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Thermal analysis of high power LEDs on the MCPCB †

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Abstract

The management of the reduced junction temperature of LEDs is a critical issue because it will affect many physical parameters such as light output, wave length and LED's lifetime. The model used in this simulation consists of a metal core PCB attached with six chips(GaN on sapphire, Ag paste, cathode/anode, silicone encapsulant, mold frame) for 5W LED module. The MCPCB is composed of an aluminum base plate, a thin layer of dielectric, and a layer of copper. The temperature distribution of the developed LED module was simulated, and the thermal behavior within this 3-D model was investigated by using a commercial computational fluid dynamic code (Fluent 6.3). The results showed that the temperature variation along the vertical direction is more dominant than that in the circumferential direction due to the heat spreading effect of the copper layer. The ratio of heat dissipation through the each thermal path was calculated and compared for various input conditions. Several parameters that increase the junction temperature, such as the thermal conductivity and thickness of the dielectric layer and the encapsulate material, heat transfer coefficient and input power were also examined. Finally, a combination of designs for attenuating the junction temperature was proposed.

Keywords: Thermal analysis; Light emitting diodes (LEDs); Metal core PCB; Dielectric layer; Encapsulation material

1. Introduction

High power light emitting diodes (LEDs) have been widely used due to their efficiency, lifetime, size and robustness. Thermal management in high heat flux is a critical design issue in developing high power LED applications because only 15% - 25% of input power turns into a visible light and the remainder is converted into a form of heat. The elevated junction temperature resulting from this conversion leads to many problems in optical performance and shortens the lifetime of LEDs. Chi et al. [1] established finite element analysis for LED lighting module with a corresponding input power and suitable boundary conditions. Their methodology and analysis results can provide a guideline for LED lighting module design.

Thermal management at the chip level handles the internal thermal resistance from the junction to the package case. Senawiratne et al. [2] investigated the temperature distribution in an LED grown on sapphire and GaN substrates and found that heat dissipation efficiency was enhanced by using GaN as the substrate. They also investigated the heat dissipation capabilities of various designs of LED dies. In general, phosphor coating layer used in white LEDs is thermally sensitive, and overheating of this layer can reduce the long-term reliability of LEDs. Fan et al. [3] proposed a phosphor thermal-isolated packaging technology, which has a thermal-isolated encapsulant layer between the LED chip and phosphor coating layer. The results showed that the new packaging can effectively reduce the heat transfer from the LED, and keep the phosphor layer cooled at uniform temperature. A direct thermal spread LED module formed by using electroless and electroplating techniques (EET) without any adhesive resin was reported by Chen et al. [4]. Their results proved that the thermal resistance of a high power LED using EET is much less than that of a conventional LED using adhesive resin. However, in their LED module a reflective mirror was designed. The heat from an LED chip mostly travels to the cathode lead and finally dissipates to the PCB. Karim et al. [5] demonstrated the effects of the material and width of a lead frame on the thermal resistance of a through hole LED. The combination of both design changes resulted in a thermal resistance reduction of 51 percent in their study. A thermally conductive adhesive with high thermal conductivity, a thin bond line, or a thermal clad can also be a solution for long-term reliability. The influence of die attach layer on thermal performance of high power light emitting diodes was investigated by Yan et al. [6].

Thermal performance can be significantly improved by an

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array of thermal vias. Yu et al. [7] showed practical methods for thermal management of high power LEDs in closely packed configurations using various PCB configurations: FR4 based with thermal open vias and FR4 with filled and capped vias, as compared to MCPCB. The boundary conditions for the external surfaces need to be carefully determined. Generally, the top surface may be considered as adiabatic due to its low thermal conductivity at the chip level. Wan et al. [8] proposed a novel porous micro heat sink system for thermal management of high power LEDs, which presented also an improvement of reliability and life of LEDs. Lee et al. [9] attempted to extract heat transfer coefficients analytically on the bottom side of a chip and proposed a method of thermal calculation combining analytical and numerical modeling tools to predict the surface temperature of the LED package. The heat transfer coefficients were found to increase with temperature difference between the LED surface and atmosphere, but the results showed relatively high value under general operational conditions.

