Improved light extracion efficiency in AlGaInP-Based Diodes (LEDs) by applying a nanohole structure on GaP window layer

MA Li*, JIANG Wen-Jing, ZOU De-Shu, Meng Li-Li, SHEN Guang-Di
Key Laboratory of Opto-electronics Technology (Beijing University of Technology), Ministry of Education, Beijing University of Technology, 100 Ping Le Yuan, Chaoyang District, Beijing 100124, China

Email: mali@emails.bjut.edu.cn

Abstract: In this letter, to enhance light efficiency of AlGaInP-based LEDs, a nanohole structure was applied to GaP window layer by using self-assemble metal layer nano-masks and inductively coupled plasma (ICP). This method has the potential advantage because both the size and density of the nanoholes are controllable. The density of nanoholes varied from $5 \times 10^8$ to $2.8 \times 10^8$ cm$^{-2}$ and size varied from 180-430 nm while increasing rapid thermal annealing temperature from 350-500°C. By using this surface texturing method, the light intensity and light output power of AlGaInP-based LEDs with textured surface (LED-Ⅱ) increases 27% and 15% comparing to LEDs with flat surface (LED-Ⅰ), respectively.

1. Introduction

High-performance AlGaInP-based LEDs have been widely used for many applications such as traffic lights, full color-displays and general lighting[1,2]. As we know, the internal quantum efficiency of AlGaInP-based LEDs has closely approaches 99%, but light extraction efficiency is still restrained by the large difference in the refractive index between the GaP window layer($n=3.2$) and

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Email: mali@emails.bjut.edu.cn Tel: +86 01067391641-842 Fax: +86 01067391641-822

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air(n=1)[2]. Considering this large distinction, only about 2.5% of internally emitted light from the active region can escape from the surface of GaP window layer[3].

Roughening the top surface of an LED is one of the methods for improving the light extraction[4], lots of surface texturing techniques have been extensively reported. Jian-Jhong Chen et al fabricated LEDs with nano-mesh ZnO layers, where the nano-mesh ZnO were uniformly arranged on the top surface of the GaP window layer[5]. Liang-Jyi Yan applied a periodic texture surface using photolithography and a wet etching process, the exterior of the etched texture consist of a series of bowl-shaped recesses [6].

These surface texturing were all designed as the fixed periodic, but for GaP material itself, fixed sidewall angle is hard to fabricate and repeat, so random roughed surface profile is a much more attractive method for producing devices without the need for expensive lithography. So in this paper, we reported a method of fabricating GaP nanohole window layer in AlGaInP based LEDs using self-assemble metal nanomask and inductively coupled plasma (ICP).

2. Experiment

The schematic cross section graphs of the AlGaInP LEDs is shown in Figure 1. The wafers were epitaxially grown on (111) GaAs substrates by metal-organic chemical vapor deposition (MOCVD) system. The LED structure consist of AlGaAs- AlAs DBR, n-AlGaIn0.5P cladding layer, an undopted (Al0.5Ga0.5)In0.5P- (Al0.1Ga0.9)In0.5P multiple-quantum well active region with dominate wavelength of 620 nm, a p-AlGaInP cladding layer and a 0.5 μm-thick p-GaP layer.

![Figure 1. Schematic cross section graphs of AlGaInP LEDs](image)

The process flowchart to form nanohole GaP window layer is shown in Figure 2(a). First, 30 nm SiO2 film layer was deposited on the surface of GaP by Plasma Enhanced Chemical Vapor Deposition. The SiO2 film layer can smooth the surface of GaP layer so that the nanomasks can form uniformly, and it also can prevent the metal atom from diffusing into GaP after rapid thermal annealing (RTA). Then, a 10 nm Au film layer was sputtered on the SiO2 thin film. All the samples were subsequently sent to RTA under flowing N2 at temperature 350-500 °C for 1 min. After RTA, the Au film would form self-assemble intermittent nano-partical because of the tension, as shown in Figure 2(b). Then, all the samples with nanomasks were etched by ICP system. The depth etched by ICP must control in
about 100 nm so that surface texturing can give efficient light extraction without damaging the electrical or optical properties of the material [7]. After the etching progress, the residual metal on the surface was removed by diluted KI liquor, and SiO$_2$ was etched by HF liquor, remaining many nanoholes on the GaP window layer, shown in Figure 2(c), the size and density of the nanoholes were estimated by the scanning electron microscope (SEM).

