LED based application design in an "Industry 4.0" approach: implementation as proposed by the Delphi4LED project

A. Poppe[1, 2], M. Rencz[1, 2], R. Bornoff[3], C. Marty[4], J. Yu[5], G. Martin[5]

[1] *Budapest University of Technology and Economics, Budapest, Hungary;*
[2] *Mentor, a Siemens business, Budapest, Hungary*
[3] *Mentor, a Siemens business, Hampton Court, UK*
[4] *Ingélux lighting design, Paris, France*
[5] *Signify, Philips Lighting, Eindhoven, The Netherlands*
Contact: poppe@eet.bme.hu, andras_poppe@mentor.com

ABSTRACT

In the Industry 4.0 era digitalization of design and manufacturing processes takes place. The aim of the Delphi4LED H2020 ECSEL R&D project of the EU (www.delphi4LED.org) is to trigger such a transition in the solid-state lighting industry by developing testing and modelling methodologies aimed at multi-domain characterization of LED based products at different levels of integration along the SSL supply chain. In this paper we describe our approaches to creating the appropriate "digital twins" of LED packages, modules and luminaires to be used in virtual prototypes applied in different system level design tasks.

BACKGROUND

At present, when designing an LED luminaire, there exist different approaches of development, depending on the size of the company. SMEs often use empiric approaches leading to rough luminaires, while bigger companies use advanced hardware and software tools to characterize parts, design versions and finally optimize all design steps. In both cases, considerable time and money is spent on prototyping, sampling, and laboratory testing. One source of the problem is e.g. the lack of LED specifications of LED vendors that would directly support actual application design. Digitalization at all integration levels of the SSL supply chain would provide remedy for these pains.

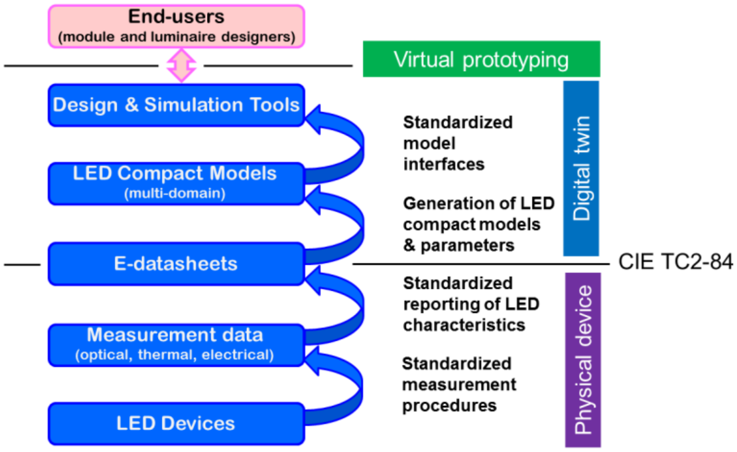


Figure 1: The Delphi4LED approach to digitalization of LED application design by creating digital twins of physical samples of packaged LEDs represented by their compact models extracted from test data, allowing module and luminaire level virtual prototyping

The ultimate goal of the Delphi4LED European project is the development of multi-domain modelling and simulation methods that are based on compact models of LEDs providing a combined description of the basic electrical, thermal optical behaviour of LEDs in order to allow efficient simulation LED applications. The foreseen modelling approach is generic in the sense that it can be applied from LED packages up to complete luminaires by creating a "digital twin" that properly represents its real, physical counterpart for simulation based experiments and optimization. The "Industry 4.0"-like approach of the project is depicted in Figure 1 and further detailed in Figure 2.

Key to this approach are standard testing techniques such as CIE's latest recommendations for optical testing of LED packages [1] or JEDEC's series of LED package thermal testing standards [2], [3] completed with a standardized way of test data reporting [4] and standard modelling approaches – yet to be developed and standardized along with standardized models aimed for different types of simulations and simulation programs capable of using these models.

THE DELPHI4LED MEASUREMENT AND MODELING WORKFLOW

As temperature is the most important operating parameter that strongly determines the operation of LEDs, thermal modelling of LED packages, modules and luminaires is our cornerstone at all integration levels from LED chip to LED luminaires.

