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Bin Tang
Jiahao Miao
Yingce Liu
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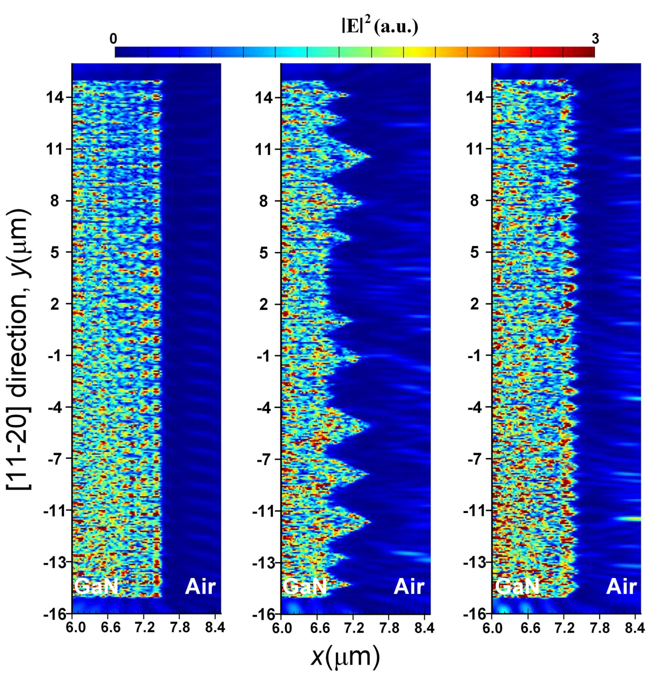
Hui Wan



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Insights Into the Influence of Sidewall Morphology on the Light Extraction Efficiency of Mini-LEDs

Bin Tang,[1,2] Jiahao Miao,[1,2] Yingce Liu,[3] Shengjun Zhou ,[1,2,4] Haohao Xu,[1,2] and Hui Wan[1,2]

[1]Key Laboratory of Hydraulic Machinery Transients, Wuhan University, Ministry of Education, Wuhan 430072, China
[2]Center for Photonics and Semiconductors, School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, China
[3]Xiamen Changelight Co., Ltd., Xiamen 361000, China
[4]State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

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Abstract: We systemically investigated the influence of sidewall morphology change based on TMAH etching on the optical performance of mini-LEDs. The dominant feature of prism structures on the sidewall of mini-LEDs with TMAH etching treatment varied from inhomogeneous to homogeneous as the TMAH etching time prolonged. Such prism structures only appeared on the sidewall along direction owing to the anisotropic TMAH etching. Experimental and simulation results demonstrated that these prism structures can effectively improve the light extraction from sidewall and homogenous prism structures on the sidewall function better in out-coupling light.

Index Terms: Light extraction efficiency, mini-LED, sidewall morphology, TMAH etching.

1. Introduction

The emergence and rapid development of mini-LEDs have been the exciting frontier of liquid crystal display (LCD) technology [1], [2]. Mini-LEDs can deliver on outstanding properties that next-generation displays are aspiring, such as: long lifetime, conformability to curved surfaces and ruggedness, low energy consumption and high resolution [3], [4]. With these prominent merits, LCDs with mini-LEDs as backlight module have gained new advantages in competition with organic light-emitting diode displays. However, to succeed in the competition for next-generation of display technology, high dynamic range feature is prerequisite, which requires more energy-efficient mini-LEDs [4], [5].

Generally, GaN-based LEDs suffer from low light extraction efficiency (LEE) owing to the total internal reflection at GaN/air interface caused by the refractive index mismatch. Various methods have been developed in broad-area LEDs to improve the LEE, such as chip geometry shaping [6], [7], surface texturing [8]–[10], photonic crystal [11], [12], and so on [13]–[19]. However, the above mentioned methods are not as efficient in micro-LEDs/mini-LEDs as in broad-area LEDs due to the reduced chip size and top emitting surface area. As far as we know, rare successful case based on these methods has been demonstrated in micro-LEDs/mini-LEDs and the few reports that aimed at improving LEE of micro-LEDs/mini-LEDs have demonstrated that increased sidewall surface area plays a critical role [20], [21]. Considering that the sidewall surface area of micro-LEDs/mini-LEDs accounts for a larger percentage of the whole light-emission-area than that of the broad-area conventional LEDs, we propose that improving the light extraction from sidewall is a promising solution for achieving highly efficient micro-LEDs/mini-LEDs.

