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Characteristics of Single-Chip GaN-Based Alternating Current Light-Emitting Diode

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In this study, a GaN-based alternating current light-emitting diode (AC-LED) with 34 numbers of microchips illuminated in each bias direction was fabricated. After calibrating the integration duration, the light output powers of the AC-LED driven by AC and DC were 388.1 and 312.8 mW when the input power was about 1 W, respectively. The flickering illumination mode of the AC-LED driven by AC decreased the heat accumulation and revealed a higher energy utilization efficiency than that of the AC-LED driven by DC. The larger blue shift and smaller full width at half maximum of the AC-LED driven by AC than those of the AC-LED driven by DC were also observed. [DOI: 10.1143/JJAP.47.8808]

KEYWORDS: GaN, light-emitting diode, alternating current, Wheatstone Bridge

1. Introduction

The significant improvements of a GaN-based light-emitting diode (LED) have attracted considerable attention as commercial productions, which have been extensively used over the past decades.[1,2] However, the physical limitation of the GaN-based LED that could only be operated in direct current (DC) leads to the rectifier becoming an essential electrocomponent for the stationary LED lighting system to transform the alternating current (AC) applied from the city power company into DC. The disadvantages of the low transformation efficiency, incompact dimensions, and short reliable lifetime of the rectifier limit the popularization of LED stationary lighting applications. A great majority of studies are focused on the increment in the internal or external quantum efficiency of the GaN-based LED, and only few workers attempt to reduce the energy consumption in the AC to DC transformation process, which could increase the energy utilization efficiency of the entire lighting system. The designs of microchips integrated on a single LED chip[3,4] or assembled multi-LED chips with the flip-chip bonding method,[5] which enabled the LED to be operated in AC power directly without any additional rectifier, have been reported. The constant driving DC voltage and the time-dependent period driving AC voltage would lead to varied properties of the AC-LED. However, the different characteristics of the AC-LED chip driven by AC from that driven by DC were rarely discussed. In this study, the single chip AC-LED with 34 microchips illuminated in each bias direction was fabricated, and the electrical and optical characteristics of the AC-LEDs driven by DC and AC were analyzed and discussed.

2. Device Fabrication

The GaN epitaxial wafer used in this study was grown on *c*-face sapphire by the metal–organic chemical vapor deposition (MOCVD) system, and the schematic of the AC-LED structure is illustrated in Fig. 1(a). The structure consisted of a low-temperature thin GaN nucleation layer, a thick n-type GaN layer, an InGaN/GaN multiple-quantum-well structure, a Mg-doped p-type AlGaN electron blocking layer, and a Mg-doped p-type GaN top contact layer. To fabricate the AC-LED, a Cl_2-based plasma etching process was first applied with an inductively coupled plasma (ICP) etcher method to expose the n-type GaN layer, and a textured isolation trench was then etched until the sapphire surface was partially exposed to perform electroinsulation between microchips. A 160-nm-thick indium tin oxide film was then evaporated onto the top p-type GaN surface to serve as both the anode and transparent contact layer, and a 500-nm-thick low-temperature passivation SiO_2 layer was deposited onto samples by a plasma-enhanced chemical vapor deposition system. The areas of anodes and cathodes were exposed by the photoresist lift-off method to prevent ohmic contact surfaces from being damaged by the ion bombardment effect in the dry etching process. The bridged Cr/Au (100 nm /2500 nm) multilayers were then evaporated on samples to serve as cathodes,[6] electrical connection channels between microchips, and bonding pads. The fabricated AC-LED was packaged with emitters and covered with silicon glue. There were 52 microchips disposed as two Wheatstone Bridge circuits connected in series, as shown in Fig. 1(b). The microchip groups A, B, C, and D served as rectifiers in transforming the input AC signal into DC, which made the microchip group E always under the forward bias condition. Electroluminescent (EL) photographs of the AC-LED driven by forward and reverse 1 mA currents are shown in Fig. 1(c). The dimensions of the AC-LED chip and microchips in the arrays were 1350×1150 and 140×190 μm^2, respectively. In this study, the DC and AC current–voltage properties were measured by the Keithley 2400 SourceMeter and Xitron 2802 analyzer, and the AC signal was generated by a 60 hertz AC sine wave power supply. The light output power was measured with the calibrated integrating sphere, and integrating durations of the AC-LED driven by DC and AC were both 50 ms.

