Vol. 33, No. 9 Journal of Semiconductors September 2012

Fabrication of high-voltage light emitting diodes with a deep isolation groove structure*

Ding Yan(丁艳)[†], Guo Weiling(郭伟玲), Zhu Yanxu(朱彦旭), Liu Ying(刘莹),
Liu Jianpeng(刘建朋), and Yan Weiwei(闫薇薇)

Key Laboratory of Opto-Electronics Technology of the Ministry of Education, Beijing University of Technology,
Beijing 100124, China

Abstract: In order to connect several independent LEDs in series, inductively coupled plasma (ICP) deep etching of GaN is required for isolation. The GaN-based high-voltage (HV) LEDs with a 5 μm deep isolation groove and an acceptable mesa sidewall angle of 79.2° are fabricated and presented. The surface morphology and construction profile of the etched groove are characterized by laser microscopy and scanning electron microscopy. After contact metal formation and annealing, the electrical properties are evaluated by I–V characteristics. The trend of the I–V curve has good accordance with conventional LEDs. The contact resistance of HV LEDs is also tested and was reduced by 4.6 Ω compared to conventional LEDs, while the output power increased by 5 W. The results show that this technique can be applied to practical fabrication.

Key words: inductively coupled plasma; high-voltage light emitting diodes GaN; deep etching
DOI: 10.1088/1674-4926/33/9/094007 **PACC:** 7865; 7369; 7340

1. Introduction

In the fabrication of GaN-based LEDs, several independent LEDs can be connected in series to improve the forward voltage and brightness, namely HV LEDs (Figure 1 is the schematic diagram). This depends on deep etching of GaN up to 5 μm to realize active region isolation. However, due to the enhanced mechanical strength and chemical inertness of GaN related materials, it is difficult to deeply etch them by wet chemical etching[1, 2]. So dry etching of GaN is a critical fabrication step for exposing desired contact regions, active region definition and isolation.

In recent years, ICP etching is widely used for GaN dry-etching due to its superior uniformity, high etch rate, and less etch damage[3]. Most of the studies on ICP etching of GaN have been reported, in which change of etch rate and influence of etching conditions on device performance are investigated[4–7].

However, there are few reports on deep etching of GaN with an etching depth of up to 5 μm, which is required for a new application— in HV LEDs. Furthermore, two-step ICP etching was performed for the deposition of the metal and to form good contacts.

In this work, we successfully fabricate HV LEDs based on two-step deep ICP etching of GaN under suitable etching conditions, and this can be applied to practical fabrication.

2. Experiment

The sapphire (Al_2O_3) substrates used in this study were 2 inch and 430 μm thick c-plane sapphire. The epitaxial wafers were all grown on sapphire substrates through metal organic chemical vapor deposition. The epi-structure consisted of a 30 nm thick low-temperature GaN nucleation layer grown at 550 ℃, a 4 μm thick Si doped n-GaN contact layer grown at 1000 ℃, a 1 μm thick undoped five-period InGaN–GaN multiple quantum-well (MQW) with the active region grown at 750 ℃, with emission at 460 nm at 20 mA operation and a 0.1 μm thick Mg doped P-GaN contact GaN layer grown at 1000 ℃. The wafer was then performed at 700 ℃ in nitrogen ambient to active Mg in a p-GaN film. The carrier concentration and mobility of the sample was approximately 3×10^{17} cm^{-3} and $\mu = 400$ $cm^2/(V{\cdot}s)$ after thermal annealing, which was determined by a Hall measurement.

For a 1.1 μm thick GaN layer to be etched to expose a n-GaN layer, a depth of $\sim$4 μm would be etched to achieve isolation. The dry etching process was performed in an Oxford instrument. The temperature of the back cooled chuck was held at 20 ℃. The chamber process was kept constant at 10 mTorr during etching. The RF chuck power was kept at 120 W with a constant inductive power of 1000 W, and the $SiCl_4/Cl_2$ (1 : 8) gas flow rate was held at 50 standard cubic centimeters per minute (sccm).