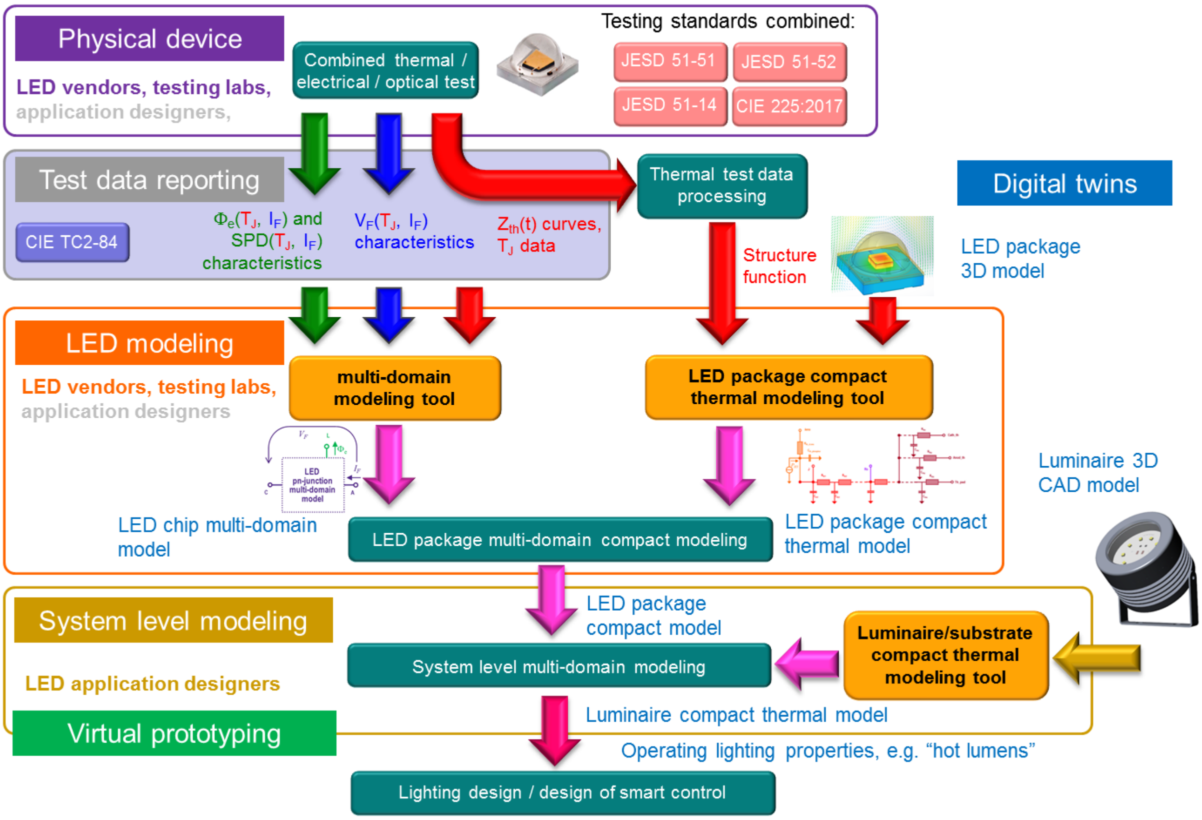


Figure 2: Delphi4LED workflow and design persona for generation and application of digital twins of LED packages, modules and luminaires

We treat the multi-domain operation basically on LED chip level/LED package level: as seen in Figure 1, the basis of the Delphi4LED approach of LED application design is that LED vendors provide the necessary data on packaged LED chips (LED packages) in an electronic format that can be further processed by software tools that extract the right models from these. To describe the multi-domain feature of LED operation, light output characteristics, thermal characteristics and electrical characteristics that have been measured in a consistent way need to be provided by the LED vendors in these a standard way. At the moment the TC2-84 technical committee of Division 2 of CIE deals with working out recommendations on reporting test data of LED packages [4].

Multi-domain characterization of LEDs

The data set used for modelling includes iso-thermal I-V-L characteristics of LEDs measured in a junction temperature range relevant from application point of view. In terms of the operating current and operating temperature (as independent, set parameters of the measurements), the selected range should cover both the peak efficiency and low efficiency operating domains. Typical selections are shown in Figure 3 and in Table 1. During the measurements of LED characteristics the T_J junction temperature should be set and regulated as recommended by the CIE 225:2017 and JEDEC JESD 51-51/51-52 documents [1], [2], [3] or by a proper combination of these methods [5], [6], [7].