Conventional PCB materials cannot meet the increasing demand of the thermal requirement of high power dissipation PCB. One of the current approaches to address this thermal dissipation is the use of a metal core printed circuit board (MCPCB). Several types of MCPCB are available on the market, but the single–layer one is still most prevalent due to its simplicity. Yung [10] described the effective thermal conductivity of a dielectric of conductive laminate and presented a suitable formula to produce an insulation dielectric of MCPCB with desired thermal conductivity value. Weng [11] illustrated how the FEM modeling technique can be used for simulating the LED package based on the industry–standard LED package and predicted the wide range of thermal performance of LED packages with different heat slugs, PCBs, cooling conditions and chip sizes for relatively low power of less than 1 W/chip. The thermal design rule and correlations may help the PCB industry to develop new product designs.

We developed a 5 W LED module for a 60 W level high power illumination system. Its thermal characteristics need to be investigated to ensure the suitability of the design. Numerical simulation was performed and compared with experiments to investigate the heat dissipation mechanism and to find the maximum junction temperature for various operational conditions. We examined several parameters that increase the system temperature and proposed a combination of designs for attenuating the junction temperature in this study.

2. Thermal model development

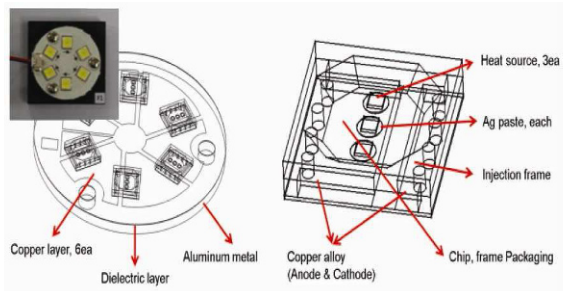
2.1 Physical model

Fig. 1 shows a schematic of the 5 W LED module developed. Three blue chips (GaN on Sapphire, 600 μm x 600 μm x 100 μm) are attached to the cathode (Cu alloy) by a die attach material (Ag paste) in a “3 in 1” packaged led lamp.

The copper frame, a cathode/anode designed to cover most of the bottom area beneath the chip, plays an important role to conduct heat away from the chip to the MCPCB. Heat-resistant polymer is molded around the chip and the cathode/anode to form an LED package. The highly reliable silicone encapsulant, resin plus phosphor, is filled in this mold for a white LED. Six LED lamps are attached by SnPb solder on the MCPCB, which is composed of a copper layer (1 Oz) for heat spreading, dielectric layer (100 μm), and aluminum metal (1.5 mm). The physical dimensions and the thermal conductivity of the LED chip and fixtures are listed in Table 1.

Table 1. Thermal conductivity and thickness of chip & LED fixture.

	Material	Conductivity (W/mK)	Thickness (㎛)
LED package	GaN	177	10
	Sapphire	42	100
	Ag paste	3	30
	Copper alloy	260	500
	Injection frame	0.47	1000
	Encapsulate	0.2	500
PCB	SnPb solder	50	100
	Cooper layer	260	35
	Dielectric layer	0.4	100
	Aluminum	200	1500

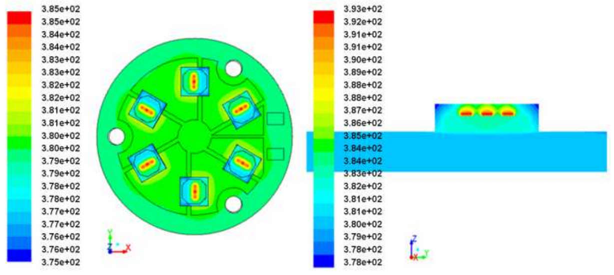


(a) LEDs on PCB (b) Details of LED package

Fig. 1. 5W LEDs package mounted on PCB.

