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Light and Lighting Conference
with Special Emphasis on LEDs
and Solid State Lighting

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HOT TOPIC FOR LEDS: STANDARDIZATION ISSUES OF THERMAL CHARACTERIZATION

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ABSTRACT

The paper discusses the increasing need for a more sophisticated thermal characterization of LEDs and LED-based products. The major concern is how to provide meaningful thermal metrics of high power LEDs and what other thermal related data should be provided on products' datasheets that would allow lighting system designers design efficient and reliable products. The paper is the condensed and revised version of a white paper [1] about the topic prepared for the EIA-JEDEC JC15 committee on standardization of thermal characterization of packaged semiconductor devices and provides a status report on the latest steps taken by the committee in this field.

Keywords: LED thermal characterization, thermal resistance of LEDs, standardization, LED modelling.

1. INTRODUCTION

Nowadays the demand for thermal standards for high-power LEDs is increasing. On the one hand metrics for fair comparison of competing products are needed; on the other hand, designers of high-power LED-based applications demand reliable and meaningful data for their daily work. Today's data sheet information does hardly meet any of these requirements. In earlier papers [1], [2] we compared the current situation in the LED world with the situation in the Integrated Circuit (IC) world over twenty years ago, observed that much can be learned from the progress achieved, and concluded with a proposal for action. Another important lesson can be learned from the introduction of Compact Fluorescent Lamps in the early seventies. Their introduction was seriously hampered by unclear, misleading and exaggerated performance claims, exactly the reason why the U.S. Department of Energy (DOE) considers it critical to guide the market introduction of LED-based products because of their energy saving potential. The main lesson learned is that selling underperforming products can discourage the early adaptation of a new technology.

This paper will address thermal issues that are specific to light emitting diodes, the drawbacks of the current situation with respect to the information in the datasheets, and emphasizes the need for electro-thermal-optical models.

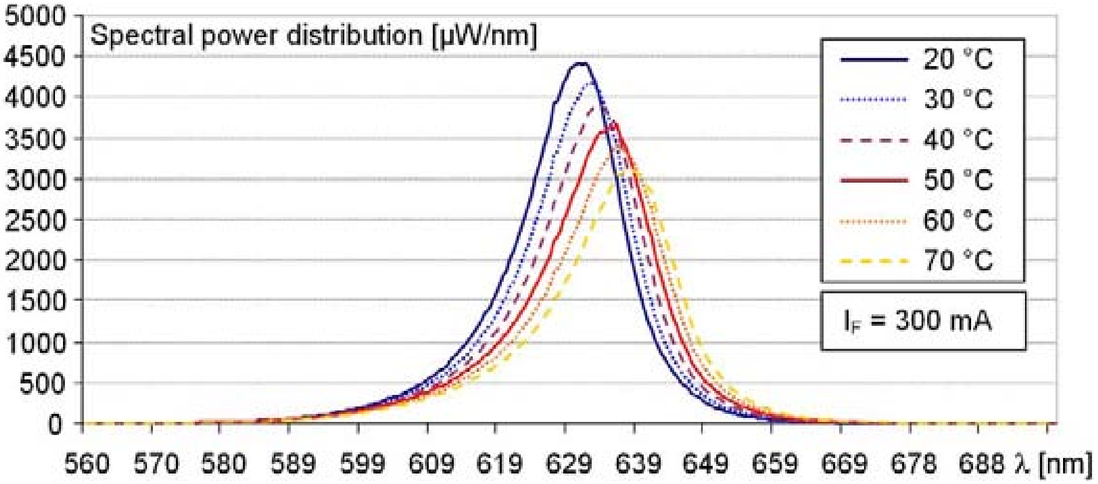

Figure 1. Temperature dependence of the spectral power distribution of a red LED driven by a constant forward current. (Indicated temperature values refer to the case temperature of the LED package.)

1.1 Junction Temperature of LEDs

Unlike two decades ago in the IC world, the junction temperature (T_J) of an LED is not just a performance indicator of the thermal design but also plays a major role in lighting design since many properties of the light output of an LED depend on the absolute junction temperature (such as peak wavelength or the total emitted optical power – as shown in Figure 1). This means that thermal management should be an integral part of the system design of an LED based lighting solution, resulting in changing roles of different engineering disciplines in the overall design process.

Consequently, since T_J of LEDs is more widely used in the design process of LED-based lighting solutions, well-established definitions of standardized thermal metrics and models will be even more important than in the IC-world, both for the LED manufacturers and the lighting system designers. Besides datasheets, another bridge between vendors and end-users of LEDs could be a well-established, general multi-domain (electrical, thermal, optical) compact model of LEDs. A system designer wants to check if a junction temperature or a solder temperature stays within prescribed limits, or, alternatively, needs a temperature value for lifetime prediction. The equation that is most used is the following:

$$T_J = R_{thJ\text{-}X}\, P_H + T_X \tag{1}$$

where in daily practice $R_{thJ\text{-}X}$ denotes the LEDs' *junction-to-environment X* thermal resistance which is a number that is supplied by the LED manufacturer, the power P_H is provided by the electronic engineer, and T_X is an often ambiguously specified reference temperature value. Recent measurement guidelines being addressed by the JC15 committee of the Electronic Industries Alliance Solid State Technology Association, (formerly known as Joint Electron Device Engineering Council or EIA-JEDEC in short) aim to provide recommendations for reference environments, calculation of the heating power and appropriate ways of measuring the thermal resistance of high power LEDs.

1.2 About the Thermal Resistance

The way how the EIA-JEDEC JESD51-1 standard [3] defines the thermal resistance is a re-arrangement of equation 1:

$$R_{thJ\text{-}X} = (T_J - T_X)/P_H \tag{2}$$

where (according to the exact wording used in JESD51-1) P_H denotes "the power dissipated in the device". (Note, that this definition of thermal resistance is not as rigorous as discussed in [1] and [2].) Equation 2 suggests building a spatial temperature difference in thermal equilibrium: heat up the junction and measure both the junction temperature and the temperature at a given reference point X. If the reference temperature is the ambient temperature (that we can control if measurements are performed e.g. on a cold plate), then in the un-heated device, in its initial thermal steady-state $T_{J0} = T_X$, i.e. the initial junction temperature and the reference point temperature are equal. After heating up the device and reaching the final thermal equilibrium of the hot junction, we shall reach the final T_J junction temperature, that is, after a transition from a cold steady state to a hot steady state (or vice versa). This procedure (also known as the static test method specified in [3]) suggests another reformulation of equation 1. Suppose, in the initial steady-state a known P_{H1} heating power is applied, while in the final steady state another known heating power P_{H2} is applied. For both cases we can express the junction temperature following equation 1:

$$T_{J1} = R_{thJ\text{-}X}\, P_{H1} + T_X \tag{3a}$$

$$T_{J2} = R_{thJ\text{-}X}\, P_{H2} + T_X \tag{3b}$$

(1)

(

Subtracting (3a) from (3b) we obtain

$$T_{J2} - T_{J1} = R_{thJ\text{-}X}\,(P_{H2} - P_{H1}) \tag{4}$$

In equation 4 we can also indicate that T_{J1} and T_{J2} junction temperatures occurred at different time instances: $T_{J1} = T_J(t_1)$ and $T_{J2} = T_J(t_2)$ when power P_{H1} or P_{H2} are applied, respectively, reached thermal equilibrium. Substituting these and re-arranging (4) yields

$$R_{thJ\text{-}X} = [T_J(t_2) - T_J(t_1)]/(\,P_{H2} - P_{H1}) \tag{5}$$

or

$$R_{thJ\text{-}X} = \Delta T_J(t)/\Delta P_H \tag{6}$$

where $\Delta T_J(t) = T_J(t_2) - T_J(t_1) = T_{J2} - T_{J1}$ and $\Delta P_H = P_{H2} - P_{H1}$. In other words, instead of using a spatial temperature difference along the junction-to-reference heat-flow path, equation 6 suggests that the "thermal resistance" as a metric can be calculated from the temporal difference of the initial and the final steady state value of the junction temperature, provided the change of the heating power at the junction is also known and the reference temperature is kept constant. A major advantage of the differential approach represented by equation 6 is that inaccuracies in junction temperature measurement cancel out. Another advantage is that the second reference temperature is no longer part of the equation. In summary: a measurement at two points at the same time is mathematically equal to measuring one point at two different times.

The *junction temperature* and the *junction-to-reference* thermal resistance as characteristic quantities serve different purposes for both system designers and device manufacturers. The goal of component designers (manufacturers) is to achieve better thermal performance of the LED device and to establish figure-of-merit values for comparison with other vendors' products. Typically *junction-to-reference* thermal resistance values are used for such purposes. The *junction-to-reference* thermal resistance values are usually the only input data for (lighting) system designers who want to study "what-if" scenarios and want to obtain sufficiently accurate prediction of *junction temperature* through which other important properties of LEDs can be also predicted, such as lifetime and light output. Since LEDs are rather complex in their operation, standardized multi-domain (thermal, electrical and optical) models would be required to predict operation of any vendors' LEDs. Outlines of such a model will be given in Section 3.

2. EXAMPLES OF PROBLEMS WITH CURRENT DATASHEETS

The topic is discussed in detail in [4]. Here we give a shorter outline only. Although most LED vendors perform thermal testing according to the EIA/JEDEC JESD51-1 standard [3], they consider the P_H power of equation 2 in an inappropriate way. For silicon diodes $P_H = I_F V_F = P_{el}$ (the electrical power supplied to the device) while in case of (high power) LEDs, emitted light energy must be considered: current associated with radiative recombination (giving rise to light output) represents a significant percentage of the total forward current I_F. Consequently, the $I_F V_F$ product does not represent the heat dissipated in the device (at the junction): the portion of power associated with light output must be subtracted from the $I_F V_F$ product when calculating the heat dissipation of an LED.

To highlight this, in Table 1 we compared two simple cases to address the consequences. Let us define R_{th_el} as the thermal resistance based on the supplied electrical power $P_{el} = I_F V_F$ only, and quantity R_{th_real} as the real thermal resistance of the LED package based on the real dissipation which is $P_H = P_{el} - P_{opt} = P_{el}(1 - \eta_e)$ where η_e denotes the overall *energy conversion efficiency* (called *radiant efficiency* in [5]) of the LED and it is calculated as the ratio of the supplied electrical power and the emitted optical power of the LED: $\eta_e = P_{opt} / P_{el}$. The emitted optical power P_{opt} can be measured as the total radiant flux $\Phi_e(I_F, T_{ref})$ of the LED at well defined, constant forward current I_F and reference temperature T_{ref} values using the procedures recommended in the CIE 127-2007 [5].

Table 1. Comparison of the values of R_{th_el} and R_{th_real} in case of two different energy conversion efficiency values.

Case 1: Efficiency η_e = 25%, supplied electrical power P_{el} = 10W, junction temperature rise $\Delta T_J = 50^{o}$C $R_{th\_el} = \Delta T_J / P_{el}$ = 50/10 = **5,00 K/W** $R_{th\_real} = \Delta T_J / (P_{el} - P_{opt}) = \Delta T_J / [P_{el} \cdot (1 - \eta_e)]$ = 50/(10×0,75) = **6,67 K/W**
Case 2: Efficiency η_e = 50%, supplied electrical power P_{el} = 10W, junction temperature rise $\Delta T_J = 50^{o}$C $R_{th\_el} = \Delta T_J / P_{el}$ = 50/10 = **5,00 K/W** $R_{th\_real} = \Delta T_J / (P_{el} - P_{opt}) = \Delta T_J / [P_{el} \cdot (1 - \eta_e)]$ = 50/(10×0,5) = **10,00 K/W**

From Table 1 one can clearly see that in case of LEDs with higher efficiency, assuming the same junction temperature rise as for less efficient LEDs, the real thermal resistance of the package is higher. Therefore, as of today, all LED vendors report R_{th_el} values on their datasheets (simply because R_{th_el} is always lower than R_{th_real}, providing a better sales argument), misleading lighting system designers during the thermal evaluation of their designs. The most urgent action point is to force LED vendors to include $R_{\mathrm{th\_real}}$ values in their datasheets.

As is widely known, the η_e overall radiant efficiency (also known as *wall-plug efficiency* or WPE in the LED industry) depends on temperature and current. This is the reason why any metric of an LED reported in a datasheet should also be reported together with the current and temperature at which the given metric was identified. Furthermore, to allow system level designers using data sheet values, it is not sufficient to present luminous efficacy (lm/W) information only, but energy conversion efficiency (radiant efficiency) should also be provided by LED vendors, possibly in terms of diagrams such as shown in Figure 2.

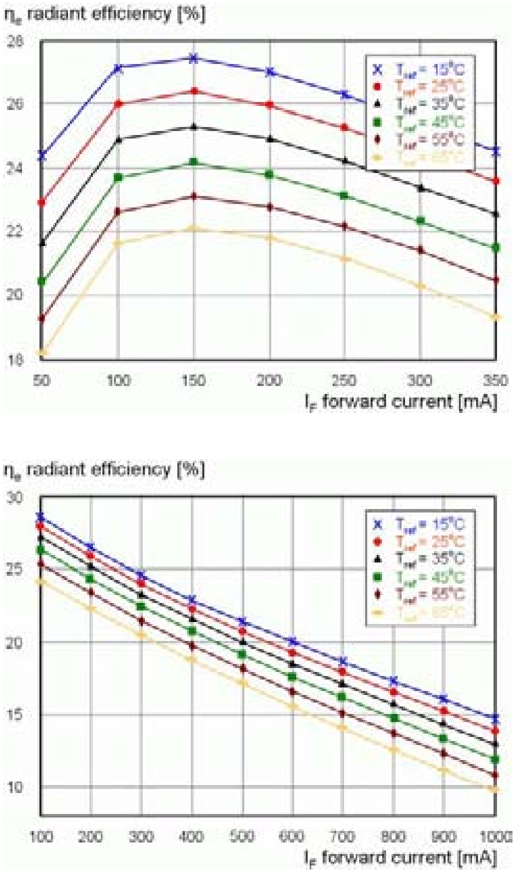

Figure 2. Radiant efficiency plots as functions of forward current for different types of power LEDs of different vendors. Plots on the top: 1W LED with high series electrical resistance, on the bottom: 3W LED with negligible electrical series resistance.

3. PROPOSAL FOR MULTI-DOMAIN LED MODELS

Because the forward voltage V_F decreases with increasing temperature which should not be neglected, the best approach is to couple the thermal and electrical calculations. In case of PN junctions it is relatively simple to construct an electro-thermal model. One may start with the classical diode equation encompassing a few temperature dependent parameters such as current constant I_0 and the effective thermal voltage $m\,U_T$ where m is a constant between 1 and 2 and $U_T \approx 26\text{mV}$ at room temperature. The PN junction model has to be completed with the thermal model of the package and the model of the light output. Issues of LED package thermal model were discussed in detail e.g. in [6]. To allow the LED model being used in lighting design, the light output should also be described. At least, emitted total flux values can be described by means of fitting a polynomial approximate model to the measured $\Phi_e(I_F, T_J)$ radiant flux or $\Phi_V(I_F, T_J)$ luminous flux functions.

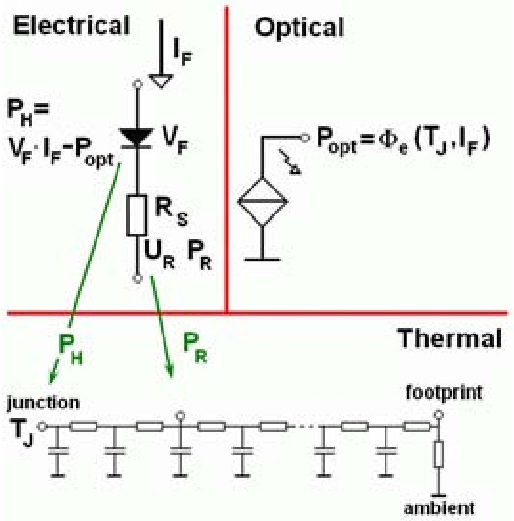

Figure 3. Sketch of a multi-domain LED model based on the one suggested in [6].

The ultimate goal is to define a standardized, general LED model that includes:

- An electrical model of the (internal) PN junction including a few temperature dependent parameters and the electrical series resistance. To illustrate this we quote the ideal diode characteristic: $I_F=I_0\,[\exp(V_F/(m\,U_T))-1]$ which describes the relation between the forward current and the forward voltage applied at the PN junction, where parameters I_0 and $m\,U_T$ are junction temperature dependent: $I_0 = I_0(T_J)$, $m\,U_T = m\,U_T(T_J)$ where $U_T(T_J) = k\,T_J/q$ (k denotes Boltzmann's constant, T_J is the junction temperature in Kelvin and q is the electron charge).

- A model of the light emission depending on the forward current (taken from the electrical model) and the temperature: $P_{\mathrm{opt}}=\Phi_{\mathrm{e}}(I_{\mathrm{F}}, T_{\mathrm{J}})$. Also, for lighting design $\Phi_{\mathrm{V}}(I_{\mathrm{F}}, T_{\mathrm{J}})$ luminous flux estimates should also be provided.

A thermal model of the package (complexity depending on the package type), ideally a BCI (boundary condition independent) model. The heat entering the junction node is $P_{\mathrm{H}} = I_{\mathrm{F}}\, V_{\mathrm{F}} - P_{\mathrm{opt}}$. If the light reduction in the LED itself is negligible then this power can be considered to be equal to $I_{\mathrm{F}}\, V_{\mathrm{F}} - \Phi_{\mathrm{e}}(I_{\mathrm{F}}, T_{\mathrm{J}})$. The heat dissipated at the series resistance of the LED chip is $P_{\mathrm{R}} = I_{\mathrm{F}}^{2}\, R_{\mathrm{S}}$. The effect of the R_{S} electrical series resistance is illustrated in Figure 2: bending of the efficiency diagrams can be explained by this series resistance. A power value P_{loss} that describes extra losses such as light absorption in the lens (ideally it is negligible) and energy loss in the phosphor (in case of white LEDs) can also be considered (not shown in Figure 3). For further details on this refer to [6]. The sum of the partial thermal resistances of the thermal model shown in Figure 3 is equal to the $R_{\mathrm{th\_real}}$ junction-to-case thermal resistance of the power LED package. Using this and the value of the heating power, the real T_{J} junction temperature can be calculated as per equation 1: $T_{\mathrm{J}} = P_{\mathrm{H}}\, R_{\mathrm{th\_real}} + T_{\mathrm{amb}}$ where T_{amb} denotes the ambient temperature considering it now as the reference temperature.

The model outlined above can easily be implemented in any circuit simulation program used by electrical engineers (such as the widely known SPICE program from the University of California, Berkeley [7]). For thermal designers, however, the complexity of such a unified LED model should not exceed the capacity of a spreadsheet application. The equations at hand might be reformulated to meet this requirement. Such a model would take electrical current (possibly with duty cycle if PWM-based dimmed applications are also to be considered) and thermal boundary conditions and would result in junction temperature, efficiency, efficacy and luminous flux estimates as output. Such a model was never needed for discrete silicon devices nor for IC’s – there, even today, the electrical operation is often studied decoupled from the thermal operation causing problems sometimes. However, for LEDs a coupled multi-domain model – possibly with standardized properties – might become mandatory. Further information on electro-thermal LED models can be found e.g. in [8].

4. SOME FURTHER QUESTIONS ABOUT LED THERMAL STANDARDIZATION

Apart from the problems with the current datasheets, many other thermal characterization issues also pose challenges. The topics listed below deserve a position on the standardization agenda:

- Both for LED vendors and users: what is needed in terms of standards and guidelines? It seems that at the device level the basic definitions of the most relevant measurement standards (EIA/JEDEC JESD51-1 [3], CIE 127:2007 [5]) are applicable to high power LEDs, with additional guidelines. E.g. the wording of JESD51-1 about "power dissipated in the device" might be completed by guidelines providing a correct interpretation for LEDs. Guidelines regarding test conditions specific to LEDs are also needed, including precise recommendations for temperature control during CIE 127:2007 [5] compliant total flux measurements.
- What do the manufacturers want as a fair and reliable thermal metric to compare products? During the panel discussion at the 14th THERMINIC Workshop in September 2008 in Rome there was an agreement among participants that the quantity denoted as $R_{\mathrm{th\_real}}$ in section 2 was acceptable.
- What do trained end-users want, and can this be realized by the manufacturers? The above panel discussion concluded the following:
    - A component datasheet should contain sufficient and reliable data to be able to predict performance and reliability of the system.
    - Datasheet values should have relevance for any application (such as compact thermal models for electronic devices).

  - Not only thermal performance but also the thermal link to optical performance and reliability should be described, e.g. besides luminous efficacy, radiant efficiency should also be reported.

Further questions to be addressed in more detail:

- How to combine recommendations of JEDEC JESD51-1 and CIE 127:2007 in order to measure LEDs' ‘thermal’ power?
- How to deal with non-uniform and non-unique die temperatures? How to tackle multiple heat-sources?
- How to cope with pulsed-type thermal measurements? How to relate the short-pulse LED test results to properties that can be measured under steady-state operating conditions?

5. STEPS TAKEN SO FAR, PERSPECTIVES

Steps taken so far include forming a task group in the JEDEC JC15 committee to deal with the topic. As described in the previous section, with additional guidelines existing measurement standards seem to be applicable to thermal testing of high power LEDs. Development of such guidelines is already in progress in the JEDEC JC15 committee. CIE has also formed two new technical committees dealing with thermal issues related to LED testing. With some coordination between these activities hopefully a set of consistent and comprehensive guidelines and recommenddations for thermal related measurement issues of power LEDs will emerge in the near future.

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Temperature dependent thermal resistance in power LED assemblies and a way to cope with it

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Abstract

Different high-end white power LEDs from different LED vendors were studied. The aim of the study was to find the optimal choice of LEDs and thermal management solutions for a street-lighting application. The primary concern was the (real) junction-to-heatsink thermal resistance of the LED or LED assembly and the real junction temperature and the actual light output of the individual LEDs under test. Since in many cases the junction-to-heatsink thermal resistance showed temperature dependence, like-with-like comparison in terms of light output characteristics was done as function of the real junction temperature instead of the reference temperature.

Keywords

LED thermal management, junction temperature of LEDs

1. Introduction

As it is widely know, the light output characteristics of light emitting diodes (LEDs) strongly depend on the operating conditions. The forward current applied to the LEDs is the primary variable – the higher the supplied current, the more light is generated by the LED. Unfortunately when a LED is driven by a constant current source the light output drops when the temperature of the LED increases. This general feature of all LEDs is best illustrated by the dependence of their light output spectra – as shown in Figure 1. In addition to efficiency drop, the color of the LEDs' light also changes as it is shown by the shift of the peak wavelength.

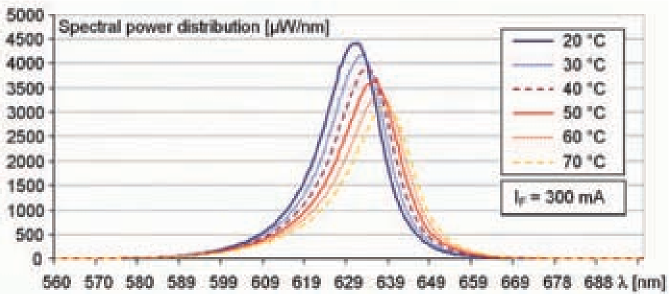


Figure 1: Current and temperature dependence of the spectral distribution of the light output of a red LED

Since light output characteristics change with temperature, proper thermal management is a key issue in power LED-based lighting applications. By keeping LEDs cool, high efficiency can be maintained. A thermal management solution that delivers better cooling also delivers more useful lumens in a given application.

This means that the real junction-to-ambient thermal resistance of the LEDs in their application environment is key factor in lighting design. Unfortunately different LED vendors report their products' thermal resistance and other temperature-related characteristics in diverse ways. Therefore standardization activities related to thermal issues of power LEDs were started in various thermal standardization bodies. A new standard for the proper measurement of LEDs' thermal resistance is currently being drafted by the JEDEC JC15 committee. This work relies on a whitepaper first published in 2008 [1] and updated several times in 2009 [2][3]. In addition to this, the International Lighting Committee (CIE) set up new technical committees (TC-2-63 and TC-2-64) to deal with the thermal aspects of LEDs. Among these committees an agreement is emerging that vendors need to consider the actual P_{opt} emitted optical power (that is, the radiant flux denoted as Φe) of the LEDs when calculating thermal resistance per the following formula:

$$R_{th\_real} = \Delta T_j \,/\, (I_F \times V_F - P_{opt}). \qquad (1)$$

Here the product of the LED's forward current and forward voltage ($I_F \times V_F$) represents the electrical power supplied to the LED and ΔT_j denotes the change of the LED chip's junction temperature as a response to the change of heating power. Precise discussion of LEDs' thermal resistance can be found e.g. in [2] or in [3].

Neglecting the optical power when determining an LED's thermal resistance yields values which are much lower than reality. If lighting designers use these numbers to calculate the expected light output of their LED-based lighting applications, the design will very likely fail to meet its light output specs. The real thermal resistance is higher, and therefore the junction temperatures will also be higher. As a result the actual luminous flux obtained from the luminaire will be below the required level. Clearly the real thermal data of the LEDs is essential to a successful LED design project.

The aim of the present study was to find the optimal choice of LEDs and thermal management solutions for a streetlighting application. The primary concern was the (real) junction-to-heatsink thermal resistance of the LED or LED assembly. Also, the temperature dependence of the light output characteristics was of major concern, since the useful lumens prescribed by the relevant national and European lighting standards had to be assured at all possible operating temperatures of the luminaire.

2. Devices under test

2.1. Aim of the study

The aim of the study was twofold. On one hand we tried to find a thermal management solution for the chosen power LEDs which had the best price/performance ratio considering also the manufacturability of the final product (street-lighting luminiare). On the other hand, the junction temperature dependence of the light output characteristics of the chosen LEDs was of major concern since even under the worst case operating conditions (highest possible luminaire temperature) the road surface illuminance level prescribed by the relevant lighting standards had to be assured.

From the point of view of the comparison of the different thermal management solutions, a precise like-with-like comparison was needed. Therefore the measurements had to provide the real junction-to-heatsink thermal resistance values (as per Eq 1). Structure function analysis of the measured thermal impedances was performed in order to allow the comparison of the different material and assembly combinations.

The measured light output characteristics were all re-scaled from the reference temperature to the junction temperature. Junction temperature was obtained as follows:

$$T_j = T_{ref} + R_{th\_real} \cdot (I_F \times V_F - P_{opt}). \qquad (2)$$

Plotting the light output characteristics (such luminous flux or efficacy) as function of the real junction temperature, again, allows like-with-like comparisons by absorbing the effect of the chosen thermal management solution. On one hand it allows to compare the LED samples of the same manufacture (providing information about the scatter of a parameter of a given product). On the other hand, LEDs from different vendors can also be compared in terms of their performance (e.g useful lumens at operating temperatures).

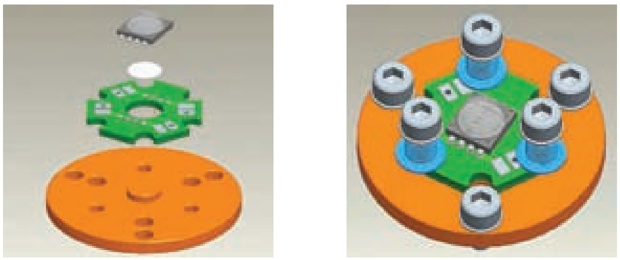
2.2. Different heat-flow path assemblies

Different high-end white power LEDs from different LED manufacturers have been studied. Here we present the measurement results for one particular vendor's multi-chip LED which is among the candidates for the final LED choice for the targeted street-lighting application. Based on these measurements the best thermal management solution was chosen and the temperature dependence of the light output characteristics was provided for the subsequent design steps such as optics design and system level thermal design.

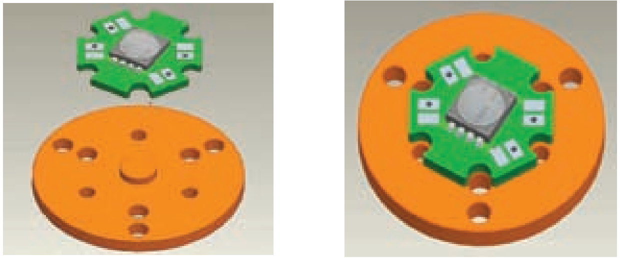
Different types of assemblies provided by the LED system integrator which were studied are as follows:

1. LED attached to an FR4 based PCB with a thermal contact hole in the middle, attached to a Cu heat-spreader block, high thermal conductivity TIM (Laird Technologies T-grease 2500 [4]) applied between the Cu block and the heat-slug of the LED package (as per Figure 2a);
2. The same setup as above (as per Figure 2a), but using a phase-change TIM (Laird Technologies T-pcm FSF-52 [5]);
3. LED attached to an FR4 based PCB with a thermal contact hole in the middle, the LED's heat-slug soldered to the Cu heat-spreader block underneath (as per Figure 2b);
4. Packaged power LED attached to an Cu-based MCPCB (as per Figure 2c) and a TIM layer applied between the MCPCB and the heat-slug;
5. same as #4, but using an Al-based MCPCB.

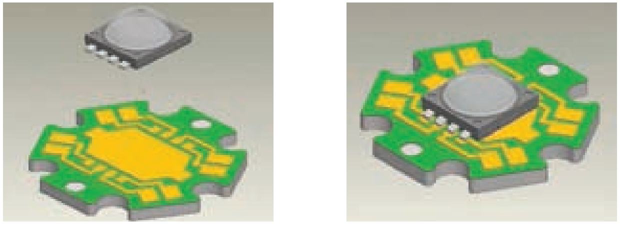
Photographs of the assembled test samples are shown in Figure 3.



a: FR4 PCB, TIM between the heat-slug and the Cu block

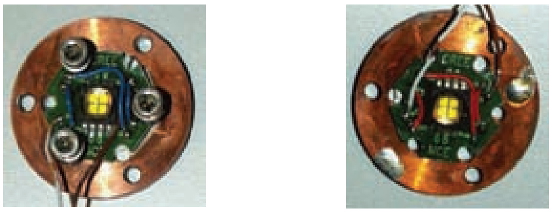


b: FR4 PCB, heat-slug soldered to the Cu block

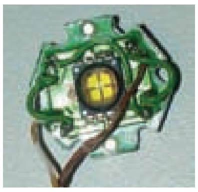


c: MCPCB-s made of Al and Cu, heat-slug soldered

Figure 2: Mechanical setups of the different thermal management solutions which have been studied



a: FR4 + TIM b: FR4 + solder



c: Al / Cu MCPCB + TIM

Figure 3: Mechanical setups of Figure 2 assembled with Cree Xlamp MCE1 series white LEDs

3. Test setups

In all of the cases the LED assembly was attached to a temperature controlled stage (cold-plate) which was aimed to model the effect of the luminaire (large thermal capacitance). The temperature of the cold-plate was varied between 15°C and 85°C. With this we aimed to mimic the possibly large variation of the temperature of the street-lighting luminaire when exposed to real outdoor environment. (From the LEDs' operation point of view temperatures below 15°C are not critical, since LEDs' performance radically improve at lower operating temperatures.)

Combined thermal and radiometric/photometric measurements were performed, complying with the recommendations of the electrical test method as per JEDEC JESD51-1 [6] and the total flux measurement method for LEDs according to the CIE 127-2007 document [7]. The schematic diagram of the setup is shown in Figure 4. In such a setup electrical power of the LED under test is provided by the thermal test equipment. The light output of the LED is measured when it is driven by its prescribed operating current and is in thermal equilibrium (steady-state) as required by [7]. The reference temperature of the LED under test is the temperature of the cold-plate which is attached to the integrating sphere of the photometric test system.

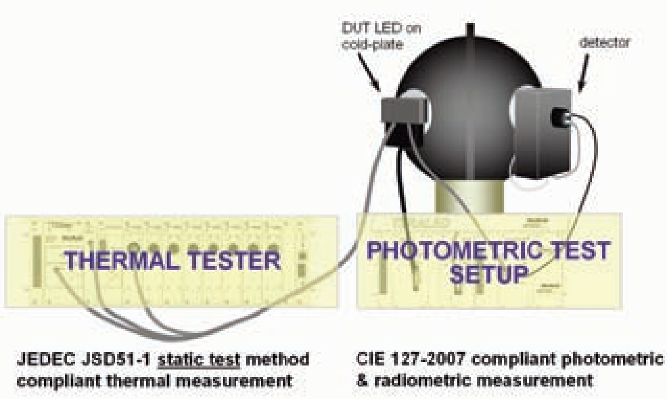


Figure 4: Schematic of the test setup suggested for combined thermal and radiometric/photometric measurement of power LEDs.

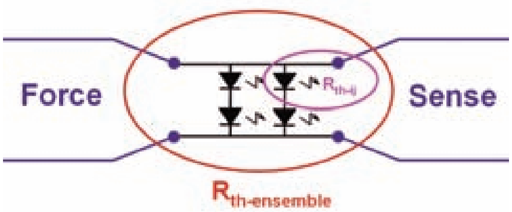


Figure 5: If a multi-chip LED package is not prepared for thermal testability, individual thermal resistances of the single chips can not be identified, only an "ensemble" thermal resistance can be measured.

With a test setup shown in Figure 4 one can make sure that the measured thermal and radiometric/photometric properties of the LED under test are consistent. Quantities ΔT_j, I_F and V_F of Eq. (1) are determined by the thermal test equipment. Quantity P_{opt} (emitted optical power) used in Eq. (1) is measured by the optical test system as the Φ_e *total radiant flux* of the LED under test. Depending on the capabilities of the optical test system, the Φ_V *total luminous flux* or the color coordinates of the LEDs light can also be measured. Thermal resistance and light output measurements can be performed for a given set of temperature and forward current values by setting electrical power level in the thermal test equipment and setting the T_{ref} temperature of the cold-plate.

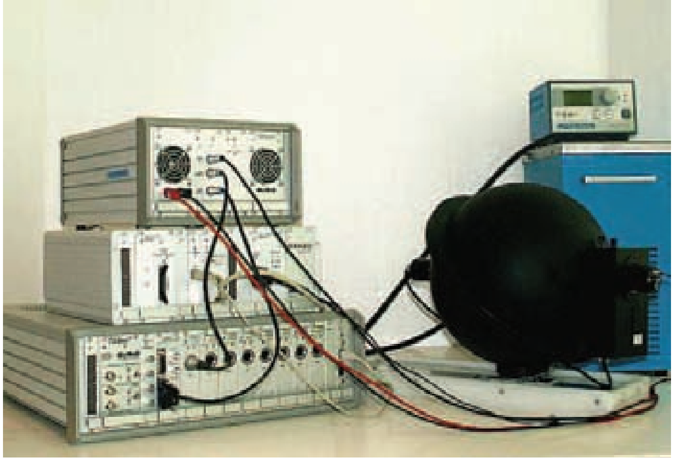


Figure 6: The actual physical test setup used to measure high power LED samples.

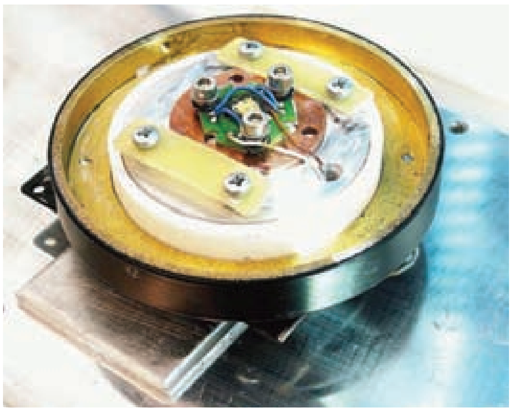


Figure 7: Test sample attached to water cooled cold-plate with a mechanical adaptor of the integrating sphere.

We had to measure LED packages with multiple chips connected in series (Xlamp MCE1 series of white LEDs from Cree – see Figure 3). In such cases one can measure the overall or "ensemble" thermal resistance of all the chips only, since the individual chips are not accessible for thermal testing. In case of the above mentioned Cree LEDs both the powering and the heat-sinking capabilities of our standard test equipment were exceeded. Therefore the Peltier-based temperature controlled DUT LED holder of the integrating sphere was replaced by a water cooled cold-plate and the thermal test equipment was extended with an appropriate power booster unit. The actual physical test setup is shown in Figure 6 and Figure 7.

4. Measurement results

10 samples of Cree Xlamp MCE1 series of white LEDs have been prepared and measured. From each assembly type (detailed in section 2) two samples were available for testing. All of the type 3 samples burnt out during the tests – probably due to the fact that during the soldering the samples suffered a fatal thermal shock. A further sample was also removed from the tests by one of our project partners dealing with optical design. Altogether results for 7 different samples are available and are reported here.

Both the thermal tests and the light output measurements were performed at 15°C, 25 °C, 40 °C, 55 °C, 70 °C and 85 °C cold-plate temperatures, using 350 mA and 700 mA forward current during heating and optical tests. For thermal tests 10 mA sensor current was applied. Optical properties were also measured at the sensor current.

4.1. Thermal measurements

In the following we present measurement results for three typical samples, being assembled in different ways: type 1 (blue line, label TG2500), type 2 (red line, label FSF52) and type 5 (green line, label AL) assemblies – as described in section 2.2.

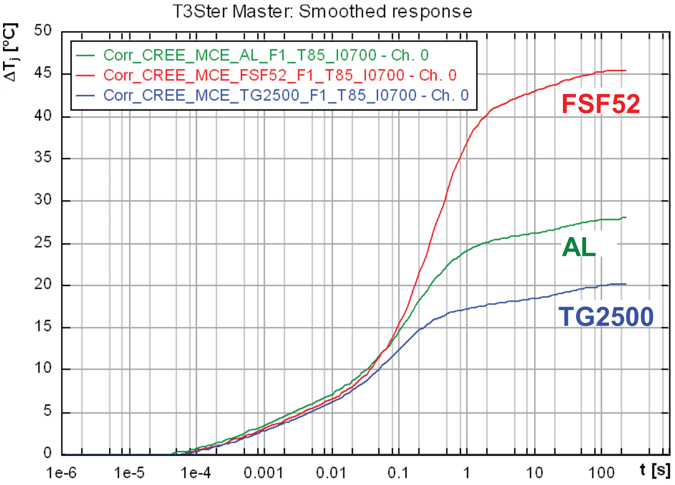


Figure 8: Junction temperature transients for three different assemblies of Cree Xlamp MCE1 series white LEDs (T_{ref}=85 °C, I_F=700 mA).

The junction temperature transients for I_F=700 mA at T_{ref}=85 °C are shown in Figure 8. These plots already suggest, that the type 1 assembly solution posses with the best heat removal property, since this resulted in the smallest junction temperature rise. The junction temperature transients divided by the real heating power (power corrected by emitted optical power) result in the real thermal impedance curves which are shown in Figure 9. From these plots we can already quantify the junction-to-heatsink thermal resistance values for each assembly. The best performing assembly solution is of type 1 (denoted by TG2500 in the result plots) with a thermal resistance value of ~3 K/W. (This value is very close to the data sheet value reported by the LED vendor.)

The thermal impedances can also be represented by means of structure functions as shown in Figure 10. The initial sections of the three structure functions coincide which corresponds to the fact, that the initial section of the three different heat-flow path structures are identical: heat-flow through the LED chip, die attach and the top of the heat-slug of the package. From the structure function plots one can see that there is a huge difference between the two types of TIMs applied by the LED system integrator.

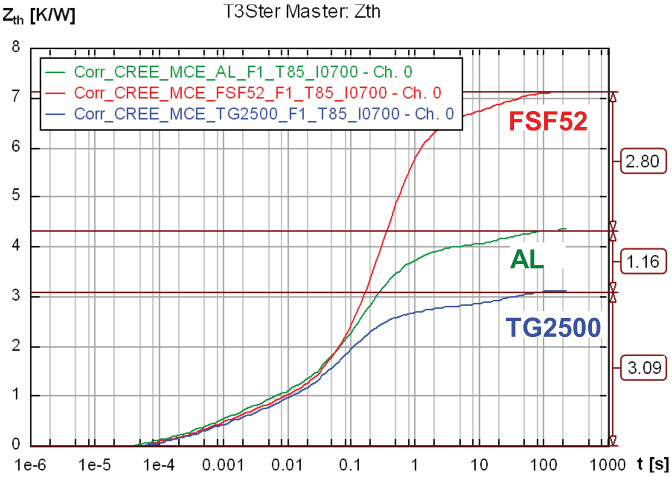


Figure 9: Thermal impedance curves for three different assemblies of Cree Xlamp MCE1 series white LEDs (T_{ref}=85 °C, I_F=700 mA).