The process flow chart is shown in Fig. 2(a). First, a 450 nm thick SiO_2 layer as an etching mask was deposited on

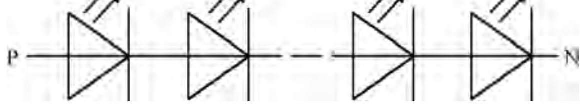

Fig. 1. Schematic diagram of a HV LED.

---

* Project supported by the National High Technology Research and Development Program of China (No. 2009AA03A1A3) and the National Key Technologies R&D Program of China (No. 2011BAE01B14).

[†] Corresponding author. Email: jilia.123@163.com

Received 28 February 2012, revised manuscript received 18 March 2012

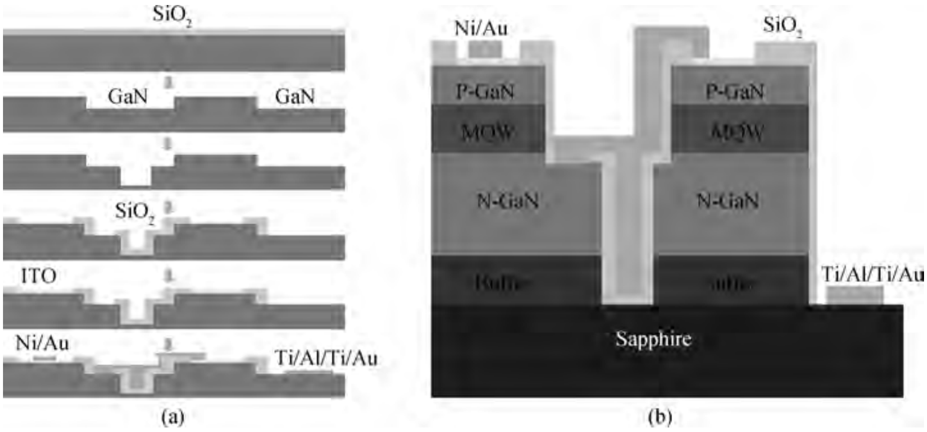

Fig. 2. (a) Process flow. (b) Structure of the GaN-based HV LED.

Table 1. Variation of the sidewall angle with the etching depth and etching rate.

Etching depth (μm)	Etching rate (nm/min)	Sidewall angle (°)
1	140	89.2
2	140	87.4
3	140	81.9
3	160	83.5
4	140	79.2
4	160	82.7

the surface of the GaN by plasma enhanced chemical vapor deposition (PECVD). Second, a standard lithography process was performed to form the patterns on the SiO$_2$ film as a mask. The n-GaN was exposed by ICP etching and the oxide mask was removed in buffered HF before the etched depth was measured using a step profiler. Third, an isolation groove was etched with a depth up to 5 μm, which is the second etching step. Fourth, a 450 nm thick SiO$_2$ layer was again deposited and patterned on the surface, as shown in the figure. It can be used as a passivation layer, and it also protects the active region and avoids the phenomenon of short-circuiting. Fifth, the sample was evaporated on 240 nm ITO film, which is an optional method to enhance the light extraction efficiency[8, 9]. At last, metal was deposited on the exposed n-GaN and isolation groove in order to make two independent LEDs in series and p-electrode and n-electrode were made. The structure of the GaN-based HV LED is shown in Fig. 2(b).

3. Results and discussion

The isolation groove is deep and hard to etch. It plays an important role in the whole fabrication. By adjusting the etch time, the etch rate and the etch selectivity over SiO$_2$ obtained at the conditions mentioned above are 140 nm/min and 8.67 respectively. Furthermore, depending on the quality of the hard mask used, an acceptable mesa sidewall angle of 79.2° is obtained. The reason for the formation of the sidewall is that with the deepening depth, etching time becomes longer. On this occasion, the sidewall near to the etching groove will get more sufficient contact with the etching gas and finally formed a downward slope. Table 1 shows the variation of the sidewall angle with the etching depth and etching rate.

