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Study on the Thermal Resistance of Multi-chip Module High Power LED Packaging Heat Dissipation System

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Abstract: Thermal resistance is a key technical index which indicates the thermal management of multi-chip module high power LED (MCM-LED) packaging heat dissipation system. In this paper, the prototype structure of MCM-LED packaging heat dissipation system is proposed to study the reliable thermal resistance calculation method. In order to analyze the total thermal resistance of the MCM-LED packaging heat dissipation system, three kinds of thermal resistance calculation method including theoretical calculation, experimental testing and finite element simulation are developed respectively. Firstly, based on the thermal resistance network model and the principle of steady state heat transfer, the theoretical value of total thermal resistance is 6.111 K/W through sum of the thermal resistance of every material layer in the major direction of heat flow. Secondly, the thermal resistance experiment is carried out by T3Ster to obtain the experimental result of total thermal resistance, and the value is 6.729 K/W. Thirdly, a three-dimensional finite element model of MCM-LED packaging heat dissipation system is established, and the junction temperature experiment is also performed to calculated the finite element simulated result of total thermal resistance, the value is 6.99 K/W. Finally, by comparing the error of all the three kinds of result, the error of total thermal resistance between the theoretical value and experimental result is 9.2 %, and the error of total thermal resistance between the experimental result and finite element simulation is only about -3.9 %, meanwhile, the main reason of each error is discussed respectively.

Keywords: High power LED, Thermal resistance, Heat dissipation system, T3Ster, Finite element simulation.

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1. Introduction

According to DOE's Solid-State Lighting (SSL) Research & Development (R&D) Multi-Year Program Plan (MYPP) [1], High power light emitting diode (LED) is identified as typical green lighting source with penetrating into illumination planning and application, such as road lighting, interior lighting and special lighting, and so on. However, on the current market, the electro-optical conversion efficiency of high power LED chip is less than 30 % at the normal drive current. Inevitably, the problem exerts much of excess input power and redundant heat and ultimately enhances the junction temperature which affects the lifetime of LED lamp [2]. Thermal management is the key technology to the development of the reliable LED lamp. In order to evaluate the level of thermal management and optimize the heat dissipation system, most of designers attach the importance of thermal resistance of LED lamp. Meanwhile, due to the complex heat transfer path of multi-chip module high power LED (MCM-LED) packaging heat dissipation system, it is necessary to develop the research on the thermal resistance calculation method.

There are some reports on the thermal resistance analysis of single-chip and multi-chip LED packaging. Lan Kim and Woong Joon Hwang presented and discussed the thermal transient management of one-chip, two-chip and four-chip high power LED packaging to analyze thermal resistance with the structure function theory [3]. Aiming at a LED street lamp prototype, S. Liu and co-workers established the multi-chip spreading resistance model [4]. Huanting Chen and co-workers developed a method for creating compact thermal models of single-chip and multi-chip LED packaging and evaluated with good agreement between the finite volume simulation and experimental data [5]. Henning Dieker compared thermal resistance of simulations of various substrate materials and packaging technologies by FLOTHERMAL software, and determined the thermal path using the T3Ster analyzer [6]. However, there have been no reports on the comparison analysis of the thermal resistance calculation method of MCM-LED packaging heat dissipation system of all the best knowledge authors.

In this paper, the prototype structure of MCM-LED packaging heat dissipation system is proposed to study the reliable thermal resistance calculation method. Then aiming at the prototype structure, three kinds of thermal resistance calculation method including theoretical calculation, experimental testing and finite element simulation are developed respectively. Finally, by comparing the three kinds of result, the cause of the errors is discussed.

2. Research Methods

2.1. Prototype Structure of MCM-LED Packaging Heat Dissipation System

In order to study the thermal resistance of high power LED lamps, the light source of the LED lamp is composed by the two same MCM-LED modules, and each module includes a 2×2 GaN-based flip chip LED (FC-LED) array which is bonded on the same silicon substrate by the gold bumps [7]. The structure of MCM-LED module is shown in Fig. 1. Lc and Wc are the size of LED chip, and the size of GaN-based FC-LED is set with 35 mm × 35 mm × 0.889 mm in this paper.

