Available online at www.sciencedirect.com
ScienceDirect
Thermochimica Acta 455 (2007) 21–25
thermochimica acta
www.elsevier.com/locate/tca

Thermal analysis of LED array system with heat pipe

Lan Kim, Jong Hwa Choi, Sun Ho Jang, Moo Whan Shin *

Department of Materials Science & Engineering, Myong Ji University, 38-2 Nam-Dong, Yongin, Kyunggi 449-728, Republic of Korea

Available online 3 December 2006

Abstract

This paper reports on thermal characterization of high power LED arrays. Thermal transient methods are used to measure the junction temperature and calculate the thermal resistance. The emphasis is placed upon the investigation of junction temperature rise of LED array for a limited range of boundary conditions which include design effect of heat pipe, convection condition, and ambient temperature. The junction temperatures of LED array with and without heat pipe at the same air velocity of 7 m/s were 87.6 °C, and 63.3 °C, respectively. The corresponding thermal resistances of LED array were measured to be 1.8 K/W and 2.71 K/W. It was found out that the measured junction temperatures and thermal resistance of LED array are increased with the input power and ambient temperature, but decreased with the air velocity. An analytical thermal model analogous with an equivalent parallel circuit system was proposed and was verified by comparison with experimental data.

Keywords: LED array; Heat pipe; Junction temperature; Thermal resistance

1. Introduction

Light emitting diode (LED) is a solid state semiconductor device that converts electrical energy into light. LEDs demonstrate a number of benefits compared to traditional incandescent lamps. Nowadays, high power LEDs are being investigated as replacements for cold cathode fluorescent lamp (CCFL) in the LCD display backlights and head light lamp for automobiles [1,2]. With further improvement LEDs have a great potential to become a new illumination source. However, the real challenge is that the life time of LEDs still be easily shortened by heat; not only by the heat from ambient but also by the heat generated within the LED itself [3,4]. In addition, the performance of unit LED is known to significantly depend on the systems where the LED packages are laid down. In an extreme case, the life time of unit LED package with an excellent thermal performance can be very short if the system around it has a poor thermal design. Therefore, effective thermal design and reliable thermal characterization of LED system are important for the unit LED package. Thermal characterization of LEDs in an array is very different from that of single LED package. The junction temperature of LED array will be significantly influenced by ambient temperature and side effect from multiple chips. It is generally known that thermal behavior of LED array is affected by more factors than in the case of unit package. There have been several reports on thermal characterization of LED packages with a single chip [5,6]. However, there have been no reports on the thermal analysis of LED array system so far to the best knowledge of the authors.

In this paper, thermal behavior of LED array system is reported. Test chips are widely used to predict the junction temperature of array system with electronic devices (CPU, CMOS, etc.) [7,8]. However, extra special test chips are not used in our experiment and LED itself is used as a test chip. The method can reduce several measuring parameters which can mislead a real junction temperature without destructing its electrical circuits.

Thermal transient measurement was done using the so-called structure function [9]. Thermal characteristics of LED array with heat pipe and without heat pipe are compared under different ambient temperatures and forced convection conditions.

2. Theoretical background

At JEDEC Standard No. 51-1, thermal resistance of a single semiconductor device is defined as:

$$R_{JX} = \frac{T_J - T_X}{P_H} \tag{1}$$

where R_{JX} is the thermal resistance between device junction and the specific environment, T_J the junction temperature of device in a steady state condition, T_X the reference temperature for the

* Corresponding author. Tel.: +82 31 330 6465; fax: +82 31 330 6457.
E-mail address: mwshin@mju.ac.kr (M.W. Shin).

0040-6031/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.tca.2006.11.031

specific environment, and P_H the power dissipation in the device [10].

