Improved light extraction in AlGaInP-based LEDs using a self-assembly metal nanomask*

Jiang Wenjing(蒋文静), Xu Chen(徐晨)†, Shen Guangdi(沈光地), Fang Rong(方瑢), and Gao Wei(高伟)

(Beijing Optoelectronic Technology Laboratory, Institute of Electronic Engineering and Information, Beijing University of Technology, Beijing 100124, China)

Abstract: This paper reports a new method of fabricating AlGaInP-based nanorod light emitting diodes (LEDs) by using self-assembly metal layer nanomasks and inductively coupled plasma. Light-power measurements indicate that the scattering of photons considerably enhances the probability of escaping from the nanorod LEDs. The light-intensity of the nanorod LED is increased by 34% for a thin GaP window layer, and by 17% for an 8 μm GaP window layer. The light-power of the nanorod LED is increased by 25% and 13%, respectively.

Key words: AlGaInP-LED; nano-mask; light power
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1. Introduction

The light-emitting diode (LED) market is growing rapidly, because of the increased demand for larger and more efficient displays used in handsets, notebook PCs, and televisions, and the rise in new applications coming out of the industrial and automotive segments. Now the internal quantum efficiency of AlGaInP LEDs can have values close to 99%[1], but because the escape cone is only 17° and half of the generated light is absorbed by the GaAs substrate, the extraction efficiency of a standard LED is quite poor.

There are a variety of approaches to enhance the extraction efficiency, such as thick window layers, incorporating a distributed Bragg reflector (DBR), truncated-inverted-pyramid (TIP) LEDs, thin-film LEDs by removing GaAs substrate, photonic crystal LEDs and all kinds of surface texture[2, 3]. But the DBR is only effective at restricted angles, and TIP and thin-film LEDs are high cost and low production[4, 5]. So the surface texture has recently become a hot research issue for its simple process and low cost. Textured surfaces have been divided into fixed structure and random profile[6, 7]. For the GaP material itself, a fixed sidewall angle is hard to fabricate and repeat, so a random roughened surface profile is a much more attractive method for producing devices without the need for expensive lithography.

In this paper, we report a technique to fabricate AlGaInP-based nanorod LEDs with controllable dimensions and densities using a self-assembly metal nanomask and inductively coupled plasma (ICP).

2. Experimental details

Figure 1 shows schematic cross section graphs of quaternary AlGaInP LEDs. The LEDs employed in this report were grown by low-pressure MOCVD (Vecco D150) on a nominally (100) plane 15° off toward to the [111] direction n^+-GaAs substrate. The AlGaInP LED consists of the following layers: $Al_{0.6}GaAs$–AlAs DBR, Si-doped n-$(Al_{0.7}Ga_{0.3})In_{0.5}P$ cladding layer, undoped active layer region of 620-nm emitting wavelength with $(Al_{0.5}Ga_{0.5})In_{0.5}P$–$(Al_{0.1}Ga_{0.9})In_{0.5}P$ multiple quantum wells, Mg-doped p-$(Al_{0.7}Ga_{0.3})In_{0.5}P$ cladding layer and Mg-doped p-GaP window layer. Two different samples were prepared, which have a less than 1 μm or an 8 μm p-GaP window layer respectively.

The process procedures of LED samples are shown in Fig. 1. First of all, to avoid damage to the ohmic-contact between the window layer and the electrode, which will induce the forward voltage to get higher, the electrode was made. Then 20 nm SiO_2 was deposited by PECVD on the surface of GaP, which ensured that metal atoms will not diffuse into GaP to absorb the light after rapid thermal annealing (RTA). Subsequently, a metal layer with thickness ranging from 5 to 10 nm was sputtered by a radio frequency dielectric sputtering system, and then all samples were sent to RTA under flowing N_2 at temperatures 400–500 °C for 1 min to form various nanometer-sized metal clusters (nanomasks)[7].

Finally, all AlGaInP-based LED samples with various metal nanomasks were then etched by the ICP system (Corial 200IL). The etchant gases were $SiCl_4$, Cl_2 and Ar[8]. After etching, the residual metal on the surface was removed by diluted KI liquor, and SiO_2 was etched by HF liquor.