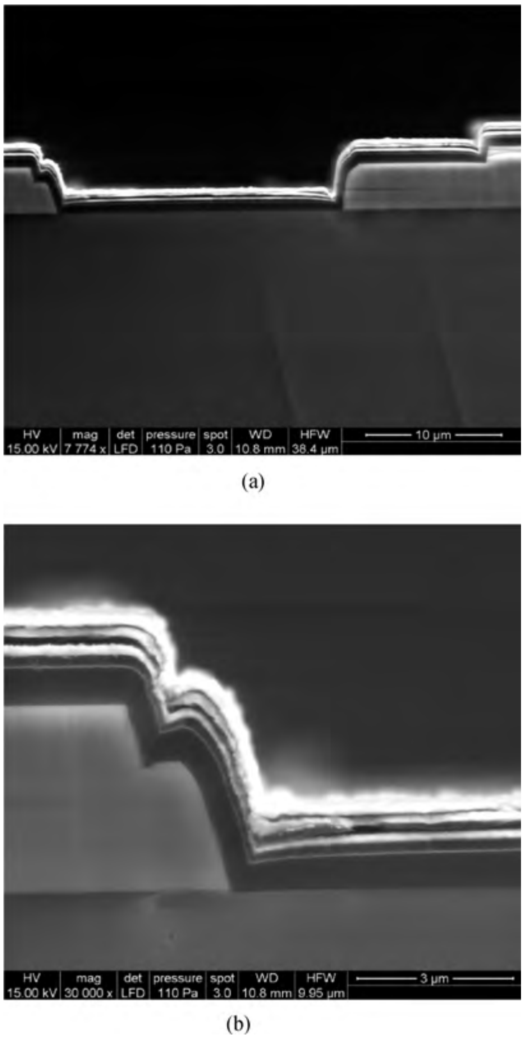

Fig. 3. SEM images of deep etched GaN. (a) Large-area view. (b) Selected area view for isolation groove.

From Table 1, we can conclude that the sidewall angle varies with the change of the etching depth and etching rate. The more shallow the etch depth, and the greater the etch rate, the isolation groove would be closer to vertical. However, the

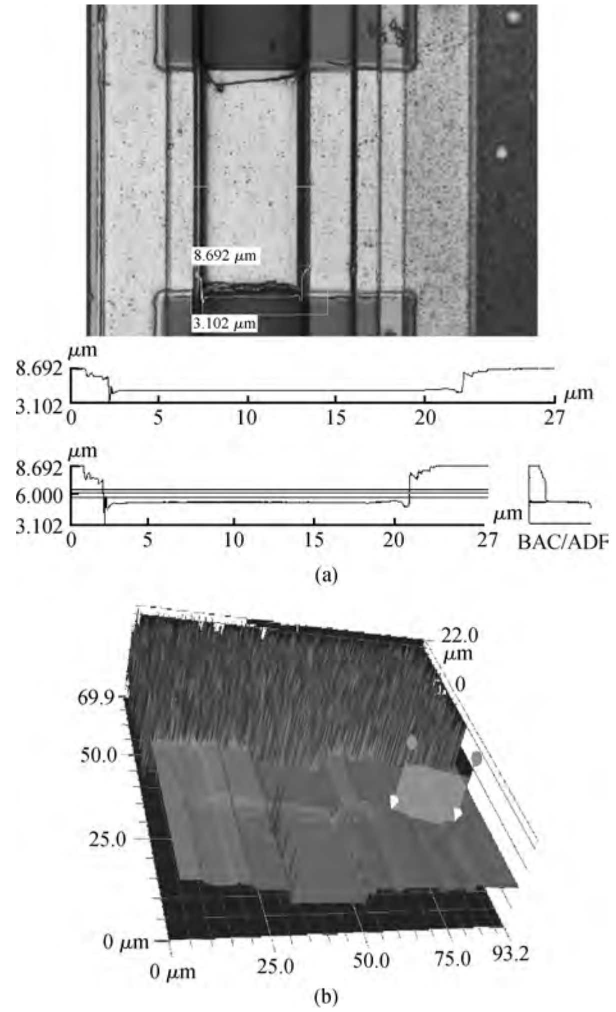

Fig. 4. Laser microscope images of the sample. (a) Dimensional measurement. (b) Internal structure simulation diagram.

