Study of High Power COB LED Modules with Respect to Topology of Chips

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***Abstract**: The thermal influence of the topology of the COB (Chip-on-Board) LED modules is examined. For this purpose CFD simulations of a powerful COB LED module thermal model are carried out and the thermal distribution at different locations of LED chips is analyzed. Simulation experiments are designed, using the substrates of ceramic materials - Alumina (Typical), Alumina (94%), Alumina (96%) and AlN. The thermal efficiency of four different structures of COB LED modules with different modes of operation and environment is examined. The simulation results are verified with thermal measurements.*

1. INTRODUCTION

The growing demand for LED applications with high output power gives rise to the need for creation of lighting systems with a higher density of packaging. One way to achieve higher power is by using COB (Chip-on-Board) LED technology.

In COB technology, LED chips are mounted directly near each other on a substrate or circuit board. This package design allows achievement of higher power density, since LEDs occupy less space while providing higher intensity and uniform light output, which greatly improves operation of lighting systems based on this technology [1], [2].

Despite the numerous advantages of COB LED technology there are still quite technical problems that are not well understood. The small size and high packaging density, together with higher power output require careful selection of solutions for heat management in the design stage. Since LED chips are very close to each other, often the designers must answer the question whit is the appropriate distance between LED chips and how they must be deployed to achieve the optimal balance between thermal and optical properties [3], [4].

Much of the current research on high-power LED arrays with respect to the topology and its effect on heat transfer is made in separate discrete one-chip LEDs.

Mohamad, Abdullah and others in [4] examined the effectiveness of the cooling of high-power LED arrays at four different positions of the separate LEDs. LEDs are arranged in an array shaped as - square, hexagon, triangle and circle. The efficiency is determined based on the temperature measurement of one from the LEDs in place of the solder, MCPCB board and heat sink. The temperature is measured with K-type thermocouples connected to the system for data collection. The coefficient of heat exchange of the various types of arrays is evaluated on the basis of the data obtained.

Other researchers such as Christensen and Graham in [5] analyzed the overall thermal behavior of high-power LED arrays composed of 25 single-chip LEDs using numerical models based on finite elements and network thermal resistances. There is examined the thermal behavior at different distances between the LEDs in the array, and the impact of different materials of package level and system level on the heat dissipation of the structure. The results of the array with respect to distance show that at one and the same output power when the distance between the LEDs is 1 mm, the transition temperature of the LEDs is higher, while at a distance of 10 mm it is lowest.

Petroski in [6] examines the effects of different distances between the LEDs in COB LED arrays. He uses the methodology for design of experiments (DOE) to analyze the factors affecting the design of

COB LED applications. Research and analysis are done for LED devices of class power of 1W.

Today, however, the modern trends in lighting systems are focused on creating more compact multi-chip COB LED devices with high power output, which, however, dissipate significant amount of heat. There are no adequate studies concerning heat transfer processes in terms of topography.

This article examines the thermal effects according to the topology of the chips in powerful multi-chip COB LED module using digital 3D models and thermal simulations. An evaluation of the heat dissipation in the structure at different distances and different arrangement of separate chips in the package is made. The behavior of the structure at various ceramic materials of the substrate is analyzed. The thermal efficiencies of the different structures of the COB LED modules with respect to dissipated thermal power and ambient temperature are compared.

2. EXPERIMENT

To study the thermal behavior in powerful multichip COB LED modules thermal simulations with CFD (Computational Fluid Dynamics) software FloTherm are held. Thermal simulations are widely used in thermal management of electronic equipment and are very useful in the design of new products especially before creation of their actual physical prototypes [7], [8].

COB LED module is thermally modeled for the purposes of the simulations. The digital model is created based on real 11W (1.05 A) LED structure. Fig. 1 shows the LED structure, and in the Table. 1 are shown the design parameters of the LED module in the simulations.