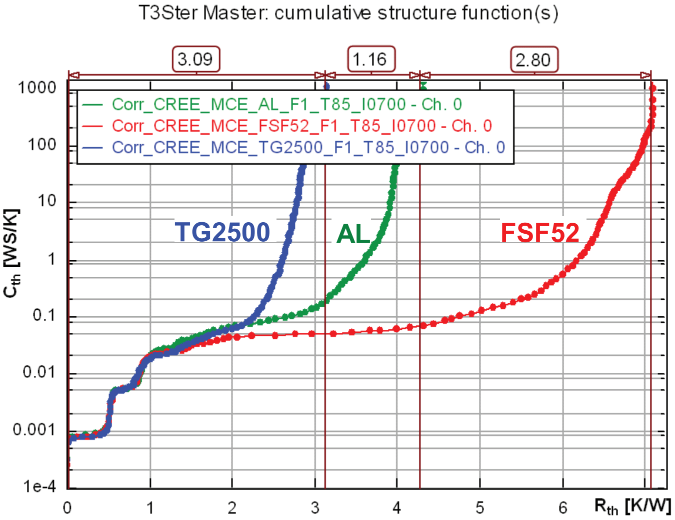


Figure 10: Structure function representation of the thermal impedances of three different assemblies of Cree Xlamp MCE1 series white LEDs (T_{ref}=85 °C, I_F=700mA).

In Figure 11 we present the structure function plots of the 2$^{\mathrm{nd}}$ LED sample assembled on an Al-based MCPCB. Its thermal resistance at T_{ref} =85 °C is 3.9 K/W which is by 0.35 K/W smaller then the thermal resistance of the 1$^{\mathrm{st}}$ sample of this kind (shown in Figure 10). What is interesting to note in Figure 11 is the temperature dependent variation of the thermal resistance of the LED assembly.

Such a temperature variation could be observed in case of all samples we measured. In every case the variation took place in the TIM layers. The tendency is that at higher reference temperatures the total junction-to-heatsink thermal resistance is reduced. This behavior is likely due to viscosity changes of the applied TIMs: at higher temperatures the TIMs fill the microscopic air-gaps of the adjecent interfaces better, resulting in smaller interfacial thermal resistances.

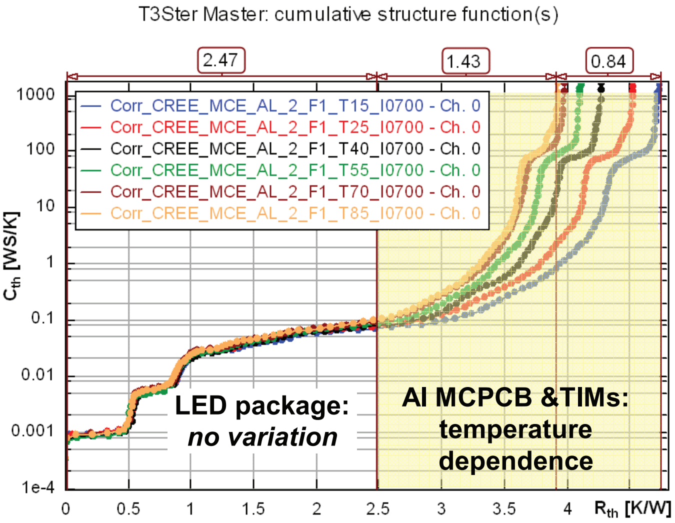


Figure 11: Structure function plots of the thermal impedance of sample marked AL_2 for I_F=700mA and of while T_{ref} vas varied between 15 °C and 85 °C.

The fact, that the total thermal resistance of the LED assembly may vary with the reference temperature highlights the importance that all metrics of power LEDs need to be reported as function of the *real junction temperature*.

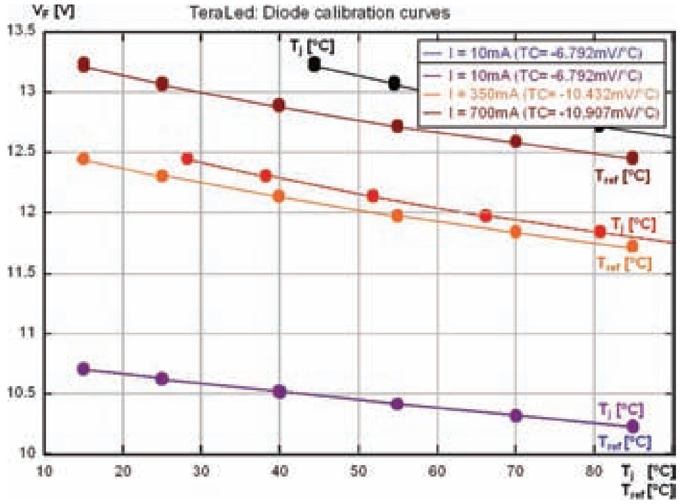


Figure 12: Temperature dependence of a LED's forward voltage at I_F=10mA (plots in the bottom), 350mA (middle plots) and 700 mA (plots on the top) shown as function of reference temperature and as function of junction temperature.

If we assume that the heating power is independent of the temperature (i.e. remains constant) while the reference temperature is increased, then in case of temperature independent thermal resistance any kind of device characteristics plotted as function of the reference temperature and plotted as function of the junction temperature must run parallel. The temperature dependent thermal resistance however, results in different slopes of e.g. the forward voltage plots as shown in Figure 12. At high forward current levels the plots have different slopes depending whether the measured data points are shown as function of the junction temperature (higher slope) or if they are shown as function of reference temperature. In case of the 10 mA sensor current however, since no significant self-heating took place at the junction, the two curves and the two slopes are identical. Again, this fact suggests that reporting of any LED device characteristic makes sense as function of the junction temperature. By doing so the effect of the temperature dependent thermal resistance can be eliminated.

4.2. Optical measurements

The usual photometric/radiometric parameters of the LEDs have been measured in our combined test setup: total radiant flux (also known as radiometric flux or emitted optical power), the total luminous flux and the color coordinates of the emitted light. From the measured color coordinates the correlated color temperature of the white LEDs was also calculated. We also calculated the energy conversion efficency and the efficacy from the measured radiant and luminous flux values, respectively.

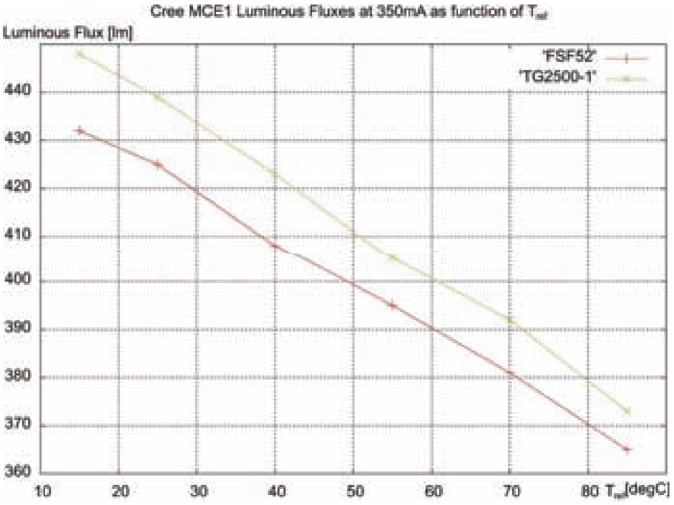


Figure 13: Luminous flux plots of Cree Xlamp MCE1 series white LEDs with two different assembly types as function of T_{ref} reference temperature (I_F=350 mA).

In Figure 13 luminous flux plots of two samples with different assemblies (thus, with different temperature dependent junction-to-heatsink thermal resistances) are shown as function of the reference temperature. As discussed in the last paragraph of section 4.1 these plots have an offset and have different slopes – as clearly seen in Figure 13. After re-scaling to junction temperature, the luminous flux diagrams of the two LED samples of the same manufacture coincide, as seen in Figure 14. Again, by re-scaling the plots of measured data points to the real junction temperatures of the devices we get rid off of the effect of the different temperature dependent thermal resistances..

In Figure 15 luminous flux plots of all measured samples with 4 kinds of different assemblies are shown as function of the junction temperature. Figure 16 presents the calculated efficacy values of the measured LEDs. Since by re-scaling the measured data to junction temperature the effect of the variations in thermal resistances is eliminated, the scatter among the plots corresponds to the scatter among the measured LED samples. We have to note, that the measured performance is better for all measured samples then the data sheet values published by the particular LED vendor.

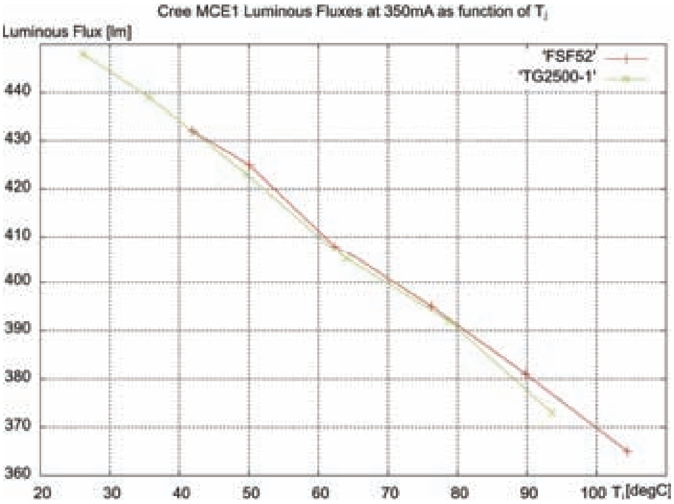


Figure 14: Luminous flux plots of Cree Xlamp MCE1 series white LEDs with two different assembly types as function of T_j junction temperature (I_F=350 mA).

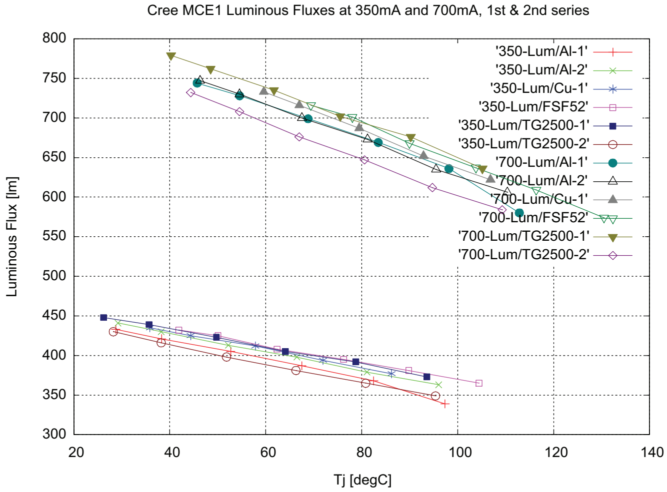


Figure 15: Luminous flux plots of 7 different samples of Cree Xlamp MCE1 series of white LEDs as function of junction temperature at 350mA (plots in the bottom) and 700mA (plots in the top) forward current

5. Conclusions

Different assembly solutions for a high power multi-chip white LED device were studied. Combined thermal and optical measurements were performed, this way the real thermal resistance of the different assembly solutions was identified and the real junction temperatures were calculated. This allowed a like-with-like comparison of the different assembly solutions. Temperature dependence of the measured thermal resistances was also observed. Its effect, however, could be eliminated by re-scaling all measured data to junction temperature. Again, this allows a fair like-with-like comparison among LED samples of the same manufacture or among LEDs of different vendors.

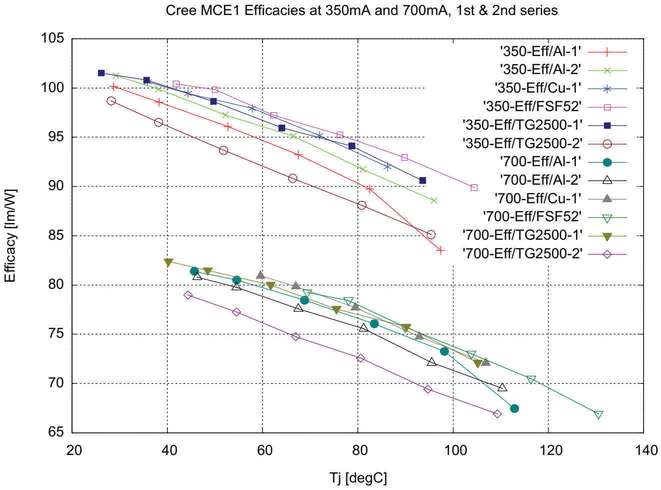


Figure 16: Luminous efficiency (efficacy) plots of 7 different samples of Cree Xlamp MCE1 series of white LEDs as function of junction temperature at 350mA (plots in the bottom) and 700mA (plots in the top) forward current

Acknowledgments

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Motivation

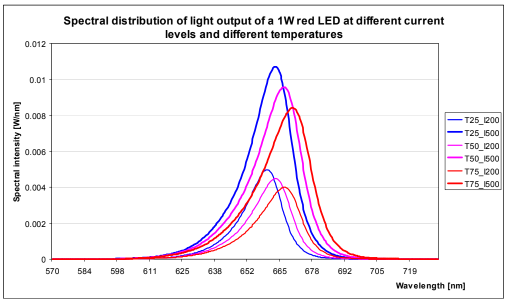
- The **KÖZLED poject** of the Hungarian National Technology Research and Development Office
  - Development of energy efficent LED based street lighting luminaires
- Our partners in the project
  - **HOFEKA** Ltd.: local manufacturer of street lighting luminaires (120+ years of expertise in Budapest)
  - **OptimalOptik** Ltd.: BME spin-off specialized in optics design
  - **HungaroLux** Ltd.: specialized in driver electronics for LED based lighting applications
  - **University of Pannonia** (Veszprém, Hungary): European center of excellence in lighting research

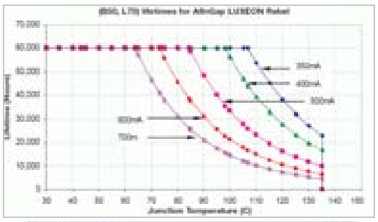
Motivation of the project

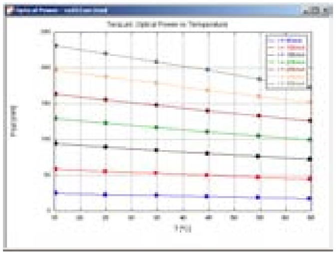
- ►Most of LED based street lighting luminaires do not comply with street lighting standards (EU/HU)
  - 20 different products were purchased and measured (using goniometry)
  - much difference from shape and uniformity of illumination
    - also a common issue in case of household retrofit solutions
- ►**Problems that we deal with within KÖZLED:**
  - Unrealiable binning of LEDs:
    - Luminous flux, color temperature measured at a temperature which is believed to be $T_j = 25^oC$ while LEDs' operational temperatures are much higher
  - Asses thermal performance of LED assemblies
  - Little information on reliability / life time data
  - What color temperature is the best for mesopic vision?

Why to deal with thermal issues?

- ► Reliability is connected to thermal issues
  - life time (failure mechanisms are thermally assisted)
  - mechanical stress
- ► Optical properties strongly depend on temperature
  - spectra
  - emitted flux / efficiency / efficacy





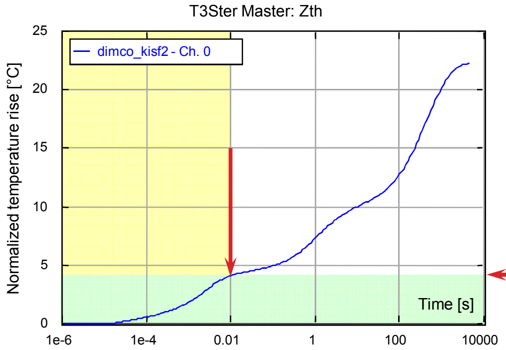


No doubt that **reliable thermal data** is a must for power LED based designs

Short pulse measurements (used for binning)

- During in-line testing photometric/colorimetric properties are measured with a short pulse
  - $T_J = T_{ref}$ = constant is assumed, ***THIS IS NOT TRUE:***
    In 10 ms significant junction temperature change may take place

Artifact!

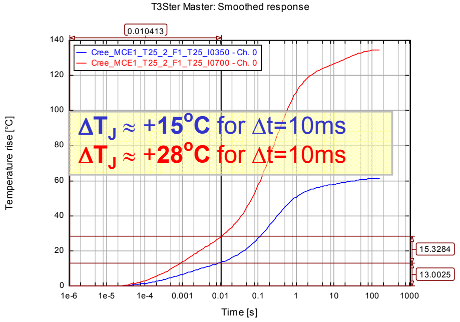


Question is if this causes big problems or not…

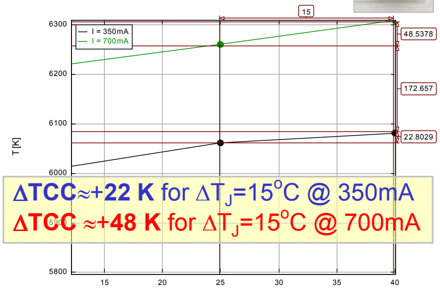
During 10 ms T_J changes almost by ~5 ^{o}C (3W device)

A 3 W LED measured in a retrofit MR16 luminaire

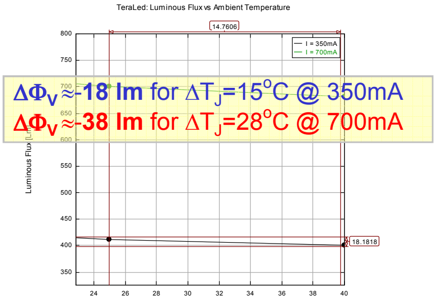
Example: 10W Cree MCE white LED



$\Delta T_J \approx +15^{o}$C for Δt=10ms
$\Delta T_J \approx +28^{o}$C for Δt=10ms



ΔTCC≈+22 K for ΔT_J=15^{o}C @ 350mA
ΔTCC ≈+48 K for ΔT_J=15^{o}C @ 700mA



$\Delta\Phi_V \approx$-18 lm for ΔT_J=15^{o}C @ 350mA
$\Delta\Phi_V \approx$-38 lm for ΔT_J=28^{o}C @ 700mA

~38 lm drop in luminous flux / LED may result in failing the compliance test of the luminaire

Our tasks within the project

- **Provide real thermal resistance data for all LED types** which are candidates for application within the project
  - 1st selection: data sheet values of luminous flux and efficacy
  - 2nd selection: optical properties (spatial distribution of light)
  - 3rd selection: thermal resistance
- Check **temperature dependence of emitted light**
- Evaluate **thermal management solutions**

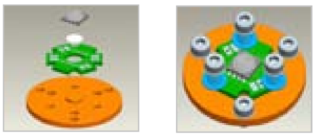
A case study from the project: Cree MCE LEDs

- Products of 5 LED vendors were measured
- Based on initial data a few LED types were selected for further consideration
- Different assembly types with **different PCB and TIM solutions** were designed, built and tested
  - Selection criteria:
    - thermal performance
    - manufacturability of luminaire,
    - costs
- 3 types of assemblies of Cree’s MCE 10W LED products, four different types of samples
  - 2 samples from each ➔ *performance of solutions*
  - 8 samples of the same LED type ➔ *scatter of LEDs*

The measured samples of Cree MCE 10W LEDs

► 3 different kinds of assemblies:

- FR4 PCB, TIM between the heat-slug and the Cu block



- FR4 PCB, heat-slug soldered to the Cu block

- MCPCB-s made of Al and Cu, heat-slug soldered

CAD images by courtesy of OptimalOptik Ltd.

Definition of R_{th} for power LEDs

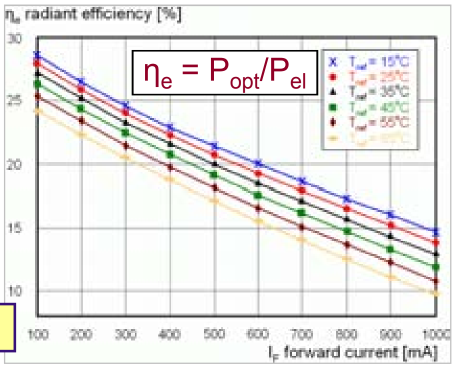
► Traditionally: $R_{th\text{-}el} = \Delta T_J / \Delta P_{el} = \Delta T_J / (\Delta I_F \times V_F)$

► Due to high efficiency, radiant flux must be considered:

$$R_{th\text{-}real} = \Delta T_J / (\Delta P_{el} - P_{opt}) = \Delta T_J / (\Delta I_F \times V_F - P_{opt}) =$$
$$= \Delta T_J / [\Delta P_{el} \cdot (1 - \eta_e)]$$

Radiant efficiency – is not a single number

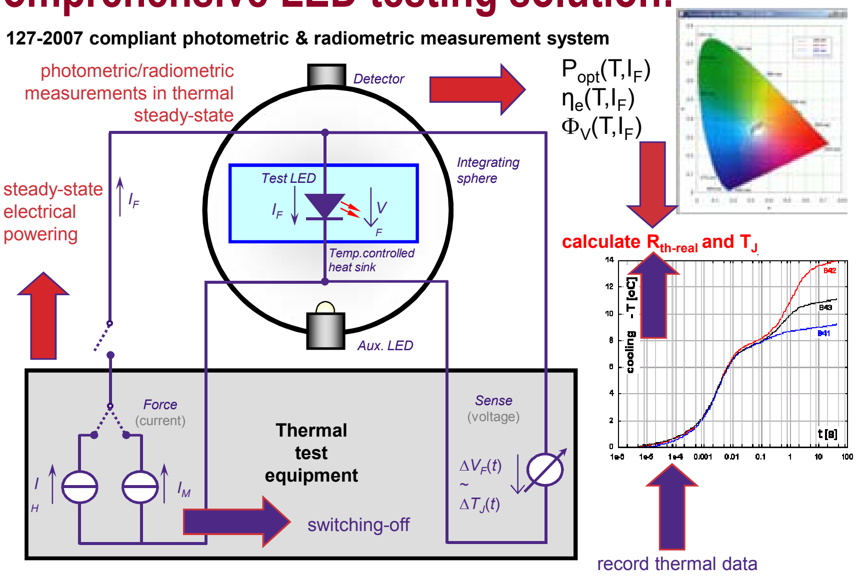
Set of such plots must be published for typical operating conditions.



$$R_{th\text{-}el}(I_F, T_J) = R_{th\text{-}real} \cdot [1 - \eta_e(I_F, T_J)]$$

Comprehensive LED testing solution:

CIE 127-2007 compliant photometric & radiometric measurement system



photometric/radiometric measurements in thermal steady-state

steady-state electrical powering

$P_{opt}(T,I_F)$
$\eta_e(T,I_F)$
$\Phi_V(T,I_F)$

calculate $R_{th\text{-}real}$ and T_J

switching-off

record thermal data

JEDEC JSD51-1 static test method compliant thermal measurement system

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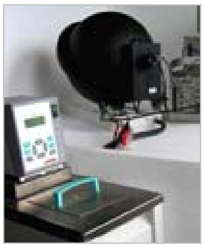
Test environment

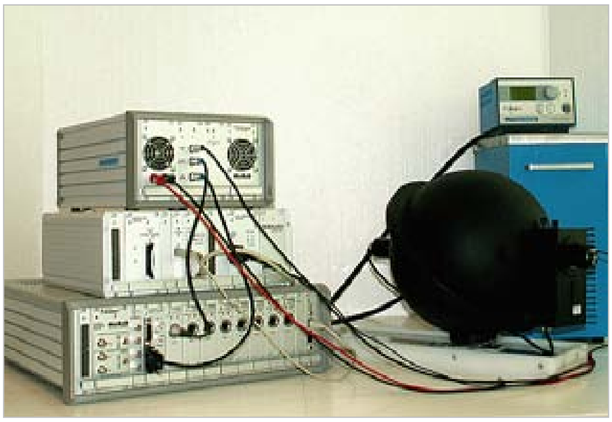
- ► Due to high dissipation, liquid cooled cold plate was used:

- ► Fixture on the cold plate holds the sample and accommodates the integrating sphere



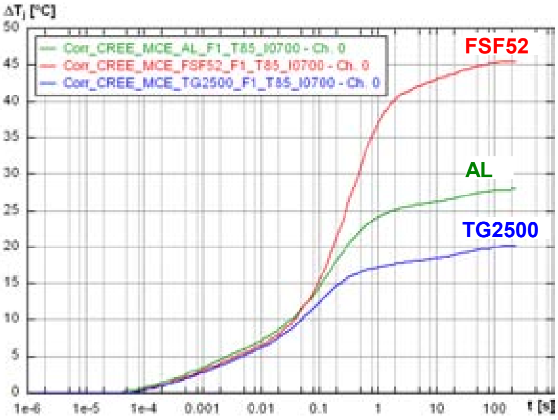
The entire system in practice

- ►Special LED booster provided the appropriate voltage at specified current



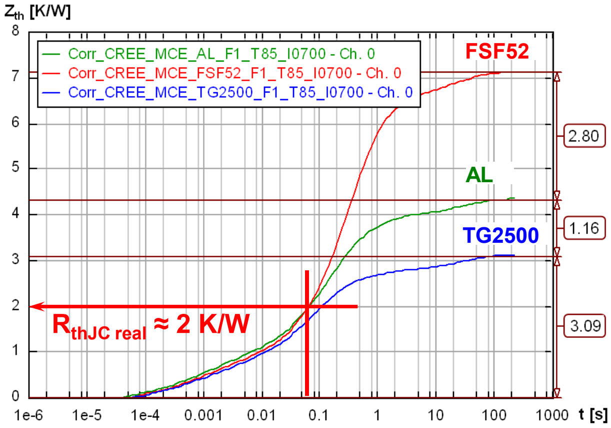
Results for 10W Cree MCE white LEDs

- ► Measured at 700 mA and 85^{o}C
  - Junction temperature change (wrt. T_{cp})



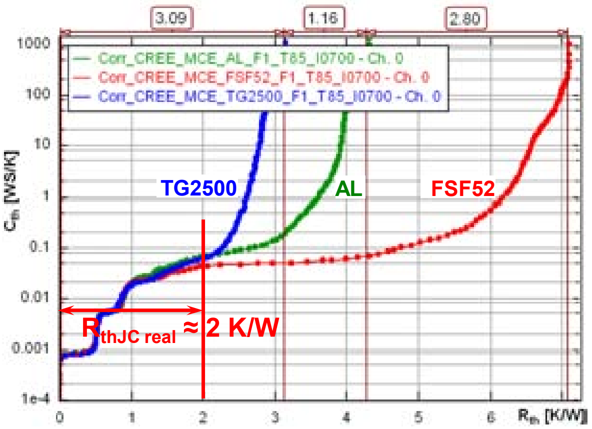
Results for 10W Cree MCE white LEDs

- ▶ Measured at 700 mA and 85°C
  - Thermal impedance of 3 samples, power corrected with P_{opt}



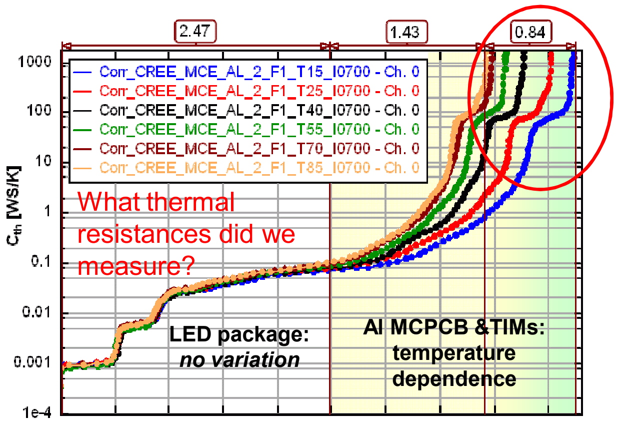
Results for 10W Cree MCE white LEDs

- ▶ Measured at 700 mA and 85°C
  - Structure functions of 3 samples, power corrected with P_{opt}



Results for 10W Cree MCE white LEDs

- Measured at 350/700 mA & between 15ºC and 85ºC
  - Structure functions of sample AL-2, power corrected with P_{opt}



What thermal resistances did we measure?

Fact or artifact?

$R_{thJC\text{-}package} + R_{th\text{-}MCPCB} + R_{th\text{-}grease}$ ➔ for "**hot lumen**" estimates

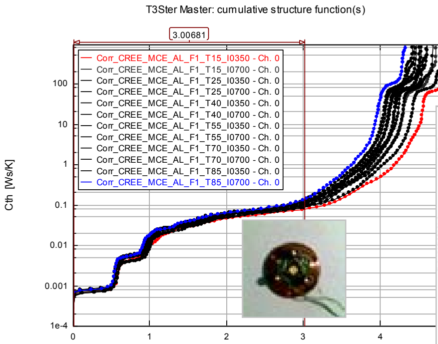
---

What R_{th}-s did we measure?

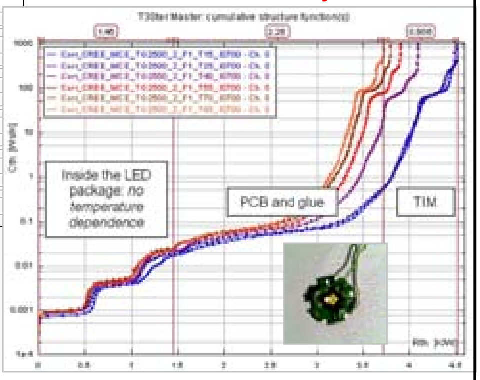
- On one hand, the real **R_{thJC}** of the package was identified in a ***dual interface technique*** like manner
  - Temperature changes resulted in different qualities of the TIM material
  - Both in the ***Z_{th} curves*** and in ***structure functions*** the identified real R_{thJC} values were very close to the data sheet values
- On the other hand, the total real $R_{thJ\text{-}cp}$ ***junction to cold-plate thermal*** resistance was also identified which is a ***good approximation of the junction-to-luminaire thermal resistance*** in the final application
  - Temperature dependence is in the right direction: for higher temperature we have lower thermal resistance

R_{th} of 10W Cree MCE white LEDs

- ► Measured at 350/700 mA & between 15°C and 85°C
  - Corrected with emitted optical power



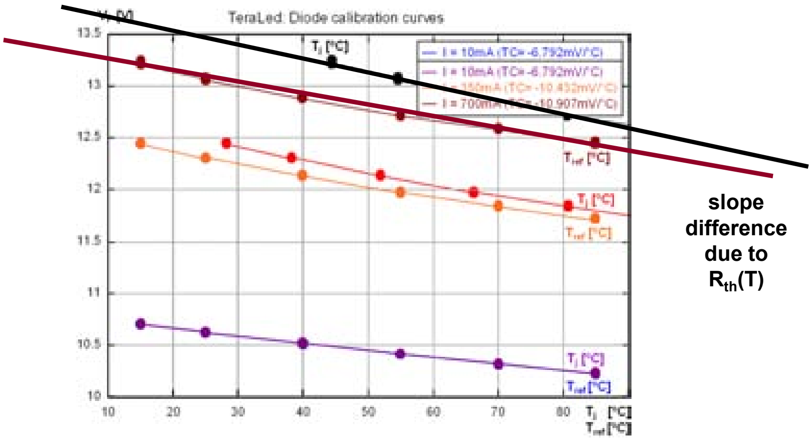
4 different thermal management solutions were studied for the LED assembly



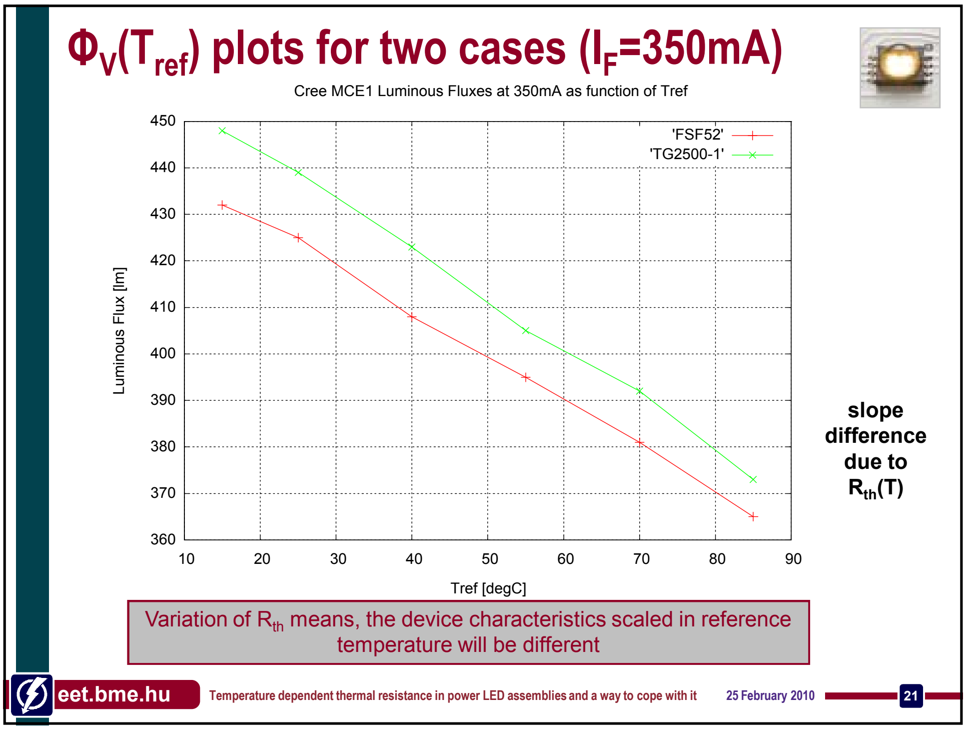
Temperature dependence of R_{th} means, the device characteristics scaled in reference temperature will be different even for the same device.

Results for 10W Cree MCE white LEDs

- ► Temperature dependence of a LED's forward voltage at reference and junction temperature: slight slope difference



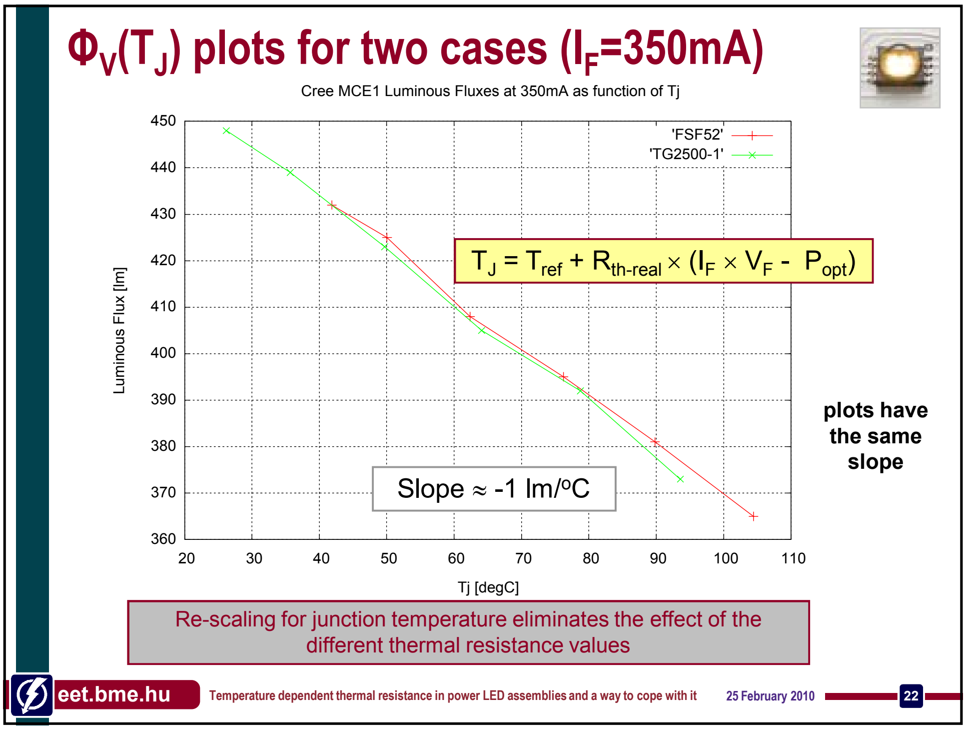
slope difference due to $R_{th}(T)$



$\Phi_V(T_{ref})$ plots for two cases (I_F=350mA)

slope difference due to $R_{th}(T)$

Variation of R_{th} means, the device characteristics scaled in reference temperature will be different



$\Phi_V(T_J)$ plots for two cases (I_F=350mA)

$T_J = T_{ref} + R_{th\text{-}real} \times (I_F \times V_F - P_{opt})$

Slope ≈ -1 lm/°C

plots have the same slope

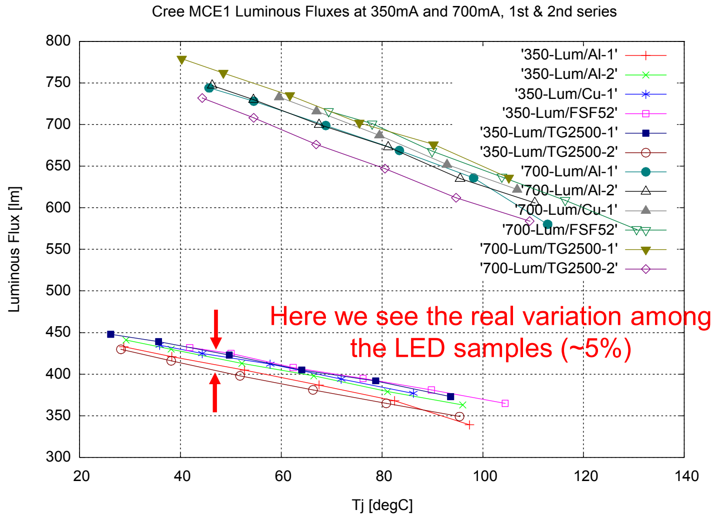
Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

Light output metrics and junction temperature

- Since the total thermal resistance of a given LED assembly may show considerable temperature dependence, one has to make sure that in every measurement
  - The reference temperature is set and recorded
  - Actual heating power is identified: $I_F \times V_F - P_{opt}$
  - Thermal resistance of the setup is known,
    - The setup is left mechanically intact while light output metrics are being measured
  - **Junction temperature is known and reported**

    $T_J = T_{ref} + R_{th\text{-}real} \times (I_F \times V_F - P_{opt})$
- All **light output metrics are always reported as function of forward current and junction temperature**

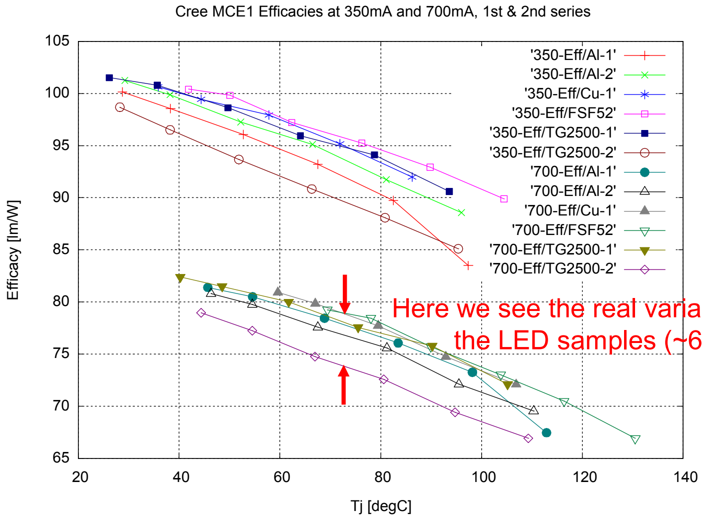
$\Phi_V(I_F,T_J)$ plots for 7 different samples



Here we see the real variation among the LED samples (~5%)

Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

$\eta_V(I_F,T_J)$ plots for 7 different samples



Here we see the real variation among the LED samples (~6.25%)

Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

---

Some conclusions

- Existing data sheets do not provide sufficient information
  - e.g. for thermal design, *efficiency data* are also required, efficacy is of no help for thermal design
  - published light output metrics do not refer to actual operating conditions (temperature)
- Agreement on the way of obtaining **LEDs' junction temperature** is needed
  - Reported metrics (e.g. luminous flux) should refer to this
  - **Suggested method:** $T_J = T_{ref} + R_{th\text{-}real} \cdot \Delta P_H$
- For a particular design project, **combined thermal and optical measurements were performed**, this way the **real thermal resistance** of the different assembly solutions was identified and the real junction temperatures were calculated.
  - **different cooling solutions were evaluated**
- **Temperature dependence of the measured thermal resistances was observed** – according to structure function analysis these are due to the applied TIM2 material

Some conclusions

- **Effect of temperature dependent thermal resistance was eliminated by re-scaling all measured data to junction temperature.**
  - This way like-with-like comparison of light output characteristics became possible both within the studied population of LEDs and with other vendors' products
  - Data about scatter of light output properties was also obtained
  - Measured performance of the particular LED package (R_{thJC}) was found to be slightly better than reported on data sheet
- Good **approximate models** of the entire heat-flow path **for luminaire level thermal simulations** were created

Acknowledgment

- This work was partially supported by the **KÖZLED** TECH_08-A4/2-2008-0168 project of the Hungarian National Technology Research and Development Office.

