Fabrication of GaN-based LEDs with 22° undercut sidewalls by inductively coupled plasma reactive ion etching*

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(Received 5 February 2013; revised manuscript received 15 April 2013)

We use a simple and controllable method to fabricate GaN-based light-emitting diodes (LEDs) with 22° undercut sidewalls by the successful implementation of the inductively coupled plasma reactive ion etching (ICP-RIE). Our experiment results show that the output powers of the LEDs with 22° undercut sidewalls are 34.8 mW under a 20-mA current injection, 6.75% higher than 32.6 mW, the output powers of the conventional LEDs under the same current injection.

Keywords: GaN, light-emitting diode (LED), undercut

PACS: 68.35.B–, 68.55.–a, 81.65.Cf, 81.40.Rs **DOI:** 10.1088/1674-1056/22/10/106802

1. Introduction

Gallium nitride is a promising wide-direct-bandgap semiconductor material for optoelectronic devices.[1] GaN-based light-emitting diodes (LEDs) can be used for many kinds of applications. For example, these LEDs have been used in full color displays, traffic light lamps, solid-state light source, and backlight for large screen displays.[2] Although the light output of GaN-based LEDs has been improved a little, it is still lower than expected. The light extraction efficiency of the LED is mainly limited to the refractive index between the GaN material and the surrounding air. The refractive indexes of GaN and air are 2.5 and 1.0 respectively, and the photons, generated in the InGaN-GaN active region, escape from the GaN film at critical angle of about 23°.[3] The light generated in the active region is emitted isotropically, and most of the light is refracted or absorbed by the materials. Therefore, the external quantum efficiency of the conventional GaN-based LED is often low.[4] The brightness of the LED can be improved by making more photons escape from either the sample surface or the sidewalls of the power chip. These methods are both used in order to provide the photons generated in the LED with multiple opportunities to find the escape cone.[5–9] It has been shown that one could construct the GaN surface so that photons can escape easily thus enhancing the LED output intensity.[10,11] It is also possible to improve the brightness of the GaN-based LED by fabricating oblique sidewalls. Gao *et al.*[12] reported on the extraction efficiency enhancement by nano-roughened p-GaN surface. He *et al.*[13] showed that the light output of a GaN-based LED could be increased by 34% by means of surface-textured ITO electrodes using nickel nanoparticle mask dry-etching. Wang *et al.*[14] used a new growth method to prepare the roughened p-GaN, whose luminous flux was improved by 45%. In the present paper, GaN-based LEDs with 22° undercut sidewalls are fabricated by forming the undercut sidewalls through controllable inductively coupled plasma reactive ion etching (ICP-RIE). The following sections are the introduction of the experimental results of the LEDs with 22° undercut sidewalls. Structural and electro–optical properties of the fabricated devices will also be discussed in detail.

2. Simulation

We employed the ray tracing method to simulate the light propagation and reflection. The software used was Trace Pro. Figure 1 shows the designed result by this program. On the right-hand side of the figure is a simplified model for a GaN-based LED, and the larger arc is a detection surface which is used to collect the emitted light. By this theoretical simulation

*Project supported by the National High Technology Research and Development Program of China (Grant Nos. 2011AA03A112, 2011AA03A106, and 2013AA03A101), the National Natural Science Foundation of China (Grant Nos. 11204360, 61210014, and 61078046), the Science and Technology Innovation Program of Department of Education of Guangdong Province, China (Grant No. 2012CXZD0017), the Industry–Academia Research Union Special Fund of Guangdong Province, China (Grant No. 2012B091000169), and the Science and Technology Innovation Platform of Industry–Academia Research Union of Guangdong Province–Ministry Cooperation Special Fund, China (Grant No. 2012B090600038).

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we designed a GaN-based LED.

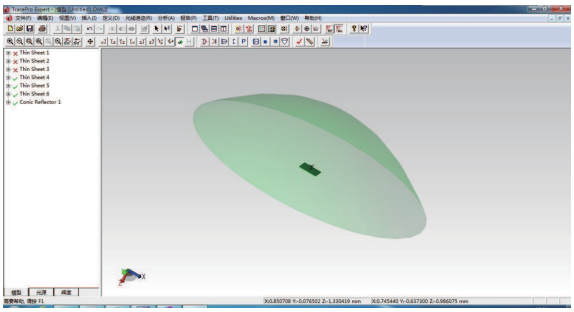


Fig. 1. (color online) The LED model designed by Trace Pro.

