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GaN-based LEDs grown on cone-shaped patterned sapphire substrates with peripheral air voids by lateral etching

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Abstract: In this study, the authors report that GaN-based LEDs prepared on 1.2μm, 1.4μm, and 1.7μm height of cone-shaped patterned sapphire substrates (CSPSS) with the formation of air voids at GaN/cone-shaped-patterned-sapphire-substrate interface by laser scribing and lateral etching with one-step MOCVD growth. With CSPSS, it can be seen that output powers were all significantly larger than that of LED with flat substrate (FS). Assisted by 20 min lateral etching, it was found that peripheral pyramid-like air-voids were formed on top of each cone of the CSPSS with 1.7μm height and the light output power increased by 13.8%, compared with the result of the CSPSS with 1.2μm height. Furthermore, it was also found that output power of LED prepared on 1.7μm height of CSPSS with 20 min lateral etching was 6.2 and 3.1% larger than those of LEDs prepared on 1.2μm and 1.4μm height of CSPSS with 20 min lateral etching, respectively.

Introduction

In recent years, GaN-based blue/green light-emitting diodes (LEDs) prepared on sapphire substrates by metalorganic chemical vapor deposition (MOCVD), have been extensively used in full-color displays and traffic light lamps. In spite of their success, however, output power of these LEDs needs to be further improved for applications such as solid-state lighting [1, 2]. The low output power of these LEDs could be attributed to (1) low internal quantum efficiency (IQE) and (2) low light extraction efficiency (LEE). The low IQE is mainly due to the high threading dislocation (TD) density of GaN films with a typical value in the order of 10^9-10^{12} cm^{-2} [3]. Such a high TD density is induced by the large mismatches in lattice constant and thermal expansion coefficient between GaN and sapphire. Thus, it is extremely important to lower the TD density so as to enhance IQE of GaN-based LEDs. On the other hand, LEE is limited mainly by the high refractive index of GaN (n=2.45). This will result in a small critical angle [$\theta_c=\sin^{-1}(n_{air}/n_{GaN})$] of only about 23°. In other words, most of the light will be reflected at the semiconductor/air interface. Thus, a significant amount of photons will be re-absorbed inside the LEDs. For the reduction of TD density, indeed, it has been shown that an epitaxial method can effectively reduce the threading dislocation density down to 10^7 cm^{-2} or less by using the epitaxial lateral overgrowth (ELOG) [4], [5]. In order to achieve such an ELOG, which first needs to grow a 2-3 μm-thick GaN epitaxial layer on the sapphire substrate, patterns the sample, and then performs second metalorganic chemical vapor deposition (MOCVD) growth. In other words, the MOCVD growth needs to perform twice. Although the ELOG process can reduce the threading dislocation density, the related growth process is complex and time consuming, and often results in a much lower production yield. For the enhancement of LEE, it is possible to use methods such as patterned sapphire substrate (PSS) [6] and roughened surface layer [7, 8]. It has been shown that PSS can not only enhance LEE by redirecting the light through slanted facets but can also enhance IQE by reducing TD density. To achieve a good coalescence with smooth surface, however, it is often necessary to grow a thick GaN layer for a long time. To overcome this problem, Lee et al. reported the growth of GaN on cone-shaped patterned sapphire substrate (CSPSS) with a much faster lateral growth rate [9]. Recently, Park et al. reported the use of air-voids to enhance LEE of GaN-based LEDs on CSPSS by chemical wet etching [10]. It should be noted that the refractive index difference between GaN and air is larger than that between GaN and sapphire. With a larger difference in refractive index, these air voids could thus enhance light scattering. Similar air-voids were also formed to enhance LEE by Lin et al. using also reported photochemical oxidation [11]. In addition, Cheng et al. reported that air-voids were formed by chemical wet etching to enhance LEE [12]. However, these three methods require performing the MOCVD growth twice. Such two-step MOCVD is complex and could often result in a low production yield. In this study, we report the formation of air-voids for GaN-based LEDs prepared on CSPSS by laser scribing and lateral etching with one-step MOCVD growth. Detailed fabrication process and the electro-optical properties of the fabricated LEDs will also be discussed.

