

Effects of Substrate on Thermal and Optical Characteristics of High-Power ThinGaN White LED

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Abstract. Thin Gallium Nitride (ThinGaN)-based light-emitting diodes (LEDs) demonstrate high extraction efficiency and brightness. Their slim designs make them appropriate for lighting applications that demand high luminous flux, small space, and stability. Thermal resistance and junction temperature values under different boundary conditions can help in understanding thermal management of ThinGaN-based LEDs. In this paper, thermal and optical characteristics of ThinGaN (UX:3) white LED mounted on Metal-Core Printed Circuit Board (MCPCB) and a SinkPad MCPCB are investigated. Thermal and optical parameters of the LED are measured by thermal transient tester (T3Ster) and spectrometer devices. Results show that the LED attached to the SinkPad MCPCB obtained lower thermal resistance and junction temperature than MCPCB.

1. Introduction

LEDs have a significant impact in lighting applications such as displays, indicators, signaling, and public lighting technology [1-3]. Advantages of LEDs include high brightness, long lifetime, reliability, and low power consumption [4, 5]. White LEDs are evolving rapidly and widely used due to their high luminous efficacy. Recently, LED manufacturers are designing more reliable and efficient white LEDs than before. The new type of white LED is of the highly efficient UX:3 chip that is based on ThinGaN technology. A metallic mirror below the active layer and scattering surface are employed in this technology to optimize the light extraction. In addition, the efficiency is increased by interring the n-type contact inside the chip that may reduce Auger recombination. The ThinGaN basic idea is confining the light to the GaN layer through a reflective mirror on the carrier side and extracting the light by a structured surface at the top side of LED. Therefore, the factors for increasing light extraction are mirror with high reflectivity, improved surface structure, and diminished the absorption within or on the GaN layer [6, 7]. This type of LED is used in applications that demand high brightness, such as automotive headlights, general lighting, or pocket projectors. High injection current yields high brightness, but causes a decline in the LED efficiency that is attributed to the increase in LED junction temperature. This will lower the reliability and efficiency of the device [8-11]. Proper thermal management would cause a reduction in junction temperature that affects the overall LED's performance. Lower junction temperature increases LED brightness, lifetime, light output, and reliability. To reduce the junction temperature, the heat at the LED chip ought to dissipate to the substrate and then to the atmosphere. One of the solutions to dissipate the heat generated on the chip is using a good heat spreader such as metal base board. A SinkPad is a MCPCB technology that allowing a direct and more efficient thermal path between the LED system and the ambience. The SinkPad can eliminate the thermal resistance introduced by the dielectric layer in MCPCB.



In this paper, the thermal and optical performance of ThinGaN (UX:3)-based white LED attached to the MCPCB and a SinkPad are investigated. The thickness of MCPCB and SinkPad is 1.57 mm and the metal base is aluminium (Al 6063). The thermal transient technique is used via T3Ster system for determining the thermal parameters of the LED. Furthermore, the LED optical properties are measured by using the spectrometer.

2. Experiment Details

Cool white LED (6500 K) of power 4.5 W (OSLON Black Flat) from Osram Opto Semiconductors was used in this work. The LED was attached to the boards which were MCPCB and SinkPad using lead-free solder paste (SAC 305, Heraeus solder paste) by surface mount technology (SMT). After soldering process, the package was fixed on a cold plate of T3Ster machine using a thermal pad of 3.0 W/m.K thermal conductivity and 0.35 mm thickness. Firstly, the calibration measurement was done to determine the calibration factor (K-Factor) of the LED. In a calibration process, a small sensor current of 1.0 mA (to ignore the generated heat in the junction) and temperature range of 20-65 °C with a step of 5 °C were employed. Secondly, the LED on each board was heated for a period of 900s and cooled down for another 900s to reach thermal equilibrium with the surrounding temperature at various injection currents and temperatures. The LED was operated at different injection currents and the temperature of cold plate was fixed at 25 °C. In addition, the LED was driven at 700 mA for various ambient temperatures. The temperature was controlled through the thermostat of the T3Ster system. The cooling curves were evaluated using T3Ster Master Software to attain the LED junction temperature and thermal resistance. The optical properties such as emission spectrum, correlated color temperature (CCT), and color coordinates of the LED package at same operating conditions was obtained using UPRtek MK350 Spectrometer.

