Enhanced Performance of LEDs Using Periodic Tent-Like Post Patterns on A-plane Sapphire Substrates

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***Abstract*—Periodic tent-like post patterns on a-plane sapphire substrates were fabricated using a two-step etching process. They were denoted as a-plane dot pattern sapphire substrate (ADPSS). Compared with the GaN-based light-emitting diode (LED) grown on a-plane sapphire without any pattern (AFlat), the ADPSS-LED has higher output power, light extraction efficiency (LEE), and external quantum efficiency (EQE), and better crystal quality. The output power of ADPSS-LED was 9.6 mW, which was 68.4% larger than the AFlat-LED. In addition, the blue shift of ADPSS-LED was found to be less than that of AFlat-LED.**

***Index Terms*—A-plane, light-emitting diode (LED), sapphire.**

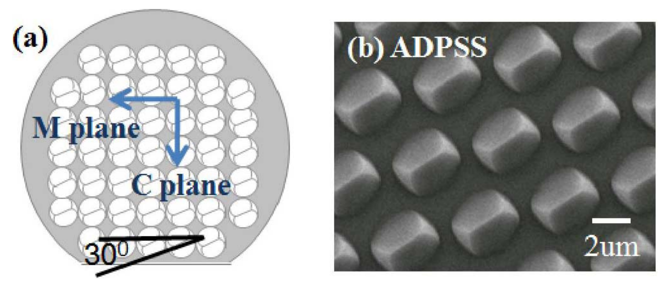

Fig. 1. Schematic illustrations and SEM image of ADPSS.

I. Introduction

LIGHT-EMITTING diodes (LEDs) are expected to play an important role in next-generation light source due to their advantages of high efficiency, long life, small size, environmental protection, various colors and wide applications. In particular, high-brightness GaN-based LEDs have attracted considerable attention for white light solid-state lighting. GaN-based LEDs are usually grown on c-plane sapphire substrate. The performance of these LEDs can be improved by using patterned c-plane sapphire substrate [1]–[3]. However, using c-plane substrate is waste of sapphire material. Since the growth direction of sapphire boule was usually along a-axis, c-axis sapphire ingot has to be drilled from the side wall of sapphire boule. As a result, only about 20% of a-axis sapphire boule was used to fabricate c-plane substrates.

The economical way to grow GaN-based LEDs on sapphire substrate is using a-plane sapphire. The lattice mismatch between a-axis sapphire and GaN lattice is only 2% [4]. Unfortunately, they have different arrangement of the lattices. To grow GaN-based LEDs on a-axis sapphire substrate is not easy. Most of previous studies were about the improvement of crystal quality, not the performance of LED.

In this study, the periodic tent-like array patterned was introduced to the a-plane sapphire substrate to grow GaN-based LEDs. The morphology, the crystallinity and the performance of LEDs were investigated.

II. Experiments

The periodic dot array patterned a-plane sapphire substrate was employed to grow GaN-based LEDs. It was designated as "ADPSS" (A-plane Dot Pattern Sapphire Substrate), which was prepared by standard photolithography (3-μm circle diameter and 1.5-μm spacing). The photoresist pattern was used as the dry-etching mask. The dot patterns were first defined by inductively coupled plasma (ICP) [5]–[12], and then etched in hot H_3PO_4—based solutions [13], [14]. Fig. 1 shows the surface morphology of the tent-like post array patterns on a-plane sapphire substrate. The height of patterns was 1.0 μm. The bottom width and length of the tent was 2.8 μm and 3.3 μm, respectively. The ridgeline direction of the tent-like patterns was about $[10\bar{1}0] + 30^\circ$ toward $[0001]$ as shown in Fig. 1.

After the clean process, the LED structures were grown by metal–organic chemical vapor deposition (MOCVD). The structures comprised a buffer layer on the ADPSS, a undoped-GaN layer film, a n-GaN layer, a Si-doped AlGaN cladding layer, an InGaN–GaN multiple quantum well (MQW) with emission wavelength in the blue region, a Mg-doped AlGaN cladding layer and a p-GaN layer.