Experiments

Samples used in this study were all grown on 1.2 μ m (CSPSS-1.2 μ m), 1.4 μ m (CSPSS-1.4 μ m), and 1.7 μ m (CSPSS-1.7 μ m) height of CSPSS by MOCVD. The LED structure consists of a 30-nm-thick GaN nucleation layer grown at 550 ^oC, a 4-µm -thick Si-doped n-GaN buffer layer grown at 1050^{o}C, an unintentionally doped InGaN/GaN multiquantum well (MQW) active region grown at 770^{o}C, a 50-nm-thick Mg-doped p-$Al_{0.15}Ga_{0.85}N$ electron blocking layer grown at 1050^{o}C, and a 0.25-µm-thick Mg-doped p-GaN layer grown at 1050^{o}C. The InGaN/GaN MQW active region consists of five pairs of 3-nm-thick $In_{0.23}Ga_{0.77}N$ well layers and 7-nm-thick GaN barrier layers. After the epitaxial growth, the samples were subsequently annealed at 750^{o}C in N_2 ambient to active Mg in the p-type layers.

After the growth, a 2000-nm-thick SiO_2 layer was first deposited onto the samples. A diode pump solid state laser (DPSSL) was then used to scribe the wafers. The scribed wafers were subsequently wet etched in a mixture of H_3PO_4 and H_2SO_4 solution at 220^{o}C for either 5 min or 20 min. An inductively coupled plasma (ICP) etcher was then used to partially etch the samples surface until the n-type GaN was exposed. A 245-nm-thick indium-tin-oxide (ITO) layer was then deposited to serve as the current spreading layer. Cr/Au (50 nm/150 nm) was subsequently deposited to serve as n- and p-pad electrodes. The epitaxial wafers were then lapped down to 100 µm and broken into 250 µm × 575 µm LED chips. For comparison, LEDs prepared on a flat sapphire substrate with standard processing method was also prepared.

Output power of the fabricated LEDs was then measured using the molded LEDs with an integrated sphere detector from top of the devices. The near-field (NF) emission images of the LEDs were also taken by a calibrated CCD camera mounted on the microscope.

Results and discussion

Figure 1 (a) shows cross-sectional images of LEDs grown on 1.2 μ m, 1.4 μ m, and 1.7 μ m height of CSPSS. It was found that the entire substrate was covered by GaN. This is due to the use of CSPSS which significantly enhanced the lateral growth of GaN [9]. In contrast, pyramid-like air-voids were formed on top of each cone of the substrates, as shown in figure 1 (b). The formation of these air-voids should be attributed to the lateral etching. Due to the large lattice mismatch, it is known that crystal quality is poor for GaN prepared on sapphire in the initial stage of growth. Thus, dislocation density in the vicinity of film/substrate interface is extremely high [13]. On the other hand, crystal quality of the epitaxial layers is significantly improved when they are away from the interface [14]. It should be noted that the etchant should be able to enter laterally from the kerf of the scribed wafers. It should also be noted that wet etching rate of GaN in the vicinity of GaN/sapphire interface should be much higher than that away from the interface due to the larger dislocation density. Through defect selective etching, we could thus form air voids at the interface between GaN and CSPSS. As we increased etching time from 5 min to 20 min, it was found that the air-voids became larger, as shown in figure 1 (c).