2.2 Simulation method

The temperature distribution was obtained by solving the following Poisson equation for a three-dimensional steady-state heat transfer problem with heat generation in a volume of LED active region. $\nabla^2 T + \dot{q}/\kappa = 0$. Numerical simulation of the tested LED module was performed by the finite volume method, which is embedded in the commercial software (Fluent V.6.3). Newton’s law of cooling boundary conditions (10 W/m^2K < h < 100 W/m^2K) was applied to the external surfaces exposed to the ambient air of 20 °C. Both convective and radiation heat transfer coefficients were considered in the temperature simulation. More than 2700000 hybrid elements, which combined the polyhedral mesh and hexahedral mesh, were used due to the very thin layer in this model. It took about 6 hours to obtain the converged solution by using a



(a) Top view (b) Side view

Fig. 2. Temperature contours of top surface and cross section of the module.

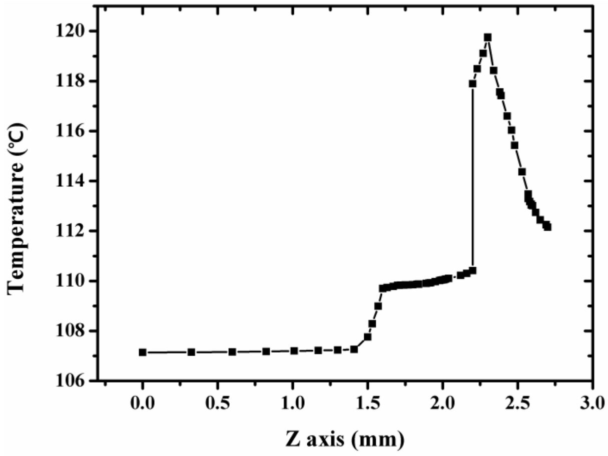
computer with i7 CPU (2.67 GHz) quad core.

3. Results and discussion

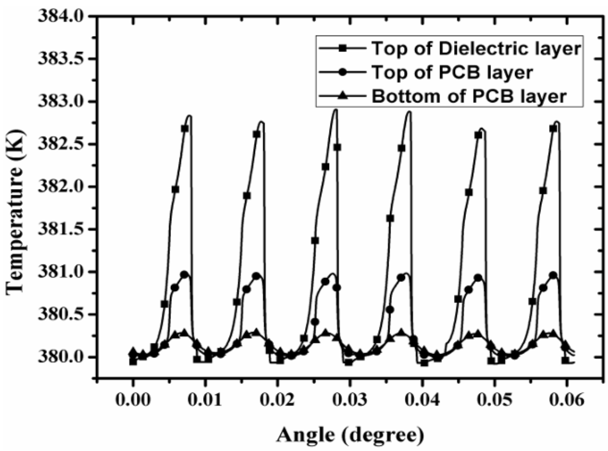
Contours of the temperature variation obtained from the simulation in the x-y plane and y-z plane of the 3D model are shown in Fig. 2 for Q = 5 W/module. The external surfaces of the module are exposed to ambient temperature at 20℃ with heat transfer coefficient of 20 W/m^{2}K. As shown in Fig. 2(a), the maximum surface temperature of the chip is about 112.3 ^{o}C, which represents the high temperature drop due to the poor thermal conductivity of the encapsulant resin. The surface of the PCB showed a uniform temperature of about 106.7^{o}C because of the heat spreading effect of the copper layer. Fig. 2(b) represents the heat dissipation through the cathode lead frame to the PCB. The maximum temperature is 119.8^{o}C at the center of the LEDs on the sapphire substrate. Also, a relatively lower temperature region of the chip was located at the anode lead frame, which is separated from the cathode frame by encapsulant with poor thermal conductivity.