The device mesa with a chip size of 300×300 μm 2 was then defined by ICP to remove Mg-doped GaN layer and MQW until the Si-doped GaN layer was exposed. The indium tin oxide (ITO) layer was then deposited to form a p-side contact layer and a current spreading layer. The Cr/Au layer was deposited

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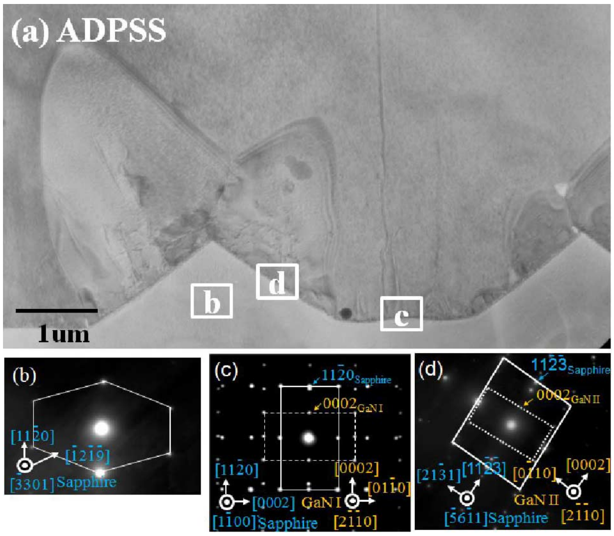

Fig. 2. Bright-field TEM images of (a) ADPSS-LED. (b), (c), and (d) are SAD patterns taken from (a) ADPSS-LED. These patterns are from (b) sapphire pattern, (c) interface region between GaN I and sapphire substrate, and (d) interface region between GaN II and sapphire.

onto the ITO layer to form the p-side and n-side electrodes. For the purpose of comparison, a-plane sapphire without any pattern was also used to grow LED structures. It was denoted as AFlat-LED (A-plane Flat LED).

III. Results and Discussion

Transmission electron-microscopy (TEM) was used to verify the natures of sapphire dot patterns and GaN crystals. Cross-sectional TEM image of GaN grown on ADPSS is shown in Fig. 2. To realize the orientation relationships among dot patterns and a-plane sapphire substrate, selected area diffraction (SAD) patterns were taken from dot patterns. As shown in Fig. 2(b), the ridgeline direction of the tent-like pattern was $[\bar{3}301]$, which was at an angle of 27.7 degrees from the $[10\bar{1}0]$ direction. This angle was close to that observed in Fig. 1.

Two kinds of GaNs were found on ADPSS-LED. One (GaN I) was initiated from a-plane of ADPSS. The other (GaN II) was from sidewalls of ADPSS. To realize the crystallographic relationships among GaN and sapphire substrate, SAD patterns were taken from GaN I, GaN II and ADPSS (Fig. 2(c) and (d)). GaN I film was polar GaN layer (0001) [15], [16]. The crystallographic relationship between GaN I and sapphire is established as $(0001)_{\mathrm{GaN\ I}}//(11\bar{2}0)_{\mathrm{sapphire}}$, $(01\bar{1}0)_{\mathrm{GaN\ I}}//(0001)_{\mathrm{sapphire}}$ and $[2\bar{1}\bar{1}0]_{\mathrm{GaN\ I}}//[1\bar{1}00]_{\mathrm{sapphire}}$. This orientation relationship is usually seen in the case of a GaN epitaxially grown on an a-plane sapphire [16]–[18]. On the other hand, the relationship between GaN II and sapphire is established as $(0001)_{\mathrm{GaN\ II}}//(11\bar{2}3)_{\mathrm{sapphire}}$ and $[2\bar{1}\bar{1}0]_{\mathrm{GaN\ II}}//[\bar{5}6\bar{1}1]_{\mathrm{sapphire}}$.

As for AFlat-LED, only GaN I was observed. The crystallographic relationship between GaN grown film and sapphire is the same as that of GaN I epitaxially grown on an a-plane of ADPSS.

The light–current–voltage (L–I–V) characteristics of the LEDs are shown in Fig. 3. The performance of ADPSS-LEDs was better than that of AFlat-LED. The light output power and

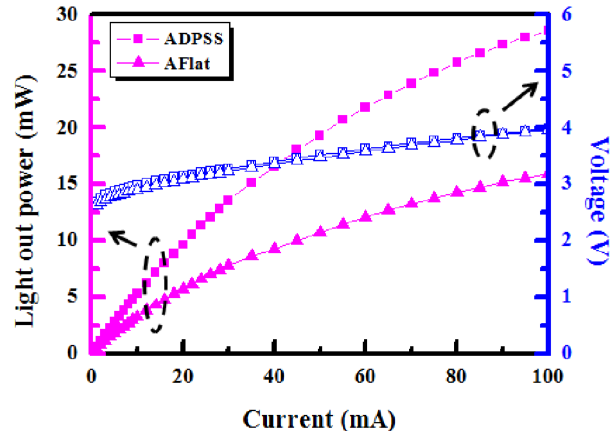

Fig. 3. L–I–V curves of LEDs.

