Improved Performance of AlGaInP LEDs by a Periodic GaP-Dish Mirror Array

Ping-Wei Huang and Yew Chung Sermon Wu

***Abstract*—A periodic GaP-dish mirror structure was introduced into AlGaInP light-emitting diodes (LEDs) through wet etching and Si wafer bonding process. It was found that the performance of these GaP-dish LEDs was better than that of conventional LED transferred to Si substrate (LED-C). In addition, the output power of GaP-dish LEDs was increased with the decrease of GaP-dish diameter. When the GaP-dish diameter decreased to 3 μm, the output power reached 2.2 mW, which was two times higher than that of LED-C.**

***Index Terms*—AlGaInP, dish, light-emitting diode (LED), mirror.**

I. Introduction

HIGH-BRIGHTNESS AlGaInP light-emitting diodes (LEDs) have attracted considerable attention for their versatile applications in traffic signals, full-color displays, and lighting. Although the internal quantum efficiency of AlGaInP LEDs has reached near 100% [1], the light extraction efficiency is still low. This is due to the total internal reflection at the surface and the absorption of downward light by GaAs substrate. The total internal reflection problem can be solved by roughening the top surface of the LEDs [2]–[4]. The light extraction efficiency of LED was enhanced because the roughened surface provided the photons multiple opportunities to escape the LED surface. On the other hand, the absorption of GaAs substrate can be solved by using distributed Bragg reflector (DBR), mirror structure, or omnidirectional reflector (ODR) [5]–[9].

To enhance the light extraction efficiency of ODR LED, Lee *et al.* introduced a stripe patterned at the bonding interface [10]. The stripe pattern was defined on the GaP layer by the inductively coupled plasma (ICP) system. It was found that the output power of the stripe-patterned ODR LED exceeds that of the ODR LED by a factor of 1.15. Unfortunately, the forward voltage of the stripe-patterned ODR LED increased due to the reduction of the p-ohmic contact region.

In this letter, to improve light output power of LEDs, a periodic GaP-dish mirror array was introduced into the LEDs through wet etching process. It was found that the output power could be enhanced by a factor of 2. In addition, the forward voltage did not increase.

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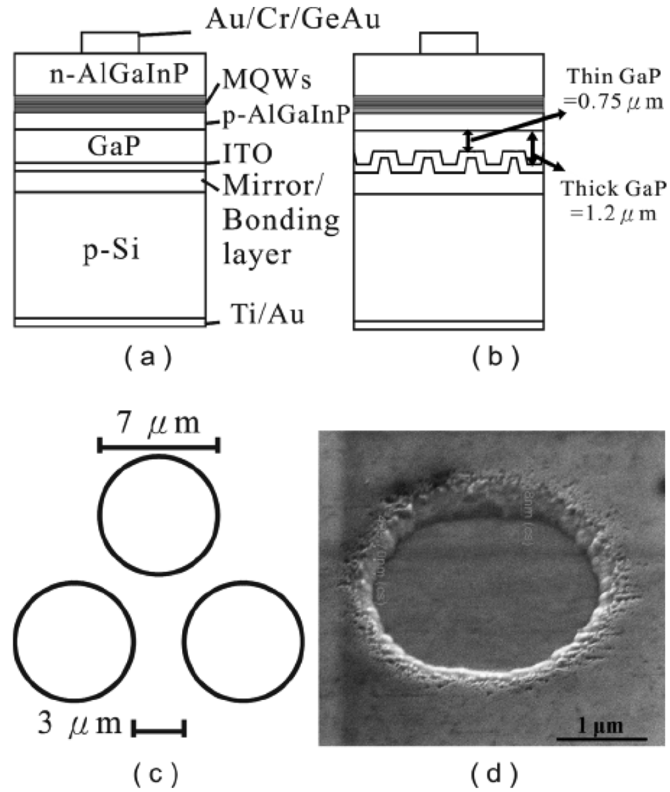

Fig. 1. Schematic illustration of LEDs: (a) LED-C, (b) GaP-dish LEDs, (c) the GaP-dish mirror array of LED-7, and (d) side view SEM image of LED-3.

II. Experiments

Two kinds of LEDs were transferred to Si substrates. Samples designated as “LED-C” were conventional LED transferred to the Si substrate. The other samples were “GaP-dish LEDs” composed of GaP-dish surfaces, as schematically illustrated in Fig. 1(a) and (b). Three types of GaP-dish LEDs were investigated. The distances between GaP dishes were all 3 μm. They were denoted as “LED-7”[7 μm diameter, as shown in Fig. 1(c)], LED-5, and LED-3, respectively.

