Vol 16 No 11, November 2007
1009-1963/2007/16(11)/3498-04

Chinese Physics

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AlGaInP thin-film LED with omni-directionally reflector and ITO transparent conducting n-type contact*

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(Received 31 January 2007; revised manuscript received 5 April 2007)

In this paper a novel AlGaInP thin-film light-emitting diode (LED) with omni-directionally reflector (ODR) and transparent conducting indium tin oxide (ITO) n-type contact structure is proposed, and fabrication process is developed. This reflector is realized with the combination of a low-refractive-index dielectric layer and a high reflectivity metal layer. This allows the light emitted or internally reflected downwardly towards the GaAs substrate at any angle of incidence to be reflected towards the top surface of the chip. ITO n-type contact is used for anti-reflection and current spreading layers on the ODR-LED with ITO. The sheet resistance of the ITO films (95 nm) deposited on n-ohmic contact of ODR-LED is of the order 23.5Ω/□ with up to 90% transmittance (above 92% for 590–770 nm) in the visible region of the spectrum. The optical and electrical characteristics of the ODR-LED with ITO are presented and compared to conventional AS-LED and ODR-LED without ITO. It is shown that the light output from the ODR-LED with ITO at forward current 20 mA exceeds that of AS-LED and ODR-LED without ITO by about a factor of 1.63 and 0.16, respectively. A favourable luminous intensity of 218.3 mcd from the ODR-LED with ITO (peak wavelength 620 nm) could be obtained under 20 mA injection, which is 2.63 times and 1.21 times higher than that of AS-LED and ODR-LED without ITO, respectively.

Keywords: AlGaInP, thin-film LED, Omni-directional reflector, ITO
PACC: 7280E, 7360F, 7865K, 7360D

1. Introduction

AlGaInP light emitting diodes (LEDs) grown on a lattice-matched GaAs substrates are capable of emission in red to yellow-green wavelength range.[1] The introduction of high brightness AlGaInP LEDs in the early 1990 has created a lot of new applications such as traffic signals, automotive lighting, outdoor multicolour displays for these high efficient solid state lighting sources.[2] However, the light extraction efficiency of these devices is limited because of the optically absorbing GaAs substrate (AS) and the internal reflection. This problem can be minimized by growing a distributed Bragg reflector (DBR) between the absorbing substrate and the standard LED active layers to reflect light emitted toward the absorbing GaAs substrate.[3] However, the improvement is limited since DBR can only efficiently reflect normal incident light, at oblique incidence angles, DBR becomes transparent resulting in optical losses.[4] The another possible way to solve this problem is to replace GaAs with a GaP transparent substrate (TS)[5−8] or with a mirror substrate[9,10] via wafer bonding after epitaxial growth. The AlGaInP LEDs with wafer-bonded GaP transparent substrates have been demonstrated to have highly reliable and efficient performance. It is worth mentioning that the AlGaInP/GaP bonding process needs a thick p-type GaP window layer, costly GaP substrates, crystallographic alignment, thin epilayer handling, and a complicated wafer bonding process. Another way of improving AlGaInP LEDs performance is the use of wafer-fused thin film LEDs with metal micro-reflectors[11] or omni-directional reflector (ODR)[12,13] for significantly increased light extraction. The performance of these AlGaInP thin film LEDs is comparable to TS-AlGaInP LED. However, the chip process for the fabrication of buried micro-reflector is very complicated and it would be more difficult to fabricate in big production yield, ODR is usually used as p-type ohmic contact, which can cause

*Project supported by the Beijing Committee of Science and Technology, China (Grant No D0404003040221), the Talent Promoting Education Plan, Beijing, China (Grant No 05002015200504) and National Basic Research Program of China (Grant No 2006CB604902).

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the injection currents to be nonuniform due to poor p-type doping of AlGaInP.

