Extraction Efficiency Enhancement of GaN-Based Light-Emitting Diodes by Microhole Array and Roughened Surface Oxide

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***Abstract*—The light-output power of GaN-based light-emitting diodes (LEDs) was enhanced by microhole array pattern and roughened GaO_x film grown on the exposed surface. The GaO_x film was grown by photoelectrochemical (PEC) oxidation via H_2O and formed a naturally rough oxide surface and GaO_x/GaN interface. Compared with that of conventional broad-area LEDs, the output power of the microhole array LED and the surface-oxidized microhole array LED increased by 1.38 and 1.82 times at 20-mA forward current, respectively. The results show that the microhole array pattern with the roughened surface oxide method could significantly enhance light extraction efficiency and be a candidate for manufacturing high-efficient low-cost GaN-based LEDs.**

***Index Terms*—Extraction efficiency, GaN, light-emitting diode (LED), photoelectrochemical (PEC).**

I. INTRODUCTION

DUE to their property of wide direct bandgap and application for blue and ultraviolet (UV) wavelength regions, III-nitride based materials are widely used to produce light-emitting diodes (LEDs) and laser diodes (LDs). In recent years, high-efficiency GaN-based LEDs have attracted much interest because of their wide-ranging applications, such as traffic lights, full-color displays, optical storage, and solid-state lighting [1]. However, the total light output from these LEDs is still rather low since the critical-angle limitation is about 23.5° between GaN $(n = 2.5)$ and air $(n = 1)$. Only about 4% of the light emitted from the LED active region can escape from the surface of the LED, and the light reflected at the wafer surface will be absorbed after multiple internal reflections in the LED structure. Many papers have discussed methods to increase light extraction efficiency [2]–[7], with most studies focusing on surface roughness and geometric shaping of LED chips. Some groups have reported high-performance GaN-based microdisk and micro-ring LEDs [8]–[11]. These μ-LEDs had higher light-output efficiencies than their conventional broad-area LED counterparts. The higher extraction efficiency of μ-LEDs resulted not only from the reduced (re)absorption of light on the micrometer scale but also from enhanced scattering that was attributed to the etched sidewall structure. However, the output light from the microhole LED still encountered an obstacle of the small light–escape ratio for the high difference of indices between GaN or InGaN and air. Most of the light emitted by the active region will be subject to total internal reflection. In this letter, we used a microhole array structure on an LED to increase the exposed area of multiple quantum wells (MQWs) and covered a roughened GaO_x film on the exposed etched sidewall surface to enhance the extraction efficiency of InGaN-based LEDs. The roughened oxide film grown on the etched sidewall surfaces of the microhole array LED structure was formed by the photoelectrochemical (PEC) oxidation method. This native roughened oxide film on the large exposed etched sidewall surface enhances light extraction efficiency without suffering from the adhesion problem and further provides an efficient surface passivation for devices [12].

II. DEVICE FABRICATION

Conventional InGaN-based LED samples were grown on c-plane sapphire substrates by metal–organic chemical vapor deposition. The LED structure contains a 2-μm-thick undoped GaN layer, a 2-μm-thick Si-doped n-GaN layer, a ten-period InGaN (3-nm)/GaN (7-nm) MQW active layer, and a 0.2-μm-thick Mg-doped p-GaN. The emission wavelength of this LED is 460 nm. The process of the InGaN-based microhole array LED began with electron-beam-evaporated Ni (5 nm)/Au (7 nm) to form a high-transparency p-type ohmic contact layer. The microhole array structure and the rectangular mesa $(350 \times 260\ \mu\mathrm{m}^2)$ were simultaneously patterned by photolithography. After removing Ni–Au layers by wet etching, the n-type layer was exposed with hole diameters of 11 μm and hole distance of 25 μm by dry etching using inductively coupled plasma reactive ion etching. Finally, Cr/Au were deposited to form p- and n-pads. A schematic structure of the microhole array LED is shown in Fig. 1(a), and a schematic cross section of the PEC-oxidized microhole array LED is shown in Fig. 1(b). Fig. 1(c) shows the geometric paths of the light emitted in a microhole array LED with and without the GaO_x film. A conventional broad-area LED with the same mesa size $(350 \times 260\ \mu\mathrm{m}^2)$ was also fabricated from the same wafer for comparison. Typical

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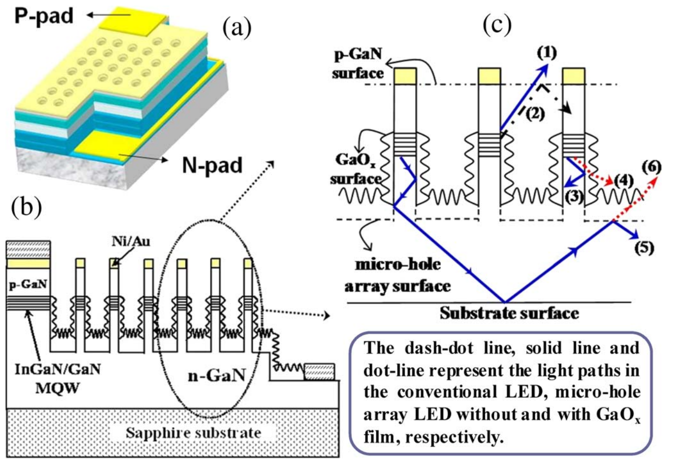