The temperature distribution along the vertical midsection of the chip is shown in Fig. 3(a) for h = 20 W/m^{2}K and Q = 5/6 W/chip without a heat sink. As expected, the maximum temperature occurs at the LED chip (GaN on sapphire) with the junction temperature $T_{junction}$ = 119.8^{o}C. The gradient of the vertical temperature profile is large in the encapsulant layer, the sapphire substrate, the die attach (AG paste), and dielectric layer of the PCB, where thermal conductivity is low. It is clear that the layers with a large temperature gradient should be made as thin as possible to reduce their thermal resistance. From the vertical temperature profile, the thermal resistance based on the temperature difference along the centerline of the package can be calculated. In this case, the total junction-to-board thermal resistance R_{j-b} is about 15.6^{o}C /W. Fig. 3(b) shows the temperature distribution along the circumferential direction of the PCB. The relatively high temperature difference between the chip and dielectric layer separated by cupper layer is repeated every 60 degrees. This temperature difference attenuates as the heat flows through the PCB thickness and becomes almost uniform, less than 0.5^{o}C, at the bottom of PCB.

In general, heat transfer through the top of the chip has been



(a) Vertical direction



(b) Circumferential direction

Fig. 3. Temperature distributions along the distance from the chip center and circumferential direction.

disregarded since it is small because of the large thermal resistance of the encapsulant. However, the information on the temperature in this region is important for predicting the color variation of phosphor. In this study, we considered the heat dissipation through the encapsulant for the quantitative analysis and compared the directional heat transfer rate (upward and downward) from the chip. Fig. 4 shows the effect of thermal conductivity of the encapsulant on the heat transfer rate. The heat transfer rate through the encapsulant in the upward direction can be neglected at low thermal conductivity. However, the heat transfer rate in the upward direction increases significantly with increased thermal conductivity until k = 0.6 W/mK.

Fig. 5 illustrates the measured temperature distribution at the top surface of the LED module developed in this study. The module was cooled by natural convection for the vertical configuration at room temperature of 20^{o}C. Fig. 5(a) shows the thermal image of the LED surface taken by the IR camera (ImageIR 5300, InfraTec) at the electrical input power of 270 mA, 17.6 V. The tested temperature profiles along the three

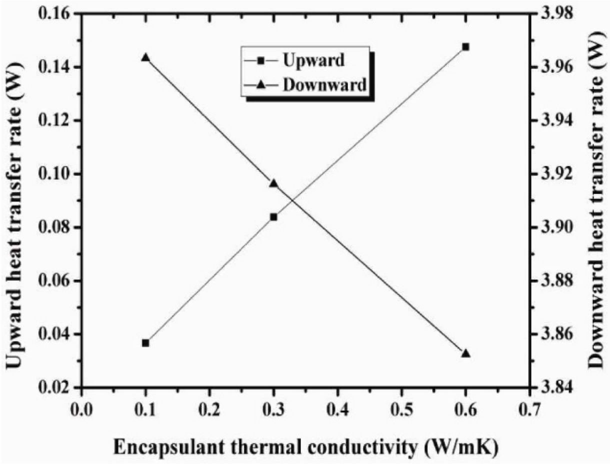


Fig. 4. Comparison of heat transfer through the upward and downward heat flow direction from the chip junction.

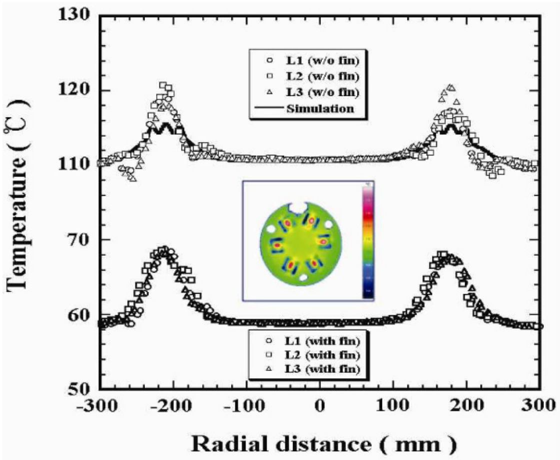
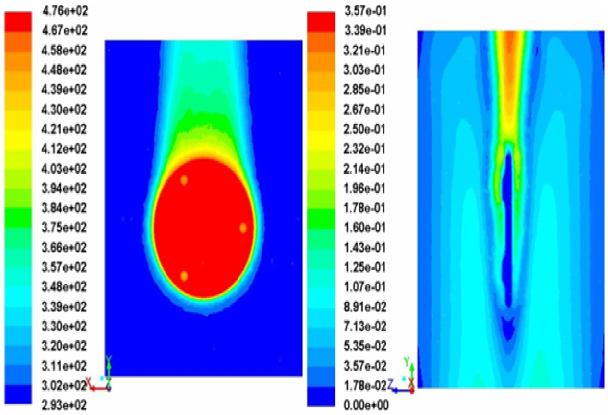


