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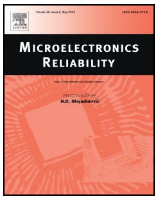

Validation methodology to analyze the temperature-dependent heat path of a 4-chip LED module using a finite volume simulation

Lisa Mitterhuber [a,*], Stefan Defregger [a], René Hammer [a], Julien Magnien [a], Franz Schrank [b], Stefan Hörth [c], Matthias Hutter [d], Elke Kraker [a]

[a] *Materials Center Leoben Forschung GmbH, Roseggerstraße 12, 8700 Leoben, Austria*
[b] *Tridonic Jennersdorf GmbH, Technologiepark 10, 8380 Jennersdorf, Austria*
[c] *Häusermann GmbH, Zitternberg 100, 3571 Gars am Kamp, Austria*
[d] *Fraunhofer-Institut für Zuverlässigkeit und Mikrointegration, Gustav-Meyer-Allee 25, 13355 Berlin, Germany*

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ABSTRACT

Thermal management in the solid-state lighting sector has become a main issue, due to reliability and efficiency issues. Herein, thermal structure function analysis provides a powerful tool to understand the heat transfer inside operated light emitting diode (LED) modules. In this paper a combined approach of simulation and experiment, as a heat path analysis of a LED module based on four flip chip LEDs, is presented. A validated simulation was used to visualize on the one hand the heat path as isothermals and on the other hand to show an alternative approach of the electrical transient correction. In addition to that, the structure function analysis also included the consideration of influence parameters in terms of different operating conditions (e.g. heat sink temperature, heating current, the use of different thermal interface materials between the device and the heatsink). This was investigated by the statistical Design of Experiments (DOE) approach. The DOE dissected the effect of each input variation to different features of the structure functions. An experimental setup showed, that the temperature of the heat sink caused the dominating effect on the thermal properties of the device. Finally numerical simulation confirmed that these effects came from the temperature dependencies of the thermal conductivities.

1. Introduction

The analysis of the thermal properties of an LED module is accompanied by the investigation of the underlying heat transport within the device. The heat produced by the junction of the LED propagates through the module's layers and ends up at the heat sink. In this work this heat transport was investigated with the help of the structure function [1,2,3]. The structure function maps this heat flow path in terms of cumulative thermal capacitances ($C_{th\Sigma}$) with respect to thermal resistances ($R_{th\Sigma}$), starting from heat source to the ambient (see Fig. 1). All essential structural changes in the heat flow path through the LED are reflected by the structure function [4].

One aim of this paper was to understand the measured structure function of a four-chip-LED module. Structure functions were obtained by thermal transient experiments and by finite volume simulations. The correlation between simulated and measured structure functions opened the possibility to assign regions of the function with regions in the module via isothermals. In addition, a simulation in accordance with the measurement, enabled an alternative approach of the electrical transient correction. A further target was the investigation of the thermal behavior of the four-chip module operated by different conditions. Therefore, a set of different operating conditions was systematically varied by means of DOE and its structure functions were evaluated. Although the operating condition should cause no differences in the structure functions under idealistic assumptions [5], a temperature dependence of the experimental structure function was observed. Hence, a finite volume simulation was performed to understand the nature of this temperature-dependence.

2. Theoretical background

The $R_{th}C_{th}$-model, which is provided by the structure function, is assumed to be linear, that means all $R_{th}C_{th}$-elements are considered to be temperature-independent. As shown in [6] the assumption of linearity of the $R_{th}C_{th}$-model should be treated with care, if the device is driven in a broad temperature range. Due to the fact, that the thermal resistance (R_{th}) is not only the change of temperature (ΔT) divided by the heating power (P_H), but also inverse proportional to the thermal conductivity (see Eq. (1)), it can also be considered as a temperature-dependent parameter. The geometry (the thickness Δx and the cross section A of a material) does not influence the non-linearity of the

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[*] Corresponding author.
E-mail address: lisa.mitterhuber@mcl.at (L. Mitterhuber).

