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Enhancement of Light Output Power of InGaN/GaN Multiple Quantum Well Light-Emitting Diodes by Titanium Dioxide Texturing

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The enhancement of external quantum efficiency in InGaN/GaN multiple quantum well (MQW) light-emitting diodes (LEDs) with a titanium dioxide (TiO_2) textured film has been observed. The output power values of conventional and TiO_2 textured LEDs at an injection current of 20 mA are 6.25 and 8 mW, respectively. The external quantum efficiencies of the conventional and TiO_2 textured LEDs at an injection current of 20 mA are 11.5 and 14.8%, respectively. The external quantum efficiency of the TiO_2 textured LEDs at an injection current of 20 mA is 28% higher than that of the conventional LEDs. A higher-output-power InGaN/GaN MQW LED has been obtained by coating with a TiO_2 textured film. [DOI: 10.1143/JJAP.47.5438]

KEYWORDS: titanium dioxide (TiO_2), textured, output power, external quantum efficiency

1. Introduction

Nitride-based compound semiconductors have been developed for use in high-performance optical devices such as light-emitting diodes (LEDs), laser diodes (LDs), photoconductive detectors, and photovoltaic detectors operating in the blue-ultraviolet (UV) range of the light spectrum. GaN-based blue and green LEDs are used in full color displays and traffic light lamps. The output power of LEDs depends on the external quantum efficiency and is suppressed by the total internal reflection between the semiconductor and air.[1] The achievement of a high extraction efficiency is an important issue in this drive to improve the output power in LEDs. Previously, it was reported that a high brightness in LEDs was achieved using a patterned sapphire substrate (PSS) technique[2–9] to improve output power. However, such methods are complex and expensive. Recently, a high extraction efficiency in LEDs grown[10] and processed[11–13] with a textured surface to enhance light scattering has been reported. This may result in the induction of reverse leakage current and a higher operation voltage. In this work, we have developed a new approach to fabricate high-external-quantum-efficiency blue LEDs using a titanium dioxide (TiO_2) textured film. The output power, external quantum efficiency, and atomic force microscope (AFM) morphology of InGaN/GaN MQW LEDs with a TiO_2 textured film will be discussed.

2. Experimental Procedure

Samples were all grown on *c*-face (0001) sapphire substrates by metal organic chemical vapor deposition (MOCVD). The LED structure comprises a low-temperature-GaN buffer layer, a 2-μm-thick unintentionally doped GaN layer, a 2-μm-thick n^+-GaN:Si layer, five periods of InGaN-GaN multiple quantum wells (MQWs), and a 0.2-μm-thick p^+-GaN:Mg layer. A detailed schematic of the structure of the TiO_2 textured InGaN/GaN MQW LEDs is shown in Fig. 1. The device mesa layer was defined by ICP etching. The device size was 1.5×10^{-3} cm^2. Mixed solutions containing TiO_2 powder (1 g) and isopropanol (25 ml) were prepared. The TiO_2 mixed solutions were then spun and coated onto the p-GaN surface. The TiO_2 textured density was about 2.6×10^8 cm^{-2}. The indium tin oxide (ITO) was evaporated onto the p-GaN surface and covered the TiO_2 textured film. Then, samples were subsequently alloyed at 600 °C in N_2 ambient. Cr–Pt–Au contacts were evaporated onto the n-GaN layer as a bonding pad and n-type ohmic contacts. The InGaN/GaN MQW LEDs were characterized by current–voltage (*I*–*V*) measurements performed with a Hewlett-Packard 4156 semiconductor analyzer. The output power characteristics were analyzed with an integrated sphere detector.

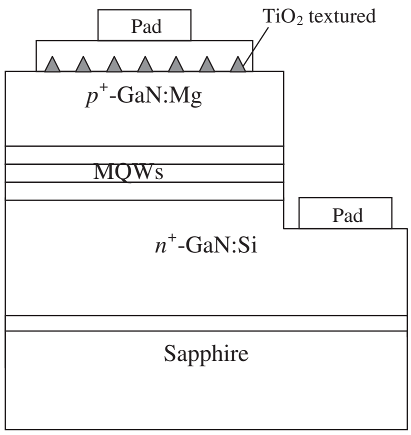

Fig. 1. Schematic structure of TiO_2 textured InGaN/GaN MQW LEDs.

3. Results and Discussion

Figures 2(a) and 2(b) show AFM images of conventional and TiO_2 textured InGaN/GaN MQW LEDs. In Fig. 2(a), the conventional InGaN/GaN MQW LED morphology is planar and smooth. The TiO_2 textured InGaN/GaN MQW LED is shown in Fig. 2(b). The thickness of the TiO_2 textured film is about 500 nm. It is known that the external quantum efficiency of LEDs is limited by the total internal reflection at the semiconductor and air interface. The refractive index of TiO_2 is approximately 2.1[14–16] and is just between those of GaN and ITO, which are 2.4 and 1.9, respectively. In the process, the textured TiO_2 film is embedded between GaN and ITO films. The textured surface may reduce the internal reflection on the surface; thus, more light can be extracted. A higher external quantum efficiency

