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GaN-Based Light-Emitting Diodes on Electrochemically Etched n^--GaN Template

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Using III-nitride materials for the fabrications of light-emitting diodes (LEDs), laser diodes, and high power electronic devices has been attracting high attention. GaN-based LEDs have shown energy-saving potential over incandescent bulbs and fluorescence lamps due to the availability of the commercialization of LEDs in the ultraviolet, blue, and green spectral regions [1]–[4]. The main approaches to enhance output efficiency of GaNbased LEDs are internal quantum efficiency (IQE) and light extraction efficiency (LEE). To improve IQE and LEE, different approaches were proposed, such as suppression of charge separation in InGaN quantum well active region [5]–[7], textured surfaces and patterned sapphire substrates [8]–[11], and nano-patterned sapphire substrates which could reduce the dislocation density in GaN-based templates grown on sapphire substrates. In this study, we report the formation of porous n^--GaN templates with various anodizing voltages and the fabrication of GaN-based LEDs on these porous n^--GaN templates. We will discuss the effects of the porous n^--GaN template on the electrical and optical properties of the GaNbased LEDs.

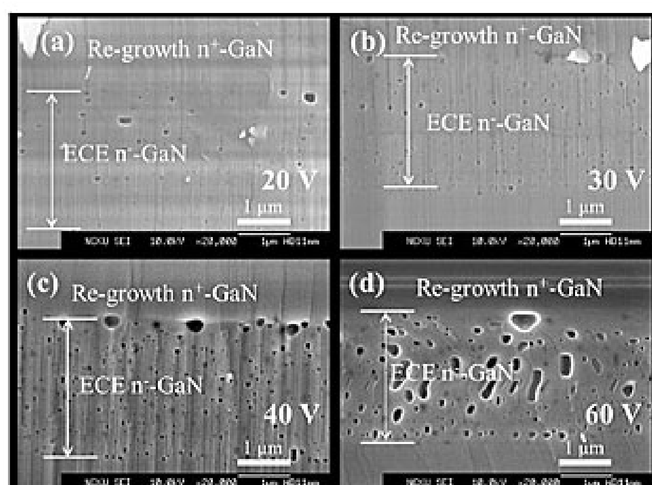

Fig. 1 SEM cross-sectional images of the full LED structure after growth on the electrochemically etched n^--GaN (ECE n^--GaN with anode voltages of (a) 20, (b) 30, (c) 40, and (d) 60 V. Scale bars are 1 μm.

Figures 1(a), 1(b), 1(c), and 1(d) show cross-sectional SEM images of the LED samples prepared on ECE treated n^--GaN templates with anode voltages of (a) 20, (b) 30, (c) 40, and (d) 60 V, respectively. During the epitaxy of the n^+-GaN layer, the pores in the n^--GaN templates reshape due to the introduced NH_3, H_2, and the high growth temperature. The ellipsoidal or facetted voids probably stem from a) etching of the void surface during heat-up, b)

dissociation of GaN in the voids, c) joining of smaller pores. As a result, the horizontal/tree-branch-like pore volumes were partitioned into ellipsoidal or facetted voids, as shown in figures 1(a)-1(d). The reshaped ellipsoidal void diameters of the ECE n^--GaN with bias voltages of 20 V, 30 V, 40 V, and 60 V after the full LEDs structure growth were in ranges of 15-150 nm, 30-180 nm, 35-330 nm, and 45-520 nm, respectively.

The LEDs grown on ECE treated nanoporous n^--GaN templates anodized at 20, 30, 40, and 60 V were named as LED II, III, VI, and V, respectively. For comparison, conventional LEDs without nanoporous n^--GaN template (i.e., LED I) were also prepared. The measured light output power and the corresponding external quantum efficiency (EQE) as a function of the injection current for the fabricated LEDs are shown in Fig. 2. The LEDs prepared on ECE treated n^--GaN template (i.e., LED II to LED V) were all larger than that observed from the conventional LED I at all currents. The 20 mA output powers increase from 8.7 mW (LED I) over 12.15 mW (LED II), 12.34 mW (LED III) and 12.97 mW (LED IV) and then drop to 9.92 mW (LED V). The corresponding EQEs are 15.3%, 21.6%, 22.1%, 23.4%, and 17.9%. Figure 3 shows far field light patterns measured from the fabricated LEDs. It can be seen that we achieved much higher emission intensity from LED II, LED III, and LED IV in the near vertical directions (i.e. $-30° \leq \theta \leq 30°$).

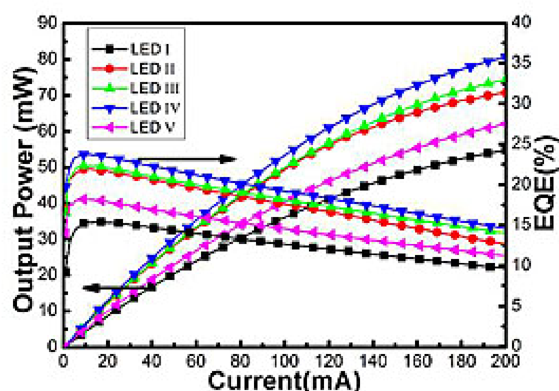

Fig. 2 Measured light output power and external quantum efficiency (EQE) for all LED samples.

In summary, we have demonstrated the fabrication of GaN-based LEDs with embedded reshaped ellipsoidal voids by using an electrochemically etched n^--GaN template. The light output power at 20 mA was up to 50% higher when grown on the n^--GaN template electrochemically etched at 40 V compared with conventional LEDs.

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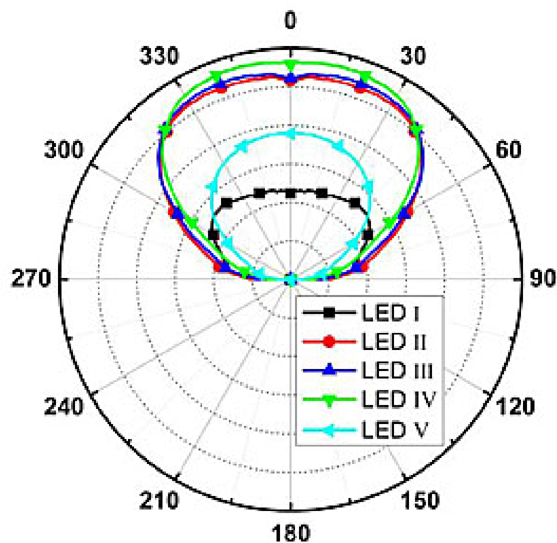

Fig. 3 Far-field light output pattern of the fabricated LEDs.

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