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Arithmetic and experimental approach to effect of visible light absorption on silicone plate in high-power LED module

Jung Hwa Jung, Hyun Jae Kim *

The School of Electrical and Electronic Engineering, Yonsei University, Seoul, Republic of Korea

A R T I C L E I N F O

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A B S T R A C T

In a light emitting diodes (LEDs), the effect of visible light absorption on silicone encapsulant temperature has largely been overlooked by the scientific community. In this paper, we develop a new optical energy model to calculate the absorption power of a silicone plate in a remote phosphor LED module. In addition, we introduce a unique experiment for visible light absorption. Three types of silicone plate are investigated – a transparent silicone plate in a blue LED and two phosphor-mixed silicone plates (YAG:Ge, yellow phosphor) in white LEDs. We discover that by mixing phosphor with transparent silicone, the absorption coefficient is increased to 2.5 times in the case of 3 wt% phosphor-mixed silicone, and 5.9 times in the case of 30 wt% phosphor-mixed silicone compare with transparent silicone plate. Moreover, we find that visible light absorption only is able to increase silicone plate temperature by 7.3 °C in the case of transparent silicone, 18.7 °C in the case of 3 wt% phosphor-mixed silicone, and 43.3 °C in the case of 30 wt% phosphor-mixed silicone.

1. Introduction

LIGHT-EMITTING DIODES (LEDs) have the following remarkable characteristics: high luminous efficiency, long lifetime, superior light quality, and eco-friendliness. Over the years, the application fields for LEDs have been extensively broadened, from backlit units to automobiles, camera flashes, general lightings, and bio applications such as medical treatment, plant growth, and bio lighting. LEDs continue to fascinate as researchers find new potential in them for applications such as UV LEDs, QD-LEDs, micro-LEDs, visible light communication, and smart grids.

For the last ten years, many LED manufacturers and researchers have aggressively pursued improving internal quantum efficiency, extraction efficiency, luminous efficacy, and package efficiency. In particular, they have focused on reducing LED-chip junction temperature because of its significant influence on LED efficiency, reliability, and various optical characteristics. Through these efforts, the useful method for measurement of LED-chip junction temperature of GaN-based LEDs [1] and new LED-chip structures for high heat dissipation, such as metal-based vertical chip and flip chip with epi-down bonding. In addition, they have been able to apply a variety of technologies for lowering LED-chip junction temperature at the package and system levels [2,3]. New packaging materials such as the interfacial materials, phosphors, optical components and heat spreaders have been introduced to improve the thermal and fluid flow properties of LED packages [4]. Over the past few years, however, they have come to consider silicone encapsulant temperature as important as LED-chip junction temperature, due to its exceedingly high optical density; this is particularly so in the development of chip scale packages (CSPs) with high power operations (approximately 5 W) and chip on boards (COBs) with ultra-high power operations (approximately 100 W).

In the case of LED packages of high optical density, such as CSPs or COBs, silicone encapsulant temperature can be much higher than LED-chip junction temperature [2,5–8]; a deterioration of a silicone plate within an LED can cause serious reliability problems; for example, wire opening, sharp decline of brightness or color, and temperature change. The possible causes of a rise in silicone encapsulant temperature are as follows:

LED-chip heat: the silicone temperature is affected by the heat from the LED-chip. Therefore, many groups have suggested the remote phosphor LED module in which the phosphor-mixed silicone as far away as possible from the first heat source (the LED chip). Moon and others [9] compared a remote phosphor scheme and on-chip phosphor by simulation and experiment. They found that the remote phosphor scheme showed improved optical and thermal characteristics compared with the on-chip phosphor.

Phosphor-conversion-loss heat: in the case of a phosphor-converted LED (pcLED), phosphor particles absorb a fraction of blue light, and then converted to longer wavelength. During the color

* Corresponding author at: Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea.

E-mail address: hjk3@yonsei.ac.kr (H.J. Kim).

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conversion process, energy losses occur; any lost optical energy is transformed into heat energy. Hwang and others [2] found that heat generation from phosphor conversion loss is one of the reasons of LED degradation through experiments and simulation. Based on the Kubelka-Munk theory, Luo et al. [10] developed a heat generation model to predict the heat generation of the phosphor by concentration and thickness of the phosphor and Hu et al. [11] calculated the light extraction efficiency and the light loss, and found that the phosphor sedimentation structure increases the light loss due to the absorption of the LED chips and substrates.

Visible light absorption with regard to the silicone in an LED [12]: thus far, little attention has been paid to this, because it is perceived to be a minor contributory factor due to a low rate of visible light absorption for silicone material. Furthermore, it is difficult to quantify the effects of visible light absorption. In [13], the effect of visible light absorption on silicone layer is ignored. But, Ed Rodriquez found that high-emissivity material, which is absorbing of the 450 nm of visible light, can be manifested as infrared radiation (IR) heat. The temperature of water was increased and a piece of paper began to smoke and burn in less than a few seconds by the heat due to visible light absorption [14].

Clearly, heat generated through visible light absorption with regard to the silicone plate in an LED cannot be ignored any longer.

In this paper, we developed a new optical energy model to calculate the absorption power of a silicone plate in a GaN-based LED chip. Three types of silicone plate were investigated – a transparent silicone plate in a blue LED and two phosphor-mixed silicone plates (YAG:Ce, yellow phosphor) in white LEDs. We predicted increments in silicone plate temperature by visible light absorption only using a unique method and interrelation between the model and the method.