3. Results and Discussion

The typical current–voltage–light output power characteristics of the AC-LED driven by AC and DC are shown in Fig. 2, and the root mean square driving AC voltage and constant driving DC voltage are labeled as V_{rms} and V, respectively. It could be observed that the forward current and light output power of the AC-LED driven by AC were both higher than those of the AC-LED driven by DC when V_{rms} and V were equal, which was attributed to different

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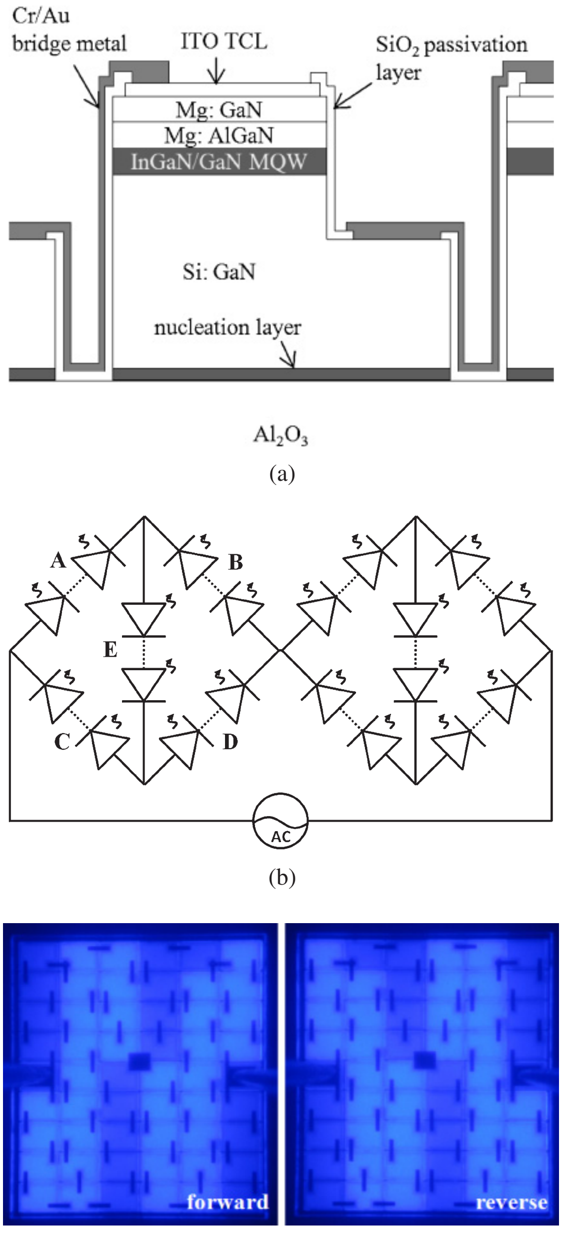

Fig. 1. (Color online) (a) Schematic structure of the GaN-based alternating current light-emitting diode. (b) Circuit diagram of the AC-LED. (c) Top-view photographs of the AC-LED driven by forward and reverse 1 mA currents.

