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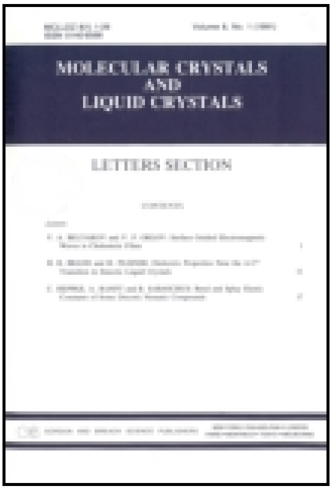

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Fabrication and Characterization of GaN-based Light-emitting Diode (LED) with Triangle-type Structure

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Fabrication and Characterization of GaN-based Light-emitting Diode (LED) with Triangle-type Structure

HWAN GI LEE,[1] JAE HWA SEO,[1] YOUNG JUN YOON,[1] YOUNG JAE KIM,[1] JUNGJOON KIM,[1] SEONGJAE CHO,[2] EOU-SIK CHO,[2] JIN-HYUK BAE,[1] JUNG-HEE LEE,[1] AND IN MAN KANG[1,*]

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This study investigated characteristics of the fabricated triangle-type light-emitting diode (T-LED), conventional triangular LED (CT-LED), and conventional square LED (CS-LED). The T-LED is expected to provide uniform current spreading that leads to high output power, low current crowding, and high light extraction in the lateral direction of the LED device, compared to CT-LED and CS-LED. The light extraction of the T-LED in the lateral direction is much higher than that of the CT-LED and the CS-LED due to enhancement of light emission from the sidewalls of the T-LED.

Keywords light-emitting diode; light emission patterns; triangle-type LED; external quantum efficiency

Introduction

Light-emitting diodes (LEDs) have become an issue of great interest in the recent decade as they promises to help provide cost-effective illumination due to considerably low economic and environmental costs [2, 3, 11]. Improvement of light emission efficiency in LEDs have been realized through improvement in crystal growth techniques, through electrical performance optimization, and the transformation of device structures [5, 6, 13]. In particular, improvement of the external quantum efficiency of GaN-based LEDs is needed to realize light efficient LEDs. However, the external quantum efficiency of GaN-based LEDs is not high enough, so the performance of LEDs is not yet sufficient to meet practical needs. External quantum efficiency is expressed as the multiplication of the internal quantum efficiency and the light extraction efficiency [1, 7]. Internal quantum efficiency is the ratio of photons changed from total generated electrons per unit time in

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LEDs. Light extraction efficiency is expressed as the number of photons emitted through the surface of the LED among the total photons generated in the LED. When the light is emitted from the inside of the LED to the exterior space, total internal reflection of light occurs due to the difference between refractive indexes of the semiconductor and air [8]. The total internal reflection makes the light extraction efficiency degraded. The critical angle of total internal reflection is an important factor in determining light extraction efficiency. To improve light extraction efficiency, various device structures and chip surface processing technologies have been studied [9, 12]. In this paper, the electrode and optical performance of triangle-type LEDs (T-LEDs) with center cathode electrode are presented.

Fabrication of T-LED

Figure 1 shows the structures of GaN-based T-LED, conventional triangular LED (CT-LED), and conventional square LED (CS-LED). All the devices were fabricated on the multilayer grown on a patterned sapphire substrate with a metal-organic chemical vapor deposition (MOCVD) technique [4]. LEDs are composed of a low-temperature grown GaN buffer layer, undoped GaN layer, Si-doped n-type GaN layer, active layers with InGaN/GaN multiple-quantum-wells (MQWs) and Mg-doped p-ype GaN layer. Fig. 1 shows the fabricated LED chip with the total surface area of $1.63 \times 10^5\ \mu m^2$. Mesa structures for n-type electrode and electrical isolation were formed by inductively coupled plasma dry etching for T-LED, CT-LED and CS-LED. In the next step, Ni (50 Å) / Au (50 Å) transparent conductive layer for electrode metal was deposited by electron beam evaporator [10]. Ohmic contact is formed by rapid thermal annealing at 750°C (at N_2/O_2 ambient for 30 s). Finally, electrode pad is formed by deposition of Ti (300Å) / Au (4000Å) by electron beam evaporation [4]. The n-type electrode was formed on the mesa etched n-GaN layer at the center of LED as show in Fig. 1(b) and the p-type electrode was formed on the p-GaN layer with triangular ring type. The T-LED, CT-LED, and CS-LED devices were fabricated on the same chip and went through the same processing conditions. Also, the areas of the p-GaN layer ($1.63 \times 10^5\ \mu m^2$), current spreading layer ($1.39 \times 10^5\ \mu m^2$) and electrodes ($10^4\ \mu m^2$) of T-LED were designed to be the same with those of CT-LED and CS-LED.

