence the optical power of the LEDs. The optical power is observed to be 13 mW with forward voltage 3.4 V at a standard operating current density of 20 A/cm$^2$. 
Figure 3 (a) shows external quantum efficiency (EQE) of LEDs as function of current density. At the current density of 20 A/cm², the EQE for the LED with standing transparent mirrorless packaging and planar-mounted packaging was observed at 23% and 22%, respectively. Accordingly, the standing transparent mirrorless packaging improves the efficiency of the LED by ~7% with respect to the planar-mounted packaging. Such improvement is due to accumulation of light extraction from all sides of the LED as offered by the standing transparent mirrorless packaging. In contrast, the light extraction that emits from the backside of LED with planar-mounted packaging has been reflected by the silver header and therefore bounced-back into the LED and thus increase the path length of photon to escape. As a result, the light extraction is only coming from the top and the sidewalls of the LED, see figure 3 (d), thereby putting the GaN substrate roughening at disadvantage. This experimental result agrees with a simulation reported by [11-12], whereby about 3% to 5% of light is loss in the backside of the GaN-on-GaN LED if the LED packaged with planar-mounted configuration. The droop efficiency of the LEDs with standing transparent mirrorless and planar-mounted configurations is almost similar, suggesting both LEDs have similar crystal-like structural properties. The droop efficiency of both LED is 26%. This implies that the standing transparent mirrorless packaging will not suffer from a serious thermal effect that could degrade the overall the LED performance at higher current.

The wall-plug efficiency (WPE) of GaN-on-GaN LED as function of current density is represented in figure 3 (b). The WPE for the LED with the standing transparent mirrorless packaging and planar-mounted packaging at 20 A/cm² is 20% and 18%, respectively. The maximum peak of WPE of the LED with standing transparent mirrorless packaging and planar-mounted packaging is 21% and 19%, respectively. The increase of the WPE for the LED with the use of standing transparent mirrorless packaging and planar-mounted packaging is 7% at 20 A/cm², and 16% at low current. The WPE is defined by the percentage of the electrical input power that is converted to optical output power. It can calculate by [13]:

\[ WPE = EQE \times \frac{V_p}{V} \]  

where \( V_p \) is the photon voltage, and \( V \) is the operating voltage. From the equation (1), the performance of WPE is directly dependence on the EQE and the operating voltage of LED. Since the voltage of both LEDs is identical, therefore the improvement of the WPE of by the standing transparent mirrorless packaging is attributed to the increase in the EQE. Despite of that, the luminous efficacy of the LED with the standing transparent mirrorless packaging is similar to the one with the planar-mounted packaging. The maximum peak of luminous efficacy of the LED with the standing transparent mirrorless packaging and the one with the planar-mounted packaging is 73 lm/W, see
This behaviour is related to the fact that is strongly depending on the distance between LED chip and the air [14]. As shown in figure 3 (d), the distance is shorter in the standing transparent mirrorless packaging than that of planar-mounted packaging, along with light loss in the reflection from the backside submount, thus reduces the efficiency of converting blue light to white spectrum. However, this issue could be improved by optimizing the position of blue LEDs and concentration of the phosphor in order to increase the luminous efficacy of white LEDs.

Figure 3. (a) EQE, (b) WPE and (c) luminous efficacy as a function of current density for GaN-on-GaN LED with standing transparent mirrorless packaging and planar-mounted packaging. (d) Schematic illustration of light path of GaN-on-GaN LED packaged with standing transparent mirrorless, and planar-mounted configurations.

4. Summary
It was found that standing transparent mirrorless packaging increased light extraction of the LED as in contrast to the standard planar-mounted LED packaging. The main reason is such packaging allowed the light emitted from the LED to extracted from all sides. In contrast, the light extraction for the LED with the planar-mounted packaging is only coming from the top and the sidewalls of the LED and has longer path length for photon to escape from the LED, along with light loss in the reflection from the backside submount. The luminous efficacy of standing transparent mirrorless packaging could be further improved by optimizing the position of the LED and phosphor concentration.

Acknowledgements
The authors would like to thank Collaborative Research in Engineering, Science & Technology Center (CREST) for their continuous support in this research. This work was supported by Research University grant (1001/CINOR/8014033), Fundamental Research Grant Scheme
(203/CINOR/6711562) and Kementerian Pendidikan Malaysia. A portion of this work was done in the UCSB nanofabrication facility.

References
[1] Fellows N, Masui H, Sato H, Asamizu H, Iza M, Zhong H, Nakamura S and DenBaars S 2008 Phys. Status Solidi (c) 5 2216
[2] Oliver R 2016 Mater. Sci. Technol. 32 737
[3] Lee M, Lee H, Song K and Kim J 2018 Nanomaterials 8 543
[4] Hurni C, David A, Cich M, Aldaz R, Ellis B, Huang K, Tyagi A, Delille R, Craven M, Steranka F and Krames M 2015 Appl. Phys. Lett. 106 031101
[5] Goubara S, Matsubara T, Yukizane K, Arita N, Fujimoto S, Ezaki T, Inomoto R, Yamane K, Okada N and Tadatomo K 2017 J. Cryst. Growth 478 123
[6] Storm D, Hardy M, Katzer D, Nepal N, Downey B, Meyer D, McConkie T, Zhou L and Smith D 2016 J. Cryst. Growth 456 121
[7] Cui H and Park S-H 2018 Opt. Quant. Electron. 50 140
[8] Yonkee B, SaifAddin B, Leonard J, DenBaars S and Nakamura S 2016 Appl. Phys. Express 9 056502
[9] Hwang D, Yonkee B, Addin B, Farrell R, Nakamura S, Speck J and DenBaars S 2016 Opt. Express 24 22875
[10] Kim J Y, Jeong T, Lee S H, Oh H S, Park H J, Kim S M and Baek J H 2017 Light extraction of high-efficient light-emitting diodes III-Nitride Based Light Emitting Diodes and Applications ed Seong T-Y et al (Singapore: Springer) vol 133 pp 341-361
[11] An P, Wang L, Lu H, Yu Zqiuo, Liu L, Xi X, Zhao L, Wand J and Li J 2016 J. Semicond. 37 064015
[12] Keraly C L, Kuritzky L, Cochet M and Weisbuch C 2017 Ray tracing for light extraction efficiency (LEE) modeling Nitride LEDs III-Nitride Based Light Emitting Diodes and Applications ed Seong T-Y et al (Singapore: Springer) vol 126 pp 301-340
[13] Kuritzky L, Weisbuch C and Speck J 2018 Opt. Express 26 16600
[14] Luo X and Hu R 2018 Chip packaging: encapsulation of nitride LEDs Nitride Semiconductor Light-Emitting Diodes (LEDs) ed Huang J et al (United Kingdom: Woodhead Publishing) pp 491-528