3. Results and discussion

3.1. Effect of the nanomasks

To get a suitable nanomask size, different thicknesses of metal layers and different RTA temperatures were studied. Figures 2(a) to 2(c) show SEM images of an 8 nm metal layer at RTA conditions of 300 °C, 400 °C and 500 °C for 1 min, respectively. At 300 °C, the metal layer could not form clusters very well, and obviously 500 °C is the best choice. The dimension of the nanorods is about 160–200 nm, and they distribute uniformly on the surface. Because the growth temperature of an AlGaInP-based LED is about 600–700 °C, it is not advis-

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† Corresponding author. Email: xuchen58@bjut.edu.cn
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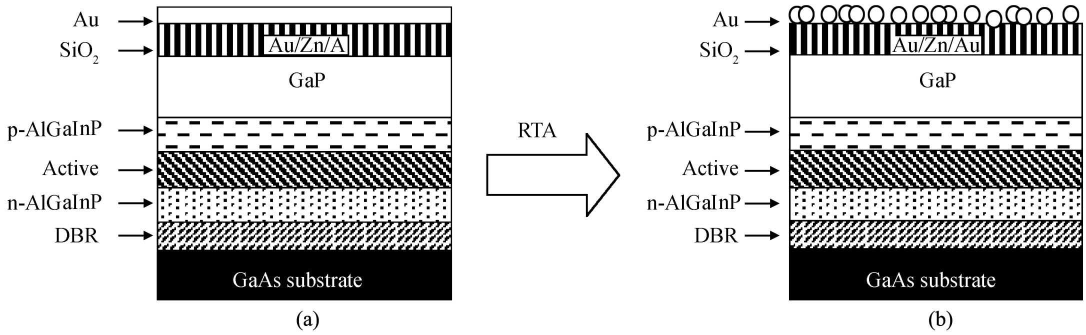

Fig. 1. Schematic illustration of the AlGaInP-based nanorod LED process. (a) Depositing SiO_2 and sputtering metal layer. (b) Metal as nanomask formation after RTA.

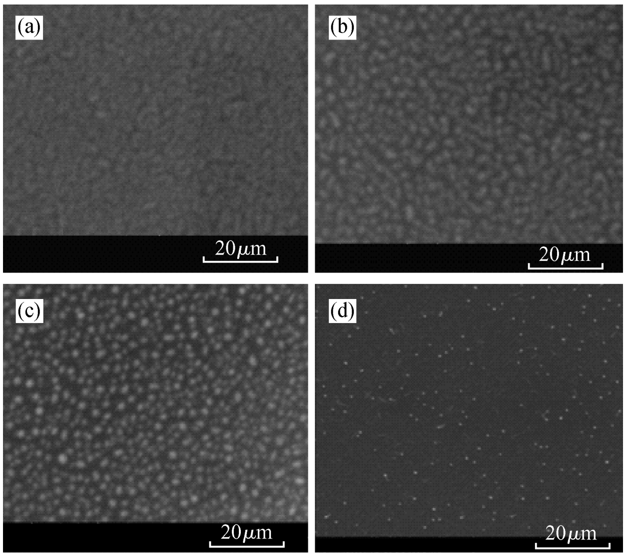

Fig. 2. (a) RTA at 300 °C for 1 min. (b) RTA at 400 °C for 1 min. (c) RTA at 500 °C for 1 min. (d) Surface profile after ICP etching.

able to adopt a higher RTA temperature, and a 5 nm layer is too thin to form a hard mask, which can go through by ICP etching. Meanwhile, if the metal layer is over 10 nm, it will be too thick to separate into the cluster.

Figure 2(d) shows an SEM image of the sample surface etched by ICP, which shows that the top surface of the GaP has formed a nano-roughened profile as a metal nanomask after RTA at 500 °C for 1 min at a fixed metal film thickness of 8 nm.

3.2. Results and discussion

The textured film geometry is schematically shown in Fig. 3; angular randomization is achieved by strong surface scattering and also increases the surface area, which can boost the external efficiency[9–11].

Figure 4 shows the characteristics of the light-power and light-intensity versus the current for the AlGaInP-based LEDs with the thin GaP and 8 μm GaP, respectively. As the figure shows, for the LED sample with 8 μm GaP etched by ICP, its light-intensity increases by nearly 17% and the light-power increases by nearly 13% compared to the normal sample without surface texture at 20 mA. For the thin GaP LED with textured surface, at 20 mA, its light-intensity increases by nearly

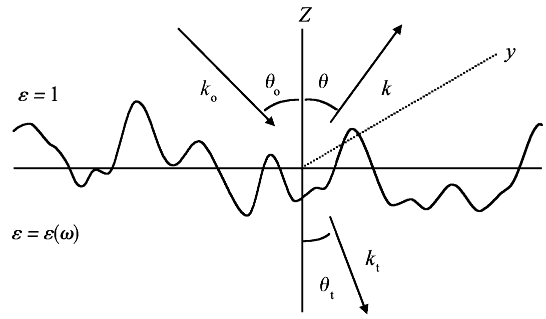

Fig. 3. Scattering geometry.