2. Structure and fabrication of the ODR-LED

In this paper, we propose a promising new type high brightness AlGaInP LED structure with both high luminous efficiency and potential for high production yield. The device employs a high reflectivity, planar, ODR and a transparent conducting indium tin oxide (ITO) n-type contact. This ODR is composed of a low-refractive-index dielectric layer and a high reflectivity metal layer. The reflectivity of ODR in the visible region of the spectrum is shown in Fig.1. As can be seen, the normal-incidence reflectivity of ODR is 92.7% at $\lambda = 630$ nm (above 92.7% for 620–770 nm). This allows the light emitted or internally reflected downwardly towards the GaAs substrate at any angle of incidence to be reflected towards the top surface of the chip, thereby reducing optical losses. ITO n-type contact is used for anti-reflection and current spreading layers on the ODR-LED. ITO is considered to be a good candidate for using as transparent contacts to many optoelectronic devices[14] due to its high electrical conductivity and low optical absorption coefficient.

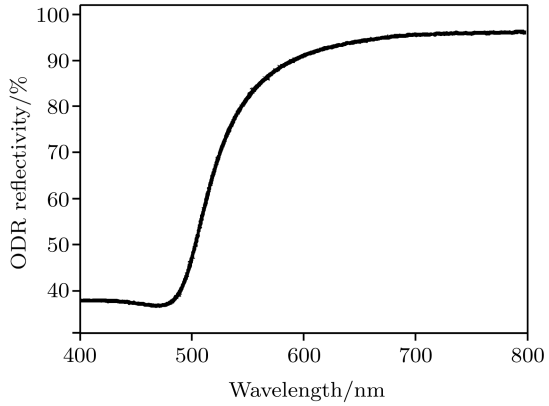


Fig.1. ODR reflectivity of in the visible region of the spectrum.

The epitaxial material of AlGaInP LED is grown by metalorganic chemical vapour deposition on temporary n^+-GaAs substrates. The epitaxial structure consists of a n-GaAs buffer layer, a n-GaInP etching stop layer, a n-ohmic contact layer, a n-current spreading layer, a n-type $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ lower cladding layer, an undoped $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ multiple-quantum well (MQW) active layer with composition aimed at an emission wavelength of approximate 620 nm, a p-type $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ upper cladding layer, p-current spreading layer.

A grid pattern low-refractive-index dielectric layer such as SiO_2 is deposited on the p-current spreading layer. An ohmic contact metal such as AuZnAu micro contacts and a high reflectivity metal layer such as Au are deposited subsequently. In order to avoid degradation of the ODR reflectivity, deposition and annealing of the micro contact were performed before the deposition of high reflectivity metal layer Au.

The AlGaInP LED epi–wafer with ODR is bonded to an 80 Au–20 Sn (wt%) alloy solder coated GaAs submount at temperature 320°C for 30 min in nitrogen ambient. GaAs is used as conductive submount for reasons of similar thermal expansion behaviour. However, other materials like Si or metal are possible to be used as a conductive submount, which may further improve the heat dissipation. After bonding, the n-type GaAs substrate, n-GaAs buffer layer, and the etching stop layer are removed by wet chemical etching. The LED chips are fabricated by depositing ITO and Cr/Au ohmic contact metal subsequently on the n–ohmic contact layer. The schematic structure of the ODR-LED is shown in Fig.2. The thickness of

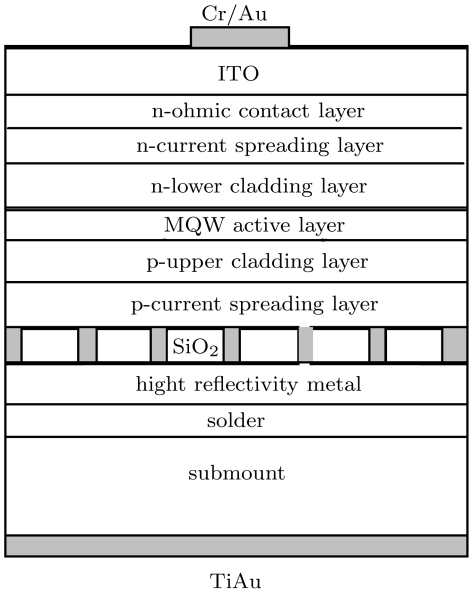


Fig.2. The schematic structure of the ODR-LED.