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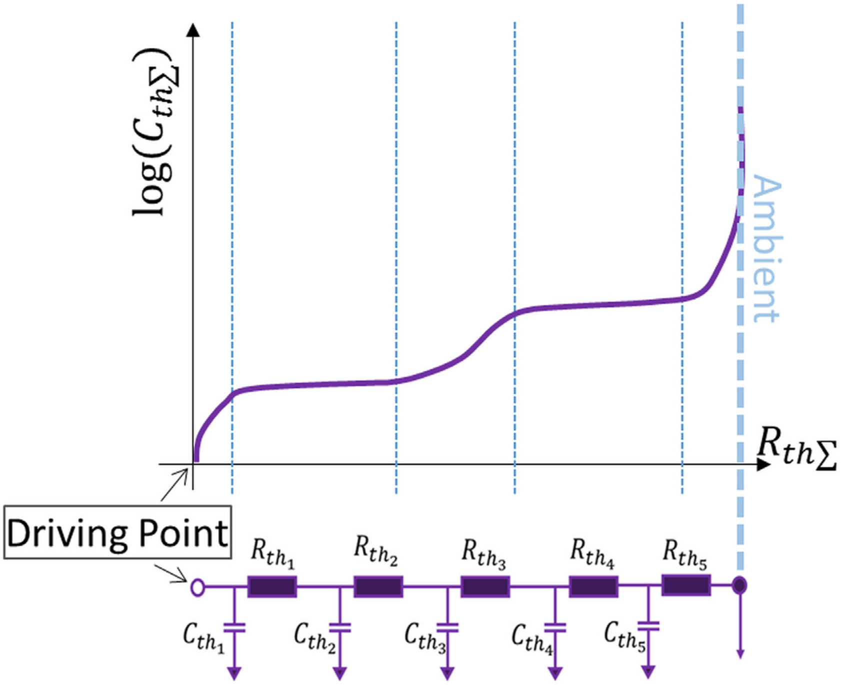

Fig. 1. Schematic of the structure function and its alternative representation as thermal $R_{th}C_{th}$-network. The heat flow starts at the driving point and ends at ambient. Each region (dotted lines) in the structure function is assigned to an $R_{th}C_{th}$-pair.

temperature depended thermal conductivity and thermal expansion can be neglected.

$$\frac{\Delta T}{P_H} = R_{th}(T) = \frac{\Delta x}{\lambda(T)\,A} \tag{1}$$

The most important source of this non-linearity effect is that the thermal conductivity (λ) is temperature- dependent. The temperature dependency can be described by a simple power law, which is valid for the temperature range of 300 K to 800 K [7]:

$$\lambda(T) = \lambda_{300K}\left(\frac{T}{300K}\right)^{-\alpha} \tag{2}$$

The thermal conductivity at 300 K (λ_{300K}) and the exponent α, which is called coefficient of temperature dependency, are material properties. Hence, the equation of the temperature-dependent thermal resistance is:

$$R_{th}(T) = R_{th300K}\left(\frac{T}{300K}\right)^{\alpha} \tag{3}$$

3. Experiment

3.1. Test setup

The investigated device was a blue LED-module consisting of four blue LED flip chips, connected in serial. Therefore, the resulted structure function had to be considered as result of all four diodes.

The device was investigated thermally according to the JEDEC JESD 51-1 standard [8] with the T3ster measurement setup, and optically within an integrating sphere complying the CIE 127-2007 [9]. The LED was measured electrically by the thermal test setup (T3Ster from Mentor Graphics), whose output is the change of diode's forwards voltage V_F as an answer of the current step from forward current I_F to measurement current. The measurement current of all conducted experiments was 10 mA, the I_F was set to 500 mA for the validation process (see Section 4) and afterwards varied according to the DOE design (see Section 5). The V_F is transformed into temperature values of the diode by a calibration procedure applying different heat sink temperatures (see Fig. 2). There was a linear dependency between V_F and heat sink temperature at the measurement current. The dependency gradient (the k-factor) of 0.0049 V/°C is used to calculate the junction temperature from the measured V_F. Hence, the output of the electrical measurement results in a thermal transient, which represents the cooling of device over time. Starting from this thermal transient, the structure function is calculated by the setup's software (T3ster Master) [10]. All further analysis is based on the structure function.

The light output of the LED was recorded, when the module was driven by the I_F at thermal equilibrium according to [9], to obtain the emitted optical power P_{opt}. The calculation of P_H is shown in Eq. (4). The electrical power P_{elec} is the product of the forward voltage V_F and the forward current I_F of the diode.

$$P_H = I_F{}^{*}V_F - P_{opt} = P_{elec} - P_{opt} \tag{4}$$

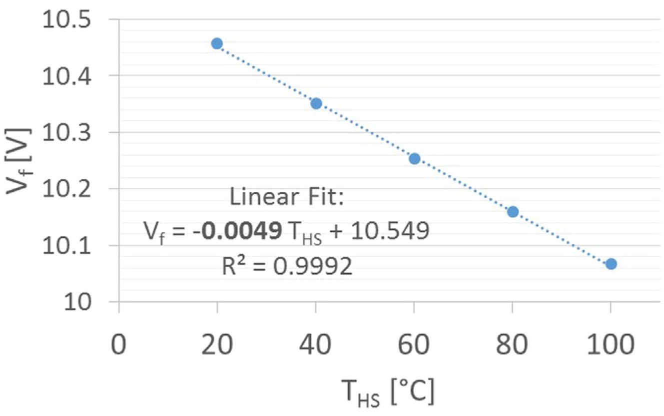

Fig. 2. Measured calibration data to determine the k-factor of the LED's diodes.

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