Thermal management of high power electronic packaging is necessary to design a heat dissipation system which can control the junction temperature of the chip and enhance the reliability of electronic system. The lower junction temperature of LED chip is not only improves its life time, but also improves light output at the same input power.

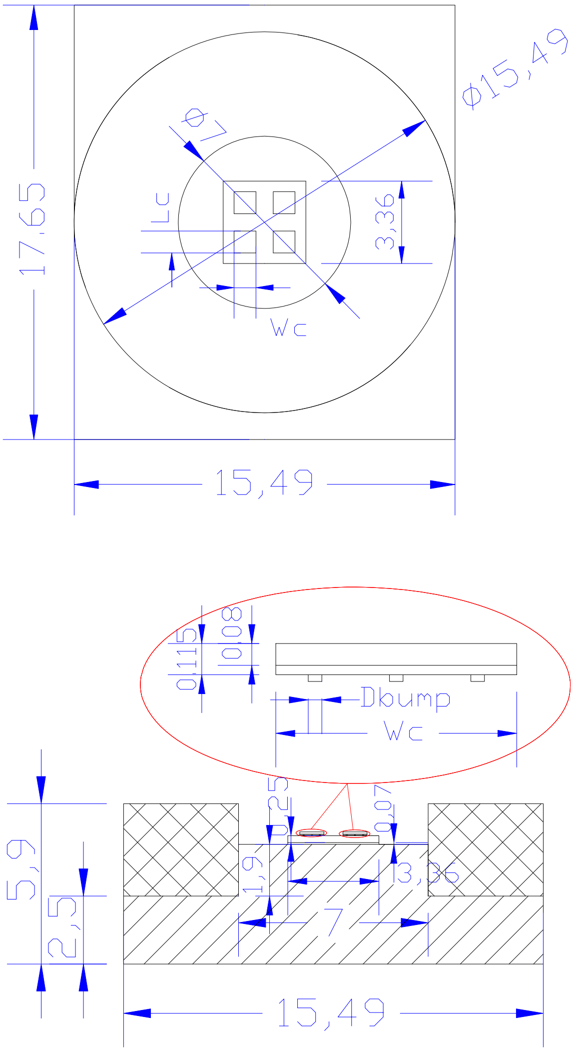


Fig. 1. Structure of MCM-LED module.

Therefore, the structure of MCM-LED packaging heat dissipation system is proposed to reduce the junction temperature of LED chip and enhance the reliability of LED lamp, as shown in Fig. 2. The MCM-LED Packaging Heat Dissipation System includes two MCM-LED modules, thermal interface material (TIM) layer, metal core printed circuit board (MCPCB) layer and heat sink. The dimension of aluminum heat sink board is 75 mm×75 mm×5 mm, and the height, thickness and number of heat sink fin are 33 mm, 3 mm and 11 respectively. Meanwhile, the thickness of TIM1 layer, TIM2 layer and PCB are 0.25 mm, 0.1 mm and 1.5 mm respectively. Aiming at the structure of MCM-LED packaging heat dissipation system, the materials in the major direction of heat flow are illustrated in Fig. 3. The heat which is generated by LED chip is transferred to the MCPCB by heat conduction, and then the heat dissipated to the surrounding environment by the heat convection of heat sink. In order to analyze the thermal resistance of MCM-LED Packaging Heat Dissipation System, all the materials parameters related to the heat transfer are listed in Table 1.

