International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

OP53

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DOI 10.25039/x46.2019.OP53

from

CIE x046:2019

Proceedings
of the
29th CIE SESSION
Washington D.C., USA, June 14 – 22, 2019

(DOI 10.25039/x46.2019)

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MULTI-DOMAIN CHARACTERIZATION OF COB LEDS

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DOI 10.25039/x46.2019.OP53

Abstract

In a recent European H2020 project on LED characterisation and modelling (Delphi4LED, www.delphi4LED.eu) the major target was to represent physical LED package types by their digital twins in form of multi-domain compact models. In this project a specific task was devoted to CoB LEDs. Phosphor converted white CoB LEDs are large area devices on a ceramic substrate of high thermal conductivity, with a few dozens of LED chips mounted, covered by a phosphor layer. Such devices represent real technical challenges both in terms of their physical measurement and modelling. In this paper we report on our work regarding measurement and modelling of such devices performed in the context of the aforementioned project.

Keywords: multi-domain modelling, CoB, LED characterisation

1 Introduction

In this paper a method for creating a multi-domain model of a CoB LED device is presented. Multi-domain modelling of (single die) LED packages / assemblies was suggested already more than a decade ago (Poppe, 2006). Besides our team, other academic groups were also dealing with LED multi-domain modelling: C. Negrea et al (2012) or K. Górecki et al (2014, 2016). Parallel with these groups, our research team followed a long path (Poppe 2013, 2015, 2016) to reach the first industrially relevant approach of chip-level multi-domain modelling of LEDs (Poppe, 2019), aimed at different styles of LED application design flows (Marty 2018, Martin 2019).

In our terminology multi-domain simulation of LEDs means a joint thermal, electrical and optical simulation, providing consistent data regarding the LEDs' electrical operating point, junction temperature and total emitted radiant/luminous flux. The thermal simulation can be properly done with the help of CFD tools (FloEFD) or by Spice-like circuit simulators on package, module or even luminaire level (Poppe 2016, 2017a), using appropriate simulation models. The Delphi4LED modelling methodologies are modular and primarily aim to use so called *compact models*. That is, the multi-domain feature of LED based systems is described by a chip level multi-domain LED model aimed for Spice like circuit simulation, the thermal features of the mechanical structure of an LED package are also represented by a network model (also known as Dynamic Compact Thermal Model or DCTM), compact thermal models of modules and even luminaires are also created and used. These network models are connected through their dedicated nodes. In this modular approach any compact model can be replaced by another model version, allowing the system level designers the flexibility of using compact model libraries to support them find the proper choice of components to meet their design goals (Martin 2019).

There have been many studies published on modelling and simulation of different aspects of CoB (Chip on Board) LEDs. Some are dealing with thermal aspects only such as the paper by Juntunen et al. (2013), but a publication by H. T. Chen et al (2015) describes a real multi-domain simulation approach. In this paper a simple thermal resistance approach is used to represent the chips' thermal environment which, in our opinion is a too simple solution. Unfortunately, CoB LED packages cannot be properly represented by a single thermal resistance or any other compact thermal model used to describe single die LED packages. Therefore, one of the tasks of the Delphi4LED project was to set up methodologies with which the LED chips of a CoB device could still be represented by a multi-domain compact model compatible with the model family developed for the mainstream Delphi4LED design flows (Poppe 2019), but the rest of a CoB device (the substrate and the phosphor layer) are represented by a simulation model of distributed nature with full 3D description.

For CoB LEDs we aimed to maintain the modularity of the models and the option of replacing certain sub-models with another version or allowing extensions, such as adding a heat-sink to the bottom of the CoB substrate, etc. It is important to assure that when some external changes are applied (e.g. the type of the thermal boundary conditions is changed or some other environmental variables are changed), the modelling process of the entire CoB device should not be repeated.

A special challenge was to integrate the multi-domain (compact) model of the blue pump chips into a complex thermal environment represented by a detailed 3D model. Another challenge was to set up the proper multi-physics model of the phosphor layer in which light propagation, absorption, wavelength conversion and heat generation and heat conduction takes place, possibly with considerable temperature dependence. Some of the thermal properties can be inferred from thermal transient measurements, but the measurement of the temperature dependence of the conversion efficiency of the phosphor layer (a composite of the phosphor itself and an organic matrix) is not straightforward.