Sidewall texturing as a simple and effective solution for improving the light extraction from sidewall has attracted much research interest. Approaches include laser scribing, inductively coupled plasma (ICP) etching combined with lithography and wet chemical etching have been developed to texture the sidewall [22]–[24]. However, the laser scribing can only be used to create grooves on the sapphire sidewall and both debris and thermal damages are inevitably incorporated in the laser scribing process [25]. These disadvantages restrict laser scribing to be an efficient approach to texturing the sidewall. ICP etching can generate various patterns on the sidewall by combining with lithography, which enables an evaluation of the influence of sidewall texture on light extraction [26]. But the plasma damage during ICP etching and sidewall contamination by etch products on the active layer induce a severe deterioration of forward and reverse voltage [27]. Compared to the above two methods, wet chemical etching is low cost and generates negligible surface damage, which is practical in mass-production [28]. With these advantages, sidewall texturing based on potassium hydroxide (KOH) and tetramethylammonium hydroxide (TMAH) wet chemical etching to improve the sidewall light extraction have been demonstrated in broad-area LEDs [24], [29]. In our recent work, the prism-structured sidewall based on TMAH etching was demonstrated an effective method for scattering out the waveguided photons in flip-chip mini-LEDs [30]. The outcoupling efficiency of photons was anticipated to have a strong dependence on the prism size according to the simulation results. However, such an anticipation has not been verified based on experimental results. Considering that the prism structure generated in the course of TMAH etching varied significantly in size with different TMAH etching durations, a systematic investigation to reveal the relationship between sidewall morphology and light extraction efficiency is of practical significance.

In this work, we systemically studied the sidewall morphology evolution of GaN-based mini-LEDs with the increase of TMAH etching time. We demonstrated that the sidewall morphology was influenced by the TMAH etching duration and more homogeneous prism structures on the sidewall were beneficial to better optical performance. The anisotropic etching property of GaN in wet chemical etching was found to play an important role, which requests the LED sidewall to be properly arranged to achieve optimal light output power (LOP) after TMAH etching treatment. Numerical simulation results based on finite-difference time-domain (FDTD) method corresponded well with the experimental results, revealing that the textured sidewall acted more effectively in extracting light out than the smooth sidewall.

2. Experimental Details

The GaN-based blue LEDs was grown on a 4-inch *c*-plane patterned sapphire substrate (PSS) using a metal–organic chemical vapor deposition (MOCVD) system. The LED epilayer included a 25-nm-thick GaN nucleation layer, a 2.2-μm-thick undoped GaN buffer layer, a 2.5-μm-thick Si-doped n-GaN layer, a 400-nm-thick InGaN/GaN superlattice layer, a 12-pair of InGaN (3 nm)/GaN (12 nm) multiple quantum wells (MQWs), a 40-nm-thick p-AlGaN electron blocking layer, and a 112-nm-thick Mg-doped p-GaN layer. The mesa structure and isolation trench were created by standard photolithographic patterning followed by ICP etching with BCl_3 and Cl_2 gases. Afterwards, the LED wafers were dipped into 1.5 mol/L TMAH aqueous solution at temperature of 60 °C for a crystallographic etching process. The LED wafers were subsequently rinsed with ample deionized water and dried with N_2 flow, followed by the evaporation of a 60-nm-thick ITO transparent conductive layer on the p-GaN layer. Cr/Pt/Au (20 nm/50 nm/1.5 μm) multilayers were deposited on the ITO and n-GaN layers to form the p- and n- electrodes. Finally, the LED wafers were thinned through

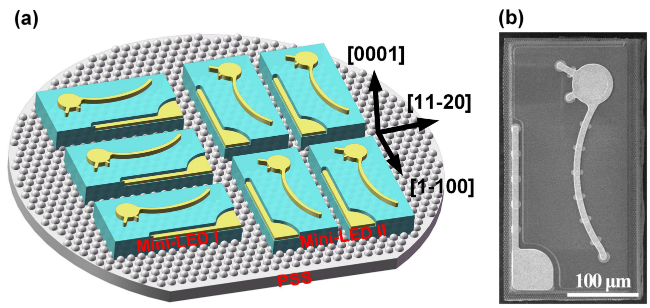

Fig. 1. (a) Schematic of the mini-LED I and mini-LED II grown on the same wafer. The two kinds of LEDs were set to be in orthogonal arrangement. (b) SEM image of the fabricated mini-LED. The size of the mini-LED chip on the wafer was 177 μm $\times$ 354 μm.