András Poppe: Standardization Issues and Progress in LED Measurement. In: Collection of lecture notes of the International LED and Green Lighting Seminar 2010, June 22-24 2010, KINTEX, Seoul, Korea, Booklet Day 1 (2010), pp. 249-279. (http://mycite.omikk.bme.hu/doc/89070.pdf)

Standardization Issues and Progress in LED Measurement

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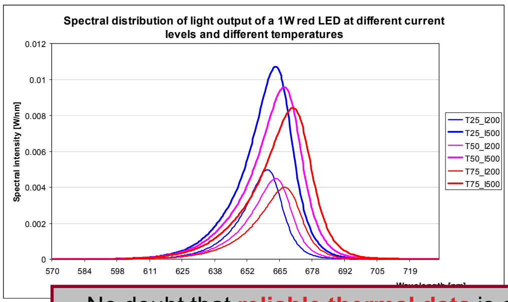
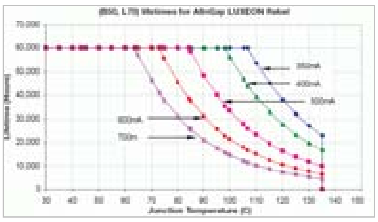
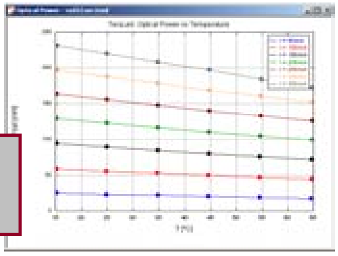
Why to deal with thermal issues?

- Reliability is connected to thermal issues
  - life time (failure mechanisms are thermally assisted)
  - mechanical stress
- Optical properties strongly depend on temperature
  - spectra
  - emitted flux / efficiency / efficacy







No doubt that **reliable thermal data** is a must for power LEDs: widely accepted **standards are needed**

Main drive for thermal characterization from a *manufacturer* point of view

- Fair comparison with competitors' data
- *In an ideal world:* provide *real* support for customers

from a *customer* point of view

Are temperatures within specs?

Starting point:

$$T_J = R_{th\ J\text{-}refX} \cdot P + T_X \qquad (1)$$

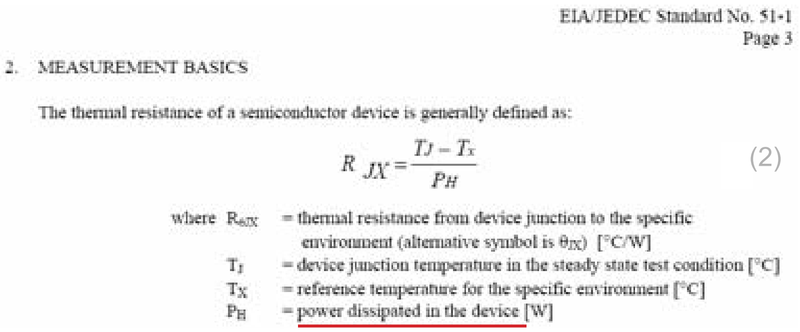
- T_X **from (often unspecified) measurements** *(own responsibility)*
- P **from estimated power dissipation** *(own responsibility)*
- $R_{th\ J\text{-}X}$ **from component datasheets** *(other's responsibility)*

If $T_{J\ calculated} > T_{specification}$ ⇒ *Redesign!*

- In case of lighting: *specified lumens at operating temperature*

A few words about thermal resistance

- Rearrange the equation: $R_{th\ J\text{-}X} = (T_J - T_X)/P$
- Original definition in the JEDEC JESD51-1 document



EIA/JEDEC Standard No. 51-1
Page 3

2. MEASUREMENT BASICS

The thermal resistance of a semiconductor device is generally defined as:

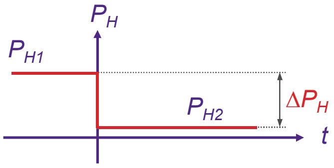
$$R_{JX} = \frac{T_J - T_X}{P_H} \qquad (2)$$

where $R_{\theta JX}$ = thermal resistance from device junction to the specific environment (alternative symbol is θ_{JX}) [°C/W]
T_J = device junction temperature in the steady state test condition [°C]
T_X = reference temperature for the specific environment [°C]
P_H = power dissipated in the device [W]

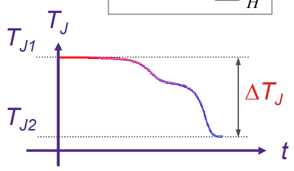
- Accurate; the questions are:
  - what is the dissipated power? *Issue for LEDs…*
  - what is the T_X reference temperature *Use cold plate!*

A few words about thermal resistance

- Alternate formulation: instead of spatial difference, let us build a ***temporal difference:***



$$R_{thJ-X} = \frac{\Delta T_J}{\Delta P_H}$$



$R_{th\ J\text{-}X}(t) = \Delta T_J(t) / \Delta P_H$

is called **Z_{th} curve**

$T_{J1} = R_{th\ J\text{-}X} \cdot P_{H1} + T_X$ (3a)

$T_{J2} = R_{th\ J\text{-}X} \cdot P_{H2} + T_X$ (3b)

$T_{J2} - T_{J1} = R_{th\ J\text{-}X} \cdot (P_{H2} - P_{H1})$ (4)

Let $T_{J1} = T_J(t_1)$ and $T_{J2} = T_J(t_2)$:

$R_{th\ J\text{-}X} = [T_J(t_2) - T_J(t_1)] / (P_{H2} - P_{H1})$ (5)

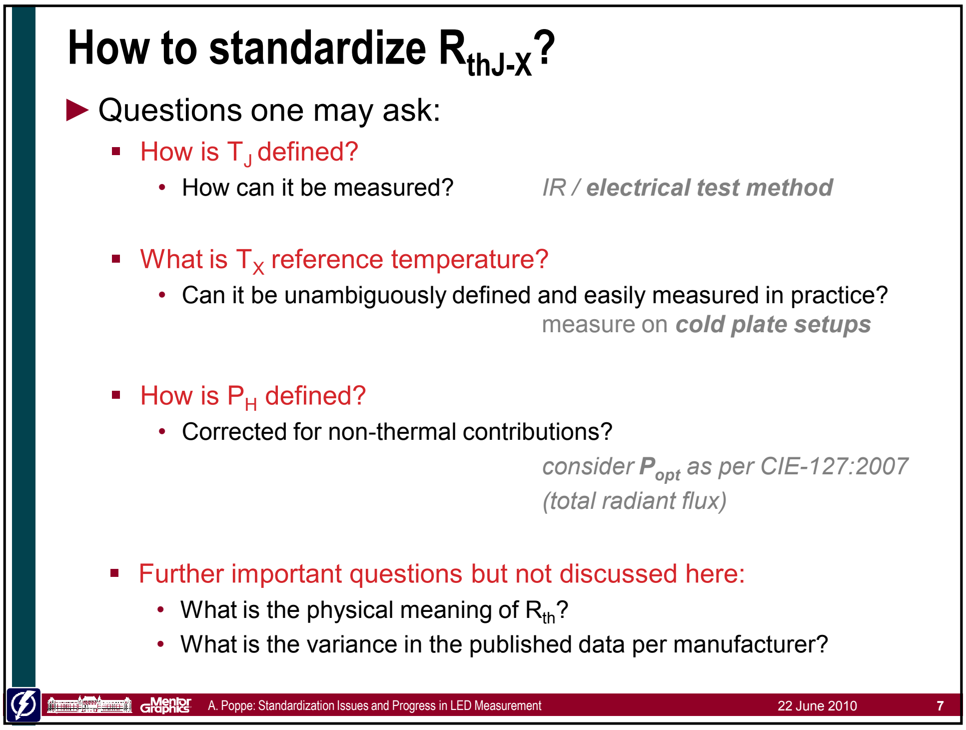
$\mathbf{R_{th\ J\text{-}X} = \Delta T_J(t) / \Delta P_H}$ (6)

If $t_1 = 0$ and $t_2 = \infty$ ➔ $\boxed{R_{th\ J\text{-}X} = \Delta T_J / \Delta P_H}$

If $P_{H2} = 0$, then $T_{J2} = T_X$ – see (3b)

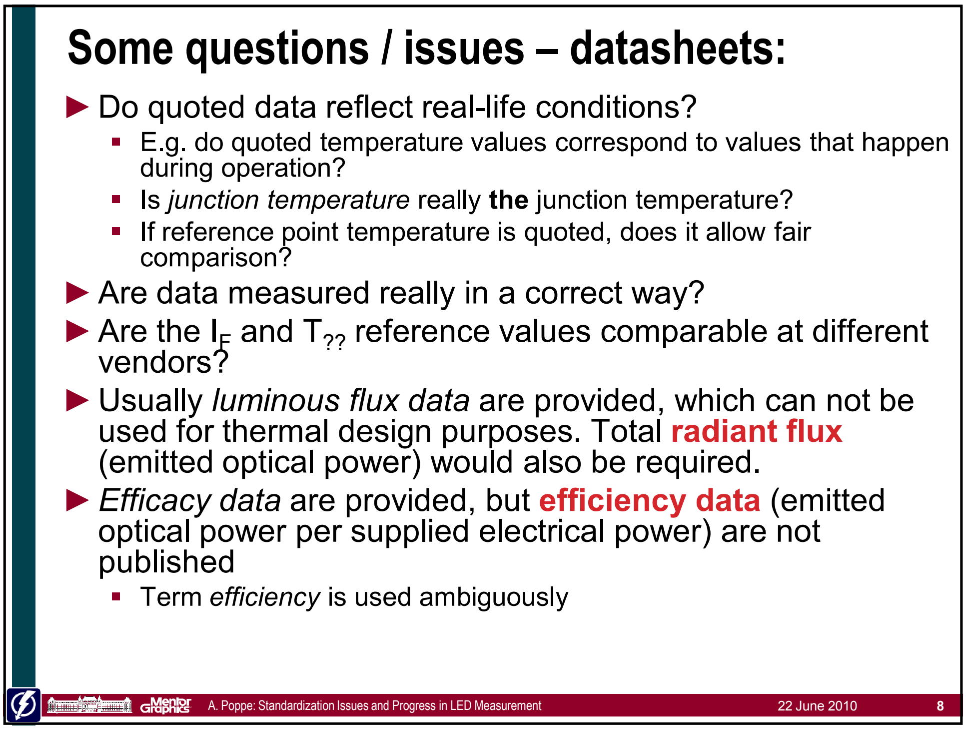
How do we know $\Delta T_J(t)$?

- The change of the forward voltage (TSP – temperature sensitive parameter) should be carefully calibrated against the change of the temperature (see JEDEC JESD51-1 and MIL-STD-750D)
- Since the temperature sensitivity of the forward voltage may show a large scatter, every single LED must be calibrated
- The same meters and current sources should be used during calibration and testing



How to standardize $R_{thJ\text{-}X}$?

- Questions one may ask:
  - How is T_J defined?
    - How can it be measured? *IR / **electrical test method***
  - What is T_X reference temperature?
    - Can it be unambiguously defined and easily measured in practice? measure on ***cold plate setups***
  - How is P_H defined?
    - Corrected for non-thermal contributions? *consider **P_{opt}** as per CIE-127:2007 (total radiant flux)*
  - Further important questions but not discussed here:
    - What is the physical meaning of R_{th}?
    - What is the variance in the published data per manufacturer?



Some questions / issues – datasheets:

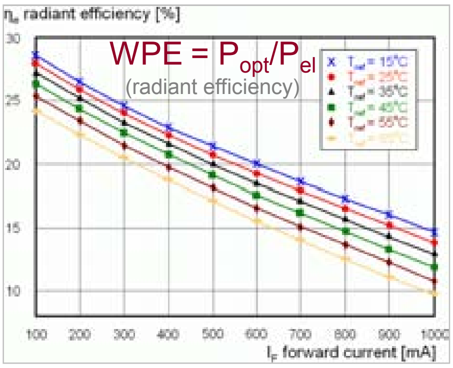
- Do quoted data reflect real-life conditions?
  - E.g. do quoted temperature values correspond to values that happen during operation?
  - Is *junction temperature* really **the** junction temperature?
  - If reference point temperature is quoted, does it allow fair comparison?
- Are data measured really in a correct way?
- Are the I_F and $T_{??}$ reference values comparable at different vendors?
- Usually *luminous flux data* are provided, which can not be used for thermal design purposes. Total **radiant flux** (emitted optical power) would also be required.
- *Efficacy data* are provided, but **efficiency data** (emitted optical power per supplied electrical power) are not published
  - Term *efficiency* is used ambiguously

Definition of R_{th} for LEDs

- ▶ Traditionally: $R_{th\text{-}el} = \Delta T_J / P_{el} = \Delta T_J / (I_F \times V_F)$
- ▶ Due to high efficiency, radiant flux must be considered:

$$R_{th\text{-}real} = \Delta T_J / (P_{el} - P_{opt})$$
$$= \Delta T_J / (I_F \times V_F - P_{opt})$$

By neglecting P_{opt} vendors report much nicer data than reality

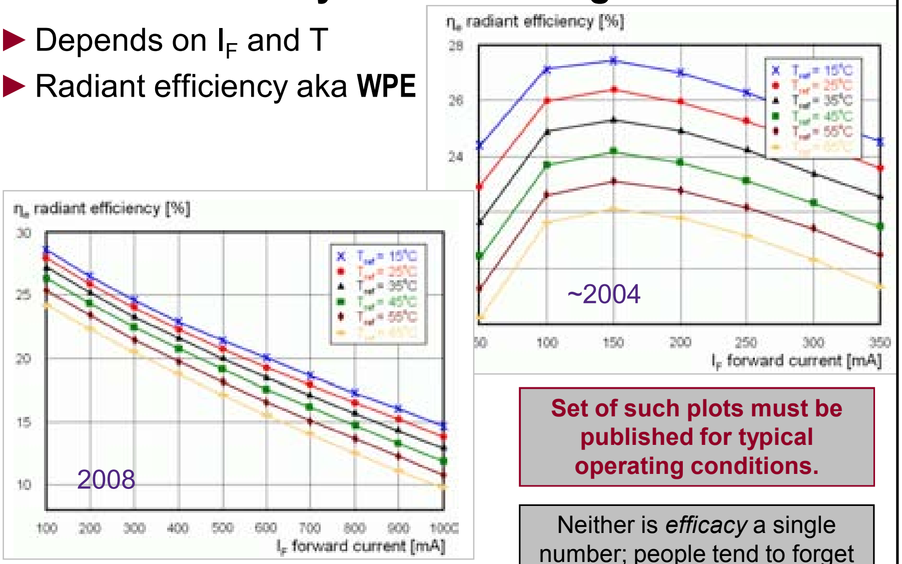


Example

- ▶ Let us assume two WPE-s (wall plug efficiency: P_{opt}/P_{el})
  $\Delta T = 50^oC$, P_{el} = 10W
  - WPE=0% (electrical only)
    ➔ "$R_{th\text{-}el}$" = $\Delta T / P_{el}$ = 50/10 = **<u>5 K/W</u>**
  - WPE = 25%
    ➔ $R_{th\text{-}real} = \Delta T / (P_{el} - P_{opt}) = \Delta T / [P_{el} \cdot (1\text{-}WPE)] =$
    $= 50/(10 \cdot 0.75) =$ **<u>6.67 K/W</u>**
  - WPE = 50%
    ➔ $R_{th\text{-}real} = \Delta T / (P_{el} - P_{opt}) = \Delta T / [P_{el} \cdot (1\text{-}WPE)] =$
    $= 50/(10 \cdot 0.5) =$ **<u>10 K/W</u>**
- ▶ By neglecting P_{opt} vendors report much nicer data than reality (taking an unfair marketing advantage)

Radiant efficiency – is not a single number

- ▶ Depends on I_F and T
- ▶ Radiant efficiency aka **WPE**

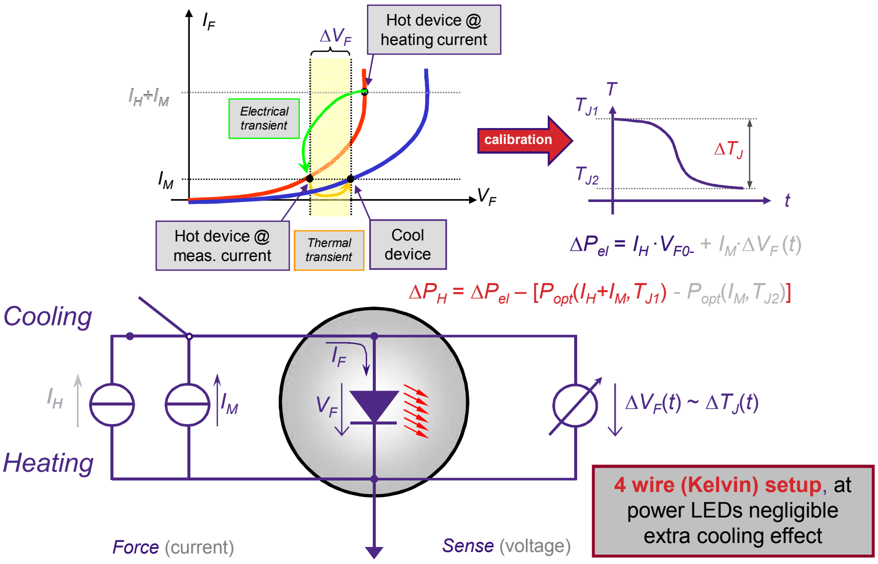


Set of such plots must be published for typical operating conditions.

Neither is *efficacy* a single number; people tend to forget this.

How thermal tests are performed?

The static electrical test method defined by the JEDEC JESD51-1 document:

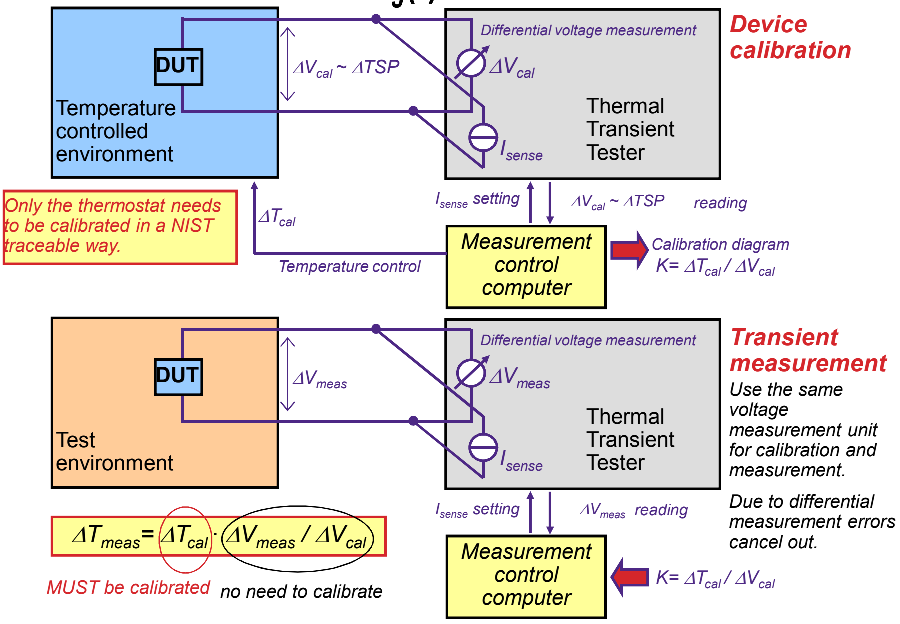


$\Delta P_{el} = I_H \cdot V_{F0-} + I_M \cdot \Delta V_F(t)$

$\Delta P_H = \Delta P_{el} - [P_{opt}(I_H+I_M, T_{J1}) - P_{opt}(I_M, T_{J2})]$

4 wire (Kelvin) setup, at power LEDs negligible extra cooling effect

How do we know $\Delta T_J(t)$?



Device calibration

DUT

Temperature controlled environment

$\Delta V_{cal} \sim \Delta TSP$

Differential voltage measurement

ΔV_{cal}

I_{sense}

Thermal Transient Tester

Only the thermostat needs to be calibrated in a NIST traceable way.

ΔT_{cal}

Temperature control

I_{sense} setting

$\Delta V_{cal} \sim \Delta TSP$ reading

Measurement control computer

Calibration diagram

$K = \Delta T_{cal} / \Delta V_{cal}$

Transient measurement

Use the same voltage measurement unit for calibration and measurement.

Due to differential measurement errors cancel out.

DUT

Test environment

ΔV_{meas}

Differential voltage measurement

ΔV_{meas}

I_{sense}

Thermal Transient Tester

I_{sense} setting

ΔV_{meas} reading

Measurement control computer

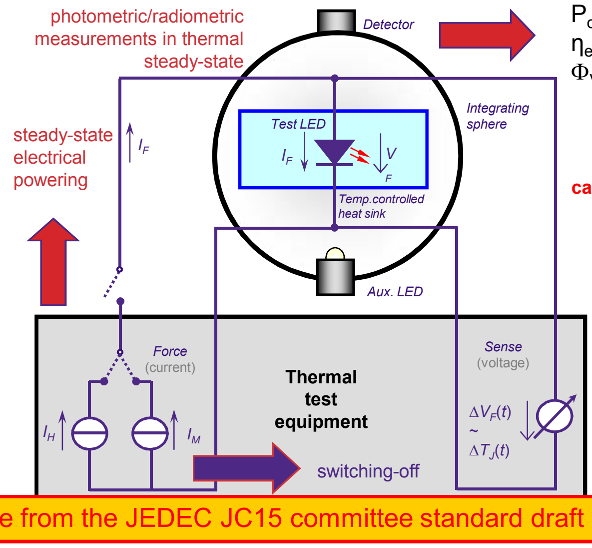
$K = \Delta T_{cal} / \Delta V_{cal}$

$$\Delta T_{meas} = \Delta T_{cal} \cdot \Delta V_{meas} / \Delta V_{cal}$$

MUST be calibrated — *no need to calibrate*

Comprehensive LED testing solution:

CIE 127-2007 compliant photometric & radiometric measurement system



photometric/radiometric measurements in thermal steady-state

steady-state electrical powering

I_F

Detector

Integrating sphere

Test LED

I_F

V_F

Temp.controlled heat sink

Aux. LED

Force (current)

I_H

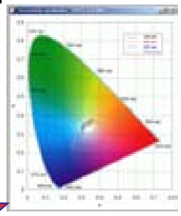
I_M

Thermal test equipment

switching-off

Sense (voltage)

$\Delta V_F(t) \sim \Delta T_J(t)$

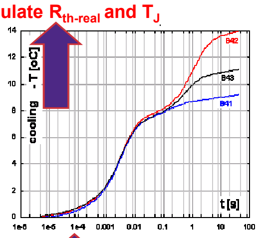


$P_{opt}(T, I_F)$

$\eta_e(T, I_F)$

$\Phi_V(T, I_F)$

calculate $R_{th\text{-}real}$ and T_J



record thermal data

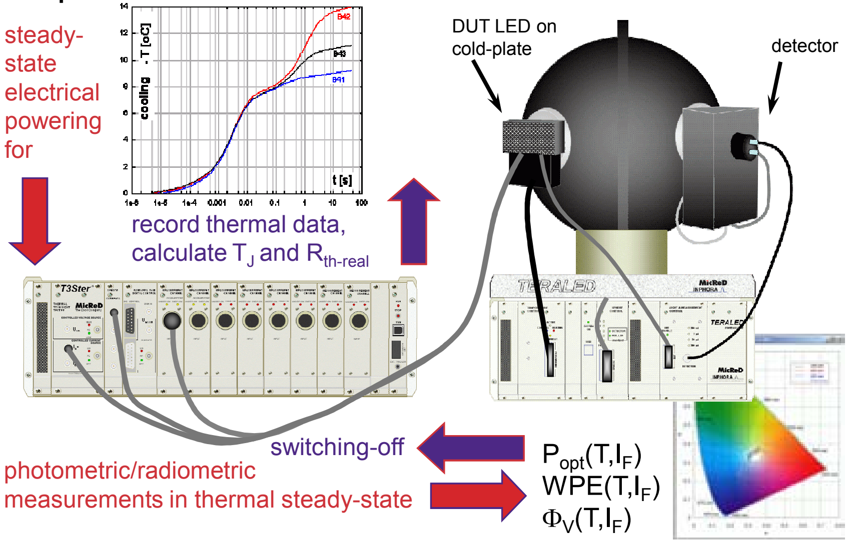
Quote from the JEDEC JC15 committee standard draft

JEDEC JSD51-1 <u>static test</u> method compliant thermal measurement system

Mentor Graphics MicReD solution for this:

JEDEC JSD51-1 static test method compliant thermal measurement

CIE 127-2007 compliant photometric & radiometric measurement



steady-state electrical powering for

record thermal data, calculate T_J and $R_{th\text{-}real}$

DUT LED on cold-plate

detector

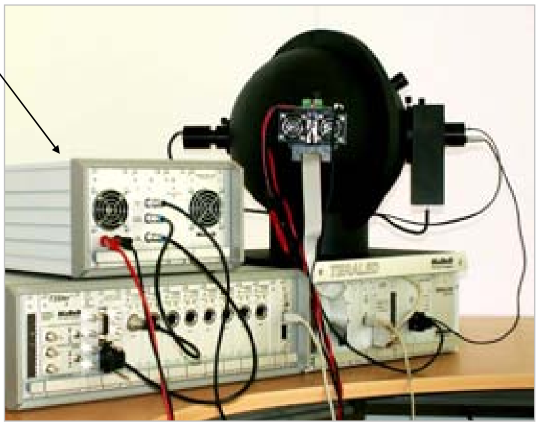
switching-off

photometric/radiometric measurements in thermal steady-state

$P_{opt}(T,I_F)$
$WPE(T,I_F)$
$\Phi_V(T,I_F)$

Such a system in practice

Special LED booster: allows high voltage across a LED line (overall forward voltage can reach 100V at standard models, 280V version is to come soon).

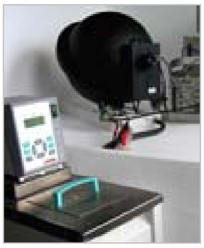


It can be added to the system in a plug&play manner if the voltage of the base tester is not sufficient.

Test environment at BME

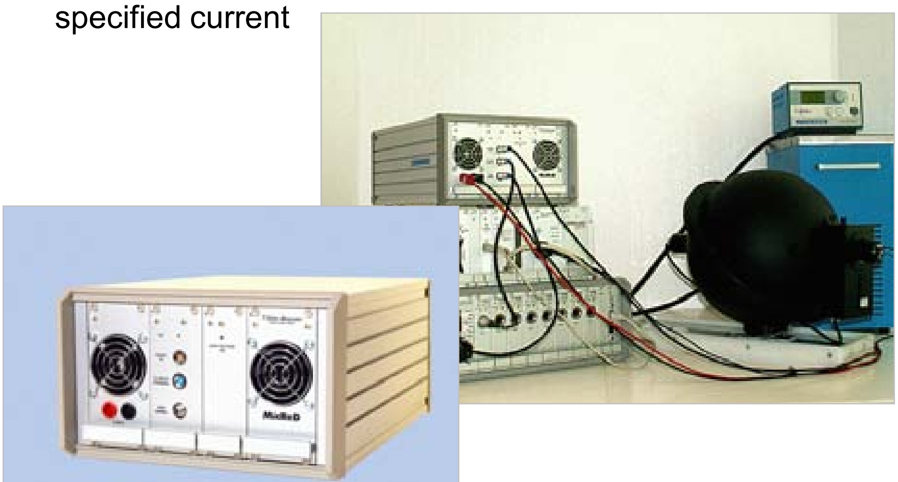
- ▶ Due to high dissipation, liquid cooled cold plate was used:

- ▶ Fixture on the cold plate holds the sample and accommodates the integrating sphere



The entire system in practice for high V_F LEDs

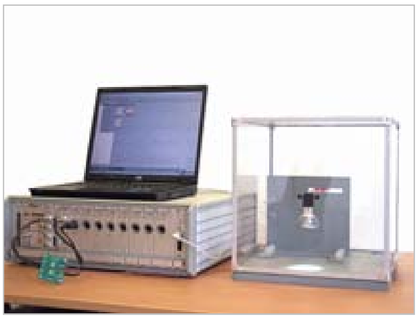
- ▶ Special LED booster provided the appropriate voltage at specified current



LED booster for high V_F voltages
(100 V and above)

Natural convection test environment

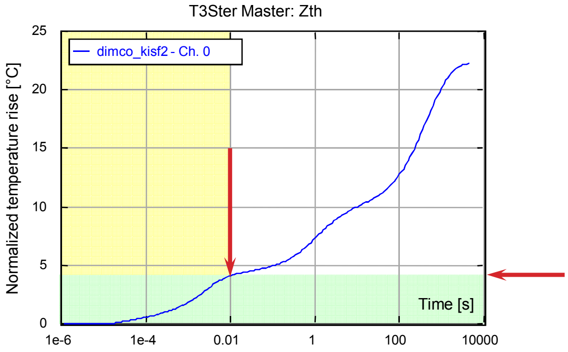
- During thermal testing, standard test environments must be used to allow like-with-like comparison
- Natural convection environments make also sense, though thermal testing times are much longer than on cold plates
- **Issue:** standard test luminaires or LED specific test boards?



- in 1ft^3 JEDEC standard still-air chamber: *resembles real application*

Short pulse measurements

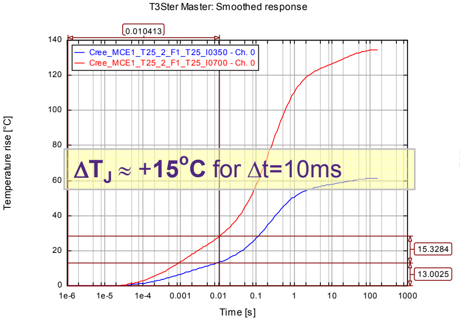
- During in-line testing photometric/colorimetric properties are measured with a short pulse
  - $T_J = T_{ref}$ = constant is assumed, ***THIS IS NOT TRUE:***
    In 10 ms significant junction temperature change may take place



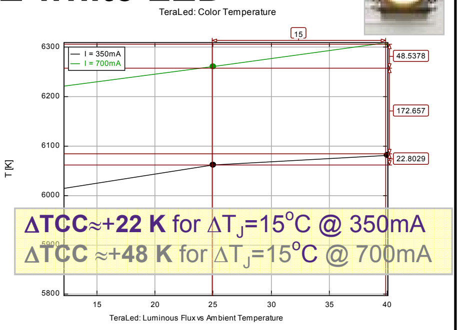
Question is if this causes big problems or not…

During 10 ms T_J changes almost by 5 ^{o}C

Example: 10W Cree MCE white LED



$\Delta T_J \approx$ **+15°C** for Δt=10ms

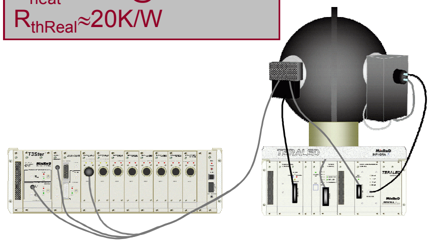


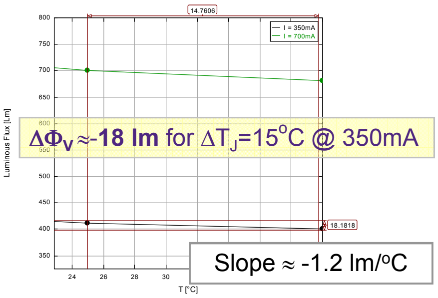
ΔTCC≈+22 K for ΔT_J=15°C @ 350mA

ΔTCC ≈+48 K for ΔT_J=15°C @ 700mA

$P_{heat} \approx$ 3W @ 350mA

$R_{thReal} \approx$20K/W





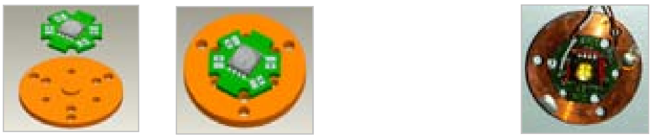
$\Delta\Phi_V \approx$-18 lm for ΔT_J=15°C @ 350mA

Slope ≈ -1.2 lm/°C

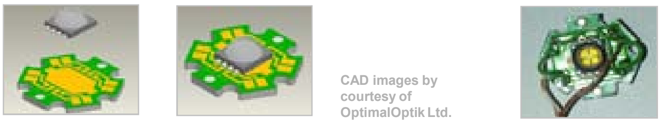
Case study: 3 setups with Cree MCE 10W LEDs

- 3 different kinds of assemblies:
  - FR4 PCB, TIM between the heat-slug and the Cu block

  - FR4 PCB, heat-slug soldered to the Cu block



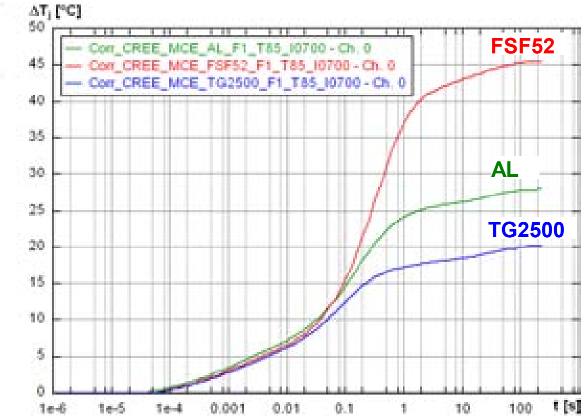
  - MCPCB-s made of Al and Cu, heat-slug soldered



CAD images by courtesy of OptimalOptik Ltd.

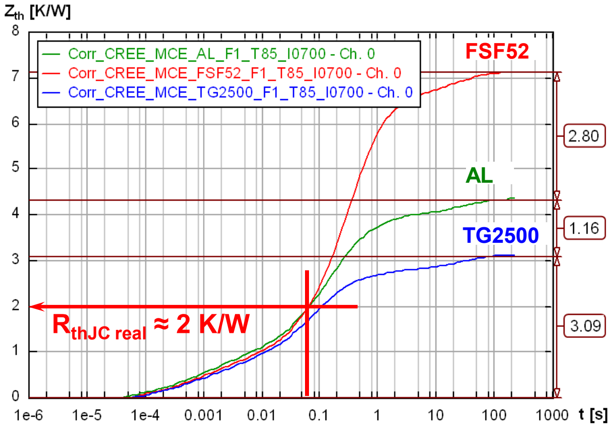
Results for 10W Cree MCE white LEDs

- ▶ Measured at 700 mA and 85°C
  - Junction temperature change (wrt. T_{cp})



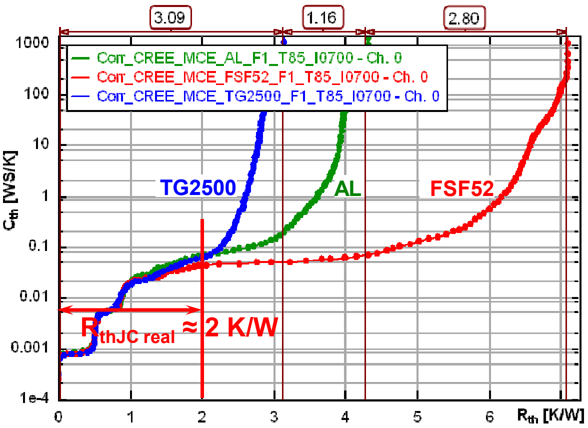
Results for 10W Cree MCE white LEDs

- ▶ Measured at 700 mA and 85°C
  - Thermal impedance of 3 samples, power corrected with P_{opt}



Results for 10W Cree MCE white LEDs

- ▶ Measured at 700 mA and 85ºC
  - Structure functions of 3 samples, power corrected with P_{opt}



$R_{thJC\ real} \approx 2$ K/W

  - R_{thJC} is identified in a way similar to the *transient double interface method*, also being standardized by the JEDEC JC15 committee

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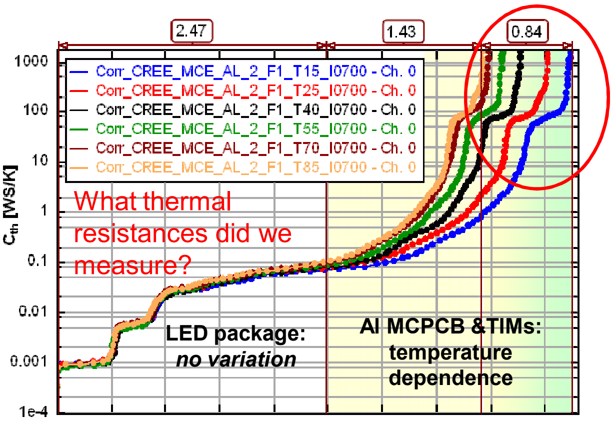
Results for 10W Cree MCE white LEDs

- ▶ Measured at 350/700 mA & between 15ºC and 85ºC
  - Structure functions of sample AL-2, power corrected with P_{opt}



What thermal resistances did we measure?

LED package: ***no variation***

Al MCPCB &TIMs: temperature dependence

Fact or artifact?

$R_{thJC\text{-}package} + R_{th\text{-}MCPCB} + R_{th\text{-}grease}$ ➔ for "**hot lumen**" estimates

The transient dual interface method for R_{thJC}

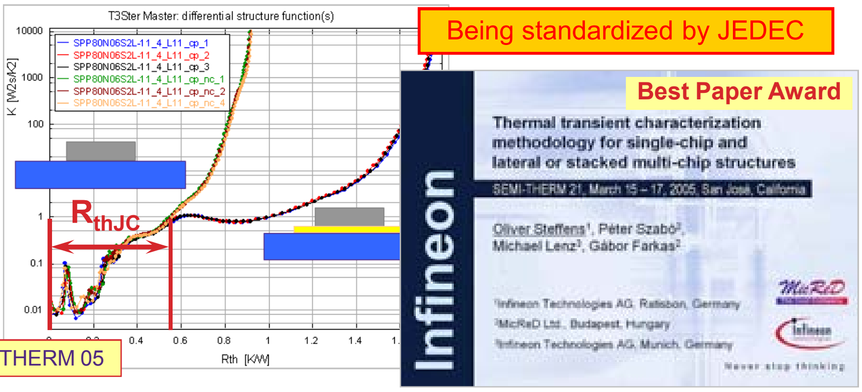
- ▶ Change of thermal interface quality at the 'case' surface
- ▶ Divergence point in measured structure functions: 'case' surface

package

Change at the case: insulating layer inserted

cold-plate

Measurement of 2 setups (2x3 min), ***structure functions***



Being standardized by JEDEC

Best Paper Award

Thermal transient characterization methodology for single-chip and lateral or stacked multi-chip structures

SEMI-THERM 21, March 15 – 17, 2005, San José, California

Oliver Steffens[1], Péter Szabó[2], Michael Lenz[3], Gábor Farkas[2]

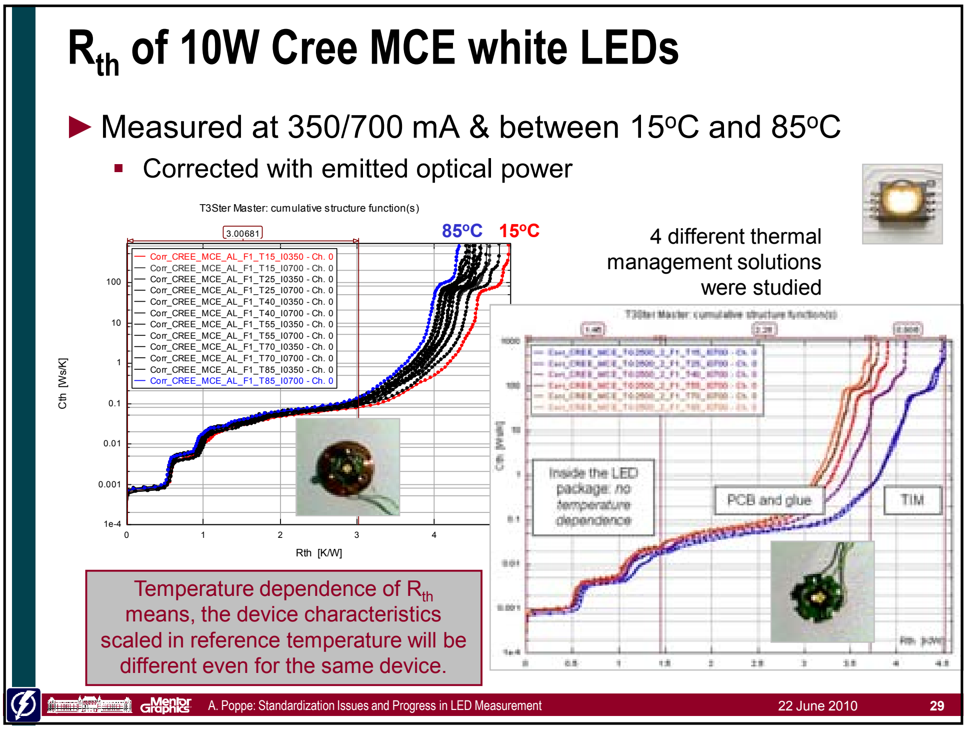
[1] Infineon Technologies AG, Ratisbon, Germany
[2] MicReD Ltd., Budapest, Hungary
[3] Infineon Technologies AG, Munich, Germany

Never stop thinking

SEMI-THERM 05

What R_{th}-s did we measure?