According to the Delphi4LED workflow, the thermal, optical and electrical characteristics of LEDs are measured in a combined test set up which complies with the above testing standards and recommendations. It is important to mention, that both from the point of view of setting the T_J junction temperature as recommended in the CIE 225:2017 document or in case of measuring the $Z_{th}(t)$ thermal impedance of LED packages and deriving their R_{thJC} junction-to-case thermal resistance, an accurate measurement of the temperature induced change of the LEDs' V_F forward voltage is needed. Furthermore, getting rid of any non-thermal related part of the measured forward voltage transient is important. Any temperature change of the LEDs' pn-junction during the period covered by these parasitic voltage transients should be accounted for by the appropriate back-extrapolation of the measured $\Delta V_F(t)$ transient. Details are described in JEDEC's JESD51-14 standard [8] which are also referred to in the CIE 225:2017 document. Currently we are working in the optimal combination and implementation of these test methods [7], [9], also considering the lessons learnt from the round-robin testing of different LED packages [10].

The interface between LED characterization and LED modelling is the right set of data, provided in a machine readable format. Besides the iso-thermal I-V-L characteristics aimed for chip-level multi-domain modelling the measured dynamic thermal characteristics of the LED packages are also needed. The most common way of provided this information is by means of the measured real $Z_{th}(t)$ thermal impedance curves, or their equivalent representations, the structure function [11].

Digital twins

The LED chip

The digital twin of the LED chip is a Spice-like multi-domain LED model as introduced earlier [12], [13], and upgraded recently [7]. As seen in Figure 2, the right set of equations / circuit macro model along with the model parameters fitted to the measured data represents the *digital twin of the LED chip*. In the future, the required measurements and model parameter identification is expected from LED vendors in a standardized format.

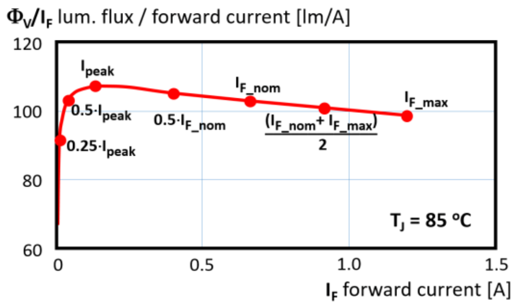


Figure 3: A typical LED efficacy diagram with forward current values suggested for measurement of isothermal I-V-L characteristics [10]

T_J [°C]	30	50	70	85	110
I_F [mA]	20	20	20	20	-
	30	30	30	30	-
	60	60	60	60	-
	100	100	100	100	-
	350	350	350	350	350
	500	500	500	500	500
	-	700	700	700	700
	-	-	1000	1000	1000

Table 1: Typical selection of junction temperature and forward current combinations for the measurement of isothermal I-V-L characteristics of mid-power LEDs [10]

Currently work is being carried out at different professional organizations and standardization bodies (such as JEDEC, CIE or IEC) on standards of LED package testing, test data reporting [4] and file formats of models.

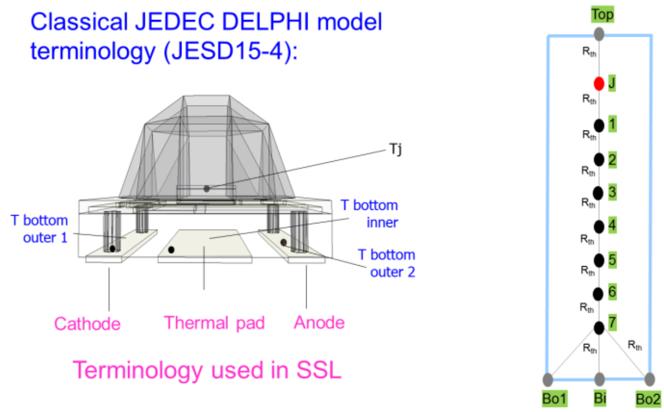
The LED package

Raw data for LED package thermal modelling is provided in form of $Z_{th}(t)$ curves (thermal impedance curves) obtained from thermal transient measurements that are performed in compliance with the LED thermal testing standards of JEDEC [2], [3]. These curves are turned into structure functions [11] and are used to calibrate detailed 3D thermal models of LED packages [15]. These calibrated detailed 3D models are the first thermal *digital twins of the LED packages*. These carry proprietary information of LED vendors as both the detailed geometry and material properties are present in these models. Therefore LED vendors do not share such models with end-users; though, end-users can also build such models based on their own LED package measurements.

