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Heat Transfer Characteristics in High Power LED Packaging

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This study uses the T3Ster transient thermal resistance measuring device to investigate the effects to heat transfer performances from different LED crystal grains, packaging methods and heat-sink substrates through the experimental method. The experimental parameters are six different types of LED modules that are made alternatively with the crystal grain structure, the die attach method and the carrying substrate. The crystal grain structure includes the lateral type, flip chip type and vertical type. The die attach method includes silver paste and the eutectic structure. The carrying substrates are aluminum oxide (Alumina) and aluminum nitride (AIN) ceramic substrates and metal core PCB (MCPCB). The experimental results show that, under the conditions of the same crystal grain and die attach method, the thermal resistance values for the AIN substrate and the Alumina substrate are 2.1K/W and 5.1K/W, respectively and the total thermal resistance values are 7.3K/W and 10.8K/W. Compared to the Alumina substrate, the AIN substrate can effectively lower the total thermal resistance value by 32.4%. This is because the heat transfer coefficient of the AIN substrate is higher than that of the Alumina substrate, thus effectively increasing its thermal conductivity. In addition, under the conditions of the same crystal grain and the same substrate, the packaging methods are using silver paste and the eutectic structure for die attach. Their thermal resistance values are 5.7K/W and 2.7K/W, respectively, with a variance of 3K/W. Comparisons of the crystal grain structure show that the thermal resistance for the flip chip type is lower than that of the traditional lateral type by 0.9K/W. This is because the light emitting layer of the flip chip crystal grain is closer to the heat-sink substrate, shortening the heat dissipation route, and thus lowering the thermal resistance value. For the total thermal resistance, the crystal grain structure has a lesser effect to the heat dissipation performance whereas the packaging method and the choice of the substrate have a relatively higher effect to the LED heat dissipation performance. Combining the above results, we see that selecting the flip chip crystal grain with a closer light emitting layer to the substrate, the eutectic structure that has better thermal conductivity and the AIN substrate can effectively increase the heat dissipation performance of the LED module.

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1. Foreword

In recent years, the luminous efficiency of the light emitting diode (LED) has been increased rapidly and is capable of meeting general lighting requirements. Compared to the traditional fluorescent light and the incandescent light, the LED has its advantages of DC driving, quick response time, long component life, simple structure, no environment pollution, small component size, vibration-resistant, suitable for mass production, abundant colors, etc. and has a great potential to replace the traditional lighting sources. Therefore, many countries have invested a great deal of money and research in order to make it a major lighting method. In addition to general-purpose lighting, the LED is also widely used in the backlights of multiple 3C products such as, intelligent mobile phones, TVs, and notebooks. It can also be applied to the street lights, projector lights or headlights that required high illumination. However, the high power LED lighting application is facing stability and lifespan reduction problems caused by high temperature.

