Applied Thermal Engineering 122 (2017) 653–660

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Thermal design of rectangular microscale inorganic light-emitting diodes

Yun Cui [a], Yuhang Li [a,b,c,*], Yufeng Xing [a], Qiguang Ji [a], Jizhou Song [b,d,*]

[a] Institute of Solid Mechanics, Beihang University (BUAA), Beijing 100191, China
[b] Key Laboratory of Soft Machines and Smart Devices of Zhejiang Province, Zhejiang University, Hangzhou 310027, China
[c] State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China
[d] Department of Engineering Mechanics, Soft Matter Research Center, Zhejiang University, Hangzhou 310027, China

HIGHLIGHTS

- A 3D analytical model is developed to study the thermal properties of rectangular μ-ILEDs.
- A scaling law for normalized temperature increase of a single μ-ILED is established.
- Thermal properties of rectangular μ-ILED array are investigated.
- Design guidelines for thermal management of μ-ILEDs are provided.

ARTICLE INFO

Article history:
Received 22 September 2016
Revised 15 April 2017
Accepted 5 May 2017
Available online 7 May 2017

Keywords:
Inorganic light-emitting diodes
Thermal design
Microscale
Geometric parameters
Analytical models

ABSTRACT

The recently developed microscale inorganic light-emitting diodes (μ-ILEDs) have attracted much attention due to their potential use in biointegrated applications such as optogenetics. It is critical to understand the thermal properties of μ-ILEDs since excessive heating may reduce the performance significantly. A three-dimensional analytical model based on the Fourier Cosine transform is developed to study the thermal properties of rectangular μ-ILEDs in this paper. The analytical prediction agrees well with finite element analysis. A scaling law for the normalized temperature increase of a single μ-ILED is established in terms of four non-dimensional parameters: the normalized shape factor $\gamma = b/a$, the normalized μ-ILED thickness $\bar{H}_{LED} = H_{LED}/a$, and $\chi_1 = k_m H_m/(k_s a)$ and $\chi_2 = k_s H_B/(k_B a)$, where a and b are the half-lengths of the μ-ILED, k and H are the thermal conductivity and the thickness with the subscripts LED, m, B and s for the μ-ILED, metal layer, encapsulation layer and substrate, respectively. The influences of these non-dimensional parameters on the normalized temperature increase are systematically investigated. The temperature increase for rectangular μ-ILED array is then obtained analytically by the method of superposition. These results provide design guidelines to minimize the adverse thermal response of rectangular μ-ILEDs.

1. Introduction

Microscale inorganic light-emitting diodes (μ-ILEDs) with characteristics in size, efficiency and lifetime enable many novel applications, which are not possible using conventional LEDs, such as stretchable optoelectronics [1–5], optogenetics [6–10] and solid-state lighting.

The recent strategy by Kim et al. [11] to fabricate μ-ILEDs has received much attention. It involves the growth of high quality epitaxial material on sapphire or Si substrates followed by the definition of arrays of individual μ-ILED. Transfer printing is then used to release the completed μ-ILED array from the grown substrate onto other unusual substrates. A photodefinable layer of benzocyclobutene (BCB) encapsulates the μ-ILED array with the p- and n-type ohmic contacts of each μ-ILED exposed for electrical interconnection. A metal layer (e.g., aluminum) is then deposited on the top to serve as interconnects and heat spreader. This strategy is applicable to interconnect multiple μ-ILEDs over a large area to create μ-ILED arrays on unusual substrates. Fig. 1(a) shows the

* Corresponding authors at: Institute of Solid Mechanics, Beihang University (BUAA), Beijing 100191, China (Y. Li) and Key Laboratory of Soft Machines and Smart Devices of Zhejiang Province, Zhejiang University, Hangzhou 310027, China.
E-mail addresses: liyuhang@buaa.edu.cn (Y. Li), jzsong@zju.edu.cn (J. Song).

http://dx.doi.org/10.1016/j.applthermaleng.2017.05.020
1359-4311/© 2017 Elsevier Ltd. All rights reserved.

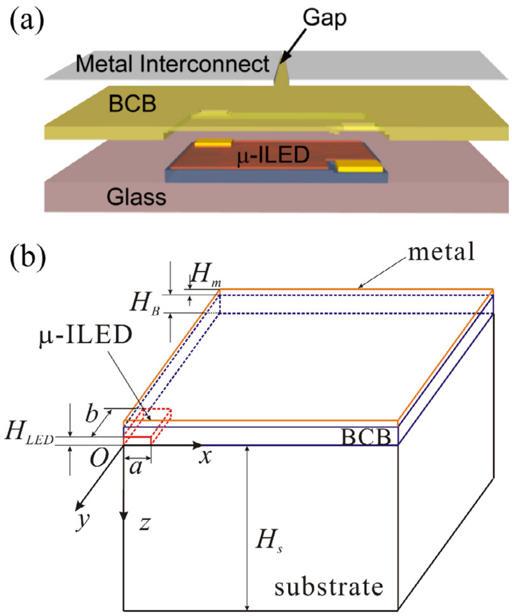

Fig. 1. (a) Schematic diagram of the layout for μ-ILED system; (b) Schematic illustration of the 3D analytical model showing a quarter geometry of the μ-ILED system.

schematic diagram of a single rectangular μ-ILED encapsulated by BCB and metal layers on a glass substrate.