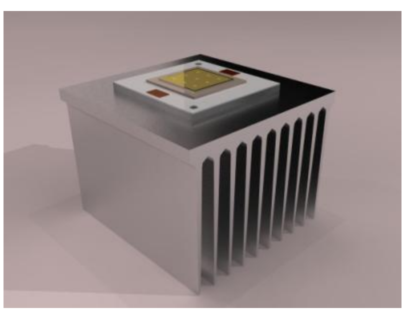

Fig. 1. Construction of COB LED module

In the simulations the COB LED module is placed on the aluminium heat sink with 10 flat ribs. The dimensions of the ribs and spacing between them are shown in Fig. 2.

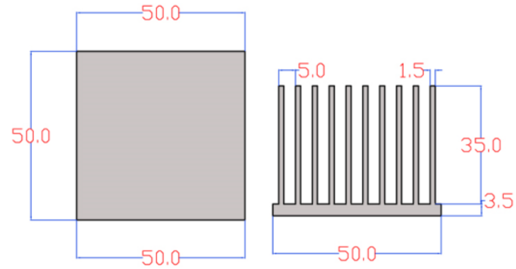

Fig. 2. Structure and size of the heat sink in the simulations

Topology LED module consists of 9 blue GaN LED chips placed in 3x3 square matrix. The LED chips have dimensions of 1mm x 1mm and are disposed on a ceramic substrate (dimensions 18mm x 18mm) which is attached to the aluminum billet (dimensions 26mm x 26mm) for better heat distribution and easier holding of the radiator. A thin layer of TIM (Thermal Interface Material) is placed between the radiator and the aluminum billet to lower the thermal resistance of the border between the two surfaces.

Since most of the power of the LEDs is converted to heat (usually in white LEDs it is between 65 to 80% at nominal current) and a smaller part is converted to light [9] it is necessary to estimate how much of the power is converted into heat before conducting the simulations.

Table 1. Construction parameters of COB LED modules

Material	Thermal Conductivity, λ [W/m·K]	Thickness [µm]
GaN (chips)	130	150
Die-attach (Sn-Ag3.5)	33	50
Alumina (Typical)	16	600
Alumina (94%)	18	600
Alumina (96%)	25	600
AlN	170	600
Silicone Square	0.2	500
TIM	4	100
Substrate (Pure Aluminum)	201	2000

The calculation of the thermal power dissipated by a LED module is as follows:

$$P_{th}=V_f * I_f * H \qquad (1)$$

where:

P_{th} – is the thermal power dissipated in the junction of the LED module;

V_f – is the forward voltage of the LED module;

I_f – is the current flowing through the unit;

H – is the thermal coefficient (the percentage of power that is converted into heat).

The calculation of maximum dissipated heat power is done at maximum V_f of the module and the corresponding operating current.

At maximum $V_{f\ max}$ = 11.5V and current I_f = 1.05A at heat factor H = 0.70 and by substituting in (1), the maximum Pth ~ 8.45W is obtained.

At the first stage there is examined the thermal reaction of LED structure at different chip to chip distances. In this study, the location of the LED chips in the COB module are shown in Fig. 3.

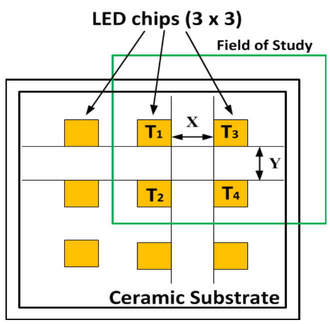

Fig. 3. Topology and distances between chips in LED module; X = Y = 1mm, 2mm, 3mm, 4mm

The chips T1, T2, T3 and T4 in the green square are marked to monitor their temperature change, resulting from the different distances between the chips in the structure.

The chips in the structure are at the same distance X = Y, symmetrically with respect to the chip T2 (in the center). Therefore there is no need to monitor the temperature of all chips, but only of those in the fenced area (field of study).

Thermal simulations are made for distances of X = Y = 1mm, 2mm, 3mm and 4mm at power dissipation of 8.45W (at maximum P_{th}), at 7.71W (at nominal P_{th}), varying ambient temperature (at T_a = 25^{0}C, 30^{0}C и 35^{0}C), in order to evaluate thermal behavior at different operating modes and conditions.