3. Results and Discussions

The LED temperature-sensitive parameter (TSP) which is the reciprocal of K-Factor that shows the relationship between the change in a forward voltage (ΔV_f) and ambient temperature (ΔT_A). The TSP of the LED under study equals to -1.59 mV/°C.

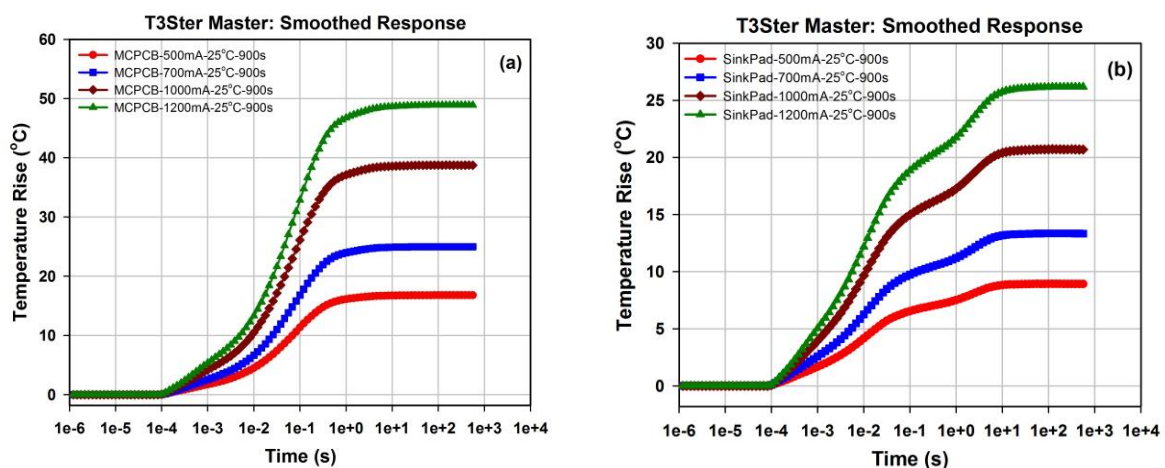


Figure 1. Junction temperature transients of high-power ThinGaN LED mounted on (a) MCPCB and (b) SinkPad at different injection currents.

The thermal transient technique was used to evaluate the thermal performance of the LED under consideration [12-14]. Structure functions and smoothed response curves were utilized to determine the LED thermal resistance (R_{th}) and junction temperature (T_J). Figure 1 represents the heating curves of the LED at different injection currents (I_f). In the beginning of heat flow, the heat is transferred

from the LED chip to the board. Obviously, the temperature rising rate of SinkPad is slower than MCPCB. This means that the heat dissipation is more efficient in SinkPad. As a result, the heat accumulation will be avoided. Once the heat dissipated to the environment is equal to the heat generated in the LED chip, the device will stabilize, and the temperature rise will decrease to zero for either MCPCB or SinkPad. The steady state at 1200 mA is 49.5 °C for MCPCB, while being 26.4 °C for the SinkPad. The results also show that there is no overheat during the experiment, which means the SinkPad perform well as the current varies from 700 mA to 1200 mA.

Based on the K-Factor value, T_J of the LED on MCPCB and SinkPad at different I_f and T_A is determined and shown in Figure 2. It is apparent that the T_J increases with I_f and T_A . Moreover, the T_J of the SinkPad is always lower than that of MCPCB. T_J of the LED on MCPCB is 74 °C when I_f is 1200 mA and 51.5 °C for SinkPad. In addition, the T_J of LED on MCPCB is 113 °C when T_A is 85 °C and 102 °C for SinkPad at 700 mA. Hence, the SinkPad demonstrates better thermal transfer performance than MCPCB at different operating conditions.