The LED is a light emitting component based on the semi-conductor luminous material. The basic light emitting theory is the carrier (electron- electron hole pair) in the semi-conductor recovers and releases by converting the electric energy into a light form when it passes through a very tiny electric current. However, in converting to the light form, only 15~30% of the electric energy is converted into light, whereas the remaining 70%~85% energy is wasted heat. Also, compared to the traditional semi-conductor component, the LED chip has a smaller heat area, causing a very high heat density which leads to the hot spot problem. Therefore, a proper heat dissipation design is required. Otherwise, the junction temperature of the LED chip will become too high. As a result, the luminous strength and the service life will be reduced. As such, the LED packaging method and the LED heat-sink module design have become major key elements in developing the LED lighting [1]. This study is intended to investigate the effect to the heat transfer performance through the experimental analysis specifically from different crystal grains of the LED module, the packaging method and the heat-sink substrate to seek the packaging design that can effectively reduce the LED junction temperature and increase its service life and stability. The LED module mainly uses thermal conduction and convection to dissipate heat. While the LED crystal grain emits light, the generated heat is transmitted to the heat-sink module by way of heat conduction, and then is transmitted to the environment by way of convection. The thermal resistance network of a traditional LED heat-sink module is shown in Fig. 1. As shown in the diagram, the factors that affect the LED heat dissipation mainly include the LED crystal grain structure, packaging method, the heat-sink substrate and the design of the heat-sink module [2]. In general, the LED crystal grain structure is divided into three common types, which are the lateral type, vertical type and the flip chip type as shown in Fig. 2. The traditional crystal grain structure uses the sapphire as the substrate to grow the gallium nitride LED. The positive and negative electrodes are made on the same side. This structure has the following shortcomings: (1) Since the front side has two electrodes, it reduces more light emitting area. (2) The co-planar structure has worse current diffusion with a current jam effect on the P-type and N-type electrodes. (3) The sapphire substrate has poor heat dissipation, thus affecting the LED service life. To overcome the above shortcomings, the crystal grain structures of the vertical type and the flip chip type are developed. The vertical type structure uses the high thermal conductive metal as the substrate to increase its conductivity. The positive and negative electrodes are located on different planes to increase the light emitting area [3]. The flip chip is the structure that is flipped over of the traditional structure. By using the submount, the weld pad of the crystal grain is joined to the metallic point of the submount. This technique not only increases the substrate thermal conductivity, but also reduces the distance between the lighting source and the substrate, which helps dissipate heat.

Normally, the LED die attach technique is to paste the LED chip to the heat-sink substrate through solder. The solder is the first contact layer on which the light emitting source dissipates its heat by way of thermal conduction and is critical to the LED service life. In general, the low-power LED module uses silver paste to die attach. However, the generated heat from the LED will deteriorate the silver paste quality after it is used for a long period of time, which will affect the thermal conductivity. Since its manufacturing cost is low and the process is easier, silver paste is still being used widely. However, for high-power LED modules, silver paste is not capable of providing sufficient thermal conductivity. The eutectic solder attach is the most preferable choice due to its reliability and thermal conductivity [4]. To further increase the thermal conductivity, new solders are being developed increasingly on the market, e.g., both diamond-added composites [5] and carbon nanotubes [6] can effectively reduce thermal resistance.

Since one of the major problems of the LED heat dissipation is heat concentration causing local high temperature, the choice of the thermal conductive substrate for the high-brightness LED modules is much more important. Common heat-sink substrates include copper foil PCB (FR4), metal core PCB (MCPCB) and ceramic substrate. As FR4 has too low a heat transfer coefficient, it has poor heat dissipation capability, only suitable for low-power LED modules. Therefore, the MCPCB is currently the substrate that replaces the FR4 substrate. By using the materials with a higher heat transfer coefficient such as aluminum or copper as the base material of PCB, MCPCB increases its thermal conductivity performance. Then, the copper foil is attached on top of it as the circuit. This substrate is cheap and is widely used. However, since the dielectric layer will hinder the heat transfer capability of the aluminum substrate, the ceramic substrate without the dielectric layer is then developed to help dissipate heat. Common ceramic substrates include Alumina substrate and the AIZ substrate [7-8]. We will describe from the above LED structures and their manufacturing method to the evaluation method of the heat dissipation effect from a general crystal grain calculation. According to the calculating formula for the thermal resistance from the light emitting layer of the crystal grain to the packaging substrate ($R_{th} = L/K \times A$, R_{th}: heat resistance, L: the length of heat conduction route, K: heat transfer coefficient, A: cross-section area of the heat conduction route), we see that generally there are two methods to reduce the thermal resistance: (1) Shorten the distance between the light emitting layer and the packaging substrate; (2) use the high thermal conductive material to replace the original material. Therefore, in this study we will perform experiments on these two aspects to compare with different crystal grain structures, die attach methods, and the heat-sink substrates. Then, we will select the LED structure and packaging method with the best heat dissipation performance.

