Thermal simulation and packaging of vertical GaN/Si LED with large size chip

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To achieve ultra-high power Light-Emitting Diode(LED), we developed a thermal simulation to design and fabricate a vertical structure LED based on Si substrate with a large size of 3 mm × 3 mm chip. It was found that the luminous flux of packaged LED increases with the increase of driving current and reaches 1284 lm at 5A. Moreover, the thermal resistance and junction temperature are 1.99°C/W and 66.96°C respectively, which are consistent with the simulated results. Due to its excellent optical and thermal properties, the vertical GaN/Si LED has important applications in special high brightness fields.

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Keywords: Vertical GaN/Si LED, Large size chip, Luminous flux, Thermal resistance and junction temperature

1. Introduction

Light-Emitting diodes (LEDs) are excellent candidates to replace the traditional light sources for various applications due to higher energy efficiency, longer lifetime and environmental friendly [1-2]. Ultra-high power LEDs are paid more and more attention to get higher light output performance in street lamps, stage lamps, interior and exterior automotive lighting illumination and other special high brightness fields of application [3]. To achieve higher luminous flux, it is necessary to drive the LED to a high current density level, which evidently engenders a large part of heat and increases the junction temperature of the device due to the Joule heating at the p-n junction [4]. Therefore, thermal problem is becoming more important with the increase of input power, which is considered to be the direct cause of the limited performance and failure of LEDs [5-6]. Moreover, for the case of GaN/sapphire LED, heat dissipation becomes the most crucial problem due to the poor thermal conductivity of sapphire [7]. To solve the thermal problem and lower the junction temperature in the high power GaN/sapphire LEDs, one of the main methods such as replacing sapphire substrate and transferring onto an electrically and thermally conductive Si substrate, has been developed to improve thermal dissipation [8]. Furthermore, compared with the lateral current conduction of GaN/sapphire LEDs, the vertical GaN/Si LEDs solve the current crowding effect due to the N and P electrodes are formed on upper and lower surfaces of LED. The vertical GaN/Si LEDs also have the advantages of single surface lighting and good directivity [9-12].

Some researchers reported the improvement and measurement of the performance parameter in white LED device with different packaging structures. However, few experimental studies on the optical property and thermal characterization of greater LED chip have been investigated, especially, for vertical GaN/Si LED with a large size of 3mm×3mm chip. Therefore, it is novel and important to evaluate the optical and thermal performance of the packaged LED. In this paper, thermal simulation using FloEFD software [13] is developed by considering the different sizes of chip at first, and we package a vertical GaN/Si LED with a large size chip of 3mm×3mm. The optical performance of LEDs at the driving current is measured via the photoelectric analysis system. Moreover, thermal transient method is used by TRA-200 LED thermal resistance structure analyser of Everfine Corporation for determining thermal parameters. The values of thermal resistance and junction temperature are obtained by analysing the thermal transient curves of LEDs using TRA-200 Software. The results of simulation and experiments confirm that the packaged vertical GaN/Si LED has excellent optical and thermal performance.

2. Thermal simulation and experiments

First of all, to predict the influence on the ability of heat dissipation with different chip sizes, thermal simulations have been performed using FloEFD software. Simulation models are developed to establish by SolidWorks software, which is consistent with the designed shape of packaged LED. The component materials of the model are GaN/Si chip, high conductivity Ag paste and AlN ceramic substrate, with thermal conductivity of 140, 78 and 170W/(m.K), respectively. The computational domain is set as 0.3 m × 0.3 m × 0.3 m, and all surfaces are non-radiant surface. The ambient temperature is set to 25°C, and the same thermal power of 3.6W is set to simulate the thermal distribution of LEDs with different size chips. The thermal resistance is defined as the ratio between the temperature variation and heat dissipation power as shown in the following equation [14]:

$$R_{thjx} = \frac{\Delta T_j}{P_{heat}} = \frac{T_j - T_x}{P_{heat}} \tag{1}$$

where R_{thjx}, T_j, T_x, $\varDelta T_j$ and P_{heat} represent the thermal resistance from junction to reference x, junction temperature, reference temperature, variation of temperature and heat dissipation power, respectively.

The simulation results of temperature distribution were obtained as shown in Fig. 1. T_j and T_x of LED with large size chip of 3mm×3mm based on Si substrate is 68.69 and 60.41°C, while 79.59 and 60.44°C for LED with small size chip of 1mm×1mm. Thus, the calculated thermal resistance of LED with large size chip of 3mm×3mm is 2.30°C/W, while small size chip of 1mm×1mm is 5.32°C/W. These calculated results indicate that the large size chip has better ability of heat dissipation, which means the higher reliability.