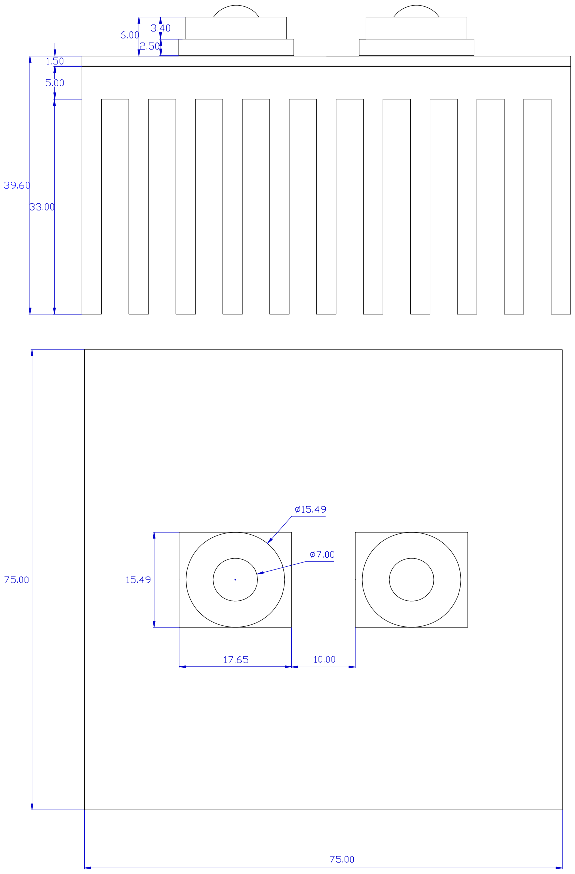


Fig. 2. Structure of MCM-LED packaging heat dissipation system.

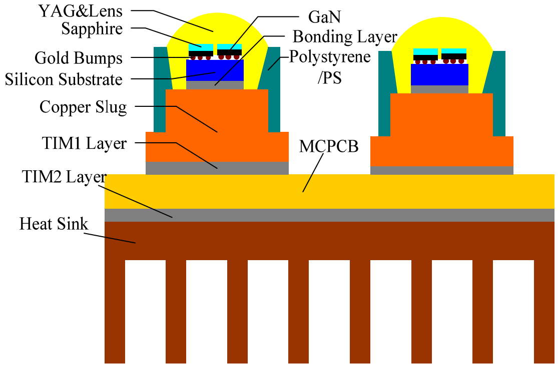


Fig. 3. Materials in the major heat flow direction.

Table 1. Heat transfer related materials parameters.

Material	k ($W \cdot m^{-1} \cdot k^{-1}$)	C ($J \cdot kg^{-1} \cdot k^{-1}$)	ρ($kg \cdot m^{-3}$)
Sapphire	41.9	730	3965
GaN	130	40	6095
Gold	300	132	19320
Silicon	124	700	2330
Copper	385	385	8930
Sn63Pb37	59	150	8400
MCPCB	2	800	2700
Aluminum	237	875	2710
Silver colloid	2.45	250	3800
TIM	0.98	711	1120

In this paper, the two MCM-LED modules are assumed completely identical and the electric power of each MCM-LED module is 4.53 W. Therefore, the electric power of each FC-LED chip is 1.133 W, and the electro-optical conversion efficiency of high power LED chip is about 27 %.

2.2. Theoretically Calculated of Thermal Resistance

Aiming at the prototype structure of MCM-LED packaging heat dissipation system, the thermal resistance network which helps to solve the complex heat transfer problems is established in the major direction of the heat flow to analyze the theoretical thermal resistance, is as shown in Fig. 4.