The equation is for a single chip package. Thermal resistance of LED arrays which have multiple heat sources can be described as the following relation using the average junction temperature of LED array, $T_{j,avg}$.

$$\theta_{ja\text{-}avg} = \frac{T_{j,avg} - T_{amb}}{P} \quad (2)$$

where $\theta_{ja\text{-}avg}$ is an average junction to ambient thermal resistance, P is the power dissipation of the entire packages, and T_{amb} is the ambient temperature. The equation assumes that each LED mounted on the array exhibits the same thermal characteristics. Because the LEDs used in this experiment are of identical geometry and power dissipation, the employment of the above equation is valid in our analysis. Total power dissipation is calculated by the measured voltage and the input current. Temperature rise can be interpreted by the change of voltage drop in a following way for LED and the slope is known as a K factor [10];

$$\text{slope} = \frac{dV_F}{dT_J} \quad (3)$$

where dV_F is the differential of forward bias voltage, and dT_J is the differential of junction temperature.

Expanding this theory to a series of multiple LEDs leads to the following expression for modified slope:

$$\text{slope\_total} = \frac{dV_{F\_total}}{dT} = \frac{n\,dV_F}{dT} = n \cdot \text{slope} \quad (4)$$

Eq. (4) indicates that the K factor for the LED array is easily defined from the slope for a unit LED package. The slope_total for the array system is n times of the slope for a single LED package, slope. For an LED array, the $n \cdot$ slope is a constant, so the total forward voltage of the LED array can be used as a temperature sensitive parameter (TSP).

3. Experiments

Commercial GaN-based LEDs coated with yellow phosphor (Luxeon V) were used for the fabrication of array in this experiment. LED arrays were prepared either with or without heat pipe. LED array is composed of six high power LEDs and mounted on 5 cm × 7.5 cm metal core printed circuit board (MCPCB) with a 2.5 cm pitch. Fig. 1 shows the schematic structure of LED array mounted on MCPCB and array system with heat pipe.

The diameter of the heat pipe is 1.27 cm and the length is 30 cm. LEDs in the array are electrically connected in series and simultaneously driven. Sensor current of 20 mA was used to detect the forward voltage of the array. Measurements were carried out by a thermal transient tester (T3ster®). The theoretical framework of the evaluation of the T3ster is based on a representation of the distributed RC networks. The structure functions are obtained by direct mathematical transformations from the cooling curve. After a calibration process, which determines the ratio between the temperature and the forward voltage drop as a temperature sensitive parameter (TSP), cooling curve was obtained. The size of Al chamber used in this experiment is 800 mm × 140 mm × 100 mm. The flow rate of coolant in the chamber was optimized so that the ambient temperature of the samples was kept constant during the measurement.

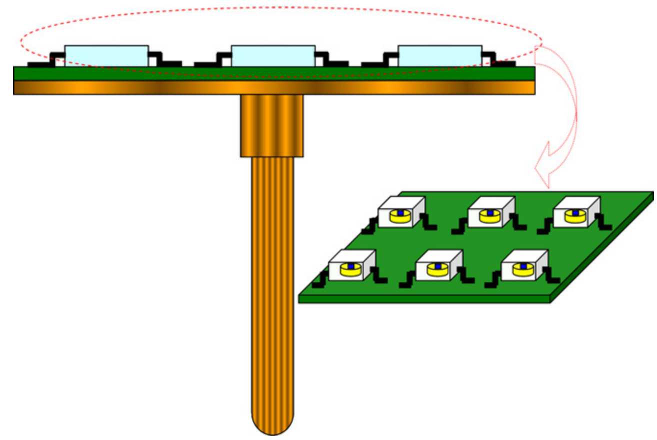

Fig. 1. Schematic structure of an LED array mounted on MCPCB.

4. Results and discussions

Fig. 2 is the forward voltage versus temperature plot obtained from the LED array without heat pipe. The linearity between the voltage drop and temperature is the K factor. The K factor of the array is 0.01969 V/°C at the sensor current of 20 mA.

The K factor of LED array is six times of one LED, because there are six LEDs connected in series. Fig. 3 represents the derivative of thermal capacitance as a function of thermal resistance for the LED array without heat pipe under several convection conditions. Thermal capacitance varies directly with both specific heat and mass; it is the quantity of heat absorbed by the sample when its temperature rises 1 °C. The peaks imply the material transitions in the heat flow path.