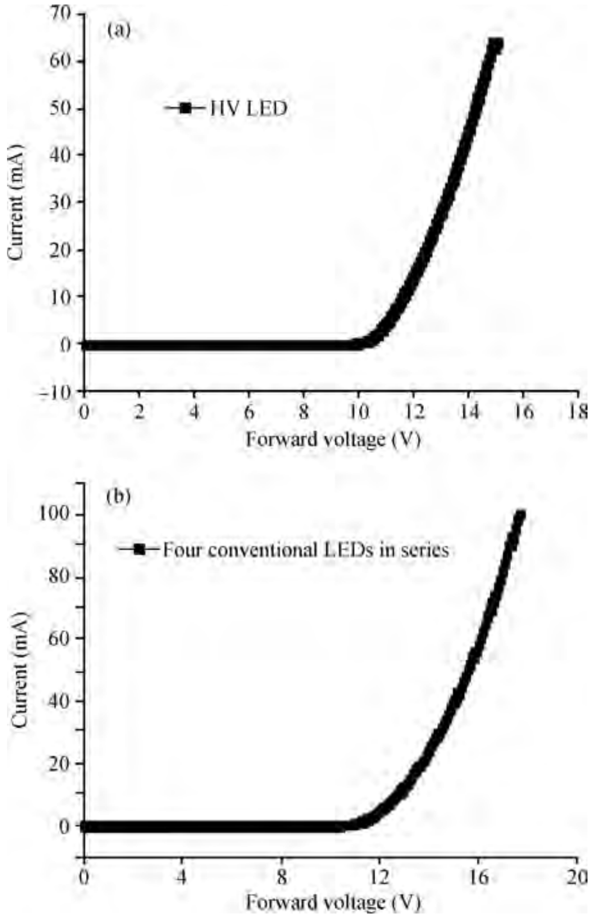

Fig. 5. I–V characteristics of the HV LED and the conventional power LED. (a) HV LED. (b) Four conventional LEDs in series.

slope is good for the deposition of SiO_2 and the metal adhered to the sidewall. Figure 3 shows the SEM images of the sidewall profile. As can be seen from the figure, the shape of the deep-etched GaN fits in with the schematic diagram shown above (Figs. 3(a) and 3(b) Enlarged view).

The deep etching structure is comprehensively evaluated by laser microscopy. From Fig. 4 we can observe the shape of the etched steps and draw the actual depth, which is very close to the value we expected. As Figure 4(a) shows, the depth of color represents the depth of the structure. Figure 4(b) shows the actual depth of the deep groove is ~5.4 μm, with the metal and ITO included.

Deep dry etching studies in the past have observed that small defect-related pits and scattered pillars appear on the surface. Qiu *et al.* point out that when the etch depth is more than 2 μm, pits or pillars are observed on the etched GaN surface[10, 11]. In this paper, we do not consider this aspect. In order to see whether this might have an effect on the sample, I–V characteristics of the HV LED and the conventional power LED were measured and analyzed, as shown in Fig. 5. From the slope of the curve, the contact resistance of the HV LED is obtained as 64.47 Ω, which is 4.6 Ω smaller than that of the conventional LED (four conventional encapsulated LEDs in series, with the same chip size and luminescence area). The HV LED exhibited very good p–n junction behavior (lower resistance contacts). At a driving current of 20 mA, the forward voltages were about 12.43 V. The conventional LEDs show the nearly same voltage, while the characteristics are very bad, which can be seen from the inflection point of the graph. To further study the influence of the deep etching on the samples, we also measured the light output power at a driving current of 20 mA. We found that the measured output power at room temperature for the HV LED and the conventional LED are 248 mW and 243 mW, respectively. This enhancement of 5 mW was attributed to relatively concentrated luminescence of the HV LED. The results show that the HV LED based on the ICP deep etching has a better structure and a higher light extraction efficiency.

