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Enhanced light extraction from InGaN/GaN-based light emitting diodes epistructure with ICP-etched nanoisland GaN:Mg surface

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Abstract. A simple and effective method is presented to fabricate surface-roughened InGaN/GaN-based light emitting diodes (LEDs) epistructure using annealing-formed, random-distributed Au particle arrays as dry etching mask. The shapes of GaN nanoislands, with horizontal diameters of 100–500 nm and vertical depths up to 140 nm, are determined by Au mask particles. Importantly, this roughened surface exhibits strong photoluminescence (PL) light-output enhancement by a factor of more than 1.6 orders of magnitude. This method will put forward new promising applications in the electroluminescent devices, especially in solid state lighting.

1 Introduction

Light emitting diodes (LEDs), in particular III-nitride LEDs, have progressed from being low-power indicators to high-power light sources [1]. High-brightness GaN-based LEDs for visible-spectrum light emission yield many potential applications in outdoor displays, automotive forward lighting, and backlighting of liquid crystal display, even solid-state lighting as an "ultimate lamp" for the future [2]. However, the low light-extraction efficiency is the bottleneck for high-power LEDs. For GaN-based LEDs, the refractive indexes of GaN (n_{GaN}) and air (n_{air}) are 2.5 and 1, respectively [3–5]. In this case, the critical angle for the light generated in the active region to escape is about 23°, and only a small fraction of light can be extracted.

To further harvest the generated light trapped within the GaN, one of the main approaches is to form a random texturing on the top *p*-GaN surfaces of the LEDs. A method widely used in the industry is by intentionally growing a rough *p*-GaN layer on top of the flat *p*-GaN surface [6,7], but it means additional growth time and further cost [8]. The surface texturing can also be applied to other interfaces of the LED structure. For example, an *n*-side-up GaN-based LED with a hexagonal "cone-like" surface has been fabricated [9]. Such a process requires sophisticated manufacturing such as laser lift-off, flip-chip, and photoelectrochemical techniques. Aside from the roughening methods mentioned above, nanoscale metal clusters have also been employed as the etch mask to achieve a uniform-depth surface texture [10,11]. But it is to some extent limited because of the use of boiling phosphoric acid and aqua-regia solution as *p*-GaN is stable enough to resist the etching of ordinary acid and alkali.

In this paper, we report on the application of inductively coupled plasma (ICP) etching using metal clusters as a mask to improve light output of an InGaN-based epistructure by a microroughened *p*-GaN surface. Importantly, the photoluminescent (PL) measurement showed that the light-output efficiency of an epistructure with an ICP-roughened surface was significantly enhanced (more than 1.6 times) compared to that of the conventional structure.

2 Experimental section

InGaN-based LED epitaxial structures were grown in a Veeco metal-organic chemical vapor deposition (MOCVD) system. A sapphire substrate was heated to 1055 °C in a stream of hydrogen and the substrate temperature was then lowered to 520 °C to grow the GaN nucleation buffer layer with a thickness of about 35 nm. The 1-μm-thick unintentionally doped GaN layer and the 2-μm-thick Si-doped *n*-type GaN film have been sequentially grown at a temperature of 1055 °C and a pressure of 500 Torr. The five-period InGaN/GaN multiple quantum wells (MQWs) structures have grown at a temperature of 720 °C at 200 Torr. The active layers consisted of a 30 Å thick InGaN-well layer and a 70 Å thick GaN-barrier layer for the InGaN/GaN MQW LED structures. Subsequently, the Mg-doped *p*-type GaN films, with a thickness of 0.25 μm, were grown at a temperature of 1020 °C and a pressure

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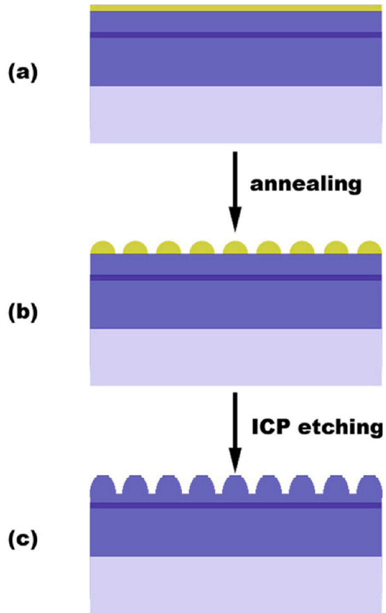

Fig. 1. (Color online) Schematic of the microroughening processing flow using Au particles as a mask for ICP etching.