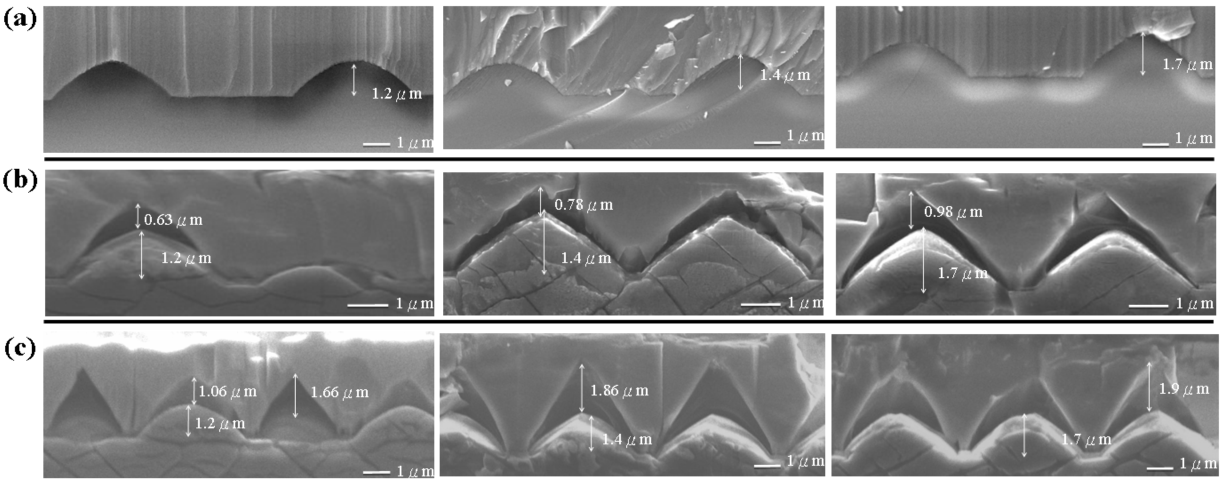

Figure 1 Cross-sectional SEM images of the GaN/CSPSS interface of (a) without etching, (b) etching 5 min, and (c) etching 20 min.

Figure 2 (a) shows output power as functions of injection current for the fabricated LEDs. It was found that output power of all LEDs increased as we increased the injection current. With 20mA current injection, it was found that output powers were 4.04, 5.94, 6.12, 6.25, 6.18, 6.28, 6.47, 6.36, 6.56, and 6.76 mW for LED-FS, CSPSS-1.2 μm, CSPSS-1.4 μm, CSPSS-1.7 μm, CSPSS-1.2 μm-5 min, CSPSS-1.4 μm-5min, CSPSS-1.7 μm-5min, CSPSS-1.2 μm-20 min, CSPSS-1.4 μm-20 min, and CSPSS-1.7 μm-20 min, respectively. With CSPSS, it can be seen that output powers were all significantly larger than that of LED-FS. It was also found that output power of CSPSS-1.7 μm was larger than those of CSPSS-1.2 μm and CSPSS-1.4 μm. This can attribute to the fact that the increased height of each cone results in more guided light toward the vertical direction to escape from the top of device surface. With 5 min lateral etching, it was found that output power of CSPSS-1.7 μm-5min was 4.6 and 3% larger than those of CSPSS-1.2 μm-5min and CSPSS-1.4 μm-5min, respectively. With 20 min lateral etching, it was found that output power of CSPSS-1.7 μm-20 min was 6.2 and 3% larger than those of CSPSS-1.2 μm-20min and CSPSS-1.4 μm-20min, respectively. Furthermore, the largest output power observed from the CSPSS-1.7 μm-20 min among all LEDs. This can attribute to not only the increased refractive index difference between the slanted GaN planes and the air voids and thus the enhanced light scattering but also the CSPSS-enhancing light scattering by 1.7 μm height of CSPSS. Figure 2 (b) shows output powers versus various heights of the cone shape without etching and with etching time 5 min and 20 min at the same 20mA.