turn-on voltages of the AC-LEDs driven by AC and DC. The turn-on voltage of the AC-LED operated in DC power was easily estimated to be the turn-on voltage of one microchip times the number of microchips illuminated in one bias direction, which was about 80 V in this study. When the AC-LED was driven by AC, the time-varying driving voltage increased from 0 V to the maximum value of $V_{rms} \times \sqrt{2}$ and then decreased back to 0 V in one-half AC sine wave input cycle. Therefore, the input AC voltage increased from 0 V to the maximum value of 84.9 V and then decreased back to 0 V in one-half cycle when the read driving AC voltage was $60V_{rms}$. The driving voltage of AC $60V_{rms}$ was temporary higher than 80 V, indicating that the turn-on voltage of the AC-LED driven by AC was as low as about 60 V. The light output power and wall plug efficiency characteristics of the

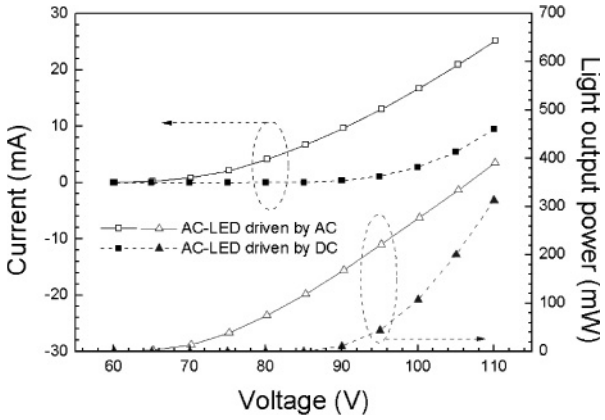

Fig. 2. Typical forward current–voltage–light output power characteristics of the AC-LED driven by AC and DC.

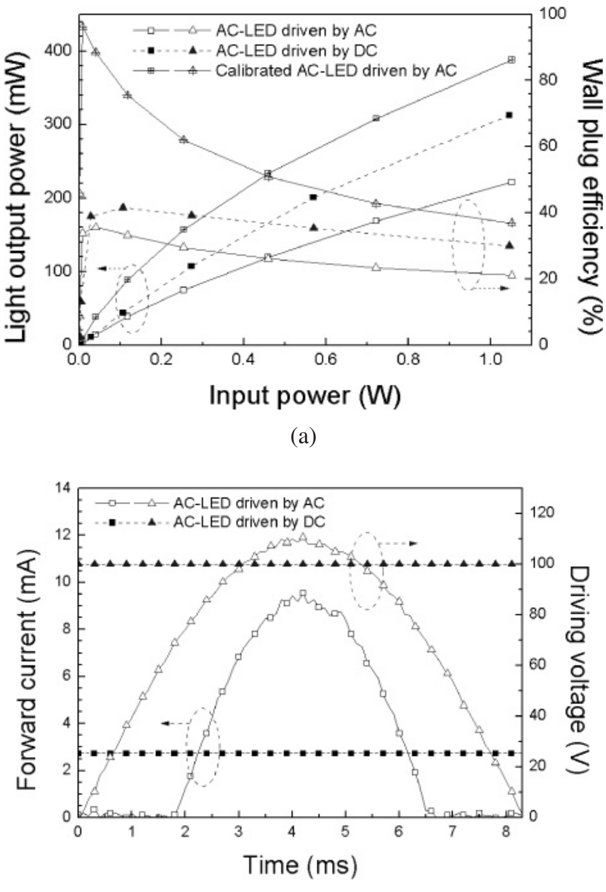

Fig. 3. (a) Measured and calibrated light output powers and wall plug efficiencies of the AC-LED driven by AC and DC as a function of the input power. (b) Time-resolved forward current and driving voltage characteristics of the AC-LED operated in AC and DC powers.