It is critical to understand the thermal properties of μ-ILEDs to avoid excessive heating, which could induce significant reduction in the μ-ILED efficiency. Many researchers have performed thermal analysis of μ-ILEDs. Lü et al. [12] studied the heat conduction of square μ-ILEDs with layouts in Fig. 1a under a constant power analytically. For simplicity, an axisymmetric model, instead of three-dimensional model, is established to capture the square μ-ILED temperature quantitatively. The simple analytic expression for the μ-ILED temperature is very useful in the design optimization of μ-ILEDs to minimize the adverse thermal effects. The operation of μ-ILEDs in a pulsed mode could further reduce the temperature of μ-ILEDs. Kim et al. [13] investigated the thermal properties of square μ-ILEDs on various substrates under a pulsed power experimentally. Li et al. [14] then established an analytic axisymmetric model to explore the dependence of the μ-ILED temperature on the geometric dimensions, material properties and loading parameters. All above studies are for square μ-ILEDs and the analytic models, reviewed in [15], adopted the axisymmetric treatment. Although these axisymmetric models can predict the temperature distributions accurately for square μ-ILEDs, they cannot be applied for rectangular μ-ILEDs, which are more general in practical applications.

Recently, three-dimensional models were established to study the thermal performance of μ-ILEDs. Zhang et al. [16] studied the thermal properties of wirelessly powered μ-ILEDs, demonstrated for potential applications in implantable devices [17], by coupling the one-dimensional heat conduction in the straight inductive coil, and three-dimensional heat conduction in the substrate. Cui et al. [18] presented a three-dimensional analytic model to illustrate the thermal properties of single rectangular μ-ILED under a pulsed power. These studies expand the application scope which is limited by axisymmetric model. However, the thermal behaviors of rectangular μ-ILEDs and rectangular μ-ILED arrays under a constant power are not studied yet, which are important in the application of μ-ILEDs in solid state lighting.

The objective of this study is to develop a rigorous analytical model, validated by finite element analysis, to perform three-dimensional thermal analysis of rectangular μ-ILEDs and provide explicit expressions for μ-ILED temperature increase in terms of geometric, material and loading parameters.

2. Three-dimensional thermal analysis of a single rectangular μ-ILED

We take rectangular μ-ILEDs in experiments [11] with the same layouts in Fig. 1a as an example to illustrate our approach. Due to the symmetry of the system, only a quarter of the system is considered. Fig. 1(b) shows the schematic diagram of the analytical model with the μ-ILED on the glass substrate encapsulated by BCB and metal layers. The thicknesses of metal, BCB and substrate are denoted by H_m, H_B and H_s, respectively. The in-plane dimension of μ-ILED is $2a \times 2b$, and the thickness is H_{LED}. The μ-ILED is modeled as a planar heat source with the input power P at the BCB/substrate interface [12,14]. This treatment enables analytical investigation of thermal properties of μ-ILEDs, which is to be validated by three-dimensional finite element analysis (FEA).

The coordinate system is established with the origin at the center of μ-ILED, x axis along the side a, y axis along the side b, and z axis pointing from the top metal layer to the bottom substrate. The temperature increase $\Delta T = T(x,y,z) - T_0$ from the ambient temperature satisfies the three-dimensional steady-state heat conduction equation

$$\frac{\partial^2 \Delta T}{\partial x^2} + \frac{\partial^2 \Delta T}{\partial y^2} + \frac{\partial^2 \Delta T}{\partial z^2} = 0. \tag{1}$$

The boundary and continuity conditions are given in the following. At the top surface of metal layer [$z = -(H_m + H_B)$], the natural convection condition gives

$$-k_m \frac{\partial \Delta T}{\partial z}\bigg|_{z=-(H_m+H_B)} = -h \cdot \Delta T|_{z=-(H_m+H_B)}, \tag{2}$$

where k_m is the thermal conductivity of metal and h is the coefficient of heat convection. The continuity of temperature and heat flux across the metal/BCB interface ($z = -H_B$) gives

$$\Delta T|_{z=-H_B^+} = \Delta T|_{z=-H_B^-} \text{ and } -k_m \frac{\partial \Delta T}{\partial z}\bigg|_{z=-H_B^+} = -k_B \frac{\partial \Delta T}{\partial z}\bigg|_{z=-H_B^-}, \tag{3}$$

where k_B is the thermal conductivity of BCB. At the BCB/substrate interface ($z = 0$), the temperature is continuous while the heat flux is only continuous outside the μ-ILED and satisfies the heat source condition inside the μ-ILED, which give

$$\Delta T|_{z=0^+} = \Delta T|_{z=0^-} \text{ and } k_B \frac{\partial \Delta T}{\partial z}\bigg|_{z=0^-} - k_s \frac{\partial \Delta T}{\partial z}\bigg|_{z=0^+} = \begin{cases} 0, & (x,y) \notin D \\ \frac{P}{4ab}, & (x,y) \in D \end{cases} \tag{4}$$

where k_s is the thermal conductivity of substrate, D is the inside region of the μ-ILED at the BCB/substrate interface, i.e., $D = \{(x,y), 0 \leqslant x \leqslant a, 0 \leqslant y \leqslant b\}$. The ambient temperature at the bottom surface ($z = H_s$) of substrate gives

$$\Delta T|_{z=H_s} = 0. \tag{5}$$

Through the Fourier Cosine transform along x and y directions,

$$\Delta \hat{T}(\alpha, \beta, z) = \int_0^\infty \int_0^\infty \Delta T(x,y,z) \cos(\alpha x) \cos(\beta y) dx dy, \tag{6}$$

Eqs. (1)–(5) become

$$\frac{\partial^2 \Delta \hat{T}}{\partial z^2} - (\alpha^2 + \beta^2) \Delta \hat{T} = 0, \tag{7}$$

$$-k_m \frac{\partial \Delta \hat{T}}{\partial z}\bigg|_{z=-(H_m+H_B)} = -h \cdot \Delta \hat{T}\Big|_{z=-(H_m+H_B)}, \tag{8}$$