Materials Physics and Mechanics 21 (2014) 283-287 Received: October 28, 2014

THERMAL ANALYSIS OF PHOSPHOR CONTAINING SILICONE LAYER IN HIGH POWER LEDs

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Abstract. Efficacy of high power light emitting diodes (LEDs) strongly depends on their thermal management. Heat generated due to non-radiative recombination of carriers in LED active region and due to Stokes losses in phosphor material leads to temperature rise in the device interior and in the phosphor containing silicone layer (PCSL). High temperature in the PCSL influences its thermal quenching behavior and changes luminescence decay time. To achieve high LED efficacy, proper thermal control of PCSL is of the great importance. In this study, we build a thermal model of the LED with PCSL and perform numerical simulations to analyze the heat distribution in the layer. Numerical analysis shows that temperature of PCSL can reach 85 °C and more. At least 30 % temperature drop is demonstrated due to the thickness variation of silicone layer.

1. Introduction

White light in LEDs can be created by using blue light solid-state emitters and yellow downconverting phosphors [1]. Phosphor particles use the exciting blue light to convert a part of it into the radiation with the wavelength corresponding to yellow light. Then both lights are mixed together to produce a white light with various color temperature. During LED device operation, temperatures near pumping blue chips can reach 150 °C [2]. In addition, there is always optical energy loss in PCSL connected to wavelength transformation (Stokes shift) and non-radiative decay, and the lost energy converts into heat [3]. All of above listed effects contribute to local temperature rise in the PCSL and can lead to such disadvantages as the shift of spectrum peaks, luminous efficacy drop, changes in color and device lifetime decreasing [4, 5]. In conventional LEDs phosphor particles are placed in a silicone gel matrix with low thermal conductivity (about 0.2 W/(m·K)**)** [6]. This is the main obstacle for effective heat dissipation from phosphor particles to the cooling system through aluminum and ceramic substrates. Phosphor self-heating phenomenon caused by low thermal conductivity of silicone encapsulant and heat generation result in the reduction of LED light output. Thermal quenching and thermally activated concentration quenching phenomena in YAG:Ce+3 phosphors are observed at temperatures near 100 °C. [7, 8] The temperature that induces the decreasing of internal quantum efficiency of the chips is higher than phosphor thermal quenching temperature [9]. Therefore, to maximize overall efficacy of the device, PCSL needs proper thermal management at the first. In this connection, LED design based on thinner PCSL is expected to reduce temperature of PSCL and to enhance the efficacy of the device [10].

The main goal of the present study is to investigate thermal behavior of thin PCSL and to describe the influence of layer thickness on local temperatures in PCSL. Numerical simulations are based on finite volume method and are verified by thermal experiments.

2. Model description

One of the most useful implementation of LED design is so-called chip-on-board (COB) configuration, for which an array of LED chips is covered with a single PCSL [11]. Model used in numerical simulations is based on commercial construction of the COB module, namely Optogan X10 [12]. Such COB contains nine blue LED chips mounted on the square ceramic substrate (9.8 × 9.8 mm). Operating current is 1 A and voltage is 10 V. Optogan X10 PCSL represents a mixture of silicone and uniformly distributed YAG:Ce+3 phosphor particles fully coating the chips. The LED module is set on the aluminum substrate, which provides uniform heat dissipation throughout thermal contact between LED module and cooling system.

Geometry of the model used in our analysis is shown in Fig. 1. It is important that the geometry of the model includes PCSL with a variable thickness. Height of PCSL in first numerical iteration is chosen to be equal to 0.5 mm. For further optimization calculations we consider thinner PCSLs with low boundary at 0.05 mm. COB is disposed on aluminum base that simulates the operation of the radiator (provides uniform heat transfer across contact area of LED module). Contact area between aluminum substrate and LED module is filled with thermal grease. LED chips are mounted on ceramic substrate by thermal glue; electrical contacts are made of silver. Thicknesses and thermal conductivities of layers comprising the device structure were taken from technical data of the LED module [12] and are given in Table 1.

Table 1. Properties of the LED module layers.