2. Modeling development

Fig. 1 shows the basic physical phenomena for reception of radiant energy when light is incident on a plane plate and is the basis of optical energy model to be discussed later. Radiant energy impinging on the surface of a plane plate is either transmitted, absorbed, or reflected. The sum of these powers is equal to the initial incident power and energy conservation is maintained [15].

2.1. Transparent silicone plate

Fig. 2 shows the schematic design of the blue LED containing a transparent silicone plate (hereafter referred to as the "TSP case"). The absorption and reflection rates of the transparent silicone plate are denoted by a_1 and r_1, respectively, and the absorption rate of the materials from which the package is constructed (that is, "the package materials") is denoted by a_2. In the TSP case, the initial radiant power, E_{B_int}, is given by

$$E_{B\_int} = E_{B\_out} + E_{B\_si\_ab} + E_{B\_si\_r}, \tag{1}$$

where E_{B_out}, $E_{B\_si\_ab}$, and $E_{B\_si\_r}$ denote the output (transmitted) radiant power, absorbed radiant power, and reflected radiant power, respectively.

Any radiant power reflected from the bottom surface of the transparent silicone plate travels toward the package, whereby upon contact with the package, it is either absorbed or reflected by the package materials. Thus, radiant power is continuously being either absorbed or reflected in the case of both the transparent silicone plate and the package materials.

In the TSP case, the amount of radiant power absorbed, $E_{B\_si\_ab}$, is given by

$$E_{B\_si\_ab} = [E_{B\_si\_ab}]_{n=1} + [E_{B\_si\_ab}]_{n=2} + \cdots + [E_{B\_si\_ab}]_{n=\infty}, \tag{2}$$

where n denotes the round of absorption (of radiant power by the transparent silicone plate). The amount of radiant power absorbed by the transparent silicone plate in the initial round of absorption is given by

$$[E_{B\_si\_ab}]_{n=1} = a_1(E_{B\_int} - E_{B\_si\_r}) = a_1(1 - r_1)E_{B\_int}. \tag{3}$$

The amount of radiant power reflected from the bottom surface of the transparent silicone plate and from the package materials is given, respectively, by

$$E_{B\_si\_r} = r_1 E_{B\_int} \tag{4}$$

and

$$E_{B\_pkg\_r} = r_1(1 - a_2)E_{B\_int} \tag{5}$$

Therefore, the amount of radiant power absorbed by the transparent silicone plate in the second round of absorption is given by

$$[E_{B\_si\_ab}]_{n=2} = a_1 r_1 (1 - a_2)E_{B\_int} \tag{6}$$

From the initial reflection – of radiant power from the bottom surface of the transparent silicone plate – onwards, there was a sharp decrease in the amount of radiant power reflected from the bottom surface of the transparent silicone plate. Similarly, there was a rapid decline in the amount of radiant power absorbed by the transparent silicone plate from the second round of absorption – of radiant power by the transparent silicone plate – onwards (see Fig. 3). Thus, in our model for the TSP case, we considered only

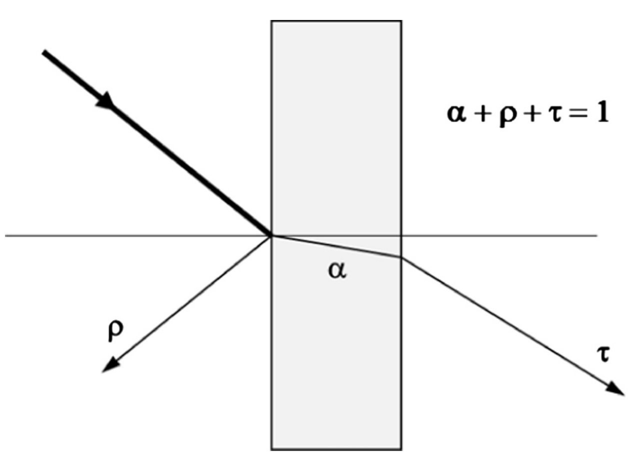

Fig. 1. Transmittance, τ, absorptance, α, and reflectance, ρ.

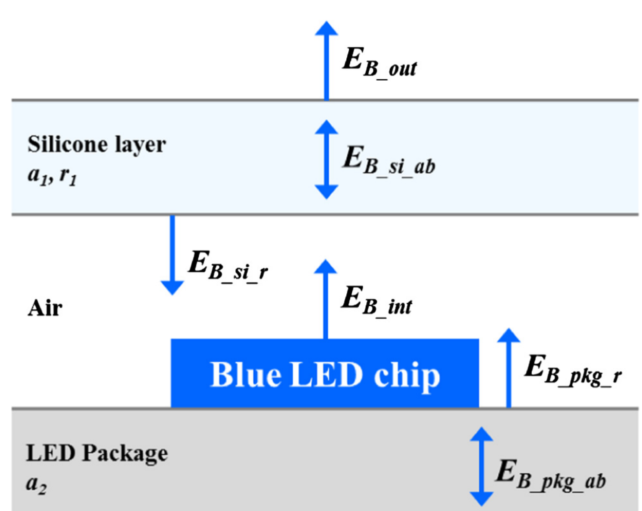

Fig. 2. Optical energy transfer in LED schematic plot with transparent silicone plate.