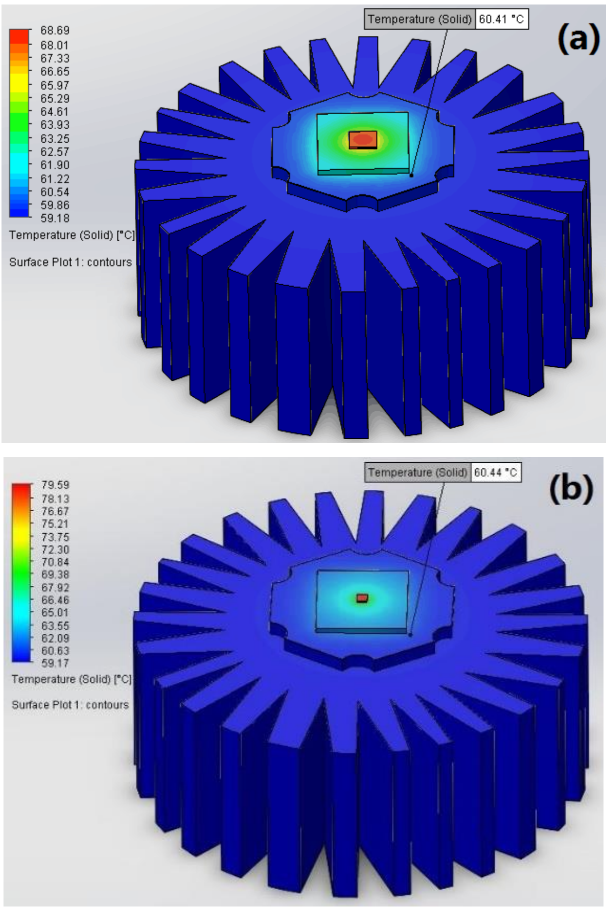

Fig. 1. Thermal distributions for vertical GaN/Si LED with different size(a) 3mm×3mm (b) 1mm×1mm

According to the simulation results, we chose the 450nm vertical GaN/Si chip with large size of 3mm×3mm to package the ultra-high power LED. Fig. 2 shows the schematic structure of the packaged LED and top view of packaged LED device using electron microscope. The P-electrode of chip was bonded by silver paste on the positive electrode region of AlN ceramic substrate, and the N-electrode was connected with the negative electrode region of the ceramic substrate through the gold wire. A hemispherical lens was covered on the ceramic substrate, and a mixture of silicone and phosphor is filled in the middle. Then the AlN ceramic substrate was mounted on a hexagonal copper plate by solder paste, which was used as a power port and a heat sink to transport heat to radiator.

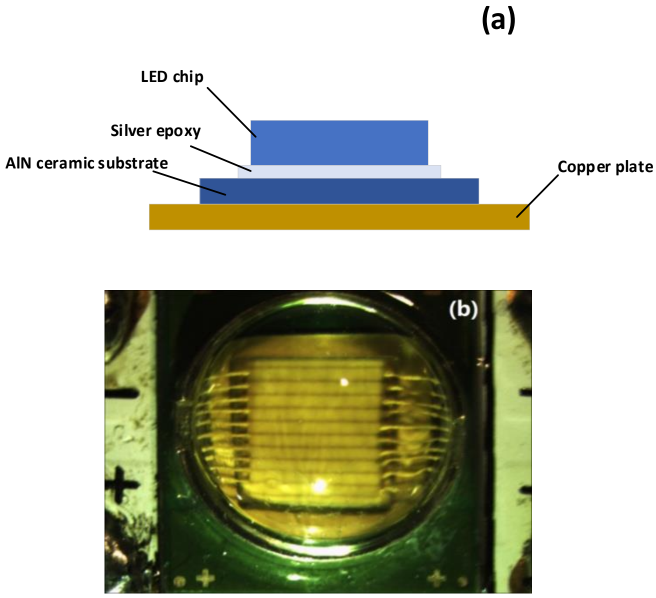

Fig. 2. (a) Schematic structure and (b) Top view of packaged LED

The luminous flux of the packaged LED was measured using the HAAS-2000 Photoelectric Analysis System manufactured by the Everfine Corporation with a 50-cm-diameter integrating sphere. The thermal parameters of the packaged LED was measured using the TRA-200 LED thermal resistance structure analyzer manufactured by the Everfine Corporation, according to the changes of temperature during cooling conditions, with the light output power excluded [15]. The packaged LED was placed on a heat sink inside a standard still-air testing oven with an ambient temperature of 25°C. The purpose of the standard still-air testing oven is to reduce the fluctuation of ambient air which tends to affect the thermal data during the process of measurement [16]. The packaged LED was driven with lower operating current to prevent self-heating effect at the junction during the testing process [17]. The testing current generally chooses the current corresponding to the voltage inflection point on the I-V curve. The heating current and the measurement current in the experiments were 2000 and 1.5 mA, respectively. The temperature sensitive parameter (K-factor) of packaged LED was determined with the measurement current in a standard measurement using temperature-controlled device and measured from 20 to 70°C, increasing at a constant interval of 10°C [18]. After that, the packaged LED was subjected to cool equilibrium with ambient temperature surrounding (T_a= 25°C) and allowed LED to cool down to achieve temperature stabilization before driving of the heating current. The cool equilibrium lasted 1 minute and then turned to the mode of thermal equilibrium. After 10 min of heating at current of 2000 mA, the LED was switched to sensing mode, which used 1.5 mA of measurement current. Then, the cooling curve of heat flow from the packaged LED to ambient was captured. The thermal resistance and junction temperature were obtained by analyzing the thermal transient curves of TRA-200 Software.

