Light–Output Enhancement in a Nitride-Based Light-Emitting Diode With 22° Undercut Sidewalls

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Abstract—**We successfully fabricated nitride-based light-emitting diodes (LEDs) with ~22° undercut sidewalls. The ~22° etching undercut sidewalls were achieved by controllable inductively coupled plasma reactive ion etching. With a 20-mA current injection, the output powers of the LED with ~22° undercut sidewalls and standard LED were 5.1 and 3 mW, respectively—a factor of 1.7 times enhancement. It was found that such undercut sidewalls could enhance the probability of escaping the photons outside from the LED in the near horizontal and in-plane directions. This simple and controllable method is beneficial to fabricate brighter LEDs.**

Index Terms—**Etching profile, GaN, light-emitting diode (LED), light extraction efficiency.**

GaN-BASED materials have attracted considerable interest in optoelectronic devices such as light-emitting diodes (LEDs) and laser diodes [1]–[4]. Recently, as the brightness of GaN-based LEDs has increased, applications such as displays, traffic signals, backlight for cell phones, exterior automotive lighting, printers, short-haul communications, and optoelectronic computer interconnects have become possible. However, the internal quantum efficiency for GaN-based LEDs is far smaller than 100% at room temperature due to the activation of nonradiative defects. In addition, the external quantum efficiency of the nitride-based LEDs is often low due to the large refractive index difference between the nitride epitaxial layer and the air. It has been reported that the refractive indexes of GaN and the air are 2.5 and 1, respectively. Thus, the critical angle for the light generated in the InGaN–GaN active region to escape is about $[\theta_c = \sin^{-1}(n_{\mathrm{air}}/n_{\mathrm{GaN}})] \sim 23°$ which limited the external quantum efficiency of conventional GaN-based LEDs to be only a few percent [5]. It is known that output light could be enhanced from the LEDs either through the sample surface or through the chip sidewalls. Previously, there has been intensive research into the improvement of light extraction efficiency (external quantum efficiency) and the enhancement of brightness in the LEDs [5]–[11]. The sidewall profile effect on light extraction efficiency enhancement was discussed in many papers [12]–[16]. Krames *et al.* reported the extraction efficiency enhancement from truncated-inverted-pyramid AlGaInP-based LEDs [14]. Eisert *et al.* reported the experimental and simulated results for enhancing light extraction efficiency from GaN-based LEDs chip with undercut SiC substrate [15]. Chang *et al.* reported 10% output power enhancement from the InGaN-GaN multiple quantum-well (MQW) LEDs by the introduction of the wavelike textured sidewalls [16]. All these methods have one thing in common, which is that photons generated within the LEDs can experience multiple opportunities to find the escape cone. As a result, the light extraction efficiency and, thus, the LED output intensity could both be enhanced significantly. It is said that a simple method to fabricate oblique sidewall will be beneficial to raise the brightness of the nitride-based LEDs. In this letter, nitride-based LEDs with ~22° undercut sidewalls were fabricated. The ~22° etching undercut sidewalls were achieved by controllable inductively coupled plasma reactive ion etching (ICP-RIE). The simulated and experimental results of the fabricated LEDs with ~22° undercut sidewalls are reported.

For quantitative estimations, we simulated light propagation and reflection using the ray tracing method provided by TracePro program. For simplicity, we employed a two-dimensional model which is similar as described in [15] on GaN-based LED structures: The top mesa width is 300 μm and depth is 2.5 μm with vertical sidewall and 23° undercut sidewall. Fig. 1 shows the light extraction efficiency of these two LED structures as a function of absorption coefficient of the GaN layer. The light extraction efficiency here was defined as the ratio of the collected power outside the LED structure and the total power generated from the active region. The result clearly shows that by adding a ~22° undercut sidewall, the extraction efficiency can be greatly enhanced. The extraction efficiency can be enhanced about a factor of 1.4–1.8 times compared with two different LED structures considering the absorption coefficient changed from 100 to 10 cm^{-1}. This suggests the choice of undercut angle ~22° shall lead to greatly enhancement of extraction efficiency.