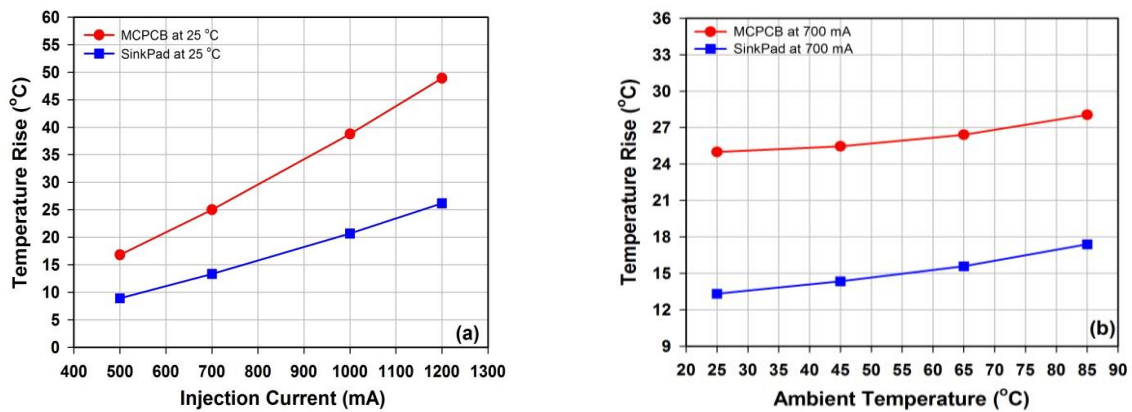


Figure 2. Temperature rise of high-power ThinGaN LED at various (a) injection currents and (b) ambient temperatures.

Figure 3 reveals the cumulative structure functions of MCPCB and SinkPad at different I_f and 25 °C. It is noticeable that the R_{th} increases with increase in I_f . However, R_{th} due to MCPCB is more increases with I_f than SinkPad. R_{th} from junction to ambient (R_{th-JA}) is called total thermal resistance that equals 12.6 K/W and 6.5 K/W at 1200 mA for MCPCB and SinkPad, respectively. Hence, the reduction in R_{th-JA} due to SinkPad is about 48%.

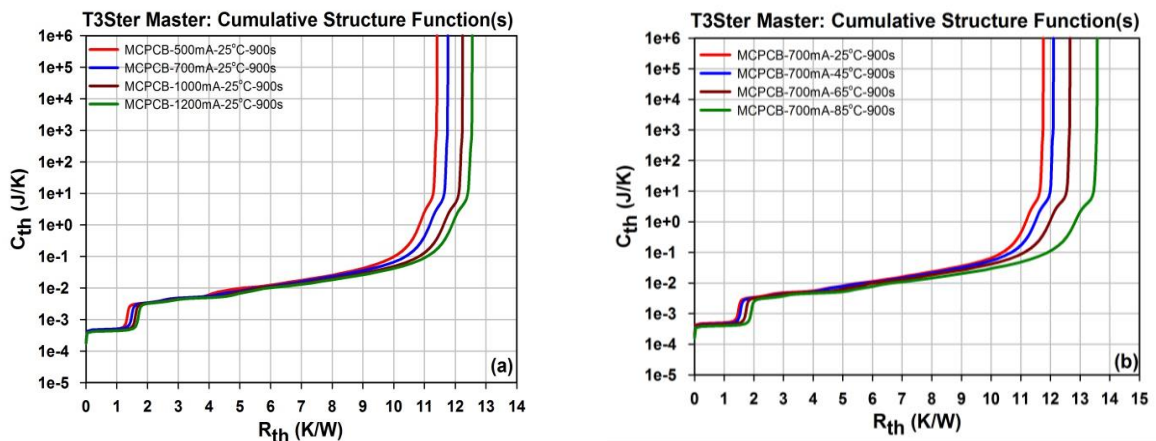


Figure 3. Cumulative structure functions of heat-flow path for high-power ThinGaN LED mounted on MCPCB at different injection currents.