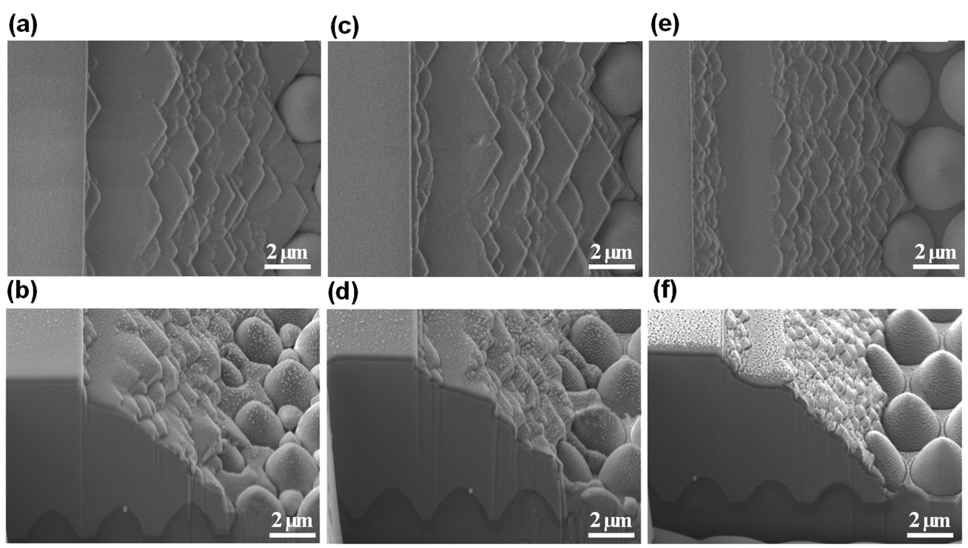

Fig. 2. SEM images of the sidewall along [11]–[20] direction: (a) Plain-view and (b) Cross-section view of the sidewall with 5 min TMAH etching treatment; (c) Plain-view view and (d) Cross-section view of the sidewall with 10 min TMAH etching treatment; (e) Plain-view and (f) Cross-section view of the sidewall with 20 min TMAH etching treatment.

backside grinding and lapping, and diced into individual chips with size of 177 μm $\times$ 354 μm. The peak emission wavelength of these mini-LEDs is 455 nm. In this work, two kinds of LED chips with orthogonal arrangement on a wafer were fabricated as shown in Fig. 1. To distinguish the two kinds of mini-LEDs, the horizontal arranged mini-LEDs were labeled as mini-LED I and the vertical arranged mini-LEDs were labeled as mini-LED II. The light output power-current-voltage (*L-I-V*) characteristics of mini-LEDs were collected using a Keysight B2901A SourceMeter with an integrating sphere.

3. Results

Fig. 2 depicted a series of sidewall morphologies of mini-LEDs as a function of the TMAH etching time. The trigonal prism structure on the sidewall was the dominant feature for mini-LEDs with TMAH etching treatment. The shape of prism structure was kept unchanged for different TMAH etching durations while the prim size showed significant dependence on the TMAH etching time. For mini-LEDs with a 5 min or 10 min TMAH etching duration, the sizes of prism structures on the sidewall fluctuated in large range, which varied from nanoscale to a few microns. More homogeneous prism