3. Results and discussion

Fig. 3 shows the luminous flux of packaged LED with the driving current ranging from 0.5A to 5A. We can see that the luminous flux increases with the increases of driving current, and the luminous flux can be up to 1284 lm at the driving current of 5A.

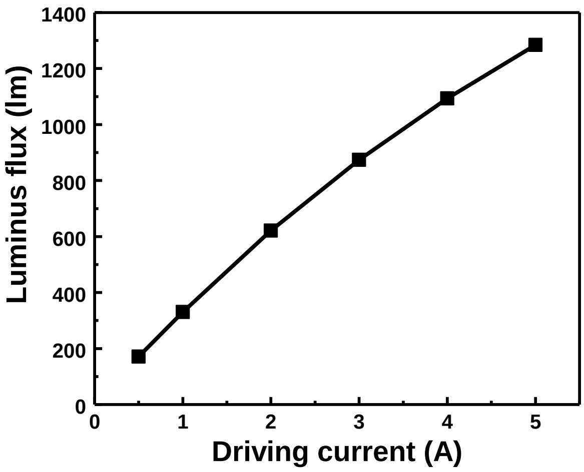

Fig. 3. Luminous flux of packaged LED as a function of driving current

Thermal resistance and junction temperature can be obtained by analyzing the change of transient forward voltage during cooling [15]. The *K*-factor of the LED was determined using a temperature-controlled device at 20°C, 30°C, 40°C, 50°C, 60°C, 70°C, and a testing current of 1.5mA to prevent self-heating effect at junction. The forward voltage of the LED has a linear relationship with junction temperature. The LED *K*-factor is obtained from the following equation [17]:

$$K = \Delta T_j / \Delta V_f \tag{2}$$

where K is LED K-factor, ΔT_j and ΔV_f are change in junction temperature and forward voltage, respectively. Here, the K-factor of testing LED is -0.56 °C/mV. The corresponding thermal resistance and junction temperature are calculated from the following equations [18]:

$$P_{dis} = P_e - P_{opt} \tag{3}$$

$$\Delta T_j = R_{thja} \times P_{dis} \tag{4}$$

$$T_j = T_a + \Delta T_j \tag{5}$$

In the equations, P_{dis}, P_e, P_{opt}, R_{thja}, T_j and T_a represent the heat dissipated power, input electrical power, light output power, total thermal resistance, junction temperature and ambient temperature, respectively.

In the experiments, electrical power, light output power and heat dissipated power of the LED under driving current of 2000 mA are 5814.00, 2207.17 and 3606.83 mW, respectively. The total thermal resistance can be obtained in the differential structure function or cumulative structure function via thermal transient curves, as shown in Fig. 4. Thus, the junction temperature of testing LED under the driving current can be calculated using (4) and (5). The thermal resistance and junction temperature under driving current of 2000 mA are 1.99 °C/W and 66.96 °C respectively, which are in good agreement with our theoretical results by thermal simulation as shown in Table 1. Form this point of view, the packaged LED has low thermal resistance and junction temperature. It can be attributed to good current expansibility to emit less heat and good thermal conductivity of Si substrate to conduct the heat quickly, and the similar phenomenon has also been reported by Jiang et al. [19].