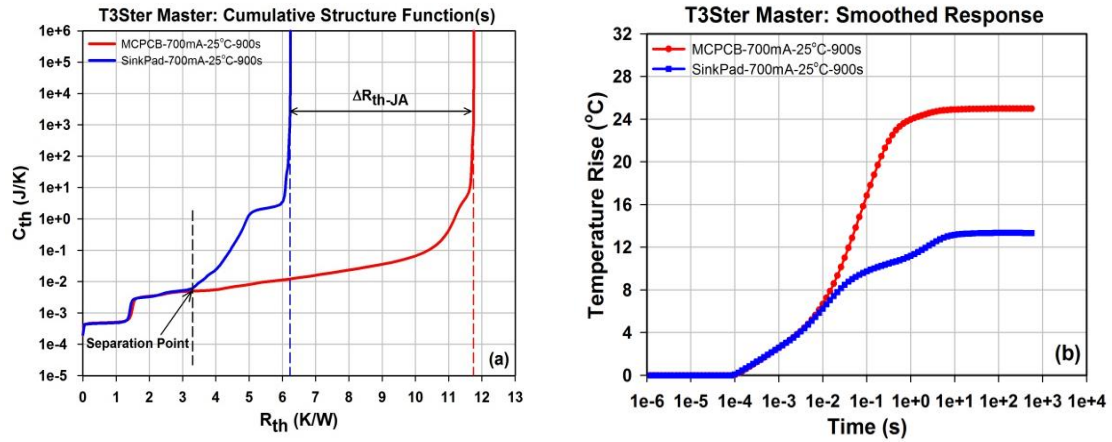


Figure 4. (a) Cumulative structure functions and (b) junction temperature transient of high-power ThinGaN LED mounted on MCPCB and SinkPad at 700mA and 25°C.

Figure 4 shows the cumulative structure functions of MCPCB and SinkPad at 700 mA and 25 °C. It is noticeable that there is a separation point between the two curves. This point means that the heat flow is entering different layers with different thermal resistance. The two samples have identical heat flow paths on the left of separation point. This region represents the R_{th} of the LED package (R_{th-JS}) which equals to 3.3 K/W. After the separation point, the heat flow will pass in the surface of the circuit board because it is the first different layer between the two thermal paths. R_{th} from the separation point to the end of a curve is for the board and TIM. It can be observed that the major R_{th} of MCPCB comes from the dielectric layer. It is noticed that the structure functions shift to the left hand when the substrate changed from MCPCB to SinkPad. This shifting demonstrates that the SinkPad has higher thermal conductivity than MCPCB. Therefore, the heat transfer from the bottom side of the LED to ambience is faster which contributes much to decrease R_{th-JA} . Also, the large R_{th} indicates a serious block of the insulating layer in the heat flow from the LED junction to the aluminum layer. Thus, the improvement of the heat conduction path has been extremely minimized in the case of MCPCB [15]. The R_{th-JA} can be divided into three parts which are partial thermal resistance from: junction to solder point (R_{th-JS}), solder point to the board (R_{th-SB}), and the board to ambient (R_{th-BA}). Therefore, R_{th-SB} significantly affects the heat conduction path and can improve the heat dissipation properties. Due to increase in LED T_j with I_f and T_A , the thermal resistance also increases as follows:

$$R_{th-JA} = \frac{\Delta T_j}{P_{heat}} = \frac{T_j - T_A}{P_{el} - P_{opt}} \quad (1)$$

where P_{heat} is the heat dissipation power and given by the subtraction of optical output power (P_{opt}) from the electrical input power ($P_{el} = I_f \times V_f$) [16, 17]. P_{heat} of SinkPad is higher than MCPCB which causes lower R_{th-JA} . Figure 5 represents the R_{th-JA} as a function of I_f and T_A . The increase in R_{th-JA} with increase in I_f can be attributed to internal series resistance, current crowding phenomenon, and the changes in conductivity of materials caused by increasing heat [18-20]. It is obvious that the heat dissipation properties improved with a good design of the substrate which can help in cooling the components of the system and increase the performance of LED device. As a result, the thermal resistance and junction temperature will be decreased that will expand the LED lifetime.

Figure 6(a) displays the LED spectra measured at 700 mA and 1200 mA. It is obvious that the LED on MCPCB and SinkPad exhibit almost similar spectra behavior at lower I_f . Nevertheless, as the I_f increases, the effectiveness of the board on the LED spectrum is noticeable. At 1200 mA, the peak wavelength of the LED on SinkPad and MCPCB are 444 nm and 446 nm, respectively. Additionally, the intensity drop is of 4 mW/nm between SinkPad and MCPCB. This is attributed to higher T_j with