Samples used in this experiment were all grown by metal-organic chemical vapor deposition with a rotating-disk reactor (Emcore D75) on c-face sapphire (0001) substrates The LED structure consists of a 30-nm-thick GaN buffer layer. The structure of the LEDs consist a 30-nm-thick low-temperature GaN nucleation layer, a 4-μm-thick Si-doped GaN layer, an undoped five-period InGaN-GaN MQW active region with emission at ~470 nm at 20-mA operation, and a 0.1-μm-thick Mg-doped

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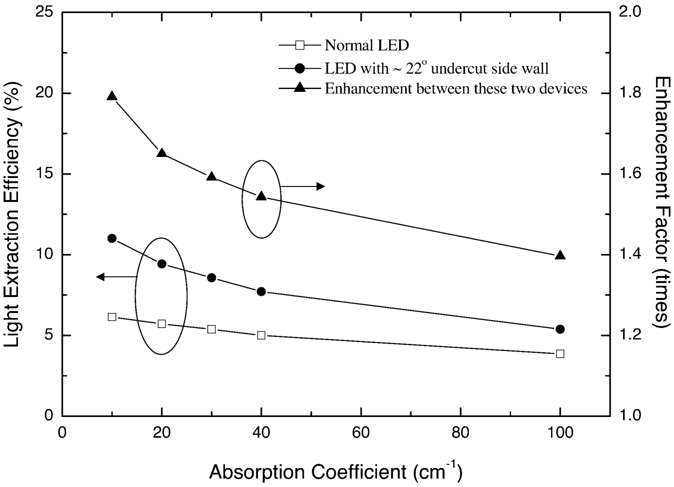

Fig. 1. Simulation describes the light extraction efficiency of LEDs with vertical and 23° sidewall as a function of absorption coefficient of the GaN layer.

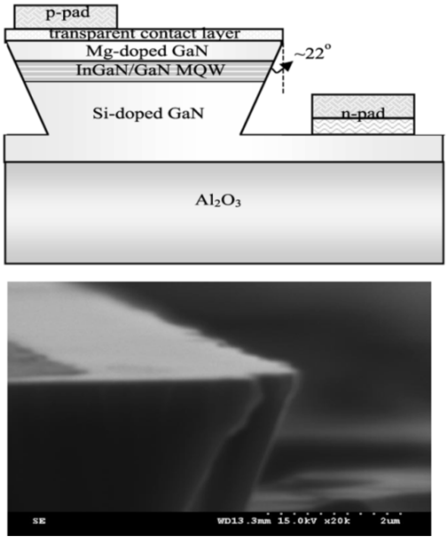

Fig. 2. Schematic diagram of the fabricated LED device with ~22° undercut angle. The inset shows SEM picture of the ~22° undercut sidewall profile on LED II.

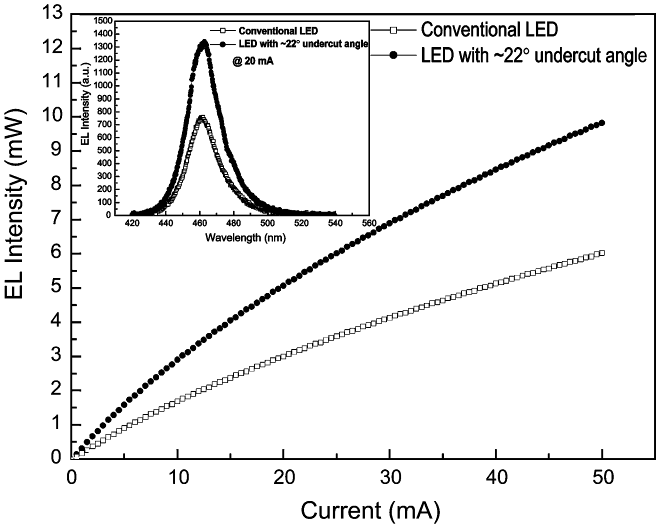

Fig. 3. EL L–I characteristics of LED I and LED II. The inset shows 20-mA EL spectra of the two LED devices.