There are several issues to cover. First, when the properties of CoB LEDs are measured in compliance with the latest available measurement standards and recommendations (such as JEDEC's JESD51-5x series of LED thermal testing standards and CIE's 225:2017 technical report), we obtain the so called *ensemble characteristics of the array of LED chips* within the CoB package[*]. A major question is how these ensemble characteristics (total radiant/luminous flux of the CoB device, overall forward voltage, overall thermal resistance) are related to the characteristics of the individual LED chips.

The multi-domain model must handle the coupling of thermal, electrical and optical properties of the LED chips, the light conversion in the phosphor layer and its heating effect, the non-linear temperature dependence of the optical and electric properties (polynomial fitting to measurement data) and the temperature dependence of the light conversion efficiency of the phosphor.

To reach these goals, the following measurements and simulations are performed: single blue LEDs are measured and simulated to validate the thermal and optical part of the model, custom phosphor converted white LEDs are made to measure the thermal and optical properties of different phosphor layers with known basic properties, the thermal conductivity and temperature dependence of the light conversion efficiency of the phosphor layer is measured and at last a CoB package is measured and simulated to demonstrate the capabilities of our multi-domain model.

2 Methods and results

To establish a modular multi-domain model for CoB LEDs, different measurements are needed for the fitting and validation of the modules of the model. To simplify the measurements and ease the interpretation of the measurement results, we carried testing and modelling of single chip phosphor converted white LED structures. First an MCPCB assembled Cree XP-E2 LED was measured and modelled, then different custom made phosphor samples with some controlled properties were measured, followed by creating, measuring and modelling single chip white LED devices in which some of the properties of the phosphor were known and controlled by us. Finally, with sufficient information on the properties of ceramics substrates and the phosphors, we created a simulation model of a realistic CoB structure. For this model parameters were extracted from measured isothermal IVL characteristics of a Lumileds 1202s CoB LED. The measurements we performed were standard JEDEC JESD51-51/51-52 and CIE 127:2007/225:2017 compliant measurements with

[*] Regarding the definition of 'ensemble characteristics' of arrays of LED junctions refer to the JEDEC JESD 51-51 standard.

protocols defined earlier in the Delphi4LED project, also used for the small round-robin test experiment of the project (Poppe, 2017b) and during regular measurements within the project.

2.1 Single chip characterization

2.1.1 Assumed physical structure of Cree XP-E2

The first stage is to validate the thermal part of the multi-domain model. For that we measured and modelled a single chip LED, a Cree XP-E2. The structure of the LED is estimated with the help of the datasheet and the measured thermal structure functions. The assumed geometry of the LED is shown in Figure 1.

2.1.2 Thermal model of Cree XP-E2

In the past European project called Fast2Light we worked out a method for multi-domain simulation of large area OLEDs (Pohl, 2012, Kohári, 2013). In case of OLEDs both heat conduction, electrical conduction (through the transparent ITO layer) and light generation (in the LEP layer) were of distributed nature. To represent the OLEDs' IVL characteristics measurement data based empirical models were used. The multi-domain system model of the OLEDs was solved with the help of the Finite Volumes Method (FVM). According to this method a 3D network of multi-domain elementary cells was obtained. This network was solved by the Successive Network Reduction (SUNRED) method, and the solution provided voltage, temperature, radiance and luminance maps. In case of OLEDs empirical models of convective heat transfer were added to the boundary cells to properly represent the heat-transfer from such large area devices.

