High performance GaN-based flip-chip LEDs with different electrode patterns

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Abstract: A high-performance flip-chip light-emitting diode (FCLED) with a Ni/Ag metallic film as high reflectivity mirror (92.67%) of p-type electrode was successfully fabricated. The effect of geometric electrode patterns on the blue InGaN/GaN LEDs was investigated and analyzed qualitatively its current spreading in the active region. With different electrode patterns, these devices were experimented and simulated by simple electrical circuits in order to confirm its current-voltage characteristics and light emission pattern. It was found that the forward voltages of these FCLEDs were about 3.6 V (@350 mA). The light output power of FCLEDs with circle-round type electrode was 368 mW at an injection current of 700 mA. From these optoelectronic measurement and thermal infrared images, we proposed some design methodologies for improved current spreading, light output power, droop efficiency and thermal performance.

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References and links

1. H. Menkara, R. A. Gilstrap, Jr., T. Morris, M. Minkara, B. K. Wagner, and C. J. Summers, “Development of nanophosphors for light emitting diodes,” Opt. Express 19(S4 Suppl 4), A972–A981 (2011).
2. Y. Zhang, S. Gautier, C. Y. Cho, E. Cicek, Z. Vashaee, R. McClintock, C. Bayram, Y. Bai, and M. Razeghi, “Near milliwatt power AlGaN-based ultraviolet light emitting diodes based on lateral epitaxial overgrowth of AlN on Si(111),” Appl. Phys. Lett. 102(1), 011106 (2013).
3. A. David, T. Fujii, R. Sharma, K. McGregor, S. Nakamura, S. P. DenBaars, E. L. Hu, C. Weisbuch, and H. Benisty, “Photonic-crystal GaN light-emitting diodes with tailored guided modes distribution,” Appl. Phys. Lett. 88(6), 061124 (2006).
4. P. Zhao and H. Zhao, “Analysis of light extraction efficiency enhancement for thin-film-flip-chip InGaN quantum wells light-emitting diodes with GaN micro-domes,” Opt. Express 20(S5 Suppl 5), A765–A776 (2012).
5. R. H. Horng, C. C. Yang, J. Y. Wu, S. H. Huang, C. E. Lee, and D. S. Wuu, “GaN-based light-emitting diodes with indium tin oxide texturing window layers using natural lithography,” Appl. Phys. Lett. 86(22), 221101 (2005).
6. M. Shatalov, A. Chitnis, P. Yadav, M. F. Hasan, J. Khan, V. Adivarahan, H. P. Maruska, W. H. Sun, and M. A. Khan, “Thermal analysis of flip-chip packaged 280 nm nitride-based deep ultraviolet light-emitting diodes,” Appl. Phys. Lett. 86(20), 220110 (2005).
7. B. Fan, H. Wu, Y. Zhao, Y. Xian, B. Zhang, and G. Wang, “Thermal study of high-power nitride-based flip-chip light-emitting diodes,” IEEE Trans. Electron. Dev. 55(12), 3375–3382 (2008).
8. Y. X. Sun, W. S. Chen, S. C. Hung, K. T. Lam, C. H. Liu, and S. J. Chang, “GaN-based power flip-chip LEDs with an internal ESD protection diode on Cu sub-mount,” IEEE Photon. Technol. Lett. 33(2), 433–437 (2010).
9. C. Y. Cho, Y. Zhang, E. Cicek, B. Rahnema, Y. Bai, R. McClintock, and M. Razeghi, “Surface plasmon enhanced light emission from AlGaN-based ultraviolet light-emitting diodes grown on Si (111),” Appl. Phys. Lett. 102(21), 211110 (2013).
10. O. B. Shechkin, J. E. Epler, T. A. Trotter, T. Margalith, D. A. Steigerwald, M. O. Holcomb, P. S. Martin, and M. R. Krames, “High performance thin-film flip-chip InGaN-GaN light-emitting diodes,” Appl. Phys. Lett. 89(7), 071109 (2006).
11. K. C. Shen, W. Y. Lin, D. S. Wuu, S. Y. Huang, K. S. Wen, S. F. Pai, L. W. Wu, and R. H. Horng, “An 83% enhancement in the external quantum efficiency of ultraviolet flip-chip light-emitting diodes with the incorporation of a self-textured oxide mask,” IEEE Electron Device Lett. 34(2), 274–276 (2013).
1. Introduction

In recent years, III-nitride compound semiconductors have attracted substantial attention for the fabrication of high-brightness light-emitting diodes (LEDs) that range from the ultraviolet to the visible region [1, 2]. To achieve high light excitation and output performance, devices must be driven at a high current density. However, most LED structures are still grown on a sapphire substrate, which results in an etched mesa shape and a side-by-side contact configuration due to the insulating substrate. With such configuration, there were severe current-crowding and heat-conducting problems resulting from the poor thermal conductivities of sapphire substrates reduce the performance of conventional lateral conducting LEDs. Additionally, another issue of energy loss is total internal reflection at the emitter/air (or epoxy) interface because of the typically high refractive index of the emitting materials [3, 4].

