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Light Extraction Enhancement of InGaN Based Micro Light-Emitting Diodes with Concave-Convex Circular Composite Structure Sidewall

Lijun Tan ¹ , Quanbin Zhou ¹, Wenlong Hu ¹, Hong Wang ^{1,2,*} and Ruohu Yao ¹¹ Engineering Research Center for Optoelectronics of Guangdong Province, School of Electronic and Information Engineering, South China University of Technology, Guangzhou 510640, China² Zhongshan Institute of Modern Industrial Technology, South China University of Technology, Zhongshan 528437, China

* Correspondence: phhwang@scut.edu.cn; Tel.: +86-136-0006-6193

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Abstract: We demonstrate that the concave-convex circular composite structure sidewall prepared by inductively coupled plasma (ICP) etching is an effective approach to increase the light efficiency without deteriorating the electrical characteristics for micro light-emitting diodes (LEDs). The saturated light output power of the device using the concave-convex circular composite structure sidewalls with a radius of 2 μm is 39.75 mW, an improvement of 7.2% compared with that of the device using flat sidewalls. The enhanced light output characteristics are primarily attributed to the increased photon emitting due by decreasing the total internal reflection without losing the active region area.

Keywords: InGaN/GaN; micro-LEDs; concave-convex circular composite structure sidewall; ICP; light extraction efficiency

1. Introduction

With the developments of semiconductor technology and the maturity of miniaturization technology, more and more new applications of the light-emitting diodes (LEDs) have been realized [1–7]. The various types of displays prepared by using mini- and micro-LEDs with a size of less than 300 μm as backlight units or self-emissive display units obtain new advantages in display technology attribute to their significant merits such as high resolution, low power consumption, long lifetime and short response time [8–10]. In order to satisfy the requirements of high dynamic range for new generation displays, it is still necessary to improve the light efficiency of the micro-LED unit because the brightness of displays should be above 1000 nits [11].

However, the light output power (LOP) of micro-LEDs is not high enough owing to the low external quantum efficiency (EQE), which is mainly limited by the high total internal reflection (TIR) at the GaN/air interface [12,13]. To this end, the photon escaped from the gallium nitride (GaN) sidewall can be increased by reducing the TIR, thereby realizing the improvement of light extraction efficiency (LEE) and light efficiency [14–16]. Several advantageous approaches have been put forward to increase the LEE, such as patterned sapphire substrates [17–19], textured surfaces [19–22], SiO_2 MS/MP [9,23,24], composite transparent conductive layer [5,25], microlens array [26,27], and photon crystals [16,28,29]. Meanwhile, the LEE can be improved by roughening the bottom [30] or sidewalls of the LED. Wherein, the methods of roughening the sidewalls mainly include convex structure [9,31,32], and wave structure [33]. Due to the difference in the size of the active region between the micro-LED and the large-sized LED, the general patterned sidewall cannot effectively improve the light efficiency for micro-LED due to the reduction of the limited active region area.

In this paper, a new appropriate approach by using concave-convex circular composite structure sidewall is put forward to improve the micro-LED performance. And the concave-convex circular composite structure sidewalls are prepared by inductively coupled plasma (ICP) etching without deteriorating the electrical characteristics. By adjusting the radius of the concave- and convex-circle, the concave-convex circular composite structure sidewalls of micro-LED can reduce the TIR to obtain the best out-coupling light efficiency. Compared to Device A with flat sidewall, Device C using the concave-convex circular composite structure sidewall with a radius of 2 μm exhibits 7.2% improvements of light output power. Therefore, the reported patterned sidewall of concave-convex circular composite structure is promising for high efficiency micro-LED applications.