the ITO layer is 95 nm (a quarter-wavelength-thick) with a sheet resistance of 23.5Ω/□. The transmittance of ITO is able to reach 90% (above 92% for 590–

770 nm) in the visible region of the spectrum as shown in Fig.3. The refractive index of ITO is 1.7008 at the wavelength of 620 nm, between AlGaInP and air, reducing the total reflection at the interface of AlGaInP, thus enhancing the light output. The LED epi-wafers are sawn into chips size of $300 \times 300\,\mu$m. For comparison, absorbing substrate (AS) LEDs and ODR-LEDs without ITO n-type contact fabricated from the same AlGaInP /GaAs epitaxial material are also prepared as references. Here the LED chips are not encapsulated for the electrical and optical measurements.

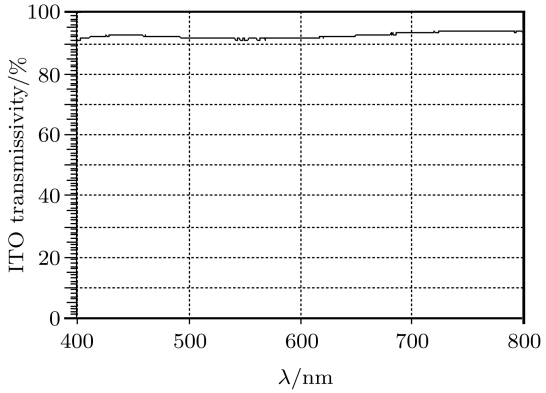


Fig.3. The transmissivity of ITO in the visible region of the spectrum.

3. Results and discussion

Figure 4 shows the light output power (mW) versus forward current (mA, DC) of the ODR-LED with ITO, ODR-LED without ITO and AS-LED. As can be seen, the light output power of the ODR-LED with ITO is significantly larger than that of the AS-LEDs, and is slightly more than that of the ODR-LED without ITO. Note that the light output from the ODR-LED with ITO at forward current 20 mA is 2.67 mW, and exceeds that of the AS-LED and ODR-LED without ITO by a factor of 1.63 and 0.16, respectively. For the reference of AS-LED, it is found that the light output increases first and then saturates quickly with injection current for large amount of Joule heat. In the ODR-LEDs or ODR-LED without ITO, the light output increases approximately linearly and then saturates slowly at higher injection currents. We attribute it to the lower power loss of wave guided light rays. Most light generated in the active region is emitted into wave guided modes by employing an ODR, thus resulting in largely reduced the photons absorption and heating. And besides, the light output from the ODR-LED with ITO increases more quickly than that of the ODR-LED without ITO at higher injection currents, it means that ITO can improve to spread current uniformly and enhance light output power for anti-reflection.

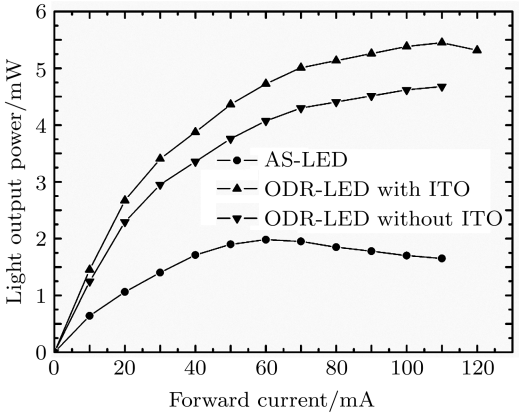


Fig.4. Light output power as a function of the injection current.