Results and Discussion

Figure 2 shows the current-voltage (I-V) measurement results of the fabricated T-LED, CT-LED, and CS-LED. At the current of 20 mA, voltages of the T- LED, CT- LED, and CS-LED are 3.08, 3.23, and 3.63 V, respectively. In addition, at the current of 100 mA, the voltages of the T- LED, CT- LED, and CS-LED are 4.09, 4.60, and 5.89 V, respectively. At an input current of 20 mA, the series resistances of the T- LED, CT- LED, and CS-LED were estimated to be 16, 21, and 36 Ω, respectively. The T-LED showed a lower series resistance and operation voltage due to the shortest current path.

Figure 3 shows optical output power as a function of injection current for the T-LED, CT-LED, and CS-LED. We found that light output power of the T-LED is 4.99 mW at 20 mA. At the current of 20 mA, light output power of the CT-LED and CS-LED is 4.29 and 3.57 mW, respectively. And at the current of 100 mA, light output power of the T-LED, CT-LED, and CS-LED is 20.25, 17.91, and 13.58 mW, respectively. In addition, fig. 4 shows light output power as a function of injection current for LEDs with three kinds of structure. As shown in fig. 4, the device light output power of the T-LED conformed by

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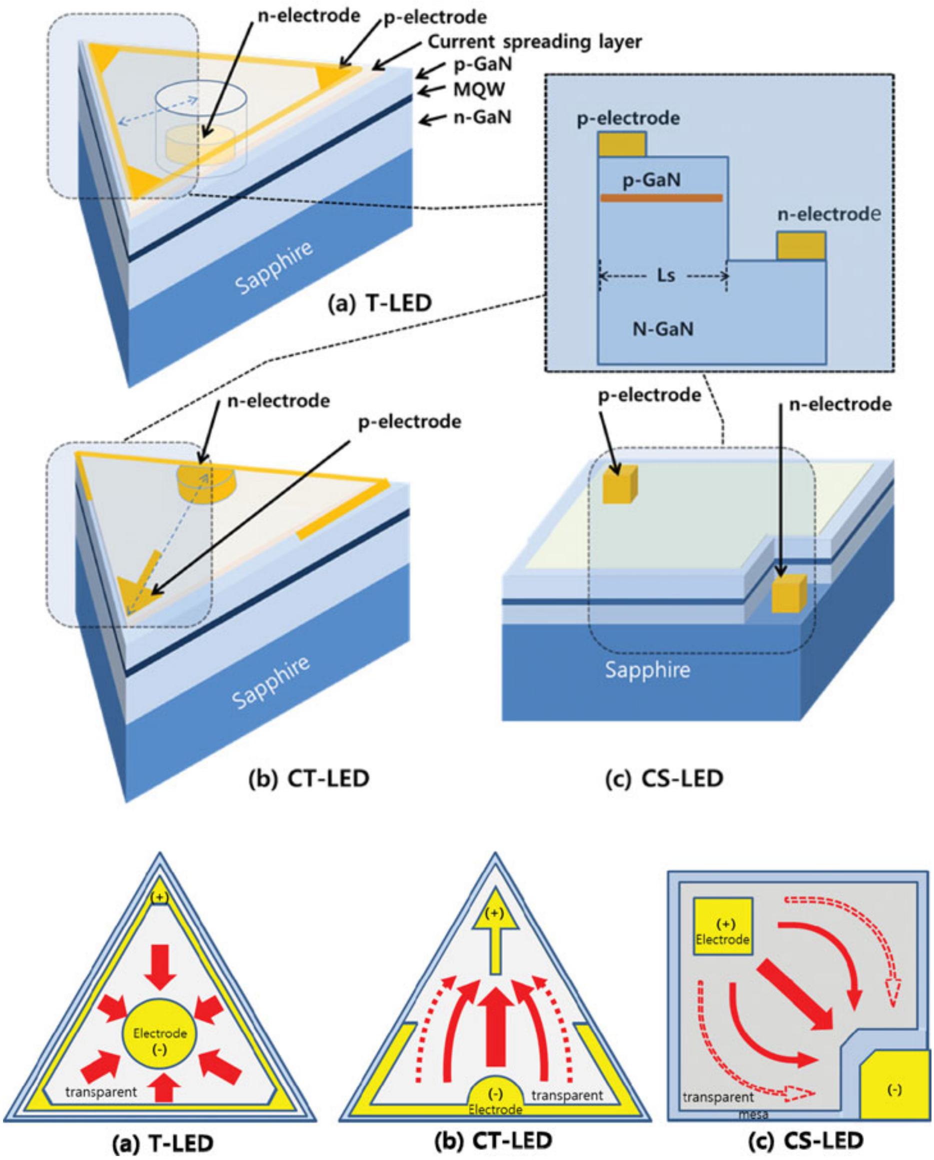