2. Materials and Methods

The epitaxial wafers used in the experiment were InGaN based blue micro-LEDs with a peak wavelength of 457 nm, composed of a 20 nm buffer layer, a 3.5 μm undoped GaN layer, a 1.8 μm n-GaN layer, 9 pairs of InGaN/GaN multiple quantum wells (MQWs), a 50 nm p-AlGaIn layer and a 165 nm p-GaN layer. For bare LED devices preparation, a 120 nm indium tin oxide (ITO) current spreading layer was deposited on the p-GaN. Subsequently, ITO was annealed at 550 $^{\circ}\text{C}$ for 3 min by rapid thermal annealing in an ambient of 200 sccm N_2 and 35 sccm O_2 . Then, the mesa regions and the designed sidewall structures, which were etched approximately 1.3 μm , were defined by using the Cl_2/BCl_3 induced coupled plasma (ICP) etching. In the preparation process of the mesa, a photoresist layer acted as a mask layer was first deposited on the top surface of the ITO and p-GaN. The sidewalls with flat patterns, concave circular patterns, and concave-convex circular composite structure patterns were then formed by using lithography technology. Subsequently, the patterned sidewalls were transferred to the LED wafer by use of ICP etching techniques. Thereafter, a 1- μm -thick silicon dioxide (SiO_2) passivation layer was deposited on the surface of ITO and mesa sidewall by plasma enhanced chemical vapor (PECVD). Finally, Cr/Al/Ti/Au (50/800/200/200 nm) multi-layer metals served as the p- and n-electrodes were sequentially deposited on the top surface of ITO layer and n-GaN layer by electron beam evaporation, respectively.

In order to study the effect of the sidewall structures on the micro-LED performance, six types of micro-LEDs with different sidewall structures were fabricated. The schematic diagrams and corresponding sidewall designs of the devices are shown in Figure 1. Device A, which had flat sidewall, was included for comparison. Device B had concave circular sidewall with a radius of 2 μm . Micro-LEDs had concave-convex circular composite structure sidewall with a concave- and convex-circle radius of 2, 2.5, 3, 3.5 μm were denoted as Devices C, D, E, and F, respectively. All investigative devices in this paper were prepared by using the same uniform LED wafer to limit process variations. The radius of the active region of all devices was 50 μm . The six kinds of micro-LEDs with different sidewall structures were studied by the scanning electron microscope (SEM). The current density-voltage (J-V) and current density-light output power (J-LOP) characteristics of micro-LEDs were measured by use of a semiconductor parameter analysis system with an integrating sphere (QUATEK PG2101, Pegasus Instrument Inc., Taipei, Taiwan).

Figure 1. The schematic diagrams and corresponding sidewall designs of studied devices.

3. Results and Discussion

The EQE of LEDs is mainly limited by the TIR between GaN and air interface [12]. Therefore, it is very important to increase photon escaping by changing the TIR [34]. The patterned sidewalls can increase photon escaping by reducing the TIR, thereby achieving an improvement in light efficiency. However, the common patterned sidewalls will lose a certain area of the active region, which is disadvantageous for the limited area of the micro-LEDs. To this end, a concave-convex circular composite structure sidewall, which reduce the loss of the active region area while reducing the TIR and increasing the photon escape, is designed in this paper. Figure 2a shows top-view SEM image of Device A (Flat) with flat sidewalls. The tilt-view SEM images of the patterned sidewalls (concave circular sidewall, concave-convex circular composite structure sidewall with the concave- and convex-circle radius of 2–3.5 μm) of Devices B–F are shown in Figure 2b–f. As shown in the above figures, the sidewalls of all devices are uniform and smooth. Meanwhile, it is found that the convex circular portion of the concave-convex circular composite structure sidewall becomes a convex-like structure. This is due to the optical proximity effect in the process of lithography, which results in the loss of a portion of area on both sides of the convex circular portion during ICP etching. As well, the concave circular sidewalls turn to wave-like structure for the same reason.

Figure 2. (a) Top-view SEM image of Device A (Flat) with flat sidewalls; (b–f) Tilt-view SEM images of sidewalls of devices B–F.

To check up the patterned sidewalls etching is damage-free process, the electrical properties, such as voltage and resistance, of micro-LEDs with flat sidewall and different patterned sidewalls are studied. Figure 3 shows the current density-forward voltage (J-V) properties of the investigated devices.