About two decades ago the methodologies for creating compact thermal models of semiconductor device packages have been developed for the electronics industry in the framework of the European project DELPHI[1]. Such compact thermal models of semiconductor devices packages are provided in the form of a network of a few thermal resistances (and later completed with thermal capacitance to account for their transient behaviour). During the years the industry-wide acceptance and support of these compact thermal models (CTMs in short) resulted in JEDEC's standards on compact thermal modelling of semiconductor device packages [16], [17], [18], [19].

According to the original DELPHI methodology and also in our present approach, from the calibrated detailed thermal models the compact thermal models are identified through an optimization process [9], [15]. In the Delphi4LED project we already create dynamic compact thermal models (DCTMs) of the LED packages. These are later used in luminaire level analysis as the actual *digital twins of the LED packages* representing their true thermal behaviour. The advantage of the compact models is that they no longer carry proprietary information, thus, LED vendors can share them with end-users without sharing their IP. Following the idea of extending the original DELPHI modelling approach to LEDs, the corresponding measurement and modelling tasks are also to be performed by LED vendors, though, the process is open to end-users as well (see Figure 2). LED package DCTMs are expected in a standard network description format. (Work regarding a vendor neutral, XML based file-format for DCTMs of semiconductor device packages is at an advanced stage within the JEDEC JC-15 committee [20]). Outlines of objects comprising a detailed thermal model of an LED package and the topology of the corresponding LED package DCTM is shown in Figure 4. Work for compact modelling of the effect of phosphor white LEDs is in progress, report on the results achieved so far is provided in [21].

A package DCTM connected to a chip level multi-domain LED model is the ultimate *digital twin of a packaged LED*, provided e.g. as a Spice netlist.



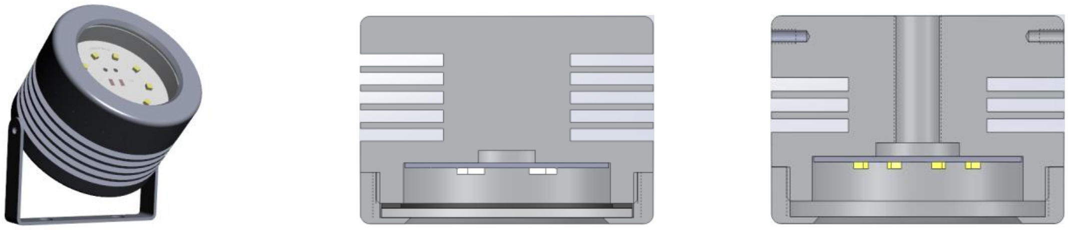
a) *b)*

Figure 4: a) Outlines of essential solid elements of a detailed 3D LED model with JEDEC JESD15-4 compliant node names used in compact thermal modelling, b) topology of the corresponding LED package dynamic compact thermal model (node J represents the LED junction; every internal node also represents a thermal capacitance which – for the sake of clarity – are omitted here). Figure is based on [15].