Fig. 1. (a) Schematic structure of the microhole array LED. (b) Schematic cross section of the surface-oxidized microhole array LED. (c) Light paths of the micro-hole array LED with/without GaO$_x$.

current–voltage (I–V) measurements were performed with a Keithley 238 current source. The light-output power was measured with a calibrated power meter with a Si detector (detector area of 10 × 10 mm^2) approximately 5 mm above the device, collecting the light emitted in the forward direction.

Following the $L-I-V$ measurement, microhole arrays were fabricated using the PEC oxidation process. A GaO$_x$ film was grown on the GaN surface by PEC oxidation in deionized (DI) water with 5-V bias. Under this bias, PEC oxidation would not affect the top-current-spreading contact layer. Using DI water as the PEC oxidation solution instead of the more commonly used KOH or H$_3$PO$_4$ solution ensures that the oxide film was not etched after it formed [13]. Microhole array LED devices were illuminated under 500-W UV light source with PEC process time of 20 min. After completing the PEC process, the $L-I-V$ measurement was performed on microhole array LEDs.

III. RESULTS AND DISCUSSION

Fig. 2(a) and (b) shows the scanning electron microscope (SEM) cross-sectional images of a microhole without and with the surface oxide film, respectively. An oxide layer was grown on the surface of n-GaN and GaN/InGaN MQWs after the PEC oxidation process. The GaO$_x$ layer thickness in Fig. 2(b) is estimated to be approximately 100 nm thick. Compared with the etched surface of the microhole array LED sample before PEC oxidation, the PEC-oxidized surface and the interface of GaO$_x$/GaN are rough. Fig. 2(b) shows that there is almost no oxide film on the exposed p-type GaN surface since the oxidation rate of p-type GaN is much slower than that of n-type GaN and InGaN.

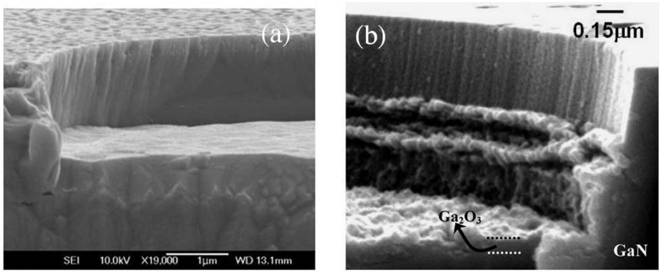

Fig. 2. SEM image of the etched sidewall and surface of the microhole (a) without and (b) with a GaO$_x$ oxide film, respectively.

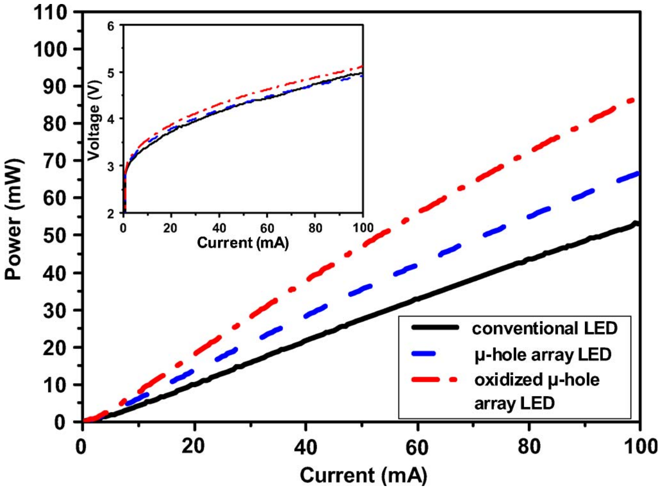

Fig. 3. $L-I$ characteristics of conventional microhole array and surface-oxidized microhole array LEDs after a 20-min PEC process. The inset shows the I–V characteristics.