The corresponding reverse-biased current-voltage properties are shown in Figure 4. The forward voltage of all devices are almost in coincidence under the same current density. Wherein, the forward voltages of all studied devices at the current density of 1273.8 A/cm^2 are approximately 4.6 V. This indicates that damage isn't introduced during the ICP etching process of patterned sidewalls, resulting in a decline in electrical characteristic. At the current density of 2292.9 A/cm^2 , all studied devices except Device B have the forward voltage of around 5.1 V. However, Device B have the forward voltage of 5.2 V. This is because the Device B using the concave circular sidewall structure loses about 5.15% of the active region area, resulting in an increase in resistance (as shown in Figure 5). With a reverse bias voltage of 10 V, the leakage current of all studied devices are approximately 29 nA. This indicates that a large reverse leakage current isn't induced during the ICP etching process of patterned sidewalls structure [31].

Figure 3. Forward voltage as a function of current density of all investigated devices.

Figure 4. Reverse biased current-voltage properties of all studied devices.

Figure 5. $I(dV/dI)$ versus current density of all studied devices.

According to the measured J-V properties, the series resistance (R_s) of the studied devices can be calculated as [31,32,35]:

$$I(dV/dI) = JS(dV/d(JS)) = (JS)R_s + nKT/q \quad (1)$$

Wherein, S indicates the area of the active region, n indicates the ideal factor, K and T indicate the Boltzmann constant and absolute temperature, respectively, and q indicate the electronic charge. Figure 5 shows $I(dV/dI)$ versus current density (J) characteristics of all studied devices. The R_s of all devices can be estimated by using $I(dV/dI)$ - J characteristics. The R_s of devices A, C, D, E, and F are around 5.0 Ω . And the R_s of Device B is 5.1 Ω , an increase of 0.1 Ω compared with those of other devices. It is further proved that the ICP etching process of patterned sidewalls is damage-free process. The results are in accordance with the comparison of forward voltage shown in Figure 3.

In order to reveal the effect of the patterned sidewalls structure on the optical properties of the devices, the relationship between light output power (LOP) and current density are studied as shown in Figure 6. And Table 1 shows the saturation LOP of all studied devices. With the increase of the current density, the LOP of all studied devices increases rapidly and then gradually becomes saturated. At the same current density, the LOP of the micro-LEDs with concave circular sidewalls are greater than those of the micro-LEDs with flat sidewalls, and the LOP of the micro-LEDs with concave-convex circular composite structure sidewalls are larger than those of the micro-LEDs with concave circular sidewalls. Meanwhile, the LOP of the micro-LEDs using the concave-convex circular composite structure sidewalls are increased along with the decrease of the radius of the concave- and convex-circle. The saturation current density of Devices A–F are 2420.3, 2433.1, 2458.5, 2458.5, 2458.5, and 2458.5 A/cm^2 , respectively. As well, the corresponding saturation LOP of Devices A–F are respectively 37.08, 37.46, 39.75, 39.09, 38.67, and 38.11 mW. Compared to Device A with flat sidewalls, the light output characteristics of Devices B–F are improved to varying degrees. In particular, the LOP of Device C using the concave-convex circular composite structure sidewalls with a radius of 2 μm is increased by 7.2%. This is because the patterned sidewalls structure reduces the TIR of the micro-LEDs, increasing the emitting probability of photons at the sidewalls and thereby increasing the LEE by permitting photons to find the escape cones of the horizontal direction [32,33,36]. However, the LOP of Device B using concave circular sidewalls is only increased by 1%, which is lower than those of Devices C–F using concave-convex circular composite structure sidewalls. This is because the patterned sidewalls structure can increase LOP, but the Device B loses nearly 5.15% of the active region area due to the use of concave circular sidewalls, which offsets part of the increased LOP, thus resulting in

an LOP enhancement of only 1%. With the decrease of the radius of the concave- and convex-circle, the LOP of the micro-LEDs with concave-convex circular composite structure sidewalls is increased. This is because for the same size of the device, the smaller the radius of the concave- and convex-circle, the more the light emitting sidewall surface that the photon can escape, the easier it is to escape, thus achieving the improvement of LOP.

Figure 6. LOP and WPE as a function of current density of all devices.

Table 1. The saturation light output power (LOP) and LOP enhancement of all studied devices.

