Vol 16 No 4, April 2007
1009-1963/2007/16(04)/1135-05
Chinese Physics
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High power and high reliability GaN/InGaN flip-chip light-emitting diodes*

Zhang Jian-Ming(张剑铭)†, Zou De-Shu(邹德恕),
Xu Chen(徐 晨), Zhu Yan-Xu(朱彦旭),
Liang Ting(梁 庭), Da Xiao-Li(达小丽), and Shen Guang-Di(沈光地)

Beijing Optoelectronic Technology Laboratory, Beijing University of Technology, Beijing 100022, *China*

(Received 3 August 2006; revised manuscript received 20 November 2006)

High-power and high-reliability GaN/InGaN flip-chip light-emitting diodes (FCLEDs) have been demonstrated by employing a flip-chip design, and its fabrication process is developed. FCLED is composed of a LED die and a submount which is integrated with circuits to protect the LED from electrostatic discharge (ESD) damage. The LED die is flip-chip soldered to the submount, and light is extracted through the transparent sapphire substrate instead of an absorbing Ni/Au contact layer as in conventional GaN/InGaN LED epitaxial designs. The optical and electrical characteristics of the FCLED are presented. According to ESD IEC61000-4-2 standard (human body model), the FCLEDs tolerated at least 10 kV ESD shock have ten times more capacity than conventional GaN/InGaN LEDs. It is shown that the light output from the FCLEDs at forward current 350mA with a forward voltage of 3.3 V is 144.68 mW, and 236.59 mW at 1.0 A of forward current. With employing an optimized contact scheme the FCLEDs can easily operate up to 1.0 A without significant power degradation or failure. The life test of FCLEDs is performed at forward current of 200 mA at room temperature. The degradation of the light output power is no more than 9% after 1010.75 h of life test, indicating the excellent reliability. FCLEDs can be used in practice where high power and high reliability are necessary, and allow designs with a reduced number of LEDs.

Keywords: GaN, light emitting diode, flip-chip, high power
PACC: 7280E，7360F，7865K，7360D

1. Introduction

The light-emitting diodes (LEDs) were first demonstrated in 1962 by the epitaxial growth of GaAsP to provide red light.[1] Since then, improvements in materials and crystal-growth techniques have enabled the production of high-brightness LEDs. When high-brightness GaN-based blue LEDs were introduced into the marketplace during the mid-1990s,[2] LEDs emission covers most of the visible spectrum, and the thought of using LEDs for general illumination became a reality. Due to long lifetime, small size, and low consumption of energy, visible high-brightness LEDs have attracted increasing interest in applications such as automobile taillights, back lighting sources, solid-state light sources and so on. For the past several years, tremendous progress has been achieved in GaN-based LEDs.[3−6] Recently, the research of white LED has become popular. Many enterprise technician and university research workers around the world have proceeded with the development on white LED. Generally, white LEDs use blue LED elements as the source of light.[7] Although the lifetime of white LEDs is much longer than those of light bulbs and fluorescent lamps, output power of the current white LEDs is still low. In other words, we need to improve the output intensity of GaN-based blue LED chips.

The GaN/InGaN material system is still not in full development, thus the GaN/InGaN material is now typically grown on sapphire (Al_2O_3) substrate.[8−11] Sapphire substrate, however, is electrically insulated, which causes both the p and n contacts to be located on the same side. Thus, conventional GaN/InGaN LEDs are limited in light extraction efficiency due to the absorption of the metal contacts, bond pads and wire bonds to the package. Due to low conductivity of p-GaN, superficial current spreading layers (Ni/Au p ohmic contact) are then applied to the conventional GaN/InGaN LED struc-

*Project supported by the Beijing Committee of Science and Technology, China (Grant No D0404003040221) and by the Talent Promoting Education, Beijing, China (Grant No 05002015200504).
†E-mail: mjianzhang@emails.bjut.edu.cn

ture, and the semi-transparent Ni/Au p contact that covers most of the LED surface is the major source of absorption, because of the transmittance of Ni/Au is only around 55%–75%, as shown in Fig.1. The thicker the p contact, the better the current spreading effect, though the thickness should be controlled to minimize light absorption. Tradeoff between light extraction efficiency and current spreading should be taken, which may limit power conversion efficiency. Furthermore, because of the insulation and low thermal resistance of the sapphire substrate, GaN/InGaN devices are sensitive to electrostatic discharge (ESD) damage and power dissipation.