The luminaire

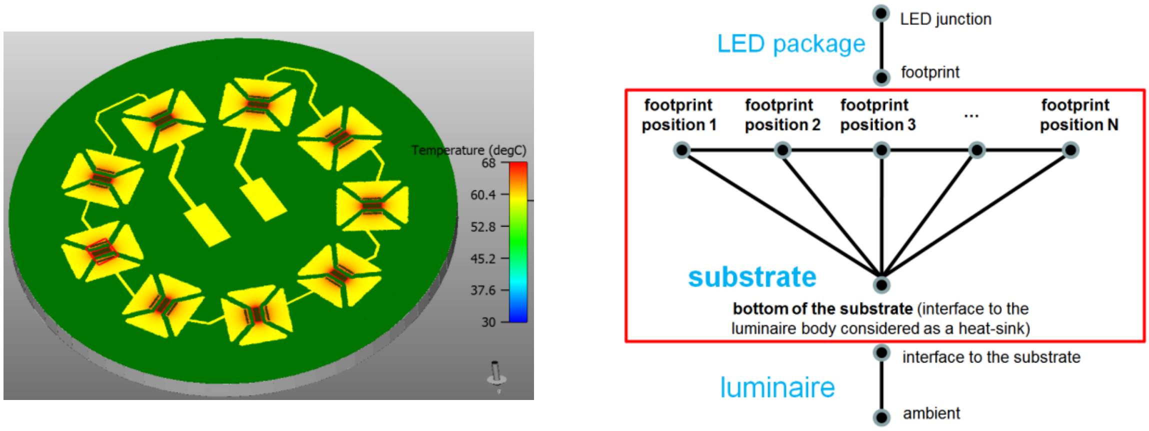
From thermal point of view a luminaire is a multi heat-source system where the heat-sources to consider are the LED packages with their footprints. An obvious digital twin of an LED luminaire is its MCAD model (such as shown in Figure 5). The thermal model, as a thermal only digital twin of the luminaire can be extracted from this MCAD model. A luminaire compact thermal modelling tool (as indicated in Figure 2) may use different approaches to provide the compact thermal model of the luminaire. One approach could be to identify and to convert the so called thermal characterization matrix of the luminaire into a Spice network [12]. Reduced order modelling techniques could also be used for obtaining a luminaire compact thermal model [21].

[1] Hence the name of our current project which commemorates its ancestor, but extended and applied for LEDs: Delphi4LED.



a) b)

Figure 5: A demonstrator luminaire design used in Delphi4LED: a)MCAD model of the luminaire, b) its two different cooling assembly design variants



a) b)

Figure 6: The substrate used in the Delphi4LED demonstrator luminaire shown in Figure 5 a) the layout arrangement of the LED package footprints, b) the schematic of the network topology of the compact thermal model of the substrate layout

In another modelling example [23] the LEDs were attached to their own individual MCPCB substrates individually and the LED package DCTMP also included this substrate. The die-cast luminaire house served both as a substrate and as a huge, common heat-sink for all these MCPCB assembled LEDs (Figure 7). The compact thermal model of this luminaire in this case was also obtained through its thermal characterization matrix. The resulting network elements were then converted into a Spice subnetwork, representing the compact thermal model of the luminaire.

Thus, depending on the design partitioning, the digital twin of the luminaire describing its thermal behaviour is the above described compact thermal model. In the first approach the thermal *N*-port model of the substrate depends solely on the layout arrangement of the footprints; the effect of the thermal boundary conditions is lumped into the single thermal resistance that represents the luminaire acting as a heat-sink. This way, libraries of substrates made of different materials and with different designs (copper coverage, footprint layout, etc) can be created for later, system level optimization.

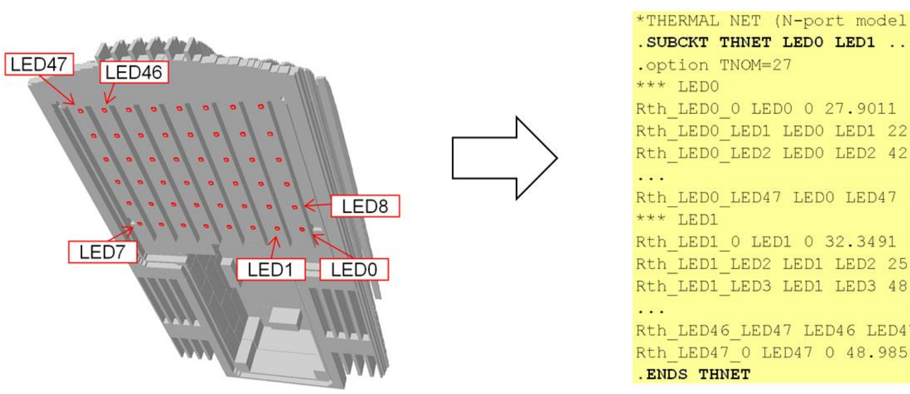


Figure 7: The 3D thermal simulation model of a streetlighting luminaire obtained from its MCAD model and a sample Spice network netlis representation of its compact thermal model [23].

