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# Enhanced light extraction from lateral side of InGaN-based LEDs grown on Nano-sized patterned sapphire substrates

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**Abstract**

**The light output power (LOP) of InGaN-based light emitting-diodes (LEDs) grown on the nano-sized patterned sapphire substrates (NPSS) and micro-sized patterned sapphire substrates (MPSS) are investigated in this paper. The InGaN-based LEDs grown on the NPSS has lower quantum-confined Stark effect (QCSE) and better crystal quality. Based on experimentally measured data and the ray-tracing simulation results, the emitted photons can be deflected to the lateral of the chip by NPSS, contrary to the MPSS wherein photons are deflected to the top of the chip.**

## 1. Introduction

In recent years, InGaN-based LEDs are useful for wide applications in backlight of flat-panel displays, and solid state lighting. In order to compete with conventional lighting sources and realize the ultimate lamp, the external quantum efficiency (EQE) of InGaN-based LEDs has to be further increased. The EQE of InGaN-based LEDs is determined by internal quantum efficiency (IQE) and light-extraction efficiency (LEE). Many significant methods have been utilized in the literatures to improve the EQE of InGaN-based LEDs, such as PSSs [1], epitaxial lateral overgrowth (ELOG) [2], and so on. Among these technologies, the PSSs method is currently being used in manufacturing industries because of its high production yield. The PSSs technique can improve both IQE and LEE by decreasing threading dislocations and enhancing light scattering. The pursuit of NPSS has been widely reported for achieving low TDs in GaN thin film [3]. Nevertheless, all prior PSSs-related studies have been pursued for enabling improved LEE (micron-sized) and reduced TDs (nano-sized). Nevertheless, until now, the enhanced light extraction from lateral side of InGaN-based LEDs grown on nano-sized PSSs has been rarely reported.

## 2. Experiments and results

The NPSS and MPSS were fabricated with photolithography and dry-etching technology. The NPSS/MPSS patterns having the diameter of 750nm/2.6μm, height of 450nm/1.6μm and periodicity of 1μm /3μm, were fabricated on the 2 inch c-plane sapphire substrate. The surface morphology, periodicity, height and diameter of the accomplished PSSs were examined by FEI Dual-Beam NOVA 600i Focused Ion Beam as shown in Figure 1.

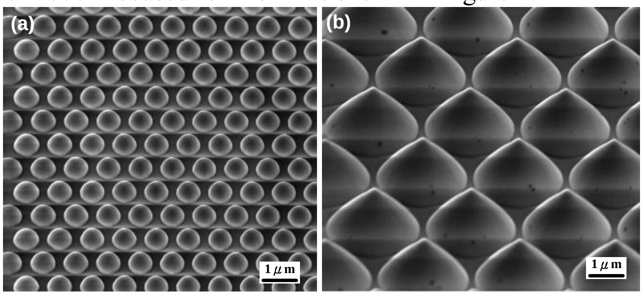


Fig. 1 The 52 degree tilted SEM images of (a) NPSS and (b) MPSS.

After the cleaning process, the InGaN-based LED samples were grown on the PSSs with Taiyo Nippon Sanso SR2000 atmospheric-pressure metal organic chemical vapor deposition (AP-MOCVD) under three-flow gas injection. The InGaN-based LED structures, which consist of a 25 nm-thick low-temperature GaN nucleation layer, a 2.5-μm-thick unintentionally doped GaN buffer layer (grown at 1180°C), and a 3-μm-thick n-GaN layer, using SiH4 as the n-type dopant, were firstly grown on the PSSs. Then, five pairs of InGaN/GaN MQWs having a 2.9-nm-thick InGaN well and a 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 p-type dopant. The InGaN-based LEDs with a conventional sapphire substrate (CSS), NPSS and MPSS were grown under the same growth conditions.

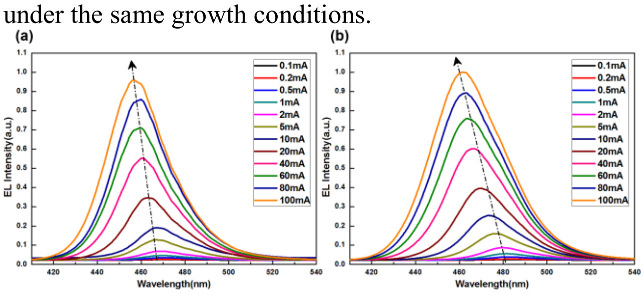


Fig. 2 Blue shifts phenomenon of the InGaN-based LEDs having the (a) NPSS and (b) MPSS.

Utilizing the excitation current dependent electroluminescence (EL) measurement was used to examine the QCSE.

Figure 2 shows the peak wavelength shifts of EL spectrum under different injection current for the InGaN-based LEDs having the NPSS, and MPSS. As show in the figure, the EL spectra of InGaN-based LEDs having the NPSS, and MPSS at the injected currents from 10mA to 100mA. The shifts in EL peak wavelength between 10-mA and 100-mA forward current for the InGaN-based LEDs with NPSS and MPSS are 14 nm and 20 nm, respectively. Therefore, the InGaN-based LED grown on the NPSS has the weaker QCSE than that grown on the MPSS.