34% and the light-power increases by nearly 25% compared to the normal sample without surface texture. The results mean that the metal nanomask is very effective in enhancing the extraction efficiency of the LEDs. Meanwhile, the different samples show different characteristics although their process is the same, and the sample with the thin GaP window layer improved much more than the sample with 8 μm GaP. One reason for this phenomenon is because the surface of the thick GaP is much rougher than the thin GaP window layer, decreasing the effectiveness of the rough surface. Another reason is because the current spreading characteristics of the thick GaP are much better than the thin GaP sample.

As is well known, most studies of surface-textured LEDs present only an improvement in optical output but never the electrical properties[12,13]. So we make the electrode first. Figure 5 shows the current–voltage and leakage characteristics of LEDs with textured surface and planar surface, which are nearly the same. This also means that using a metal nanomask by ICP etching would not influence the electrical properties of the LEDs under suitable conditions.

4. Conclusion

In summary, we report a method to fabricate a controllable dimension and density of AlGaInP-based nanorod LEDs by varying the metal-mask initial layer thickness using ICP etching. For the thin GaP LED, the light-intensity was increased by 34%, and the light-power was increased by 25%; for the 8 μm GaP LED, the light-intensity was increased by 17%, and the light-power was increased by 14%. On studying the thickness of the metal layer, ICP etching and RTA conditions in depth,

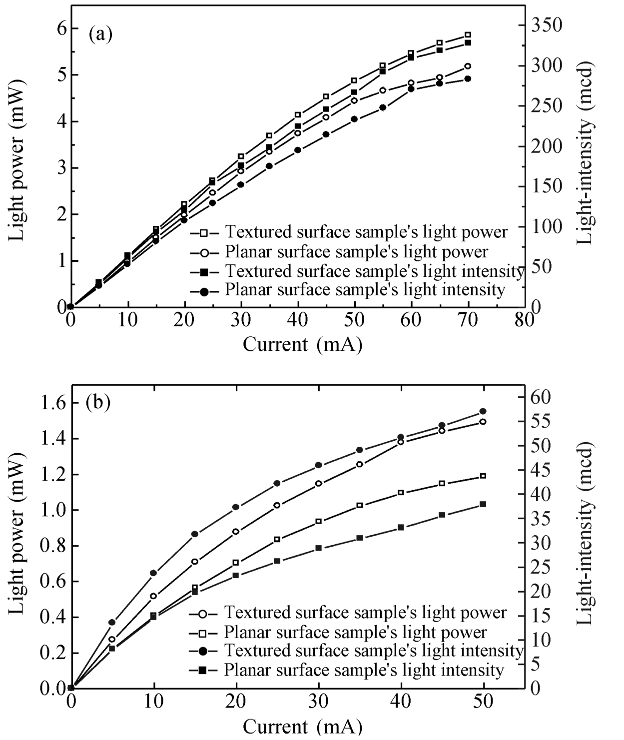

Fig. 4. Light-power and light-intensity versus current in the textured surface and planar surface LEDs with (a) 8 μm GaP or (b) with thin GaP.

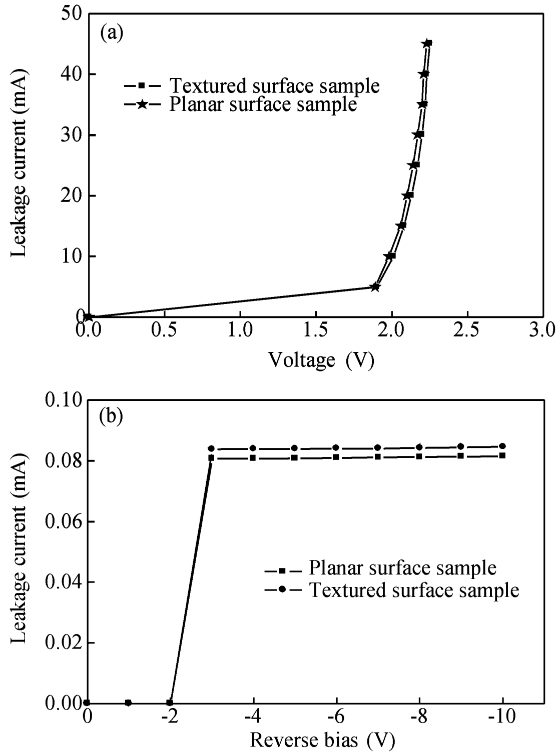

Fig. 5. (a) Current–voltage and (b) leakage characteristics of LEDs with textured surface and planar surface.

better results can be obtained.

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