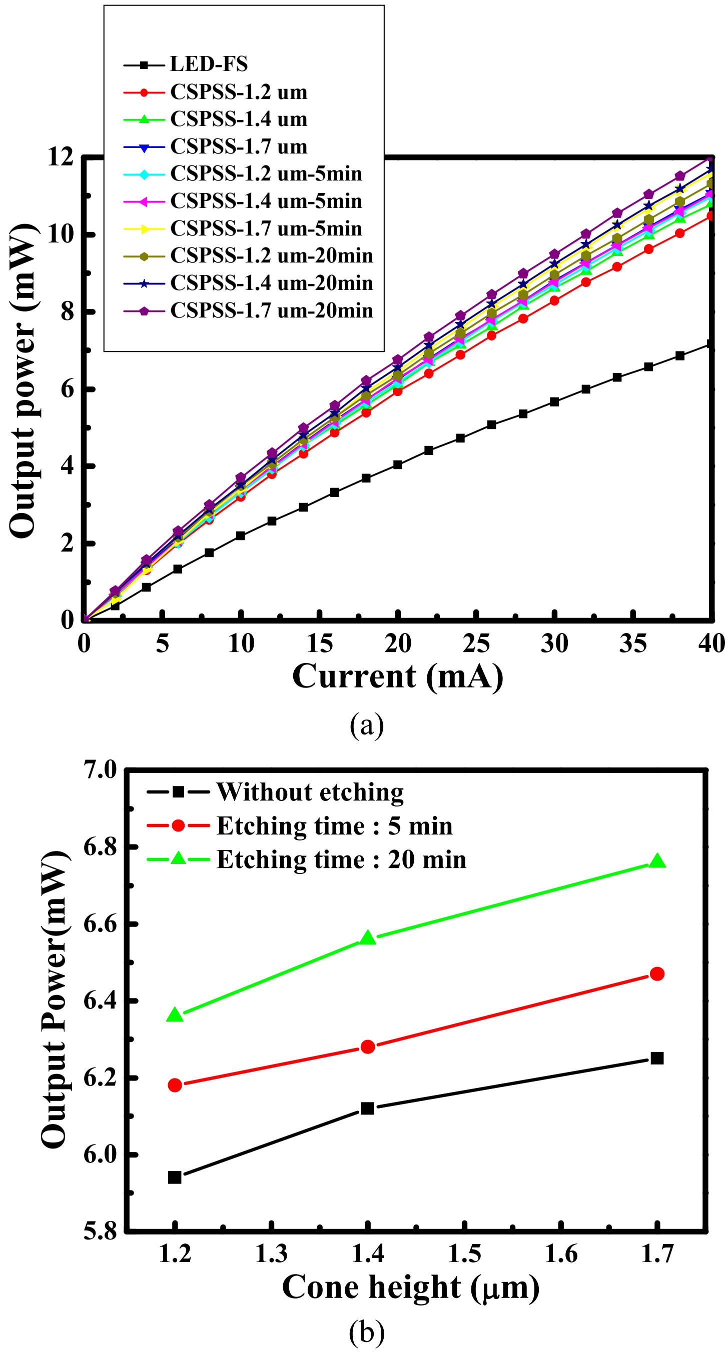

Figure 2 (a) Output power as functions of injection current for the fabricated LEDs and (b) output power versus different heights of the cone shape at the same 20 mA.

Summary

In summary, we report that GaN-based LEDs prepared on 1.2 μm, 1.4 μm, and 1.7 μm height of CSPSS with the formation of air voids at GaN/CSPSS interface by laser scribing and lateral etching with one-step MOCVD growth. With 5 min lateral etching, it was found that pyramid-like air-voids were formed on top of each cone of the substrates. As we increased etching time from 5 min to 20 min, it was found that the air-voids became larger. It was also found that output power of CSPSS-1.7 μm-20 min was 6.2 and 3% larger than those of CSPSS-1.2 μm-20min and CSPSS-1.4 μm-20min, respectively. Furthermore, it was found that we can achieve the largest output power from CSPSS-1.7 μm-20 min among all LEDs.