The second stage involves exploring the possibilities for improving the thermal characteristics of the base structure by application of ceramic substrates with high thermal conductivity. Simulations are made for substrates of the materials - Alumina (Typical, 94%, 96%) and AlN. Characteristics of these materials used in the simulations are given in Table 1.

The choice is dictated by the fact that the use of various ceramic substrates is quite popular solution for controlling heat transfer in the powerful COB modules and guarantee their performance and reliability [10]. The goal is to find the optimal choice between the material of the substrate and the distance between the chips.

For the assessment of this study there is used the junction temperature T_j of the chip in the centre of the structure (T2), where the heat and the thermal resistance of the junction to the environment $R_{j\text{-}a}$ are concentrated.

Thermal resistance $R_{j\text{-}a}$ is calculated according to the procedure in [9]:

$$R_{j-a} = \frac{T_j - T_a}{P_{th}} \quad (2)$$

where:

$R_{j\text{-}a}$ – thermal resistance between the junction of the LED module and the environment;

T_j – junction temperature;

T_a – the ambient temperature;

P_{th} – thermal power dissipated by the LED module, which is calculated according to (1).

The third stage includes the study of temperature distribution in the LED structure at different arrangements of LED chips in the array. Simulations are made for three LED structures with 9 LED chips. The study aims to determine which type of construction offers better heat dissipation from the structure. Accordingly, to determine which design structure is optimal in terms of thermal efficiency.

3. Thermal Simulations

The thermal simulation results for different constructions of COB LED modules for studying the effects of the chip to chip distance at the maximum dissipated thermal power P_{th} = 8.45W are shown in Fig. 4a, b, c and d.

The simulations are carried out at ambient temperature of 25^0C.

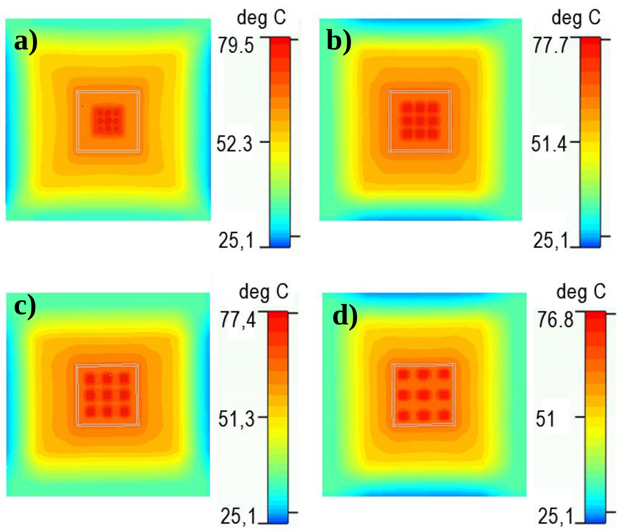

Fig. 4. Thermal distribution at P_{th} = 8.45W in COB structures at a) distance of 1mm, b) distance of 2mm, c) distance of 3mm and d) distance of 4mm between chips

Table 2 gives the junction temperature T_j of LED chips in different structures of the studied area in simulations.

Table 2. Junction temperature, T_j of chips in different structures at P_{th} = 8.45W

Distance	T_1 [^{0}C]	T_2 [^{0}C]	T_3 [^{0}C]	T_4 [^{0}C]
1mm	78,9	79,5	78,3	78,8
2mm	77,2	77,7	76,9	77,4
3mm	77,2	77,4	77,1	77,2
4mm	76,7	76,8	76,7	76,7

Table 3 presents results of the simulations of various structures at thermal power dissipation P_{th} = 7.71W.

The results of thermal simulations clearly show that with increasing of the distance, the temperature of the LED chips in the COB structure starts to decrease. Temperature gradient between the structure with distance 1mm and the structure with distance 4mm for the chip T2 in the centre of the structure is 2.5^0C at P_{th} = 8.45W.

Although the LEDs are arranged symmetrically relative to the chip T_2 and are at one and the same distance, their temperatures are different.