At present, Epistar is the only manufacturer that fabricates a HV LED. For a comparison, five chips were selected and encapsulated under the same conditions, and then were measured. The mean value of the five LEDs was calculated and obtained. The HV LEDs produced by us and Epistar were marked as samples A and B, respectively. Table 2 shows the comparative data produced. From the data, we found that our products have better optical properties, including a higher luminous efficiency and a higher output power. Furthermore, the light output decays by almost the same value after 1000 h (it is only higher by 1%), which means it has good reliability and stability.

Table 2. Comparative data for samples A and B.

HV LED @ 20 mA	Sample A	Sample B
Forward voltage (V)	12.43	12.00
Flux (lm)	2.29	2.15
Output power (mW)	248	240
Luminous efficiency (lm/W)	10	9.5
Contact resistance (Ω)	64.47	62.83
Degradation after 1000 h	$\leqslant 3\%$	$\leqslant 2\%$

4. Summary

A HV LED with two-step ICP deep etching of GaN is designed and fabricated. A 5 μm deep isolation groove and an acceptable mesa sidewall angle of 79.2° are presented through laser microscopy and SEM images. In order to compare it with the traditional LED, four packaged dependent LEDs were connected in series with the same lighting area and chip size. At a driving current of 20 mA, the forward voltage of 12.43 V is obtained. Furthermore, the contact resistance and output power of the HV LED can achieve 64.47 Ω and 125 mW, which are reduced by 4.6 Ω and increased by 5 W, respectively, when compared with the results of the conventional LED. The results show that it can be applied to practical fabrication.

References

[1] Shul R J, McClellan G B, Casalnuovo S A, et al. Inductively coupled plasma etching of GaN. Appl Phys Lett, 1996, 69(8): 1119

[2] Song I J, Lee S K, Lee K, et al. Properties of etched Ga- and N-faces of freestanding GaN substrate using inductively coupled plasma-reactive ion etching. Jpn J Appl Phys, 2002, 41(3B): L317

[3] Kao C C, Kuo H C, Yeh K F, et al. Light-output enhancement of nano-roughened GaN laser lift-off light-emitting diodes formed by ICP dry etching. IEEE Photonics Technol Lett, 2007, 19(11): 849

[4] Huang H W, Lin C H, Yu C C, et al. Investigation of GaN-based vertical-injection light-emitting diodes with GaN nano-cone structure by ICP etching. Mater Sci & Eng B, 2008, 151(3): 205

[5] Han Y, Xue S, Guo W, et al. Characteristics of n-GaN after ICP etching. Proceedings of the SPIE, the International Society for Optical Engineering, 2002, 4918: 193

[6] Wang P, Cao B, Gan Z, et al. A study of GaN-based LED structure etching using inductively coupled plasma. Journal of Physics: Conference Series, 2011, 276(1): 012082

[7] Lin F, Shen B, Lu L, et al. Identification and elimination of inductively coupled plasma-induced defects in $Al_xGa_{1-x}N$/GaN heterostructures. Chin Phys B, 2011, 20(7): 77303

[8] Gao Wei, Guo Weiling, Zhu Yanxu, et al. Reliability of AlGaInP light emitting diodes with an ITO current spreading layer. Journal of Semiconductors, 2009, 30(6): 064004

[9] Meng Lili, Chen Yixin, Ma Li, et al. ICP dry etching ITO to improve the performance of GaN-based LEDs. Journal of Semiconductors, 2011, 32(1): 014010

[10] Qiu Rongfu, Lu Hai, Chen Dunjun, et al. Optimization of inductively coupled plasma deep etching of GaN and etching damage analysis. Appl Surf Sci, 2011, 257(7): 2700

[11] He Anhe, Zhang Yong, Zhu Xuehui, et al. Improved light extraction of GaN-based light-emitting diodes with surface-textured indium tin oxide electrodes by nickel nanoparticle mask dry-etching. Chin Phys B, 2010, 19(6): 068101