Fig. 5. Thermal image and temperature profile of the tested LED module.



(a) Temperature contour (b) Velocity contour

Fig. 6. Temperature and velocity contours of the module in natural convection.

different radial directions are shown in Fig. 5(b). The thermographic data are analyzed by using the software IRBIS 3. There are some temperature deviations between surface temperatures of the chip because the input power and illumination efficiency of each chip cannot be exactly uniform. The average temperature of the top of the LED package is 118.6°C. The maximum temperature profile predicted by the simulation result is also plotted in Fig. 5(b). The maximum temperature of 115.7°C deviates less than 5% compared to the measured results. This error may be attributed to the slightly different values in the real physical dimensions and/or thermal properties of the LED chip and fixtures. However, the simulated results closely matched the experimental results. The tested natural heat transfer coefficient for a vertical circular disk is about h = 8.8 W/m^{2}K from the equation $Nu_d = 1.759\ Ra_d^{\ 0.15}$ by Kobus et al. [12], which is comparable to the radiation heat transfer coefficient h_r = 8.9 calculated by $h_r = \varepsilon\sigma(T_s + T_o)(T_s^2 + T_o^2)$ in this study. The result from our thermal model shows good agreement with the experimental result only when including this radiation effect. The junction temperature decreases evidently from 118.6°C to 68.3°C when a heat sink (Aluminum, 3.3 cm x 3.3 cm, 9 x 9 pin fin type) is attached at the bottom of LED module. To check the efficiency of this model, free convection flow past a 3-D vertical LED module in a room temperature has been investigated. Fig. 6(a) shows the contour of temperature field near the LED module without radiation. The relatively high temperature of about 203°C at the module indicates the need for additional cooling, such as forced convection or heat sink for robust operation. The convection heat transfer coefficient was found to be 8.7 W/m^{2}K, similar to that of the test model. When the radiation boundary condition was applied to the base surface, the combined and radiation heat transfer coefficient was 17 W/m^{2}K and 8.3 W/m^{2}K, respectively. The result confirms that the correlation equation can reasonably predict the combined heat transfer coefficient by using allowable junction temperature of 110°C in this study. Fig. 6(b) shows the contour of velocity field near the LED module with natural convection heat transfer to the still air at 20°C. The increased velocity increased to 0.36 m/s due to the effect of buoyancy assisting flow through the upward of the module.

Advancement in LED technology aims to enhance brightness by increasing input power. However, the junction temperature of the LED chip will increase as the input power increases, and therefore affect LED performance such as in light output, wavelength and LED lifetime. The junction temperature for four different input powers is illustrated in Fig. 7.

The junction temperature increases almost linearly with input power for every convection heat transfer coefficient. Note that the junction temperature is very sensitive to the convection heat transfer coefficient of the external surfaces under the fixed LED structure. In general, free convection boundary condition of h = 10 W/m^{2}K was applied around a module. It was found that the junction temperature without heat sink exceeds the applicable limit 120°C with h = 10 W/m^{2}K at Q =