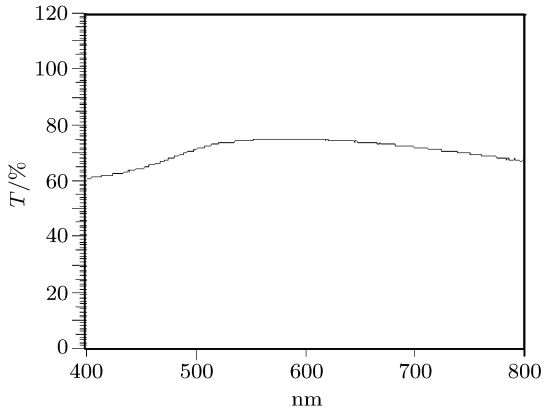


Fig.1. Ni2nm-Au5nm transmittance in the visible region of the spectrum.

2. Structure and fabrication of the FCLEDs

One possible way to solve these problems is to use flip-chip technology.[11−14] Without bonding pads or wires on top of the devices, photons could be escaped freely from the substrates and high light power output could be obtained. In this paper, we present a flip-chip technology for nitride-based layers with Al reflector. The electrical and optical properties of the fabricated devices are reported.

In this FCLED design, a LED chip is composed of two parts: LED die and Si submount. The LED die is inverted to mount on a Si submount. All the light is extracted through the transparent sapphire substrate, avoiding absorption from the n and p ohmic contacts, bond pads and wire bonds. For an inverted design, the p electrode is the dominant factor for light extraction because it covers most of the LED surface to provide uniform current injection into the multiple quantum well (MQW) active region. Therefore, the FCLEDs can use a thick reflective p ohmic contact (Ni/Au/Al multilayer p ohmic contact) that provides better current spreading and lower thermal resistance. The reflective p ohmic contact is located on the bottom so downward propagating light is redirected up through the sapphire, increasing light extraction. The n electrode is also an optical loss mechanism, but it has commonly been considered less significant because it covers less device area. However, when the reflectivity of the p electrode in FCLEDs is increased, the reflectivity of the n electrode must be considered. So highly reflective ohmic contacts enable enhanced light output power, especially for large area flip-chip devices.

As for the submount, Si crystal is a good choice to fabricate the submount substrate due to its lower thermal resistance. The submount is provided with electronic functionality within the LED die. A Si submount is fabricated with circuits for ESD protection, which, e.g. in Zener diodes, are connected in parallel with the LED die to protect the LED from ESD. Therefore, GaN/InGaN FCLEDs may have enough ability to withstand ESD damage.

Based on the above considerations, a consummate FCLED is accomplished via three steps. The process is carried out as follows. First, the epitaxial material of GaN/InGaN LED is grown by metalorganic chemical vapour deposition on sapphire substrates as shown schematically in Fig.2. The epitaxial structure consists of an n-GaN buffer layer, GaN barriers, the active region composed of the MQW with composition suitable for an emission wavelength of approximate 465 nm, a p-GaN electron blocking layer and a thick, heavily doped p-GaN cap layer for fabricating the metal contact.

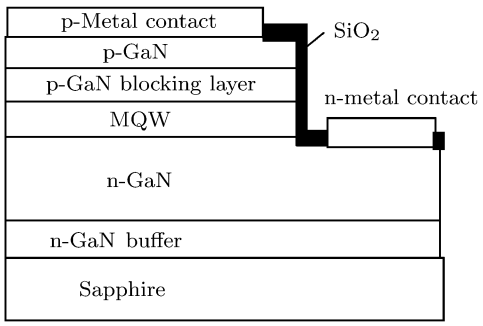


Fig.2. schematic cross view of the FCLED die.

Then, the fabrication of the FCLED die involves standard photolithography and etching steps to shape

the structure (Fig.2). First, a dry etch is carried out to etch the p-GaN layer and MQW active region up to the n-GaN layer. More care in etching depth control is required when reached the n-GaN layer. Then, the p-GaN contact at the top of the LED structure is formed by using thick, highly reflective ohmic contacts, e.g. Ni/Au/Al, while Ti/Al/Ti/Au multi-layers are used to contact the n-GaN. Next, atop the thick p and n contact are the interconnects as conductive interfaces. The interconnects may be made of thermally and electrically conductive pastes, Au stud-bumps, or eutectic joints Au–Sn solder bumps. Thus, the FCLED die is finished.

