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GaN-based LED with embedded air voids array structure

[1]D.S. Kuo, [1]S. J. Chang, [2]T. K. Ko, [2]W. Y. Yen and [2]S. J. Hon

[1] Institute of Microelectronics & Department of Electrical Engineering Advanced Optoelectronic Technology Center , Center for Micro/Nano Science and Technology, National Cheng Kung university , Tainan 70101 , Taiwan , Republic of China
[2] Epistar Corporation, Nitride device research and development center
Hsin-Shi, Tainan 744, Taiwan , Republic of China
E-mail: kendex_kuo@epistar.com.tw

1. Introduction

GaN-based light-emitting diodes (LEDs) are important devices that has been used extensively in our daily life [1-2]. As the brightness of GaN-based LEDs has increased, it is now possible to apply these devices in backlight of liquid display panels and in solid-state lighting. Nowadays, most GaN-based LEDs are prepared on sapphire substrate by metalorganic chemical vapor deposition (MOCVD). It is known that output power of these LEDs is mainly limited by the total internal reflection occurred at the top GaN/air interface and one can enhance light extraction by roughening the LED surface [3]. Similar total internal reflection also occurs at the bottom GaN/sapphire interface. In this study, we report the formation of air void arrays with controlled size and density embedded in the GaN epitaxial layer. GaN-based LEDs with such embedded arrays were also prepared.

2. Experiments

Samples used in this study were grown on c-face sapphire substrate by MOCVD [12]. We first deposited a 30-nm-thick low-temperature GaN nucleation layer and a 2-µm-thick undoped GaN layer on sapphire substrate. A 400-nm-thick SiO2 layer was subsequently deposited by plasma enhanced chemical vapor deposited (PECVD). Photolithography and inductively coupled plasma (ICP) etching were then used to form 3µm x 3µm (i.e., LED III) and 5µm x 5µm (i.e., LED II) GaN hole arrays. The samples were then immersed in phosphoric acid at 180oC for 5 min to remove dry-etching induced damages. After the removal of SiO2 mask, the samples were loaded onto the MOCVD system again to grow a 1.5-µm-thick undoped GaN layer so as to achieve a smooth GaN surface. A standard LED structure, similar to those reported in references [13] and [14], was subsequently deposited. The as-grown samples were then furnace annealed at 750oC in N2 ambient to activate Mg in the p-layers. Standard procedures were then applied to fabricate the 250 µm x 580 µm LED chips with .indium-tin-oxide (ITO) p-contact and Ti-Al-Ti-Au n-contact. Figure 1 shows schematic diagram of the LEDs with embedded air void arrays. For comparison, standard LEDs without the embedded air void array were also prepared (i.e. LED I).