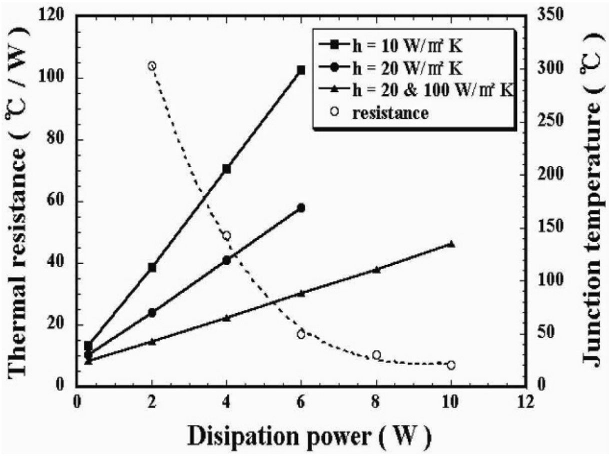


Fig. 7. Effect of heat transfer coefficient and input power on the junction temperature and thermal resistance.

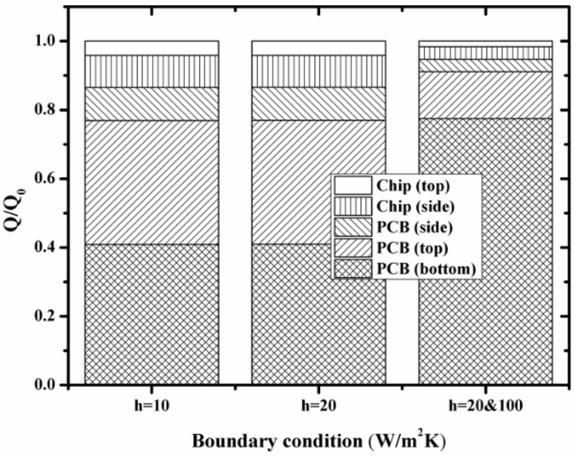


Fig. 8. Effect of encapsulate and die attach materials on the temperature distribution along the distance from chip.

5 W. This junction temperature can be lowered to T_j = 64°C by using a higher convection heat transfer coefficient of h = 100 W/m^{2}K at the base of the PCB. We can choose the heat sink corresponding to this convection coefficient with base-to-ambient thermal resistance $(1/hA)$ $R_{\text{base}-\text{ambient}}$ = 11.1°C /W. The maximum power is limited by the thermal resistance of the LED. The optimized condition to keep the allowable junction temperature under study (110°C) is also plotted in Fig. 7. The correlated equation $R = 199.4 - 58.7Q_o + 6.0Q_o^2 - 0.2Q_o^3$ represents the required thermal resistance as a function of dissipated power.

The encapsulants used in phosphor-converting white LEDs are thermally sensitive, and overheating can lead to degraded output light and reduced long-term operation reliability. Various encapsulant materials (*Dow Corning 3-4207*, *Dow Corning 255, Sylgard Q3-3600*) with thermal conductivity ranging from k = 0.1 W/mK to 0.8 W/mK can be used. The effect of the thermal conductivity of the encapsulant material on the temperature distribution in the module is shown in Fig. 8. The

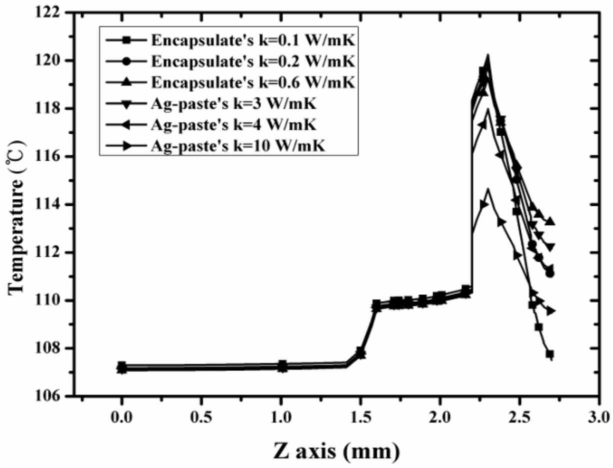


Fig. 9. Comparison of heat dissipation rate for various thermal paths.