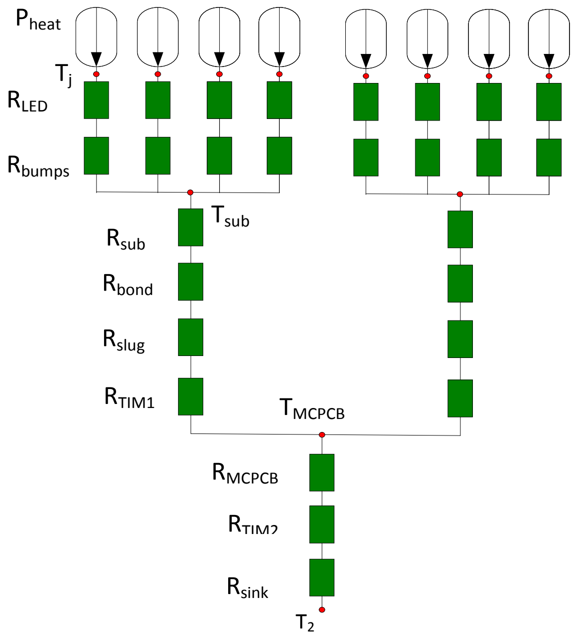


Fig. 4. Thermal resistance network of MCM-LED packaging heat dissipation system.

In the theoretical calculated of thermal resistance, some material layers in the secondary direction of heat flow are neglected, such as polystyrence layer, YAG&lens layer, and the thermal contact resistance is neglected in the interface between two layers.

The total thermal resistance of MCM-LED packaging heat dissipation system is written as Eq. (1).

$$R_{total} = {\Delta T_{total}} \big/ {8P_{heat}} , \tag{1}$$

where R_{total} is the total thermal resistance of MCM-LED packaging heat dissipation system, and P_{heat} is the thermal power of LED chip, and ΔT_{total} is the temperature difference between junction temperature and ambient temperature, is as shown in Eq. (2).

$$\begin{aligned}\Delta T_{total} &= T_j - T_a \\ &= (T_j - T_{sub}) + (T_{sub} - T_{MCPCB}) + (T_{MCPCB} - T_a) \\ &= P_{heat}(R_{LED} + R_{bumps}) + 4P_{heat}(R_{sub} + R_{bond} \\ &+ R_{slug} + R_{TIM1}) + 8P_{heat}(R_{MCPCB} + R_{TIM2} + R_{\sin k}),\end{aligned} \tag{2}$$

where T_j, T_a, T_{sub} and T_{MCPCB} are the junction temperature, ambient temperature, silicon substrate surface temperature and MCPCB surface temperature respectively, and R_{LED}, R_{bumps}, R_{sub}, R_{bond}, R_{slug}, R_{TIM1}, R_{MCPCB}, R_{TIM2} and R_{sink} are the thermal resistance of LED chip, bumps of FC-LED layer, silicon substrate, bonding layer, heat slug layer, TIM1 layer, MCPCB layer, TIM2 layer and heat sink respectively. The total thermal resistance R_{total} is shown as Eq. (3).

$$\begin{aligned}R_{total} &= \frac{R_{LED} + R_{bumps}}{8} + \frac{R_{sub} + R_{bond} + R_{slug} + R_{TIM1}}{2} \\ &+ R_{MCPCB} + R_{TIM2} + R_{\sin k}\end{aligned} \tag{3}$$

The thermal resistance of heat sink (R_{sink}) is composed by R_{board} , R_{fins}, R_{air} which is the outside convection resistance of heat sink, and R_s which is the spreading resistance of the board, is as shown in Eq. (4).

$$\begin{aligned}R_{\sin k} &= R_{board} + R_{fins} + R_{air} + R_s \\ &= \frac{h_{board}}{k_{Al}A_{board}} + \frac{h_{fin}}{11 \times k_{Al}A_{fin}} + \frac{1}{hA_0} + R_s\end{aligned} \tag{4}$$

where h_{board} is the thickness of the heat sink board, A_{board} is the area of the heat sink board, h_{fin} is the height of fins, A_{fin} is the cross-sectional area of fin, A_0 is the area of heat sink in the convective environment, k_{Al} is the thermal conductivity of heat sink, h is the nature convection coefficient, and the number of fin is 11.