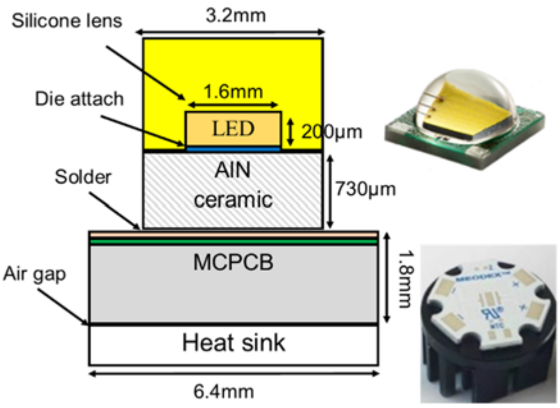

Figure 1 – Estimated, simplified structure of a Cree XP-E2 LED device

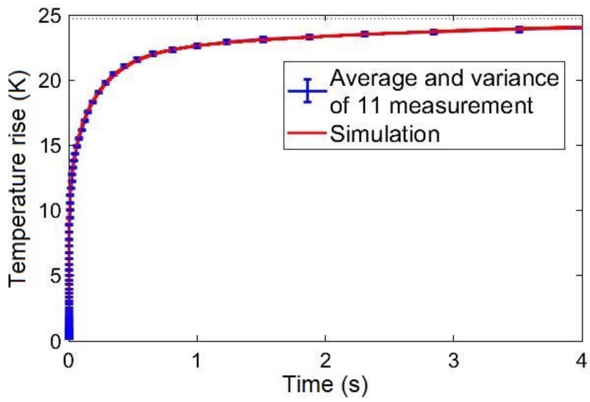

Figure 2 – Temperature transient for Cree XP-E2 single chip LED obtained by measurements and multi-domain simulation

This modelling approach was adapted to (inorganic) LEDs / CoB LEDs. In case of LEDs however, as a first approximation, we can neglect both the radiative and convective heat-transfer from the open surfaces of the package. This results in a purely conductive model that can be efficiently handled by the SUNRED algorithm. This way we built a 3D SUNRED model of a Cree XP-E2 device as shown in Figure 1. (This model can be considered as a single chip CoB device.) With this model junction temperature transients were simulated that could be compared to measured such transients (see Figure 2).

2.1.3 Measurement of Cree XP-E2 LEDs

The XP-E2 devices were measured with the T3Ster measurement instrument combined with the TeraLED optical measurement device from Mentor with a special, dual DUT port 50 cm integrating sphere manufactured by LightingMetrics. The spectral data were captured with an absolute irradiance calibrated CAS-140CT spectroradiometer from Instrument Systems. The measurements were junction temperature controlled as suggested in CIE 225:2017 and were in-line with the JEDEC 51-1 and 51-5x family of standards.

2.1.4 Verifying the thermal model

The thermal part of the multi-domain model is validated through the comparison of the cooling curves as results are available both from modelling and from measurements. The measurement is performed 11 times with different samples of the same type of LEDs. As the model is fairly detailed (10 layers assumed) and the layer parameters are in concordance with the structure functions, we expect excellent agreement. The results from measurements and SUNRED simulation are shown in Figure 2. For demonstration purposes only that case is shown, where the forward current was set to 700 mA. The difference between the simulation and the average of the measurement data is below the variance of the 11 measured LED responses. Therefore, we can state that the thermal part of the model performs well. The next challenge is to model the phosphor layer, and its heat production.

2.2 Phosphor layer characterization and modelling

2.2.1 Fabrication of custom made white LEDs

Custom made phosphor converted white samples were fabricated in order to investigate the thermal and optical performance of the phosphor layer in an LED through isothermal IVL characterisation meeting JEDEC's and CIE's test requirements and recommendations. Exactly the same chip-package-starboard assembly (flip chip power LED from a well-recognised vendor) was used to assure that the only difference between the measurements is caused by the phosphor layer itself. The aim was to convert different amount of photons using the same blue excitation every time. (Chips were measured before and after adding the phosphor layers.)

The original lens was removed and replaced by a custom fabricated clear polydimethylsiloxane PDMS one. The process was repeated 4 times to examine the reproducibility. A complete isothermal IVL characterisation was performed after each deposition. The radiant flux deviation was found to be below 3 % between the individual lenses. The selected blue reference device was within 0.3% of the average characteristics.

Figure 3 – Process steps of the custom built white LED

Phosphor converted white LEDs were then fabricated by proximate conformal phosphor deposition before forming the clear lens. The phosphor powder was mixed with PDMS in 50-50 m/m% and light conversion layers of four different thicknesses were deposited.