It is very important to analyze the current flowing, thermal management and light emission pattern in a LED chip. In general, the conventional nitride-based LEDs emit photons from the p-side indium-tin-oxide (ITO) contact [5]. A significant amount of photons must be obstructed by the bonding pads and wires. Therefore, an approach that can simultaneously satisfy thermal management and light extraction has been developed by flip-chip technology. Using this technology, the LED structures were commonly bonded to a high thermal conductivity submount such as silicon or copper by the solder attachment process. Without the blocking of bonding pads and wires, photons can be emitted freely from the thinned sapphire substrates. Moreover, these LED devices have high extraction efficiency compared to that of conventional LEDs due to the lower refractive index contrast between sapphire substrate (n = 1.76) and air (n = 1). The flip-chip technology also provides a “sapphire-free” thermal path for the generated device heat to efficiently dissipate from contacting solders to the underlying heat sink. Thus, the flip-chip LED was expected to be effective in enhancing the light extraction efficiency, light output and heat dissipation [6–9], and has been extensively used in the fabrication of high power and high efficiency LEDs [10, 11].

For the high-power LEDs requiring larger chip size and much higher injection current, the effect of poor current spreading on the efficiency droop will become more pronounced. Although the flip-chip LEDs can provide better light extraction and thermal performance, current spreading is still an essential problem for the input power yield. It had been reported that the nonuniform current spreading, so-called current crowding effect, was strongly related to chip reliability and efficiency droop [12–14]. However, several analytical models have been proposed to evaluate the current spreading versus the electrode pattern [15, 16]. The geometric pattern for electrodes can affect the status of current spreading, and a well-designed electrode pattern provides improved electrical characteristics via the uniform current spreading [17–19].

In this study, we have designed and fabricated flip-chip GaN-based LEDs (abbreviated as FCLEDs) with an improved electrode pattern so as to produce a uniform current spreading and
enhance the light output power. Using the SpeCLED simulation software, further analysis of the current spreading effect on the chip performance of designed n-electrode patterns was investigated. There were three kinds of electrode patterns of FCLEDs: branch-solid (BS), branch-dashed (BD), and circle-round (CR), respectively. We have demonstrated the lateral current spreading effect on the efficiency droop in a chip using the designed pattern at high power operation, which can provide a more direct and quantitative insight of the current spreading effect. Moreover, the high-performance FCLEDs require p-Ohmic reflector layers that have high reflectivity, low contact resistance, and good thermal stability. The Ni/Ag reflector as a high reflectivity metal mirror (92.67%) of p-type electrode was also fabricated to improve the light extraction. With a well-designed electrode pattern, these FCLEDs show that uniform current spreading enhances output power in LED chips through the electrical and optical performance.