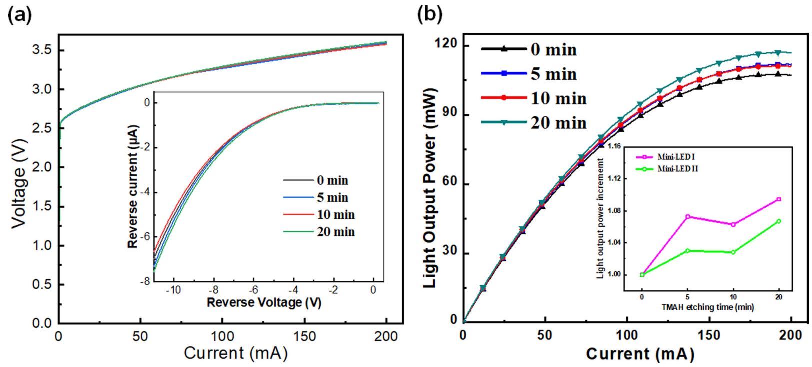

Fig. 3. (a) *I-V* curves of mini-LED I with different TMAH etching durations. The inset showed the reverse *I-V* characteristics of mini-LED I with different TMAH etching durations. (b) *L-I* curves of mini-LED I with different TMAH etching durations. The inset showed the LOP increments of mini-LED I and mini-LED II under 130 mA injection current.

structures were observed on the sidewall of mini-LEDs with a 20 min TMAH etching duration and the mean size of prism structures was about 550 nm.

Fig. 3(a) showed the *I-V* characteristics of mini-LED I with different TMAH etching durations. The forward *I-V* characteristics of investigated mini-LEDs with different TMAH etching durations almost overlapped. The inset of Fig. 3(a) showed the reverse *I-V* characteristics of mini-LED I with different TMAH etching durations. Under a reverse voltage of 10 V, the reverse currents of mini-LED I with TMAH etching time of 0, 5, 10 and 20 min were 5.04, 4.91, 5.26 and 5.48 μA, respectively. These slight variations in *I-V* characteristics of mini-LEDs with different TMAH etching durations suggested negligible electrical damage was incorporated by the TMAH etching treatment. The *L-I* curves in Fig. 3(b) demonstrated better light output performance of mini-LEDs with TMAH etching treatment compared to the mini-LEDs without TMAH etching. With injection current of 130 mA, the LOPs of mini-LED I with TMAH etching time of 0, 5, 10 and 20 min were 98.05, 100.75, 100.97 and 107.31 mW, respectively. Since all the mini-LEDs were with the same epitaxial and device structure, they were anticipated to have an identical internal quantum efficiency (IQE). Thus the increments in LOP of TMAH treated mini-LED I were suggested to arise from improved LEE, which was associated with the prism structure on the sidewall. The variation in LOPs of mini-LEDs with different TMAH etching durations implied that the LEE was influenced by the sidewall morphology. The inset of Fig. 3(b) compared the LOP increments of mini-LED I and mini-LED II with various TMAH etching durations relative to the mini-LEDs without TMAH etching treatment under 130 mA injection current. All the TMAH treated mini-LED I and mini-LED II showed increments in LOP compared to the mini-LED without TMAH etching. However, it is noteworthy that mini-LED I always presented higher LOP than mini-LED II with same TMAH etching duration. Because the only difference between mini-LED I and mini-LED II was their orthogonal arrangement on the wafer, the difference in LOP increments caused by TMAH etching was proposed originating from the anisotropic etching property of GaN during the TMAH etching process.

Fig. 4 provided more evidence on the relationship between LOP increment and anisotropic TMAH etching. As shown in Fig. 4(a), the LOPs of mini-LED without TMAH treatment, mini-LED I with 20 min TMAH treatment and mini-LED II with 20 min TMAH treatment were 98.05, 107.31 and 104.89 mW, respectively. Fig. 4(b) showed the light emission mapping images of the above three devices under 60 mA injection current. Compared with the emission image of mini-LED without TMAH etching treatment, the most remarkable difference in the emission images of mini-LED I and mini-LED II with 20 min TMAH treatment appeared in the nearby region of sidewall along [11]–[20] direction. It was noteworthy that the sidewall along [11]–[20] direction well corresponded to the textured sidewalls after TMAH etching treatment as demonstrated in our previous work [30]. Such results implied that the textured sidewall functioned more effectively in coupling light out than the smooth sidewall. Hence, with the same TMAH etching duration, the better performance of mini-LED

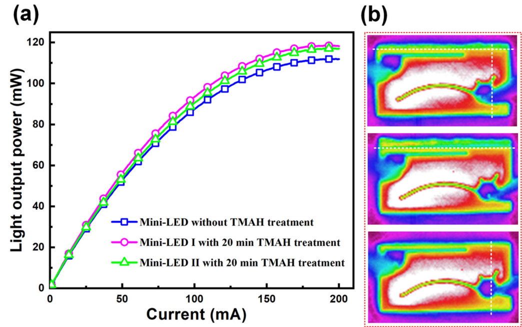

Fig. 4. (a) *L-I* curves of mini-LEDs without TMAH treatment and with 20 min TMAH etching treatment. (b) Top: Light emission mapping image of mini-LED without TMAH treatment. Middle: Light emission mapping image of mini-LED I with 20 min TMAH treatment. Bottom: Light emission mapping image of mini-LED II with 20 min TMAH treatment.