Device	Saturation Current Density (A/cm^2)	Saturation Light Output Power (mW)	Enhancement of Light Output Power
Device A (Flat)	2420.3	37.08	0%
Device B (Concave)	2433.1	37.46	1%
Device C (2 μm)	2458.5	39.75	7.2%
Device D (2.5 μm)	2458.5	39.09	5.4%
Device E (3 μm)	2458.5	38.67	4.3%
Device F (3.5 μm)	2458.5	38.11	2.8%

In order to further verify the influence of the concave-convex circular composite structure sidewalls on light output characteristics, the relationship between the calculated wall plug efficiency (WPE) and current density is studied as shown in Figure 6, the EL intensity as a function of wavelength is investigated as shown in Figure 7. At a current density of $1006.3 \text{ A}/\text{cm}^2$, the WPE of Devices A–C are 7.81%, 7.83%, and 8.36%, respectively. Similarly, Devices C and B have an enhancement of 7.04% and 0.3% compared with Device A, respectively. The EL intensities of Device C are much higher than that of Devices A and B. Furthermore, compared to Device A, the EL intensities of Device B are slightly greater. The results are consistent with the comparison of LOP shown in Figure 6. It is further proved that the concave-convex circular composite structure sidewalls achieve an improvement in micro-LED light efficiency without losing a large amount area of active region, on account of the TIR reduction.

For further revealing the mechanism of concave-convex circular composite structure sidewall on light extraction, the propagation of transverse electric (TE) and transverse magnetic (TM) polarized blue photons with a ratio of 1.8:1 were simulated by using finite-difference time-domain (FDTD) method [37–39]. The FDTD simulation model of the different sidewall structures and the corresponding simulated electric-magnetic field intensity distribution nearby the sidewalls are shown in the Figure 8. To avoid unnecessary reflected light, the top and bottom boundaries used perfectly matched layers (PML). The lateral boundaries used periodic due to the sidewalls pattern was periodic [40]. The polarized point sources with a wavelength of 457 nm were placed in the MQW [39]. The left and right boundary were 17 μm far from the polarized point sources, respectively. As well, the relative distance between the polarized point sources and the sidewall of the devices A~F is 2 μm , as shown in Figure 8. To measure

the total output power and the escaped power, two detection monitors were placed around the polarized point sources and in air near the sidewalls, respectively. The grid size in computational domain was 10 nm. The simulation parameters such as the refractive index could be found in [41–43]. From the Figure 8, the polarized photons emitting from flat sidewall is mainly confined in the center region. Compared with the flat sidewall, the polarized photons also emitting from the both sides of center region in the concave circular sidewall and concave-convex circular composite structure sidewall in addition to the center region. As well, the total polarized photons emitting from concave circular sidewall and concave-convex circular composite structure sidewall are improved to varying degrees, especially in the concave-convex circular composite structure sidewall. This indicates that the enhancement mainly due to the reduction of the total internal reflection at the sidewall. Figure 9 shows simulated sidewall LEE enhancement factors of all sidewall structures. When the radius of the concave- and convex-circle is 2 μm , the concave-convex circular composite structure sidewall obtains the largest LEE, which is in accord with the experimental results of Device C. It is further proved that the concave-convex circular composite structure sidewall is an effective approach to improve the LEE.

Figure 7. EL intensity versus wavelength of studied devices.

Figure 8. (a–c) Electric field-magnetic intensity distribution (left) and FDTD simulation model (right) of the flat sidewall (Device A), concave circular sidewall (Device B) and concave-convex circular composite structure sidewall (Device C).

Figure 9. The simulated sidewall LEE enhancement factors of all sidewall structures.

4. Conclusions

The concave-convex circular composite structure sidewall as an effective approach for increasing the photons emitting from the GaN sidewalls was demonstrated in this paper. After the ICP etching process, the concave-convex circular composite structures were formed on the GaN sidewall, and damages causing a drop in electrical characteristics were not introduced. The LOP of Device C using the concave-convex circular composite structure sidewalls with a radius of 2 μm is 39.75 mW and increase by 2.67 mW, an improvement of 7.2% compared with that of Device A using flat sidewalls. The enhanced light output characteristics are primarily attributed to the increased photon emitting due to the decreasing total internal reflection at the patterned sidewalls. In consequence, the reported texturing approach of concave-convex circular composite structure is promising for high-efficiency micro-LED applications.

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