Material	Thermal conductivity λ, W/(m·K)	Thicknesses of layers, mm
Phosphor particles	12	
Encapsulating gel	0.2	0.5
Silver	429	0.04
Ceramics (Al_2O_3)	19	0.63
Sapphire (chips)	23	0.15
Thermal grease	3	0.1
Thermal glue	5	0.02
Aluminum	160	20

3. Numerical simulation

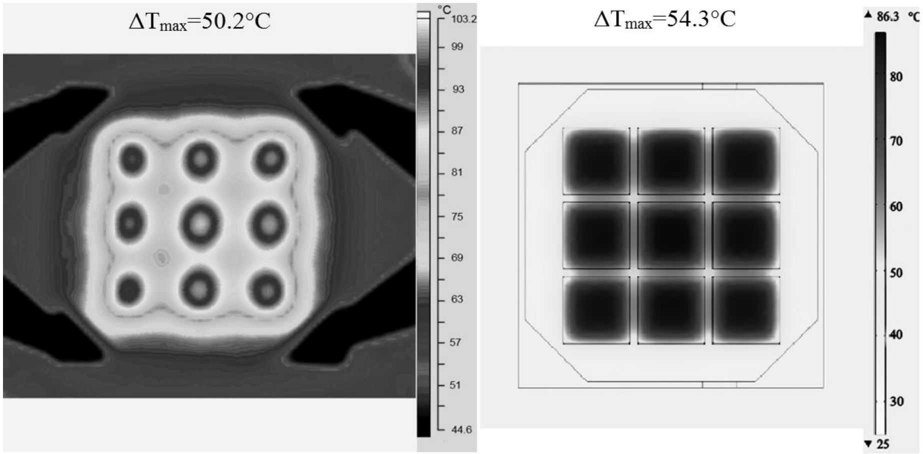
We conducted the numerical analysis of the heat transfer in the COB with finite volume simulation method by utilizing COMSOL Multiphysics software. Fourier’s equation of heat transfer

$$C_p \rho \frac{\partial T}{\partial t} = \lambda \nabla^2 T + q\,, \tag{1}$$

was solved numerically for each layer with corresponding material properties: heat capacity C_p, material density ρ, temperature T, thermal conductivity λ, and specific heat generation q.

Boundary conditions were set as heat generation power for every single chip and bulk volumes in PCSL. These values were evaluated from the experiments with coated and uncoated COB modules [12]. Heat generation powers in the active region and in PCSL were found to be equal 6 W and 1 W, respectively.

the chart in Fig. 4. As a result of parametric simulation, we predict the drop of $\Delta T_{\max}$ about 50 % with PCSL thickness change from 0.5 mm to 0.1 mm. Further reduction of PCSL thickness doesn't make sense, because the effect of thermally activated concentration quenching becomes very strong [8].



(a) (b)

Fig. 3. Temperature field on the surface of PCSL obtained in the experiment (a) and in the simulation (b)

6. Conclusions

Conducted numerical simulations are in a good correlation with available experiments. The obtained results allow us to make the following conclusions:

1. Local high temperature in PCSLs is caused by low thermal conductivity of silicone encapsulant. Volumetric heat generation due to Stokes shift and luminescence decay leads to phosphor self-heating and thermal quenching phenomena.
2. Thin PCSLs with thickness about 0.1 mm prevents local overheating. This effect is determined by decreasing of the thermal resistance between hot spots and ceramic substrate and higher heat transfer coefficient.

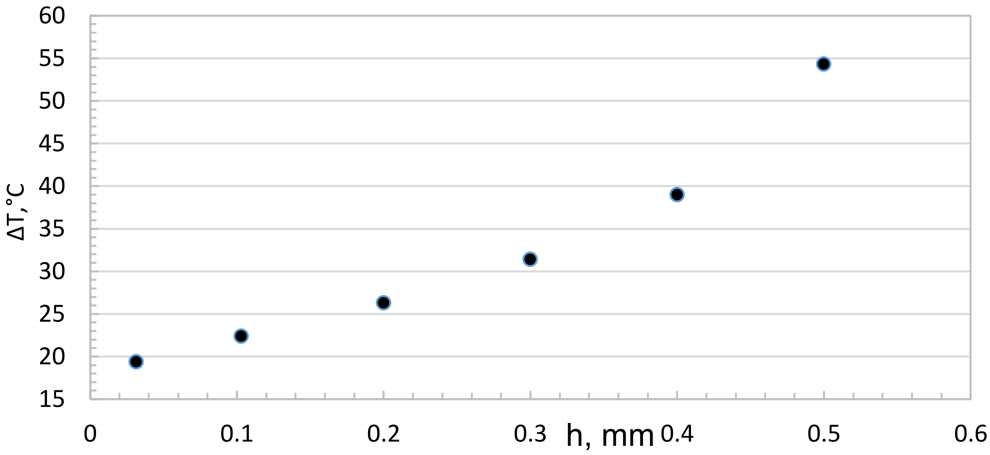


Fig. 4. Dependence of temperature difference between PCSL and radiator of the PCSL height.

Acknowledgement

The authors would like to acknowledge the support from International Research Laboratory program at ITMO University.

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