- ▶ On one hand, the real **R_{thJC}** of the package was identified in a ***dual interface technique*** like manner
  - Temperature changes resulted in different qualities of the TIM material
  - Both in the ***Z_{th} curves*** and in ***structure functions*** the identified real R_{thJC} values were very close to the data sheet values
- ▶ On the other hand, the total real $R_{thJ\text{-}cp}$ ***junction to cold-plate thermal*** resistance was also identified which is a ***good approximation of the <u>junction-to-luminaire thermal resistance</u>*** in the final application
  - Temperature dependence is in the right direction: for higher temperature we have lower thermal resistance

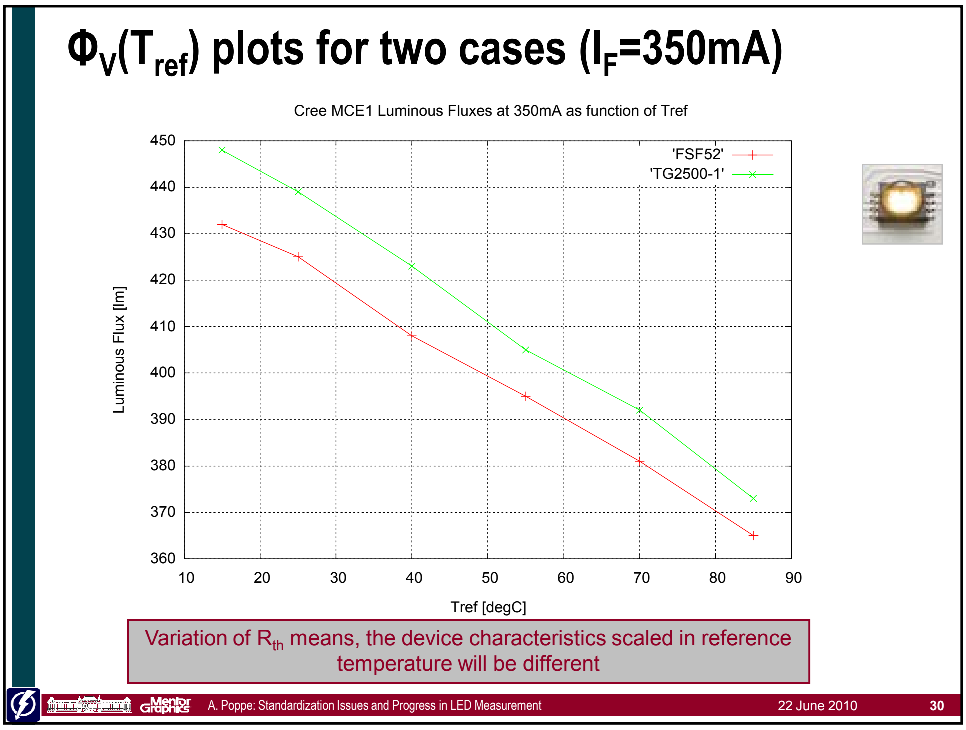


R_{th} of 10W Cree MCE white LEDs

- Measured at 350/700 mA & between 15°C and 85°C
  - Corrected with emitted optical power

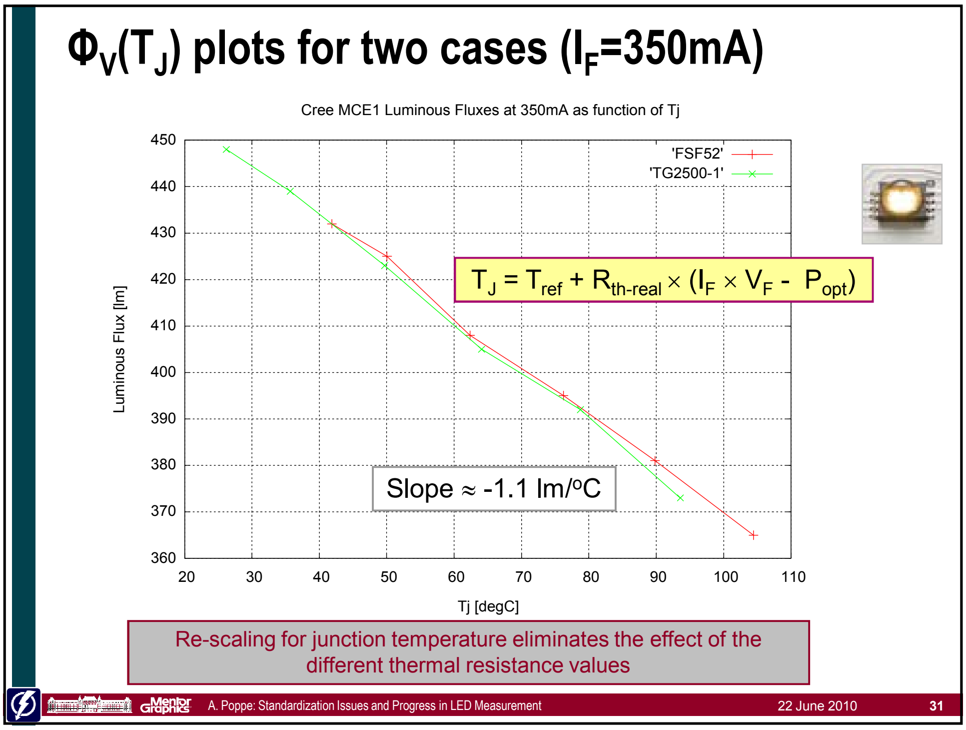
4 different thermal management solutions were studied

Temperature dependence of R_{th} means, the device characteristics scaled in reference temperature will be different even for the same device.



$\Phi_V(T_{ref})$ plots for two cases (I_F=350mA)

Variation of R_{th} means, the device characteristics scaled in reference temperature will be different



$\Phi_V(T_J)$ plots for two cases (I_F=350mA)

$T_J = T_{ref} + R_{th\text{-}real} \times (I_F \times V_F - P_{opt})$

Slope ≈ -1.1 lm/°C

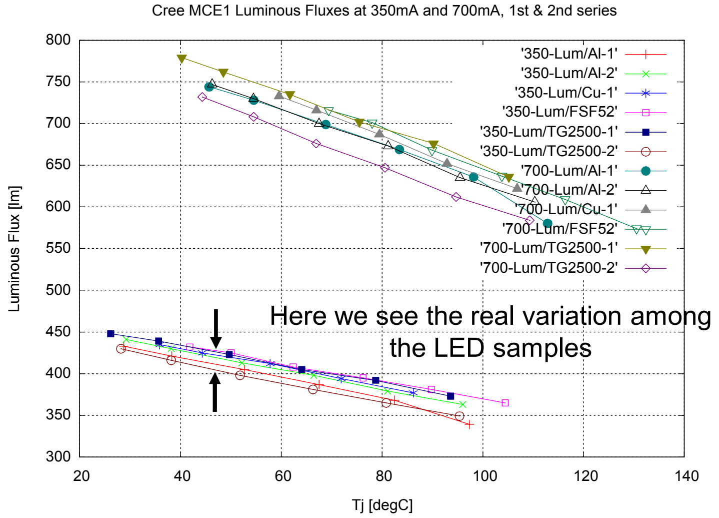
Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

---

Light output metrics and junction temperature

- Since the total thermal resistance of a given LED assembly may show considerable temperature dependence, one has to make sure that in every measurement
  - The reference temperature is recorded and reported
  - Actual heating power is identified: $I_F \times V_F - P_{opt}$
  - Thermal resistance of the setup is known,
    - The setup is left mechanically intact while light output metrics are being measured
  - **Junction temperature is known** (see the electrical test method as per JEDEC JESD51-1) **and reported**
- All **light output metrics are always reported as function of forward current and junction temperature**

$\Phi_V(I_F,T_J)$ plots for 7 different samples



Here we see the real variation among the LED samples

Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

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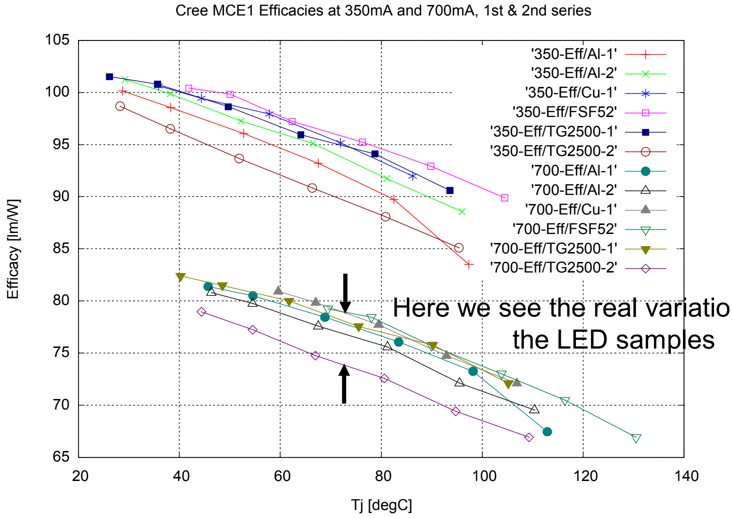
$\eta_V(I_F,T_J)$ plots for 7 different samples

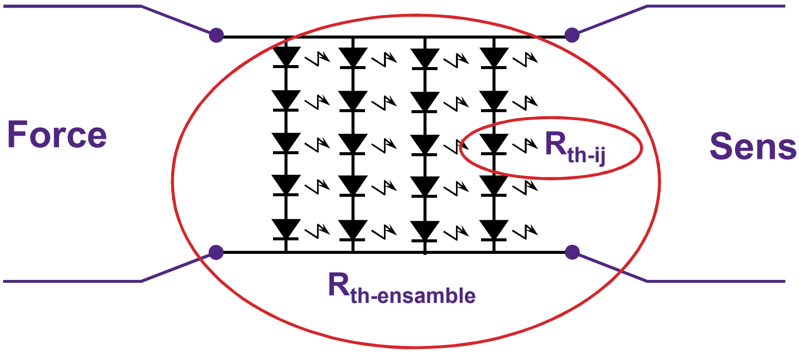


Here we see the real variation among the LED samples

Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

Problem of multiple LED chips

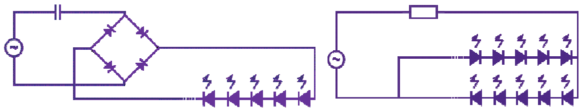
- Individual R_{th} vs 'ensemble' R_{th}?



- Measurement guidelines should be explicit about this!
  - Typically ‘ensamble R_{th}’ is measured, since there is
- No way to measure $R_{th\text{-}ji}$-s unless LED array is *designed for thermal testability*
- *JEDEC propose to use terms* single light source / multi-light source LED

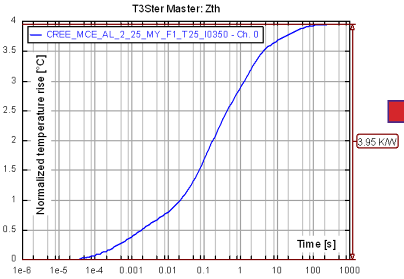
Problems of testing AC LEDs – driving mode

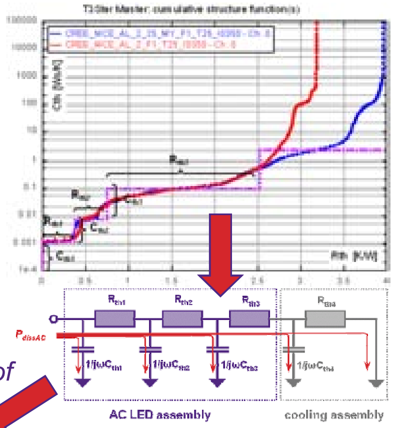
- How to define “Z_{th}” for AC LEDs?
  - Depends on frequency
  - An option: $Z_{th}(\omega) = T_{J\_AC}(\omega)/P_{dissAC}(\omega)$ – as usual in electrical engineering, assuming linearity and a single ω angular frequency
- Problems:
  - Dissipation has high harmonic contents ➔ multiple frequencies
  - How to measure T_{J_AC} properly?
- **There is one “Z_{th}” only – it’s a dynamic property!!!**
- Different P_{dissAC} values result in different T_{J_AC} values
- Actual P_{dissAC} depends on driving mode
  - Extreme cases in theory:
    - Voltage generator driven LEDs
    - Current generator driven LEDs
  - Due to different ballasts actual situations are in between.
  - Some typical cases:



Problems of testing AC LEDs – “Z_{th}”

- ▶ There is a single “Z_{th}” of the heat-flow path only
- ▶ Can be represented by structure functions and RC models





A simple model can be created, suitable even for hand calculations.

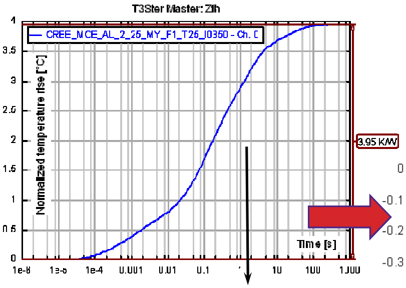
At higher frequency the absolute value of $Z_{th}(\omega)$ is smaller

$$Z_{th}(\omega)=\frac{1}{j\omega C_{th1}}\times\left\{R_{th1}+\frac{1}{j\omega C_{th2}}\times\left(R_{th2}+\left[\frac{1}{j\omega C_{th3}}\times\left(R_{th3}+Z_{th-cooling\_ass}\right)\right]\right)\right\}$$

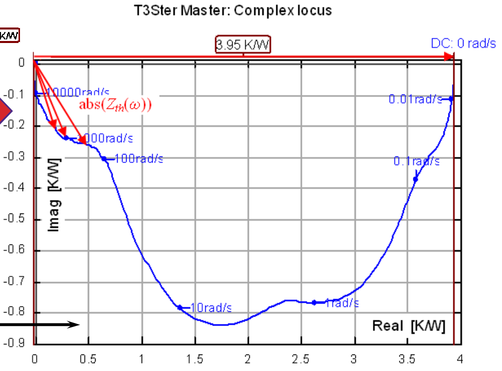
The problem is P_{dissAC}…

Problems of testing AC LEDs – “Z_{th}”

- ▶ There is a single “Z_{th}” of the heat-flow path only
- ▶ Frequency domain representation is Ok for AC LEDs



At higher frequency the absolute value of $Z_{th}(\omega)$ is smaller:



$$Z_{th}(\omega)=\underbrace{\frac{1}{P_{dissDC}}\int_{0}^{\infty}\overbrace{a(t)}\,e^{-j\omega t}dt}$$

This is not for hand calculations…

Problems of testing AC LEDs – dissipation

- The AC dissipation for voltage generator driven case:

$$P_{dissAC}(\omega) = U_{MAX}^2 \cdot \frac{I_0}{mU_T} \cdot \frac{1}{1!}\sin^2(\omega t) + U_{MAX}^3 \cdot \frac{I_0}{(mU_T)^2} \cdot \frac{1}{2!}\sin^3(\omega t) +$$

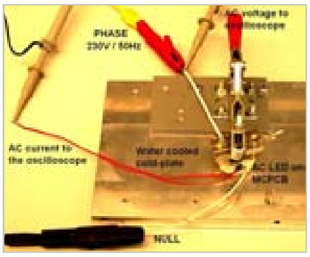
$$+U_{MAX}^4 \cdot \frac{I_0}{(mU_T)^3} \cdot \frac{1}{3!}\sin^4(\omega t) + \ldots$$

Multiple frequencies

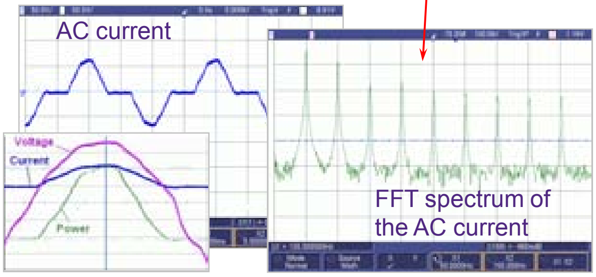
- The AC dissipation for current generator driven case:

$$P_{dissAC}(\omega) = U_0 \cdot I_{\max} \sin(\omega t) +$$

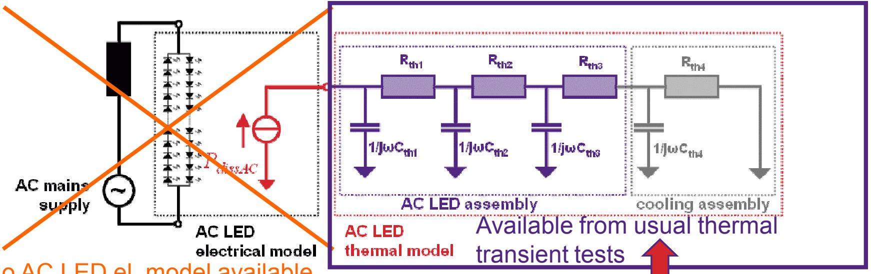
$$+ mU_T \cdot I_{\max}\left[\frac{\sin(\omega t) - 1}{1} - \frac{[\sin(\omega t) - 1]^2}{2} + \frac{[\sin(\omega t) - 1]^3}{3} \mp\right] \cdot \sin(\omega t)$$



SSC Archie driven by 50Hz mains



AC LEDs: simulate or measure?



Available from usual thermal transient tests

No AC LED el. model available

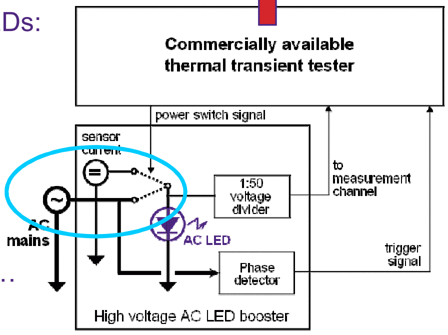
Rather, measure the "AC Z_{th}" of LEDs:

Not trivial how to switch from 240V ***AC driving voltage*** to 10 mA ***DC testing current.***

We are working on that…

Switching should take place in a well defined phase of the AC signal

Still more feasible than simulation…



More details at the THERMINIC Workshop in Barcelona (Spain) October 2010

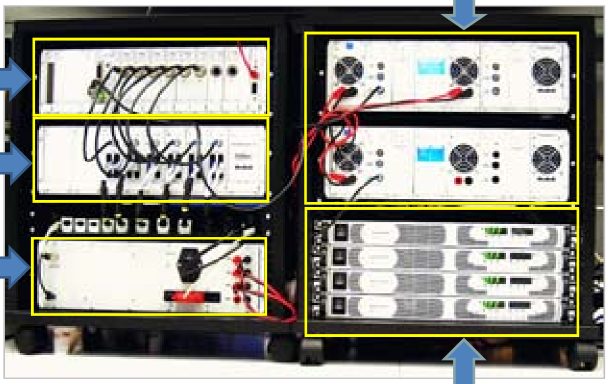
Large scale thermal testing of LEDs

- Used by some leading vendors
- K-factor calibration and actual testing combined, followed by structure function analysis
- High throughput (~10^3 pcs/hour) with multi-channel LED boosters

LM80 compliant test chamber

Large scale thermal testing of LEDs

- Example:



4 channel 1500 W Booster

T3Ster

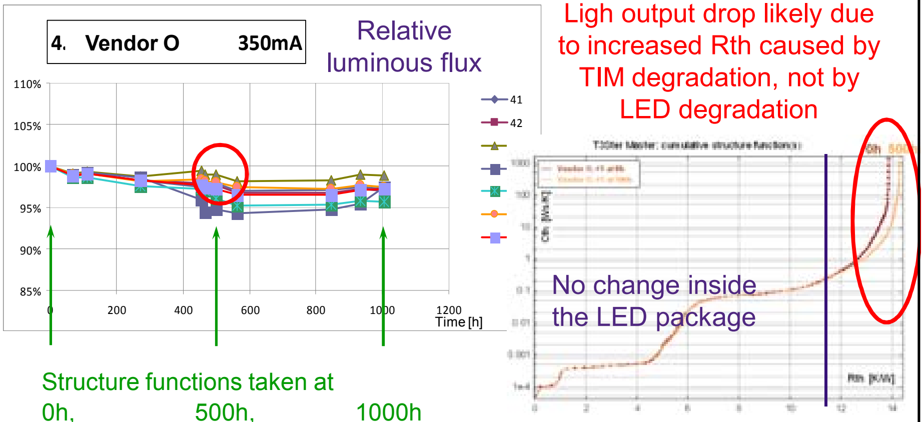
Sense Box

Force Box

External power supplies 150V 10A

Recent results from LM80 test of different LEDs

- ► In cooperation with University of Pannonia, Veszprém (Hungary), prof. J. Schanda's group within the KöZLED project of the Hungarian Goverment and the SE2A ENIAC project
- ► 8 different kinds of LEDs from 4 vendors, so far 1000h burning time



Relative luminous flux

Ligh output drop likely due to increased Rth caused by TIM degradation, not by LED degradation

No change inside the LED package

Structure functions taken at
0h, 500h, 1000h

Measurement setups in our LM80 tests

LM80 test chamber with all the LEDs assembled

All measurements are done in-situ to eliminate any R_{th} change which is NOT due to ageing

In-situ thermal transient measurement

In-situ light output measurement

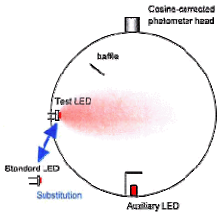
How about existing standards?

▶ Is JEDEC JESD51-1 "good" for LEDs?

- yes, for DC cases
  - but the "power dissipated in the device" has to be calculated as P_{el}-P_{opt}
  - reference temperature needs to be well established and kept constant
  - for LEDs, the *static test method* must be used
- **Possible new measurement guidelines**:
  - measure P_{opt} according to CIE 127-2007, use the static test method
  - *measure on a cold plate*, $T_{ref} = T_{cold\ plate}$
  - calculate junction temperature as follows: $T_J = T_{ref} + R_{th} \cdot \Delta P_H$

▶ Is CIE 127-2007 "good" enough?

- yes, for DC cases for sure
  - thermal aspects of total flux measurement are precisely specified,
  - but scattered around in the document
  - *arrangement b of Figure 9* allows e.g. TEC-based control of LED package temperature: *attach DUT LED to a cold plate*
- **Possible measurement guidelines:**
  - *4 wire connection to DUT LED* to comply with JESD51-1, *attach DUT LED to cold plate*
  - Identify and report junction temperature



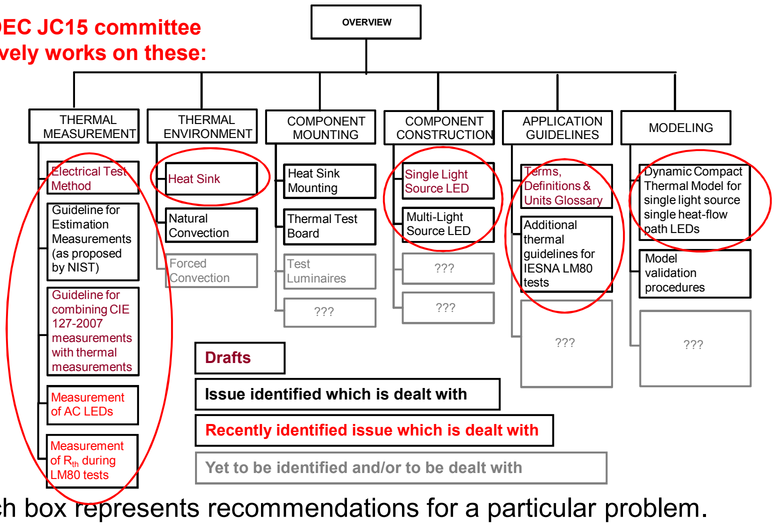
Standardization activities at JEDEC

▶ JC15 committee on thermal standards of semiconductor devices: ***LED standardization task group***

- Initiated by Philips, OSRAM and Mentor Graphics MicReD
- White paper published in September 2008, most recent versions of the white paper:
  - Eurosime'09, Electronics Cooling Magazine, LED Professional Review, CIE Solid-State Lighting Conference'09
- Panel discussion at the 14th THERMINIC Workshop in Rome, Italy
  - Philips Lighting, OSRAM OS, Lumileds, Mentor/MicReD/BME, KETI
- JEDEC JC15 Committee Meetings:
  - **March 2009:** decided to work out ***LED thermal characterization guidelines***:
    - — recommended metrics and test methods: JESD51-1, $R_{thJC\text{-}real}$
    - — recommended test environments: cold plate, *still-air – what board?*
    - — recommendations for compact thermal modeling of LED packages?
  - **February 2010:**
    - — Comprehensive guidelines worked out and discussed, overview document suggested
  - **June 2010:**
    - — Updated overview document and thermal measurement

Approach of the JEDEC JC15 committee

- Overview document (not yet accepted)



JEDEC JC15 committee actively works on these:

- OVERVIEW
  - THERMAL MEASUREMENT
    - Electrical Test Method
    - Guideline for Estimation Measurements (as proposed by NIST)
    - Guideline for combining CIE 127-2007 measurements with thermal measurements
    - Measurement of AC LEDs
    - Measurement of R_{th} during LM80 tests
  - THERMAL ENVIRONMENT
    - Heat Sink
    - Natural Convection
    - Forced Convection
  - COMPONENT MOUNTING
    - Heat Sink Mounting
    - Thermal Test Board
    - Test Luminaires
    - ???
  - COMPONENT CONSTRUCTION
    - Single Light Source LED
    - Multi-Light Source LED
    - ???
    - ???
  - APPLICATION GUIDELINES
    - Terms, Definitions & Units Glossary
    - Additional thermal guidelines for IESNA LM80 tests
    - ???
  - MODELING
    - Dynamic Compact Thermal Model for single light source single heat-flow path LEDs
    - Model validation procedures
    - ???

Drafts

Issue identified which is dealt with

Recently identified issue which is dealt with

Yet to be identified and/or to be dealt with

- Each box represents recommendations for a particular problem.
  - New modules can be easily added

Standardization activities at CIE

- Two new TC-s established, dealing with thermal aspects
  - **TC 2-63: Optical Measurement of High-Power LEDs**
    - To develop a CIE recommendation on methods for the operation of high-power LEDs in DC and in pulse mode, *at specified junction temperatures, for optical measurements*.
  - **TC 2-64: High Speed Testing Methods for LEDs**
    - To prepare a technical report on *high speed testing methods for electrical, thermal and optical quantities during the production* of LEDs and the conversion of the values to DC operational conditions including the related time dependent functions.
- **Light and Lighting Conference with Special Emphasis on LEDs and Solid State Lighting**, 27-29 May Budapest, Hungary
  - TC meetings
    - Initial information exchange, discussion of ideas
    - Foreseen date of any document ~2012
    - **TC 2-63:**
      - What is important?
      - How to identify the junction temperature?
      - What test environments/methods are the right ones?
    - **TC 2-64:**
      - Parameters are not constants during testing time - how to cope with this?

Standardization status (from Y. Ohno)

LED chips/ packages

(low power)
CIE 127:2007
CIE TC2-46

(high power)
IES LM-80
Lumen maintenance
IES TM-21
IESNA new project
CIE TC2-63, 64

SSL products
(Integrated LED lamps &
LED luminaires)
IES LM-79 Photometric meas.
ANSI C78.377 Chromaticity
CIE TC1-69 Color rendering
IEC xx (performance of self-ballasted LED lamps)

LED arrays / modules
CIE TC2-50 LED clusters and arrays

Safety UL 8750
CIE TC2-58 radiance/luminance
Several projects in IEC TC34A

LED light engines
(ASSIST Recommends ..)
IESNA new project

Definitions (terminology)
IES RP-16 addendum a
IEC TS 62504

Standardization status / CIE

Division 2 Physical Measurement of Light and Radiation (Director, Y. Ohno, USA)

TC2-46	CIE/ISO standards on LED intensity measurements (J. Scarangello, USA)
TC2-50	Measurement of the optical properties of LED clusters and arrays (J. Schuette, Germany)
TC2-58	Measurement of LED radiance and luminance (K. Kohmoto, Japan)
TC2-63	Optical measurement of High-Power LEDs (Y. Zong, USA)
TC2-64	High speed testing methods for LEDs (G. Heidel, Germany)

Division 1 Vision and Color (Director, R. Luo, UK)

TC1-69	Colour Rendition by White Light Sources (W. Davis, USA)

Proposal from NIST how to set T_J to a certain value for CIE 127-2007 compliant flux measurements. A bit complicated but compatible with JEDEC JC15 proposals.

Some conclusions (1)

- Existing data sheets do not provide sufficient information
  - e.g. for thermal design, *efficiency data* are also required, efficacy is of no help for thermal design
- Agreement on measuring 'real' R_{th} of single chip / single light source LEDs is required – great progress at JEDEC JC15 committee
  - one should consider *the real heating power* not juts the supplied electrical power – would allow real thermal design
  - this would also provide a *fair basis of comparison* for LED vendors
- Agreement on the way of obtaining LEDs' junction temperature is needed
  - Reported metrics (e.g. luminous flux) should refer to this
  - Suggested method: $T_J = T_{ref} + R_{th}\cdot\Delta P_H$
  - Even if the NIST method is used to define the junction temperature, best practice is to measure back with the above formula
- Standard *test environments* are also part of a like-with-like comparison
  - measuring on *cold-plates* yields meaningful and repeatable results
  - JEDEC JESD51-4 like *natural convection environments* might also be useful for application specific thermal metrics

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Some conclusions (2)

- For a particular design project, **combined thermal and optical measurements were performed**, this way the **real thermal resistance** of the different assembly solutions was identified and the real junction temperatures were calculated.
  - **different cooling solutions were evaluated**
- **Temperature dependence of the measured thermal resistances was observed** – according to structure function analysis these are due to the applied TIM2 material
- **Effect of temperature dependent thermal resistance was eliminated by re-scaling all measured data to junction temperature.**
  - This way like-with-like comparison of light output characteristics became possible both within the studied population of LEDs and with other vendors' products
  - Data about scatter of light output properties was also obtained
  - Measured performance of the particular LED package (R_{thJC}) was found to be slightly better than reported on data sheet
- Good **approximate models** of the entire heat-flow path can be created suitable for steady-state, transient and AC simulations, provided that proper LED electrical models are available

Some conclusions (3)

- Issues related to thermal impedance of AC LEDs were discussed
  - The major problem is the high harmonic contents of the dissipated AC power
    - Difficult to calculate, thus, difficult to model the actual AC thermal impedance
    - Better measure
      - Not trivial to switch between the AC heating signal and the DC test signal
      - Switch always at the same phase of the AC signal
    - Standardization bodies need to pay special attention to this

- In LM80 tests thermal transient tests help eliminate the effect of TIM ageing from the measurement results. Work is still in progress in this regard.

- Work both at JEDEC and CIE is in progress
  - JEDEC JC15 plans to lunch the 1st measurement guidelines ~2010
    - Overview document
    - Test procedures
    - Test environments
    - Guidelines for other standards how to properly deal with thermal aspects

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  - **Clemens Lasance** (emeritus) of Philips Research for discussions of different aspects of LED thermal standardization and for the common work regarding thermal testing and modeling

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Konferenciakiadványban megjelent cikk és annak előadás változata

Emerging standard for thermal testing of power LEDs and its possible implementation

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ABSTRACT

Nowadays the demand for thermal standards for power LEDs is increasing. On one hand metrics for fair comparison of competing products are needed; on the other hand, designers of power LED-based applications need reliable and meaningful data for their daily work. Today's data sheet information does hardly meet any of these requirements. In 2008 the JEDEC JC15 committee on thermal standardization of semiconductor devices decided to take action and created a task group to deal with thermal standardization issues of power LEDs. CIE has also created two new technical committees (TC2-63, TC2-64) which also aim to address thermal issues during measurement of high brightness / high power LEDs. This paper deals with thermal issues that are specific to light emitting diodes by describing novel test methods which may form basis of new measurement guidelines or standards including combined thermal and radiometric measurement of LEDs. Thermal issues in connection with short pulse measurements of LEDs and some thermal aspects of LM80 tests are also discussed.

Keywords: LED thermal testing, LEDs’ real thermal resistance, junction temperature, short pulse tests, thermal aspects of LM80 tests

1. INTRODUCTION

As it is widely known, the light output characteristics of light emitting diodes (LEDs) strongly depend on the operating conditions. The forward current applied to the LEDs is the primary variable – the higher the supplied current, the more light is generated by the LED. Unfortunately, when a LED is driven by a constant current source the light output drops with increasing temperature. This general feature of all LEDs is best illustrated by the dependence of their light output spectra – as shown in Figure 1. In addition to the efficiency drop the color of the LEDs’ light also changes as it is shown by the shift of the peak wavelength. Therefore the junction temperature (T_J) of an LED is not just a performance indicator of the thermal design but also plays a major role in lighting design since many properties of the light output of an LED depend on the absolute junction temperature. This means that thermal management should be an integral part of the system design of an LED based lighting solution. Consequently, since T_J of LEDs is more widely used in the design process of LED-based lighting solutions, well-established definitions of standardized thermal metrics and models will be needed both by the LED manufacturers and the lighting system designers.

By keeping LEDs cool high efficiency can be maintained. A thermal management solution that delivers better cooling also delivers more useful lumens in a given application. This means that the real junction-to-ambient thermal resistance of the LEDs in their application environment is a key factor in lighting design. Unfortunately different LED vendors report their products’ thermal resistance and other temperature-related characteristics in diverse ways. Therefore standardization activities related to thermal issues of power LEDs were started in various thermal standardization bodies. A new standard for the proper measurement of LEDs’ thermal resistance is currently being drafted by the JEDEC JC15 committee. This work relies on a whitepaper first published in 2008[1] and updated several times in 2009[2, 3]. In addition to this, the International Commission on Illumination (CIE) set up new technical committees (TC-2-63 and TC-2-64) to deal with the thermal aspects of LEDs.

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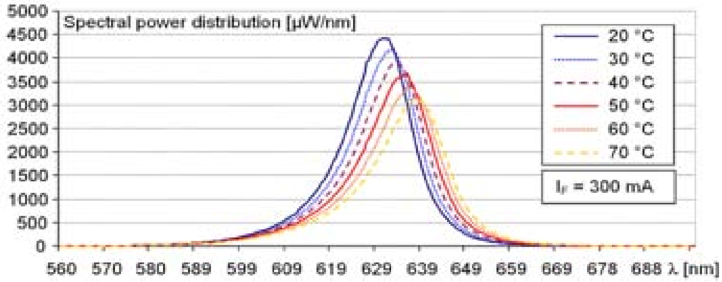

Figure 1: Current and temperature dependence of the spectral distribution of the light output of a red LED.

Among these committees an agreement is emerging that vendors need to consider the actual P_{opt} emitted optical power (that is, the radiant flux usually denoted as Φ_e) of the LEDs when calculating thermal resistance. A twofold interpretation can be defined, such as

$$R_{th\text{-}el} = \Delta T_J / (I_F \times V_F) \tag{1a}$$

$$R_{th\text{-}r} = \Delta T_J / (I_F \times V_F - P_{opt}). \tag{1b}$$

Here the product of the LED's forward current and forward voltage ($I_F \times V_F$) represents the change of electrical power when the LED is switched on from zero current to a constant I_F forward current and ΔT_J denotes the change of the LED chip's junction temperature as a response to the change of heating power. (1a) gives an estimate on the temperature reached when only the electric characteristic of the LED is known. (1b) says that for describing the heat removing capability of the physical structure the real thermal resistance has to be calculated from the temperature change and the heating power. Obviously that part of the electric power which leaves the device as light does not add to the heating.

Both definitions give back the same ΔT_J change if we multiply the proper R_{th} by the proper power value. However, as all parameters of the LED; including efficiency; changes with the current level and actual temperature, $R_{th\text{-}r}$ is a much more robust device descriptor while $R_{th\text{-}el}$ strongly depends on the actual operating point. Understanding both measures and using real thermal data are essential to successful LED design projects.

A more detailed discussion of LEDs' thermal resistance will be given in Section 2, together with the description of an alternate, transient based formulation of electrical test method for thermal measurements. Overview of the basic quantities is given there and we propose a combined test setup and a test procedure which allows to measure thermal and radiometric/photometric properties (real thermal resistance, real junction temperature) of power LEDs in a consistent way. Case studies of section 3 demonstrate the importance of LED junction temperature and thermal resistance for producing data sheet values and in short pulse tests used for binning. We shall highlight the importance of the thermal resistance variations in LM80 tests and suggest in-situ measurement techniques to reduce this problem to minimum.

2. APPLICATION OF THE ELECTRICAL TEST METHOD TO MEASURE LED'S THERMAL RESISTANCE

2.1 Junction temperature as performance indicator

As said, a lighting system designer wants to check if a junction temperature or a solder temperature stays within prescribed limits, or, alternatively, needs a temperature value for lifetime prediction. The equation that is most used is the following:

$$T_J = R_{thJ\text{-}X} \cdot P_H + T_X \tag{2}$$

where in daily practice $R_{thJ\text{-}X}$ is a number that is supplied by the LED manufacturer, the heating power P_H is usually supplied by the electronic engineer, and T_X is a *reference temperature* that depends on the definition: either it is some (often unspecified) ambient temperature, or the temperature of a point on the package or board in question (reference point X).

Eq. (2) is a linearization of the problem. This is justified in many cases because the materials used have more or less small dependence on the actual temperature. Cooling effects (radiation, turbulent convection) typically improve at higher temperatures, in such a way the designer assuming linearity overestimates the peak temperature in the systems and remains on the safe side. The largest non-linearity effect is just the above mentioned change of the light conversion efficiency.

2.2 Formulations of the thermal resistance as a metric of LED packages

The way how the EIA/JEDEC JESD51.1 standard[4] defines the thermal resistance is the re-arrangement of eq. (2):

$$R_{thJ-X} = \frac{T_J - T_X}{P_H} = \frac{[\Delta T_J]_X}{P_H} \tag{3}$$

where T_X denotes the temperature of the reference point X and P_H denotes the power dissipated in the device (as stated on page 3 of the JEDEC JESD51-1 document[4]). $[\Delta T_J]_X$ is the change of the junction temperature with respect to the reference temperature, that is, a *difference of temperatures measured at two different locations*.

Eq. (3) suggests building a spatial temperature difference in thermal equilibrium: heat up the junction and measure both the junction temperature and the temperature at reference point X. This requires two temperature measurements simultaneously, using two "thermometers" which both need to be calibrated. When using the electrical test method[4] the junction is one of the thermometers through the calibration of the *TSP* (*temperature sensitive parameter*) of the semiconductor chip. In case of LEDs – as for any other pn-junction – the TSP is the V_F forward voltage of the device measured at forced, constant forward current. The other thermometer which measures the T_X reference temperature of environment X is typically a thermocouple which also has to be properly calibrated.

If the reference temperature is the ambient temperature (that we can control if measurements are performed e.g. on a cold-plate), then in the un-heated device, in its initial thermal state $T_{J0} = T_X$, i.e. the initial junction temperature and the reference point temperature are equal.

Figure 2: Junction-to-X thermal resistance calculated from a temporal difference of the junction temperature and the power dissipated in the device.

After heating up the device we reach a final thermal equilibrium. We can continuously record the T_J junction transition during the heating, from a cold steady state to a hot steady state (or vice versa in a cooling process).

This continuous procedure – also known as the 'static' test method – suggests another reformulation of eq. (2). Suppose, in the initial steady-state a known P_{H1} heating power is applied, while in the final steady state another known heating power P_{H2} is applied (see Figure 2). For both cases we can express the junction temperature based on the pattern of eq. (2):

$$T_{J1} = R_{thJ-X} \cdot P_{H1} + T_{refX} \tag{4a}$$
$$T_{J2} = R_{thJ-X} \cdot P_{H2} + T_{refX} \tag{4b}$$

Subtracting (4a) from (4b) we obtain

$$T_{J2} - T_{J1} = R_{thJ-X} \cdot (P_{H2} - P_{H1}). \tag{5}$$

2.3 Thermal impedance

In eq. (5) we can also indicate that T_{J1} and T_{J2} junction temperatures occurred at different time instances: $T_{J1}=T_J(t_1)$ and $T_{J2}=T_J(t_2)$. Substituting these and rearranging (5) yields

$$R_{th\ J-X} = [T_J(t_2) - T_J(t_1)] / (P_{H2} - P_{H1}) \tag{6}$$

or

$$R_{th\ J-X} = \Delta T_J(t) / \Delta P_H \tag{7}$$

where $\Delta T_J(t) = T_J(t_2) - T_J(t_1) = T_{J2} - T_{J1}$ and $\Delta P_H = P_{H2} - P_{H1}$.