The basic processes of these LEDs were almost the same. The AlGaInP multiquantum-well (MQW) LED structures were grown on GaAs substrates through metal–organic chemical vapor deposition (MOCVD). The GaAs structure consisted of an n-GaAs buffer layer, an n-InGaP etching stop layer, an n-GaAs ohmic contact layer, an AlInP n-cladding layer, an undoped $(Al_{0.15}Ga_{0.85})_{0.5}In_{0.5}P$ MQW active region, an AlInP p-cladding layer, and a 1.2-μm p-GaP window layer.

To fabricate the GaP-dish LEDs, the dish structure was defined on the GaP layer by the standard photolithography and subsequently etched with a chemical solution

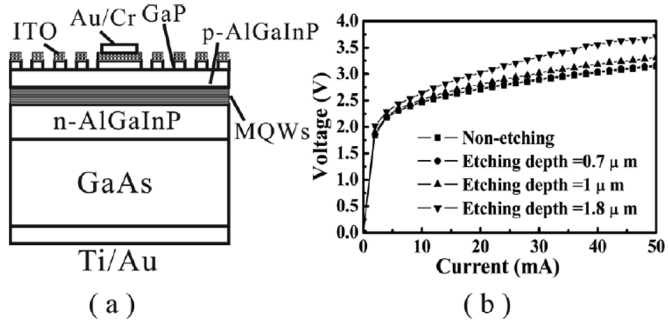

Fig. 2. (a) Schematic illustration of p-side-up LED-5 structure (before transfer to Si substrate). (b) Current–voltage characteristic of the p-side-up LED-5.

of $1.5HCl$: $1.5H_2O_2$: $7.0CH_3COOH$ for 1 min [11]. An ITO–Ni–Ag–Ni mirror system was then introduced on the etched surface to reflect the downward photons, as shown in Fig. 1(b)[12]. The mirror system consisted of a 300-nm indium–tin–oxide (ITO) current spreading layer, a 2-nm Ni layer, a 200-nm Ag metal layer, and a 2-nm Ni layer. The LEDs wafer was subsequently bonded to a Si substrate with a metal layer[13].

After the bonding process, the GaAs substrate and the InGaP etching stop layer were removed by chemical etching in solutions of $1NH_4OH$: $10H_2O_2$ and $1HCl$: $10H_2O$, respectively.

The Au–Cr–GeAu and Ti–Au were then deposited as n-side and p-side electrodes, respectively. Finally, the wafer was cut into 300 μm× 300 μm chips for the subsequent measurement. For the purpose of comparison, the performances of these LEDs were fabricated from a single LED epitaxial wafer with a split wafer experiment. The samples described herein were only cut into chips without encapsulation.

III. Results and Discussion

Before transferring to the Si substrate, the performances of LED-5 with various etching depths were investigated. Fig. 2(a) shows this p-side-up LED structure. Fig. 2(b) shows the current–voltage (*I–V*) characteristics of these LEDs. It was found that the forward voltages of LED-5 were decreased with the etching depth. This is because an increase of the GaP window layer thickness (decrease of etching depth) would improve current spreading throughout the LED area [14]. As shown in Fig. 2(b), when the etching depth was less than 0.7 μm, the forward voltage of GaP-etched LED (2.72 V) was almost the same as that of p-side-up LED-C without etching. For safety reason, the etching depth for n-side-up GaP-dish LEDs was selected as 0.45 μm.

Fig. 1(d) shows the side view SEM image of LED-3 GaP surface after wet etching. The etched dish surface was smooth, while the edge of dish structure was rough due to the side etching. The etching depth was approximately 0.45 μm. The GaP surfaces of LED-5 and LED-7 were like that shown in Fig. 1(d). The only difference was the diameter of GaP dish.

Fig. 3 shows the *I–V* characteristics of LEDs (after transfer to Si substrates). It was found that the forward voltages (at 20 mA) of LED-C, LED-3, LED-5, and LED-7 were 2.749, 2.712, 2.694, and 2.687 V, respectively. The forward voltages of three GaP-dish LEDs were all lower than that of LED-C.

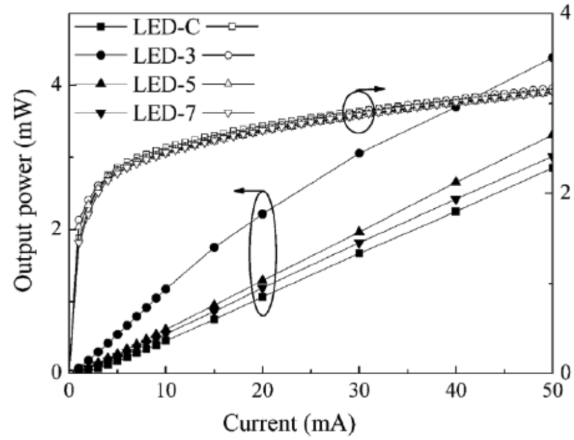

Fig. 3. Current–voltage (hollow symbols) and output power–current (solid symbols) curves of the LEDs.