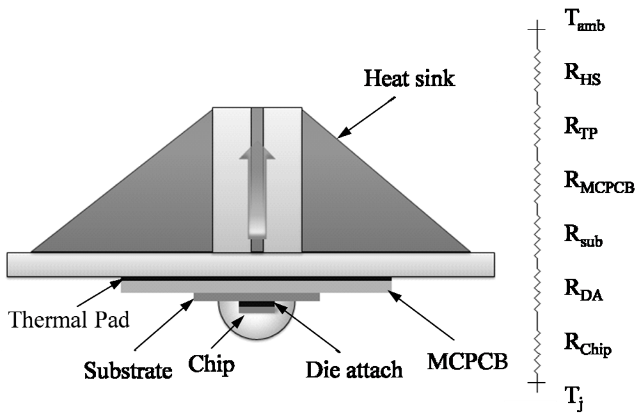
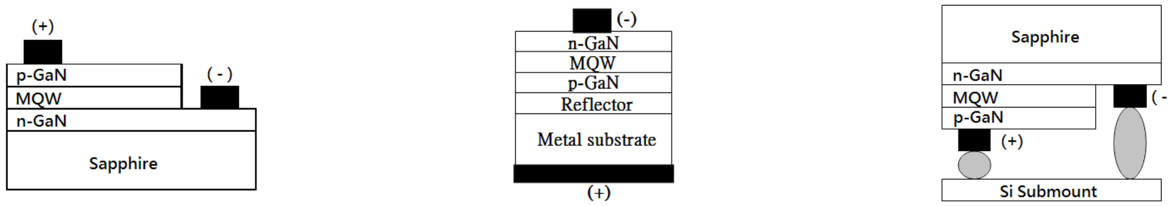


Fig. 1 Heat Transfer network of LED module

2. Measurement theory

The thermal resistance measuring equipment for this experiment is the T3Ster transient measuring device. Its measurement theory is the electrical test method (ETM) as specified in JESD51-1 and the transient dual interface method (TDIM) as specified in JEDEC51-14. Then, we will use the T3Ster Master software to calculate the LED entire thermal resistance. The T3Ster measuring system mainly includes the hardware measurement and software calculation. The first part of the hardware measurement is calibration of the



(a) (b) (c)

Fig. 2 Packaging types (a) Lateral (b) Vertical (c) Flip Chip

temperature-sensitive parameter (TSP) for the component under test. With the characteristics that the forward bias of the semi-conductor varies with temperature, we can define the K factor as in the formula (1).

$$K = \frac{\Delta T_j}{\Delta V_f} \tag{1}$$

Where, ΔT_j is the variance of the LED junction temperature and ΔV_f is the variance of the forward bias. The input measuring current is 1mA. The calibration temperature is 25°C to 115°C. Place the component under test in the temperature controller. Adjust the ambient temperature and observe the variance of the forward bias. Then, the K factor can be determined by using the formula (1). The measurement results show that the temperature of the component under test varies linearly with the forward bias. The second part of the hardware measurement is to record the transient variance of the forward bias. With that, we can determine the variance of the junction temperature. Input the component under test in the operating current. The temperature rises increasingly until it becomes stable. Then, change the operating current to the input measuring current (1mA). The temperature starts to drop to 25°C. We can determine the cooling curve for the variance of the forward bias with time during this process. Then, we can determine the Foster type R-C network from the cooling curve by using the mathematical operations such as, deconvolution and discretization. After it is changed to the Cauer type R-C network, the structural function diagram is then determined. The thermal resistance value for each part of the component can be further determined. Refer to the literature [9] for measurement theory details.