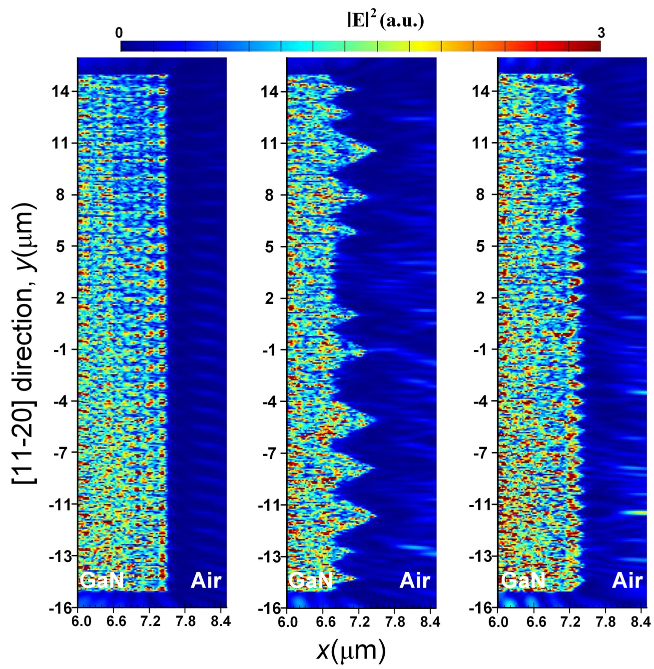

Fig. 5. Simulated intensity profile for a cross section with each device in the *x-y* plane: mini-LED without TMAH treatment (left); mini-LED with 5 min TMAH treatment (middle); mini-LED with 20 min TMAH treatment (right).

I can be reasonably explained by its larger textured sidewall surface area owing to the orthogonal arrangement of mini-LED I and mini-LED II on the wafer as shown in Fig. 1(a).

In order to estimate the influence of such sidewall morphologies created by TMAH etching on the LOP increments of mini-LEDs, FDTD simulation was performed. In the FDTD simulation model, perfect matched layer (PML) boundary condition was adopted to avoid the reflected electromagnetic wave at the edge of the structure. The simulation model was built based on the above depicted epitaxial structure and virtual sidewall morphology. Considering the amount of memory and computing time, the simulation domain was set to be 15 μm $\times$ 30 μm. The grid size in the simulation domain was set to be 10 nm to ensure reasonable calculation accuracy. A series of point dipole sources with emission wavelength of 455 nm were positioned in the center region of MQW as light source. Cross-sectional discrete Fourier transform (DFT) monitor was used to get the spatial light intensity distribution. According to the simulated intensity profile as shown in Fig. 5, the textured sidewall allowed more photons propagating across the GaN/air interface, which may arise from light scattering out of the prism structures through multiple reflections and refractions. Furthermore, stronger light intensity distribution in the air was found for the textured sidewall with more homogeneous prism structures, implying regular prism structures on the sidewall functioned more efficiently in coupling light out.

4. Conclusion

In summary, we have investigated the influence of sidewall morphology based on TMAH etching on the optical performance of mini-LEDs. The sidewall morphology varied as the TMAH etching time prolonged. With TMAH etching time of 5 or 10 min, inhomogeneous prism structures with size fluctuating from nanoscale to a few microns dominated the sidewall morphology. A longer TMAH etching time of 20 min led to more homogenous prism structures on the sidewall. Experimental and simulation results demonstrated that these prism structures on the sidewall can effectively improve the light extraction from sidewall and the homogenous prism structures was better at coupling light out from the sidewall than the inhomogeneous prism structures. The anisotropic etching property of GaN in wet chemical etching is another essential factor that should be kept in mind, which demands the LED sidewall to be in well-organized orientation to achieve optimum output performance.

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