VIRTUAL PROTOTYPING OF LUMINAIRES

The complete digital twin of an LED luminaire is obtained by combining the above luminaire compact thermal model with the digital twin of the LED package (chip level multi-domain model completed with the package DCTM). Using such a digital twin of complete luminaire as a virtual prototype, hot lumen calculations can be performed under different environmental conditions or different design versions (such as shown in Figure 5b) can be evaluated. With the obtained hot lumens higher level modelling of the luminaire is possible; designers can check if a design variant meets the system level specs or special embedded models can be developed that may support temperature compensated constant light output control [24].

LED Type	Tot.Rad.Flux			Tot.Lum.Flux			CIE 1931 x			
	Median [W]	MAD [W]	MAD / Median [%]	Median [lm]	MAD [lm]	MAD / Median [%]	Median [-]	MAD [-]	MAD / Median [%]	Median [-]
type A	0,8350	0,0486	5,82	33,54	2,36	7,04	0,149	0,0012	0,81	0,031
type B	0,6389	0,0389	6,09	213,00	0,75	0,35	[illegible]	[illegible]	0,80	0,363
type C	0,5345	0,0147	2,75	89,39	1,85	2,07	0,698	0,0007	0,10	0,301
type D	2,4999	0,0613	2,45	709,92	16,84	2,37	[illegible]	[illegible]	0,21	0,399
type E	0,0310	0,0024	7,74	16,17	1,26	7,78	0,183	0,0022	1,21	0,740
type A										
A10	0,7950	0,0485	6,10	32,84	1,53	4,67	0,149	0,0001	0,07	0,032
A11	0,8480	0,0354	4,17	32,49	1,27	3,91	0,150	0,0002	0,13	0,029
A12	0,8462	0,0419	4,95	34,35	1,18	3,45	[illegible]	[illegible]	[illegible]	0,031
A13	0,8281	0,0473	5,71	34,85	2,03	5,83	[illegible]	[illegible]	[illegible]	0,032
A14	0,8543	0,0394	4,61	35,23	1,28	3,64	0,149	0,0002	0,13	0,032
type B										
B10	0,6373	0,0386	6,06	212,13	12,53	5,91	0,349	0,0018	0,52	0,367
B11	0,6488	0,0351	5,41	213,96	11,21	5,24	0,351	0,0014	0,40	0,362
B12	0,6352	0,0337	5,31	210,29	11,71	5,57	0,347	0,0010	0,29	0,364
B13	0,6290	0,0381	6,06	207,78	13,43	6,46	0,351	0,0013	0,37	0,362
B14	0,6316	0,0387	6,13	209,67	12,48	5,95	0,352	0,0013	0,37	0,364

Spread of samples

Spread of test results

Figure 8: Detail from the statistical analysis of the results of the round-robin test 5 different LED types, performed by 7 participating laboratories [10]