MCPCB which causes shrinking in band gap energy. As a result, the peak wavelength shifts towards longer wavelength (red shift) [21]. In this case, the quantum efficiency reduces and leads to more non-radiative recombination in LED active region [22]. Ratio of the radiant power within blue emission (B) to the total radiant power (W) of the LED is defined as B/W. The total radiant power (W) is the blue emission (B) and phosphor emission (Y). The B/W increases with the input current (Figure 6(a)) which means the blue emission part enhances the total radiant power. The B/W ratio varies between MCPCB and SinkPad which is mainly because of their different heat transfer performance. Higher junction temperature decreases both of the blue emission of the LED chip and phosphor efficiency [23]. Also, it can be observed that there is a degradation in the energy of phosphor converted light which is due to the thermal quenching effect of phosphor or the silicone carbonization [24, 25]. This means that the phosphor temperature is also an important factor that characterizes the thermal performance of white LEDs besides the junction temperature [26]. Variation in the spectrum causes corresponding change in the chromaticity coordinates. Figure 6(b) exhibits the x- and y-color coordinates variation with I_f at 25 °C. Apparently, with increasing I_f , the white point shifts to higher correlated color temperature (CCT) for both MCPCB and SinkPad. The CCT of MCPCB and SinkPad samples is almost changes linearly with increasing I_f . This is due to that the blue light emission from the LED chip increases with I_f and leads to shifting in the color coordinates to the blue portion in the chromaticity diagram that known as a blue shift mechanism [15]. Moreover, higher CCT leads to more blue light to convert to yellow light which results in increase in the overall efficiency of the LED device [27]. As the current varies from 400 mA to 1200 mA, the chromaticity change ($\sqrt{\Delta x^2 + \Delta y^2}$) is 0.0206 and 0.0396 for MCPCB and SinkPad, respectively. The higher color change in case of using SinkPad is because of its bigger shift to the blue region in the chromaticity diagram. The chromaticity shift can be further explained in terms of the emission spectra. It is known that the blue emission increases with increasing I_f . As a result, the overall emission of LED light and the chromaticity coordinates of the two samples shift toward higher CCT. The maximum intensity of the blue emission (BE) is 6.77 and 7.12 mW/nm at 700 mA for MCPCB and SinkPad, respectively. Furthermore, the BE at 1200 mA is 7.52 and 10.9 mW/nm for MCPCB and SinkPad, respectively. This variation is due to the difference in thermal characterization between MCPCB and SinkPad. Higher junction temperature reduces the blue light efficiency and subsequently LED total efficiency. It is shown from the results that the color shift and CCT values for the LED on SinkPad is as expected because its higher thermal conductivity than MCPCB. Therefore, the efficiency of the LED on SinkPad is higher and more blue light is produced by the LED chip that results in higher blue shift.

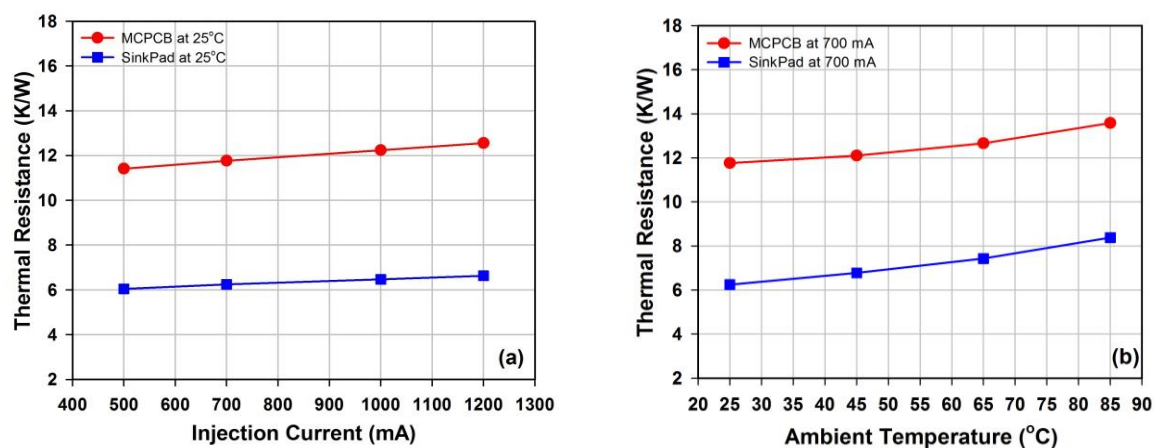


Figure 5. Thermal resistance of high-power ThinGaN LED at various (a) injection currents and (b) ambient temperatures.

