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Research paper

Effective heat dissipation and geometric optimization in an LED module with aluminum nitride (AlN) insulation plate

Min Woo Jeong, Seung Won Jeon, Sang Hun Lee, Yongchan Kim*

Department of Mechanical Engineering, Korea University, Anam-Dong, Sungbuk-Ku, Seoul 136-713, Republic of Korea

HIGHLIGHTS

- An enhanced model is proposed in LED module to achieve effective heat dissipation.
- The enhanced model uses AlN insulation plate instead of dielectric layer.
- The geometric configuration is optimized by using response surface methodology.
- The effects of design parameters on the thermal resistance are investigated.
- The enhanced model represents effective heat dissipation and electrical insulation.

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ABSTRACT

The heat dissipation performance in a conventional chip on board (COB) LED module is limited by the very low thermal conductivity of the dielectric layer. In this study, an enhanced model is proposed to achieve effective heat dissipation using an aluminum nitride (AlN) insulation plate instead of the dielectric layer. Initially, the geometric configuration of the enhanced model was optimized by using response surface methodology. The effects of each design parameter were also analyzed in terms of the one-dimensional and spreading thermal resistances. In the optimized enhanced model, the junction temperature and total thermal resistance were 24.1% and 55.2% lower, respectively, than the conventional COB module with the copper-based substrate. At the heat input of 15 W, the luminous efficacy of the optimized enhanced model was about 13.9% higher than that of the conventional COB module.

1. Introduction

Light emitting diodes (LEDs) have been used in various fields, such as indoor/outdoor lamps, backlight units of display devices, fishery lights, and automotive headlamps, because of their high energy efficiency, long life, and eco-friendliness [1–3]. In addition, the LED has mechanical stability and durability due to its simple structure. Recently, chip on board (COB) technique has been widely used in an LED module to increase mounting density and light output [4,5]. In the LED, only about 20% of the input energy converts to light energy, and the remaining 80% converts to thermal energy [6]. Heat generation increases with increasing power input and light output, resulting in an increase in local temperature (viz. a hot spot). Hot spot formation in the LED tends to decrease life-time and reliability. However, one of the most important issues is the degradation of the light output and luminous efficacy. The light output decreases with increasing the local temperature of an LED module at the same power input. Therefore, thermal design, which dissipates the heat generated in the LED chip through a heat spreader, is a very important issue in the LED module.

LED chips can be classified into vertical and lateral types based on the arrangement of electrodes [7–9]. Initially, the lateral LED chip was widely used. However, with the advancement in LED technology, the vertical LED chip has been extensively used because of its higher operation current and light output [7–9]. The lateral LED chip contains dielectric material, such as sapphire substrate, at the bottom of the chip; but the vertical LED chip necessarily requires a dielectric layer to electrically insulate between the LED chip and metal heat spreader. An LED module with the vertical LED chip shows very high thermal resistance because the thermal conductivities of commonly used dielectric layers are approximately 0.3–3 W m^{-1} K^{-1} [10–12]. Therefore, it is necessary to enhance the thermal performance of the dielectric layer to achieve effective heat dissipation in an LED module.

* Corresponding author. Tel.: +82 2 3290 3366; fax: +82 2 921 5439.
E-mail address: yongckim@korea.ac.kr (Y. Kim).

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Nomenclature

A	cross-sectional area (m^2)
E	luminous efficacy (lm W^{-1})
E_0	rated efficacy at the rated temperature (lm W^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
k_e	relative reduction rate with increasing temperature (–)
l	thickness of conduction material (m)
P_h	heat input (W)
R_{1D}	one-dimensional thermal resistance (K W^{-1})
R^2_{adj}	adjusted coefficient of determination (–)
R_{sp}	spreading thermal resistance (K W^{-1})
R_{sp1}	spreading thermal resistance between chip and AlN insulation plate (K W^{-1})
R_{sp2}	spreading thermal resistance between AlN insulation plate and base plate (K W^{-1})
R_{tot}	total thermal resistance from junction to substrate (K W^{-1})
T	temperature (°C)
T_0	rated temperature (°C)
T_j	junction temperature, maximum temperature in the LED chip (°C)
$T_{j,avg}$	average junction temperature (°C)
$\overline{T}_{cb}$	mean surface temperature of contacting plane at base plate (°C)
$\overline{T}_{cs}$	mean surface temperature of contacting plane at source (°C)
$\overline{T}_{sb}$	mean temperature of substrate bottom surface (°C)
X_1	width of AlN insulation plate (mm)
X_2	thickness of AlN insulation plate (mm)
X_3	thickness of base plate (mm)
Y	thermal resistance from junction to substrate (K W^{-1})
Z^*	dimensionless thickness from chip to bottom of substrate (–)
Greek symbols	
β	coefficients of the second-order response surface model