GaN. The as-gown samples were rapidly thermal annealed at 750 °C for Mg-type activation. Fig. 2 depicts a schematic diagram of the LED device with undercut sidewalls. The process for conventional LED (LED I) and undercut LED (LED II) began with the deposition of 0.6-μm-thick SiN_x onto the sample surface using plasma-enhanced chemical vapor deposition. By means of photoresist lithography, the mesa pattern could be defined after wet etching SiN_x and removing photoresist by buffer oxide etching solution and acetone, respectively. The mesa etching was then performed with Cl_2–Ar as the etching gas in an ICP-RIE system (SAMCO ICP-RIE 101iPH) which the ICP source power and bias power operated at 13.56 MHz. An additional etching for LED II to form undercut sidewalls ~22° was carried out after mesa etching with zero bias power ($Cl_2/Ar = 30/5$ sccm; 6 Pa chamber pressure; 500 W ICP power). The undercut angle of the sidewall profile is defined as the angle between the vertical line and the sidewall. The control of the undercut angle can be performed using ICP-RIE under zero bias power condition, and the detailed study on the effect of etching sidewalls was already submitted to publish elsewhere [17]. After the removal of the SiN_x mask, the etching depth and profile of samples were measured by the Dektek II stylus profilometry measurements and scanning electron microscopy (SEM), respectively. Conventional LED chips with the same device area (300×300 μm^2) were also fabricated using the same wafer for comparison studies. Finally, the metal contact layers, including transparent contact and pad layers, were patterned by a liftoff procedure and deposited onto samples using electron beam evaporation. Ni–Au (3/5 nm) was used for transparent contact and Ti–Al–Ni–Au (30/150/30/150 nm) was used for n-type electrode. Finally, Ni–Au (20/1500 nm) was deposited onto both exposed transparent and n-type contact layers to serve as bonding pads. Fig. 2 also shows the SEM picture of sidewalls profile on LED II, respectively. It can be seen that the ~22° oblique sidewall profile compared with initial etching mesa. It is very close to the critical angle ~23° between GaN and air.

Current–voltage (I–V) characteristics of these two diodes (LED I and LED II) were also measured. It was found that the I–V curves were almost identical for these two devices. The 20-mA forward voltages were both around 3.5 V for the LED with undercut sidewalls and the LED with normal sidewalls. Such an observation indicates that the undercut sidewalls will not result in any degradation in the electrical properties of nitride-based LEDs. In the electroluminescence (EL) measurement, the continuous current was injected into a device at room temperature. The light output was detected by a calibrated large area Si photodiode placed by 5-mm distance from the device top. This detecting condition covers almost all the power emitting from LEDs. Fig. 3 shows the intensity–current (L–I) characteristics and spectra of LED I and LED II. It can be seen that EL intensity of the LED II is larger than that observed from the normal LED. At injection current of 20 mA, it could be found that the MQW emission peaks of these two devices were all at about 470 nm and the light output power of LED I and LED II

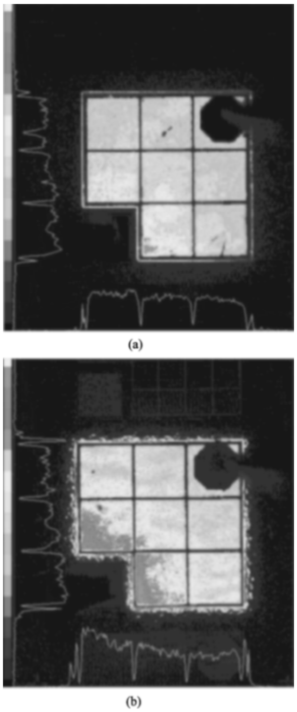

Fig. 4. Photos of (a) LED I and (b) LED II at a dc current injection of 40 mA. Each intensity distribution was also shown in the figure.

was about 3 and 5.1 mW, respectively. This can again be attributed to the larger light extraction efficiency with ∼22° undercut sidewalls. In other words, we could achieve a factor of 1.7 times output power enhancement from the InGaN-GaN MQW LEDs by the introduction of the undercut sidewalls. The results can be mainly attributed to the enhancement of light extraction efficiency, as shown in our simulation results.

To further investigate the influence of ∼22° undercut sidewalls on light–output performance of a LED chip, intensity distribution measurements were performed on LED I and LED II. Fig. 4(a) and (b) shows the photos of LED I and LED II with injecting a 40-mA dc current in these two different device, respectively. Each intensity distribution was also shown in the same figure. It is noted that the intensities trench in the LED output pattern is induced by the mesh of p-type metal. The EL intensities observed from LED II were obviously greater than those observed from LED I at the same injection current especially near the horizontal edge. Such an enhancement could be attributed to the undercut sidewalls that photons could have a larger probability to be emitted from the device in the near horizontal and in-plane directions and, thus, achieve even brighter LEDs.

In summary, high efficient nitride-based LEDs with ∼22° undercut sidewalls have been fabricated. The ∼22° etching undercut sidewalls were achieved by ICP-RIE with a simple and controllable process. It was found that such undercut sidewalls could enhance the probability of escaping the photons outside from the LED in the near horizontal and in-plane directions. With a 20-mA current injection, the output powers of the LED with ∼22° undercut sidewalls and normal LED were 5.1 and 3 mW, respectively (a factor of 1.7 times enhancement). This simple and controllable method is beneficial to fabricate brighter LEDs.

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