3. Experimental system

3.1 Thermal resistance measurement of the packaging layer

The experimental parameters for the packaging layer include three crystal grain structures, two die attach methods and three substrates with 1W power. For experimental analysis, we made six LED packaging types (see Fig. 3), which are (a) Type1: lateral type crystal grain, silver paste for die attach and Alumina substrate; (b) Type 2: lateral type crystal grain, eutectic structure and AIZ substrate; (c) Type 3: Flip chip, eutectic structure and Alumina substrate; (d) Type 4: Flip chip, eutectic structure and AIZ substrate; (e) Type 5: Flip chip, eutectic structure and aluminum substrate; (f) Type 6: Vertical type crystal grain, silver paste die attach and Alumina substrate. Refer to Table 1 for specifications. The dimension of the substrate is 1.5cm (L) x 1.5cm (W). Thicknesses for the ceramic substrate and the aluminum substrate are 0.26mm and 1.6mm, respectively. In order to investigate the effect from the different substrate thickness to the diffusion thermal resistance, in this study we also made the aluminum substrate with the same length and width but different thickness for experiments. For these LEDs, we selected 50V driving voltage and variable current at a range of 0.2A to 1A. With the variable current, we can conduct analysis for the LED with different input power and different substrate thickness. The input power for LED can be 10W to 50W. The length and width of the aluminum substrate are 3.1cm x 3.1cm while thicknesses are 0.9mm, 1.1mm and 1.6mm. The aluminum substrate is attached with epoxy dielectric layer and copper foil on top of it with thickness of 0.08mm and 0.035mm, respectively. The materials and dimensions of the variable power LED are shown in Table 2.

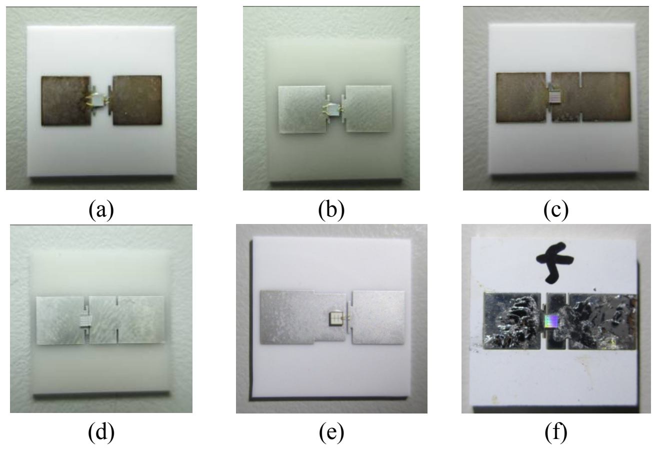


Fig. 3 Photos of samples (a) Type 1 (b) Type 2 (c) Type 3 (d) Type 4 (e) Type 5 (f) Type 6

Table 1 A list of LED packaging

	Chip	**Die-attach**	**Substrate**
Type1	Lateral	Silver paste	Al_2O_3
Type2	Lateral	Eutectic	*AlN*
Type3	Flip Chip	Eutectic	Al_2O_3
Type4	Flip Chip	Eutectic	*AlN*
Type5	Flip Chip	Eutectic	*MCPCB*
Type6	Vertical	Silver paste	Al_2O_3

Table 2 Materials and dimensions of the adjustable LED

	Material	Dimension (mm)
Encapsulant	silicon	radius=4.25
Chip	InGaN	1.1×1.1×0.17
Die-attach	eutectic	thickness≅0.01
Submount	AlN	length×width×thickness = 9×9×0.5
Substrate	Al	length×width=31×31 thickness=0.9, 1.1, 1.6

4. Results and discussions

4.1 Crystal grain

Comparisons of the effects to the heat dissipation performance from the crystal grain structure: the crystal grain structures for Type 2 and Type 4 are lateral type and flip chip, respectively. The thermal resistance values for them are 1.9K/W and 0.9K/W, respectively. Since the light emitting layer of the flip chip is closer to the heat-sink substrate, the heat dissipating route is shortened, thus reducing the thermal resistance value by 52.63%. The thermal resistance values for Type 1 (lateral) and Type 6 (vertical) are 1.9K/W and 1.2K/W, respectively. With the laser ablation technique, we removed the sapphire substrate of the lateral structure and then coated a better thermal conductive substrate by using the electroplating method. From the experimental measurement, this vertical structure shows a lower thermal resistance value.