maximum temperature decreases slightly by less than 1.0 °C at increased thermal conductivity of encapsulant. However, the corresponding temperature at the external surface of chip increases significantly by more than 5.7°C at lower thermal conductivity (k = 0.1 W/mK). The blue chips are bonded to the lead frame with a die-attach material. In this study, we considered Ag paste (k = 3 W/mK) as the die-attach material and investigated the effect of thermal conductivity on the temperature along the center line of the module. Temperature variations occurred only at the package when the thermal conductivity of the die attach-material was changed. Furthermore, the junction temperature dropped significantly when thermal conductivity was increased from 3 W/m^{2}K to 10 W/m^{2}K. The current model (*Trutherm A 853, k = 3 W/mK*) applies relatively low thermal conductivity (*Trutherm A 853, k = 3 W/mK*) due to the good workability. However, results indicate that high thermally conductive adhesive such as *Trutherm A 801 L, k = 30 W/mK* can be applied for high power LED module in spite of worse workability.

The amount of heat generated in the chip can be removed through the various heat flow paths from the chip to the surroundings. The ratio of heat dissipated through the each external surface to the heat generated at the junction is shown in Fig. 9. The primary heat flow can be determined from this figure. In the case of uniform convection boundary conditions (h = 10 W/m^{2}K, h = 20 W/m^{2}K), 36% and 41% of the heat generated at the chip is dissipated out through the top and bottom surfaces of PCB, respectively. The rest of the heat is removed through the other directions of flow paths, such as the top/ side of the package and the side of the PCB. Less than 5% of heat was removed through the encapsulant surface of the package. As expected, the higher heat transfer coefficient at the bottom of PCB significantly affected efficient thermal dissipation through the bottom of the PCB. Less than 2% of heat was removed through the encapsulant surface and most of the heat (77%) was dissipated through the bottom of the PCB.

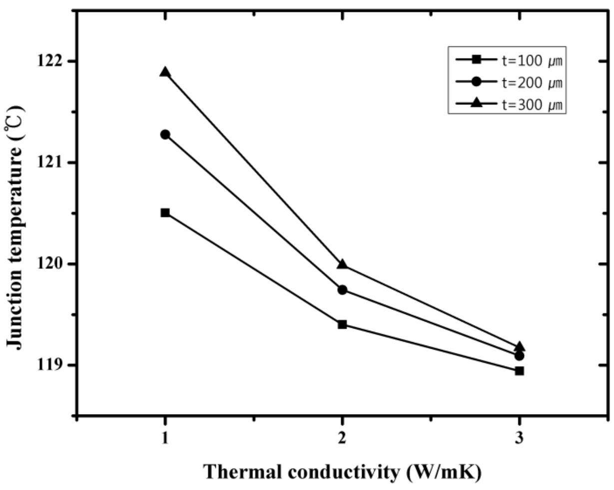


Fig. 10. Effect of thermal conductivity & thickness of dielectric layer on the junction temperature.

The influence of the dielectric layer of the PCB on the junction temperature is shown in Fig. 10 for various thermal conductivities at three different thicknesses of t = 100 μm, t = 200 μm and t = 300 μm. The junction temperature also decreases as the thermal conductivity increases at a fixed t. This confirms the large rate of decrease in the junction temperature for small thermal conductivity. This figure also indicates that the thicker the dielectric layer, the higher the junction temperature due to the increased thermal resistance. However, Fig. 10 shows that the thickness and thermal conductivity of the dielectric layer investigated in this study had relatively small effect on the junction temperature, less than 3°C.

4. Conclusions

Numerical simulation was performed to investigate the heat dissipation mechanism in a high power LED model. The effect of several parameters on the junction temperature was examined to confirm the thermal efficiency of the model developed in this study.

The results from our thermal model show fairly good agreement with experimental results when combined radiation and natural convection boundary condition was applied for a vertical circular disk. Free convection flow past a 3-D vertical LED module was investigated to confirm the reasonable combined heat transfer coefficient by using allowable junction temperature (110°C) in this study.

The junction temperature increased almost linearly for various input powers. The optimized condition to keep the allowable junction temperature under study (110°C) is presented by the correlation equation $R = 199.4 - 58.7Q_o + 6.0Q_o^2 - 0.2Q_o^3$, which provides the required thermal resistance as a function of dissipated power.