AC-LEDs driven by AC and DC as a function of input power are shown in Fig. 3(a). The input power here was the result of the integration of the forward current timed the driving voltage, corresponding to the real consumed power. The light output power of the AC-LED driven by DC was higher than that of the AC-LED driven by AC, which was attributed to the improper integration duration. The time-resolved forward current-driving voltage characteristics of the AC-LEDs driven by AC and DC at an input power of about

0.25 W are shown in Fig. 3(b). The forward current of the AC-LED driven by AC could be measured only when the driving voltage was higher than the DC turn-on voltage, which was 80 V in this study. Therefore, in the integration duration of 50 ms, the dark duration of the AC-LED driven by AC was integrated and led to the underestimation of the time-averaged light output power. For the accurate calculation of the light output power of the AC-LED driven by AC, the dark duration should be excluded. Equation (1) shows the equation for the calibration of the light output power of the AC-LED driven by AC.

$$L_{calib} = \frac{L_{meas}}{t_h/t}, \quad (1)$$

where L_{calib} is the calibrated light output power of the AC-LED driven by AC, L_{meas} is the light output power of the AC-LED driven by AC measured by the integrating sphere, t_h is the duration of the driving AC voltage being higher than 80 V, and t is the measurement integrating time. As shown in Fig. 3(a), the light output power of the AC-LED driven by AC after the calibration was higher than that of the AC-LED driven by DC, and the calibrated light output powers of the AC-LEDs driven by AC and DC were 388.1 and 312.8 mW at an input power of about 1 W, respectively. Consequently, the higher light output power of the AC-LED driven by AC than that of the AC-LED driven by DC was tentatively ascribed to the flickering illumination mode caused by the alternating driving AC voltage, which led to the decrease in heat accumulation and the improvement in energy utilization efficiency. The EL peak wavelengths and full widths at half maximum (FWHMs) of the AC-LEDs driven by AC and DC provided more lines of evidence, as shown in Fig. 4. The larger peak wavelength blue shift of the AC-LED driven by AC than that of the AC-LED driven by DC was observed, and the blue shift of the AC-LED peak wavelength could be attributed to the charge-screening and band-filling effects. It is well-known that the injected current weakens the quantum confined Stark effect and enhances the band-filling effect,[7,8] and therefore, the larger blue shift of the AC-LED driven by AC than that of the AC-LED driven by DC could be attributed to the injected current of the AC-LED driven by AC was higher than that driven by DC. However, the FWHM of the AC-LED driven by DC was larger than that of the AC-LED driven by AC as the input power increased. The larger FWHM of the AC-LED driven by DC than that of the AC-LED driven by AC indicated that the flickering illumination mode of the AC-LED driven by AC showed good heat dissipation and revealed the enhancement of the energy utilization efficiency as compared with that of the AC-LED driven by DC.

4. Conclusions

The single chip AC-LED integrated with a number of microchips and arranged as the Wheatstone Bridge circuit was demonstrated. After the calibration, the AC-LED driven by AC revealed a higher light output power, a larger blue shift, and a smaller FWHM than the AC-LED driven by DC. The flickering illumination mode of the AC-LED driven by AC showed good heat dissipation and therefore enhanced the energy utilization efficiency of the AC-LED compared with that of the AC-LED driven by DC. This result indicates that the AC-LED could be a potential general lighting solution because of not only its more compacted volume and less expensive lighting module but also its higher energy utilization efficiency than the conventional DC LED.

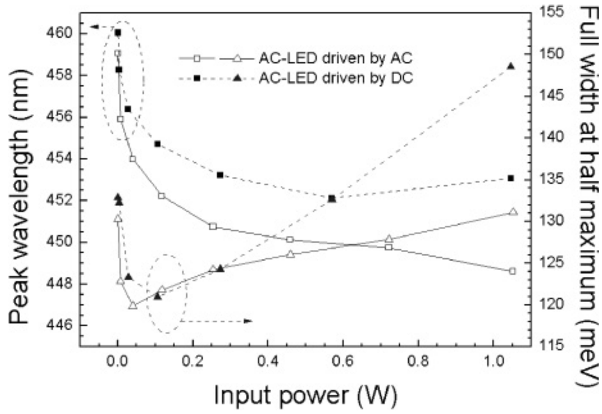

Fig. 4. EL peak wavelengths and FWHMs of the AC-LED driven by AC and DC as a function of the input power.

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