In the simulation, we set that 10 thousand beams emerged from the active region of the LED, and we did not consider the effect caused by the absorption coefficients of the materials. We calculated that the numbers of rays received by the detection surface of two models were 5136 for vertical walls and 6890 for 22° undercut sidewalls. The calculation results of two different LED structures suggest that the extraction efficiency can be enhanced about 1.35 times by the introduction of 22° undercut sidewalls. Figure 2 shows the illuminance map of these two LED structures. We can see clearly that the illuminance of the LED with

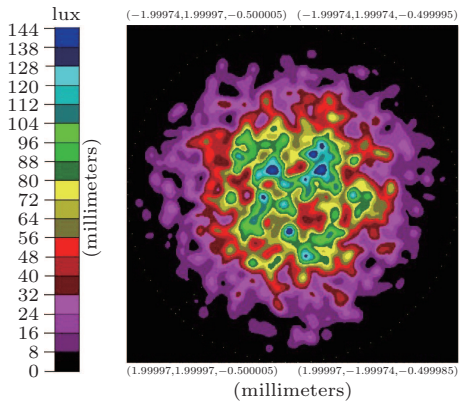


Fig. 2. (color online) Illuminance maps of conventional LED (a) and improved LED (b).

undercut sidewall is a little larger than that of the conventional one. The light extraction efficiency here is defined as the ratio of the collected luminous flux outside the LED to the total luminous flux generated from the active region. Through the theoretical simulation, we obtained the extraction efficiencies of the conventional LED and the LED with undercut sidewall to be 0.3067 and 0.3916, respectively. From a comparison between these two numbers it follows that the increase of the light extraction efficiency is 27.7%. The result clearly shows that introducing a 22° undercut sidewall can lead to great enhancement of extraction efficiency.

The GaN-based LED with vertical sidewalls or with 22° undercut sidewall can be designed as follows. Its top mesa width and the depth are 300 μm and 2.5 μm, respectively. The LED structure consists of a 50-nm-thick GaN buffer layer, a 30-nm-thick GaN nucleation layer, and a 4-μm-thick Si-doped GaN layer. The InGaN-GaN multiple quantum well (MQW) consists of five pairs of 3-nm-thick $In_{0.21}Ga_{0.79}N$ well layers and 7-nm-thick GaN barrier layers. Figures 3(a) and 3(b) depict a schematic diagram of the LED devices with undercut sidewalls and a conventional LED.

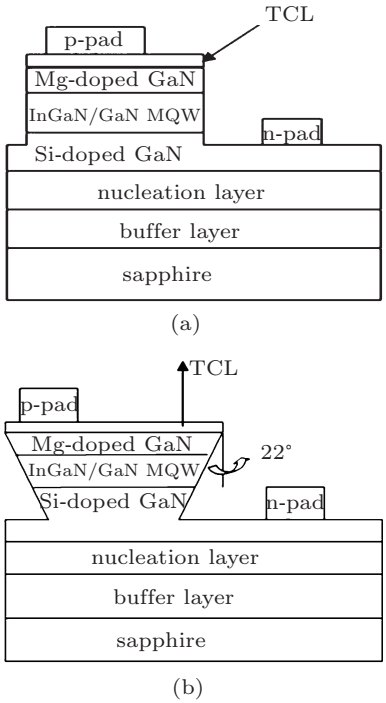


Fig. 3. Schematic diagrams of two LED structures: (a) conventional LED, (b) LED with undercut sidewall. TCL: transparent contact layer, MQW: multiple quantum well.

3. Experiment

The examined samples used in this study were all grown on *c*-face (0001) sapphire substrates using a metal–organic chemical vapor deposition (MOCVD).[15] The as-grown wafers were rapidly and thermally annealed at 750 °C

