Influence of patterned sapphire substrates with different symmetry on the light output power of InGaN-based LEDs

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Background

• In order to compete with conventional lighting sources and realize the ultimate lamp, the external quantum efficiency (EQE) of InGaN-based LEDs must be enhanced.

• The EQE of InGaN-based LEDs is determined by internal quantum efficiency (IQE) and light extraction efficiency (LEE).

• Many significant methods have been proposed in the literatures for improving the EQE of InGaN-based LEDs, such as patterned sapphire substrates (PSSs) [2-6], surface structure [9-11], semi/non-polar quantum wells (QWs) [12-15], and so on.
• However, among these technologies, the **PSS method** has attracted considerable attention because of its ability to improve both IQE and LEE.

• The previous published articles have shown that the light output power (LOP) of InGaN-based LEDs is dependent on the configuration of these parameters including spacing [16], slanted angle [17], shape [18], height [19], and density [20].
• Nevertheless, studies concerning the effect of PSSs with different symmetry on the LOP of InGaN-based LEDs were still limited.

• In this paper, the effect between the LOP and the InGaN-based LEDs grown on PSSs with different symmetry is investigated in detail through simulation and measurements. The different symmetry of PSS used for experimentation include square lattice arrangement (SLA) and hexagonal lattice arrangement (HLA).
Methods

• The SLAPSS and HLAPSS were fabricated with photolithography and dry etching technology. The photoresist pattern was transferred to the substrate directly by inductively coupled plasma reactive ion etching (ICP-RIE).

• The post patterns with the diameter of 2.65 μm, height of 1.6 μm, and periodicity of 3 μm were fabricated on a 2-in. c-plane sapphire substrate.
Figure 1 The SEM images of PSSs with different symmetry. (a, b) Top surface views of SLAPSS and HLAPSS. (c, d) Fifty-two-degree tilted views of SLAPSS and HLAPSS.
After the cleaning process, the InGaN-based LED samples were grown on the PSSs with Taiyo Nippon Sanso SR2000 (Taiyo Nippon Sanso, Dalian, China) atmospheric pressure metal organic chemical vapor deposition (AP-MOCVD) under a three-flow gas injection. Prior to the growth, substrates were thermally baked at 1,180°C in hydrogen gas to remove surface contamination.

The InGaN-based LED structures were initially grown on the PSSs, and their structure consists of a 25-nm-thick low-temperature GaN nucleation layer, a 2.5-μm-thick unintentionally doped GaN buffer layer, and a 3-μm-thick n-GaN layer, using SiH4 as the n-type dopant.
• Then, five pairs of InGaN/GaN multiple-quantum wells (MQWs) having a 2.9-nm-thick InGaN well and an 11-nm-thick GaN barrier (grown at 800°C and 850°C, respectively) were deposited, followed by a 20-nm-thick p-AlGaN electron-blocking layer and a 120-nm-thick p-GaN layer, using Cp2Mg as a p-type dopant.

• To gain insight into the correlation between the PSSs with different symmetry and the strain variation in the GaN epitaxial layers, the micro-Raman measurement is required.
The Raman shifts of the E$_2$(high) mode of InGaN-based LEDs grown on the CSS, SLAPSS, and HLAPSS are 569.11, 569.08, and 568.82 cm$^{-1}$, respectively.
• The residual compressive strain can be calculated through the measured E2(high) mode Raman shift [22], the associated residual compressive strain is calculated to be $-1.22 \times 10^{-3}$ for the InGaN-based LEDs grown on the CSS.

• The other calculated values of the residual compressive strain are $-1.21 \times 10^{-3}$ and $-1.07 \times 10^{-3}$ for the InGaN-based LEDs having the SLAPSS and HLAPSS, respectively. This reveals that the InGaN-based LED grown on the HLAPSS has the lowest residual compressive strain.
• Based on the previous study published by our group [23], the smaller residual compressive strain can result in a weaker quantum-confined Stark effect (QCSE) in MQWs, which enhanced the LOP of InGaN-based LEDs.

• Therefore, the effect of InGaN-based LEDs having the PSSs with different symmetry on the QCSE was further elucidated by utilizing the excitation current dependent electro-luminescence (EL) measurement.
Result and discussion

• Based on the experimental results of Raman and excitation current-dependent EL measurement, it can be determined that the growths of the InGaN-based LED on the higher symmetry of HLAPSS can acquire a better crystalline quality.

• To obtain the LEE contribution of PSSs with different symmetry, a TracePro (Lambda Research Corporation, Littleton, MA, USA) ray tracing simulation was used to calculate the LEE of InGaN-based LEDs.
Figure 4 TracePro ray tracing results for the InGaN-based LEDs having the CSS, HLAPSS, and SLAPSS. The associated LEE with different samples is evaluated from the bare LED simulation results, and the insets show the cross-sectional ray tracing image.
Figure 6 The LOP as a function of the forward current. The LOP of InGaN-based LEDs grown on CSS, SLAPSS, and HLAPSS is plotted as a function of the forward current.
Conclusions

• Furthermore, the LEE of InGaN-based LEDs on SLAPSS and HLAPSS appeared similar from the ray tracing simulation.

• In comparison to the InGaN-based LED grown on the CSS at an injection current of 20 mA, the increased LOP value of the samples grown on the SLAPSS and HLAPSS is reported to be 60% and 82%, respectively.
References


• 9. Lee ML YHY, Lin RM, Hsieh CJ, Su VC, Chen PH, Kuan CH: Utilizing two-dimensional photonic crystals in different arrangement to investigate the correlation between the air duty cycle and the light extraction enhancement of InGaN-based light-emitting diodes. IEEE Photonics J 2014, 6:8200408.


Thank you for your attention