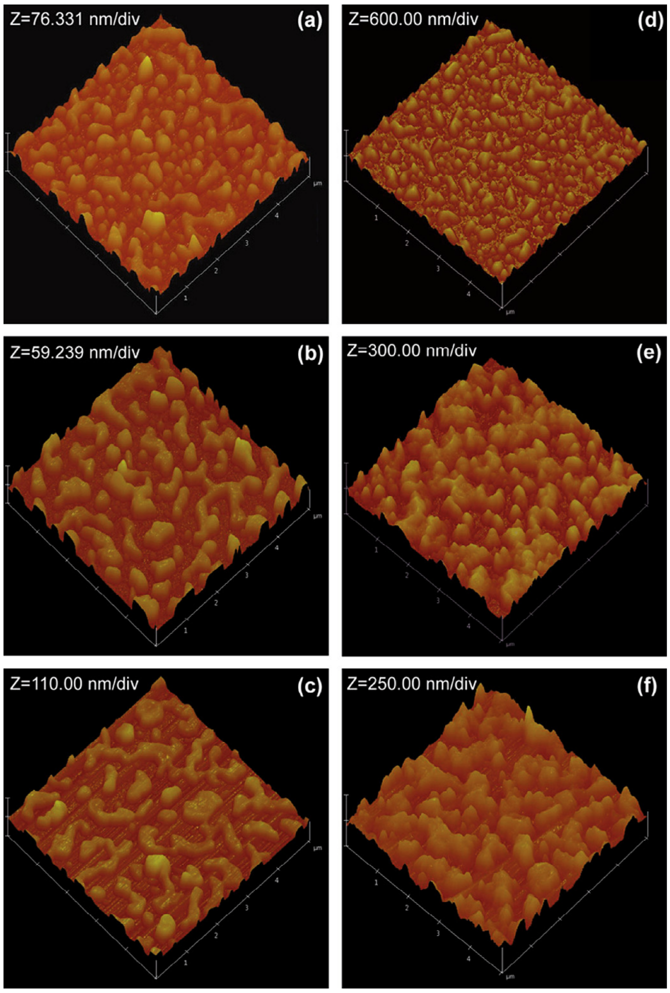

Fig. 2. (Color online) AFM scans of GaN LED surface after annealing (a–c) and after ICP etching (d–f) for 7 nm-Au, 8 nm-Au and 9 nm-Au samples respectively (all the scanned area were 5 μm × 5 μm).

of 200 Torr. The epitaxial wafer has been processed by a rapid thermal annealing at 550 °C under N_2 atmosphere.

The surface morphologies of samples after annealing and after ICP etching were examined through a Veeco Digital Instrument Dimension 3100 atomic force microscope (AFM). The photoluminescent spectra were recorded on a Hitachi F-4500 fluorescence spectrophotometer at room temperature. The emitting light field distribution mapping was obtained from a NT-MDT NTEGRA Spectra with laser confocal mode.

3 Results and discussion

3.1 Formation of microroughened p-GaN surface

The microroughening Mg doped GaN process is shown in Figure 1. Firstly, Au was deposited onto the *p*-GaN with a Hitachi E-1045 ion sputter. The deposition rate of Au was controlled at 10 nm/min and the depositing thickness was calculated from sputtering time. Here, three kinds thickness of as-deposited Au layers were adopted (7 nm, 8 nm and 9 nm). After deposition of gold, the wafer was annealed in N_2 at 520 °C for 10 min. During the annealing process, the coated Au film began to shrink owing to surface extension and finally a layer of separate Au particles were formed (Fig. 1b). After cooled to room temperature, the wafer was transported to ICP chamber. After 2 min dry etching (BCl_3 as etching gas), the area covered by Au particles was protected from been etched and uncovered *p*-GaN was etched away by accelerated Cl-based plasma. Finally, as indicated in Figure 1c, separate island-shaped *p*-GaN surface structure was formed.

It is noteworthy that Cl_2 as a commonly used etching gas for GaN was totally forbidden because Cl_2 has a obvious etching effect on metal (including Au) and may result in the invalidation of Au mask. In addition, the formed Au particles were not always etched away completely, especially when the deposited Au was thick. So, it is sometimes necessary to undergo a post-treatment to eliminate the left Au particles with aqua regia.