2. Experimental

GaN-based LEDs were grown on c-plane (0001) sapphire substrates by a metal organic chemical vapor deposition system. At first, a 50-nm-thick low-temperature GaN buffer layer was deposited on the sapphire substrate at 550 °C. The epilayers of the LED structure, listed in order from a low-temperature GaN layer to surface, were as follows: a 2-μm-thick undoped GaN layer, a 3-μm-thick n-GaN layer, 10 pairs of InGaN/GaN multiple quantum well (MQW) active layers, a 25-nm-thick Mg doped p-AlGaN electron blocking layer, and a 0.1-μm-thick p-GaN layer. Furthermore, indium tin oxide (ITO) and Ni/Ag/Ni/Pt layers were deposited on top of p-GaN as an ohmic contact layer and reflector by electron beam evaporating system, respectively. After growing these structures, the mesa region was defined by an inductively coupled plasma (ICP) etcher using Cl₂ and BCl₃ gases until n-GaN layer for the n-electrode contact was exposed. The mesa patterns have three kinds of electrode pattern types of these FCLEDs, as shown in Figs. 1(a)-1(c), such as BS, BD and BR patterns, respectively. In addition, the passivation on the sidewall of the mesa was then coated. The Cr/Au/Sn (5 nm/ 100 nm/ 2 μm) metals were then deposited on the top of p- and n-contacts as bonding pads for all the devices. Finally, the sapphire substrates were lapped and polished to around 150 μm for all FCLEDs. On the other hand, the Al₂O₃ (100 nm) layer as an insulator was deposited on the silicon submount by atomic layer deposition (ALD). Then, photolithography and wet etching were subsequently performed to define the p- and n-contact pad patterns. The Cr/Au/Sn (5 nm/ 1 μm/ 2 μm) metals were deposited on the Al₂O₃–Si submount for the cathode and anode of flip-chip circuits. Hence, the LED chips were flip-chip bonded on an Al₂O₃–Si submount using ultrasonic flip-chip bonder. The schematic device structures of the FCLEDs were shown in Fig. 1(d). In this study, the current spreading effect on the chip performance of designed n-electrode patterns was simulated by SpeCLED simulation software. Moreover, the current–voltage (I–V) characteristic and light output power of the FCLEDs were measured using an Agilent 4155B semiconductor parameter analyzer at room temperature and integration sphere detector (CAS 140B, Instrument Systems), respectively.

3. Result and discussion

The reflection spectra with the wavelength range from 200 to 1000 nm of the metal mirror (Ni/Ag) with different annealing temperatures were measured and shown in Fig. 2. It was found that the reflectivity of such metal mirror was decreased as annealing temperature increased. Especially, the reflectivity was extremely low (53%) as the temperature exceeds 450 °C, which resulted from a metallic atomization at high temperature. In this study, a metal mirror during the flip-chip process (at 250 °C) still remained a higher reflectivity than 92.67% at the wavelength of 450 nm. As a result, the use of Ni/Ag reflectors is a promising technique for the production of high power blue FCLEDs.
Fig. 1. There were three kinds of n-electrode patterns of FCLEDs: (a) branch-solid, (b) branch-dashed, and (c) circle-round, respectively. The schematic device structures of the FCLEDs were shown in (d).

Fig. 2. Reflection spectra of the metal mirror (Ni/Ag) with different annealing temperatures.

The surface morphology of all LEDs structures with designed electrode patterns were given in Figs. 3(a)-3(c). In general, the current crowding mainly occurs near the n-electrode [14]. From the results of the simulation, the current density distribution in the active layer of the designed n-electrode patterns of LED chips for an injection current of 350mA were shown in Figs. 3(d)-3(e). It was shown that the highest current density of devices was observed on the edge of BS types of electrode patterns. After changing the electrode design, the current crowding still exists in the upper regions of BD sample. Conversely, the CR sample offers uniform current spreading near the current injection location; thus, the yield of the active layer of CR sample was larger than that of BS and BD samples. Moreover, the active areas of BD, BS, and CR patterns were 0.81 mm², 0.97 mm² and 1.1 mm², respectively. It can be found that the more uniform current spreading was achieved by the increase in additional electrode interval and decrease the pattern area. Obviously, the current spreading in the FCLED with CR pattern (abbreviated as CR-FCLED) was superior to that with BS pattern (abbreviated as BS-FCLED) and BR pattern (abbreviated as BR-FCLED), hence the improved localized current crowding can also relieve the joule heat resulting from high current injection. Furthermore, the current density pattern is similar to the light emission pattern. Higher current density means more carriers and more radiative recombination. The light emitting intensity distribution in the all LED chips with an area of 1150 μm × 1150 μm at an injection current of 350 mA for different electrode patterns were shown in Figs. 4(a)-4(c), and it can be seen that the experimental result shows a very good agreement with 3-dimensional simulation ones as shown in Figs. 4(d)-4(f). This result shows that the electrode pattern of CR sample offers light emission pattern uniformity and higher brightness than that of BD and BS samples because of the uniform current spreading and increased area lights.
Fig. 3. (a)-(c) Plane-view surface images of FCLEDs with designed electrode patterns after lapping and polishing the sapphire substrate. (d)-(f) SpecLED simulation of the current density distribution with different electrode patterns in the active layer.

Fig. 4. (a)-(c) Measured light emission images and (d)-(f) calculated light intensity distribution in the all LED chips of 1150 μm × 1150 μm at an injection current of 350 mA for the designed electrode patterns.

