Improved light extraction of wafer-bonded AlGaInP LEDs by surface roughening*

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Abstract: By using the wafer bonding technique and wet etching process, a wafer bonded thin film AlGaInP LED with wet etched n-AlGaInP surfaces was fabricated. The morphology of the etched surface exhibits a pyramid-like feature. The wafer was cut into 270×270 μm^2 chips and then packaged into TO-18 without epoxy resin. With 20-mA current injection, the light intensity and output power of LED-I with surface roughening respectively reach 315 mcd and 4.622 mW, which was 1.7 times higher than that of LED-II without surface roughening. The enhancement of output power in LED-I can be attributed to the pyramid-like surface, which not only reduces the total internal reflection at the semiconductor–air interface but also effectively guides more photons into the escape angle for emission from the LED device.

Key words: AlGaInP; light-emitting diodes; metal bonding; surface roughening
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1. Introduction

High brightness AlGaInP light emitting diodes (LEDs) have been widely used in automobile headlights, outdoor displays, traffic lights and LCD backlights. However, the light extraction efficiency is still low. This is because of the GaAs substrate absorption and the total internal reflection at the interface. The substrate absorption problem can be partially solved by growing distributed Bragg reflectors (DBRs)[1, 2], but the DBRs can only reflect the light strongly near the vertical angle. Another approach is based on wafer bonding technology. The LED structure featured with a transferred substrate and an omni-directional reflector (ODR) have been developed to eliminate the absorption of the GaAs substrate. On the other hand, the total internal reflection problem can be resolved by roughening the top surface. Many advanced methods have been applied to decrease the internal reflection, such as photonic crystal[3] structure and moth-eye structure[4, 5].

In this study, a highly efficient wafer bonded AlGaInP LED with surface roughening is proposed to improve the light extraction efficiency. An ODR composed of GaP–SiO_2–Au was formed between the AlGaInP-based epilayer and the Si substrate to reflect the downward light. Moreover, a wet method of roughening the n-side AlGaInP is proposed. This etching process for n-side AlGaInP is simple and inexpensive. Related process steps and results will be discussed in subsequent paragraphs.

2. Experiments

A schematic cross section of the Au/Au metal bonded and surface textured LED is shown in Fig. 1. The AlGaInP LED wafers were grown on GaAs substrate by metal–organic vapor deposition (MOCVD). The epitaxial structure with dominant wavelength at 625 nm consists of an n-GaAs buffer layer, an n-GaInP etching-stop layer, an n^+-GaAs ohmic-contact layers, a 2 μm n-AlGaInP current-spreading layer, an n-AlGaInP cladding layer, an undoped AlGaInP MQW active layer, a p-AlGaInP cladding layer and a 0.6 μm thick p-GaP layer. The GaP works as a window layer and current spreading layer. After MOCVD, a $\lambda/4n$ (n = 1.45)-thick (1050 Å) SiO_2 was deposited on the GaP surface by plasma-enhanced chemical vapor deposition. Subsequently, the hole (diameter of 6 μm, and spacing of 14 μm) array was etched in the SiO_2 layer by photo-

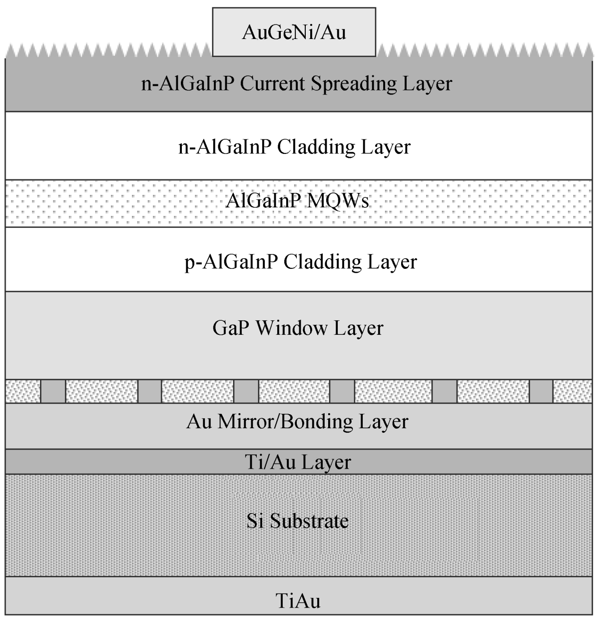

Fig. 1. Schematic cross section of an LED with metal bonding and surface roughening.

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lithography without removing the photoresist. A triple layer of Au/Zn/Au was deposited as an ohmic-contact layer and then was lifted off. The hole array was full of Au/Zn/Au. A 1-μm Au layer was sputtered onto the SiO_2 layer as a reflector and bonding layer. The calculated reflection of the GaP–SiO_2–Au ODR exceeds 90%[6] in the spectrum range above 600 nm. Likewise, the 150 nm/1 μm-thick Ti/Au metal was placed on the surface of the Si substrate as a function of adhesive, ohmic contact and bonding layer. The processed wafer was then bonded with the Si substrate in SUSS SB6E bonder at 260 ℃ for 90 min.