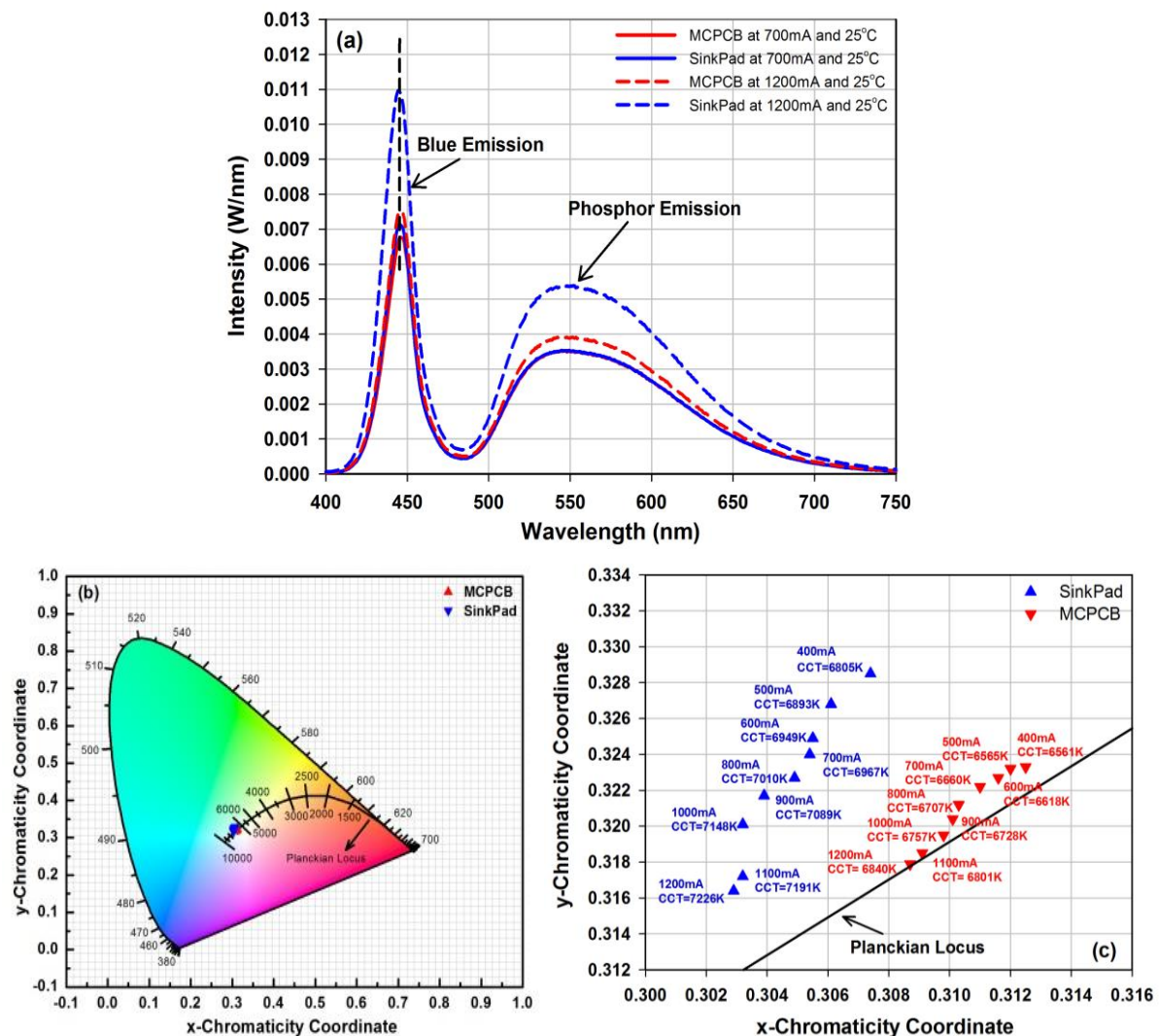


Figure 6. (a) Emitting spectra and (b) x-y chromaticity space and (c) chromaticity coordinates of high-power ThinGaN LED at different currents.

4. Conclusion

In this paper, thermal and optical characteristics of high-power ThinGaN white LED soldered on MCPCB and SinkPad are investigated. The thermal and optical parameters of the LED are measured via T3Ster and spectrometer devices. The thermal resistance and junction temperature are determined using thermal transient method through T3Ster system. It is found that at injection current of 1200 mA, the junction temperature and total thermal resistance of SinkPad is lower by 23 °C and 6 K/W than of MCPCB, respectively. In addition, the SinkPad has a better chromaticity shift control at high injection currents than MCPCB.