Next, standard micro-electronic processes such as oxidation, heavy doping, photolithography and etching techniques are used to fabricate back-to-back Zener diodes. The process of fabricating the interconnect is similar to that of the FCLED die as shown schematically in Fig.3.

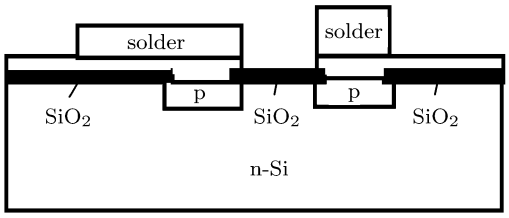


Fig.3. A schematic cross view of the submount.

Finally, the FCLED die is inverted to solder to the Si submount via the interconnect as shown in the cross section in Fig.4. Figure 4(a) shows a top view (through the substrate) and Fig.4(b) shows a schematic cross section view of the FCLED. As shown in Fig.4(a), the contact shape is 'fingers', to minimize the spreading resistance in the n-GaN by reducing the current spreading distance. Thus, the fabrication of the flip-chip LED process is completed, the chip dimensions being $1 \times 1\,\mathrm{mm}^2$.

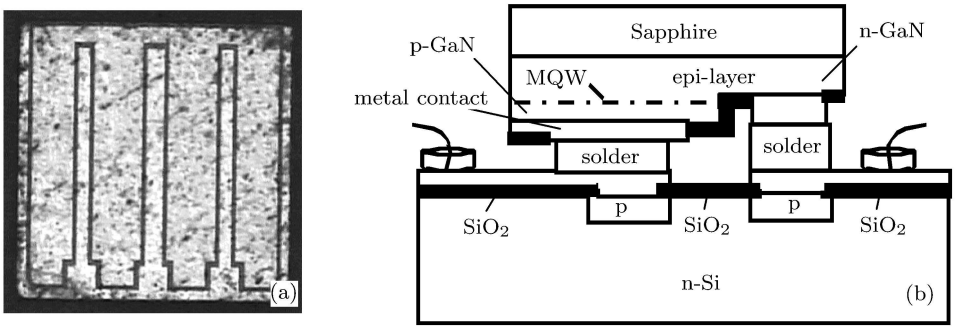


Fig.4. (a) A top view (through the substrate). (b) A schematic cross view of FCLED.

3. Results and discussion

Here the LED chips are not encapsulated for the electrical and optical measurements by a calibrated Si photodetector with integrating sphere and LED luminous intensity distribution tester.

Figure 5 shows that ESD shock influences on the voltage (at 200 mA) for FCLED and conventional GaN/InGaN LED. The data are obtained on the Switzerland TRANSIENT-2000 equipment, according to the ESD IEC61000-4-2 standard (human body model). As shown in Fig.5, the FCLED can easily withstand at least 10 kV ESD shock without significant voltage degradation or failure, while the conventional LED will degrade dramatically, leading to a catastrophic failure at 1 kV ESD shock.

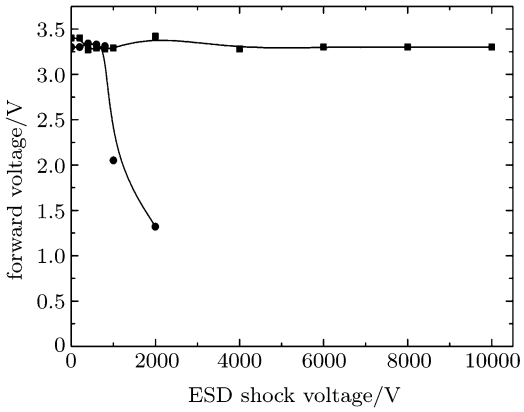


Fig.5. ESD shock influences on the voltage (at 200 mA) for a FCLED (■) and a conventional GaN/InGaN LED (●).