The spreading resistance of the board of heat sink R_s is written as Eq. (5) and Eq. (6) [8].

$$\begin{aligned}R_s &= \frac{\psi_{avg}}{\sqrt{\pi}k_{Al}A} = \frac{\sqrt{A_{board}} - \sqrt{A_{MCM-LED}}}{k_{Al}\sqrt{\pi A_{MCM-LED}A_{board}}} \\ &\times \frac{\lambda k_{Al}A_{board}R_0 + \tanh(\lambda h_{board})}{1 + \lambda k_{Al}A_{board}R_0 \tanh(\lambda h_{board})}\end{aligned} \tag{5}$$

$$\lambda = \frac{\pi^{3/2}}{\sqrt{A_{board}}} + \frac{1}{\sqrt{A_{MCM-LED}}}, \tag{6}$$

where $A_{MCM-LED}$ is the cross-sectional area sum of the two MCM-LED modules bottom surface, and R_0 is the average thermal resistance of the heat sink board.

Therefore, according to Eq. (3), (4), (5), (6), the R_{total} is the total thermal resistance of MCM-LED packaging heat dissipation system in Eq. (3) can be obtained by theoretical calculation.

$$R_{total} = 6.111 \,{}^{K}\!/_{W}$$

Assuming that the value of h is 5 W/(m^{2}k), and ambient temperature is 25 ºC. The junction temperature of LED is estimated by Eq. (7).

$$\begin{aligned}T_j &= 8P_{heat}R_{total} + T_a \\ &= 8 \times 1.133 \times (1 - 0.27) \times 6.111 + 25 = 65.435^{\circ}C\end{aligned} \tag{7}$$

2.3. Experimental Value of Thermal Resistance

Aiming at the prototype structure of MCM-LED packaging heat dissipation system, the thermal resistance experiment is carried out by T3Ster which is a thermal transient tester, and the experimental materials are shown in Fig. 5. The theoretical framework of the evaluation of the T3Ster is based on a representation of the distributed RC networks [9, 10].

Fig. 5. Experimental materials.

Firstly, the K factor is test by the integrating sphere. Sensor current is used to detect the forward voltage of the MCM-LED module. Based on the JESD51-1 standards [11], considering the environment temperature of the lab is 11 ºC, the test temperature of the test chamber is set with 10 ºC, 30 ºC, 50 ºC, 70 ºC and 90 ºC. Fig. 6 is the forward voltage versus temperature plot. The linearity between the voltage and temperature is K factor, and the value of K factor is -5.615 mV/K when the sensor current is 2 mA.

Secondly, Fig. 7 shows that the luminous power of the two MCM-LED modules is about 2450 mW when the drive current is 750 mA. Fig. 8 shows that the electric power of the two MCM-LED modules is 9.059 W when the drive current is 750 mA. Therefore, the electro-optical conversion efficiency of high power LED chip is about 27 % at the drive current. The experimental results of the electric power and the electro-optical conversion efficiency of LED chip stay the same level as the assuming condition which is applied in the theoretically calculated of thermal resistance.

Finally, the total thermal resistance of the MCM-LED packaging heat dissipation system is obtained by the T3Ster experiment which is shown in Fig. 9. Fig. 10 represents the derivative of thermal capacitance as a function of thermal resistance for the MCM-LED packaging heat dissipation system, and the total thermal resistance is about 6.729 K/W.

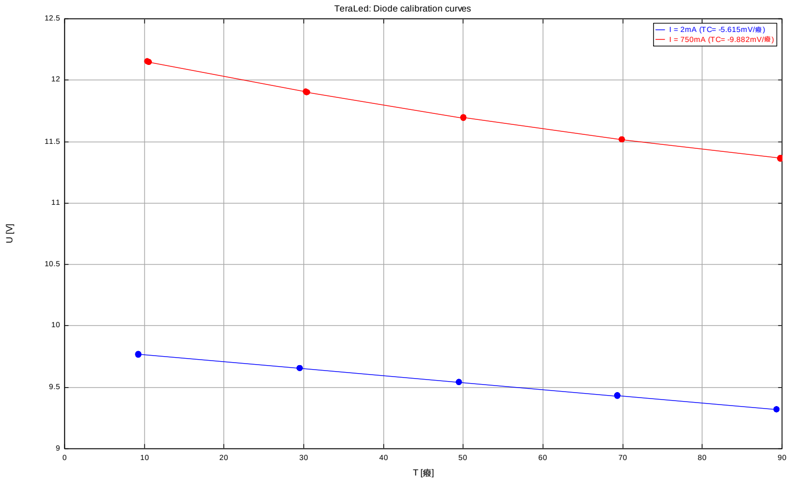


Fig. 6. Forward voltage versus temperature plot showing the K factor.