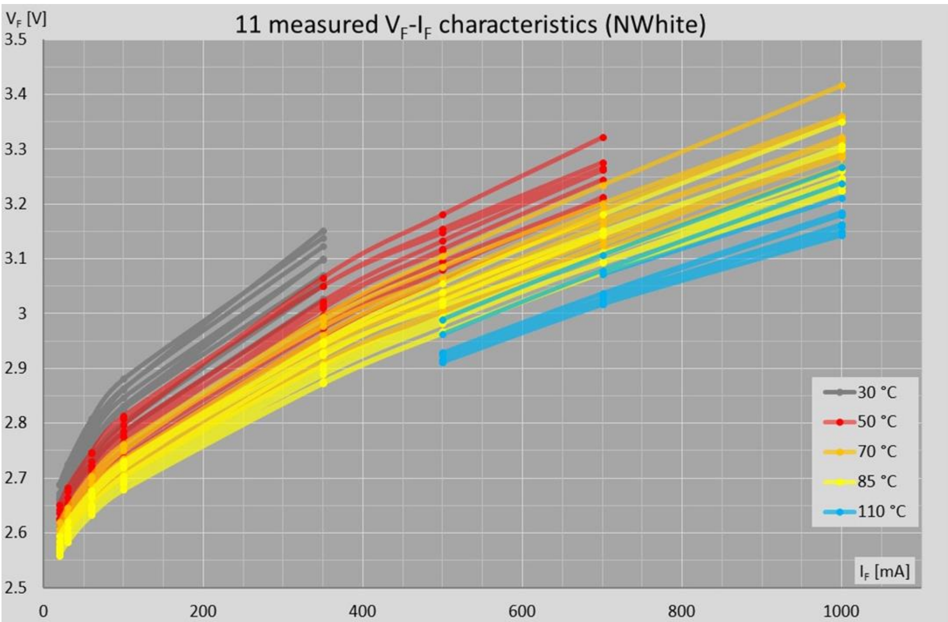


Figure 9: Variations of measured iso-thermal LED characteristics for 11 samples from the same binning class

EXPECTED AND MEANINGFUL ACCURACY OF MODELS

Results of round-robin testing of LEDs

In the round-robin testing of experiment of the Delphi4LED project [10] 5 samples of 5 LED types (3 colour types, 2 white LEDs) were circulated among the 7 participating laboratories. The measured flux values (total radiant / luminous flux) had a scatter of roughly 3-8%, depending on the type of the LED. The same flux values measured by the participating laboratories for every individual LED sample also had a scatter up to 4-8%, see the detail of the summary of statistical analysis in Figure 8.

Expectation of end-users

In terms of luminous flux, end-users expect 2..5% deviation of simulation results from measured ones [26]. In the light of the round-robin test results this expectation seems to be unrealistic, especially if the laboratory providing input data for modelling is different from the laboratory providing test results for the verification of the final product, though, the proposed models can be precisely fitted to test results in a sufficiently wide range of the relevant forward current and junction temperature ranges. In terms of thermal resistance, the expectation of end-users is ~5% difference between measurement and simulation results. From the round-robin measurement results it seems, that this expectation can be met; even for wide range of thermal time-constants (if dynamic simulation is needed).

In the project a specific task is devoted to the analysis and modelling the parameter variability, in which a larger population of LEDs (11 samples from the same binning class) have been characterized by the multi-domain measurement techniques outlined earlier and methods to quantify the variations of the different measured characteristics have been developed [27], [28]. Here again, significant variations of the different measured LED characteristics were found. In order to eliminate lab-to-lab variations from the analysis, test results of one of the Delphi4LED testing labs were considered only. In Figure 9 the variation of the measured iso-thermal LED I-V characteristics can be seen: the range of curves corresponding to different LED samples overlap significantly for different temperatures.

Based on the statistical analysis related to these measurements recommendations of for creating the multi-domain LED package models have been made. According to these, from the point of view a given characteristic (e.g. the thermal impedance), the "median" device has to be modelled and statistical models for the variation of the parameters the given model are set up are recommended to study the effect of variations within a given LED population. Details about the current status and results of this modelling work will be published elsewhere [27], [28]; this work is still on-going, the recommendations may change in the future.

CONCLUSIONS

Electric and optical parameters of LEDs show strong dependence on current and temperature; consequently a few numbers in a datasheet are unsuitable for proper LED characterization and do not provide sufficient information for fast and accurate design of LED applications. To tackle this problem, the members of the Delphi4LED consortium worked out an "Industry 4.0" compliant approach in which, based on the results of novel multi-domain testing of physical LED samples and through simulation of calibrated detailed 3D thermal simulation models thereof, compact models are created to be used as digital twins of the LEDs. The same thermal modelling concept is extended to different sub-assemblies of a luminaire which, combined with the LED package multi-domain models allow virtual prototyping of complete LED luminaires. With this technique not only "hot lumen" calculations are possible, but complex, higher level multi-domain design tasks like setting up a temperature compensated constant light output control can also be accomplished. Though the proposed compact models can be fitted to the test data rather precisely in the relevant forward current and junction temperature ranges, according to the findings of our round-robin testing realistic expectation for the ultimate accuracy is ~5% difference in the simulated and measured thermal and optical properties.

ACKNOWLEDGMENTS

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