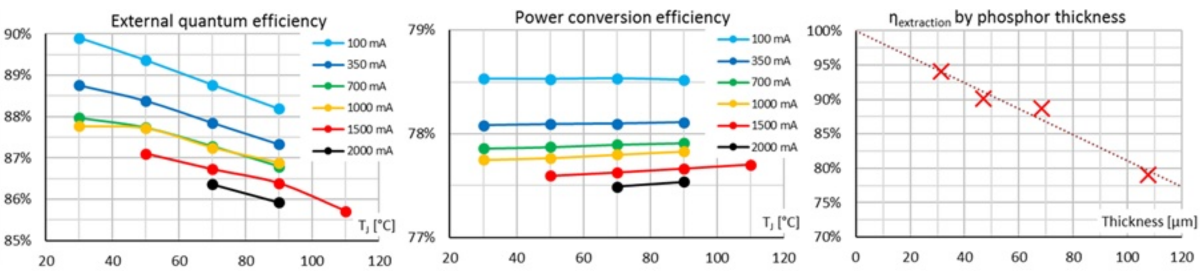

Figure 4 – efficiency curves of the light conversion layer (Schubert, 2006)

2.2.2 Characterisation of custom made phosphor converted white LEDs

For each phosphor layer setup, complete isothermal IVL characterisation was performed for 6 forward current values at 5 junction temperatures. Spectral data was used to calculate various efficiency curves (Figure 4) of the light conversion layer (Schubert 2006). After characterisation, the lenses were dismounted and cross sectioned to measure the thickness of the phosphor layers (Figure 5). As it is shown in these figures, the temperature of the phosphor layer has significant impact on the external quantum efficiency, and on blue absorption, which affects not just the efficiency of the LED but the colour of the resulting light, too. That is one reason why it is unavoidable to establish joint thermal, electrical and optical models in case of LEDs.

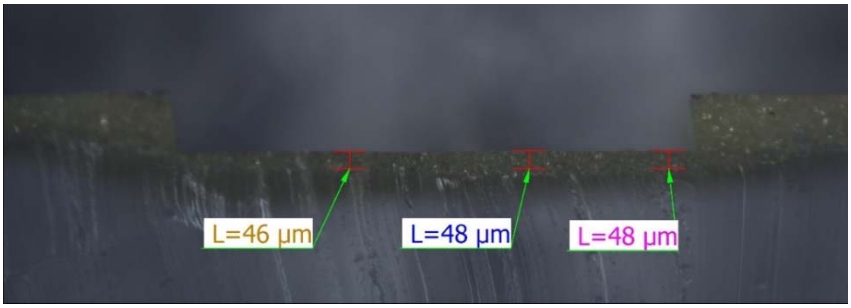

Figure 5 – cross sectioned measurement of the phosphor layers thickness

2.2.3 Physical model

Modelling the blue emitted light propagation in phosphor layer theoretically requires the calculation of:

- Blue absorption (heat effect) and scattering
- Blue to yellow conversion (heat effect)
- Yellow absorption (heat effect) and scattering

In case of thin phosphor layer, or wide LED area, the intensity of the light can be assumed homogeneous in lateral dimensions, so the driving equation for blue light can be expressed as a linear attenuation equation called Beer-Lambert law. Solving this equation gives us the intensity distribution of blue light as a function of the distance from the LED surface. From these results, the distribution of yellow light can also be determined analytically. For parameter fitting only two intensity measurements are needed with different phosphor thickness values. Other measurements were performed to verify the model.

Mass fraction (m/m %)	Thermal conductivity (W/m^{2}K)	Variance in thermal conductivity measurement
0	0,22	0,004
25	0,29	0,009
50	0,4	0,002
66	0,61	0,006
75	0,66	0,001

Table 1 – Thermal conductivity of custom phosphor layers

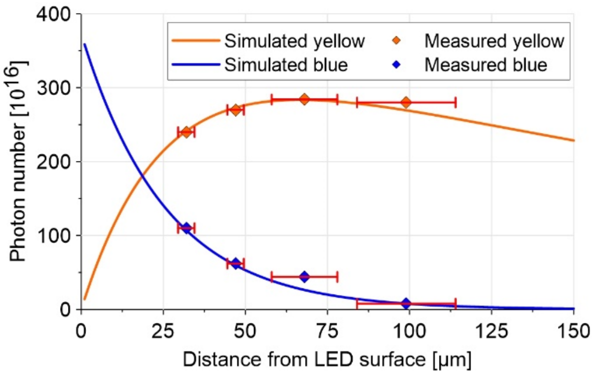

Figure 6 – The photon numbers of blue and yellow light while it goes through on phosphor layer with different thickness

2.3 Phosphor layer modelling results

Thermal conductivity of the PDMS (Polydimethylsiloxane) and phosphor-powder mixture was measured with the DynTIM measurement (DynTIM) equipment in accordance with 2.2.1. Different mass fractions were investigated. The results are shown in Table 1. Four custom white LEDs were built with layer thicknesses of 32, 47, 68 and 99 µm. The measured results of two of them were used to fit our light conversion model, the other two were used for the verification. The results are shown in Figure 6. The model works properly, at least for the 32–99 µm layer thickness range.