After the bonding process, the GaAs substrate and the n-GaInP etching stop layer were removed by chemical etching. The AuGeNi/Au was deposited and shaped as an n-side electrode. To further improve the extraction efficiency, the n-AlGaInP surfaces of the LEDs were etched using the 1HCl : 2.5H_2O solution at 25 ℃ for 20 s of etching time to form a patterned surface. After polishing the Si wafer, a bilayer of Ti/Au was deposited on the Si wafer as a rear electrode. Finally, the wafer was annealed under 435 ℃ for 40 s in nitrogen ambience. Chips made from this wafer have an area of 270 × 270 μm^2 and a thickness of 140 μm. The LED chips were packaged into TO18 without epoxy resin encapsulation.

3. Results and discussions

Three kinds of LEDs were investigated. The LED with Au/Au metal bonding and wet etched surfaces was named as LED-I. The processes for LED-II were almost the same as those for LED-I. The major difference was that the surfaces of LED-II did not go through any roughening treatments. For comparison, a conventional LED with an absorbing GaAs substrate was fabricated, namely LED-III. The main processes of LED-III are simple. After making the epitaxial wafer clean, AuZnAu and AuGeNi/Au were deposited as a p-type electrode and an n-type electrode, respectively. The LED-III has a flat surface, and the chip size is 270 × 270 μm^2 too. The three kinds of LEDs have the same starlike up-electrodes.

In order to investigate the electrical and optical properties of the fabricated LEDs, we measured the operation voltage, light intensity and output power as a function of applied current. Figure 2 shows the typical I–V characteristics of the LEDs. The threshold voltages (measured at 20 mA) of LED-I and LED-II are almost identical. This indicates that the introduction of the wet etching process barely increased the series resistance, in spite of the reduced thickness of the n-AlGaInP layer, and did not do any damage to the electrical properties.

The output power of the LEDs was determined by using a calibrated integrating sphere, and the light intensity was measured by an intensity testing instrument. Figure 3(a) illustrates the relationship between the current injection and the on-axis light intensity. With a current injection of 20 mA, the light intensity of LED-I, LED-II and LED-III was 315, 173 and 33 mcd, respectively. Compared with LED-II, the luminous intensity of LED-I has been greatly enhanced. In other words, the luminous intensity was markedly increased by 82% under the etching solution of 1HCl : 2.5H_2O for 20 s of etching time.

Figure 3(b) reveals the relationship between the direct current injection and the light output power of the LEDs (without any epoxy resin encapsulated). With 20 mA current injection, the output power of LED-I (roughened surface), LED-II (flat surface) and LED-III (conventional absorption substrate) is 4.622, 2.71, and 0.656 mW, respectively. Compared with LED-III, the light output power for LED-II was increased by 4.13 times. This shows that the Si substrate with the ODR structure replacing the GaAs substrate contributes to reflecting downward photons generated from the active region to the surface. Not only can the ODR structure reflect light to the top surface, but also the roughened top surface can enhance the probability of more photons escaping from the LEDs. Compared with LED-I and LED-II, 70% light output power enhancement was observed with the current injection at 20 mA.

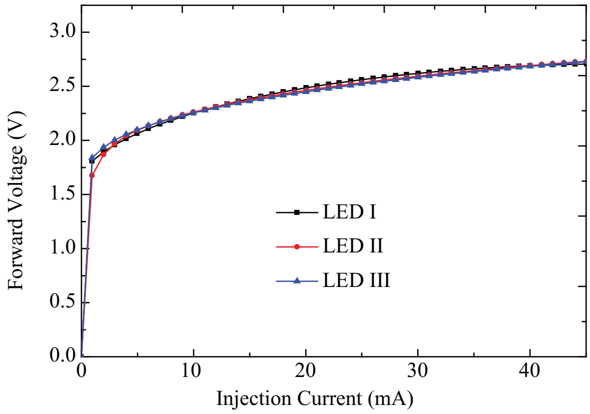


Fig. 2. Typical I–V characteristics of LED I, LED II and LED III.

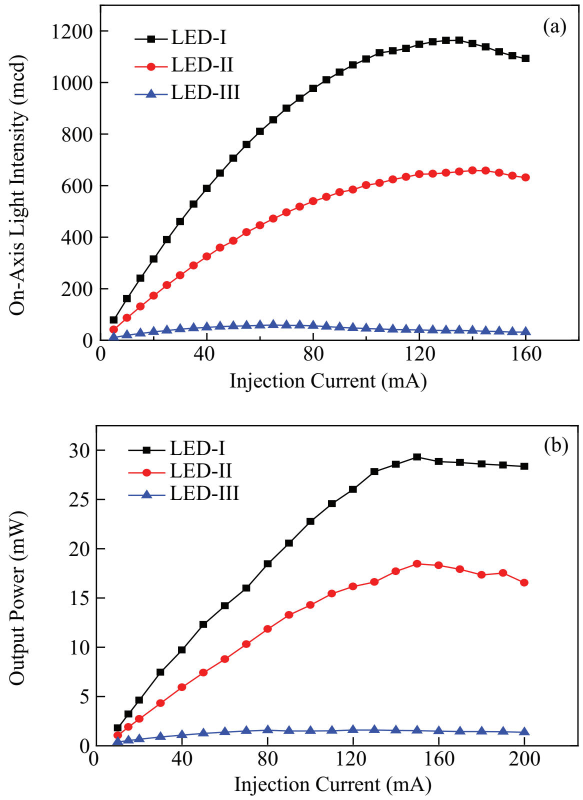


Fig. 3. (a) Relationship between the pulse current injection and on-axis light intensity of LEDs I, II and III. (b) Relationship between the direct current injection and the light output power of LEDs I, II and III.