Figure 1. Schematic views and planar views of the fabricated (a) T-LED, (b) CT-LED, and (c) CS-LED.

fabrication is about 4.96 mW at 20 mA and is 13.8% higher than a 4.36 mW CT-LED and 42.1% higher than a 3.49 mW CS-LED. At an injection current of 100 mA, light output power of the T-LED (20.42 mW) is higher than that of either the CT-LED (18.08 mW) or the CS-LED (13.71 mW). The light emitting efficiency of both CT-LED and CS-LED is dominated by the diagonal current path due to non-uniform current spreading, and light extraction along the edge is negligibly small. On the other hand, with the T-LED, the n-type electrode is surrounded by the p-type electrode in all directions. Thus, the current spreads more uniformly on the surface, and thus, electron-hole radiative recombinations

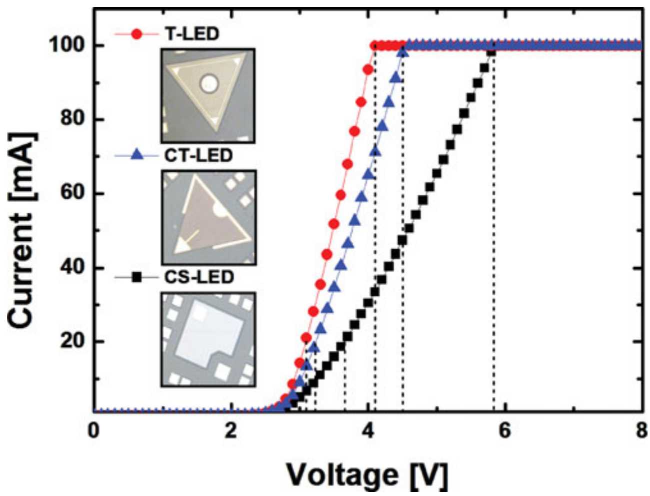

Figure 2. Fabricated *I-V* curves characteristics of the T-LED, CT-LED, and CS-LED.

are increased. The measurement results show that light output power in the T-LED can be highly improved, with an increase in the probability of photon emission, by reducing total internal reflection at the three sidewalls of the T-LED, compared to the CT-LED and CS-LED.

Figure 5 shows the luminescence efficiency of the T-LED, CT-LED, and CS-LED. Luminescence efficiency is defined as the ratio of luminous flux of input power. At an input current of 20 mA, the luminescence efficiency measurement results of the T-LED, CT-LED, and CS-LED were estimated to be 8.65, 8.01, and 6.14 cd/W, respectively. In addition, at the current of 100 mA, luminescence efficiencies of the T-LED, CT-LED, and CS-LED are 4.21, 3.88, and 2.67 cd/W, respectively. Furthermore, fig. 6 shows the angular

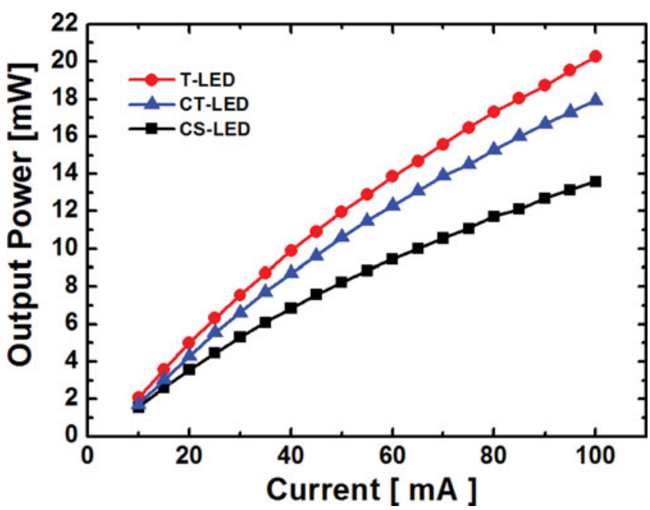

Figure 3. Light output power as a function of injection current with the T-LED, CT-LED, and CS-LED.