The total thermal resistance of array is found to decrease with the velocity of air flow. The thermal resistance is about 6.8 °C/W at the natural convection state and about 2.8 °C/W at an air velocity of 7 m/s. At an air velocity above 2 m/s, the thermal resistance of array drops rapidly. It is worth while considering the difference in thermal resistance between the unit

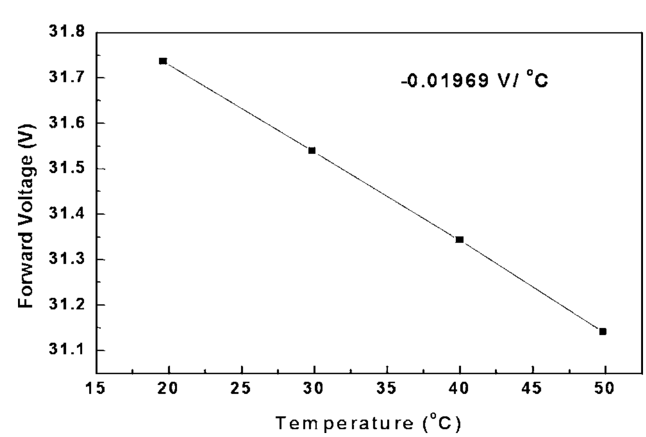

Fig. 2. Forward voltage vs. temperature plot showing a K factor of LED array.

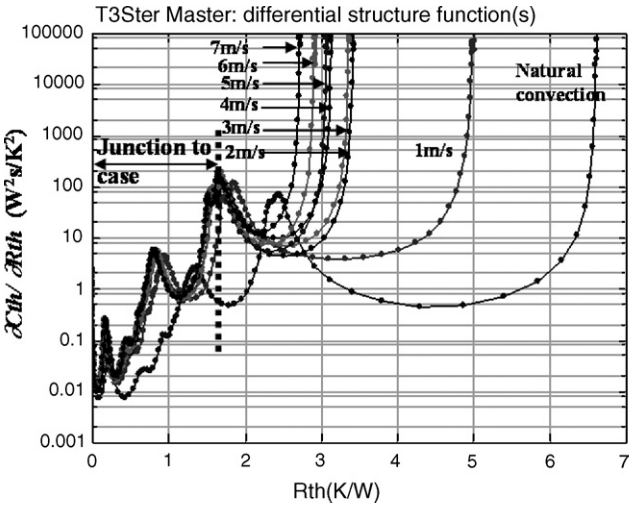

Fig. 3. Differential structure functions of LED array as a function of convection condition (without heat pipes).

LED package (8 °C/W [11]) and the value of 1.8 °C/W which was measured in this experiment. The deviation can be well explained by considering an equivalent thermal circuit of LED array as was described in Fig. 4.

Because MCPCB is one, thus the temperature of the MCPCB is assumed to be the same. The temperature difference between the junction and the ambient is expressed for each LED chip as

$$\Delta T_{\mathrm{J}i,\mathrm{a}} = \Delta T_{\mathrm{J}i,\mathrm{MCPCB}} + \Delta T_{\mathrm{MCPCB,a}} = P_i\theta_i + \left(\sum_{k=1}^{6} P_k\right)\theta_0 = P_i\theta_i + P_{\mathrm{total}}\theta_0 \quad (5)$$

where $\Delta T_{\mathrm{J}i,\mathrm{a}}$ is the temperature difference between the ith chip and ambient, $\Delta T_{\mathrm{J}i,\mathrm{MCPCB}}$ the temperature difference between the ith chip and the slug, $\Delta T_{\mathrm{MCPCB,a}}$ the temperature difference between the MCPCB and the ambient, P_i the input power of the ith chip, θ_i the partial thermal resistance between the ith chip and the MCPCB, and θ_0 is the partial thermal resistance between the MCPCB and ambient. Because the heat is generated at the junction and flows to the environment through the MCPCB, P_{total} is the sum of P_i. Defining $\Delta T_{\mathrm{J,avg}} = T_{\mathrm{j,avg}} - J_{\mathrm{amb}}$, let us assume that $\Delta T_{\mathrm{J,avg}} = \Delta T_{\mathrm{J}i,\mathrm{a}}$ ($i = 1$–6). Applying Eq. (2) into Eq. (5), leads to the total thermal resistance as follows:

