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High light-extraction efficiency induced by evanescent wave coupling effect in GaN-based light-emitting diodes

AIST[1], Asahi Kasei Corp.[2], °Guo-Dong Hao[1], Ahmed Mohammed Jahir,[1] Tokio Takahashi,[1] Mitsuaki Shimizu,[1] Xue-Lun Wang[1], Hiroyuki Kishi,[2] Yukiko Hayashi,[2] and Keigo Takeguchi[2]

E-mail: gd.hao@aist.go.jp

While the internal quantum efficiency of a GaN LED has been greatly improved over the past years, improvement of the light-extraction efficiency which is another major factor contributing to the efficiency of an LED is still strongly desired. The light-extraction efficiency (η_{ext}) is seriously limited owing to the occurrence of total internal reflection caused by the large refractive index contrast between GaN (n~2.5) and air. In a conventional flat-surface LED, only the light inside the narrow escape cone can be extracted to air, which accounts only for a few percent of the total light. We have proposed a novel light extraction technique based on an evanescent wave coupling effect in a small ridge structure. Using this technique, the light outside the escape cones can be directly extracted to air through a unique evanescent-to-propagating light transformation effect. Significant enhancement of light-extraction efficiency has been demonstrated in a thin-film AlGaInP LED by fabricating a ridge structure on the light-extracting surface. Here, we report on the successful implementation of this technique to the GaN-based blue LED by forming truncated cones on the surface of p-GaN and the observation of a significant improvement of η_{ext} over the conventional techniques.

The GaN blue LED wafer used in this study was grown on a (0001) sapphire substrate by metal organic vapor phase epitaxy. The LED structure was composed of a 30-nm-thick low-temperature GaN buffer layer, a 3-μm-thick Si-doped n-type GaN layer, 5 period GaInN/GaN multiple quantum wells, a 20-nm-thick $Al_{0.2}Ga_{0.8}N$ electron blocking layer, an 800-nm-thick Mg-doped p-type (p~5×10^{17} cm^{-3}) GaN layer, and a 30-nm-thick heavily Mg-doped p^+-GaN cap layer for ohmic contact formation. Truncated-cone structures arranged in the triangular lattice configuration with a lattice constant of 1 μm were fabricated by using photolithography and inductively coupled plasma etching on the p-GaN surface. A schematic of the cross-section of the GaN LED with truncated cones is shown in Fig. 1.

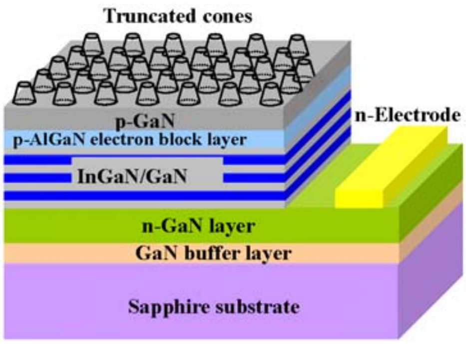

Fig. 1 Schematic cross-section of the GaN LED with truncated cones on the light-extraction surface.

We measured the light output power of the fabricated LEDs by using a prober system in which a calibrated Si photodiode was mounted on the top of the device. As shown in Fig. 2, the device with truncated cone structures on the surface showed a light output power of about 2.3 times stronger than that of a reference planar-surface device at an injection current of 40 mA. The enhancement ratio decreases slowly with increasing current but remains as high as 1.9 times at an injection current of 350 mA, which is attributed to a more serious thermal heating effect in the truncated cone LED. Taking into account the heating effect, a 2.2 times enhancement in η_{ext} of the truncated cone device is evaluated as compared with the planar one. As the truncated cone occupation is only 30%, we believe that the η_{ext} could be further improved by increasing the occupation ratio and optimizing the geometrical shape of the truncated cones.

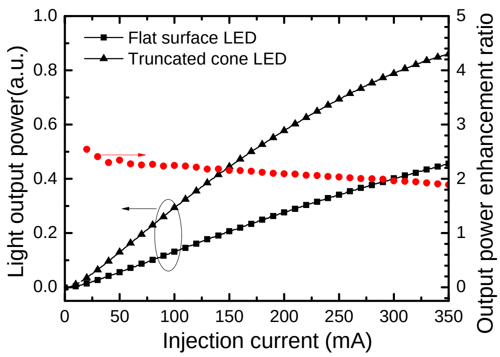

Fig. 2. Comparison of the measured injection current dependence of light output power of the flat-surface and truncated-cone LEDs and the enhancement ratio of the light output power of the truncated-cone LED compared to the flat-surface LED.