TABLE I
Parameters and Performances of LEDs

	XRD FWHM		EPD	EL		LED		
	(002) GaN	(102) GaN		FWHM	Blueshift	Voltage	Power	EQE
	arsec	arsec	$cm^{-2}(\times 10^9)$	nm	nm	V	mW	%
ADPSS	298.9	305.8	0.52	16	0.36	3.1	9.6	15.5
AFlat	438.5	819.4	1.26	17.9	7.3	3.1	5.7	9.2

the external quantum efficiency (EQE) of LEDs were listed in Table I. The output power of ADPSS-LED was 9.6 mW, which was 68.4% larger than the AFlat-LED at an injection current of 20 mA. The EQE of ADPSS-LED was 15.5%, which was 9.2% larger than the AFlat-LED. This indicates that light extraction efficiency (LEE) of ADPSS-LED and/or GaN crystal quality are better than those of AFlat-LED. Since the surface of ADPSS substrate was "rougher" than that of AFlat substrate, obviously the LEE of ADPSS-LED was better than that of AFlat-LED [19], [20].

The nature of GaN crystal quality was analyzed by (1) X-ray diffraction (XRD), (2) electrical luminescence (EL) and (3) screw dislocation density, which can be characterized by etching pit density (EPD). As listed in Table I, compared with AFlat-LED, the full width at half maximum (FWHM) of (002) GaN was decreased from 438.5 to 298.9 arcsec, and the FWHM of (102) GaN was decreased from 819.4 to 305.8 arcsec. EL analysis also revealed that the ADPSS-LED has a smaller FWHM value (16 nm) than that of AFlat-LED (17.9 nm). Besides, the EPD of ADPSS-LED was 0.52×10^9 cm^{-2}, which was less than that of the AFlat-LED, 1.26×10^9 cm^{-2}. These results all indicate the GaN structural quality of ADPSS-LED are better than that of AFlat-LED as listed in Table I.

The observed differences in crystal qualities might be due to the lateral growth of GaN. In this case, most of the growth of GaN was initiated not from sidewall surfaces but a-planes. As the growth time increased, GaN epilayers on the bottom a-plane covered these sidewall surfaces by lateral growth, which is similar to the epitaxial lateral overgrowth (ELOG) mode [16], [17].

Beside the improvement of GaN structural quality, the blue shift of ADPSS-LED was found to be less than that of AFlat-LED, as shown in Fig. 4. When the injection current of LEDs increased from 20 to 80 mA, the blue shift of the wavelength of ADPSS-LED was 0.36 nm, which was only

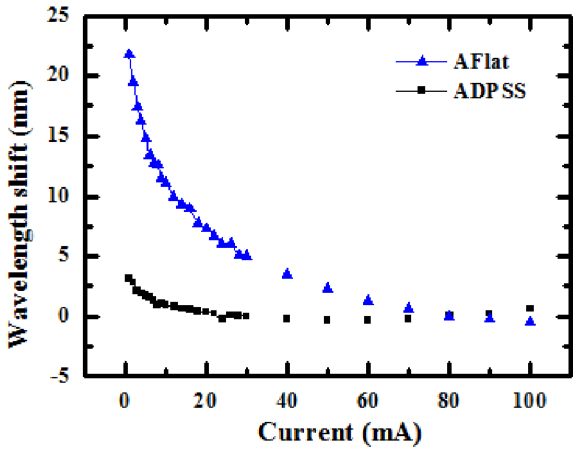

Fig. 4. Blue shifts phenomenon of AFlat-LED and ADPSS-LED by various injections current.

4.9% of AFlat-LED (7.3 nm). In other words, compared with AFlat-LED, ADPSS-LED not only has higher brightness, but also has smaller blue shift [21], [22].

IV. Conclusion

Periodic dot array a-plane sapphire substrate (ADPSS) was employed to grow GaN-based LEDs. ADPSS was fabricated using two steps etching process. The shape of dot patterns was tent-like. The ridgeline direction of the tents was [$\bar{3}$301], which was at an angle of 27.7 degrees from the [10$\bar{1}$0]. The output power of ADPSS-LED was 9.6 mW, which was 68.4% larger than the AFlat-LED at an injection current of 20 mA. The crystallinity of ADPSS-LEDs was better than that of AFlat-LED. Compared with AFlat-LED, the FWHM of (002) GaN was decreased from 438.5 to 298.9 arcsec, and the FWHM of (102) GaN was decreased from 819.4 to 305.8 arcsec. Besides, the ADPSS-LED has a smaller blue shift value than AFlat-LED. In other words, compared with AFlat-LED, ADPSS-LED not only has higher brightness, but also has smaller blue shift.

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