2.3.1 Measurements to aid phosphor modelling

The aforementioned 50 cm integrating sphere with dual DUT ports was used in an arrangement as seen in Figure 7 to capture the spectral power distribution (SPD) of the secondary emission of wavelength conversion materials. As a detector, the CAS-140CT spectroradiometer was used in this task. The DUT ports of the sphere are facing each other. This allowed to focus the excitation blue light on the phosphor sample mounted on a temperature controlled stage on the other port of the sphere. A black cone with a small aperture was used to decrease the amount of blue light inclining not the sample but the sphere. This ensured to capture reasonable levels of converted light without saturating the spectroradiometer with the blue excitation, that is only a necessary bad in this setup. The samples were exposed to variable intensities of blue light, while the temperature of the phosphor samples was controlled in a wide range (15-150°C). This allowed the investigation of the temperature dependent behaviour of some wavelength conversion materials (different custom made phosphor patches and actual, inactive CoB devices as well).

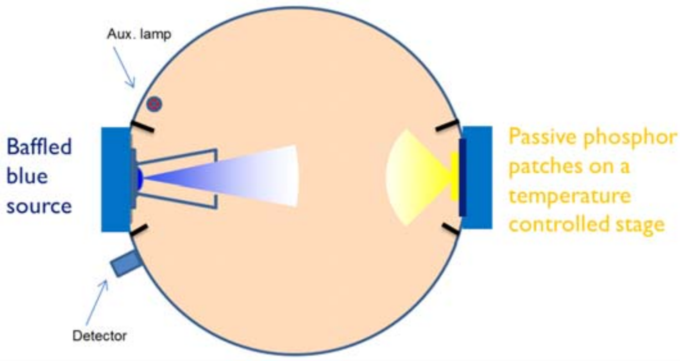

Figure 7 – Schematic measurement setup of the remote phosphor samples

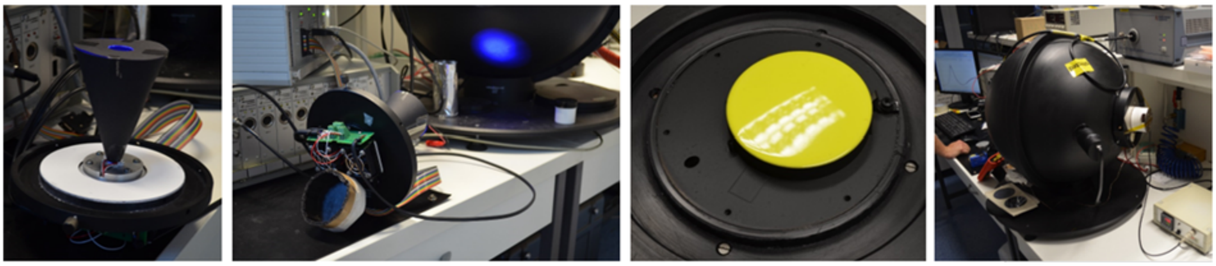

Figure 8 – Photos on the focusing cone and on the remote phosphor samples

The base material of the phosphor samples was PDMS (see in Figure 8). A 1 mm thick medal was poured on a black-painted Aluminium plate. Also the whole thermostat was painted black to minimise the scattering blue light in the sphere.

2.3.2 Remote-phosphor measurement results

As our integrating sphere is not calibrated for the above unusual geometrical arrangement, only an estimated blue reference SPD is used for temperature dependent efficiency calculations. Figure 10 show the conversion efficiencies of the characterised two custom made PDMS samples (Powder 1 and Powder 2) and of a factory original phosphor layer in the form of a large diameter CoB device. The CoB device was in OFF state during all measurements, the anode and cathode were shorted.