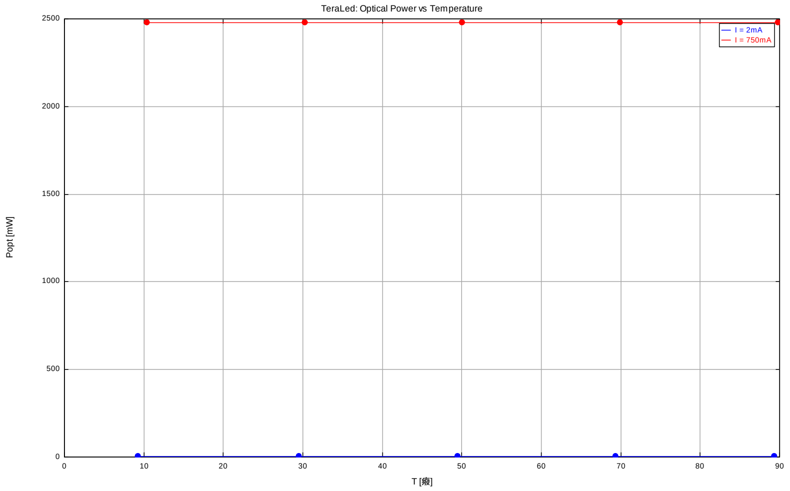
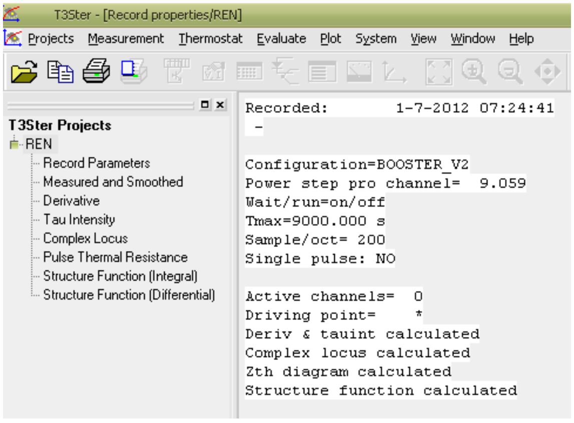


Fig. 7. Luminous power of the two MCM-LED modules at the drive current of 750 mA.



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Recorded:       1-7-2012 07:24:41
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Configuration=BOOSTER_V2
Power step pro channel=  9.059
Wait/run=on/off
Tmax=9000.000 s
Sample/oct= 200
Single pulse: NO

Active channels=  0
Driving point=    *
Deriv & tauint calculated
Complex locus calculated
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Structure function calculated
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Fig. 8. Electric power of the two MCM-LED modules at the drive current of 750 mA.

Fig. 9. T3Ster experiment.