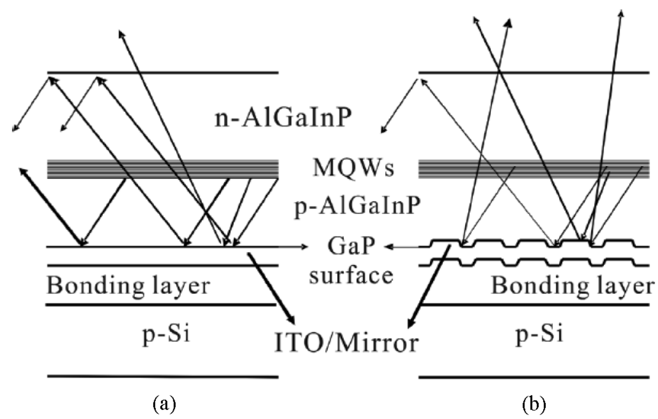

Fig. 4. Possible photon paths inside the structures of the: (a) LED-C and (b) GaP-dish LEDs.

This is because the GaP thickness above GaP-dish structure $(= 1.2 - 0.45 = 0.75\ \mu\text{m})$ was thinner than the flat unetched region (1.2 μm), as shown in Fig. 1(a) and (b). As a result, the series resistance of GaP-dish LED was lower than that of LED-C. In other words, the forward voltages of GaP-dish LEDs were all lower than that of LED-C. In addition, as shown in Fig. 1, the GaP-dish areas (thinner GaP area) increased with the diameter of GaP-dish structure since the distance among the GaP dish was all 3 μm. In other words, the series resistance decreased with the increase of GaP-dish diameter. As a result, LED-7 had the lowest forward voltage. Also, it is worth noting that the dish structures were defined using a wet method, which would not damage the surface.

Fig. 3 also indicates that the output powers of GaP-dish LEDs were higher than that of LED-C. This is because the dish structure not only reflected the downward photons to the front side, but also redirected the photons, which were originally emitted out of the escape cone, back into the escape cone, as shown in Fig. 4. In contrast, LED-C mirror could only reflect the downward-traveling light, but not necessarily redirect the photons back into the escape cone. Hence, the powers of GaP-dish LED were higher than that of LED-C.

In addition, it was also found that the powers of GaP-dish LED were increased with the decrease of the GaP-dish diameter.

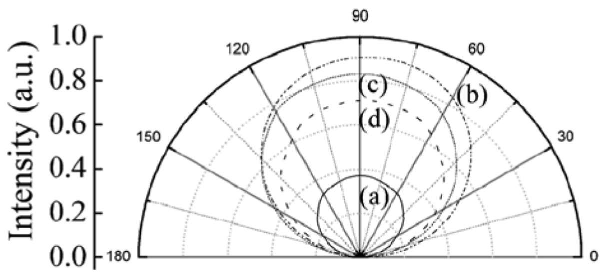

Fig. 5. Radiation patterns of LEDs: (a) LED-C, (b) LED-3, (c) LED-5, and (d) LED-7.

This is because, as shown in Fig. 1(d), only the edge of GaP-dish structure was rough due to the side etching. Only this edge area of the GaP dish could redirect the photons. The fraction of edge area (total edge areas on the GaP to the area of GaP) is given by

$$F = \frac{0.5\pi Dh}{\frac{\sqrt{3}(d+D)^2}{4}}$$

where D is the diameter of the GaP dish, h is the etching depth $(= 0.45\ \mu\mathrm{m})$, and d is the distance between GaP dishes $(= 3\ \mu\mathrm{m})$. When D decreased from 7 to 3 μm, the fraction (F) increased. As a result, the powers of GaP-dish LED were increased with the decrease of the GaP-dish diameter. When D decreased to 3 μm, the output power of LED-3 reached 2.2 mW, which was two times higher than that of LED-C.

Fig. 5 showed the beam patterns of the LEDs. The beam patterns of GaP-dish LEDs were similar to that of LED-C. This is because, as shown in Fig. 1(d), most of the GaP-dish surface area was smooth, only the edge area of the GaP-dish structure was rough.

IV. Conclusion

In summary, GaP-dish mirror LEDs were fabricated through wet etching and wafer bonding process. The etched dish surface was smooth, while the edge of the dish structure was rough. The forward voltages of GaP-dish LEDs were all lower than that of LED-C since the GaP thickness above GaP-dish structure was thinner than the flat unetched region. The output powers of GaP-dish LEDs were higher than that of LED-C because the dish structure not only reflected the downward photons to the front side, but also redirected the photons, which were originally emitted out of the escape cone, back into the escape cone. In addition, it was also found that the powers of GaP-dish LED were increased with the decrease of the GaP-dish diameter. When the diameter decreased to 3 μm, the output power of LED-3 reached 2.2 mW, which was two times higher than that of LED-C.

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