Fig. 3 and the inset show the I–V and $L-I$ characteristics of conventional microhole array structure and PEC-oxidized microhole array structure LEDs, respectively. The forward voltages V_F's of conventional LEDs, microhole array LEDs, and surface-oxidized microhole array LEDs biased at 20 mA were 3.72, 3.78, and 3.87 V, respectively. The V_F's of microhole structure and surface-oxidized microhole LEDs are slightly higher than that of conventional LEDs, which might result from reduction in the total active area. Furthermore, the V_F of the microhole array LED with PEC oxidation is higher than that without PEC oxidation. This phenomenon might be caused by a slight deterioration in ohmic contacts due to oxide film growth on the periphery of the contact. Fig. 3 shows that the light-output power of the microhole array LED is 38% greater than that of the conventional LED at a bias current of 20 mA. Notably, the $L-I$ characteristics also show that the light output of the surface-oxidized microhole array LED is 82% greater than that of the conventional LED and 33% greater than that of the microhole array LED at 20-mA forward current. The light-output enhancement of the microhole array LED with and without the surface oxide film might be partial from higher current density with etched holes and partial from enhancement of extraction efficiency. By considering LEDs biased at the same current density of 2×10^4 mA/cm^2, the light-output power of the microhole array LED and that of the surface-oxidized microhole array LED are 28% and 66% greater than that of the conventional LED, respectively. The light-output enhancement mechanism is schematically shown in Fig. 1(c). In a conventional LED, most of the output light will be reflected at the interface between p-type GaN and air due to the critical angle shown by path (2). Alternatively, the microhole array structure could expose large MQW sidewall areas, resulting in increased escape opportunity for photons [i.e., path (1)] and

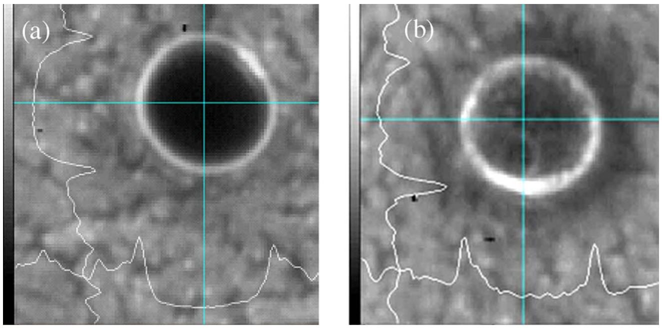

Fig. 4. Beam-view image of the single microhole structure (a) without and (b) with a GaO_x film on the surface.

reduced (re)absorption of light in the microhole array structure. Consequently, applying the microhole structure to LEDs would increase the output power compared to conventional LEDs. The increased light output of surface-oxidized microhole array LEDs might be due to the intermediate GaO_x film on the etched sidewall surface of GaN and GaN/InGaN MQWs in the holes and mesa region. Although the microhole structure can increase the exposed sidewall area of MQWs, the problem of critical-angle limitation between GaN-based materials and air still exists. The occurrence of the light trapped due to critical-angle limitation is shown in path (3) of Fig. 1(c). The GaO_x film grown on the surface of the GaN-based material will increase the roughness of the interface between the oxide film and the GaN/InGaN layers, as shown in Fig. 2(b). This increased roughness would increase the light–escape opportunity to enhance light extraction efficiency. Path (4) of Fig. 1(c) shows that the light–escape opportunities result from the roughened GaO_x surface or GaN–GaO_x interface of the microhole array LED.

Fig. 4(a) and (b) shows the emission images and the intensity profile of a single hole in a microhole array LED and a surface-oxidized microhole array LED at an operating current of 20 mA, respectively. A bright luminescence ring is observed at the periphery of both holes from Fig. 4, representing the increased light extraction from the periphery of the holes. Most of the light inside the conventional LED structure propagates laterally in the plane of p- or n-type layers [i.e., path (2) in Fig. 1(c)], but could be extracted from the etched sidewall of the microhole structure [i.e., path (1) in Fig. 1(c)], causing the bright emission ring at the periphery of the holes. By comparing the single-hole emission image of the nonoxidized microhole array LED [Fig. 4(a)] with that of the surface-oxidized structure [Fig. 4(b)], it is found out the surface-oxidized microhole has more a brighter image inside the hole area than the nonoxidized structure. This means that more light is being scattered from the hole areas of the surface-oxidized microhole LED. In the nonoxidized microhole LED, some light would be guided inside the n-type region like light path (5) for the internal reflection, as shown in Fig. 1(c). The GaO_x film on the sidewall and the etched surface of the microhole LED could reduce the guided mode because of the rough GaO_x surface or interface of GaO_x/GaN and couple out more light like light path (6) in Fig. 1(c). Therefore, the surface-oxidized microhole LED has a brighter image inside the hole area than the nonoxidized structure.

IV. CONCLUSION

High extraction efficiency of GaN-based LEDs with a microhole array pattern and a native roughened surface oxide film was demonstrated. The light-output power of the surface-oxidized microhole array LED is 82% greater than the conventional broad-area LED at an operating current of 20 mA. The $L-I-V$ characteristic measurement reveals that the microhole array and PEC oxidation processes do not degrade the I–V characteristics of conventional LEDs and could enhance the light-output power of the GaN-based LED. From the emission images of a single hole of microhole LEDs with and without surface oxidation, the images reveal that the microhole array LED with a GaO_x oxide film could extract more light than the conventional LED. This surface-oxidized microhole array LED could be a candidate for fabricating high-power/high-efficiency or white-light LEDs.

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