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Experimental identification of LED compact thermal model element values

Marcin Janicki*, Tomasz Torzewicz, Agnieszka Samson, Tomasz Raszkowski, Andrzej Napieralski

Department of Microelectronics and Computer Science, Lodz University of Technology, Wolczanska 221/223, 90-924 Lodz, Poland

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ABSTRACT

This paper discusses, based on a practical example, the problem of power LED thermal modelling. The precise determination of thermal resistance is crucial for accurate computation of junction temperature, which influences both device lifetime and reliability as well as its operating parameters. Here, diode heating curves are recorded at different levels of dissipated power and in various cooling conditions. Moreover, the devices are soldered to the substrate in different ways, what renders possible the determination of their junction-to-case thermal resistances. For each case, an adequate compact thermal model is generated using the Network Identification by Deconvolution method and validated against the measurements.

1. Introduction

The Light Emitting Diodes (LEDs) are the most dynamically developing type of light sources. Owing to their numerous advantages, such as relatively high energy efficiency and long operating life, these devices are commonly used in many indoor and outdoor lighting applications. The most important factor affecting operating and lighting parameters of LED devices is temperature. Thus, in order to ensure the stability of their parameters and improve the reliability of LED light sources, thermal simulations are carried out during their design. The main goal of these simulations is the determination of LED junction temperature [1].

Thermal simulations are typically carried out using the software based on the finite element or volume numerical methods. Unfortunately, these methods require the knowledge of the exact structure geometry and material thermal properties. Furthermore, additional problems pose the complexity of the mesh which might render the simulation time unacceptably long [2].

Thus, an attractive alternative constitute compact thermal models (CTMs) which typically consist of a very limited number of thermal capacitors and resistors, yet they provide acceptable simulation accuracy. Moreover, CTMs disclose no proprietary information and they could be easily employed in some electrical or multidomain simulators for the computation of device operating temperature [3,4].

This paper introduces an alternative methodology for the generation of LED CTMs based on the evaluation of experimental results obtained for a white power LED. The following section presents in detail the device dynamic temperature measurements, which are carried out in various cooling conditions and for different values of dissipated power. Then, the obtained results are processed further providing the information required for the determination of CTM element values. Finally, the LED heating curves are simulated using the generated CTMs and compared with the measured ones.

2. Temperature measurements

The temperature measurements discussed and analysed in this paper were carried out for commercially available XP-G3 white LEDs manufactured by Cree. The device heating curves were recorded with the transient thermal tester T3Ster®, manufactured by Mentor Graphics, in compliance with the methodology outlined in the JESD51-x standards 'Methodology for the Thermal Measurement of Component Packages (Single Semiconductor Devices)' developed by the JEDEC JC-15 Committee.

The investigated LEDs were soldered to the 25 mm × 25 mm × 2 mm Metal Core PCB (MCPCB) made of aluminium alloy. The measurements were taken for diode heating current values ranging from 100 mA to 1000 mA, both with natural convection cooling and forced water cooling on a cold plate. The cold plate temperature values were set to 25 °C, 50 °C and 75 °C.

In order to determine the device junction-to-case thermal resistance R_{jc}, the diodes were soldered to the MCPCB in different ways; first with all its pads properly soldered to the substrate, and then leaving the thermal pad unconnected. Although, this experimental arrangement differs from the one described in the JEDEC standard, where the device is attached either with or without the application of thermal grease [5], the separation points of these heating curves, as demonstrated later on, also can indicate the value of this resistance. Additionally, a

* Corresponding author.
E-mail address: janicki@dmcs.p.lodz.pl (M. Janicki).