The measurement results show that not only the efficiency of the phosphor layer depends on the temperature, but slightly the wavelength of the converted photons as well. Because of the experimented linearity in conversion efficiency (Figure 10), this effect can be built in the multi-domain model. With the characterised phosphor layer, the multi domain model for CoB LED can be established.

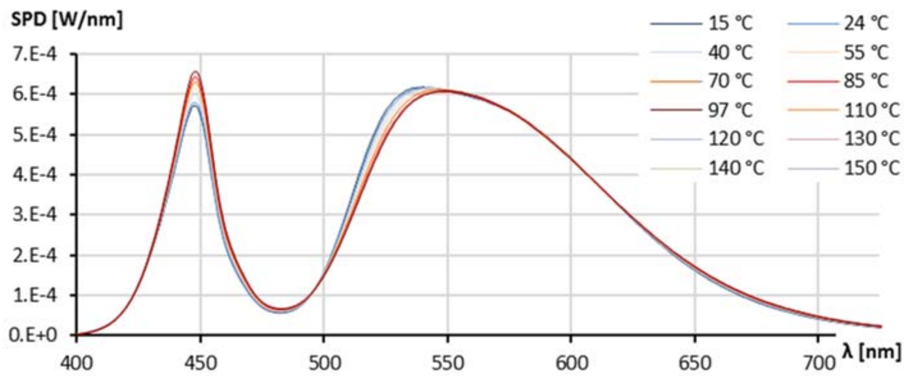

Figure 9 – Temperature dependent SPD of a custom made remote phosphor sample

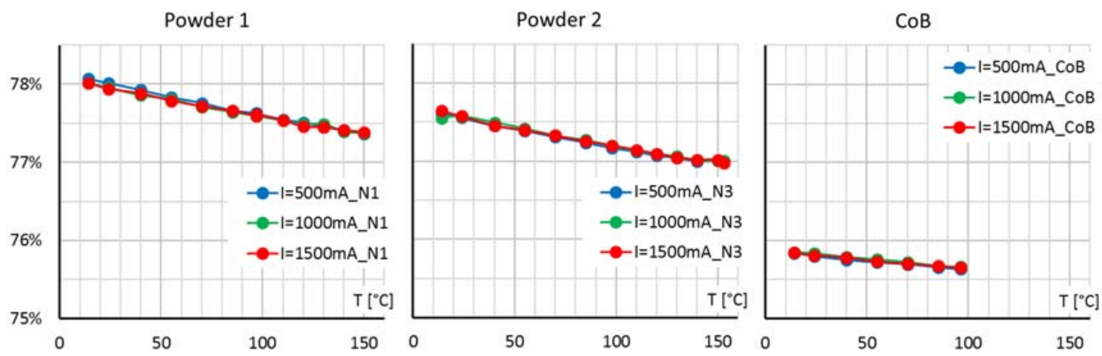

Figure 10 – Power conversion efficiency

2.3.3 Compact model of phosphor layer in the multi-domain model

In the model, the LED package is divided into small cuboid cells by the Finite Volumes Method. Each cell can have three domain models: electrical, thermal and optical. However, an actual cell contains only the required domain model(s). A domain model is represented by a network. Figure 11 shows the two cells that are essential for phosphor modelling. In the junction cell the electrical domain is represented by the resistivity of the material (resistors) and the nonlinear model of the junction (diode symbol). The thermal domain is represented by the thermal resistivity, the heat capacitance and the dissipated power. The optical domain is represented by the emitted radiant power. The Joule-heat of the electrical resistors appears entirely in P_d dissipated power however, the power drop of the junction (product of junction voltage and current, $V_j \cdot I_j$) is distributed between the dissipated and the radiant power.

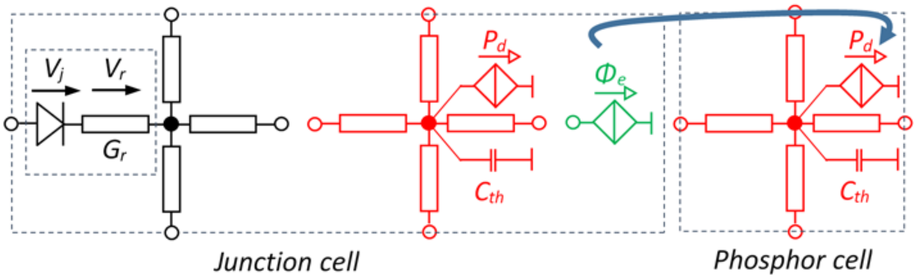

Figure 11 – Multi-domain LED model with phosphor in 2D:
black – electrical, red – thermal, green – optical domain.