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References

[1] I. Akasaki and H. Amano, Crystal growth and conductivity control of group III-nitride semiconductors and their applications to short wavelength light emitters Jpn. J. Appl. Phys. 36 (1997) 5393-5408.

[2] S. J. Chang, C. H. Kuo, Y. K. Su, L. W. Wu, J. K. Sheu, T. C. Wen, W. C. Lai, J. F. Chen, and J. M. Tsai, 400nm InGaN/GaN and InGaN/AlGaN multiquantum well light-emitting diodes, IEEE J. Sel. Top. Quan. Electron. 8 (2002) 744-748.

[3] S. Nakamura, T. Mukai, and M. Senoh, Candela-class high brightness InGaN/AlGaN double-heterostructure blue light-emitting diodes, Appl. Phys. Lett.64 (1994) 1687-1689.

[4] T. Mukai, K. Takekawa, and S. Nakamura, InGaN-based blue light-emitting diodes grown on epitaxial laterally overgrown GaN substrates, Jpn. J. Appl. Phys.37 (1998) L839-L841.

[5] I. Kidoguchi, A. lshibashi, G. Sugahara, and Y. Ban, Air-bridged lateral epitaxial overgrowth of GaN thin films, Appl. Phys. Lett.76 (2000) 3768-3770.

[6] W. K. Wang, D. S. Wuu, S. H. Lin, P. Han, R. H. Horng, T. C. Hsu, D. T. C. Huo, M. J. Jou, Y. H. Yu, and A. K. Lin, Efficiency improvement of near-ultraviolet InGaN LEDs using patterned sapphire substrate, IEEE J. Quan. Electron. 41 (2005) 1403-1409.

[7] Y. J. Lee, H. C. Kuo, T. S. Lu, and S. C. Wang, High light-extraction GaN-based vertical LEDs with double diffuse surfure, IEEE J. Quan. Electron. 42 (2006) 1196-1201.

[8] S. J. Chang, L. W. Wu, Y. K. Su, Y. P. Hsu, W. C. Lai, J. M. Tsai, J. K. Sheu, and C. T. Lee, Nitride-based LEDs with 800^{o}C-grown p-AlInGaN/GaN double cap layers, IEEE Photon. Technol. Lett.16 (2004)1447-1449.

[9] J. H. Lee, D. Y. Lee, B. W. Oh, and J. H. Lee, Comparison of InGaN-based LEDs grown on conventional sapphire and cone-shape-patterned sapphire substrate, IEEE Trans. Electron Dev. 57 (2010) 157-163.

[10] E. H. Park, J. Jang, S. Gupta, I. Ferguson, C. H. Kim, S. K. Jeon, and J. S. Park, Air-voids embedded high efficiency InGaN-light emitting diode, Appl. Phys. Lett. 93 (2008) 191103-1-191103-3.

[11] C. F. Lin, K. T. Chen, and K. P. Huang, Blue light-emitting diodes with an embedded native gallium oxide pattern structure, IEEE Electron Dev. Lett. 31 (2010) 1431-1433.

[12] Y. J. Cheng, M. H. Lo, P. M. Tu, C. H. Wang, C. W. Hung, S. C. Hsu, H. C. Kuo, H. W. Zan, S. C. Wang, C. Y. Chang, and S. C. Huang, High efficiency light emitting diode with anisotropically etched GaN-sapphire interface, Appl. Phys. Lett. 95 (2009) 041109-1-041109-3.

[13] X. J. Ning, F. R. Chien, P. Pirouz, J. W. Yang, and M. A. Khan, Growth defects in GaN films on sapphire: The probable origin of threading dislocations, J. Mater. Res.11 (1996) 580-592.

[14] C. H. Ko, S. J. Chang, Y. K. Su, W. H. Lan, J. F. Chen, T. M. Kuan, Y. C. Huang, C. I. Chiang, J. Webb, and W. J. Lin, On the carrier concentration and Hall mobility in GaN epitaxial layers, Jpn. J. Appl. Phys.41 (2002) L226-L228.

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