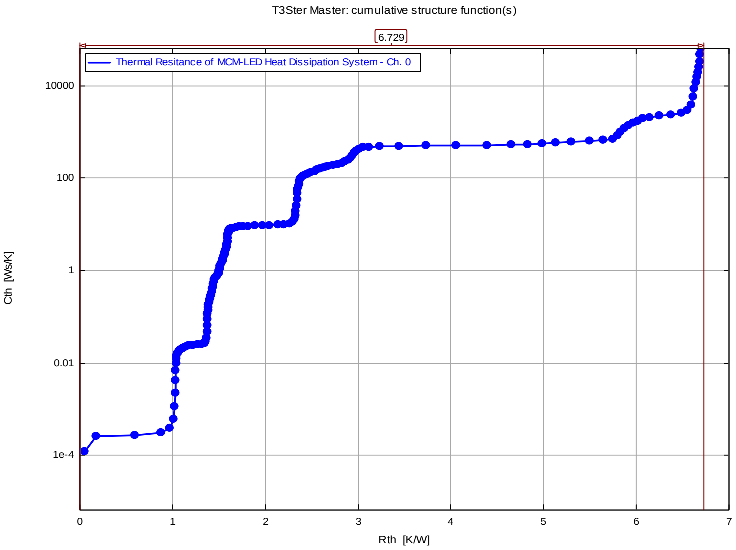

Fig. 10. Cumulative structure functions of the MCM-LED packaging heat dissipation system.

2.4. Finite Element Simulation of Thermal Resistance

In order to facilitate the complex of finite element model and improve the calculation speed of computer, some structures are neglected, such as the pins of MCM-LED module, bonding wires. Based on the numerical analysis method and MCM-LED packaging heat dissipation system, a 3-D finite element model (FEM) is developed by the software ANSYS, which is shown in Fig. 11. The element type is SOLID 70.

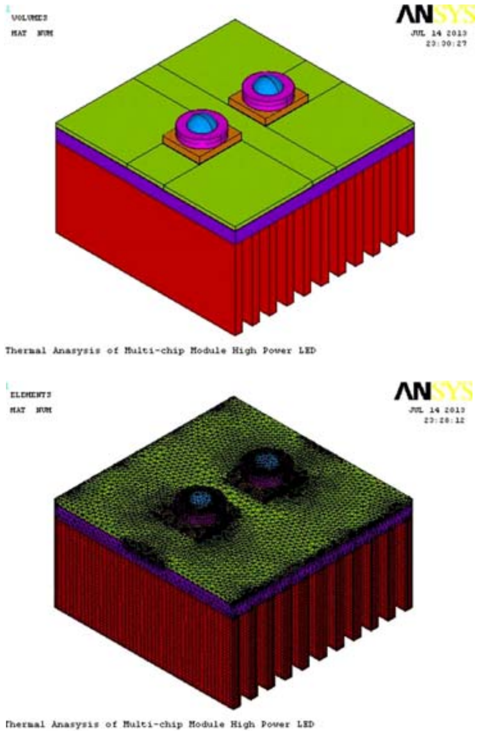

Fig. 11. FEM of MCM-LED packaging heat dissipation system.

The electric power of each FC-LED chip is 1.133 W and the electro-optical conversion efficiency of high power LED chip is about 27 %. The GaN-base active layer of LED chip is known as a heat source, and the heat generating is 2.99×1010 W/m^3. The ambient temperature is set to 25ºC, and the nature convection coefficient is 5 W/(m^2·k).

The temperature distribution of MCM-LED packaging heat dissipation system is shown in Fig. 12. The simulation result reveals that the junction temperature of LED is 71.225ºC. The total thermal resistance of finite element simulation is calculated by the Eq. (8), and the value of Rtotal is 6.99 K/W.

$$R_{total} = \frac{T_j - T_a}{P_h} = 6.99\, {}^{K}\!/_{W}\,, \qquad (8)$$

where Ph is the total heat power dissipation in the two MCM-LED modules.

3. Results and Discussion

The total thermal resistance and junction temperature of theoretical value, experimental result and finite element simulation are compared, which is shown in Table 2. The results indicate that the order of total thermal resistance is theoretical value (6.111 K/W) < experimental result (6.729 K/W) < finite element simulation (6.99 K/W).