![Diagram](image)

**Figure 2.** (a) Schematic illustration of the nanohole GaP window layer’s process; (b) SEM of surface morphology after RTA; (c) SEM of nanohole on GaP window layer

3. **Results and Discussion**

The rapid thermal annealing temperature need to be chosen above 300 ℃ to form Au self-assemble nano-masks. The samples were annealed at between 350 ℃ to 500 ℃ for 1 min. Figure 3(a) (b) (c) and (d) displays SEM images of GaP nanohole window layer of the samples annealed at 350 ℃, 400 ℃, 450 ℃ and 500 ℃, respectively. Figure 3(e) shows the dependence of density and mean size of the nanohole on annealing temperature. The mean size of the nanohole increases from about 220 nm to 430 nm when the temperature rises from 350 ℃ to 500 ℃. The densities decrease from $5 \times 10^8$ cm$^{-2}$ to $2.8 \times 10^8$ cm$^{-2}$ as well. At 350 ℃, the temperature is too low to produce enough tension for Au thin film forming self-assemble nano-masks, so nanohole formed at this temperature is much smaller than the others. When temperature rises, Au thin film can rupture adequately, the apertures between Au nano-masks become larger, so after ICP etching, size of the nanoholes increases with the rising of temperature.
Figure 3. SEM images of GaP nanohole window layer of samples annealed at: (a) 350 °C; (b) 400 °C; (c) 450 °C; (d) 500 °C; (e) The dependence of density and mean size of the nanohole on annealing temperature.

Jelena Vuckovic demonstrated that good dispersion appears on the textured surface while surface texturing dimension is half of the wavelength [8]. So we selected the sample which was annealed at 450 °C for 1 min to finish the process of the LED devices. This type of LED is named LED-II. Meanwhile, conventional LEDs without surface texturing (named LED-I) were also fabricated for comparison.

Comparison of measured current-voltage (I-V) of LED-I and LED-II is shown in Figure 4. Under an injection current (I_F) of 20 mA, the measured forward voltage (V_F) of LED-II is 2.15 V, which is relatively high compared to 2.10 V of LED-I. To understand the damage effect of ICP process, the dynamic resistances were extracted from the I-V characteristics. The series resistance for LED-I and LED-II were approximately 10.22 and 10.72 Ω at the injection current of 20 mA. The forward voltage and the series resistance of LED-II were a little larger than that of LED-I. It indicates that ICP etching may lead to some plasma damage on the surface of p-GaP window layer, but these differences are so tiny that they can not effect properties of LED devices.

Figure 4. Typical I-V characteristics of LEDs with textured surface and LEDs with flat surface.
Figure 5 (a) shows the possible photon paths at the interface between p-GaP and surrounding air for LEDs without surface texturing. For a LEDs with a microroughened p-GaP top surface, the angular randomization of photons can be achieved by surface scattering from the microroughened top surface of the LED, as shown in Figure 5(b). The light extraction efficiency of LEDs enhanced by surface roughness is shown in Figure 5(c). It shows the experimental light output power and light intensity versus the current for these two kinds LEDs. As Figure 5(c) shows, the light intensity and light output power of LED-II increases about 27% and 15% compared to LED-I at 20 mA, respectively. This indicates that the method of fabricating GaP nanohole window layer is powerful for light extraction enhancement. Moreover, it has the potential advantage because both the size and the density of the nanoholes are controllable.

![Figure 5](image)

**Figure 5.** (a) Possible photon paths at the interface between the p-GaP surface and air; (b) The LED structure with a microroughened surface, the photons can be escaped out from the LED to air; (c) Light output power and light intensity versus the current in the flat surface and textured surface LEDs

4. Conclusion

In summary, GaP nanohole window layer was fabricated by using self-assemble metal nano-mask and inductively coupled plasma. Both the size and density of the nanoholes are controllable. By using this nanohole structure in AlGaInP-based LEDs, light intensity and light output power increases about 27% and 15% at 20 mA, respectively. To deep study the temperature and time of RTA, ICP etching condition, better result can be obtained.

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