Table 3. Junction temperature, T_j of chips in different structures at P_{th} = 7.71W

Distance	T_1 [^{0}C]	T_2 [^{0}C]	T_3 [^{0}C]	T_4 [^{0}C]
1mm	75,5	76,1	74,9	75,4
2mm	73,9	74,4	73,7	74,1
3mm	73,9	74,1	73,8	74
4mm	73,5	73,6	73,5	73,6

By increasing the distance between the chips it is observed significant decrease of the temperatures between chips. Most preferably, this can be seen in the structure with a distance of 4mm, in this case the temperature gradient is only $0,1^0$C. This effect is explained by better heat dissipation due to reduced heat influence between chips in the structure.

Similar results are observed in the simulations with less heat output.

Fig. 5a, b and c show the thermal behaviours of the structure with chip to chip distance 3mm (at P_{th} = 8.45W) at ambient temperatures T_a = 25^0C, 30^0C and 35^0C.

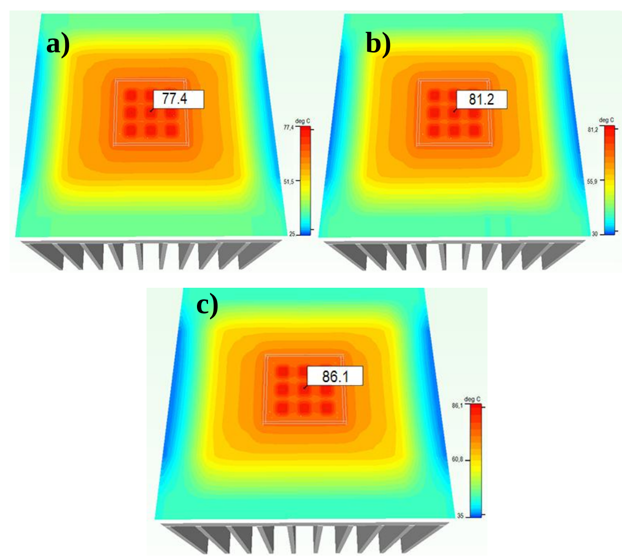

Fig. 5. T_j of LED in the centre of the structure at a) T_a = 25^0C, b) T_a = 30^0C, c) T_a = 35^0C

The results of these thermal simulations show that the temperature of the structure increases substantially with increasing of T_a.

However, T_j of the chip T_2 in the centre with the highest temperature remains well below critical for most LED modules transition temperature of 120 - 130^0C. This shows that this construction has a very good thermal management and can operate reliably and stably, even in much higher ambient temperatures.

Fig. 6a and 6b show the thermal behaviour of structures with ceramic substrates from Alumina (Typical) and AlN at distances between chips of 2mm and P_{th} = 7.71W. The simulations are made for T_a = 25^0C.

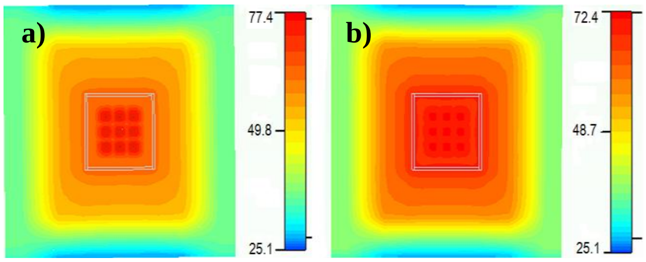

Fig. 6. Heat distribution in structures with substrates from a) Alumina (λ = 16W/m·K), b) AlN (λ = 170 W/m·K)

Table 4. Junction temperature, T_j of chips in different structures at P_{th} = 7.71W

Substrate	Distance	T_j [^{0}C]	R_{j-a} [^{0}C/W]
Alumina (Typical)	1mm	76,1	6.62
	2mm	74,4	6.40
	3mm	74,1	6.36
	4mm	73,6	6.30
Alumina (94%)	1mm	75,9	6.60
	2mm	74,2	6,38
	3mm	73,9	6,34
	4mm	73,4	6,27
Alumina (96%)	1mm	75,3	6,52
	2mm	73,7	6,31
	3mm	73,5	6,29
	4mm	73	6,22
AlN	1mm	73,6	6,30
	2mm	72,4	6,14
	3mm	72,3	6,13
	4mm	71,9	6,08

Table 4 shows the results for T_j of structures with various substrates and the calculated R_{j-a} for each construction.