Figure 6 shows the light output power (mW) and forward voltage versus forward current (mA, dc) for a

blue FCLED. The forward voltage of this FCLED is 3.3 V at forward current 350 mA. At the same time this FCLED exhibits light output powers of 144.68 mW at forward current 350 mA, and of 236.59 mW at 1.0 A of forward current with a forward voltage of 3.6 V. As can be seen in Fig.5 the FCLED can easily operate up to 1.0 A without significant power degradation or failure.

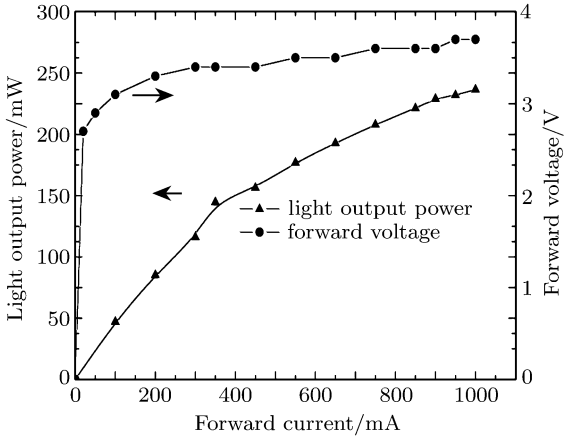


Fig.6. Light output power and forward voltage versus forward current for FCLED.

The luminous intensity versus forward current (*L-I*) curve for the FCLED is shown in Fig.7. It is found that the FCLED provides the best *L-I* performance, and presents a favourable luminous intensity of 0.786 cd (at 350 mA, a peak wavelength of 462 nm). As the forward current increases, the saturation in luminous intensity is not observed for the FCLED, meaning that the FCLED performance is not saturated and degraded. It is clearly shown that the FCLED produces high luminous intensity.

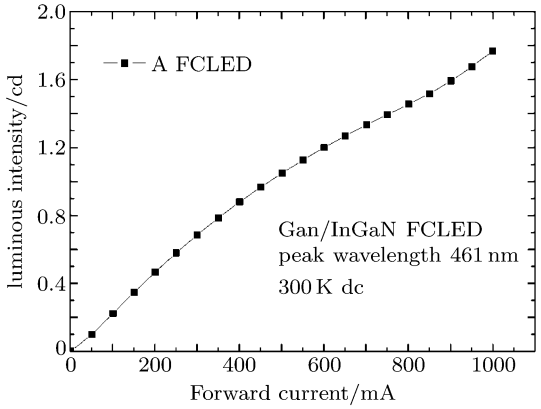


Fig.7. *L-I* curve for FCLED.

The life test of FCLEDs is performed at forward current of 200 mA at room temperature. As shown in Fig.8, the degradation of the light output power is no more than 9% after 1010.75 h of life test, indicating the excellent reliability. This favourable life test performance is attributed to the optimized contact scheme and flip-chip structure.

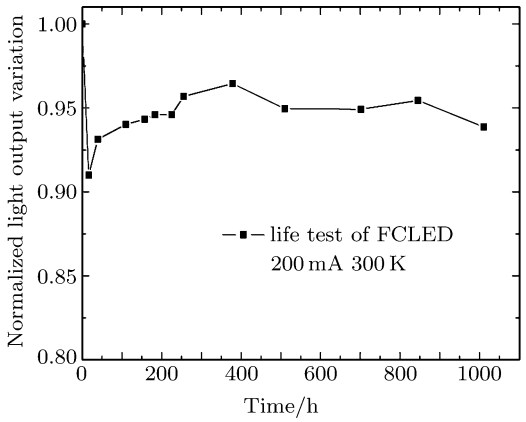


Fig.8. Variation of light output power as a function of time.

4. Conclusion

In summary, high-power and high-reliability FCLEDs have been fabricated. Because back-to-back Zener diodes are connected in parallel with the LED die to protect the LED from ESD, the FCLEDs can tolerate at least 10 kV ESD shock, with ten times more capacity than the conventional GaN/InGaN LEDs. The light output of the FCLEDs at forward current 350 mA with a forward voltage of 3.3 V is 144.68 mW, and of 236.59 mW at 1.0 A of forward current. By employing an optimized contact scheme, the FCLED can easily operate up to 1.0 A without significant power degradation or failure. The degradation of the light output power is no more than 9% after 1010.75 h of life test, indicating the excellent reliability.

Acknowledgment

The author would like to thank Professor Rhoda Perozzi for her contribution to this paper.

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