Enhancing light extraction from LEDs

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LEDs with embedded donut-shaped air voids show great potential as highly efficient sources of next-generation solid-state lighting.

High-brightness LEDs based on gallium nitride (GaN), with luminescent wavelengths from infrared to ultraviolet (0.7–6.2 eV), have already been extensively used in large full-color displays, traffic and signal lights, short-haul optical communication, backlighting for liquid crystal displays, and regular light fixtures. However, to fulfill the criteria of next-generation projectors, automobile headlights, and high-end light fixtures, further improvements to the optical power and external quantum efficiency are required.

The key issue limiting the development of GaN-based vertical-cavity surface-emitting lasers, which undergo a similar manufacturing process, is the lattice mismatch between GaN and sapphire substrates. This mismatch causes difficulty in growing a highly reflective structure. Due to this and a thermal expansion coefficient misfit, the GaN-based epilayer suffers high threading dislocation densities (TDDs, approximately $10^8$–$10^{10}$ cm$^{-2}$), which compromise the internal quantum efficiency. In addition, the high refractive index of GaN restricts the escape angle of emitted light, and this, at only 23°, results in poor light extraction efficiency (LEE). Various growth techniques have been proposed to improve the crystalline quality of a GaN-based epitaxial layer on a sapphire substrate. Examples include epitaxial lateral overgrowth (ELOG), microscale silicon nitride (SiN$_x$) or silicon oxide (SiO$_x$) patterned masks, and patterned sapphire substrates (PSS).

We have made LEDs on crown-shaped patterned sapphire substrates (CPSS). The fabricated LED has donut-shaped air voids between the PSS and GaN epilayer interface, which improve both epitaxial crystal quality and LEE. We have also analyzed the electro-optical properties of the LEDs in detail.

We prepared epitaxial structures for GaN-based LEDs on three differently shaped sapphire substrates. To fabricate CPSS, we first prepared sapphire substrates with periodic patterns (2 μm diameter and 3 μm spacing) by standard photolithography. A silicon dioxide (SiO$_2$) film 200 nm thick was applied by plasma-enhanced chemical vapor deposition and served as the dry-etching hard mask. We used the photoresist pattern as the mask and over-exposed the photoresist during photolithography, employing a buffer-oxide etching (BOE) solution to create the donut-shaped pattern. Similar photolithography processes were implemented for the hemisphere-shaped PSS (HPSS), but we omitted the over-exposure process. HPSS samples were then etched by reactive ion etching and dipped into the BOE solution to remove the SiO$_2$ mask.

Scanning electron microscope (SEM) images of the CPSS are shown in Figure 1(a). For comparison, the cross section of a conventional HPSS is also shown in Figure 1(b). The diameter and interval of each crown-shaped pattern were 3 μm and 2 μm,
respectively, while the height of the cone shape was about 1.17 μm. We also grew LED structures on plane sapphire to make conventional LEDs (C-LEDs). Figure 1(c) shows the cross-sectional SEM image of the CPSS-LEDs. The air voids (with a refractive index n≈1) were formed between the CPSS (n≈1.7) and GaN (n≈2.5) epilayer on top of the crown shape. These embedded donut-shaped air-voids can significantly increase the LEE due to enhanced scattering; see Figure 1(d).

We then placed the patterned substrates in a metalorganic chemical vapor deposition (MOCVD) device for regular LED structure growth, followed by standard fabrication and testing procedures. Compared with C-LEDs, the output powers of HPSS-LEDs and CPSS-LEDs increased by 20% and 32.1%, respectively. The enhanced light-current-voltage (L-I-V) characteristics, shown in Figure 2, can be attributed to two factors. Firstly, the TDDs are reduced by ELOG on the crown tops of the PSS. This also greatly reduces the number of non-radiative recombination centers and increases photon generation efficiency. This finding is similar to that reported for GaN grown on recess-patterned PSS by Wuu and colleagues.2 Secondly, the scattering effect caused by the CPSS air voids means that more photons can be extracted from the LEDs. It has been reported that the inclined facets of PSS can redirect photons back to the device surfaces, leading to higher LEE.3 As a result, there is an additional 9.8% output power enhancement for LEDs grown on CPSS compared to those grown on HPSS, which lack the donut-shaped air voids between the PSS and GaN epilayer.

To probe further, we calculated the LEE of total radiant flux (LEE_TRF) of the LED by varying the crater angle (θ) indicated in Figure 3. LEE_TRF considers the rays that escaped from every surface of the LEDs. A smaller crater angle indicates a steep slope with greater depth in the crater, whereas a larger angle implies a slant slope from the edge of the crater. From the simulation results, the patterned shape with a crater angle in the range of 30° to 35° induces the largest LEE. Using these results, it is possible to optimize the range of crater angles and predict the optical enhancement via optical ray-tracing. From previous results,4 air voids can be treated as scattering centers due to the difference of refractive indices between the void (n≈1) and the material (n≈2). HPSS, on the other hand, lack air voids as an extra scattering medium and are therefore macroscopically incapable of being as effective as the CPSS. This was confirmed using our ray-tracing simulation: the calculated result for the increase in power output was 25.8% for HPSS, compared to over 40% for CPSS.

In summary, we have overcome problems previously encountered when pairing GaN and sapphire substrates by implementing CPSS for use in LEDs. The resulting donut-shaped air voids increase scattering and reduce non-radiative recombination centers, thereby increasing light extraction efficiency. Our next step will be to optimize crater angles for optical enhancement to further increase the efficiency of the device.

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**Figure 2.** Light output power and voltage as a function of current for the three fabricated LEDs. C-LED: Conventional LED.

**Figure 3.** Optical properties as a function of crater angle for the CPSS. Light extraction efficiency of total radiant flux (LEE_TRF) considers the rays that escape from every surface of the LED.
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References