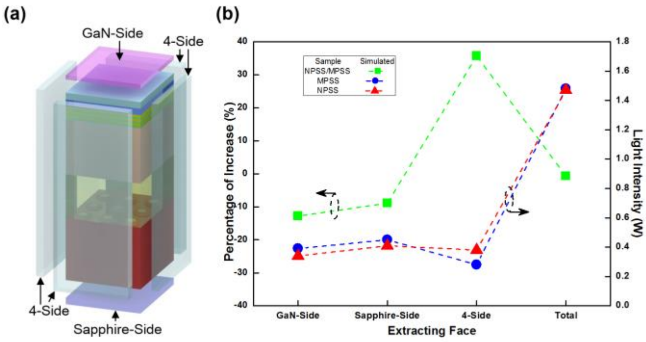


Fig. 3 (a) Schematic diagram of different receiver positions considered in the simulation. (b) Light Intensity and percentage of increase of InGaN-based LEDs grown on the NPSS and MPSS detected at different detector.

To gain greater insight into the influence of NPSS and MPSS on the LEEs of our InGaN-based LEDs, we performed Trace-Pro ray-tracing simulations to calculate the light extraction from each face of the InGaN-based LEDs. As depicted in Figure 3(a), we placed four different receivers as close as possible to the GaN side face (GaN-Side), the sapphire side face (Sapphire-Side), and the four side face (4-Side) of the LED structures. To clearly identify the principle behind the improvement in light extraction between NPSS and MPSS, the percentage increase in light intensity was defined as that from the InGaN-based LED grown on the NPSS divided by that from the InGaN-based LED grown on the MPSS. Figure 3(b) displays the light intensities and percentage increases for InGaN-based LEDs constructed on the NPSS and MPSS, detected using the various detectors. The simulations revealed a significant percentage increase on the 4-Side.

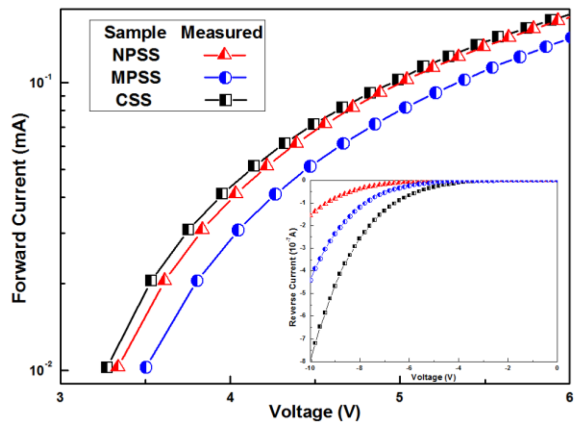


Fig. 4 Forward I-V characteristics and reversed I-V characteristics of InGaN-based LEDs having the CSS, NPSS and MPSS.

Figure 4 shows the current-voltage (I-V) characteristics of the InGaN-based LEDs, fabricated with the standard 250×575 $\mu m^2$ LED die processed in the industry. The forward voltages of the InGaN-based LEDs grown on the CSS, NPSS, and MPSS at an injection current of 20mA were 3.53, 3.61, and 3.8V, respectively. The reverse leakage current of InGaN-based LEDs is shown in the inset of figure 3. The reverse currents at a voltage of -10V for the InGaN-based LEDs grown on the CSS, NPSS, and MPSS are $-8.1\times10^{-7}$, $-1.55\times10^{-7}$, and $-1.64\times10^{-7}$ A, respectively. As compared with the InGaN-based LED grown on the MSS, the samples grown on the NPSS have lower leakage current due to the better crystalline quality of GaN epitaxial layers. Figure 5 (a) shows light intensity (light emitted toward the upward direction measured by placing the detector on the top of unpackaged LEDs) of the devices as the function of injection current. It observed that the InGaN-based LEDs with the MPSS have higher intensity than that with the NPSS. According to the above simulation results, this result is due to light extracted from lateral side of LEDs. Therefore, individual LED chip were packaged and measured by using integral sphere. Figure 5(b) shows the LOP versus forward current. Compared with the InGaN-based LED grown on the CSS at an injection current of 20mA, the enhanced LOP values of the samples grown on the NPSS and MPSS are by up to 38% and 34%, respectively. At high current injection, the stronger LOP of the sample with NPSS can also be contributed from the lower QCSE in the GaN epitaxial layers [4].

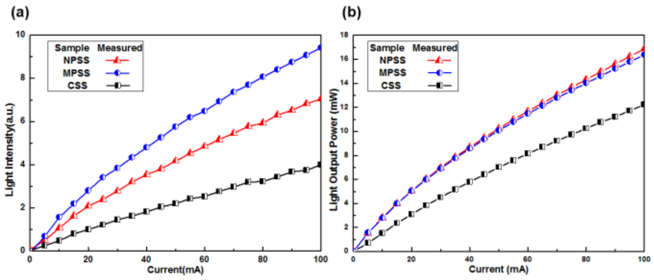


Fig. 5 (a)L-I characteristics of unpackaged and (b) packaged InGaN-based LEDs having the CSS, NPSS and MPSS.

## 3. Conclusions

This paper reports that the growth of InGaN-based LEDs on the NPSS can extract more light from lateral side than on the MPSS. Furthermore, reduction of QCSE in the InGaN/GaN MQWs is observed. As a result, the mitigation of the efficiency droop for the InGaN-based LED on the NPSS occurs.

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## References

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