$$\theta_{\text{ja-avg}} = \frac{\Delta T_{\mathrm{J}i,\mathrm{a}}}{P_{\mathrm{total}}} = \frac{P_i\theta_i + P_{\mathrm{total}}\theta_0}{P_{\mathrm{total}}} \quad (6)$$

Applying Eq. (6) into the LED array system with six LED packages, it is simplified as

$$\theta_{\text{ja-avg}} = \frac{(1/6)P_{\mathrm{total}}\theta_i + P_{\mathrm{total}}\theta_0}{P_{\mathrm{total}}} = \frac{1}{6}\theta_i + \theta_0 \quad (7)$$

The total thermal resistance is the sum of $(1/6)\theta_i$ ($\theta_i = \theta_1 = \theta_2 = \theta_3 = \theta_4 = \theta_5 = \theta_6$) and θ_0. This means that the increase in the number of unit package in a system results in the decrease of total thermal resistance due to spatially distributed power. The analytical analysis brings the thermal resistance value of unit LED package and that of array in a good agreement. Under the natural convection condition, the junction temperature was almost reached to the maximum operable temperature of LEDs. Under the forced convection condition, the junction temperatures decreased with the velocity of air flow in a range from 1 m/s to 7 m/s. However, the junction temperature was found to significantly drop by utilizing heat pipes. Fig. 5 shows the cooling effects of heat pipes on junction temperature for different air velocity. The effect of air flow on junction temperature is clearly diminished when the air velocity is same or greater than 2 m/s and even reaches saturation when heat pipes are utilized. It is known that the life time of LED package is determined by the junction temperature. Heat deteriorates the properties of epoxy in LED package and leads to the degradation of light transmission generated at the p–n junction of LED chip. Therefore, lowering the junction temperature by utilizing heat pipes enables higher capability of operation current and higher flux of light compared to the LED array without heat pipes. The fact is meaningful in the application of LED systems.

The differential structure function from the LED array with heat pipes is shown in Fig. 6. The result is compared with the

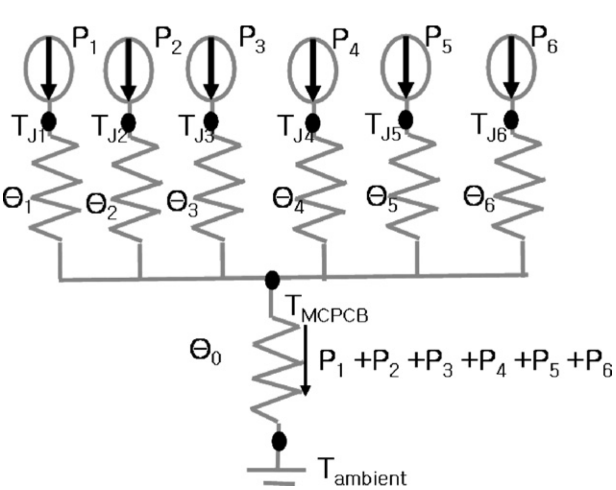

Fig. 4. Equivalent circuit of LED arrays investigated in this study.