3.2 Microroughened surface morphology observation from AFM images

The surface morphology of *p*-GaN layer after annealing and ICP dry-etching was examined by AFM, as shown in Figure 2. As for all the three samples (7 nm-Au, 8 nm-Au and 9 nm-Au sample), a random distributed Au particles with a size of approximately 100−500 nm was formed after annealing at 520 °C for 10 min (Fig. 2a–2c), which is close to the emitted wavelength (450 nm) of the epitaxial wafer. The distance between two particles was about 500 nm. Section profiles obtained from AFM (not shown here) indicated that the vertical height of Au particles was 30−60 nm. The increase in height, with respect to the thickness of as-deposited gold layer, was attributed to the contract of Au film when annealing. Figures 2d–2f showed the topography of microroughened surface after both ICP etching process and removal of the remaining Au clusters. The average height of etched rough surface was about 100−140 nm. The enlarged surface roughness of etched p-GaN compared to that of gold clusters covered was due to the difference of etching selective ratio between gold and p-GaN. With respect to gold, p-GaN had a more brittle resistance to Cl-based ICP etching and 30−60 nm Au cluster can induce the formation of ca. 100−140 nm p-GaN roughening. In addition, the shape of roughened island is determined by the shape of Au cluster. So, we confirmed that the microroughening was uniformly formed on the top p-GaN surface using Au metal clusters as mask.

These size features of the etched surface could probably offer favorable escape ability of the generated photons to enhance the light extraction efficiency. However, as reported by Hsieh et al. [8] and Huh [10], their average roughness of etched surface was less than 10 nm and 70 nm, respectively. Their light-outputs were enhanced by 52.4% and 27.9%. Herein our etched depth is about 140 nm for more than 1.6-fold increased light extraction. So, the optimal roughness is a disputable question and need further investigation.

Other larger thickness of Au was also checked, but it was difficult to form separate Au islands after annealing. And the higher annealing temperature or longer time may cause the inter-diffusion of MQWs elements, resulting in lower internal quantum efficiency. So, only less than 10 nm Au films (7 nm, 8 nm and 9 nm) were adopted in this paper.

3.3 Light extraction enhancement of microroughened epistructure

To investigate the influence of microroughened p-GaN surface on light extraction, we measured the PL light output intensity from both the front side (top side, Fig. 3) and backside (substrate side through the sapphire, Fig. 3 inset) of conventional and etched epistructure excited with Xe lamp at 385 nm. The peak wavelengths of the four samples are around 450 ± 5 nm. To eliminate the effect of epitaxial ununiformity, the intensities of back side detection were collected for calibration. The intensity ratio detected from back side is 3.3:1.9:0.88:1 for 9 nm-Au, 8 nm-Au, 7 nm-Au and conventional sample, from which we can see a relatively large difference. However, when the PL intensities were collected from the front side, this negative effect was removed artificially. The peak intensities of microroughened surface had an increase of about 6.7, 3.0 and 1.5 folds for 9 nm-Au, 8 nm-Au and 7 nm-Au compared to that of the conventional. To sum up, after divided by the back side data, the intensity of top side detection has a great rise of about 2, 1.6 and 1.7 times respectively. This clearly demonstrated the enhanced light extraction of surface-roughened structure.

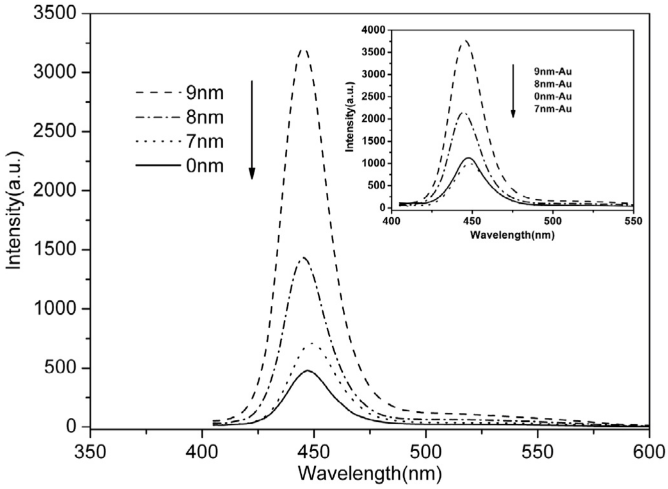

Fig. 3. Photoluminescent spectra (top detection) of conventional and surface-rougheded p-GaN for 7 nm-Au, 8 nm-Au and 9 nm-Au samples respectively (insert: bottom detection for calibration purpose).