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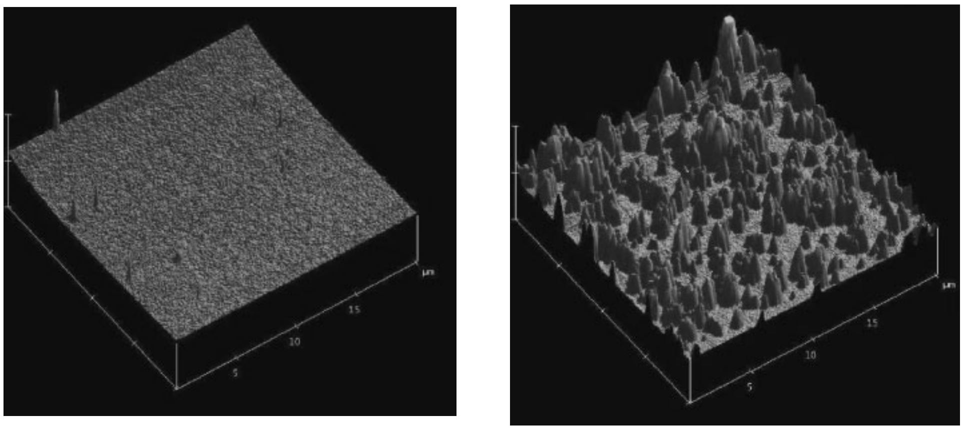

(a) (b)

Fig. 2. AFM images of (a) conventional LED (b) TiO_2 textured InGaN/GaN MQW LED.

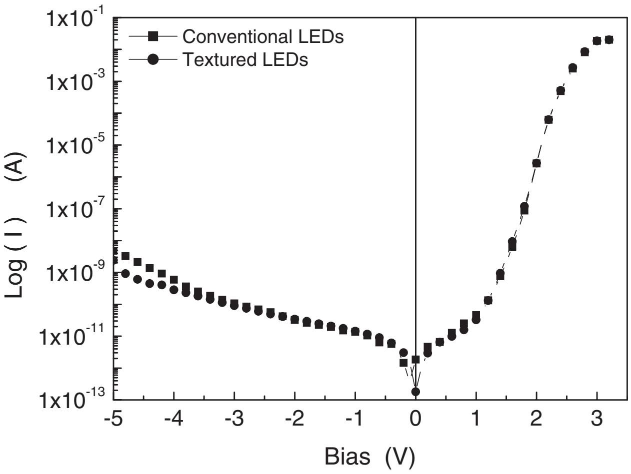

Fig. 3. Current–voltage characteristics of TiO_2 textured InGaN/GaN MQW LEDs.

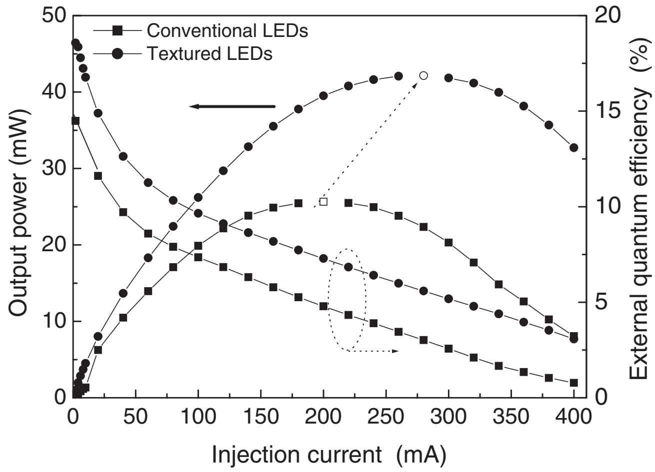

Fig. 4. Output power and external quantum efficiency values of conventional and TiO_2 textured InGaN/GaN MQW LEDs.

for InGaN/GaN MQW LEDs induced by coating with a TiO_2 textured film can be expected. The I–V characteristics of the TiO_2 textured InGaN/GaN MQW LEDs are shown in Fig. 3. In the forward-biased region, the curves are match quite well for samples with and without TiO_2. With the nanoscaled TiO_2 film, a higher conductivity can be observed owing to the enhancement of the charge transport behavior on the nanoscale between different materials.[17] In addition, the conductivity of the nanoscaled TiO_2 film increases under photon illumination.[18] The nanoscaled TiO_2 film showed well behavior in conductivity and no significant current difference in the forward-biased region. In the reverse-biased region, the current is the same within -3 V. When biased at -5 V, the sample with TiO_2 shows weaker leakage current characteristics. According to data of GaN-based devices grown on a sapphire substrate using epitaxial lateral overgrown (ELOG) techniques, dielectric mask may suppress threading dislocation and decrease leakage current.[19,20] In this work, the partially TiO_2 textured film on top of the p-GaN surface may effectively cover and suppress threading dislocation or decrease the number of defects due to the insulating material.