By comparing the three kinds of result, the cause of errors is discussed. Firstly, at the theoretical value and experimental result aspects, the error of total thermal resistance and junction temperature are 9.2 % and 5.8 %, respectively. The main reason of the error is that the calculation cross-sectional area of material layer is bigger than the actual application area in the theoretical calculation of thermal resistance. Therefore, the theoretical value is less than the experimental result, and the suitable cross-sectional area of material layer should be selected by experience in the theoretical calculation of thermal resistance to improve the accuracy of theoretical calculation. Secondly, at the experimental result and finite element simulation aspects, the error of total thermal resistance and junction temperature are only about -3.9 % and -2.5 %. The main reason of the error is that the nature convection which should be loaded in some outside surface of MCM-LED packaging heat dissipation system is neglected in the finite element simulation. Due to only consider the nature convection on the surface of fins, so the finite element simulation result is a little more than the experimental result.

4. Conclusions

In this research, aiming at the designed prototype structure of MCM-LED packaging heat dissipation system, the total thermal resistance is analyzed by theoretical calculation, experimental testing and finite element simulation, respectively. Firstly, with establishing thermal resistance network model of the MCM-LED packaging heat dissipation system and using the principle of steady state heat transfer, the material layer thermal resistance and total thermal resistance (6.111 K/W) are theoretically calculated. Secondly, the thermal resistance experiment is carried out by T3Ster to obtain the experimental result of total thermal resistance, which is 6.729 K/W. Thirdly, a detail FEM of MCM-LED packaging heat dissipation system is established, and the junction temperature experiment is also performed to calculated the finite element simulated result of total thermal resistance, which is 6.99 K/W. Finally, by comparing the error of the three kinds of result, the cause of errors is discussed.

Acknowledgements

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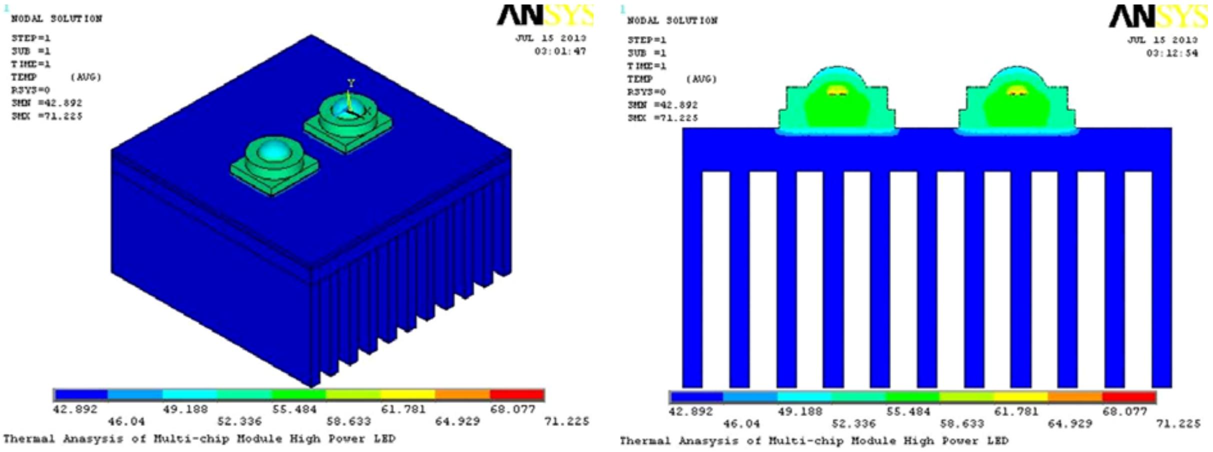

(a) (b)

Fig. 12. Temperature distribution of finite element simulation.

Table 2. Compare results of total thermal resistance and junction temperature.

		Theoretical Value		**Finite Element Simulation**	
Experimental Result	Total Thermal Resistance (K/W)	Total Thermal Resistance (K/W)	Error	Total Thermal Resistance (K/W)	Error
	6.729	6.111	9.2 %	6.99	-3.9 %
	Junction Temperature (ºC)	Junction Temperature (ºC)	Error	Junction Temperature (ºC)	Error
	69.5	65.435	5.8 %	71.225	-2.5 %

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