3. Results and discussions

Figure 2 shows cross-sectional scanning electron microscope (SEM) image of LED III. It was found that an air void array with the designated size and density was indeed formed at the GaN/sapphire interface. It was also found these voids were wizard's-hat-shaped. Similar voids have also been observed by Zheleva et al. using pendeo-epitaxy [15]. Figure 3 shows electroluminescence (EL) spectra measured from the three LEDs fabricated in this study. With the same 20 mA injection current, it was found that EL peaks of these three LEDs all occurred at 433 nm with the same full-width-half-maximum (FWHM) of 20 nm. The same peak wavelength and FHWM should be attributed to the same epitaxial structure used in these three devices. Figure 4 shows measured L-I-V characteristics of the three devices. Under 20 mA current injection, it was found that forward voltages were 3.17, 3.15 and 3.18 V for LED I, LED II and LED III, respectively. The almost identical forward voltages should also be attributed to the same epitaxial structure used in these three LEDs. It also indicates that the formation of the embedded air void arrays will not degrade electrical properties of the devices. It was also found that output powers measured from the LEDs with embedded air void arrays were always larger than that measured from the conventional LED. With 20 mA injection current, it was found that the LED output powers were 9.73, 13.76 and 15.23 mW for the LED I, LED II and LED III, respectively. In other words, we can achieve 56% and 41% enhancement in LED output power by embedding the 3µm x 3µm and 5µm x 5µm air void arrays. It should be noted that the refractive index of GaN (i.e., 2.4) is much larger than that of air (i.e., 1). Thus, light scattering should occur at the GaN/air void interfaces. As a result, we could achieve larger light extraction efficiency similar to the LEDs prepared on PSS [3]. Compared with LED II with 5µm x 5µm air void arrays, it was also found that output power of LED III with 3µm x 3µm air void arrays was larger. This is probably related to the larger number of GaN/air void interfaces available for LED II. To maximize the LED output power, we should optimize the size and density of the air voids. Such experiments are underway and the results will be reported latter. Figure 5 shows light output pattern of the LEDs fabricated in this study. During these measurements, we injected a 20 mA DC current into these three different kinds of LEDs. It can be seen again that we achieved the larger output intensity from LED III with 3µm x 3µm air void arrays, followed by LED II with 5µm x 5µm air void arrays. On the other hand, output intensity measured from the conventional LED I was the smallest. It should be noted that the 161o divergence angle observed from the two LEDs with embedded air void arrays (i.e., LED II and LED III) was smaller than the 172o divergence angle observed from the conventional LED (i.e., LED I). This should again be attributed to the fact that the air void arrays can effectively scatter and re-direct photons emitted from the active region of the LEDs. As a result, we could enhance light emission in the near vertical direction and thus achieve a narrower beam profile.

4. Conclusions

In summary, we report the formation of formation of air void arrays with controlled size and density embedded in the GaN epitaxial layer by patterning and re-growth. It was found that wizard's-hat-shaped voids were formed after coalescence. GaN-based LEDs with such air void arrays were also fabricated. It was found that we can achieve 56% enhancement in LED output power by embedding 3μm x 3μm air void arrays due to the effective scattering and re-direction of photons emitted from the active region of the LEDs.

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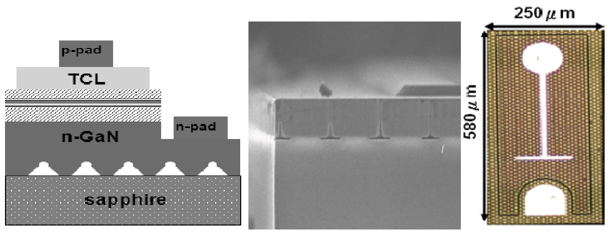


(a) (b) (c)

Fig. 1 (a)Schematic diagram ;(b) Cross section view of scanning electron microscopy image and (c) top view of GaN-based LED with embedded air voids array structure.

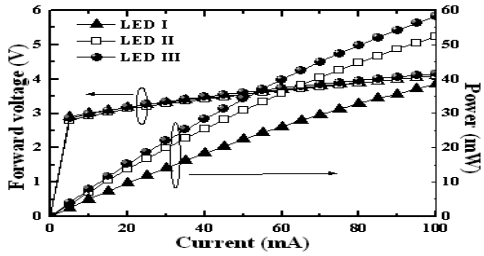


Fig. 2 L-I-V characteristics of the three devices

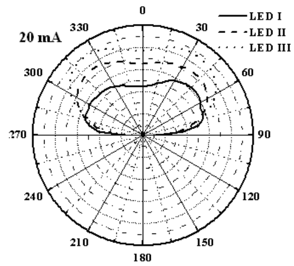
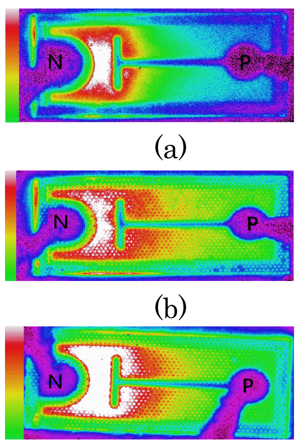


Fig 3. Light output pattern of the LEDs fabricated in this study.



(a)

(b)

(c)

Fig 4. The near field image of the GaN-based LED with (a) conventional LED I, (b) 5μm x 5μm (LED II) and (c) 3μm x 3μm (LED III) embedded air voids array structure.