The output power values and external quantum efficiencies of the conventional and TiO_2 textured InGaN/GaN MQW LEDs are shown in Fig. 4. The output power values of the conventional and TiO_2 textured InGaN/GaN MQW LEDs at an injection current of 20 mA are 6.25 and 8 mW, respectively. The external quantum efficiencies of the conventional and TiO_2 textured InGaN/GaN MQW LEDs at a wavelength of 460 nm are 11.5 and 14.8%, respectively. Therefore, the external quantum efficiency of the TiO_2 textured InGaN/GaN MQW LEDs is 28% higher than that of the conventional InGaN/GaN MQW LEDs. A higher output power in InGaN/GaN MQW LEDs can be obtained by coating with a textured TiO_2 film on top p-GaN surface. The thermal effects and output power saturation phenomenon for the InGaN/GaN MQW LEDs are obvious in Fig. 4. It was known that the saturated output power of LEDs increases as the applied injection current increases owing to less heat forming in devices.[21] The saturated injection currents of the conventional and textured LEDs were 200 and 280 mA, respectively. We found out that applying a higher injection current leads to a higher saturated output power in TiO_2 textured InGaN/GaN MQW LEDs. Less heat will thus generate in the TiO_2 textured InGaN/GaN MQW LEDs.

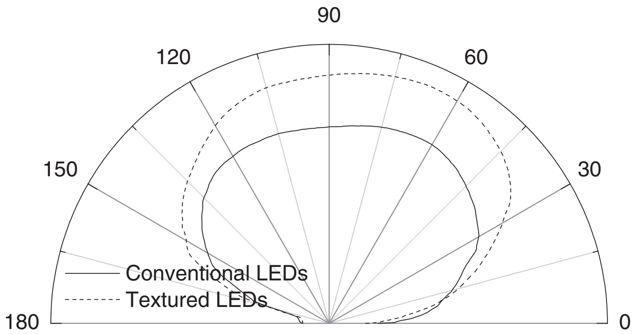

Fig. 5. Polar radiation patterns of InGaN/GaN MQW LEDs with textured TiO_2 film. The dotted line indicates the pattern of the TiO_2 textured LEDs.

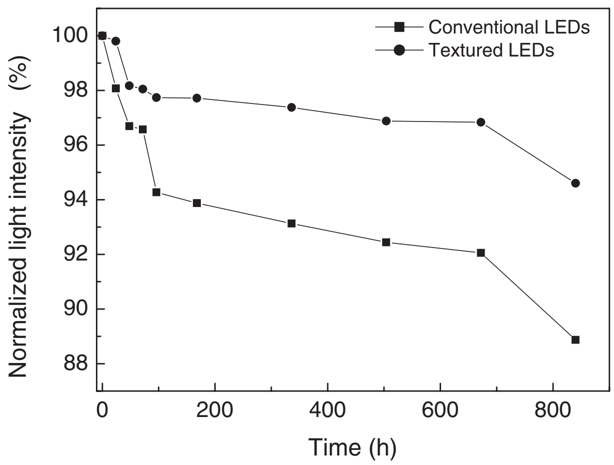

Fig. 6. Room temperature life test of conventional and textured LEDs burned and measured at injection currents of 50 and 20 mA.

The polar radiation pattern of the InGaN/GaN MQW LEDs coated with a TiO_2 textured film is wider than that of the conventional LEDs, as shown in Fig. 5. In general, the output power and external quantum efficiency values of LEDs is limited by the total internal reflection between the semiconductor and air interface for a flat surface.[1] A reduction of the total internal reflection effect and an increase in the level of surface light scattering induced by forming an appropriate TiO_2 textured densities at a top p-GaN surface can be anticipated. Light escapes from the LEDs into air much more easily with a textured surface. The higher output power of the InGaN/GaN MQW LEDs with the wider polar radiation pattern induced by coating with an appropriately textured TiO_2 film was observed. This result is in good agreement with those of other reports on the PSS technique[22,23] and epitaxial growth surface roughness.[24]

Figure 6 shows the results of room temperature reliability tests on the conventional and textured LEDs burned and measured at injection currents of 50 and 20 mA, respectively. The decay of normalized light intensity for the textured LEDs was 6% less than that for the conventional LEDs (12%) after 840 h. This result can be attributed to the less heat generated in the TiO_2 textured InGaN/GaN MQW LEDs and the better I–V characteristics of such LEDs.

4. Conclusions

The improvement of external quantum efficiency of InGaN/GaN MQW LEDs coated with a TiO_2 textured film has been studied. The output power values of the conventional and TiO_2 textured InGaN/GaN MQW LEDs at an injection current of 20 mA are 6.25 and 8 mW, respectively. The external quantum efficiencies of the conventional and TiO_2 textured InGaN/GaN MQW LEDs at an injection current of 20 mA are 11.5 and 14.8%, respectively. The external quantum efficiency of the TiO_2 textured InGaN/GaN MQW LEDs at an injection current of 20 mA is 28% higher than that of the conventional InGaN/GaN MQW LEDs. A higher output power and wider polar radiation pattern in InGaN/GaN MQW LEDs are effectively obtained by coating with a TiO_2 textured film.

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