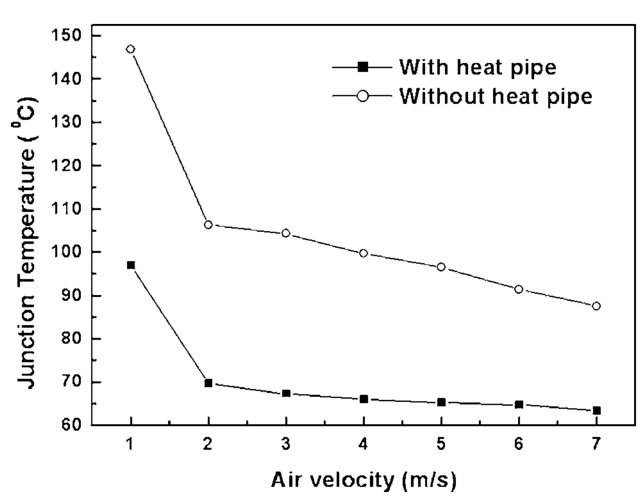

Fig. 5. Comparison of junction temperature of LED array without and with heat pipes under different air velocity.

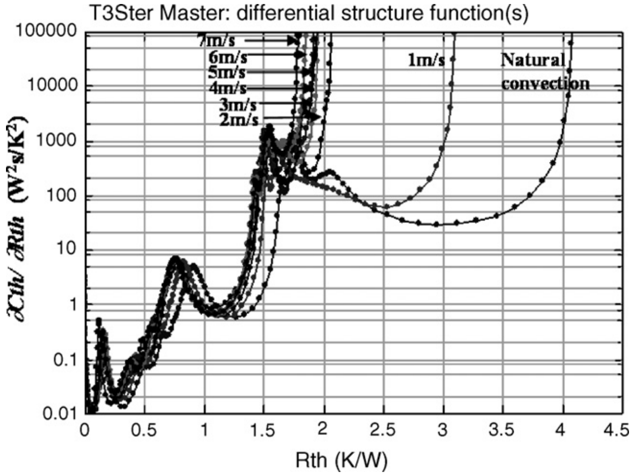

Fig. 6. Differential structure functions from the LED array with heat pipes.

data obtained from the LED array without heat pipes (Fig. 3). The total thermal resistance is 1.8 °C/W when the air flow rate is 7 m/s and is about 0.91 °C/W less than the value for the case without heat pipe (Fig. 3).

Without heat pipe, the partial thermal resistance from junction to MCPCB is about 1.65 K/W and from MCPCB to ambient is 1.06 K/W at an air velocity of 7 m/s. When heat pipe was attached, however, the partial thermal resistance from junction to MCPCB is about 1.55 K/W and from MCPCB to ambient is 0.24 K/W at air velocity of 7 m/s. The results indicate that heat pipes reduce total thermal resistance of LED array by an effective control of thermal resistance from MCPCB to ambient. The condenser section of heat pipe is the major heat transfer path to the ambient. Therefore, the temperature of condenser section of heat pipe was controlled to evaluate its effects on the junction temperature of LED array. The condenser section of the heat pipe was dipped into an isothermal liquid bath. Fig. 7 shows the change of junction temperatures of LED array as a function of input power at different ambient (liquid bath) temperatures.

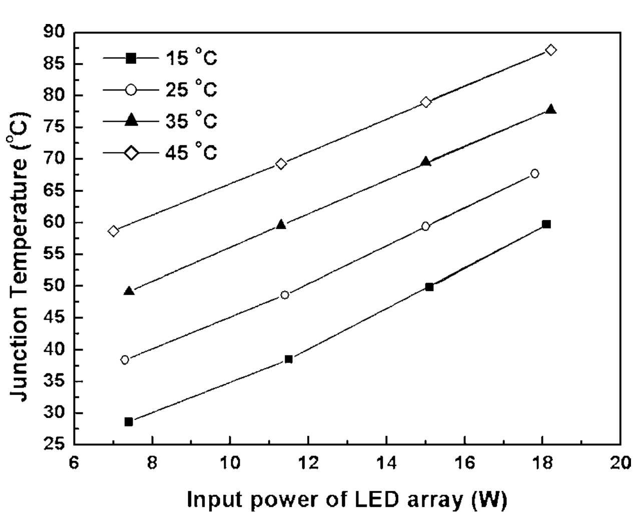

Fig. 7. Junction temperature of LED array with heat pipe at dipping liquid temperature of 15 °C, 25 °C, 35 °C, 45 °C.