A phosphor cell has only a model in the thermal domain. The dissipated power is a function of the incoming radiant power and the temperature of the cell. Our purpose was to create the simplest model with acceptable accuracy, so the incoming radiation arrives directly from the adjacent junction cell. A more sophisticated model can provide more accurate results however; it requires more (measured) data of the LED which limits the usability of such a model.

2.4 Characterization of CoB device

2.4.1 Structure of CoB device

We modelled a Lumileds 1202s CoB LED device which consists of 24 LED chips with lateral dimension of 600 µm ×700 µm, covered by a phosphor layer placed on an aluminium pad with solder layer between them. The actual CoB LED device and its model are shown in Figure 12. The thickness and position measurements are performed by a digital calliper, after the phosphor layer was removed. The structural details of the LED chips are neglected in the multi-domain model, since could not measure one chip only. Even so, following the procedure of Juntunen et al (Juntunen 2013), from the structure functions obtained by "ensemble measurement" of the LED array the thermal resistance was properly set. The luminous flux of a naked blue LED chip was calculated with the help of the phosphor layer model with the assumption that the phosphor layer properties were roughly the same as the custom phosphor layer properties.

Figure 12 – CoB LED (left) and its 3D model (right)

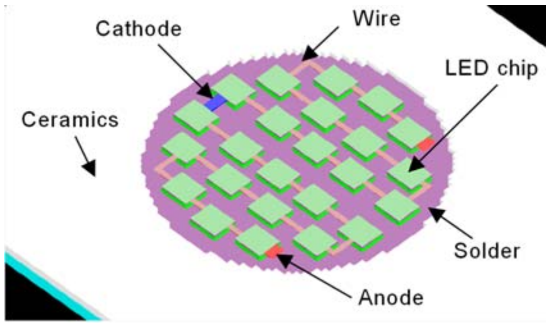

Figure 13 – CoB LED model: internal structure without the phosphor

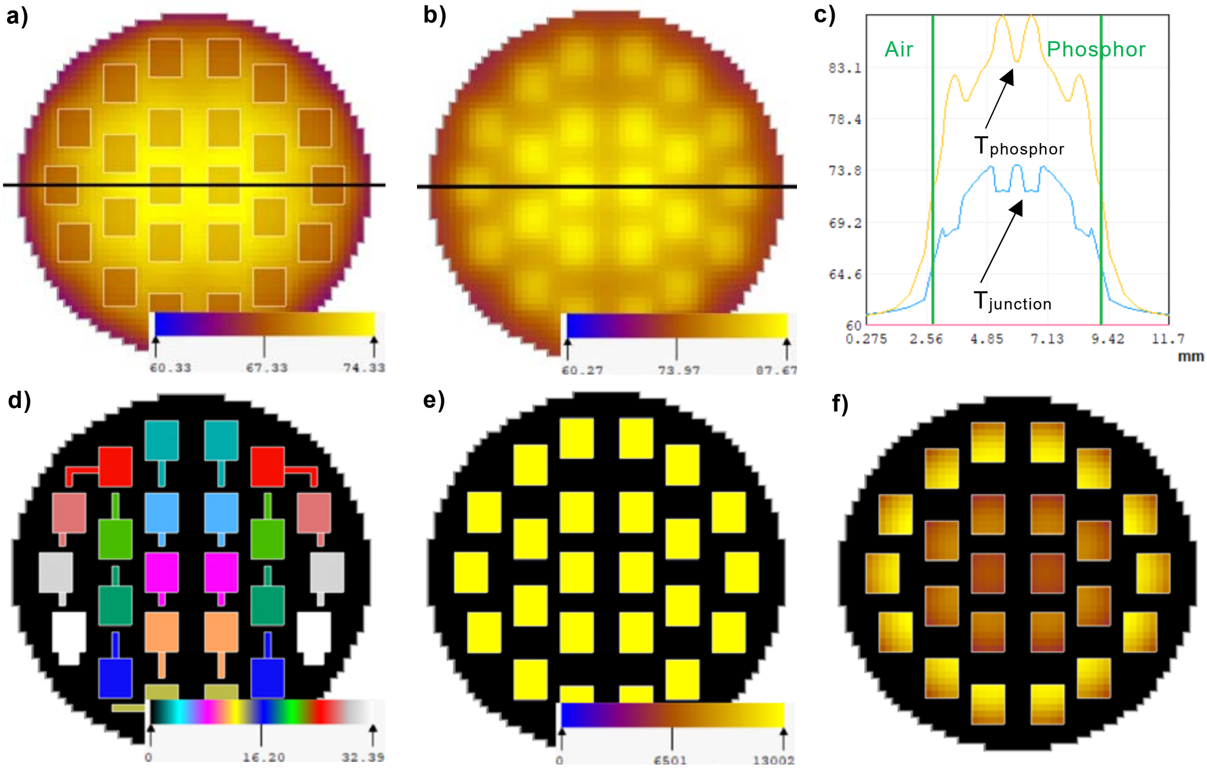

Figure 14 – Simulated results. a) Junction layer temperature [°C]. b) Phosphor layer temperature [°C]. c) Temperature in the black line cross-section of a) and b). d) Anode layer voltage [V]. e) Radiant power density from the junction [W/m^2]. f) Magnified inhomogeneity of the radiant power density.

2.4.2 Thermal, optical and electrical measurement techniques for CoB

The CoB devices were measured with the very instrumentation as in the case of the Cree XP-E2 devices, completed with the high voltage capable T3Ster Booster Device from Mentor. This way the device voltage range of the T3Ster equipment was raised to accommodate the voltage levels of the multi-chip LED string in this case. These measurements were also junction temperature controlled and were in-line with the JEDEC 51-1 and 51-5x family of standards.

2.4.3 CoB LED model

Electrically two strings of 12 serially connected LEDs are connected in parallel to the input, see Figure 13. Two-parameter (*I, T*) polynomial functions were fitted on the measured *V-T-I* and *Φ-T-I* data by the least squares method. 23,7% radiation-to-dissipation conversion rate was considered in the phosphor (from measured spectral data) the measured radiant power of the phosphor-covered CoB LED was scaled up with this factor to get the radiant power equation of the junction.