4.2 Die attach method

From the gray block on Fig. 4, we can observe the thermal resistance values of different die attach methods. The silver paste die attach is used for Type 1 and Type 6 and their thermal resistance values are 5.2K/W and 5.7K/W, respectively with an error of 8%. The thermal resistance values for Type 2 to Type 5 (with eutectic joining) are at a range of 2.7 – 4.2K/W. In calculation with an average of 3.7K/W, the thermal resistance value for the eutectic structure vs. the silver paste die attach can be lowered by 32%. Although the eutectic structure has a better overall heat-transfer property than the silver paste, its stability of the heat-transfer property is worse. Horng et al., [10] compared the good die attach material against the defective die attach material with gaps. The measurement result shows that due to the gap and defect the thermal resistance value increases from 0.8K/W to 4.4K/W. This result is similar to this experimental measurement result, i.e., the thermal resistance instability caused by the manufacturing process or the material defect is significant. Therefore, special care should be taken in the manufacturing process. In addition, the average thermal resistance value at 3.7K/W for the eutectic joining of this experiment is almost equal to the average thermal resistance value at 3.5K/W for the similar structured LED measured by Kim et al. [3]. Therefore, the measurement results for the thermal resistance values are reliable.

4.3 Heat-sink substrate

For the heat-sink substrate, in this study we selected Alumina substrate, AIZ substrate and aluminum substrate. Their average thermal resistance values are 6.83, 2.9 and 1.9K/W, respectively. The AIZ substrate, same as the ceramic substrate, has a higher heat transfer coefficient by almost 5 times against the Alumina substrate. Therefore, its thermal resistance value is reduced by 57.6%. However, the AIZ substrate is more expensive by 2.5~3 times than the Alumina substrate, so their price/performance ratio shows not much difference. The aluminum substrate has a dielectric layer with poor thermal conductivity in the middle. However, its thermal resistance value is the smallest among these three substrates. It is asserted that it is the result of the diffusion thermal resistance. The research made by Chen et al. [11] on different substrate thicknesses and different area ratios pointed out that for a general electronics packaging, the total thermal resistance value will first decrease and then increase with the increase of the substrate thickness, and at the turning point is the best thickness. Among the three area ratios of 0.3, 0.5 and 0.7, the smaller the area ratio (i.e., the smaller of the chip area vs. the substrate area) and the smaller the substrate thickness, the more important the diffusion thermal resistance effect is. When the substrate thickness is smaller than 20mm, the diffusion thermal resistance will decrease with the increase of the substrate thickness. In this study, we used approx. 1mm^2 heat area of the LED crystal grain and approx. 1.5cm x 1.5cm substrate area. Under the low area ratio (As/Ap) condition, the diffusion thermal resistance is dominant. The ceramic substrate and the aluminum substrate are 0.26mm and 1.6mm thick, respectively. Though the ceramic substrate has a lower 1D thermal resistance, it has a very high diffusion thermal resistance, leading to a higher total thermal resistance value than the aluminum substrate. From above

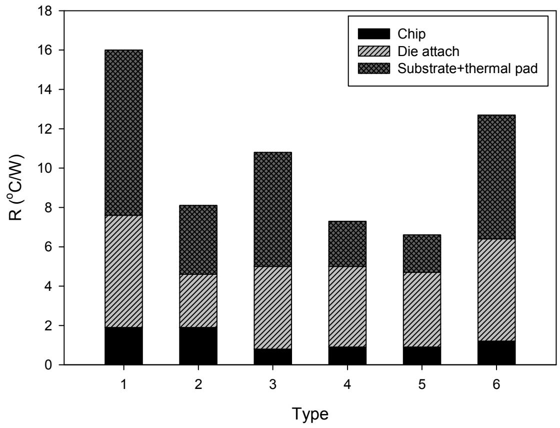


Fig. 4 Thermal resistances of different layers

discussions, the experimental results of this study have the same trend as the analytical results mentioned in literatures.