Heat dissipation rate through various thermal paths from the package to the surroundings was also estimated. Less than 2% of heat is removed through the encapsulant surface and most of the heat (77%) is dissipated through the base of a PCB with heat sink.

The effect of the thermal conductivities of encapsulants and die-attach materials on the junction temperature was investigated. We examined also the influence of the dielectric layer of the PCB on the junction temperature. The effect of thickness of the dielectric layer on the junction temperature was dominant for small thermal conductivity.

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Nomenclature

Nu_d : Nusselt number
Q : Heat dissipated heat power (W)
Q_0 : Heat generated at the junction (W)
$R_{j\text{-}b}$: Thermal resistance junction to base (°C/W)
Ra_d : Rayleigh number
T_o : Temperature (K)
$T_{junction}$: Temperature at junction (K)
h : Convection heat transfer coefficient (W/m^{2}K)
h_r : Radiation heat transfer coefficient (W/m^{2}K)
k : Thermal conductivity (W/mK)
ε : Emissivity
σ : Stefan-Boltzmann constant (W/m^{2}K^4)

References

[1] W. H. Chi, T. L. Chou, c. N. Han, S. Y. Yang and K. N. Chiang, Analysis of thermal and luminous performance of MR-16 LED lighting module, *IEEE Trans, Compon. Pack. Tech.,* 33 (4) (2010) 713-721.

[2] J. Senawiratne, Y. Li, M. Zhu, Y. Xia, W. Zhao, T. Detchprohm, A. Chatterjee, J. L. Plawsky and C. Wetzel, Junction temperature measurements and thermal modeling GaInN/ GaN quantum well Light Emitting Diodes, *Journal of Electronic Materials,* 37 (5) (2008) 607-610.

[3] B. Fan, H. Wu, Y. Zhao, Y. Xian and G. Wang, Study of phosphor thermal-isolated packing technologies for high-power white Light-Emitting Diodes, *IEEE Photonics Technology Letters*, 19 (15) (2007) 1121-1123.

[4] K. C. Chen, Y. K. Su, C. L. Lin, Y. Lu, W. Li, W. Chuang, J. Q. Huang and S. M. Chen, Thermal management and novel package design of high power light-emitting diodes, *Electronic Components and Technology Conference, Florida,* May (2008) 795-797.

[5] A. A. Karim, P. P. A. Narayana and K. N. Seetharamu, Thermal analysis of LED package, *Microelectronics Inter-*

national, 23 (1) (2006) 19-25.
[6] B. Yan, J. P. You, N. T. Tran, Y. He and F. G. Shi, Influence of die attach layer on thermal performance of high power light emitting diodes, *IEEE Trans, Compon. Pack. Tech*., 33 (4) (2010) 722-726.
[7] J. H. Yu, W. Oepts and H. Konijn H, PC board thermal management of high power LEDs, *24th IEEE SEMI-THERM Symposium*, San Jose, March (2008) 63-67.
[8] Z. M. Wan, J. Liu, K. L. Su, X.H. Hu and S. S. M, Flow and heat transfer in porous micro heat sink for thermal management of high power LEDs, *Microelectronics Journal*, 42 (2011) 632-637.
[9] T. H. Lee, L. Kim, W. J. Hwang, C. C. Lee and M. H. Shin MH, Thermal analysis of GaN-based LEDs using the finite element method and unit temperature profile approach, *Phys. Stat. sol.* (b), 241 (12) (2004) 2681-2684.
[10] W. K. C. Yung, Using metal core printed circuit board as a solution for thermal management, *Journal of the HKPCA*, *24* (2007) 12-16.
[11] C. J. Weng, Advanced thermal enhancement and management of LED packages, *International Communications in Heat and Mass Transfer, 36* (2009) 245-248.
[12] C. J. Kobus and G. L. Wedekind, An experimental investigation into natural convection heat transfer from horizontal circular disks, *International Journal of Heat and Mass Transfer*, 44 (2001) 3381-3384.

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