Figure 4 shows a scanning electron micrograph (SEM) im-

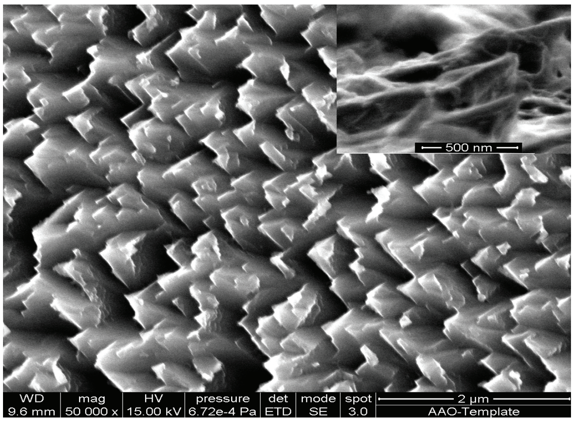
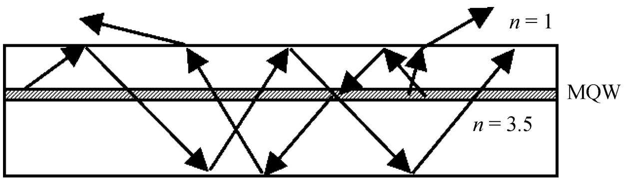
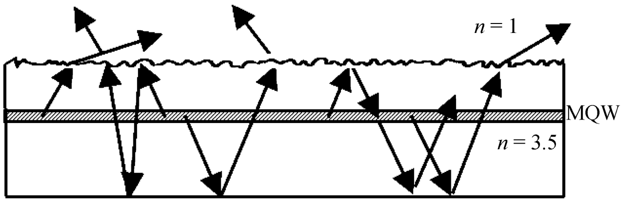


Fig. 4. Scanning electron micrograph (SEM) image of the roughed surface of the LED after the wet etching



(a)



(b)

Fig. 5. Possible photons paths inside the structures of (a) LED-II and (b) LED-I.

age of the roughened surface of LED-I. Notice that the surface morphology of the LED displays a pyramid-like feature, which tilts towards a specific direction. This is believed to be related to the surface polarity of the n-AlGaInP[7]. Furthermore, the etched surface exhibits the structure with a height of approximately 500–700 nm, which is close to the emitted wavelength (625 nm). The light extraction efficiency could be enhanced because these size features of the etched surface could probably offer favorable escape ability of the generated photons[8]. For LED-II with flat surfaces, only 5%[9] of the light from the active region can emit to the surrounding area because of the total internal reflection. Figure 5(a) shows the possible photon path for LED-II with a smooth surface. The light outside the escape cone is reflected into the chip and then repeatedly reflected, then reabsorbed by active layers or electrodes and finally changed into Joule heat, coupled with a temperature rise in the active region. When the heat becomes greater, there will be more adverse effects on the internal quantum efficiency, and finally these factors result in low light output power and restricted luminance intensity.

For the flat surface, photons beyond the escape angle can't be extracted even after the reflection. But for LED I with the roughened surface, as shown in Fig. 5 (b), the pyramid-like surface redirected the orientation of the internal reflected photons, and the reflected photons can be extracted again. The external efficiency can be enhanced. So the light output power of LED I can be greatly enhanced; moreover, the roughened surface, together with the ODR structure, provides the photons with multiple opportunities to escape from the LED structure. Therefore, LED-I outperforms LED-II and LED-III in light output power and on-axial light intensity. Furthermore, the fabrication of LED-I does not need complicated processes. Roughening the top AlGaInP surface with 1HCl : 2.5H_2O solution at 25 ℃ for 20 s etching time is a direct and effective approach for improving the light intensity and optical power.

In this paper, high efficiency AlGaInP LED with Au/Au metal bonding and surface roughening has been introduced to improve the light extraction efficiency. The roughened surface can reduce the internal reflection in the semiconductor–air interface and guide more photons into the escape angle to be emitted from the LEDs. The results indicate that LED-I has a higher light output power and larger light intensity than LEDs with a flat surface (LED-II) and absorption substrate LEDs (LED-III). With a 20 mA injection current, the measured output power of LED-I reaches 4.622 mW, which is 70% higher than LED-II. The light intensity reaches 315 mcd, which is markedly increased by 82%. The fabrication of LED-I is simple and inexpensive, so it is feasible for mass production.

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