There are several studies to make direct contact between the LED chip and heat spreader [13–17] by eliminating the dielectric layer. Juntunen et al. [10,18] proposed the insertion of a copper thermal via in the dielectric layer, which reduced the thermal resistance by approximately 55%. However, these methods are suitable only for an LED module with a lateral chip. Since it is impossible to make direct contact between the LED chip and heat spreader in a vertical chip, alumina film and diamond-like film were used as dielectric layers [19,20] to reduce the thermal resistance of an LED module with the vertical chip. However, the alumina film dielectric layer can only be applied with an aluminum heat spreader. In addition, the diamond-like film dielectric layer has problems, such as high price and delamination. Recently, aluminum nitride (AlN) has been used in an LED module because of its high thermal conductivity (about 170 W m^{-1} K^{-1}) and electric insulation [21–23]. The AlN heat spreader does not require a dielectric layer, resulting in lower thermal resistance. However, it should be noted that the AlN heat spreader is expensive and brittle to be used as a large heat spreader [4,15,23].

An AlN insulation plate, which has higher thermal conductivity than the dielectric layer, can reduce the cost and risk of brittleness, compared with the AlN heat spreader. However, studies on the effects of geometric parameters on the heat dissipation performance of an LED module with the AlN insulation plate are very limited. In this study, an AlN insulation plate was applied between the LED chip and heat spreader to overcome the disadvantages of the AlN heat spreader. Initially, the configuration of the AlN insulation plate was optimized using response surface methodology. The effects of the design parameters on the heat dissipation were also investigated. The heat dissipation performance of an LED module using the optimal AlN insulation plate was compared with that using the AlN heat spreader and dielectric layer. In addition, the luminous efficacy in LED chips using an AlN insulation plate was compared with those using AlN- and copper-based substrates.

2. Experimental apparatus and numerical method

2.1. LED models

In an LED module, a chip is bonded on an electric circuit by die-attach, and the electric circuit is positioned on a substrate (also called board). The substrate not only supports components, but also functions as a heat spreader. A conventional metal core printed circuit board (MCPCB) consists of a dielectric layer and metal base plate. In this study, an enhanced model was proposed to improve the heat transfer performance by substituting an AlN insulation plate for the dielectric layer. The heat dissipation performance of the enhanced model was compared with those of the AlN- and copper-based substrates.

Fig. 1 shows the configuration of LED models considered in this study. As shown in Fig. 1(a), the copper-based substrate is the most commonly used substrate in the MCPCB. Copper was used as a heat spreader, and a dielectric layer was coated on the base plate. As shown in Fig. 1(b), the AlN-based substrate does not require a dielectric layer because of the electric insulation of AlN. The

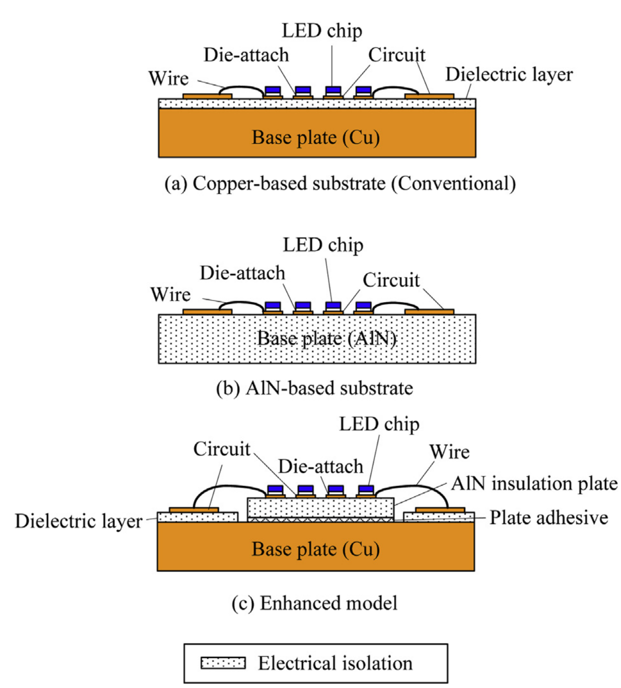

Fig. 1. Configuration of LED models.