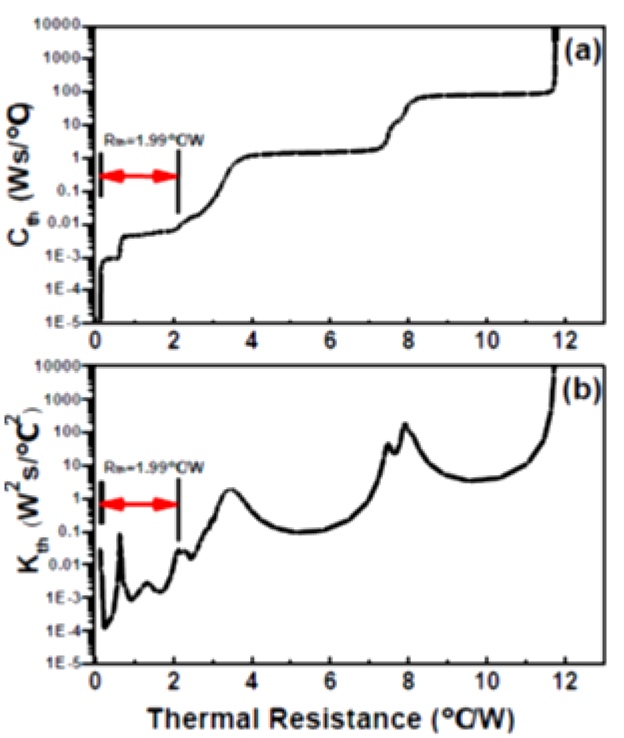

Fig. 4. (a) Cumulative structure function (C_{th}) and (b) differential structure function (K_{th}) of vertical GaN/Si LED with large size chip

Table 1. Junction temperature and thermal resistance of vertical GaN/Si LED with large size chip in measurement and simulation

	Junction temperature (°C)	**Thermal resistance (°C /W)**
Testing value	66.96	1.99
Simulated value	68.69	2.30

To sum up, the vertical GaN/Si LED with large size chip not only improves the current distribution to increase the luminous intensity, but also reduces the thermal resistance and junction temperature to improve the reliability. Thus, this kind of LED can greatly improve driving current to obtain higher luminous flux output, and have important applications in street lamp, stage lamp, automotive lighting illumination and other fields.

4. Conclusion

In this work, we designed and fabricated one vertical GaN/Si LED with excellent optical and thermal performance, which has broad applications in street lamp, stage lamp, automotive lighting illumination and other special high brightness fields.

Acknowledgments

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References

[1] E. F. Schubert, J. K. Kim, Science **308**(5726), 1274 (2005).
[2] M. H. Chang, D. Das, P. V. Varde, M. Pecht, Microelectronics Reliability **52**(5), 762 (2012).
[3] D. A. Mills, III-Vs Review **16**(1), 30 (2002).
[4] R. H. Horng, C. C. Chiang, H. Y. Hsiao, X. Zheng, D. S. Wuu, H. I. Lin, Applied Physics Letters **93**(11), 310 (2008).
[5] L. Yang, J. Hu, K. Lan, M. W. Shin, Physica Status Solidi **3**(6), 2187 (2006).
[6] N. Narendran, Y. Gu, Journal of Display Technology **1**(1), 167 (2005).
[7] C. F. Chu, C. C. Cheng, W. H. Liu, J. Y. Chu, F. H. Fan, H. C. Cheng, T. Doan, C. A. Tran, Proceedings of the IEEE **4**(1), 17 (2007).
[8] W. S. Wong, T. Sands, N. W. Cheung, M. Kneissl, Applied Physics Letters **77**(18), 2822 (2000).
[9] F. Y. Jiang, J. L. Liu, L. Wang, C. B. Xiong, W. Q. Fang, C. L. Mo, Sin-Phys. Mech. Astron. **45**(6), 067302 (2015).
[10] Q. Sun, W. Yan, M. X. Feng, Z. C. Li, B. Feng, H. M. Zhao, H. Yang, Journal of Semiconductors **37**(4), 61 (2016).
[11] H. Kuang, S. A. He, Y. Luo, X. Q. Zhang, Z. H. Xiong, Advanced Materials Research **884-885**, 283 (2014).
[12] Y. Jiang, Z. H. Xiong, Q. Xiang, Applied Mechanics & Materials **246-247**, 1154 (2013).
[13] M. E. Raypah, M. K. Dheepan, M. Devarajan, F. Sulaiman, Applied Thermal Engineering **101**, 19 (2016).
[14] C. P. Ching, M. Devarajan, W. C. Liew, IEEE, International Conference on Photonics IEEE, 1 (2011).
[15] C. P. Wang, T. T. Chen, H. K. Fu, T. L. Chang, P. T. Chou, IEEE Transactions on Electron Devices **60**(5), 1668 (2013).
[16] N. Teeba, P. Anithambigai, K. Dinash, D. Mutharasu, Quality Electronic Design IEEE 21 (2011).
[17] S. Subramani, T. Nadarajah, M. Devarajan, Microelectronics International **30**(2), 77 (2013).
[18] R. L. Liang, J. Zhang, S. Wang, Q. Chen, L. L. Xu, J. N. Dai, C. Q. Chen, IEEE Transactions on Electron Devices **64**(3), 1174 (2017).
[19] F. Y. Jiang, W. H. Liu, Y. Q. Li, W. Q. Fang, C. L. Mo, M. X. Zhou, H. C. Liu, Journal of Luminescence **122**(1), 693 (2006).

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