The junction temperature is increased almost linearly with the input power. The higher junction temperature was observed under the higher ambient temperature as was expected. The effect of heat pipes is activated by the temperature difference between the MCPCB and the ambient. Therefore, direct control of the temperature of condenser section can effectively improve the efficiency of heat pipe. It is worth while pointing out that the thermal resistance of heat pipe can be estimated from Fig. 7. When input power of LED array is 18.1 W, the junction temperature of LED array is 59.7 °C at an ambient temperature of 15 °C. Thus total thermal resistance of LED array from junction to ambient can be estimated to be about (59.7 °C − 15 °C)/18.1 W = 2.47 °C/W. From the measured structure function of LED array (Fig. 6), the partial thermal resistance from MCPCB to ambient of 2.47 °C/W − 1.55 °C/W = 0.92 °C/W is calculated. It must be noted, however, that the value 0.92 °C/W includes the resistance from the interfaces inside the packaging component and much higher than the typical value of heat pipe.

5. Conclusions

Thermal characterization of high power LED arrays was performed for the first time by the thermal transient method using structure function. Equivalent thermal circuit model was proposed to explain the thermal resistance of LED array with multi LED packages and demonstrated to be in agreement with experimentally measured data. Several boundary conditions, including ambient temperature and convection condition, were applied for thorough evaluation of LED arrays with and without heat pipe. It was demonstrated that applying heat pipe effectively decreases the total thermal resistance of LED array, and was proved to be a good solution for controlling junction temperature of high power LED systems.

Acknowledgement

The authors acknowledge the Korean Institute of Industrial Technology Evaluation and Planning for financial support.

References

[1] F.M. Steranka, J. Bhat, D. Collins, L. Cook, M.G. Craford, R. Fletcher, N. Gardner, P. Grillot, W. Goetz, M. Keuper, R. Khare, A. Kim, M. Krames, G. Harbers, M. Ludowise, P.S. Martin, M. Misra, G. Mueller, R. Mueller-Mach, S. Rudaz, Y.-C. Shen, D. Steigerwald, S. Stockman, S. Subramanya, T. Trottier, J.J. Wierer, Phys. Stat. Sol. (a) 194 (2) (2002) 380.

[2] M. George Craford, Proceedings of the International Society for Optical Engineering 2005 (SPIE), vol. 5941, San Diego, CA, USA, 2005, pp. 594101_1–594101_10.

[3] W.J. Hwang, P. Szabó, G. Farkas, M.W. Shin, Proceedings of the 10th International Workshops on Thermal Investigations of ICs and Systems (THERMINIC), Sophia Antipolis, France, September, 2004, pp. 91–95.

[4] J. Park, M. Shin, C.C. Lee, Opt. Lett. 29 (22) (2004) 2656.

[5] L. Kim, G.W. Lee, W.J. Hwang, J.S. Yang, M.W. Shin, Phys. Stat. Sol. (c) 0 (7) (2003) 2261.

[6] W.J. Hwang, T.H. Lee, L. Kim, M.W. Shin, Phys. Stat. Sol. (c) 1 (10) (2004) 2429.

[7] C. Cahill, T. Compagno, J. O'Donovan, O. Slattery, C. O'Mathuna, J. Barrett, I. Drouhin, C. Val, J.P. Tigneres, J. Stern, P. Ivey, M. Masgrangeas, A. Coello-Vera, Proceedings of the 11th IEEE Semiconductor Thermal Measurement, Modeling and Management Symposium (SEMI-THERM 11), San José, CA, USA, February, 1995, pp. 10–16.
[8] SEMI G32-94, Guideline for unencapsulated thermal test chip.
[9] V. Székely, IEEE Trans. Circuits Syst. 38 (7) (1991) 711.
[10] EIA/JEDEC Standard No. 51-1.
[11] http://www.lumileds.com/pdfs/DS34.pdf.