Furthermore, the 8 nm-Au sample was selected for light field distribution mapping and the result was displayed in Figure 4. It should be mentioned that a photoresist pattern was positioned on the surface of conventional epistructure after annealing but before ICP etching. When etching, the region covered by photoresist was protected from been etched and the other region was etched to form microroughened structure. When the light field mapping of 8 nm-Au sample was recorded, the region covered by photoresist (namely not etched surface region) showed relatively weak light intensity compared to roughened surface as shown in Figure 4a. For comparison purpose, two points (marked in Fig. 4a with two crosses) from protected surface and etched surface were selected respectively to demonstrate the effect of surface roughtening. It is obvious in Figure 4b that the point on protected region had a lower PL intensity and the point from roughened surface with intensity of as high as 1.5 times, nearly consistent with the value estimated from Figure 3. This may mean that the roughened surface indeed had a function of enhancing light extraction. It is interesting that there existed two black spot, as marked in Figure 4a with two circles. This may arise from the dislocations in GaN layers.

It is obvious that the ICP-etched depth rises with the increasing size of Au particles under the same etching conditions. As for 7 nm-Au and 8 nm-Au samples, the maximal depth etched is about 60 and 100 nm. The effect of roughening was not so obvious and there was only an increase of PL intensity about 1.6 times. But for the 9 nm-Au sample, the mask can act effectively and the maximum of etched depth is about 140 nm. To our surprise, the result shows that the light extraction was enhanced by 2 folds due to the rougher surface. In addition, the textured p-GaN partially reduces the piezoelectric effect, which may attribute to enhance the light output power.

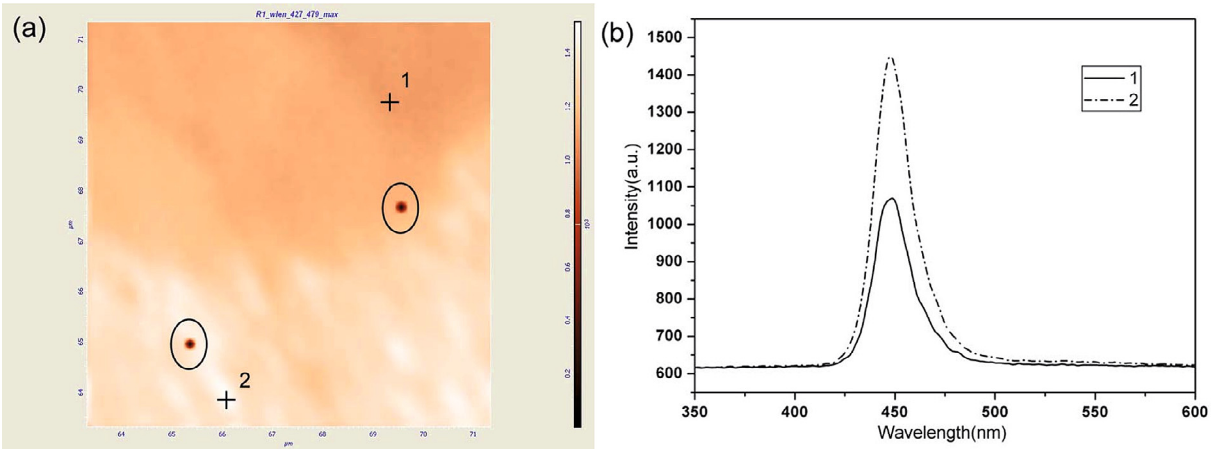

Fig. 4. (Color online) (a) Photoluminescent light intensity mapping of 8 nm-Au sample exited with 325 nm laser, (b) photoluminescent spectra of spot 1 and spot 2 as marked in Figure 4a.

The improvement of light-extraction efficiency can be attributed to the surface roughening in the GaN-air interface, as the roughened top surface was considered to give the photons multiple chances for the generated photons to reach the air-semiconductor interface within the angle of the escape cone for the textured surface. Forming a roughened surface in the *p*-GaN layer requires the plasma dry etching, resulting in plasma damage to the *p*-GaN layer and sometimes even in the MQWs layer. Many groups have reported that the electrical characteristics of LEDs containing etched structures were degraded due to etching damage to the *p*-GaN and reduction of the effective ohmic contact area owing to 2D etched hole array. Here our experimental data showed the same result and this challenge will be settled in the forthcoming future such as annealing in N_2 or NH_3 atmosphere [12,13].

4 Conclusions

In summary, using annealing-formed Au clusters as a dry etching mask, we presented a simple and effective method to roughen *p*-GaN surface. The thicker deposited Au produced larger Au particles and the formed roughened *p*-GaN islands showed an etched depth of about 140 nm. Importantly, the PL intensity of InGaN-based MQWs was increased by a factor of 1.6−2 orders. After solving the problem of dry etching damage, this microroughening method may be a promising solution to enhance the light extraction from LED surface.

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