In other words, instead of using a spatial temperature difference along the junction-to-X heat-flow path, eq. (7) suggests that the 'thermal resistance' as a metric can be calculated from the difference of the initial and the final steady state value of the junction temperature, provided the change of the heating power at the junction is also known and the reference temperature is kept constant. This means that instead of the difference of temperature at two different locations (spatial difference – see eq. (3)) we take the *temporal difference* of the junction temperature only. A major advantage of the differential approach represented by eq. (7) is that offset errors, which are typical in junction temperature measurement, cancel out. Another advantage is that the second, reference temperature is no longer part of the equation, reducing the need of calibration of temperature measurement as well as eliminating possible ambiguities about the definition of the reference point of power LEDs.

In summary: a measurement at two points at the same time is mathematically equal to measuring one point at two different times. Equation (7) results in the classical expressions of the (steady-state) *thermal resistance* and *thermal impedance* as follows:

If $P_{H2} = 0$ then $T_{J2} = T_x$, thus, if t_1=0 and t_2=∞ we get back eq. (3)

Eq. (7) can be formulated such that a 'thermal resistance' value at any t time instance after switching the heating can be obtained:

$$R_{thJ-X}(t) = \frac{\Delta T_J(t)}{\Delta P_H} = Z_{thJ-X} \qquad (8)$$

The quantity defined by eq. (8) is time dependent and is equivalent to the concept of the *thermal impedance* as described in MIL-STD 750D[5]. Thermal impedance describes the dynamics (time evolution) of the change of the junction temperature as a response to step-wise switching of the heating power. If t_1=0 and t_2=∝ then eq. (8) defines $R_{thJ-X}(\propto)$ which is equal to the classical R_{thJ-X} steady-state thermal resistance.

The thermal impedance as a time function is usually given in logarithmic time scale. It is equal to the time function of the junction temperature change $\Delta T_J(t)$ projected to an excitation of 1W change in the heating power. Thermal impedances can be described in time-domain as shown in eq. (8) or in frequency-domain (which is important e.g. for AC LEDs). The so called *structure functions* can also be considered as representations of Z_{thJ-X} junction-to-X thermal impedances. (For further theoretical details on the structure function please refer to technical literature[6,7].)

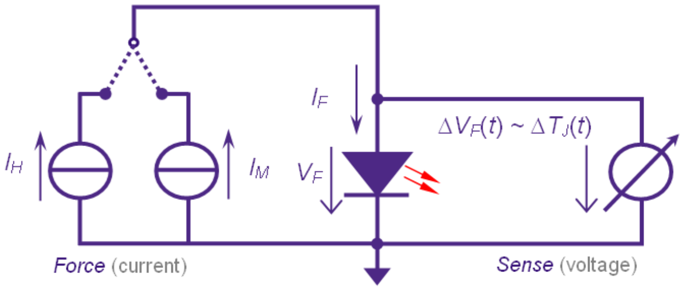

Figure 3: Diode thermal measurement circuit.

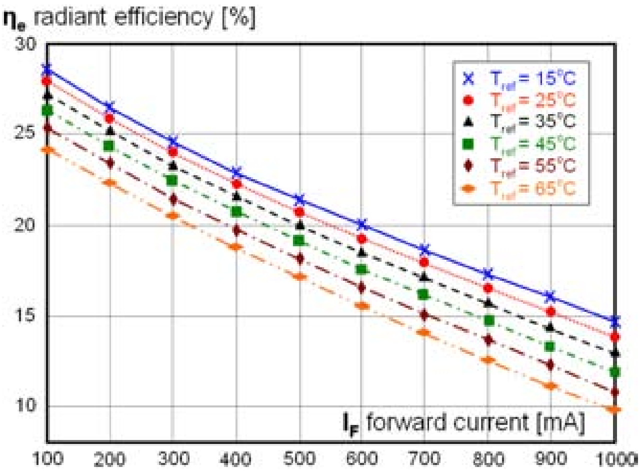

Figure 4: Temperature and forward current dependence of the energy conversion efficiency (also known as radiant efficiency).

2.4 Measuring the real thermal impedance and the real junction temperature of LEDs

The simplest way of measuring the thermal impedance of LEDs is based on the electrical test method[4,5] using the four wire test setup (also known as Kelvin-setup) shown in Figure 3. Since the energy conversion efficiency of LEDs strongly depends on temperature (Figure 4), the thermal impedance (resistance) measurement is best started in a hot stabilized state when the LED's I_F forward current is set to a given I_H *heating current* – the switch shown in Figure 4 is set to I_H. (In this case, at constant current and temperature the light output gets also stabilized, assuring a constant heating power at the LED's pn-junction.)

When using the so called *static test method* (defined in the JEDEC standard[4]) in *cooling mode*, the stabilized hot state of the LED under test should be reached. In this hot steady state the forward current of the LED is abruptly switched to the I_M *measurement current* – switch in Figure 4 is set to I_M. Usually $I_M << I_H$, thus the LED is nearly *switched off*, resulting in a negative *power step*. Switching down from I_H to I_M causes a sudden decrease in the V_F forward voltage. During the longer cooling process we observe a slower growth of the voltage again, this $\Delta V_F(t)$ growth is used to measure the $\Delta T_J(t)$ junction temperature change. In the linearized model the forward voltage change and the junction temperature change are related through a constant *temperature sensitivity* value:

$$V_F\left(I_M, t\right) = V_{Fi}\left(I_M\right) + S_{VF}\cdot\left[T_J(t) - T_J(0)\right] \tag{9}$$

$S_{VF} = S_{VF}(I_M) = \delta V_F(I_M)/\delta T_J$ slightly depends on the I_M current. $V_{Fi}(I_M)$ denotes the initial (hot) value of the forward voltage 'just after' the switching – in subsequent paragraphs a more precise definition of the timing will be given.

Theoretically one has to wait infinite time for the junction temperature – hence the forward voltage – to get stabilized in the cold state at the small I_M measurement current. Therefore, based on eq. (9) the V_{Ff} final value of the forward voltage after switching the forward current of the LED can be expressed as follows:

$$V_{Ff} = V_F\left(I_M, t = \infty\right) = V_{Fi}\left(I_M\right) + S_{VF}\cdot\left[T_J(\infty) - T_J(0)\right] \tag{10}$$

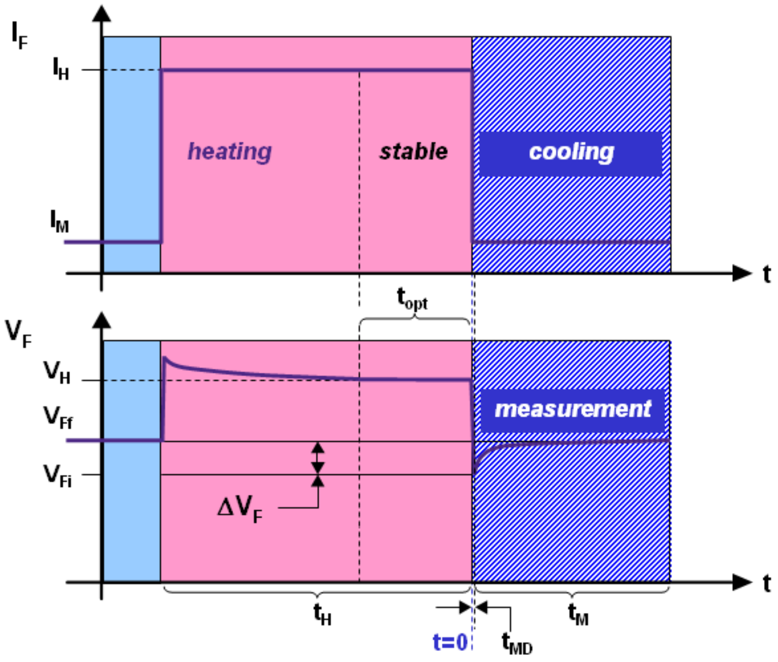

Figure 5: LED thermal measurement waveform (linear time scale).

The forward current and forward voltage waveforms together with key timing parameters of the test procedure are shown in Figure 5. The t_H *heating time* should be sufficiently long to allow all operating parameters of the LED under test (forward voltage, junction temperature, radiant flux) to stabilize. When the forward current of a pn-junction is abruptly switched, there is an electrical transient inherently present. This transient finishes when the large diffusion charge corresponding to the heating current is depleted from the pn-junction and the device reaches the charge level belonging to the measurement current. The switching time required depends on the charge to be depleted and on the switching circuitry. During the switching process the change of the forward voltage does not represent the temperature change of the LED chip. Therefore a t_{MD} delay time has to be chosen such that the measurement starts early enough to capture the beginning of the junction temperature transient, but still the distorted data of the parasitic electrical transient are not recorded. The different transients of the forward voltage after switching the forward current are shown in Figure 6.

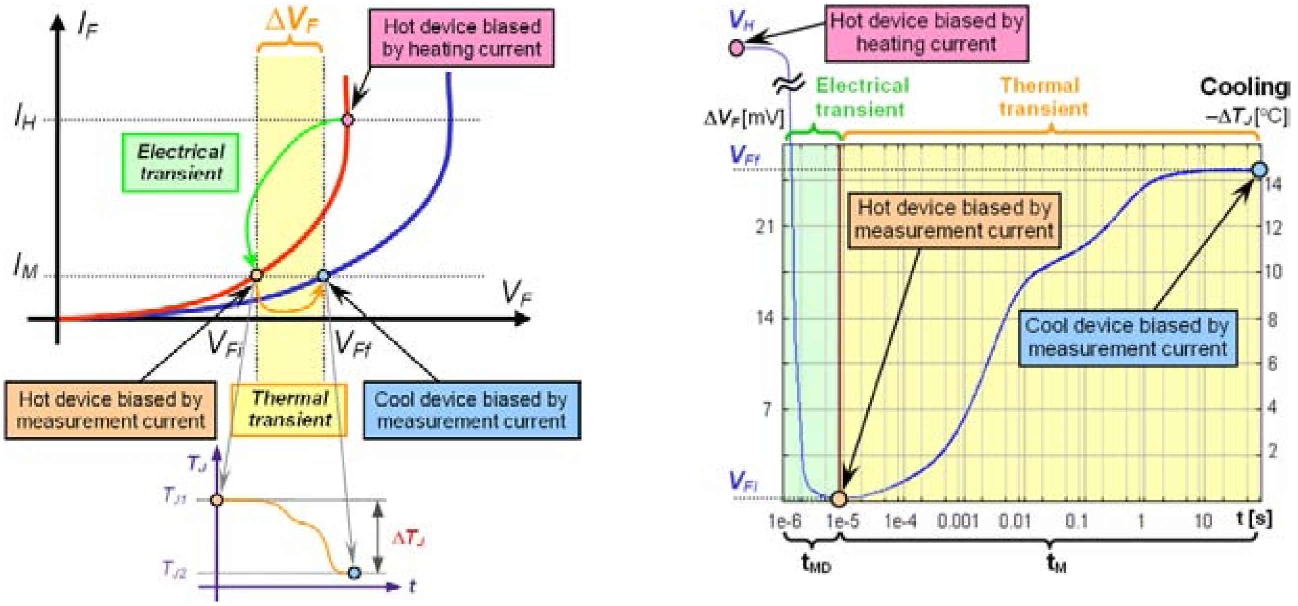
a)
b)

Figure 6: Electrical and thermal state transitions of a LED a) shown in the I-V characteristic of the device and b) shown as a time function measured after time instance t=0 of the test waveform of Figure 5.

Since during the electrical transient of the forward voltage significant change of the junction temperature may take place, appropriate data correction has to be applied: the initial value of the junction temperature has to be back extrapolated[4] based on the value measured at time instance t_{MD}. The measured $\Delta V_F(t)$ forward voltage change is converted to junction temperature change through the sensitivity: $\Delta T_J(t) = \Delta V_F(t) / S_{VF}$.

For calculating the thermal impedance/thermal resistance, besides the change of the junction temperature the ΔP_H change of the heating power has also to be known – see eq. (1). In the last moment before switching off the power, when all electric and light related parameters of the device are stable the remaining heating power is equal to

$$P_{elH} - P_{optH} = I_H \cdot V_H - \Phi_e(I_H, \mathrm{T}_{J1}) \qquad (11)$$

where V_H is the forward voltage at I_H heating current and $\Phi_e(I_H, \mathrm{T}_{J1})$ is the total radiant flux of the LED. This latter is influenced directly by I_H and also through the stabilized T_{J1} junction temperature at I_H in the given environment.

The small heating power caused by the I_M measurement current shall be calculated as

$$P_{elM} = I_M \cdot V_{Fi} + I_M \cdot \Delta V_F(t). \qquad (12)$$

We can see that this power slightly increases during the measurement, but $\Delta V_F(t)$ is much smaller than V_{Fi}. During the heating a similar change in the forward voltage causes a much larger change in the powering being multiplied by a much higher I_H current. An obvious advantage of the cooling measurement is that the power change while heating has not to be taken into consideration as we use the stabilized value in the starting steady state. The total heating power when the measurement current is applied is equal to

$$P_{HM} = P_{elM} - P_{optM} = I_M \cdot V_{Fi} + I_M \cdot \Delta V_F(t) - \Phi_e(I_M, \mathrm{T}_J(\mathrm{t})) \qquad (13)$$

where $\Phi_e(I_M, \mathrm{T}_J(\mathrm{t}))$ denotes the total radiant flux of the LED when the measurement current is applied. From equations (11) and (13) the change of the heating power is

$$\begin{aligned}\Delta P_{H\text{-}corr} &= P_{HH} - P_{HM} = \\ &[I_H \cdot V_H - \Phi_e(I_H, T_{J1})] - [I_M \cdot V_{Fi} + I_M \cdot \Delta V_F(t) - \Phi_e(I_M, T_J(t))] = \\ &I_H \cdot V_H - I_M \cdot V_{Fi} - I_M \cdot \Delta V_F(t) - \Phi_e(I_H, T_{J1}) + \Phi_e(I_M, T_J(t))\end{aligned} \tag{14}$$

Since both terms $I_M \cdot \Delta V_F(t)$ and $\Phi_e(I_M, T_J(t))$ are negligible (error < 1%), the change of heating power of the LED can be calculated as

$$\Delta P_{H\text{-}corr} \approx I_H \cdot V_H - I_M \cdot V_{Fi} - \Phi_e(I_H, T_{J1}) \tag{15}$$

In Figure 7 the heating power of a 10 W white LED is provided both according to eq. (14) and (15) together with the measured radiant flux values for 700 mA heating current and 10 mA measurement current. As generally stated above, simplified heating power calculations according to eq. (15) result in an error of about 0.6%.

V_H	13.240 V
I_H	0.700 A
I_M	0.010 A
V_{Fi}	10.650 V
ΔV_F total	0.300 V
P_{optH}	2.38 W
P_{optM}	0.036 W
$I_H \cdot V_H$	9.268 W
$I_M \cdot V_{Fi}$	0.107 W
$I_M \cdot \Delta V_F$	0.003 W
$\Delta P_{H\text{-}corr}$ as per (14)	6.782 W
$\Delta P_{H\text{-}corr}$ as per (15)	6.743 W
Total error	*0.578 %*

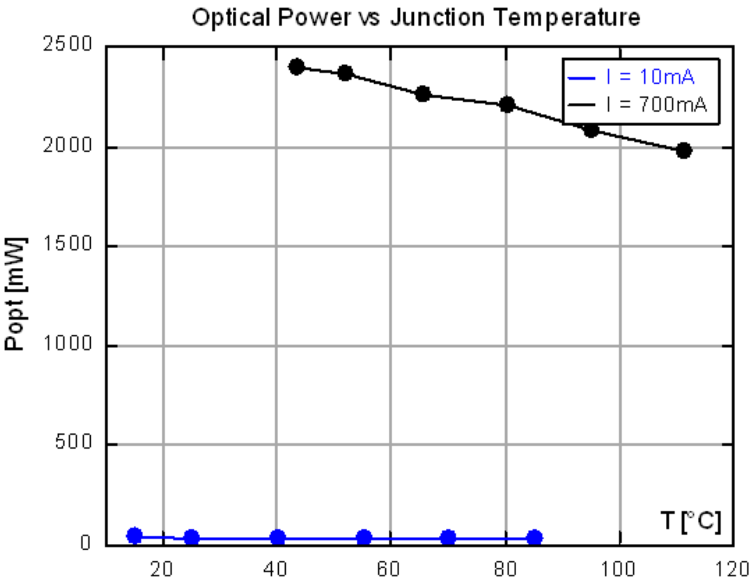

Figure 7: Heating power calculations and measured values of the emitted optical power for a 4 chip 10 W white LED package at 700 mA heating and 10 mA measurement current.

The advantage of the application of the static test method in cooling mode for LEDs' thermal measurement is that it can be combined with the measurement of the $\Phi_e(I_H, T_{J1})$ total radiant flux in full compliance with the recommendations of the CIE 127-2007 document[8] – as it will be discussed in the subsequent section.

Using expression (15) for the heating power of LEDs the real junction-to-reference X thermal resistance measured by the static test method reads as

$$R_{thJ-X} = \frac{V_{Fi} - V_{Ff}}{I_H \cdot V_H - I_M \cdot V_{Fi} - \Phi_e(I_H, T_{J1})} \cdot \frac{1}{S_{VF}} \tag{16}$$

and for the thermal impedance we get

$$Z_{thJ-X} = R_{thJ-X}(t) = \frac{\Delta V_F(t)}{I_H \cdot V_H - I_M \cdot V_{Fi} - \Phi_e(I_H, T_{J1})} \cdot \frac{1}{S_{VF}} \tag{17}$$

In order to distinguish quantities measured according to formulae (16) and (17) from thermal resistance/impedance values calculated *without* considering the total radiant flux of LEDs, they shall be called *real thermal resistance* and *real thermal impedance* and shall be denoted by R_{th-r} and Z_{th-r}, respectively. Once the real thermal resistance and the real heating power of an LED is known, than based on eq. (2) its junction temperature can be calculated:

$$T_J = P_{H\text{-}corr} \cdot R_{thJ\text{-}X\text{-}r} + T_X \tag{18}$$

(18) has the elegance that a nearly constant R_{th-r} descriptor is multiplied by a power which *does* depend on the current and temperature. Using R_{thel} we should multiply a varying structure descriptor by a power depending on the current but not on the radiant flux, a picture being far from physical reality.

Substituting the values from equations (11) and (16) into eq. (18) we get the following expression for the LED's junction temperature when the I_H heating current is applied:

$$T_J = T_X + \frac{\left[I_H \cdot V_H - I_M \cdot V_{Fi} - \Phi_e(I_H, T_J)\right] \cdot \left(V_{Fi} - V_{Ff}\right)}{I_H \cdot V_H - I_M \cdot V_{Fi} - \Phi_e(I_H, T_J)} \cdot \frac{1}{S_{VF}} \tag{19}$$

where T_X is the known temperature of the reference environment (also referred to as *reference temperature*,) the voltages and currents are all known, and $\Phi_e(I_H, T_J)$ is also measured at the same time.

The S_{VF} sensitivity is identified in a device calibration procedure prior or after all other quantities are measured. Since properties of LEDs need to be known by the end-user at operating temperatures, the best practice is to measure LEDs' properties (thermal resistance, forward voltage, light output characteristics) at different values of the T_X reference temperature.

This way eq. (19) provides a simple and accurate alternative to the procedure published by Y. Zong and Y. Ohno from NIST[9]. Setting a thermostat temperature is much easier than regulating it until a certain junction temperature is reached. Instead of applying a complex control scheme to find a T_X reference temperature where the junction is at a specified T_J temperature when the I_H heating current is applied, one sweeps the reference temperature in the range of interest (e.g. from 15 °C to 85 °C with a step of 5 °C) and measures the properties of the LED under test, including its real thermal resistance.

2.5 Environment for thermal test, measurement of the total radiant flux

The thermal transient shown in Figure 6b was measured on a temperature controlled cold-plate. Measurements on a cold-plate are fast as the aggressive cooling helps reaching the steady state quickly. We see the properties of the LED package (LED assembly) but there is no need to wait for a large heat-sink to reach thermal steady-state. Below 10 W power TEC-based cooling is usually sufficient at cold-plate temperatures above ~10 ºC. For higher power liquid circulators provide sufficient heat sinking capability.

The other advantage of using cold-plates as test environment for power LEDs is that the T_X reference temperature in eq. (19) is known as it is the cold-plate temperature: $T_X = T_{cp}$. For measuring the total radiant flux the cold-plate with the mounted test LED should be attached to an integrating sphere through a mechanical adaptor. Such a fixture + cold-plate solution is shown in Figure 8a. Figure 8b shows how the total flux of the mounted test LED is being measured in an integrating sphere using the strict substitution method[8].

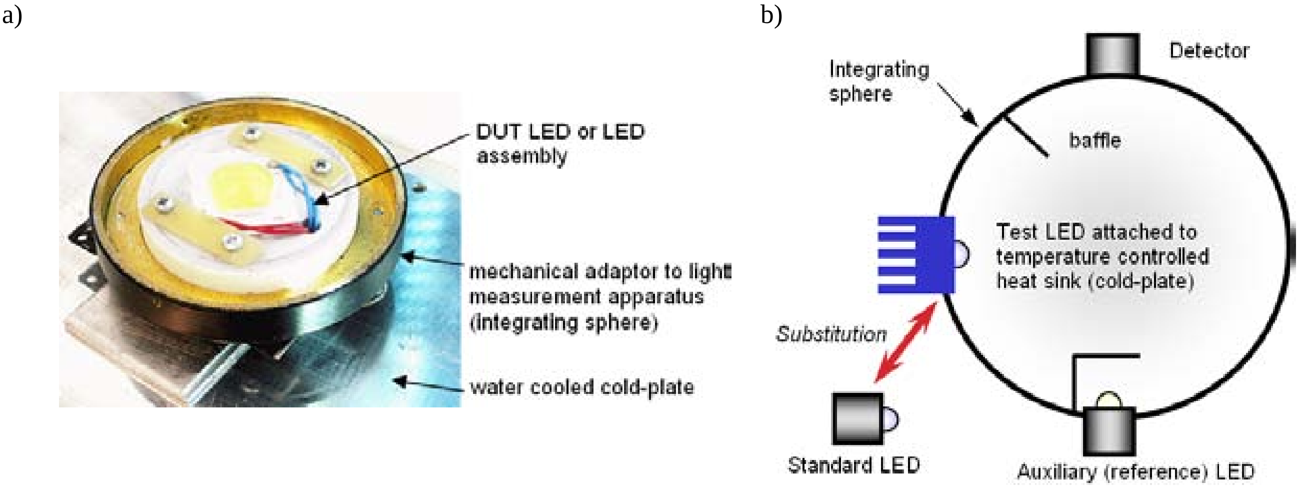

Figure 8: a) Temperature controlled mounting stage – b) connected to the DUT port of an integrating sphere.

In order to assure consistency between the measured light output and thermal resistance values, the LED + cold-plate structure must be kept intact between thermal test and optical measurements. The best practice is to consider the cold-plate + integrating sphere as the thermal test environment for power LEDs. The scheme of the thermal testing apparatus completed with a temperature controlled cold-plate and integrating sphere (as thermal test environment) is shown in Figure 9.

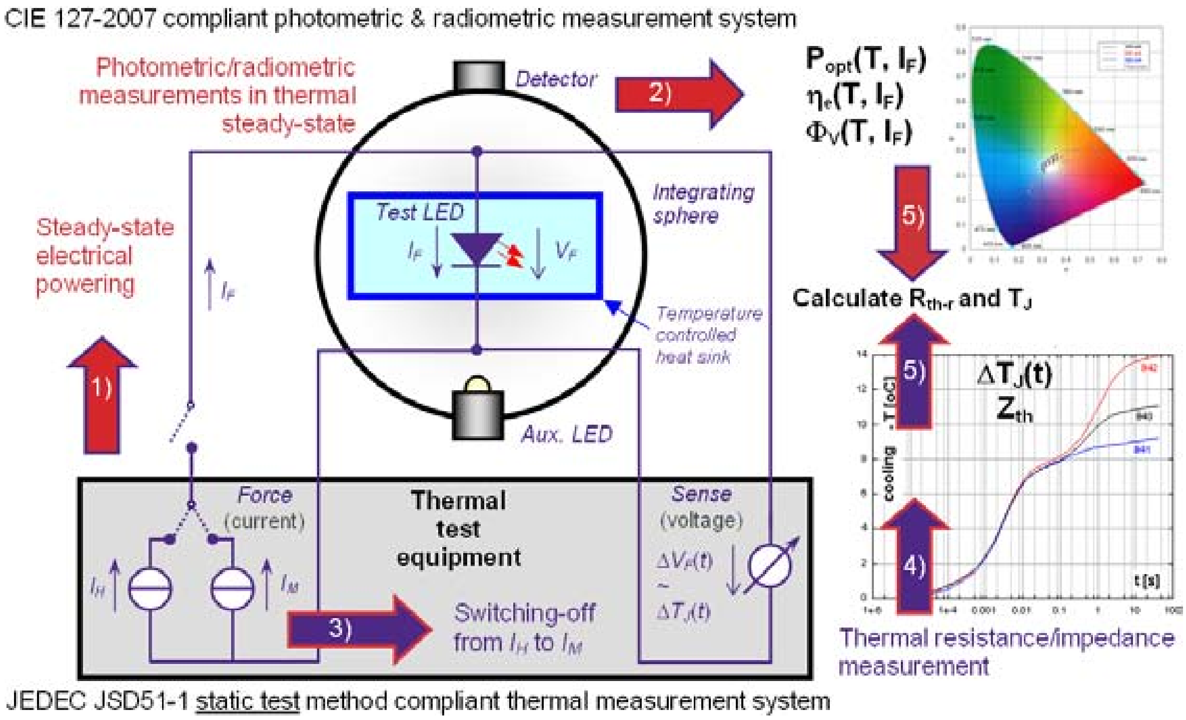

Figure 9: Schematic of a combined thermal and radiometric/photometric LED measurement setup with major steps of the measurement procedure.

In case of a TEC cooled cold-plate the settling time of the T_{cp} temperature is typically very fast, therefore LEDs' characteristics can be measured very quickly in an automated way. Note, that for different operating points (pairs of different I_F and T_{cp} values) the self-absorption correction of the test LED needs to be performed only once, the substitution with a standard LED can also be done independently from the series of measurements, therefore in Figure 9 we did not indicate the substitution with a standard LED. Figure 10 presents a practical realization of a combined thermal and radiometric/photometric measurement system in which a JEDEC JES51-1 static test method[4] compliant thermal test equipment is completed with a CIE 127-2007[8] compliant total flux measurement system.

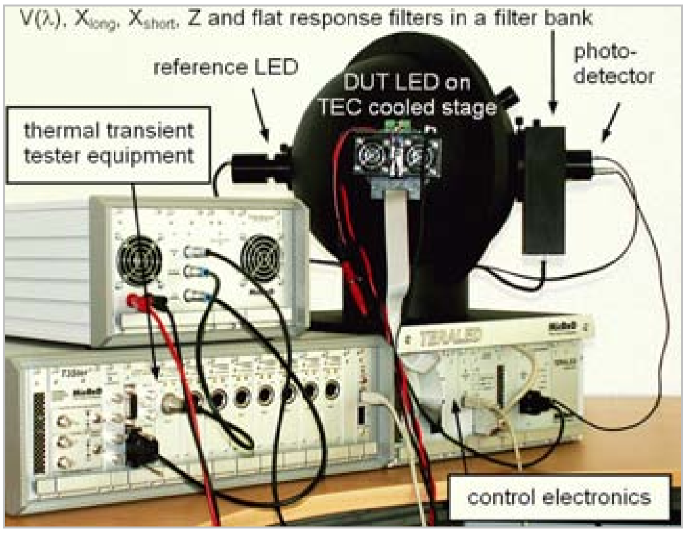

Figure 10: Practical realization of a combined thermal and radiometric/photometric LED measurement station using commercially available equipment.

3. CASE STUDIES

In this section we present a couple of measurement examples where simultaneous measurement of the thermal and optical properties of high power LEDs was performed. First we show that presenting the light output characteristics as function of the real junction temperature eliminates the effect of possible variations in the thermal resistance of the samples. In the second example we discuss the temperature related problems of LEDs' short pulse testing.

3.1 Characteristics of 10 W white LEDs with different thermal management solutions

In a recent study[10] we examined different samples of a 10 W white LED from one of the leading vendors. The goal of the study was to assess different thermal management solutions. The basic difference among the samples was in the material of the PCB used to mount the LED packages and in the quality of the thermal interface between the heat-slug of the LED package and the environment.

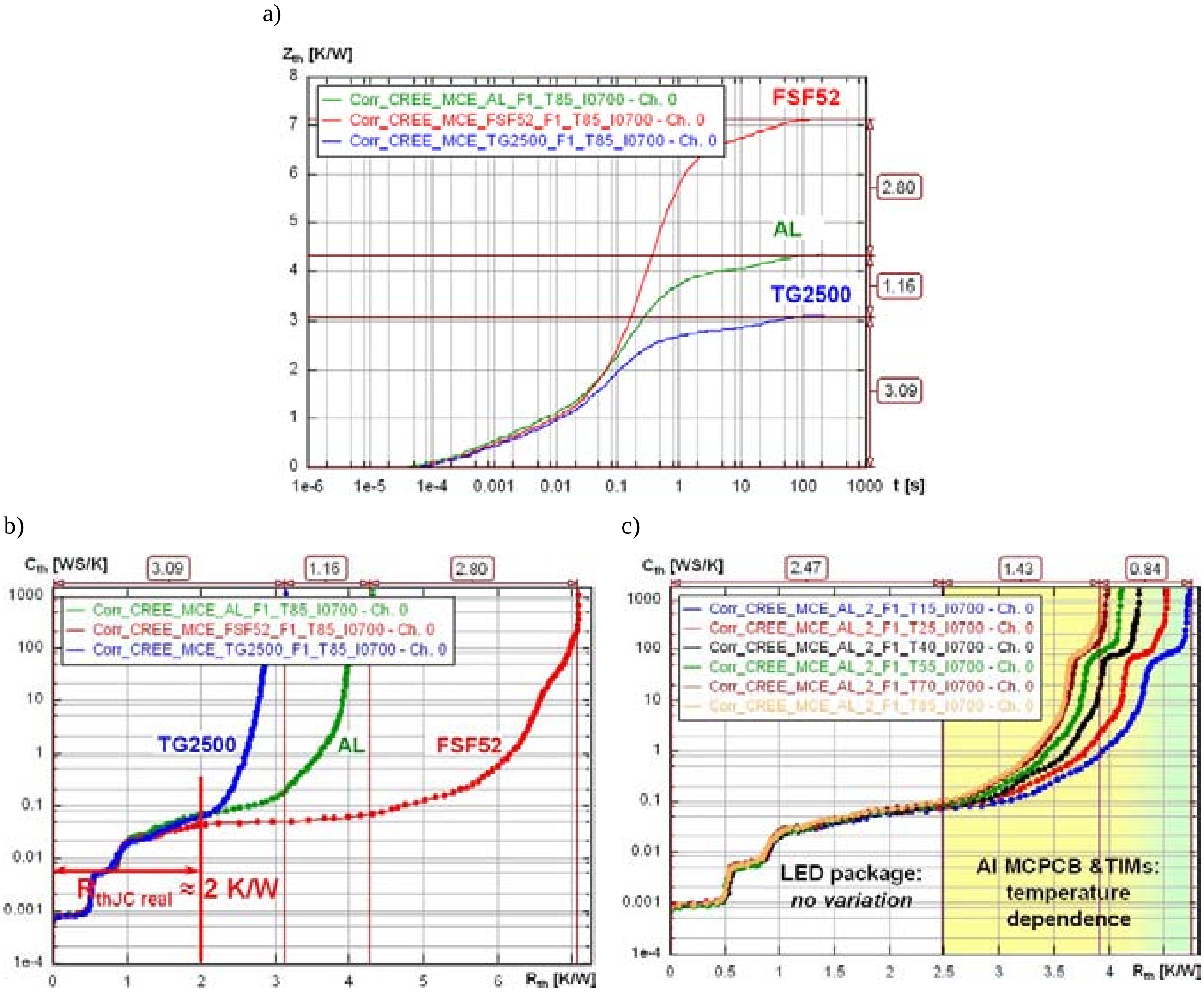

Figure 11: Results of thermal impedance measurements: a) real Z_{th} curves for 3 different LED samples measured at 700 mA forward current and 85 °C cold-plate temperature, b) the real thermal impedance of Figure 11a in structure function representation, c) the structure function representation of the thermal impedance of sample AL_2 measured at different cold-plate temperatures.

The measurement procedure followed the scheme shown in Figure 9. In all cases (all together 7 samples of 4 different combinations) the real thermal resistance of the LED assembly was measured with the test setup shown in Figure 10. The measurements were carried out at 15 °C, 25 °C, 40 °C, 55 °C, 70 °C and 85 °C cold-plate temperatures for all samples. The LEDs were driven by 350 mA and 700 mA forward current. In each case the thermal impedance diagrams of the LEDs were corrected by the total radiant flux according to eq. (17). The S_{VF} temperature sensitivity of each sample was carefully calibrated on a cold-plate at 10 mA measurement current. In Figure 11 we present some of the thermal impedance curves.

Figure 11a shows the thermal impedances of three samples in the usual Z_{th} diagram form. Note that the initial sections of the Z_{th} diagrams coincide – these sections correspond to the heat-flow inside the LED package, until the end of the heat-slug ("case"). The divergence point of the Z_{th} diagram at about 2 K/W is the data sheet value of the junction-to-case thermal resistance specified by the vendor.

Figure 11b shows the same thermal impedances in the form of *cumulative structure functions*. (Structure functions are the thermal capacitance vs. thermal resistance maps of the junction-to-ambient heat-flow path of a packaged semiconductor device. For definition of structure functions and the related theoretical background refer to the corresponding technical literature[6, 7].) The initial sections of the structure functions of Figure11b nicely fit – representing the same geometry and material distribution in the LED packages. From the thermal resistance value of 2 K/W (as also seen in Figure 11a), the curves start diverging – corresponding to the fact that thermal management of the three samples is different, due to different thermal interface materials and PCB substrates. Again, this divergence point represents the real R_{thJC} (*junction-to-case*) thermal resistance value of the bare LED packages. This R_{thJC} identification method is called *the transient dual interface method*, based on the original idea published by Steffens et al[11] and being standardized today by JEDEC. Figure 11c shows results of a single sample in structure function representation at different cold-plate temperatures (15°C .. 85°C).

It is interesting to see that the value of the total junction-to-ambient (cold-plate) thermal resistance varies with temperature. According to the structure functions this variance occurs in the last section of the heat-flow path, which is the thermal interface material (TIM) applied between the MCPCB and the cold-plate. At higher temperatures the interface resistance shrinks – due to the lower viscosity of the thermal grease being used. This result highlights the importance of reporting the cold-plate temperature at which the thermal and optical measurements were performed.

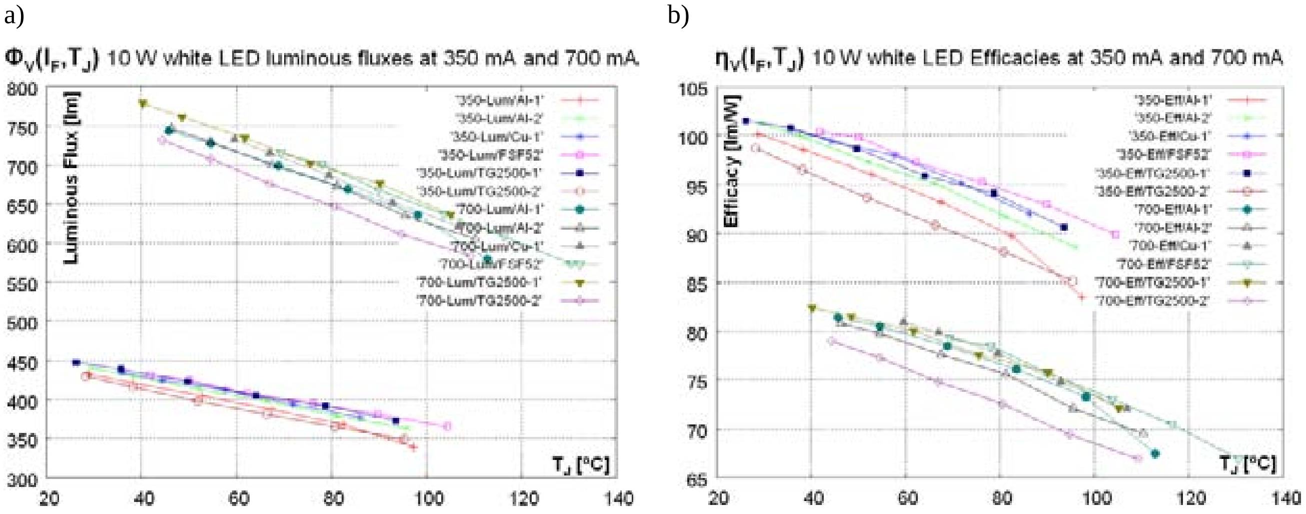

Figure 12: a) Luminous flux vs. junction temperature and b) efficacy vs. junction temperature diagrams for seven samples of 10 W white power LEDs measured at 350 mA and 700 mA forward current.

To eliminate the effect of the temperature dependent variation of the thermal resistance of the LEDs' heat-flow path, for every measured data point the real junction temperatures were calculated according to eq. (18)[10], see also the measurement flow in Figure 9. The resulting luminous flux characteristics and efficacy values for all investigated LED samples are shown in Figure 12: they are plotted as functions of the real junction temperature. The variation among the luminous flux (Figure 12a) and efficacy plots (Figure 12b) corresponds to the variation among the packaged LEDs – the effect of the different thermal resistance of the different thermal management solutions is eliminated from the results. It is interesting to note, that the slope of luminous flux vs junction temperature diagrams (close to -1.15 .. -1.2 lm/°C) are fairly identical.

These results highlight the importance of the effect of the actual thermal resistance of the LEDs when their light output characteristics are measured. To obtain consistent and repeatable results one needs to make sure that the actual thermal resistance is known and possibly remains unchanged between repeated tests. To eliminate the effect of any thermal resistance variation the best practice is to re-scale all measurement results to the identified junction temperatures.

3.2 Temperature dependence of light output characteristics and its consequence regarding short pulse test results

In production testing of LEDs short test pulses are applied and it is assumed that during the tests there is no significant change of the junction temperature. Therefore, all light output characteristics measured this way are reported for a nominal 25 °C junction temperature. This practice suffers from two problems: (i) normal operating junction temperatures of high power LEDs are different from this value, therefore light output characteristics provided for an assumed 25 °C junction temperature are of no practical help for actual design purposes; (ii) the constant junction temperature assumption for short pulse tests is basically *not true*.

In Figure 13a we show measurement results of the same10 W white power LEDs as in section 3.1. Typical duration of short pulse tests is like 10 ms. As we see there is a significant junction temperature elevation at this time when the devices are measured in free air. (This boundary condition was chosen to mimic the conditions of in-line testing.). In case of 350 mA forward current the junction temperature change is roughly 15 °C and in case of 700 mA forward current it is roughly 30°C. Figure 13b and Figure 13c show the temperature dependence of the luminous flux and the correlated color temperature (key parameters for lighting design) of the same device, measured with the test setup shown in Figure 10.