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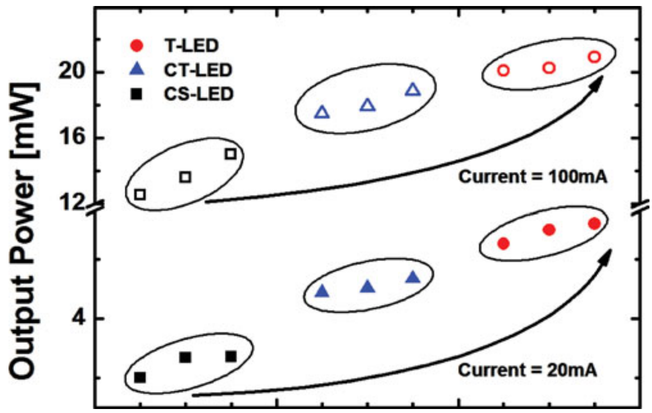

Figure 4. Light output power characteristics of the fabricated LEDs measured at an injection current of 20 mA and 100 mA.

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dependence of the light emission patterns of the T-LED, CT-LED, and CS-LED at an injection current of 20 mA. It is clearly seen that the light emission patterns of the T-LED, CT-LED, and CS-LED were about the same in the near vertical directions, since surface morphologies of the T-LED, CT-LED, and CS-LED devices were similar. In contrast, light emission patterns observed from the LED with the T-LED were larger than those observed from the CT-LED and CS-LED in the near horizontal directions. From the results above, the T-LED confirmed that the injection current flows uniformly inward on the MQW layer over the entire LED, and thus, the effective electron-hole recombination area across the MQWs is increased. However, the CT-LED and CS-LED are dominated by the diagonal current path due to the non-uniform current spreading. This means that the series resistance in the electrical characteristics was still high [14]. The reason is that CT-LED and CS-LED

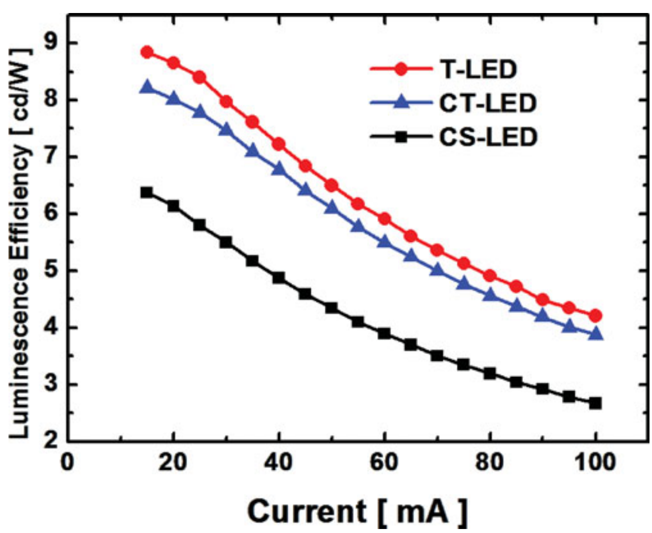

Figure 5. Measured luminescence efficiency of T-LED, CT-LED, and CS-LED at an injection current.

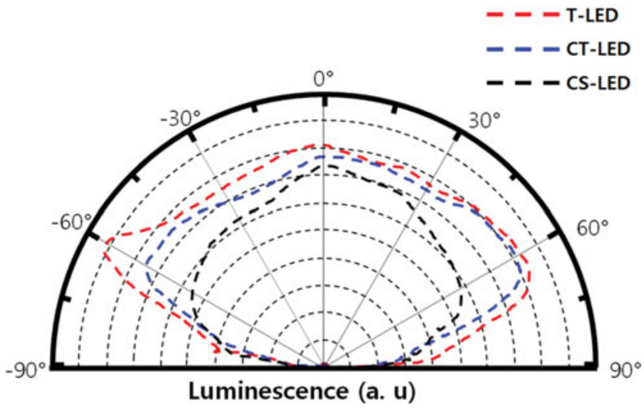

Figure 6. Light emission patterns of T-LED, and CT-LED and CS-LED at the injection current of 20 mA.

have long current path and current high crowding effect from the electrode gap. Also, the triangular structure of the T-LED increases the light emitted from the inside of the device to the air through the sidewall since the angles of incidence for triangular sidewall surface are almost 90° and the total internal reflection inside the T-LED is dramatically reduced.

Conclusions

We fabricated and demonstrated T-LED, CT-LED, and CS-LED devices. Through the electrode structure, the T-LED demonstrated higher electrical and current spreading and then higher optical performance. In the light emission patterns, light extraction in the lateral direction of the T-LED was much higher than that of the CT-LED and CS-LED. It has been revealed that the proposed LED structure would be a feasible solution for improving the performances of LEDs.

Acknowledgments

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