4.4 Diffusion thermal resistance effect

In this study, we further performed experimental measurement for the diffusion thermal resistance effect by selecting the variable power LED as the heat source and making three different aluminum substrate thicknesses, which are 0.9, 1.1 and 1.6mm. Refer to Table 2 for relevant specifications. The experimental measurement is made with 5W increment, from 10W to 50W. The measurement results are shown in Fig. 5. For the 10W condition, the thermal resistance value for the thickness of 1.6mm is 1.3K/W, which is lower than 1.9K/W and 2.2K/W for thicknesses of 1.1mm and 0.9mm, by 31% and 41%, respectively. This measurement result also shows that a thinner substrate is not necessarily the better. The thermal diffusion effect should also be taken into consideration. For the thickness of 1.6mm, the thermal resistance value is increased from 1.34K/W for 10W to 1.8K/W for 50W by approx. 25.5%. The increase percentages of the thermal resistance for thicknesses of 1.1mm and 0.9mm are 29.6% and 35.3%, respectively. This result shows that the higher the heat flux, the higher the diffusion thermal resistance gets. It is noteworthy that in previous literature [11, 12], the area ratio is used as the comparison parameter. With the same heating power, the larger the heating area, i.e., the higher area ratio, the lower the heat flux of the heat source gets, leading to a lower diffusion thermal resistance. In this study, we retain the area ratios of the heat source and the substrate to reduce the heat flux by controlling the wattage. The measurement results show the trend is the same as the result mentioned in the above literature. We discuss the reasons as follows: Lowering the heat flux will reduce the heat zone in the substrate, which is equal to enlarging the equivalent thickness with the heat transfer mechanism on the substrate (i.e., reducing the above heat source effect to the bottom of the substrate.) Within the substrate thickness range measured in this study (i.e., when the diffusion thermal resistance effect is significant), the diffusion thermal resistance will decrease with the increase of the heat transfer equivalent thickness of the substrate, thus reducing the heat flux and in turn reducing the diffusion thermal resistance.

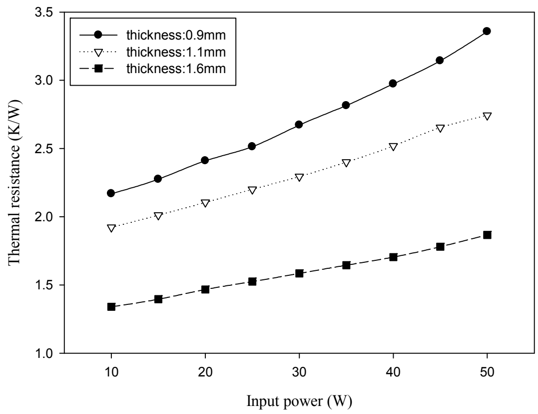


Fig. 5 Thermal resistances of different substrates with different thicknesses

5. Conclusions

This paper investigates the thermal resistance values of the LED crystal grain, the packaging method and the heat-sink substrate by using the T3Ster measuring device. We have made six different types of LEDs, which are: Type 1: lateral crystal grain, silver paste die attach and Alumina substrate; Type 2: lateral crystal grain, eutectic structure and AIN substrate; Type 3: Flip chip, eutectic structure, and Alumina substrate; Type 4: Flip chip, eutectic structure, and AIN substrate; Type 5: Flip chip, eutectic structure and aluminum substrate; Type 6: vertical type crystal grain, silver paste die attach and Alumina substrate. The experimental results show that the thermal resistance values for crystal grains of the lateral type, flip chip and vertical type are 2K/W, 1.04K/W and 1.34K/W, respectively. Since the light emitting layer of the flip chip is closer to the heat-sink substrate, the heat dissipation route is shortened, thus reducing the thermal resistance value by 48%. The sapphire substrate of the lateral type crystal grain has been replaced by the vertical type structure with the high thermal conductive substrate, thus also reducing the thermal resistance value by 33%. The variance of the thermal resistance between the silver paste die attach and the eutectic solder can be up to 3K/W. Using the eutectic solder with a higher heat-transfer coefficient (K=50W/m*K), the thermal resistance value can be lowered by 52.6%. The substrate selection should surely be made based preferably on the materials with a higher heat-transfer coefficient. However, from this experiment, we can see that the optimum selection of the material thickness is also one of the key elements that can affect the heat resistance. This study is mainly intended to investigate the heat dissipation performance in the packaging layer. In the real natural convective situation, the heat-sink design is absolutely more important.