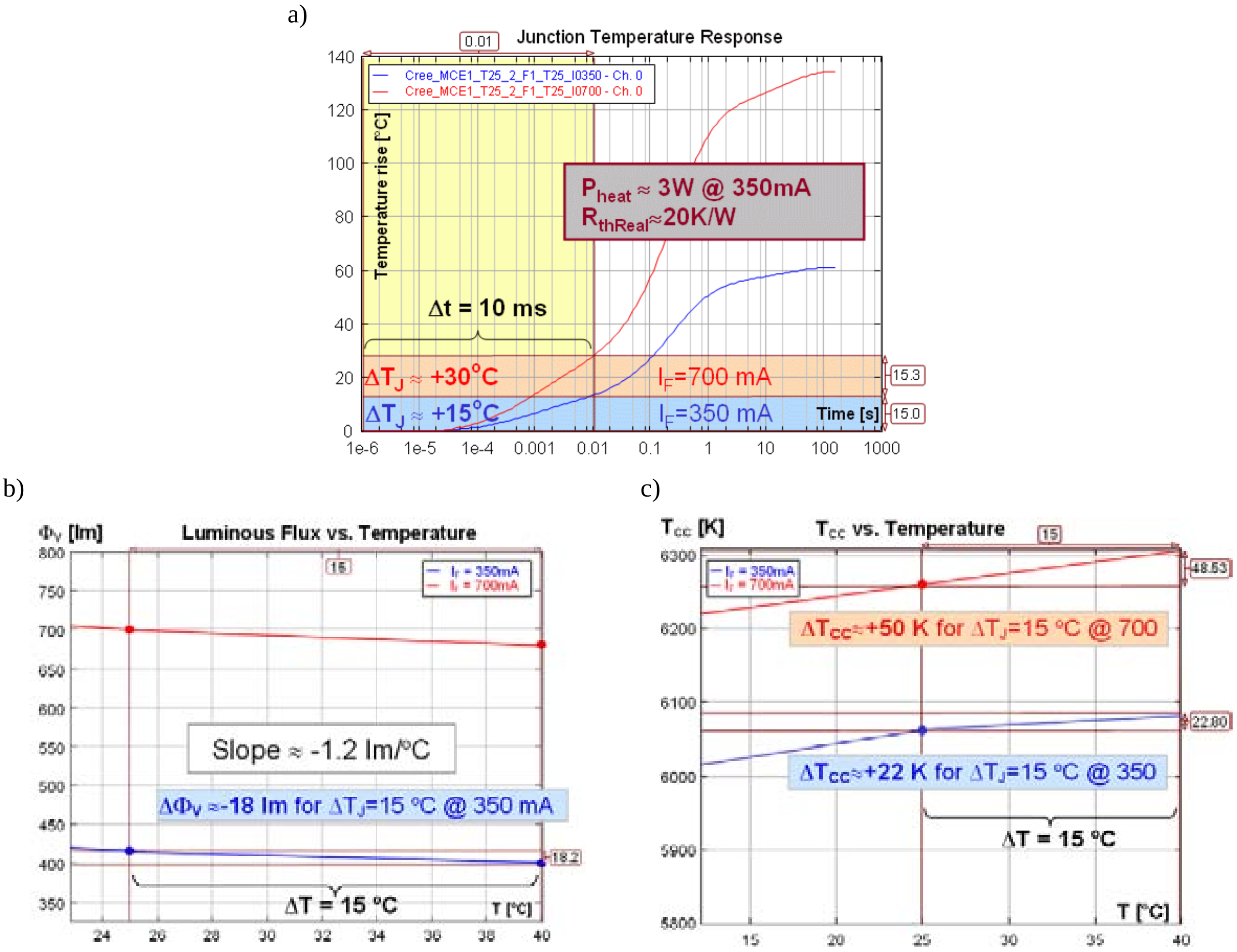

Figure 13: a) Junction temperature elevation of a 10 W white LED in free air at 350 mA and 700 mA forward current b) temperature dependence of the luminous flux and c) of the correlated color temperature of the device.

As one can see if the junction temperature is increased by 15 °C, the luminous flux drops by app. 18 lm when the LED is driven by 350 mA forward current and the correlated color temperature increases about 22 K. In case of 700 mA forward current the color temperature shift will be roughly 50 K during 10 ms. These problems have been recognized by CIE and a technical committee (TC2-64) was set up to address these issues.

One possible solution to account for these junction temperature induced shifts is to establish a standardized LED model as we suggested earlier[3]. After having calibrated the parameters of such a model for a given LED type the light output characteristics measured during short pulse tests can be extrapolated to junction temperatures corresponding to typical operating conditions of LEDs.

3.3 Thermal problems in LM80 tests

For light output measurements the LM80 standard[12] requires the case temperature of the LED(s) under test be set to 25°C. But as we have shown in sections 3.1 and 3.2, it is not the case temperature which is relevant; it is the junction temperature which influences the results of photometric and colorimetric measurements. As Figure 12a and Figure 13b show, LEDs' emitted luminous flux drops with increasing junction temperature. According to Figure 13c the correlated color temperature also shifts, etc. There could be three reasons why the junction temperature may increase – see also eq. (2): (i) the reference temperature is elevated; (ii) the dissipated power in the device is increased; (iii) the thermal resistance is increased.

During LM80 tests it is required[12] that (i) the LEDs under test should be driven by constant DC current and (ii) the temperature of the test chamber is kept constant. Therefore the only reason why light output change due to junction temperature elevation may occur is the increase in the junction-to-ambient thermal resistance of the LEDs under test. Unfortunately the LM80 standard does not provide any provision about the mechanical setup of the measurements; it only requires "conformance to appropriate laboratory test method" – which through normative reference means methods defined in the CIE 127-2007 document[8]. Therefore, if LED(s) under test are removed from the test chamber and are attached to a photometric test system, through the unrepeatable changes of the interfacial thermal resistance between the DUT and the heat-sink of the photometric test system significant error can be introduced in the light output measurement results.

Therefore in the lumen maintenance measurements of LEDs in-situ measurements are preferable. In the long term stability studies that are carried out by the research team of prof. J. Schanda at the University of Pannonia in Veszprém, Hungary (see Figure 14) in-situ measurements are being used. In an LM80 compliant test environment 60 power LEDs are burnt simultaneously. Each LED is attached to a temperature controlled heat-sink, when the test chamber is closed also the temperature of the surrounding air is controlled – see Figure 14a. Relative light output and chromaticity coordinates are obtained from in-situ partial flux measurement performed in an ALI-like arrangement (Figure 14b).

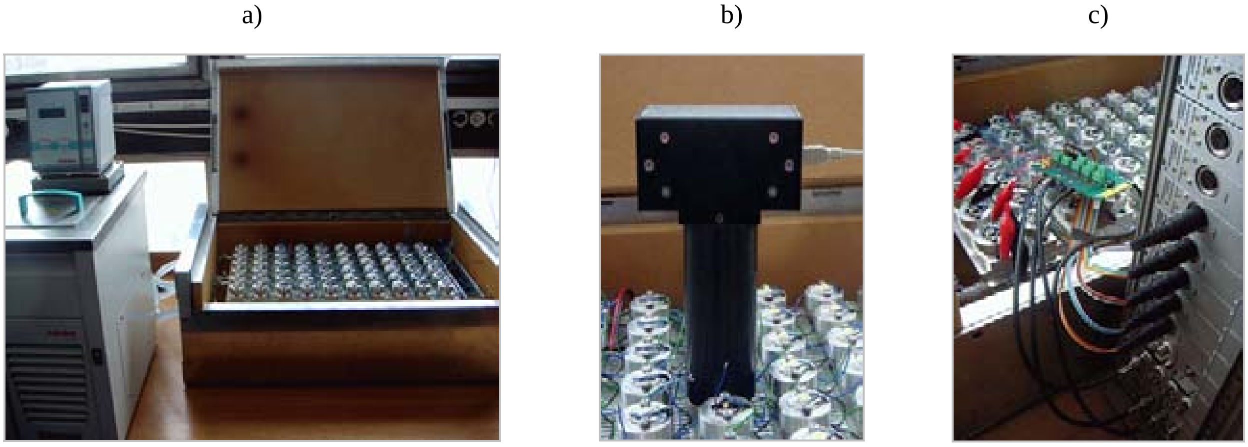

Figure 14: LM80 test chamber, a) 60 devices and the liquid circulator temperature control, in-situ measurement of the b) light output, c) thermal impedance (*photos by courtesy of the University of Pannonia, Veszprém, Hungary*)

In 500 h time intervals the thermal impedances of the investigated LEDs are also measured in-situ with a commercially available thermal transient test equipment (Figure 14c). Applied forward current values are 350 mA (and in some cases 700 mA). During tests forward voltages of all LEDs are measured at 25 °C, 55 °C and 85 °C case temperature at a measurement current of 10 mA. This way the S_{VF} temperature sensitivities of the forward voltages of all LEDs are also identified for the purpose of thermal transient testing. The measured thermal impedance curves are converted to structure functions. Structure functions help to trace structural changes along the junction-to-ambient heat-flow path of the investigated LEDs. This way we monitor the changes of the thermal resistance of the different sections of the LEDs' heat-flow path (such as die attach interface resistance, the thermal resistance of the package-MCPCB interface, etc). Figure 15 presents an example from our common measurement results. Figure 15a shows the relative light output changes of all samples from vendor O. In Figure 15b the structure functions of sample #44 from vendor O can be seen; measured at the start of the tests (at 0h) and after 500h of ageing .

The structure functions in this case clearly show that no structural degradation took place inside the LED assembly (packaged LED attached to an MCPCB) but the interfacial thermal resistance between the LED and the heat-sink has increased. This increase is due to the degradation of the thermal conductivity of the applied thermal interface material (conventional thermal grease in this case). This means, that the few percent drop in the light output of sample #44 is not solely due to the ageing of the LED itself, the ageing of the applied TIM material also contributes to the light output degradation through the increased thermal resistance. Since only in-situ measurements are used in this experiment, the mechanical structure of every LED under test is kept intact. Thus, any mechanical change observed during this life-time testing experiment is solely due to aging. Based on the junction temperature sensitivity of the light output characteristics the effect of the thermal resistance increase (e.g. TIM ageing) can be processed out from the measurement results.

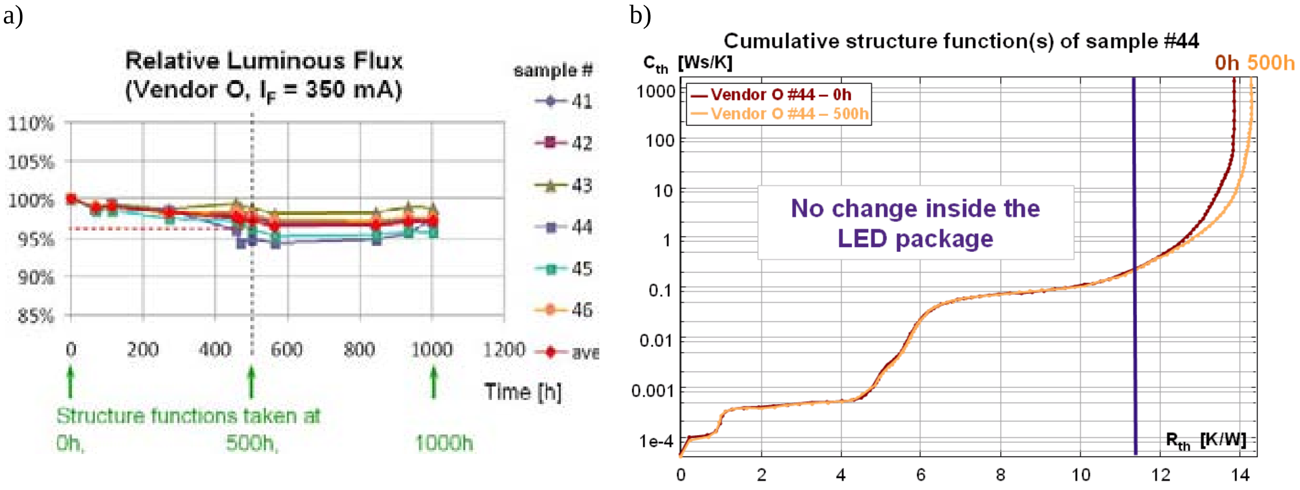

Figure 15: Intermediate measurement results of LED life-time tests: a) relative light output change of LED samples from vendor O (*by courtesy of the University of Pannonia, Veszprém, Hungary*), b) structure functions show ageing of TIM.

4. SUMMARY

In this paper we described a test setup which allows measuring the thermal and light output properties of power LEDs in a consistent way – forming a comprehensive LED testing station. The equipment and test procedures are based on existing thermal[4] and light output measurement[8] standards. Since the energy conversion efficiency of LEDs depends on both the applied forward current and the junction temperature, it is essential that both the thermal and photometric measurements are started in the hot thermal steady-state of the LED under test – therefore the cooling mode realization of the static test method is recommended for use in thermal tests. For both kinds of test it is recommended to attach the test LED to a temperature controlled heat-sink.

Performing the combined thermal and radiometric/photometric measurements in a wide range of reference temperatures (corresponding to real-life operating conditions) temperature dependence of the LED parameters can be identified. Through a few case studies the importance of the junction temperature and the reference temperature was shown – for example in case of short pulse tests used for binning. To account for the effects of junction temperature changes in short pulse test application of multi-domain LED models is proposed.

In different examples the variation of the interfacial thermal resistance between the heat-sink and the LED assembly was shown which was attributed to changes of properties of the applied TIM materials. Short term variations are caused by temperature change induced viscosity changes while long term variations are due to TIM degradation. It was also shown, that variations of these interfacial thermal resistances may influence the results of LM80 tests. In order to reduce these undesired variations to a minimum it is recommended to perform the light output measurements during LM80 tests in-situ. Also, in-situ thermal impedance/resistance measurements are suggested during LM80 tests to monitor structural changes of LEDs during ageing.

ACKNOWLEDGEMENTS

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Emerging standard for thermal testing of power LEDs and its possible implementation

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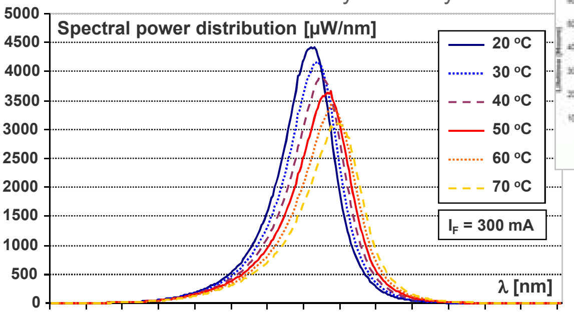
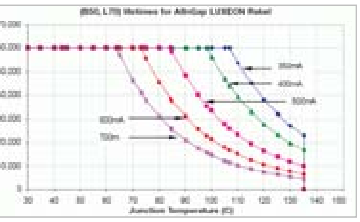
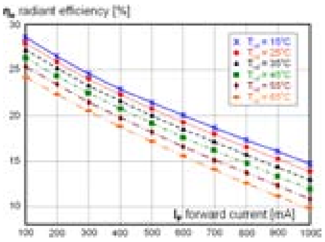
Why to deal with thermal issues?

- Reliability is connected to thermal issues
  - life time (failure mechanisms are thermally assisted)
  - mechanical stress
- Optical properties strongly depend on temperature
  - spectra
  - emitted flux / efficiency / efficacy



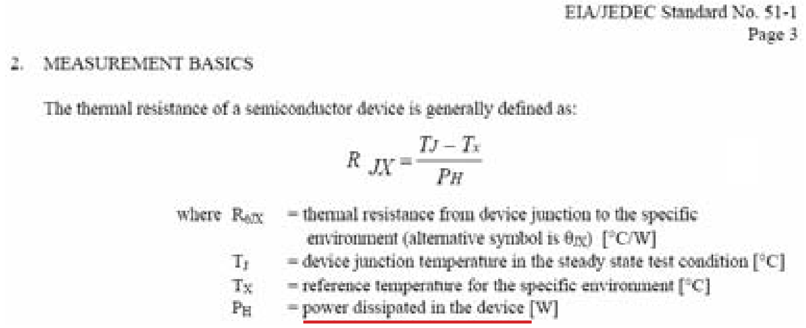




No doubt that **reliable thermal data** is a must for power LEDs: widely accepted **standards are needed**

A few words about thermal resistance of LEDs

- Original definition in the JEDEC JESD51-1 document



EIA/JEDEC Standard No. 51-1
Page 3

2. MEASUREMENT BASICS

The thermal resistance of a semiconductor device is generally defined as:

$$R_{JX} = \frac{T_J - T_X}{P_H}$$

where $R_{\theta JX}$ = thermal resistance from device junction to the specific environment (alternative symbol is θ_{JX}) [°C/W]
T_J = device junction temperature in the steady state test condition [°C]
T_X = reference temperature for the specific environment [°C]
P_H = power dissipated in the device [W]

- Classically, for Si semiconductor diodes: $R_{th\text{-}el} = \Delta T_J / (I_F \times V_F)$ (1a)
- Accurate; the questions are:
  - what is the dissipated power of an LED? *Subtract radiant flux*
  - what is the T_X reference temperature *Use cold plate!*
- For LEDs, consider the radiant flux: $R_{th\text{-}r} = \Delta T_J / (I_F \times V_F - P_{opt})$ (1b)
- Both $R_{th\text{-}el}$ and $R_{th\text{-}r}$ are correct, if proper power is used to calculate T_J

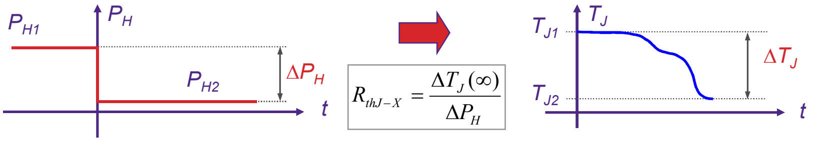
Junction temperature – performance indicator

- Calculation: $T_J = R_{thJ\text{-}X} \cdot P_H + T_X$ (2)
  - $R_{thJ\text{-}X}$ *junction-to-reference_X thermal resistance* supplied by the LED vendor
  - P_H *heating power* measured/calculated by the LED user
    - How?
  - T_X *reference temperature* (un)specified by the LED user
- Used in the design process to decide if the foreseen cooling is sufficient or not...
  - Not enough: in case of LEDs, prediction of "hot lumens" is also required

Differential formulation of the thermal resistance

$$R_{thJ-X} = \frac{T_J - T_X}{P_H} = \frac{[\Delta T_J]_X}{P_H}$$

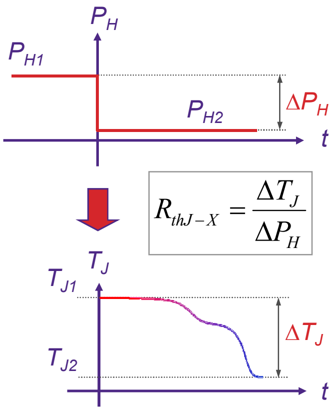
Instead of spatial difference (temperature values at junction and reference point) temporal difference of the junction temperature can be used



$$R_{thJ-X} = \frac{\Delta T_J(\infty)}{\Delta P_H}$$

Differential formulation of the thermal resistance

- Alternate formulation: instead of spatial difference, we can also calculate with a ***temporal difference*** of the junction temperature (temp. transient):



$$R_{thJ-X} = \frac{\Delta T_J}{\Delta P_H}$$

$T_{J1} = R_{th\ J\text{-}X} \cdot P_{H1} + T_X$ (4a)

$T_{J2} = R_{th\ J\text{-}X} \cdot P_{H2} + T_X$ (4b)

$T_{J2} - T_{J1} = R_{th\ J\text{-}X} \cdot (P_{H2} - P_{H1})$ (5)

Let $T_{J1}=T_J(t_1)$ and $T_{J2}=T_J(t_2)$:

$R_{th\ J\text{-}X}=[T_J(t_2) - T_J(t_1)\,]\,/\,(P_{H2} - P_{H1})$ (6)

$\boldsymbol{R_{th\ J\text{-}X}(t)=\Delta T_J(t)\,/\,\Delta P_H}$ (7)

If t_1=0 and t_2=∞ ➔ $\boxed{R_{th\ J\text{-}X}=\Delta T_J / \Delta P_H}$

If P_{H2} = 0, then T_{J2}= T_X – see (4b)

$R_{th\ J\text{-}X}(t) = \Delta T_J(t)\,/\,\Delta P_H$

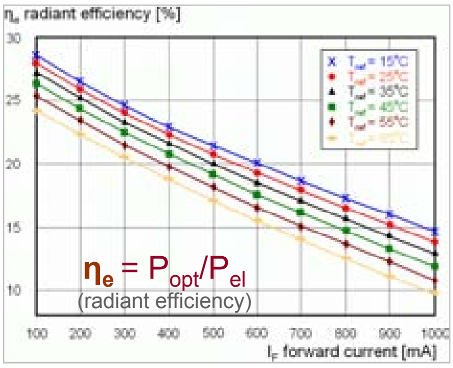
is called **Z_{th} curve**

Importance of the definition of R_{th} for LEDs

- Traditionally: $R_{th\text{-}el} = \Delta T_J / P_{el} = \Delta T_J / (I_F \times V_F)$
- Due to high efficiency, radiant flux must be considered:

$$R_{th\text{-}r} = \Delta T_J / (P_{el} - P_{opt})$$
$$= \Delta T_J / (I_F \times V_F - P_{opt})$$

By neglecting P_{opt} vendors report much nicer data than reality



EXAMPLE:

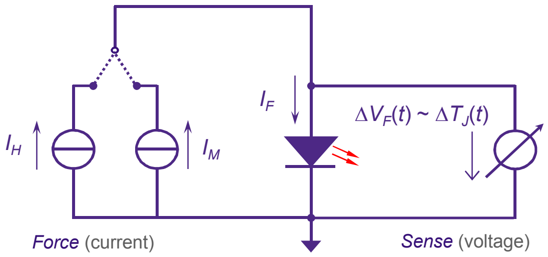
- Let us assume two η_e -s
  ΔT = 50°C, P_{el} = 10W
  - η_e =0% (electrical only)
    ➔ "$R_{th\text{-}el}$" = $\Delta T / P_{el}$ = 50/10 = **5 K/W**
  - η_e = 25%
    ➔ $R_{th\text{-}r} = \Delta T / (P_{el} - P_{opt}) = \Delta T / [P_{el} \cdot (1\text{-}\eta_e)]$ =
    = 50/(10·0.75) = **6.67 K/W**
  - η_e = 50%
    ➔ $R_{th\text{-}r} = \Delta T / (P_{el} - P_{opt}) = \Delta T / [P_{el} \cdot 1\text{-}\eta_e)]$ =
    = 50/(10·0.5) = **10 K/W**

The electrical test method for junction temperature measurement of LEDs

How do we know $\Delta T_J(t)$?

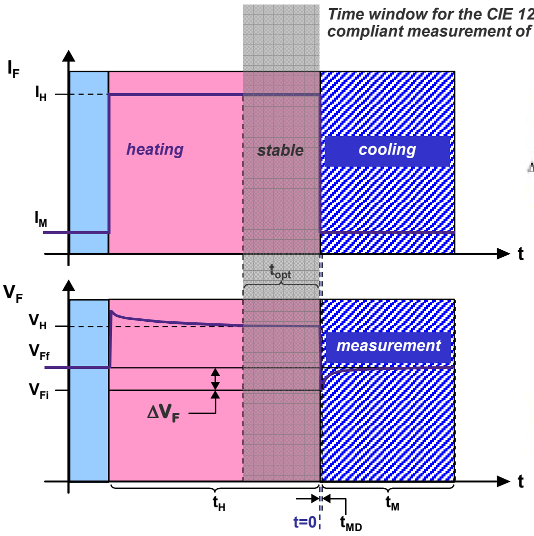
- The LEDs′ forward voltage under forced current condition can be used as a very accurate thermometer
- The change of the forward voltage (TSP – temperature sensitive parameter) should be carefully calibrated against the change of the temperature (see JEDEC JESD51-1 and MIL-STD-750D)
  - In the calibration process the S_{VF} temperature sensitivity of the forward voltage is obtained

$$V_F(I_M,t) = V_{Fi}(I_M) + S_{VF}\cdot[T_J(t) - T_J(0)]$$

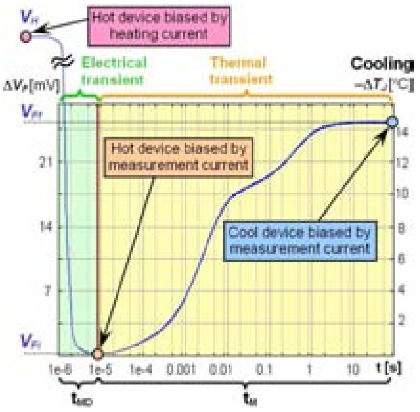


- Forward voltage change due to temperature change is measured using a 4 wire setup (Kelvin setup)

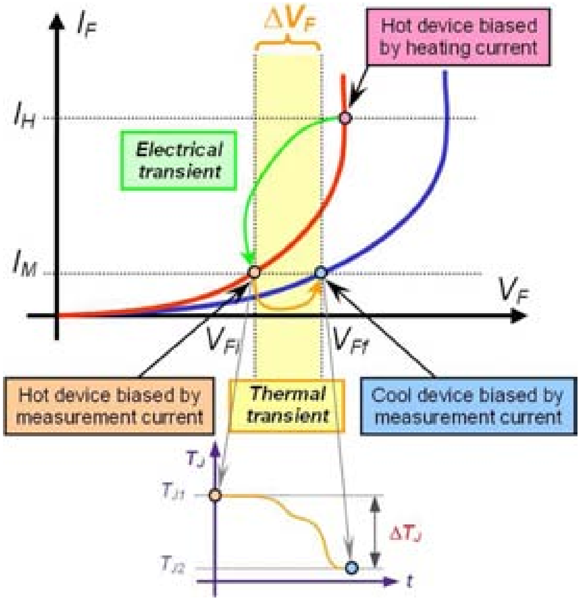
The measurement waveforms

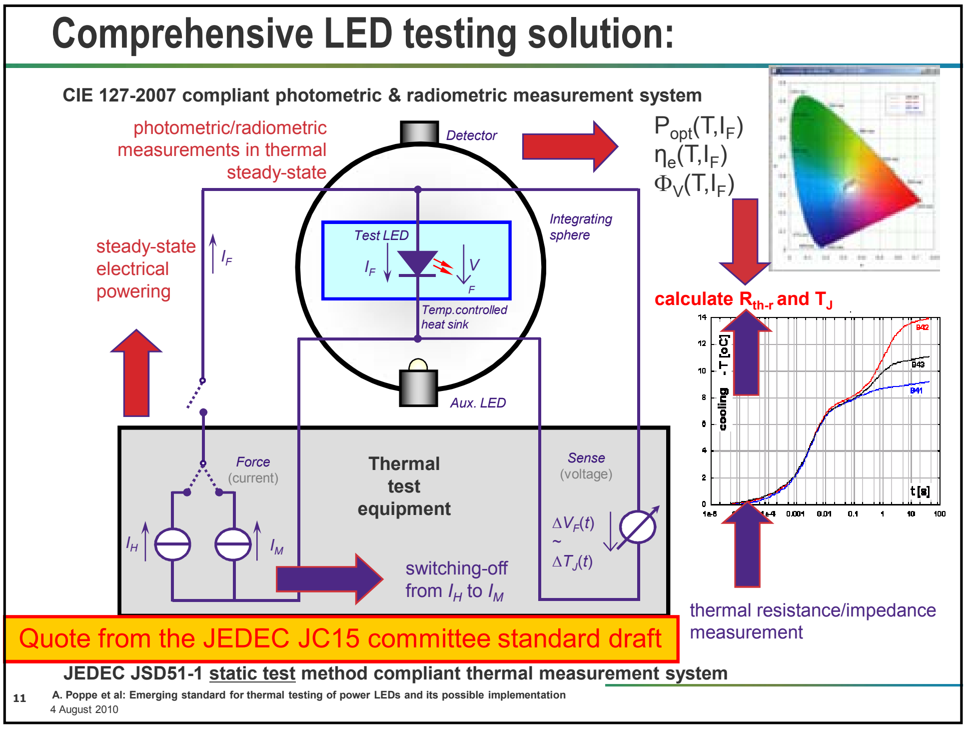


Time window for the CIE 127-2007 compliant measurement of the light output



The transient processes in the I-V characteristic:





Comprehensive LED testing solution:

CIE 127-2007 compliant photometric & radiometric measurement system

photometric/radiometric measurements in thermal steady-state

steady-state electrical powering

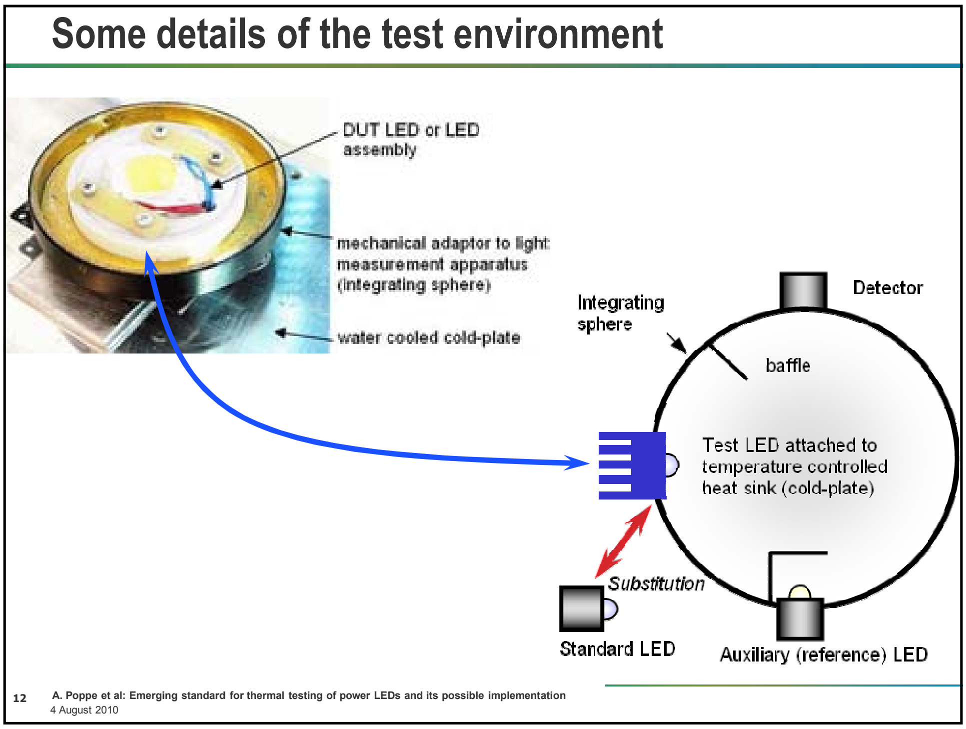
$P_{opt}(T,I_F)$
$\eta_e(T,I_F)$
$\Phi_V(T,I_F)$

calculate R_{th-r} and T_J

thermal resistance/impedance measurement

Quote from the JEDEC JC15 committee standard draft

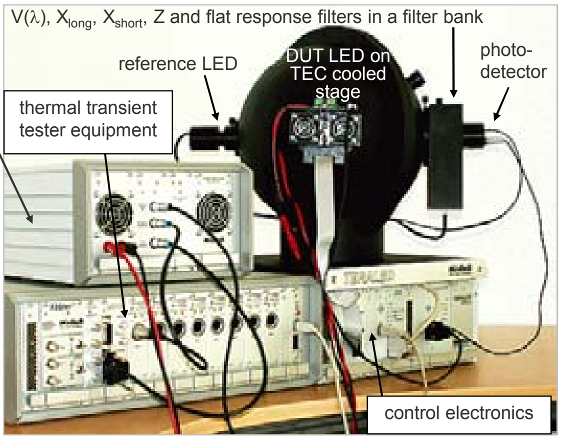
JEDEC JSD51-1 static test method compliant thermal measurement system



Some details of the test environment

The Mentor Graphics MicReD implementation:

Special LED booster: allows high voltage across a LED line (overall forward voltage can reach 280V).



$V(\lambda)$, X_{long}, X_{short}, Z and flat response filters in a filter bank

reference LED

DUT LED on TEC cooled stage

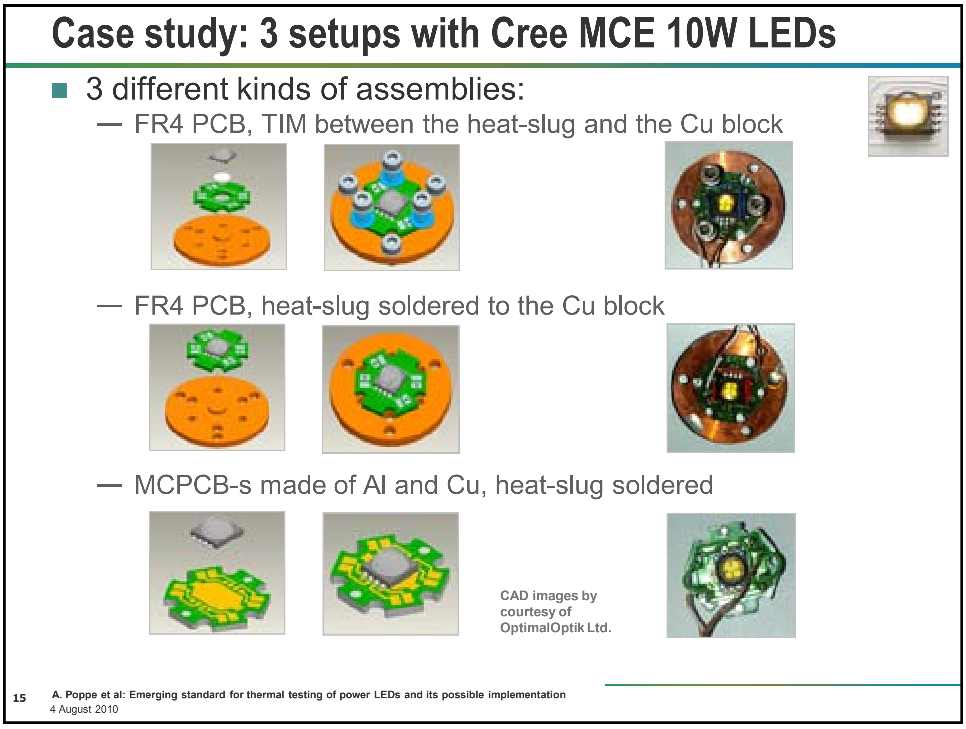
photo-detector

thermal transient tester equipment

control electronics

It can be added to the system in a plug&play manner if the voltage of the base tester is not sufficient.

Case study:
Thermal management solutions for a 10W white LED and its light output characteristics as function of forward current and junction temperature

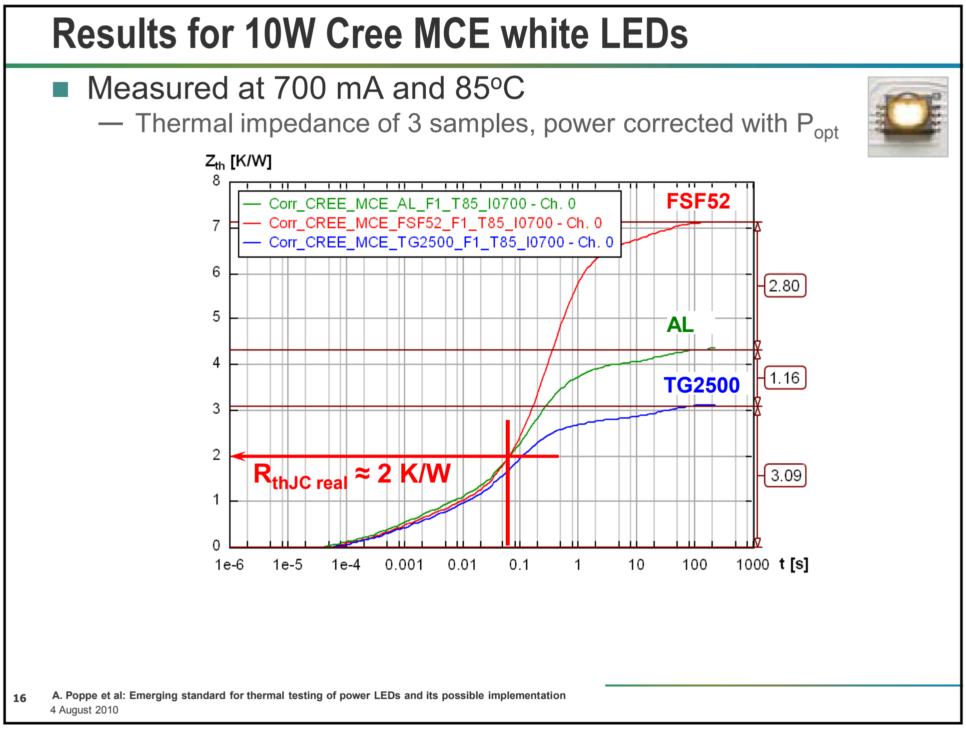


Case study: 3 setups with Cree MCE 10W LEDs

- 3 different kinds of assemblies:
  - — FR4 PCB, TIM between the heat-slug and the Cu block
  - — FR4 PCB, heat-slug soldered to the Cu block
  - — MCPCB-s made of Al and Cu, heat-slug soldered

CAD images by
courtesy of
OptimalOptik Ltd.

15 A. Poppe et al: Emerging standard for thermal testing of power LEDs and its possible implementation
4 August 2010



Results for 10W Cree MCE white LEDs

- Measured at 700 mA and 85°C
  - — Thermal impedance of 3 samples, power corrected with P_{opt}

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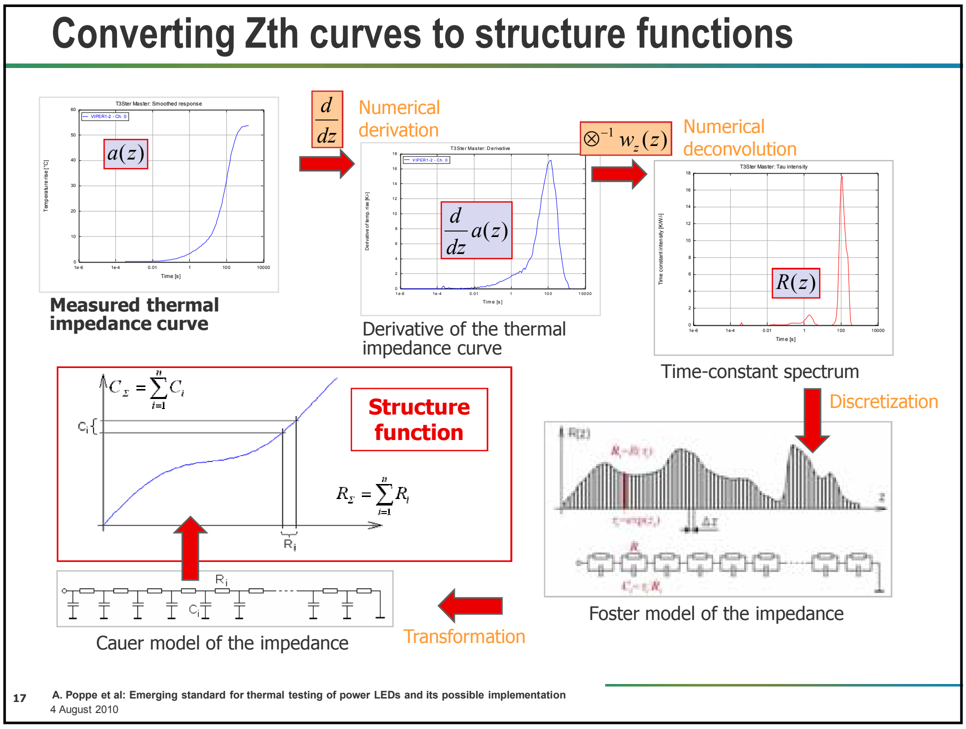
4 August 2010

Converting Zth curves to structure functions



$a(z)$

Measured thermal impedance curve

$\frac{d}{dz}$

Numerical derivation

$\frac{d}{dz} a(z)$

Derivative of the thermal impedance curve

$\otimes^{-1} w_z(z)$

Numerical deconvolution

$R(z)$

Time-constant spectrum

Discretization

Foster model of the impedance

Transformation

Cauer model of the impedance

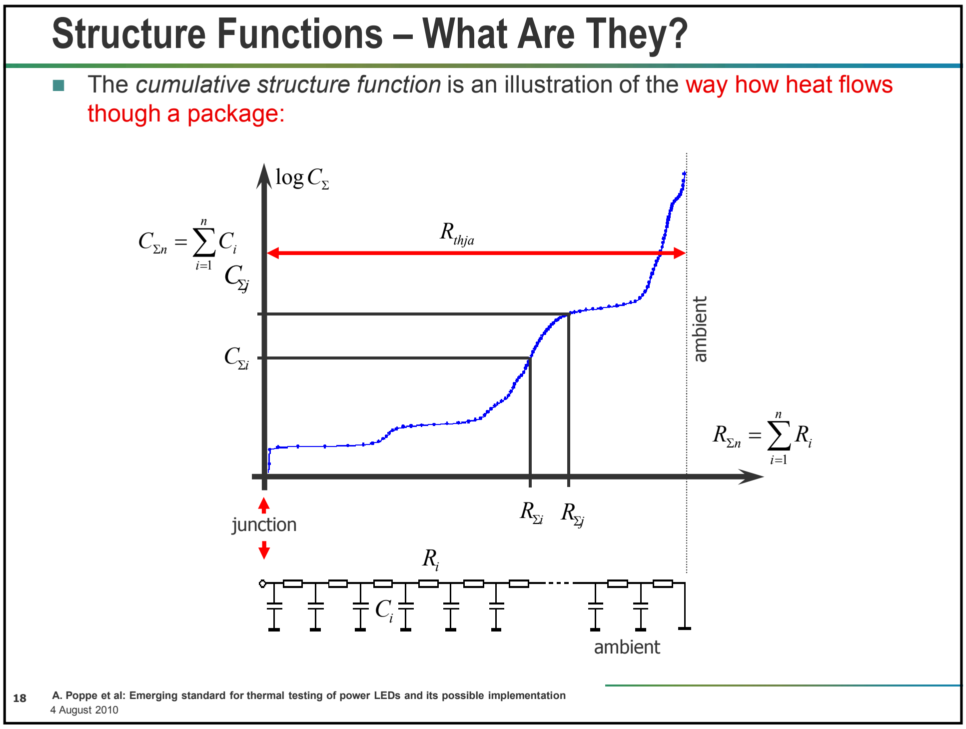
Structure function

$C_\Sigma = \sum_{i=1}^{n} C_i$

$R_\Sigma = \sum_{i=1}^{n} R_i$

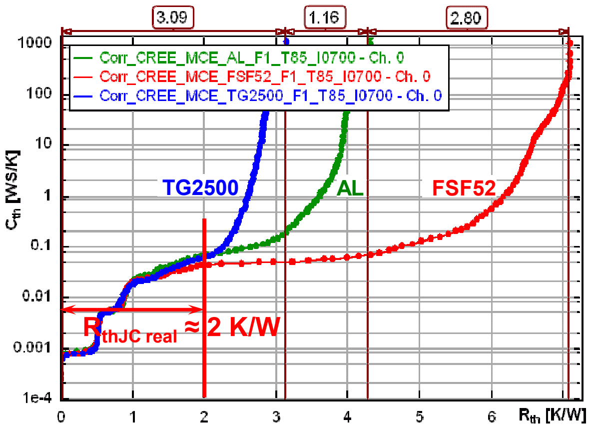
Structure Functions – What Are They?