The luminous intensity versus forward current (L–I) curve of the ODR-LED with ITO, ODR-LED without ITO and AS-LED is shown in Fig.5. It is found that the ODR-LED with ITO provides the best L–I performance, and presents a favourable luminous intensity of 218.3 mcd (@20 mA, a peak wavelength of 620 nm), and is 2.63 and 1.21 times higher than the luminous intensity of AS-LED and ODR-LED without ITO, respectively. As the forward current increases, the saturation in luminous intensity of the ODR-LED with ITO is also higher than that of AS-LED and ODR-LED without ITO respectively, it means that a great improvement in the performance of the ODR-LED with ITO is obtained. It is clearly shown that the ODR-LED with ITO can improve to produce high luminous intensity.

The life test of ODR-LEDs with ITO is carried out at forward current of 50 mA in room temperature. As shown in Fig.6, the degradation of the light output power was no more than 5% after 956.67 h of life test, indicating the excellent reliability. This favourable life test performance is attributed to the high-reflectivity ODR and the optimized ITO structure. To further improve the performance of ODR- LED with ITO, we will roughen the top surface to increase the light extraction efficiency.

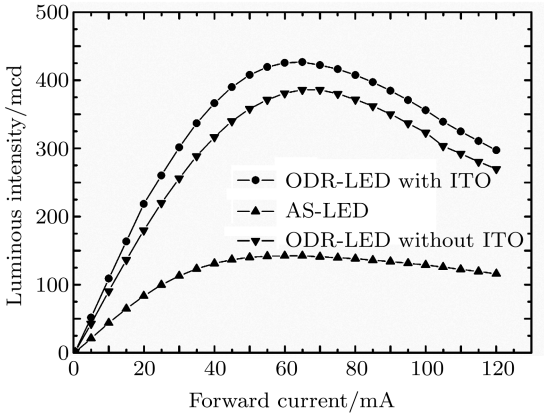


Fig.5. Luminous intensity as a function of the injection current.

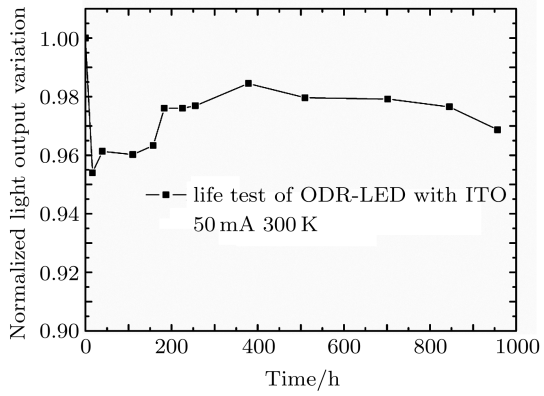


Fig.6. Light output power variation as functions of time.

4. Conclusions

High brightness AlGaInP thin-film LED with ODR and transparent conducting ITO n-type contact has been fabricated. The normal-incidence reflectivity of ODR is 92.7% at $\lambda = 630$ nm (above 92.7% for 620–770 nm). It is found that the sheet resistance of the ITO films (95 nm) is of the order 23.5Ω/□ with up to 92% transparency for 590–770 nm of the spectrum. ITO n-type contact can improve to spread current uniformly and enhance light output power for anti-reflection. The light output from the ODR-LED with ITO at forward current 20 mA exceeds that of AS-LEDs and ODR-LED without ITO by about a factor of 1.63 and 0.16 respectively. A favourable luminous intensity of 218.3 mcd from the ODR-LED with ITO could be obtained under 20 mA injection, which is 2.63 and 1.21 times higher than that of AS-LED and ODR-LED without ITO respectively.

Acknowledgment

The authors would like to thank Zhang Xiao-Jia, Su Zhen-Zhen, Liu Na, Han Jin-Ru, Liu Ying for device fabrication.

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