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REFERENCES

[1] N. Narendran, Y. Gu, J. P. Freyssinier, H. Yu, and L. Deng, "Solid-state lighting: Failure analysis of white LEDs" *Journal of Crystal Growth*, **268**, 449-456 (2004)

[2] C. A. Tran, C. F. Chu, C. C. Cheng, W. H. Liu, J. Y. Chu, H. C. Cheng, F. H. Fan, J. K. Yen, and T. Doan, "High brightness GaN vertical ligh emitting diodes on metal alloyed substrate for general lighting application" *Journal of Crystal Growth*, **298**, 722-724 (2007)

[3] H. H. Kim, S. H. Choi, S. H. Shin, Y. K. Lee, S. M. Choi, and S. Yi, "Thermal transient characteristics of die attach in high

power LED PKG" *Microelectronics Reliability*, **48**, 445-454 (2008)

[4] R. H. Horng, J. S. Hong, Y. L. Tsai, D. S. Wuu, C. M. Chen, and C. J. Chen, "Optimized Thermal Management From a Chip to a Heat Sink for High-power GaN-Based Light-Emitting Diodes" *IEEE Transactions On Electron Devices*, **57**, 2203 - 2207 (2010)

[5] B. H. Liou, C. M. Chen, R. H. Horng, Y. C. Chiang, and D. S. Wuu, "Improvement of thermal management of high-power GaN-based light-emitting diodes" *Microelectronics Reliability*, **52**, 861-865 (2012)

[6] L. Yin, L. Yang, W. Yang, Y. Guo, K. Ma, S. Li, and J. Zhang, "Thermal design and analysis of multi-chip LED module with ceramic substrate" *Solid-State Electronics*, **54**, 1520-1524 (2010)

[7] L. Yang, J. Hu, S. Jang, and M.W. Shin, "Thermal design of ceramic packages for high power light-emitting diodes" *Semiconductor Science and Technology*, **22**, 705-708 (2007)

[8] S. A. Said, B. A. Akash, "Experimental Performance of a Heat Pipe" *International Communications in Heat and Mass Transfer*, **26**, 679-684 (1999)

[9] K. S. Yang, C. H. Chung, M. T. Lee, S. B. Chiang, C. C. Wong, and C. C. Wang, "An experimental study on the heat dissipation of LED lighting module using metal/carbon foam" *International Communications in Heat and Mass Transfer*, **48**, 73–79 (2013)

[10] R. H. Horng, R. C. Lin, Y. C. Chiang, B. H. Chuang, H. L. Hu, and C. P. Hsu, "Failure modes and effects analysis for high-power GaN-based light-emitting diodes package technology" *Microelectronics Reliability*, **52**, 818-821 (2012)

[11] Y. S. Chen, K. H. Chien, Y. S. Tseng, and Y. K. Chan, "Determination of Optimized Rectangular Spreader Thickness for Lower Thermal Spreading Resistance" *Journal of Electronic Packaging*, **131**, 011004.1-011004.8 (2009)

[12] Y. S. Chen, K. H. Chien, C. C. Wang, T. C. Hung, Y. M. Ferng, and B. S. Pei "Investigations of the Thermal Spreading Effects of Rectangular Conduction Plates and Vapor Chamber" *Journal of Electronic Packaging*, **129**, 348-355 (2007)