- The *cumulative structure function* is an illustration of the way how heat flows though a package:



Results for 10W Cree MCE white LEDs

- Measured at 700 mA and 85°C
  - Structure functions of 3 samples, power corrected with P_{opt}



  - R_{thJC} is identified in a way similar to the *transient double interface method*, also being standardized by the JEDEC JC15 committee

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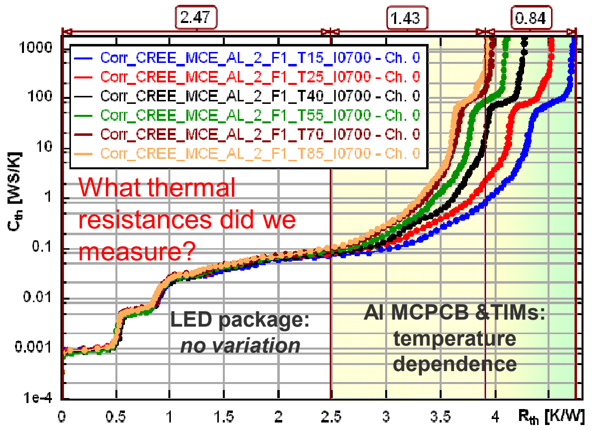
Results for 10W Cree MCE white LEDs

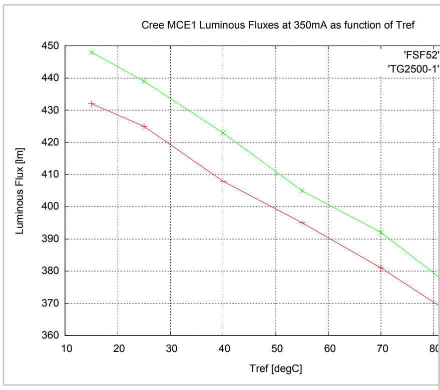
- Measured at 350/700 mA & between 15°C and 85°C
  - Structure functions of sample AL-2, power corrected with P_{opt}



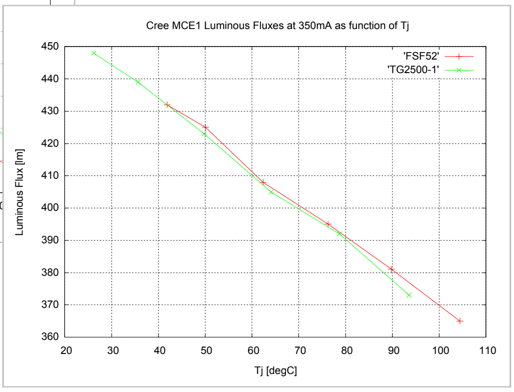
$R_{thJC\text{-}package} + R_{th\text{-}MCPCB} + R_{th\text{-}grease}$ ➔ for "**hot lumen**" estimates

Changes in TIM quality contribute to light output variations

$\Phi_V(T_{ref})$ plots for two cases (I_F=350mA)



$$T_J = T_{ref} + R_{th\text{-}r} \times (I_F \times V_F - P_{opt})$$



Variation of R_{th} means, the device characteristics scaled in reference temperature will be different

No need for a sophisticated control of the TEC in the integrated sphere

Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

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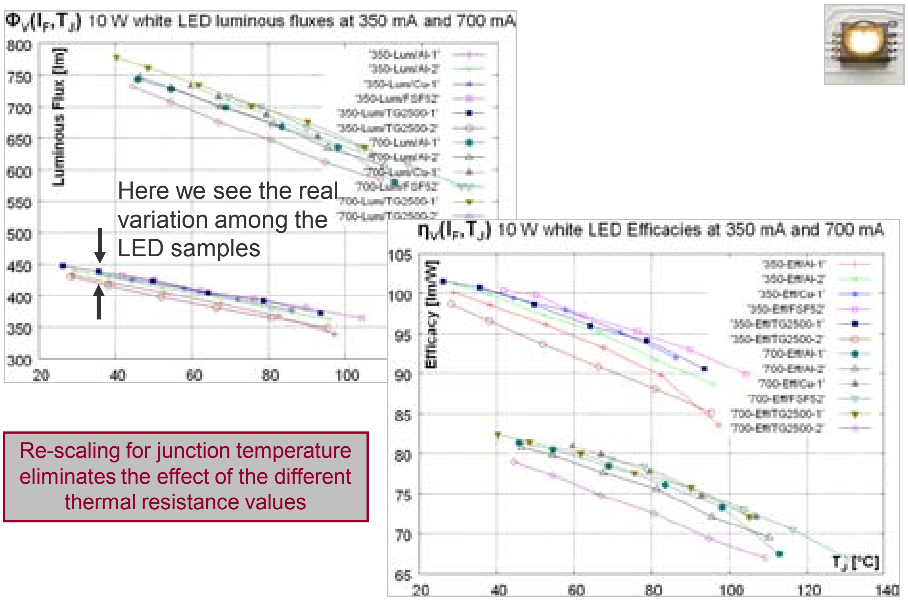
$\Phi_V(I_F,T_J)$ and $\eta_V(I_F,T_J)$ plots for 7 different samples



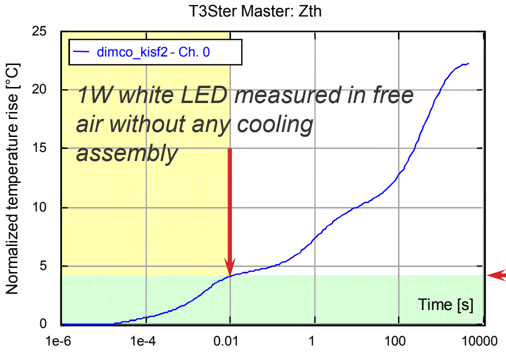
Here we see the real variation among the LED samples

Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

Further problems:
Thermal issues in short-pulse testing and in LM80 tests

Short pulse measurements

- During in-line testing photometric/colorimetric properties are measured with a short pulse
  - $T_J = T_{ref}$ = constant is assumed, ***THIS IS NOT TRUE:***
    In 10 ms significant junction temperature change may take place

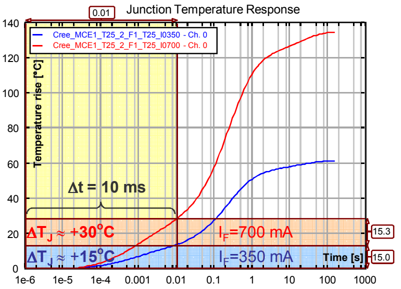


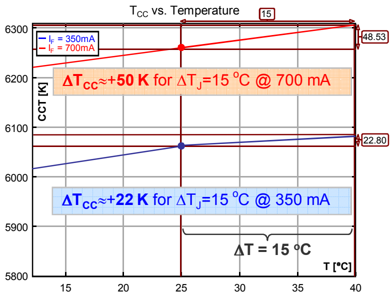
Question is if this causes big problems or not…

During 10 ms T_J changes almost by 5 °C

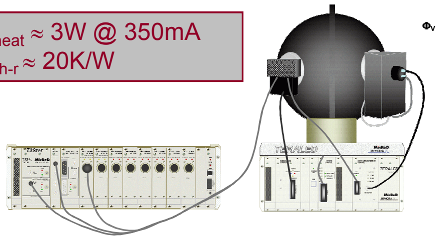
Addressed by CIE TC 2-64

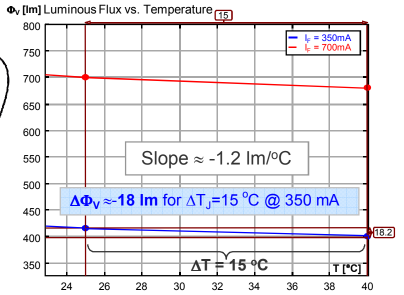
Example: 10W Cree MCE white LED





P$_{heat}$ ≈ 3W @ 350mA
R$_{th-r}$ ≈ 20K/W

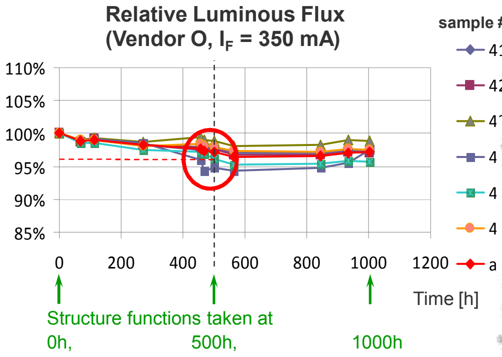




Addressed by CIE TC 2-64

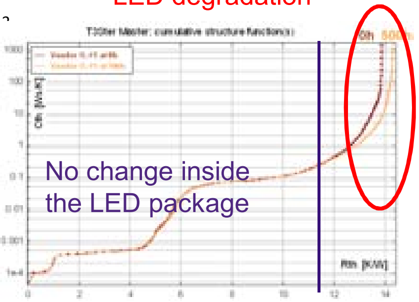
Recent results from LM80 test of different LEDs

- In cooperation with University of Pannonia, Veszprém (Hungary), prof. J. Schanda's group within the KöZLED project of the Hungarian Goverment



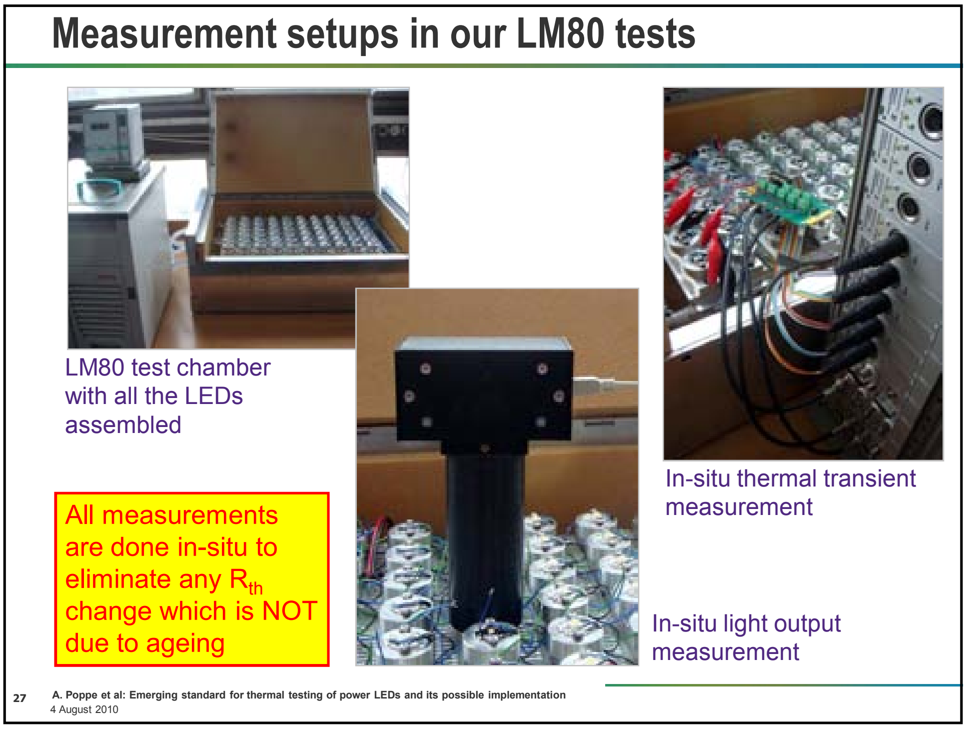
Structure functions taken at
0h, 500h, 1000h

Ligh output drop likely due to increased R$_{th}$ caused by TIM degradation, not by LED degradation



No change inside the LED package

- 8 different kinds of LEDs from 4 vendors, so far 2500h burning time, processing measurement data in progress



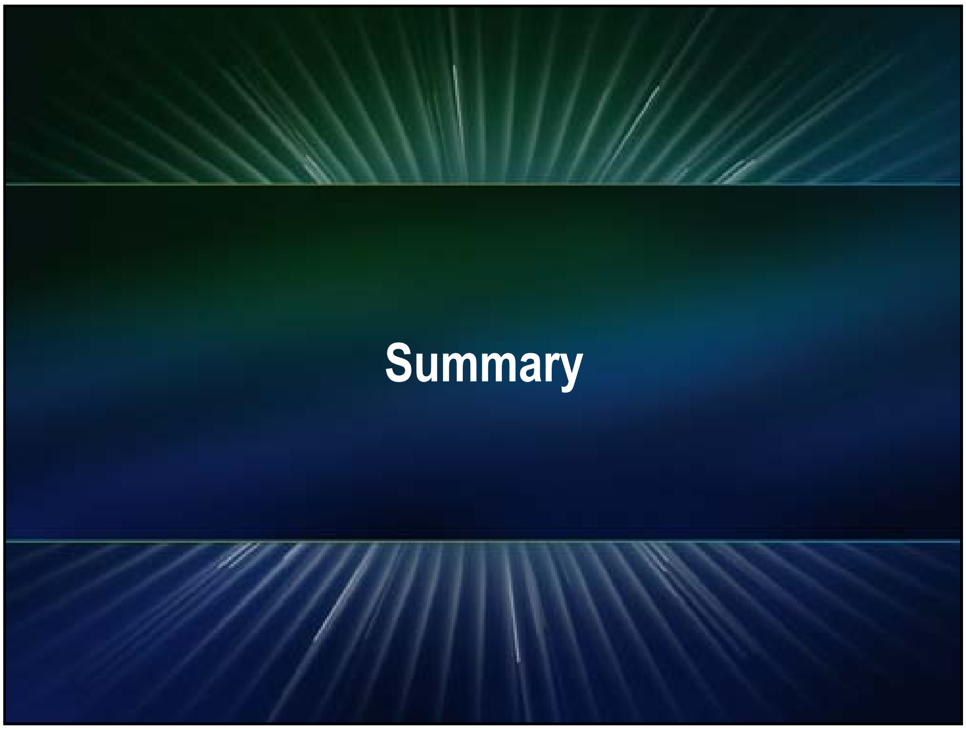
Measurement setups in our LM80 tests

LM80 test chamber with all the LEDs assembled

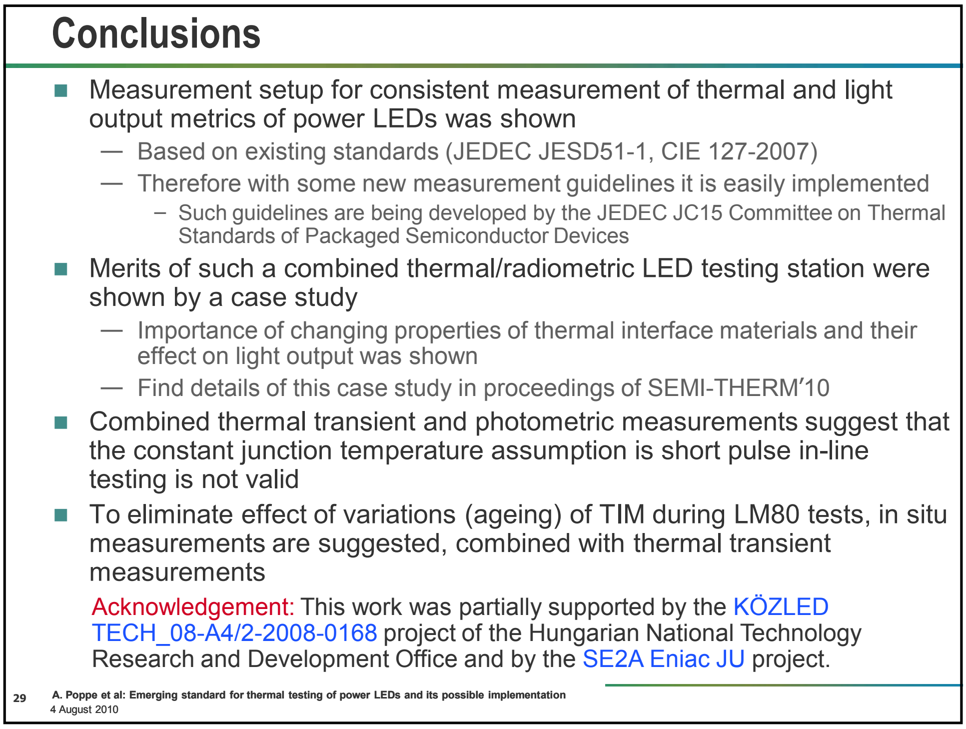
All measurements are done in-situ to eliminate any R_{th} change which is NOT due to ageing

In-situ thermal transient measurement

In-situ light output measurement



Summary



Conclusions

- Measurement setup for consistent measurement of thermal and light output metrics of power LEDs was shown
  - Based on existing standards (JEDEC JESD51-1, CIE 127-2007)
  - Therefore with some new measurement guidelines it is easily implemented
    - Such guidelines are being developed by the JEDEC JC15 Committee on Thermal Standards of Packaged Semiconductor Devices
- Merits of such a combined thermal/radiometric LED testing station were shown by a case study
  - Importance of changing properties of thermal interface materials and their effect on light output was shown
  - Find details of this case study in proceedings of SEMI-THERM’10
- Combined thermal transient and photometric measurements suggest that the constant junction temperature assumption is short pulse in-line testing is not valid
- To eliminate effect of variations (ageing) of TIM during LM80 tests, in situ measurements are suggested, combined with thermal transient measurements

Acknowledgement: This work was partially supported by the KÖZLED TECH_08-A4/2-2008-0168 project of the Hungarian National Technology Research and Development Office and by the SE2A Eniac JU project.

Gábor Marosy, Zoltán Kovács, Gábor Molnár, András Poppe: Diagnostics of LED-based streetlighting luminaires by means of thermal transient method. In: Proceedings of the 16th International Workshop on THERMal INvestigation of ICs and Systems (THERMINIC'10). Barcelona, Spanyolország, 2010.10.06-2010.10.08., pp. 18-23. Paper Paper 46. (ISBN: 978-2-35500-012-6) (http://mycite.omikk.bme.hu/doc/91836.pdf)
Kiadónál: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5636332&tag=1
Teljes kötet: http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5621663

6-8 October 2010, Barcelona, Spain

Diagnostics of LED-based streetlighting luminaires by means of thermal transient method

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***Abstract*- In this paper we investigate what kind of failures are likely to happen in LED based streetlighting luminaires and what are the requirements for being able to detect these by means of thermal transient testing. Based on preliminary results of long term stability studies of LEDs done in cooperation with the Pannon University in Veszprém, Hungary one should expect degradation of different thermal interfaces. Except the die attach, the relevant thermal interfaces are likely to be detectable by relatively low resolution thermal transient measurements. The measurement hardware can be realized as an add-on to the LED driver circuitry present in the luminaire. Problems related to lack of K-factor calibration are also dealt with.**

I. INTRODUCTION

Today one may observe a tremendous change in the world-wide lighting industry. Solid-state lighting, especially high power / high brightness LEDs appeared on the market and with increasing energy conversion efficiency they are competing with traditional light sources. The development trend of LEDs resembles Moore’s law of the conventional semiconductor industry. In case of LEDs – instead of the integration density – the light output (measured in lumens) per package is a metric of the development.

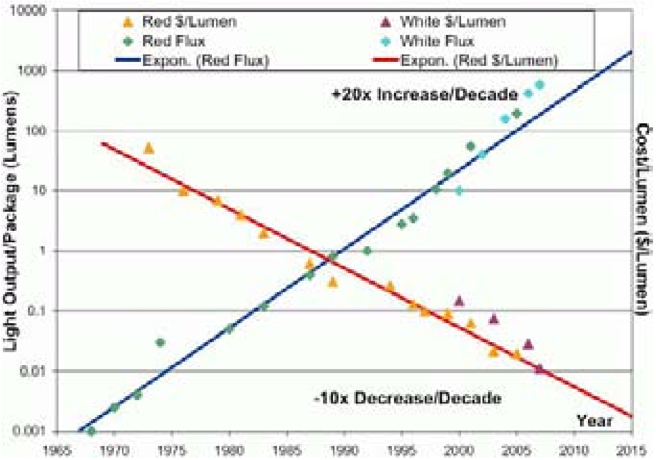

Fig. 1. Development trend of LEDs: exponential growth of luminous flux/package and exponential decay of related costs (source: US DoE SSL-roadmap, March 2008 [1]).

As shown in Fig.1, this metric follows an exponential trend: the emitted luminous flux per package doubles ever year. Another trend is the continuous price decrease measured in $/lumen (cost of generating 1 lumen of luminous flux): in 10 years this figure dropped by an order of magnitude.

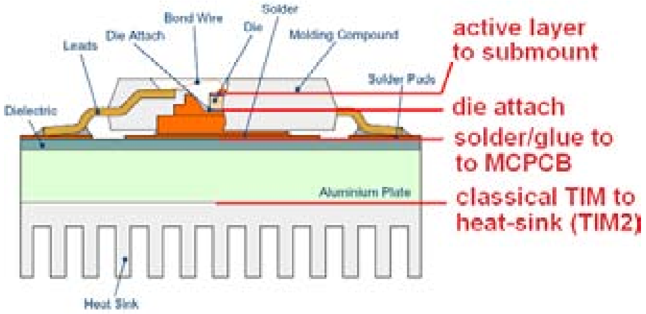

Fig. 2. Different thermal interfaces in the junction-to-ambient heat-flow path of typical LED applications.

As of today the cost of light from LEDs is still a bit above the cost of light from traditional light sources but one can already observe a rapid spread of LED based lighting solutions. One reason for this is the energy saving, since the efficacy (light output per supplied electrical energy) of white LEDs has already reached or even exceeded the efficacy of many traditional light sources. Another aspect of LEDs is the low voltage operation – operation at voltage levels close to the ones traditionally used in any kind of digital control electronics. This allows implementing various dimming and control functions in any kind of LED based lighting application. These are benefits, which already compensate for the yet higher cost of light. LEDs are already widely used in retail lighting, signage, in certain automotive applications and in recent years they appeared in general in-door lighting and outdoor lighting, including streetlighting.

The major problem in case of the application of LEDs as light sources is that their light output strongly depends on the LED junctions’operating temperatures. The heat generated during operation may leave the LEDs mainly by convection – other ways of heat-transfer may take place only from the surface of the cooling assemblies attached to the LEDs or from the luminaires / enlcosures which contain the LEDs as light sources. The conductive heat-transfer from the junction till the surface of the cooling assemblies / luminaires takes place through a number of thermal interfaces (see Fig. 2). Degradation of these thermal interfaces such as delamination or material ageing results in increased thermal resistance, thus in higher junction temperature – leading to the drop of the light output or even to fatal failures.

Inspired by the original idea of V. Székely et al life-time thermal testing and monitoring of LED luminaires seems to be a viable option. In the subsequent sections we investigate different aspects of the implementation of this idea by using the LEDs themselves as temperature sensors. Om one hand we investigate what kind of failures may occure in a LED based streetlighting luminaire which can be detected by thermal transient tests, while on the other hand we aim to define conditions of detectability of these possible failures.

II. LEDS' THERMAL CHARACTERIZATION IN THE DESIGN PHASE

In an earlier paper [2] we described our methodology of characterizing white power LEDs from different vendors mounted onto different sub-assemblies and using different thermal interface materials which were aimed at the application in a streetlighting luminaire. With the series of measurements – besides obtaining thermal data for luminaire level thermal simulations such as described in the subsequent section – we also identified the light output metrics of these LEDs as function of the actual operating junction temperature (data used in optical design of luminaries). Results shown in Fig. 3 originate from combined thermal and radiometric measurements – thus any change of the energy conversion efficiency of the LED due to changes in operating conditions were accounted for, as it is already suggested as future LED testing standard [3], [4].

These measurements also highlighted the fact, that the thermal interface material applied between the luminaire and the sub-assembly (MCPCB for example) may change its properties e.g. with the change of the ambient temperature (Fig.3) thus, changes in thermal properties of the TIM between the luminaire and the MCPCB carrying the LEDs is likely to happen. This assumption is confirmed by long term stability studies (discussed in the subsequent section) which are still on-going at the time of writing this paper.

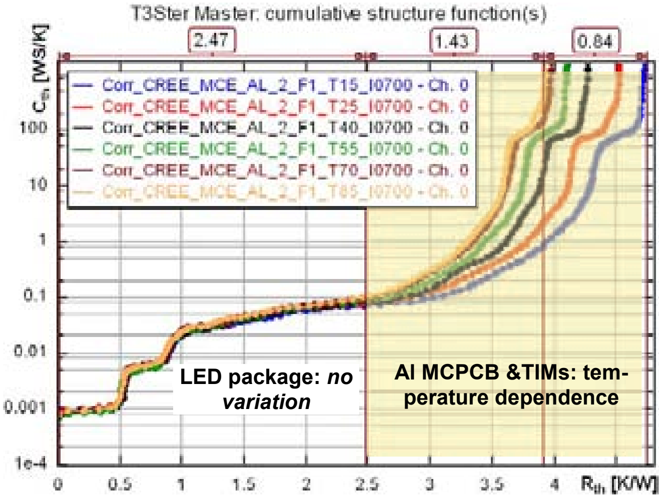

Fig. 3. Different thermal interfaces in the junction-to-ambient heat-flow path of typical LED applications [2].

III. LEDS' LONG-TERM STABILITY

In cooperation with the University of Pannonia (Veszprém, Hungary) long term reliability studies of power LEDs are being performed. The research team at the University of Pannonia studies the long term stability of the light output of the LEDs in a test environment as prescribed by the IESNA LM80 standard for lumen maintenance measurements [5].

Our aim with participating in these studies is twofold. On one hand we are convinced that besides the ageing of the phosphor and the lens thermal resistance changes are significant contributors to light output variations during the useful lifetime of white power LEDs. On the other hand we are interested what structural changes take place in the LEDs' packages during their operation. Therefore thermal transient measurements and subsequent structure function analysis is performed at 500h intervals.

According to the LM80 standard, between two subsequent photometric measurements the LEDs under test are burnt with their nominal forward current (typically 350 mA) at case temperatures of 55 °C and 85 °C, representing conditions expected as typical operational conditions of the investigated devices.

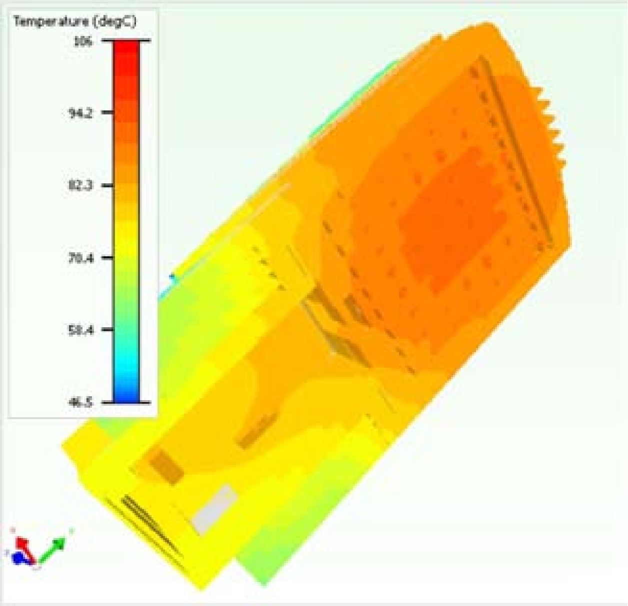

Fig. 4. CFD thermal analysis results for a new LED based streetlighting luminaire design confirm expected operating conditions of the LEDs investigated in LM80 tests.

In order to confirm that these conditions really represent operating conditions of power LEDs in streetlighting luminaries, we performed a CFD analysis of a LED luminaire design[1] in which 48 white power LEDs were assumed to be present. The total energy consumption of the luminaire was 150 W, including the losses in the LED driver electronics and the electrical power consumption of the LEDs. In case of the LEDs we subtracted their predicted radiant flux from

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[1] The luminaire we investigated was designed by HungaroLux Ltd, a project partner of both university research teams participating in the KÖZLED project sponsored by the Hungarian Goverment, aimed at the development of new LED based streetlighting luminaires.

their electric power in order to calculate their actual dissipation. For cooling the luminaire only natural convection was considered, assuming 35 °C ambient temperature as worst case. For the junction-to-case thermal resistance of the LED packages we accepted the data sheet value (6 K/W) provided by the vendor since every time we measured the thermal resistance of the LEDs of this vendor, we always confirmed their data sheet values.

The results of the CFD simulation (performed by FloTHERM v9.1 from Mentor Graphics) are shown in Fig. 4. According to these results the case temperatures of the LEDs mounted in the luminaire varied between cca. 85 °C and 95 °C thus thermal conditions set during the LM80 tests represent the expected operating conditions of LEDs in a streetlighting luminaire.

As part of this experiment we perform thermal transient tests and subsequent structure function analysis on all LED devices mounted in the LM80 test chamber (Fig. 5a). 60 LEDs from leading European and North American vendors as well as from some Asian vendors are burnt. At the time of writing this paper 3000 h of ageing time has already elapsed while the LEDs were operated at their nominal forward current at 85°C ambient temperature. During the test the mechanical structure of the LEDs under test are kept intact, the light is measured in-situ in the test chamber (Fig. 5b). Our thermal transient measurements are also performed in-situ (Fig. 5c). Therefore any change in the heat-flow path structure that we may observe during the long term test (about 10000h is planned) is solely due to ageing.


a)
b)
c)

Fig. 5. LM80 test chamber, a) 60 devices and the liquid circulator for temperature control, in-situ measurement of the b) light output, c) thermal impedance (*photos by courtesy of the University of Pannonia, Veszprém, Hungary*).

With the help of this study we obtain a clear picture about what kinds of failures maybe present in LED based street-lighting luminaries that can be detected by means of thermal transient tests during the operation of such luminaries.

In Fig. 6 and Fig. 7. we provide some preliminary results of this study. Structure functions shown in these figures correspond to the heat-flow paths of LED samples measured at the start of the tests (0h – blue curves) and subsequent functions (plotted with red, black and green) measured after 500h, 2000h and 3000h of ageing.

In Fig. 6a (sample #44 from vendor O) the plots almost perfectly co-inside except the final section which corresponds to the TIM layer between the LED assembly (MCPCB) and the cold-plate of the test chamber, confirming the assumption that TIM suffers ageing even after relatively short useful hours of operation of a luminiare. Until 3000h of ageing the TIM and a small structural degradation inside the LED assembly contributed about +6% to the total junction to ambient thermal resistance with respect to its initial value. According to the structure functions of Fig. 6a and the junction temperature transients (Fig. 8) the package of the given LED type (having the structure shown in Fig. 2) suffered only little structural degradation.

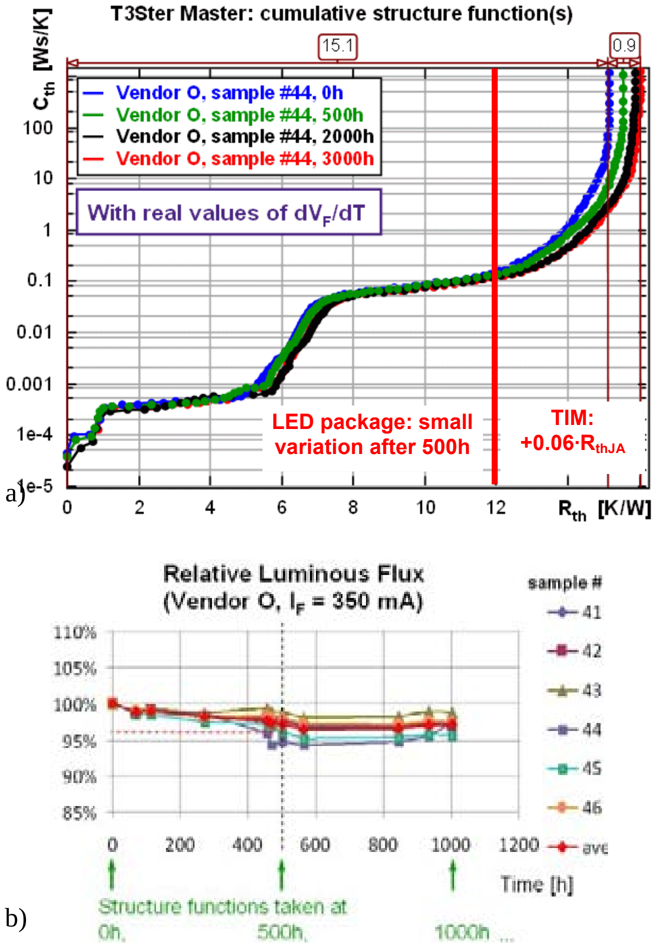

Fig. 6. LM80 test results, a) structure functions taken at 0h and 500h, 2000h and 3000h showing degradation of TIM material b) light output changes (*light output measurement results by courtesy of the University of Pannonia, Veszprém, Hungary*).

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In the experiment light output is continuously monitored according the requirements of the LM80 standard (see Fig. 6b) and the LEDs' forward voltage is regularly measured at 3 different temperatures (25 °C, 55 °C and 85 °C). From these forward voltage measurements the temperature sensitivity of the forward voltage is calculated which is used during our thermal transient tests based on the JEDEC JESD51-1 electrical test method [6], [7]. The change of the temperature sensitivity of the forward voltages of all the LED samples from vendor O is presented in Fig. 7.

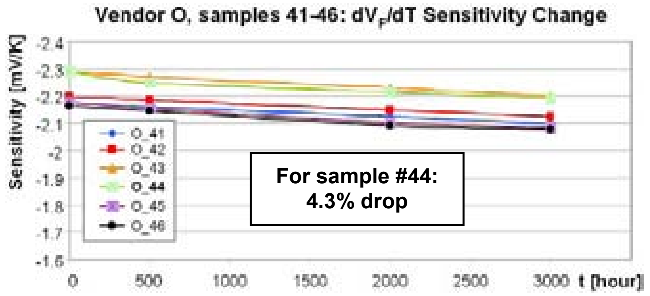

Fig. 7. Change of the temperature sensitivity of the forward voltage of LED samples from vendor O measured at 0h, 500h, 2000h and 3000h of the LM80 tests.

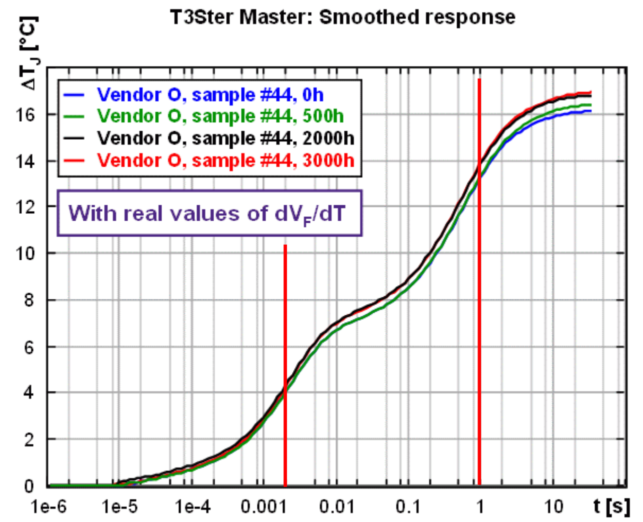

Fig. 8. Junction temperature transients measured at 0h, 500h, 2000h and 3000h of the LM80 tests, calculated with actual temperature sensitivities of the forward voltage.

The junction temperature transients as responses to switching the power on/off are calculated from measured forward voltage transients using these sensitivity values [7]. The junction temperature transients of LED sample #44 obtained this way are shown in Fig. 8. (The structure functions of Fig. 6a were calculated from these junction temperature transients.) Note in Fig. 8, that until cca. 2ms all transients run together; a slight deviation among the curves starts around this time: curves taken at 0h and 500h still run together but curves captured at 2000h and 3000h start deviating from these. At around 1s this deviation is more pronounced and at around 3s we can also observe that the transient captured at 500h of burning starts deviating from the curve captured at the start of the LM80 tests. A total increase of the entire R_{thJA} junction to ambient thermal resistance of roughly 6% can be also predicted from these junction temperature transients.

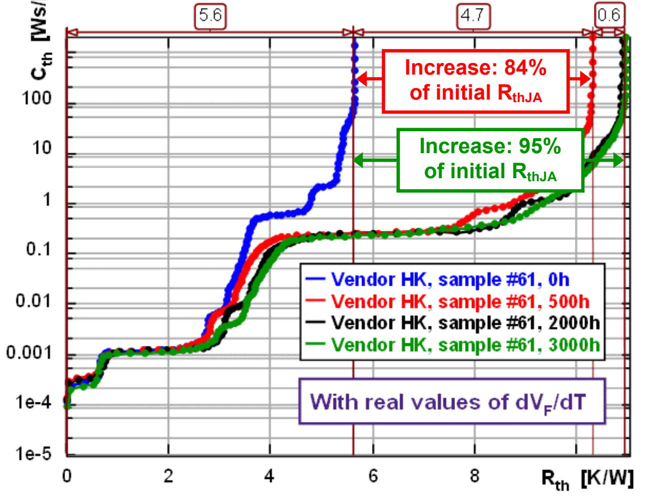

Fig. 9. Structure function plots for the junction to ambient heat-flow path of sample #61 from vendor HK at 0h, 500h, 2000h and 3000h of ageing.

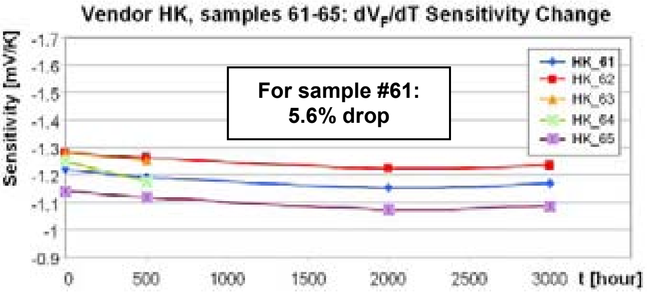

Fig. 10. Change of the temperature sensitivity of the forward voltage of LED samples from vendor HK measured at 0h, 500h, 2000h and 3000h of the LM80 tests.

Note, that the variation of the temperature sensitivity of the forward voltage, the total junction to ambient thermal resistance and the relative light output change of all LED samples from vendor O were in the same order of magnitude (around 5..6%).

In case of another vendor some properties of LED samples showed much larger variations. In Fig. 9 we present structure functions calculated from measured junction temperature transients with actual temperature sensitivities of the forward voltage. In this case 84% increase of the junction to ambient thermal resistance with respect to its initial value was measured after 500h of ageing. After 3000h of burning time this change of thermal resistance increased to 95% of the initial value while there was only 5.6% variation in the temperature sensitivity of the forward voltage (see Fig. 10).

Since for all the 60 LED samples in the LM80 test chamber the same thermal interface material was used, this further increase of thermal resistance is partly due to TIM degradation (as seen e.g. in case of samples from vendor O) partly due to further structural degradation of the LED assembly (degradation of the thermal interface between the MCPCB and the bottom of the LED package – delaminating glue layer). Light output of LEDs from vendor HK has also significantly dropped – samples #63 and #64 were removed from the test when their relative luminous flux dropped below 70% of the initial value (no further dV_F/dT sensitivity data in Fig. 10 at 2000h and 3000h).

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Besides the possible temperature induced degradation of thermal interface materials vibration may also contribute to the increase of the interfacial thermal resistance between an MCPCB based LED assembly and the body of a streetlighting luminaire, not to mention other harsh conditions (such as humidity and natural temperature cycling) that LEDs in a streetlighting luminaire might be exposed to. At the moment we do not have experimental data on these but we are planning to perform some other tests in order to obtain information how these factors may contribute to the increase of LEDs' junction to ambient thermal resistances.

IV. DIAGNOSTICS OF LED LUMINAIRES IN THE FIELD

Outdoor environment can be at least as harsh as the conditions provided in the LM80 test chamber. Therefore, based on the preliminary results we already have we expect different structural integrity problems in the junction to ambient heat-flow paths of LEDs assembled into streetlighting luminaires. Thermal transient testing is a possible means of detecting such problems and providing early warning, allowing electric works to plan scheduled maintenance of the streetlighting luminaires.