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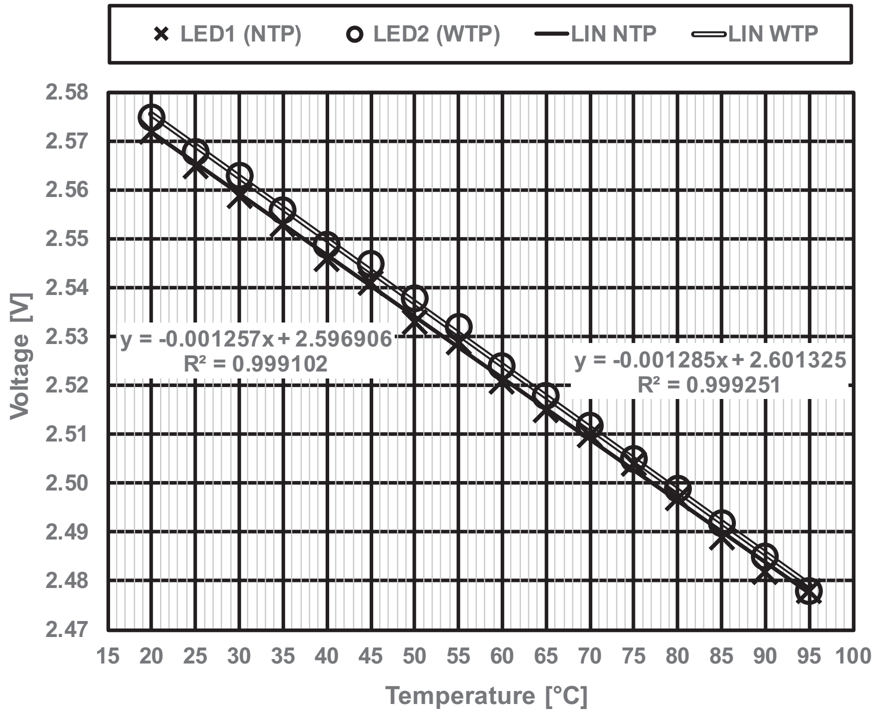

Fig. 1. LED calibration curves.

thermocouple was placed on the MCPCB surface so as to measure its temperature rise value over the ambient.

Before the actual measurements the LEDs were calibrated using a cold plate for the forward current of 5 mA. This value was later used for measurements of junction temperature during the device cooling phase. The measured diode sensitivity, as can be seen in Fig. 1, was −1.29 mV/K with the thermal pad soldered (WTP) and −1.26 mV/K with the unconnected pad (NTP), but this slight difference results rather from the discrepancies between individual devices. Nevertheless, both these values are very close to the one of −1.30 mV/K provided by the manufacturer in the datasheet.

During the measurements the LEDs were heated with the constant current values until thermal steady states were reached. For the natural convection cooling it required almost half an hour whereas with the forced water cooling it took just a few tens of seconds. Then, the diodes were switched off and their junction temperature values were measured with the forward current value for which the devices had been previously calibrated.

The measurement results obtained for the 700 mA LED heating current are presented in Fig. 2 as the heating curves which were found by subtracting the respective steady state temperature rise values from the measured ones. Moreover, each time the temperature rise values were normalized with respect to the real heating power, computed as described later on in this section. The single lines in the figure represent the curves registered for the cold plate temperature of 25 °C, the double lines for the temperature of 75 °C and the dashed ones for the natural convection cooling. Always the lighter lines show the results for the diode with the unconnected thermal pad, as previously denoted by NTP.

Indeed, as pointed in the figure by the arrow, the heating curves for the device with the unconnected thermal pad diverge already before 100 ms indicating the exact time instants when heat diffuses into the substrate, hence rendering possible the determination of the R_{jc} resistance. Furthermore, the influence of altered cooling conditions becomes visible only after a couple of seconds. The thermal resistance values increase by some 9 K/W due to the unconnected pad and by almost 35 K/W when the device is cooled by natural convection. In turn, the curves obtained for different heating current values and the cold plate temperature of 50 °C are compared in Fig. 3. Here, again the curves registered for the LED with the unconnected pad are represented with lighter lines (NTP). As can be seen, the effects of the unconnected thermal pad are visible at the same time instant as in the previous figure.

Equally important for the proper thermal modelling of LEDs is the determination of the device radiant efficiency. This quantity, expressed in percent, is the ratio of the radiated optical power to the electrical one, calculated as the product of diode current and junction voltage drop. For larger diode currents proportionally less energy is transformed into light and more of it is converted into heat, consequently the LED efficiency decreases [6,7].

This hypothesis was confirmed by additional measurements of the LED optical power, which were carried out in a lightproof box shown in Fig. 4. The dimensions in the figure are expressed in millimetres. During the measurements, the MCPCB with the investigated diode was placed inside the box either tightly squeezed to the cold plate or suspended in the air. The distance of the sensor from the LED, as indicated in the figure, was 17 cm. The final value of the heating power was computed based on the indications of the sensor and the typical spatial distribution of the light provided by the manufacturer.

The measurement showed that the device efficiency, as expected, decreases gradually with the increasing current and at the current of 1000 mA amounts to only 73% of its original value measured for the current of 100 mA. The measured efficiency values were considered then in all thermal analyses presented in the following section for the computation of the LED real heating power.

3. Thermal analyses

More insight into the thermal phenomena provided cumulative structure functions and time constant spectra obtained with the software provided together with the thermal tester and implementing the Network Identification by Deconvolution (NID) thermal analysis method [8]. The curves computed for the earlier discussed cases are presented in Figs. 5–8. The line types and colours are consistent with