The results show that the material of the substrate has a significant influence on the heat transfer processes. As expected, the substrate from AlN with λ = 170 W/m·K indicates the lowest temperature of the chip T2, in all cases studied, because to very good heat dissipation.

The results for R_{j-a} of all designs show that the lowest R_{j-a} is the design from AlN (R_{j-a} = 6.08^{0}C/W) with chip to chip distance 4mm.

Simulations showing the thermal efficiency of different designs with regard to the arrangement of the LED chips are shown in Fig. 7a, b and c. These simulations are made at P_{th} = 6.9W and T_a = 25^0C.

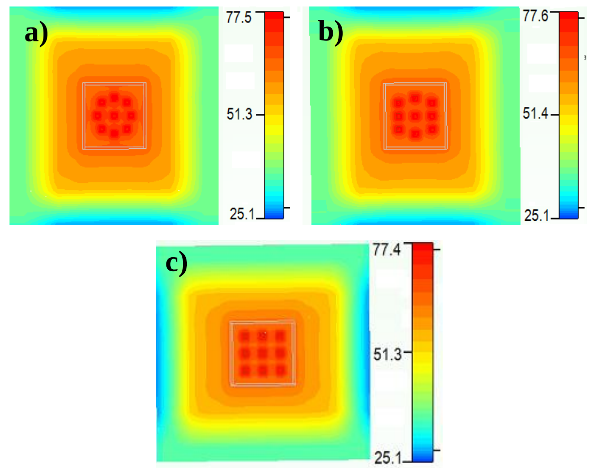

Fig. 7. Temperature distribution in structures with different arrangement of chips

Simulations show that the square array of Fig. 7c has a very good heat distribution and the lowest temperature is 77.4^{0}C. The highest temperature is 77.6^{0}C for the design of fig.7b.

4. Verification of the Thermal Simulation Results

For verification of the results of thermal simulations infrared (IR) thermography is used. IR thermography is widely used in thermal analysis of electronic equipment [11].

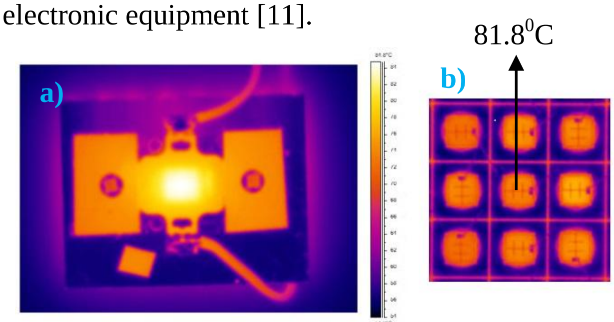

Fig. 8. IR thermographic image a) COB LED module seen from above, b) the temperature distribution of the chip level

Fig. 8a shows the studied structure of COB LED module with chip to chip distance of 1mm subjected to IR thermographic study.

Fig. 8b shows the temperature distribution in the chip construction and the temperature of the chip in the centre of the structure is marked ($T_j = 81.8^0$C).

The results of IR thermography and those obtained by thermal simulation for design with 1mm distance between chips (temperature of the chip in the centre $T_j = 79.5^0$C), show good matching computer modelling model with real physics experiment.

5. CONCLUSION

The study shows that the location and distance of LED chips has a significant importance in the design of LED arrays. The optimal structure is that with a distance between chips 3mm. That is because this structure provides a possibility to establish a sufficiently tight packaging with good thermal performance over a wide range of ambient temperatures.

With respect to the used substrate, the results indicate that the optimal substrate is Alumina (96%). It has high thermal conductivity and offers low thermal resistance close to that of AlN.

Research on the location of the LEDs in the array shows that the optimal distribution of heat in the structure offers the square array.

Acknowledgement

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