The simulation was run at 100 mA driving current and 60°C ambient temperature. The results can be seen in Figure 14. Figure 14a, b and c show the temperature distribution in the centre of the junction and the phosphor layer. The temperature of the phosphor is significantly higher than that of the junction because the conversion loss warms the phosphor up and its heat conductivity is low (see Table 1). Figure 14d presents the voltage in the anode of the LEDs. The forward voltage of an LED chip is about 2,7 V at 100 mA forward current and the presented temperature. These ~2,7 V voltage steps along an LED string can be observed in the figure. Figure e) shows the radiant power density distribution of the junctions. The calculated minimum power density is 99% of the maximum. This small difference is magnified in figure e) because an interesting effect can be observed: the inner part of the outer ring is brighter than the outer part, but the inner LEDs are darker. This is the result of two opposing effects: the forward voltage of an LED is lower at higher temperatures, resulting in higher current densities in the hotter parts of an LED junction, while the luminous intensity of the LED decreases when the temperature increases.

3 Conclusions

In this paper we presented a methodology to physically characterise phosphor layers and phosphor plus blue pump LED chip samples for the sake of obtaining data for setting up a multi-domain model for CoB LEDs. The key to reach such a model is the measurement and modelling of the properties of the phosphor layer. The established multi-domain model is implemented into an in-house solver, which handles the non-linearities of the problem. The results show fairly good agreement with the measured data, however, the multi-domain model still needs some refinement: as a final goal, one of the standard multi-domain LED chip models of the Delphi4LED project needs to be incorporated into our CoB simulator.

4 Acknowledgement

This research received funding from the European Union’s Horizon 2020 research and innovation program through the H2020 ECSEL project Delphi4LED (grant agreement 692465). Co-financing of the Delphi4LED project by the Hungarian government through the NEMZ_16-1-2017-0002 grant of the National Research, Development and Innovation Fund is also acknowledged. Sample preparations and measurements were also supported by the K 128315 grant of the National Research, Development and Innovation Fund.

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