for the activation of the p-type dopant. An SiN_x layer was then deposited on the sample surface by plasma-enhanced chemical vapor deposition. Photolithography was subsequently used to determine the mesa pattern. The mesa etching was carried out in an ICP-RIE system by using Cl_2 and Ar as the etching gas. After the wet etching of SiN_x, we removed the photoresist by buffer oxide etching solution (BOE). The additional etching to form undercut sidewalls was performed after mesa etching with zero bias power. The detailed study about the etching sidewalls has already been carried out and reviewed elsewhere.[16] The etching depth and profile of samples were measured by the Dektek-II stylus profilometry measurements and SEM. The conventional LED chips with the same device area (300 μm × 300 μm) were also fabricated using the same wafers for comparison study. Then the metal contact layers that contained a transparent contact layer and pad layer were patterned by a lift-off procedure.[17] Subsequently, we deposited Ni–Au (3/5 nm) and Ti–Al–Ni–Au (30/50/30/150 nm) metal layers, respectively, as the p-type contact and n-type contact layers by using electron beam evaporation. For comparison, we used an ICP dry etcher to partially etch the conventional LED with vertical sidewalls till the n-type GaN layer was exposed. The same metal layers were deposited on the transparent contact layer (TCL) and n-type contact layer in order to obtain the conventional LED. Finally, Ni–Au (20/1500 nm) was deposited on the exposed transparent and n-type contact layers to serve as bonding pads.

4. Results and discussion

When the LED chips were fabricated into devices, the current–voltage (*I–V*) characteristics of both the undercut and conventional LEDs were measured at room temperature. Figure 4 shows the measured *L–I–V* characteristics of the two LEDs. The forward voltages of these two LEDs are both approximately 3.24 V at a driving current of 20 mA. The observed voltage behavior indicates that the undercut sidewalls will not degrade the electrical properties of the GaN-based LEDs. Under 20-mA current injection, the LEDs output powers are 34.8 mW and 32.6 mW for the undercut sidewalls and vertical sidewalls LEDs, respectively. In other words, we could achieve 6.75% enhancement from the InGaN–GaN MQW LEDs by the introduction of the undercut sidewalls, much lower than our simulated results of 27.7%. By comparing with the conventional LEDs, the larger output power measured from the undercut LED could be attributed to the enhancement of light extraction efficiency. Electroluminescence (EL) spectra of the LEDs were also measured as shown in Fig. 5. At an injection current of 20 mA, it is found that EL peak positions of the two LEDs occur at about 456 nm with the same full-width at half-maximum (FWHM) of 20.75 nm. It is observed that EL intensity of the undercut LED is larger than that of the conventional LED. Intensity–current (*L–I*) characteristics were measured with an integrated sphere detector.

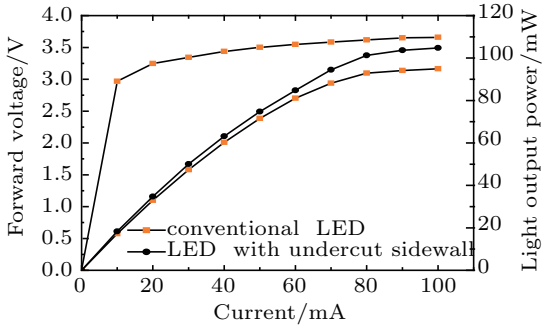


Fig. 4. (color online) *L–I–V* characteristics of the fabricated LEDs.

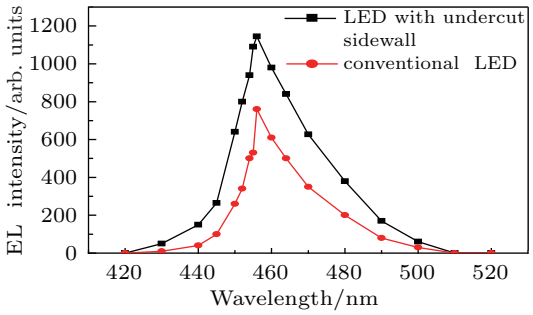


Fig. 5. (color online) EL spectra of the fabricated LEDs.

5. Conclusions

In summary, the GaN-based LEDs with 22° undercut sidewalls that could enhance the output power have been fabricated. First of all, we use Trace Pro program to simulate the luminous fluxes of two different LED structures and the result clearly shows that the LED with 22° undercut sidewalls can enhance the escape probability of photons inside the active region of the LED. The increase is 27.7%. Then these two LEDs are fabricated by ICP-RIE. The test result is that the output power is enhanced only by 6.75%, indicating that the method of forming the 22° undercut sidewalls by ICP-RIE is effective to enhance the output power, though the experimental result is a little lower than the theoretical simulation result. So this technology should be valuable for increasing the external quantum efficiency of GaN-based LED. Besides, we also find that using this simple and controllable method to form oblique sidewalls does not degrade the electrical properties of the devices.

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