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References

- [1] Chiu H-J, Lo Y-K, Chen J-T, Cheng S-J, Lin C-Y and Mou S-C 2010 *Industrial Electronics, IEEE Transactions on* **57** 735-43.
- [2] Gu L, Ruan X, Xu M and Yao K 2009 *Power Electronics, IEEE Transactions on* **24** 1399-408.
- [3] Gacio D, Alonso J M, Calleja A J, Garcia J and Rico-Secades M 2011 *Industrial Electronics, IEEE Transactions on* **58** 589-99.
- [4] Cheng T, Luo X, Huang S and Liu S 2010 *International Journal of Thermal Sciences* **49** 196-201.
- [5] Hu J, Yang L and Shin M W 2008 *Journal of Physics D: Applied Physics* **41** 035107.
- [6] Baur J, Baumann F, Peter M, Engl K, Zehnder U, Off J, Kuemmler V, Kirsch M, Strauss J and Wirth R 2009 *physica status solidi (c)* **6**.
- [7] Laubsch A, Sabathil M, Baur J, Peter M and Hahn B 2010 *IEEE transactions on electron devices* **57** 79-87.
- [8] Chitnis A, Sun J, Mandavilli V, Pachipulusu R, Wu S, Gaevski M, Adivarahan V, Zhang J, Khan M A and Sarua A 2002 *Applied Physics Letters* **81** 3491-3.
- [9] Cao X, LeBoeuf S, Rowland L, Yan C and Liu H 2003 *Applied Physics Letters* **82** 3614-6.
- [10] Pavesi M, Manfredi M, Salviati G, Armani N, Rossi F, Meneghesso G, Levada S, Zanoni E, Du S and Eliashevich I 2004 *Applied physics letters* **84** 3403-5.
- [11] Egawa T, Ishikawa H, Jimbo T and Umeno M 1996 *Applied physics letters* **69** 830-2.
- [12] Farkas G, vanVoorstVader Q, Poppe A and Bognár G 2005 *IEEE transactions on components and packaging technologies* **28** 45-50.
- [13] Choi J H and Shin M W 2012 *Microelectronics Reliability* **52** 830-5.
- [14] Kim L and Shin M W 2007 *IEEE Transactions on Components and Packaging Technologies* **30** 632-6.
- [15] Ding X, Tang Y, Li Z, Chen Q, Li Y and He Y 2015 *International Communications in Heat and Mass Transfer* **66** 32-9.
- [16] Alexander H, Maximilian S, Liu E and Gordon E 2015 *Chinese Physics B* **24** 068105.
- [17] Siegal B 2003 *Laser Focus World* **39** S12-S4.
- [18] Yang L, Hu J, Kim L and Shin M W 2006 *physica status solidi (c)* **3** 2187-90.
- [19] Jayasinghe L, Dong T and Narendran N 2007 In: *Optical Engineering+ Applications: International Society for Optics and Photonics* pp 666911--6.
- [20] Ji P F and Moon C-H 2013 *Solid-State Electronics* **85** 1-5.
- [21] Peng L-H, Chuang C-W and Lou L-H 1999 *Applied physics letters* **74** 795-7.
- [22] Liu J, Tam W-S, Wong H and Filip V 2009 *Microelectronics Reliability* **49** 38-41.
- [23] Tang Y, Ding X, Yu B, Li Z and Liu B 2014 *Applied thermal engineering* **66** 632-9.
- [24] Smet P F, Parmentier A B and Poelman D 2011 *Journal of the electrochemical society* **158** R37-R54.
- [25] Luo X, Fu X, Chen F and Zheng H 2013 *International Journal of Heat and Mass Transfer* **58** 276-81.
- [26] Ma Y, Hu R, Yu X, Shu W and Luo X 2017 *International Journal of Heat and Mass Transfer* **106** 1-6.
- [27] Ye H, Koh S, Yuan C and Zhang G 2012 In: *Electronic Packaging Technology and High Density Packaging (ICEPT-HDP), 2012 13th International Conference on: IEEE* pp 1535-9.