Another issue that may be raised by the lateral current spreading effect is the electric-thermal problem in LEDs, such as the higher surface temperature and local overheating of chip. Hence, the lateral current spreading effect on the thermal management is extremely important for the high power applications. To investigate the thermal properties of all FCLED samples, the chips were lighted up at 350 mA for 10 min to reach the thermal equilibrium before the measurement. From the samples of BS-FCLEDs, BD-FCLEDs and CR-FCLEDs shown in Fig. 5, IR camera images clearly indicated the current crowding effect in the FCLEDs with BS and BD types of electrode patterns, which resulted in the local overheating and higher average chip. The highest temperatures were 70.65 °C, 69.19 °C and 68.24 °C for BS-FCLEDs, BD-FCLEDs and CR-FCLEDs, respectively. However, the difference between the minimum and maximum values of temperature observed in all chips of BS, BD and CR samples were 6.64 °C, 3.82 °C, 1.83 °C, respectively, further indicating that the CR-FCLEDs has a more uniform temperature distribution due to the uniform current spreading.

Fig. 5. IR camera images of FCLED samples with the designed electrode patterns for an injection current of 350mA.

To demonstrate the superior electrical properties of these FCLEDs with designed electrode patterns, the current–voltage characteristics were measured. It was found that the forward voltages at 20 mA for all samples were approximately 2.8 V. With an injection current of 350 mA, the forward voltage of FCLEDs was reduced from 3.75 to 3.63 as the area of electrode patterns decreased. The decrease in forward voltage could be attributed to better current spreading distribution while the series resistance was reduced. Figure 6 shows the light output power and wall plug efficiency (WPE) of FCLEDs as a function of injection current. It was clearly observed that the light output powers of the CR-FCLEDs were larger than those of the BS-FCLEDs and BD-FCLEDs. Under 700 mA current injections, it is found that the enhancement of light output powers of the BS-FCLEDs and CR-FCLEDs could be significantly raised from 307 mW to 368 mW and the WPE could be increased from 10.23% to 12.23%. The output power of the CR-FCLEDs was enhanced by a factor of 19.87% compared to that of the BS-FCLEDs. Specifically, all FCLEDs showed a high-brightness performance driven at a high...
current density because of the good heat dissipation of the Si substrate and a novel reflective mirror layer. Moreover, the external quantum efficiency (EQE) of the CR-FCLEDs with an injection current of 700 mA was calculated to be 19.26%, which is an increase of 3.15% compared to that of the BS-FCLEDs (16.11%). To further clarify the origin of the current spreading effect of FCLEDs with designed electrode patterns, the efficiency droop behaviors of samples were also calculated using the data of Fig. 6. It can be found that the EQE of FCLEDs rises and peaks at a low injection current, and then drops with the increasing of the injection current density. For the FCLEDs with CR type of electrode pattern, the magnitude of efficiency droop at 700 mA current injection is as large as 54.8% compared to the peak value. The efficiency droop was reduced by a factor of 4.43% compared to that of the BS-FCLEDs, as a result of the improved current spreading. In addition, the internal quantum efficiency (IQE) of 84.64% for all FCLEDs was determined using the temperature-dependent integrated PL intensity. The light extraction efficiency (LEE) of BS-FCLEDs, BD-FCLEDs and CR-FCLEDs were calculated to be 19.03%, 21.01%, and 22.75%, respectively. These results show that the most important requirement for a competitive FCLED is governed by the uniform current spreading and increased area lights through an improved electrode pattern in the search for one that offers better performance.

![Fig. 6. Light output power and wall-plug efficiency as function of injection current of FCLEDs with the designed electrode patterns.](image)

4. Conclusion

In conclusion, we have successfully demonstrated a high output power GaN-based FCLEDs with a novel Ni/Ag reflector exhibited high reflectivity of 92.67% over blue wavelengths. Due to a higher thermal conductivity of Si submount, the devices achieve lower operation voltage and surface temperature under high current injections. Through the well-designed n-electrode patterns, current spreading distributions in the experimental results were in good agreement with those in the simulation. The results show that the circle-round type of electrode pattern has a more uniform current distribution in the n-GaN layer, resulting in a lower drop efficiency and higher light output power in the LED chip. In addition, the light output power of CR-FCLEDs was 368 mW at an injection current of 700 mA. These superior device performances indicate that the flip-chip technique with a well-designed electrode pattern can be used to fabricate LEDs for high-power solid-state lighting.

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