According to present safety standards, LEDs in a streetlighting luminaire may be driven with a low voltage only. Therefore the luminaires should contain dedicated LED driver circuitry. As said in the introduction, electrical properties of LEDs allow integrating different control functions with the LED driver circuitry. Such control functions may include advanced dimming schemes, communications over the power lines, diagnostic functions etc.

A. Testing during dimming

LED dimming is typically implemented by a pulse-width modulated square-wave signal of the forward current. In the ON cycles the LED is driven by a constant current. The ratio of the ON-OFF cycle (the fill-factor of the PWM signal) determines the time-average of the perceived intensity of the light output of the LED. The frequency of the PWM signal is in the order of magnitude of ten kHz which is fast enough for the human eye to integrate the light but slow enough for an LED to follow with the emitted light. This switching allows time windows for measuring the dimmed LEDs' junction temperature transients in time windows which in length are close to time windows usually available in in-line testing. Therefore features of LEDs' in-line testing are also applicable to such situations [8].

As implicitly described in a recent paper of prof. Székely [9] accurate information is required for the thermal behaviour of a structural element (along the junction to ambient heat-flow path) with a characteristic thermal time-constant of τ then accurate thermal transient data is needed from the time interval of [0.1τ, 10τ]. This constraint regarding the ratio of thermal time-constants and testing time window means that time windows available during dimming allow us to characterize the quality of the LEDs' die attach only. Besides the constraints regarding the measurement time we also have requirements for the time resolution of the measurements. Considering these needs requirement for the time resolution is in the µs range. This is already close to the specifications of expensive laboratory thermal test equipment, therefore implementation of thermal transient testing in PWM-type dimming circuitry is not realistic in streetlighting luminaires. (It is worth noting, that upto now we have not found die attach delamination during the LM80 tests.)

B. Scheduled thermal tests

Since the luminaires are foreseen to contain sophisticated control and communications circuitry, it is feasable to implement conventional thermal transient testing schemes (as per the JEDEC JESD51 series of standard [7], [8]). With the control circuitry anyway presnt in the luminaire, during the day the individual LEDs in the LED array of the luminaire can be switched on for a few minutes and can be switched off – allowing the measurement of cooling transients with time resolution in the millisecond range. These transients – according to [9] – are sufficient to capture thermal time constants in the 0.1s and above which are sufficient to detect structural changes in the thermal interfaces between the LED package and MCPCB and between the MCPCB and the luminaire. Requirements for the electronics to measure thermal transients with such time resolution are more relaxed, therefore the implementation of such a measurement seems to be financially viable.

Our team is developing communications and measurement circuitry aimed at scheduled thermal transient tests of LED based luminaries. Detectability of the above structural failures and options of data processing will be briefly touched in the subsequent section.

C. Problems during thermal transient based diagnostics

As the JEDEC JESD51-1 [8] standard prescribes the temperature sensitive parameter (TSP – in case LEDs: the forward voltage) of the semiconductor device being tested has to be carefully calibrated (K-factor calibration). This is impossible in case of mass-produced products – like LED luminaires. Even if the K-factor calibration was performed during production, the temperature sensitivity of the forward voltage would also change with the environmental conditions (ambient temperature), not to mention sensitivity changes during life time as shown Fig. 7 and Fig. 10. Therefore during the thermal transient tests in the field we should process the measured forward voltage transients of the LEDs without converting them to temperature transients by considering specific temperature sensitivities of the forward voltage.

If mechanical failures have to be detected solely from measured forward voltage transients (as indicators of the junction temperature transients), due to the above mentioned variations of the temperature sensitivity we face the problem of detectability. Fig. 11 presents the measured junction temperature transients and structure functions of LED sample #44 without considering the actual temperature sensitivity of its forward voltage. Since the thermal resistance variation and the variation of the temperature sensitivity of the forward voltage are in the same order of magnitude but with opposite sign, the variation of the thermal resistance of the junction to ambient heat-flow path extracted solely from the measured raw forward voltage transients is undetectable.

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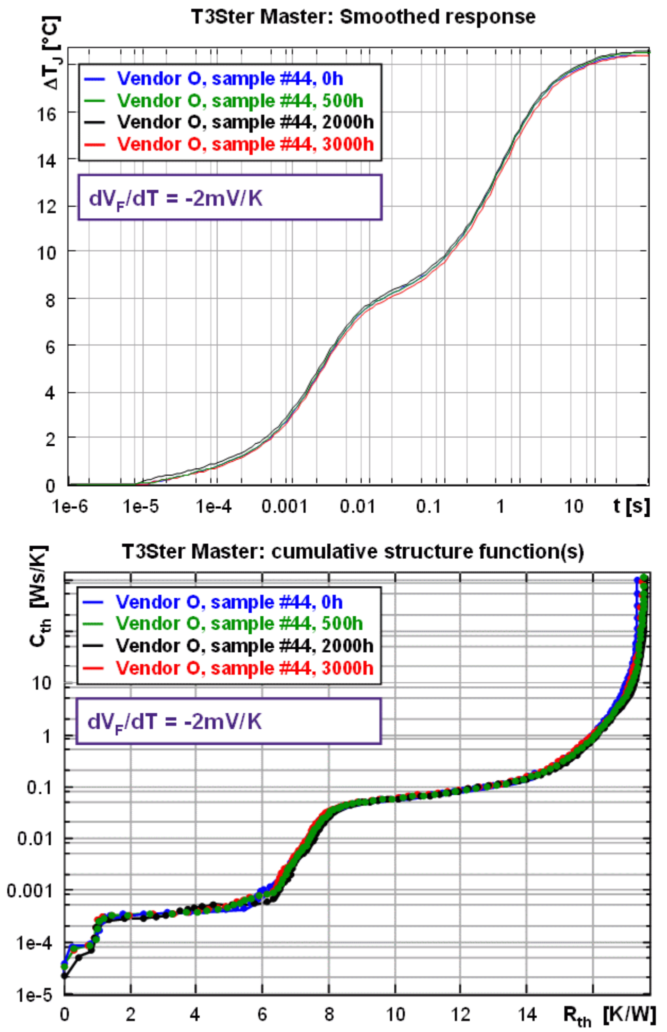

Fig. 11. Junction temperature transients and corresponding structure functions captured of LED sample #44 at 0h, 500h, 2000h and 3000h of the LM80 tests, without considering the actual temperature sensitivity of the forward voltage.

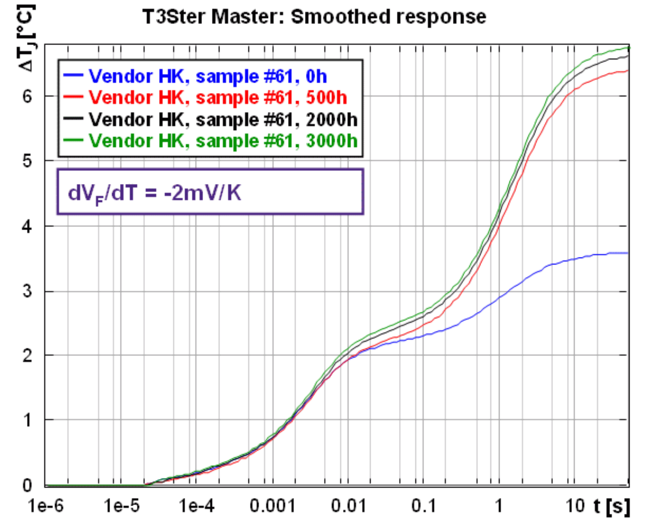

Fig. 12. Junction temperature transients of LED sample #61 captured at 0h, 500h, 2000h and 3000h of the LM80 tests, without considering the actual temperature sensitivity of the forward voltage.

When the variation of the thermal resistance is much bigger then the variation of the temperature sensitivity of the forward voltage, mechanical failures occurring in the heat-flow path can be still well detected solely from measured forward voltage transients – as it was the case with LED sample #61 in our experiments, see Fig. 12. Further complications in data processing may come from the temperature dependence of the thermal resistance of the applied TIM (see Fig. 3).

V. CONCLUSIONS

We made an analysis of possible structural integrity issues in the junction to ambient heat-flow paths of LEDs to be used in streetlighting luminaires. Preliminary results of long term stability studies of LEDs suggest that in harsh environment we should expect degradation of the different thermal interfaces. If the degradation exceeds a given limit (resulting thermal resistance change bigger then variation of temperature sensitivity of the forward woltage), with built-in thermal transient measurement based diagnosis early warnings can be provided and maintenance of luminaires can be scheduled to avoid fatal breakdown. Data processing similar to what has been suggested for in-line testing [8] can be used to overcome the problem of lack of TSP calibration.

ACKNOWLEDGMENT

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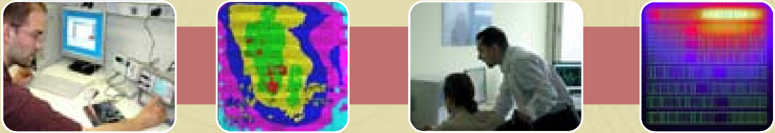
Budapest University of Technology and Economics

Department of Electron Devices

Diagnostics of LED-based streetlighting luminaires by means of thermal transient method

Gábor Marosy, Zoltán Kovács, András Poppe



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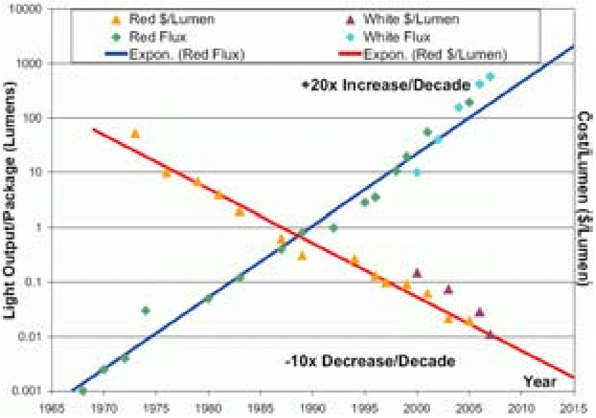
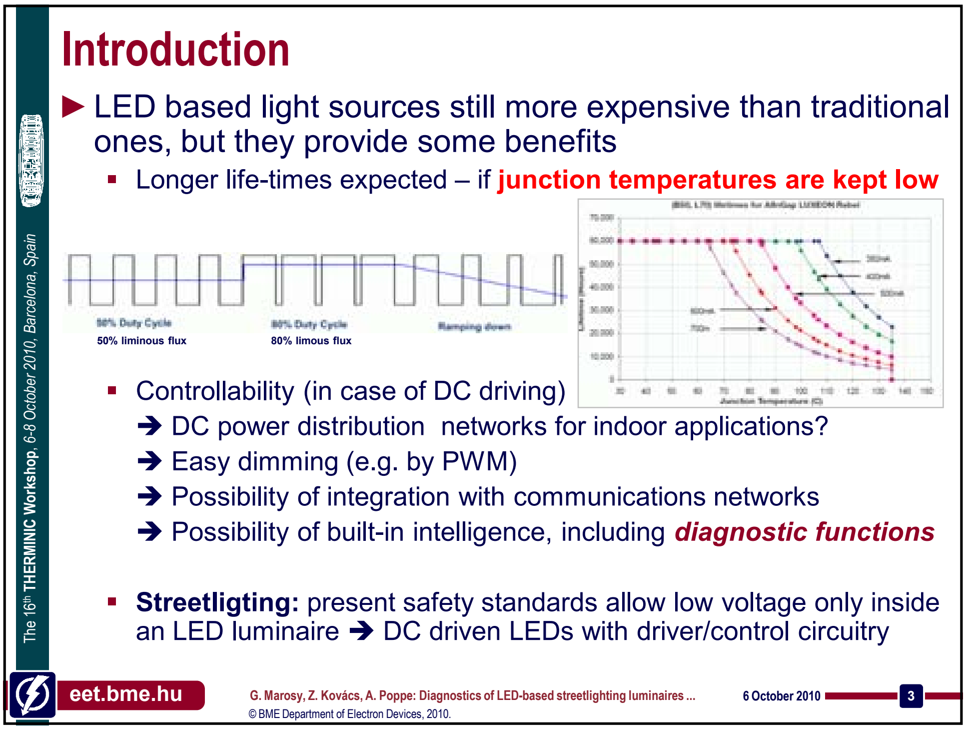
Introduction

- Similar trends in SSL like Moore's Law in microelectronics



- Continuous decrease of price of light [$/lm]
  - More application fields, streetlighting is among the early birds
  - Low voltage levels ➔ controllability



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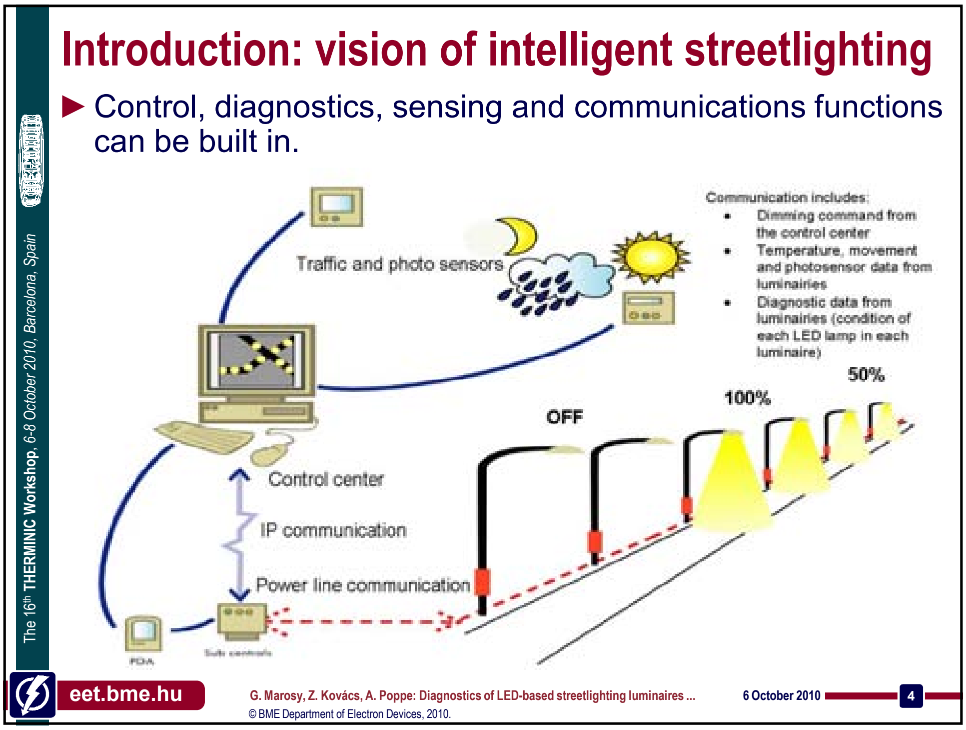
Introduction

- ► LED based light sources still more expensive than traditional ones, but they provide some benefits
  - Longer life-times expected – if **junction temperatures are kept low**

  - Controllability (in case of DC driving)
    - ➔ DC power distribution networks for indoor applications?
    - ➔ Easy dimming (e.g. by PWM)
    - ➔ Possibility of integration with communications networks
    - ➔ Possibility of built-in intelligence, including ***diagnostic functions***
  - **Streetligting:** present safety standards allow low voltage only inside an LED luminaire ➔ DC driven LEDs with driver/control circuitry



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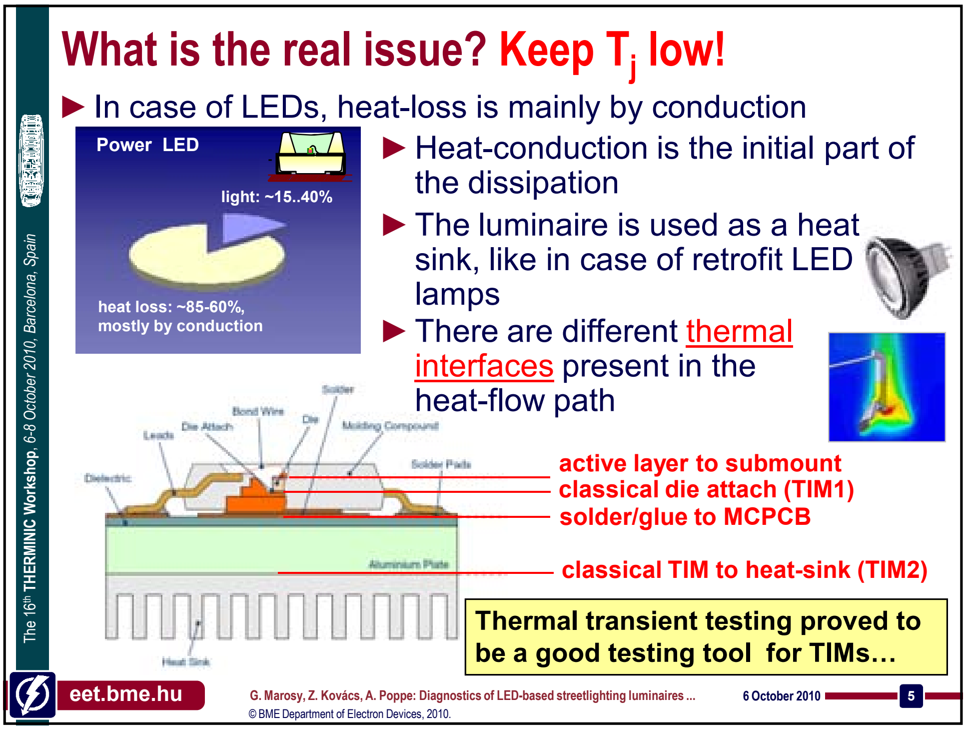
Introduction: vision of intelligent streetlighting

- ► Control, diagnostics, sensing and communications functions can be built in.

Communication includes:
- Dimming command from the control center
- Temperature, movement and photosensor data from luminairies
- Diagnostic data from luminairies (condition of each LED lamp in each luminaire)



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What is the real issue? Keep T_j low!

- In case of LEDs, heat-loss is mainly by conduction

- Heat-conduction is the initial part of the dissipation
- The luminaire is used as a heat sink, like in case of retrofit LED lamps
- There are different thermal interfaces present in the heat-flow path

active layer to submount
classical die attach (TIM1)
solder/glue to MCPCB
classical TIM to heat-sink (TIM2)

Thermal transient testing proved to be a good testing tool for TIMs…

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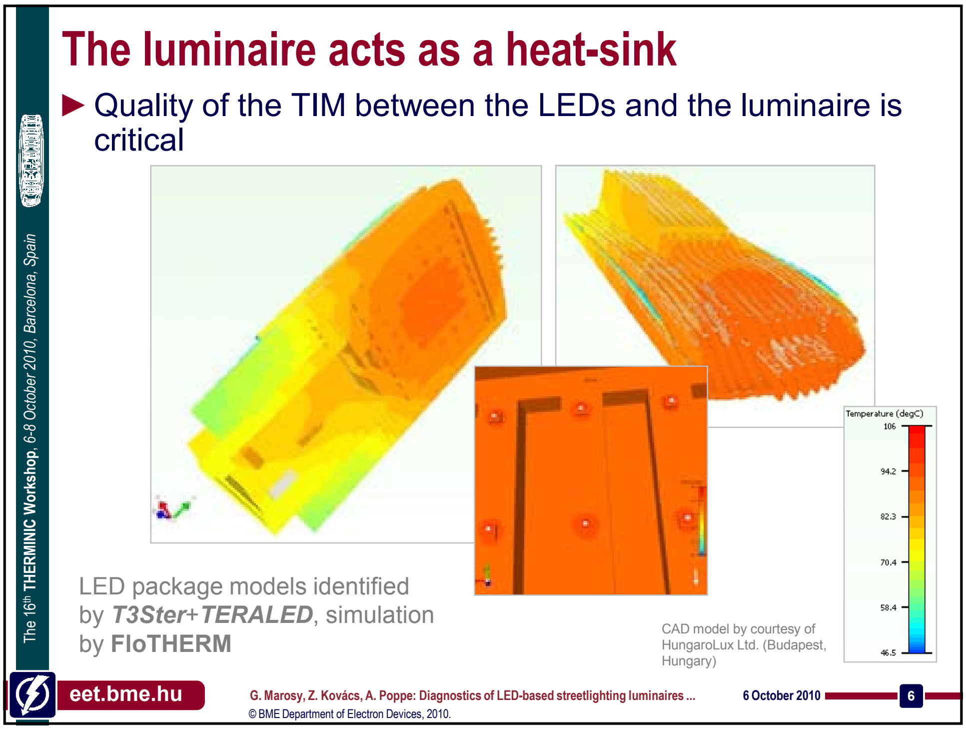

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The luminaire acts as a heat-sink

- Quality of the TIM between the LEDs and the luminaire is critical

LED package models identified by ***T3Ster+TERALED***, simulation by **FloTHERM**

CAD model by courtesy of HungaroLux Ltd. (Budapest, Hungary)

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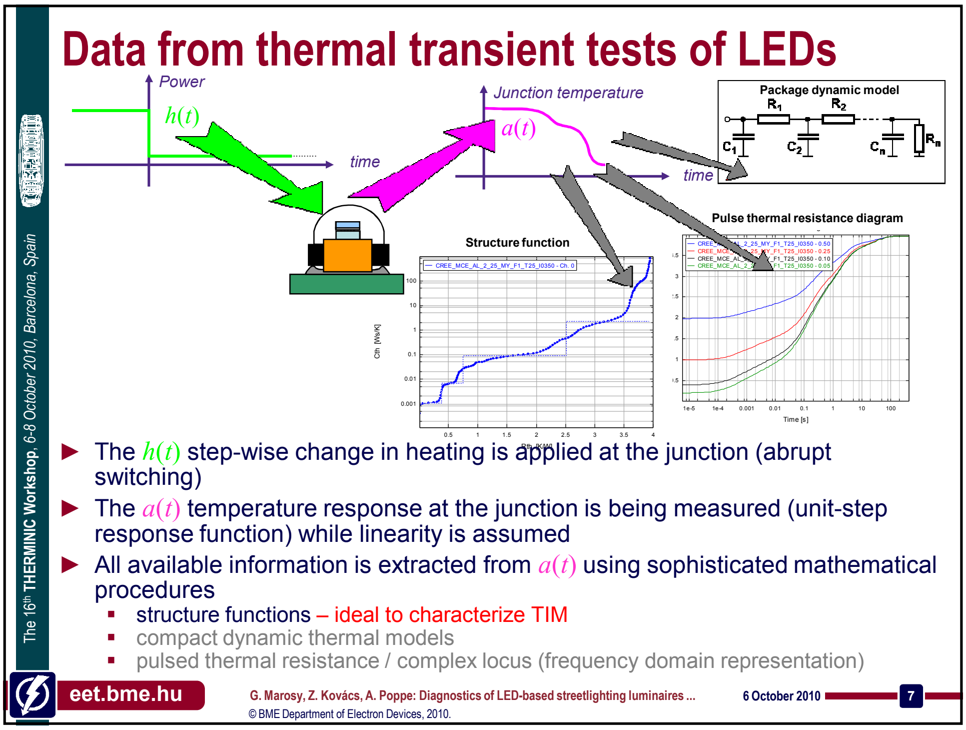
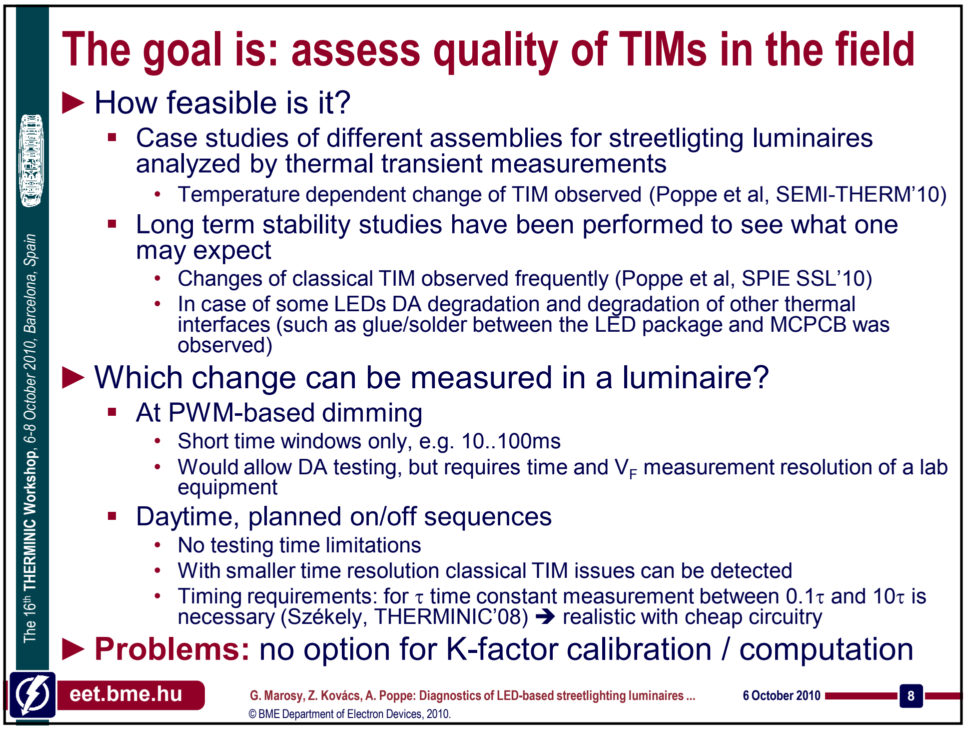


Data from thermal transient tests of LEDs

- ▶ The $h(t)$ step-wise change in heating is applied at the junction (abrupt switching)
- ▶ The $a(t)$ temperature response at the junction is being measured (unit-step response function) while linearity is assumed
- ▶ All available information is extracted from $a(t)$ using sophisticated mathematical procedures
  - structure functions – ideal to characterize TIM
  - compact dynamic thermal models
  - pulsed thermal resistance / complex locus (frequency domain representation)



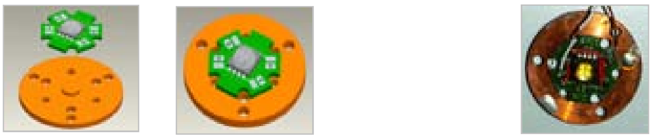
The goal is: assess quality of TIMs in the field

- ▶ How feasible is it?
  - Case studies of different assemblies for streetligting luminaires analyzed by thermal transient measurements
    - Temperature dependent change of TIM observed (Poppe et al, SEMI-THERM'10)
  - Long term stability studies have been performed to see what one may expect
    - Changes of classical TIM observed frequently (Poppe et al, SPIE SSL'10)
    - In case of some LEDs DA degradation and degradation of other thermal interfaces (such as glue/solder between the LED package and MCPCB was observed)
- ▶ Which change can be measured in a luminaire?
  - At PWM-based dimming
    - Short time windows only, e.g. 10..100ms
    - Would allow DA testing, but requires time and V_F measurement resolution of a lab equipment
  - Daytime, planned on/off sequences
    - No testing time limitations
    - With smaller time resolution classical TIM issues can be detected
    - Timing requirements: for τ time constant measurement between 0.1τ and 10τ is necessary (Székely, THERMINIC'08) ➔ realistic with cheap circuitry
- ▶ **Problems:** no option for K-factor calibration / computation

Case study – for the KÖZLED project

- 3 different assemblies with high-end 10W white LEDs
  - FR4 PCB, TIM between the heat-slug and the Cu block

  - FR4 PCB, heat-slug soldered to the Cu block

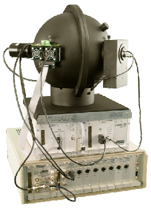


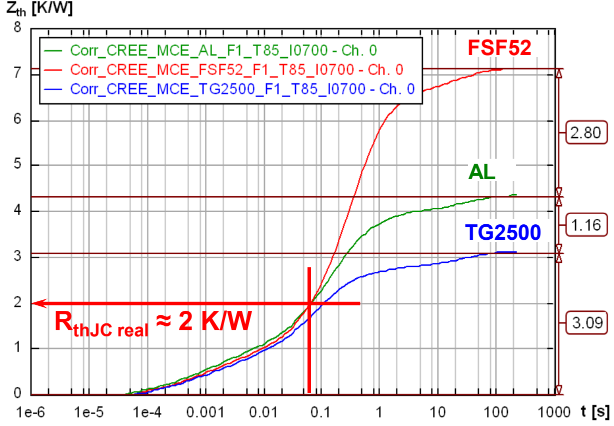
  - MCPCB-s made of Al and Cu, heat-slug soldered

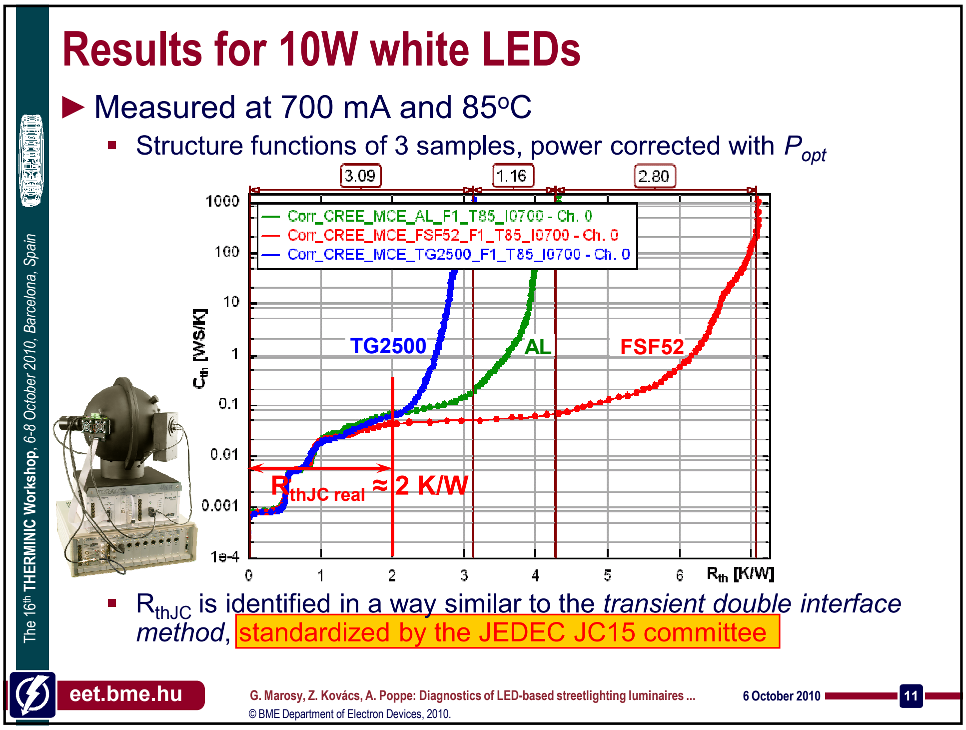
CAD images by courtesy of OptimalOptik Ltd.

Results for 10W white LEDs

- Measured at 700 mA and 85°C
  - Thermal impedance of 3 samples, power corrected with P_{opt}







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Results for 10W white LEDs

▶ Measured at 700 mA and 85°C

- Structure functions of 3 samples, power corrected with P_{opt}
- R_{thJC} is identified in a way similar to the *transient double interface method*, standardized by the JEDEC JC15 committee

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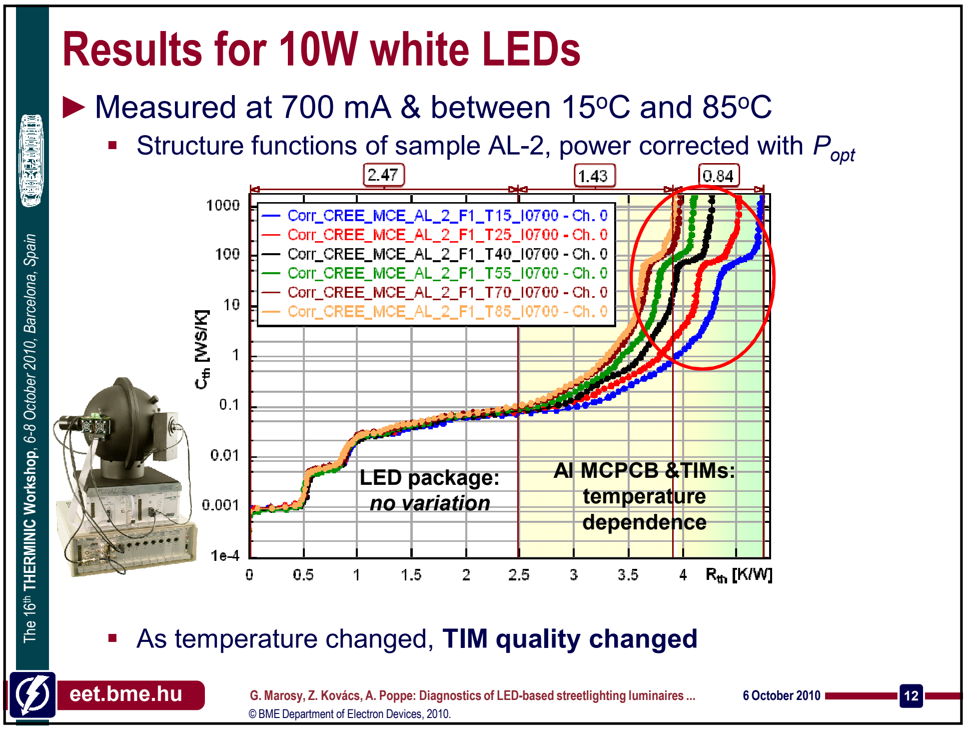

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Results for 10W white LEDs

▶ Measured at 700 mA & between 15°C and 85°C

- Structure functions of sample AL-2, power corrected with P_{opt}
- As temperature changed, **TIM quality changed**

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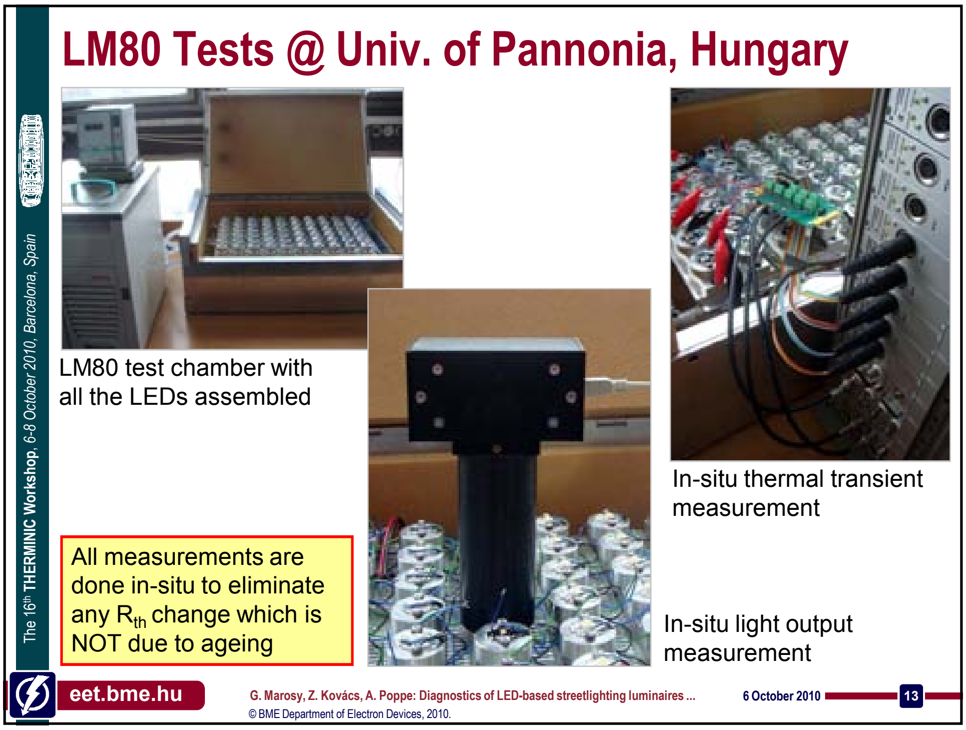


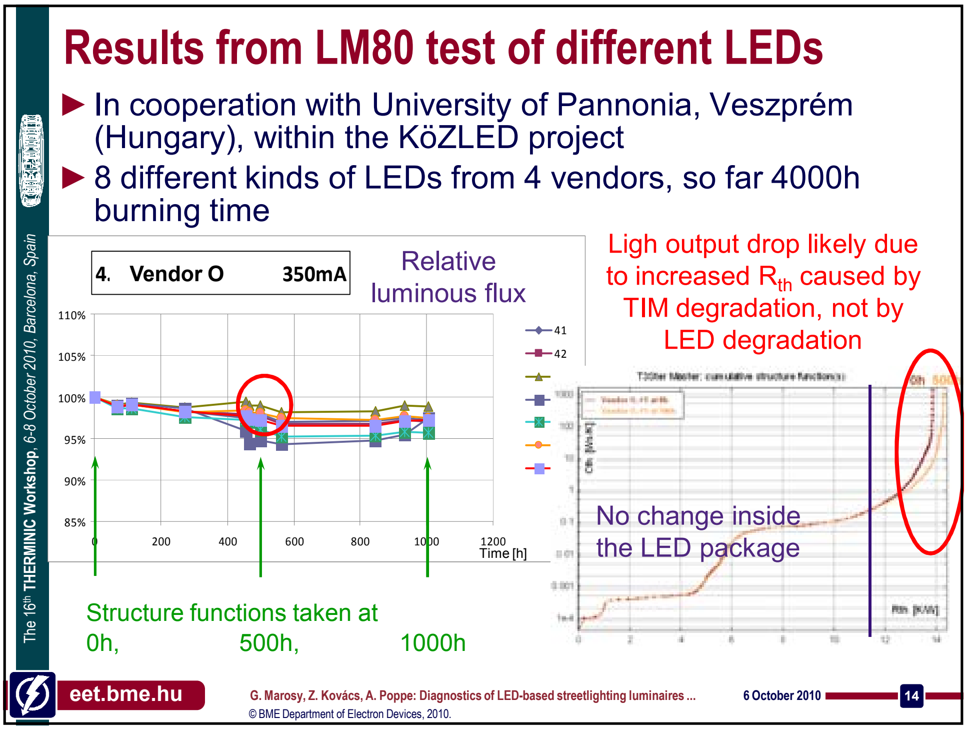
LM80 Tests @ Univ. of Pannonia, Hungary

LM80 test chamber with all the LEDs assembled

All measurements are done in-situ to eliminate any R_{th} change which is NOT due to ageing

In-situ thermal transient measurement

In-situ light output measurement



Results from LM80 test of different LEDs

- In cooperation with University of Pannonia, Veszprém (Hungary), within the KöZLED project
- 8 different kinds of LEDs from 4 vendors, so far 4000h burning time

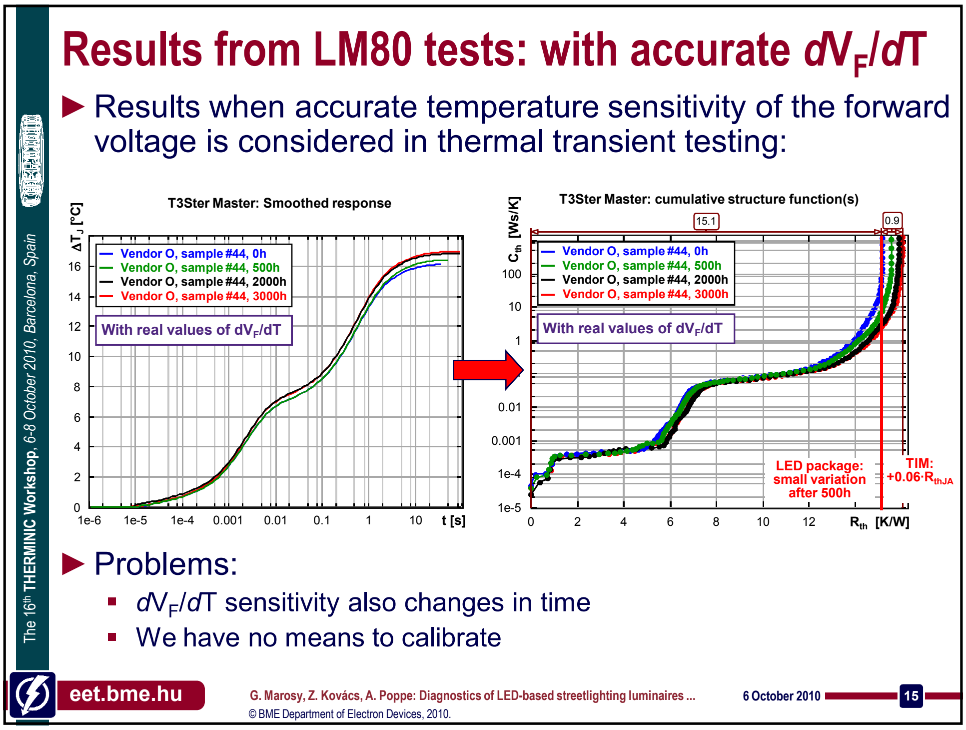
4. Vendor O 350mA

Relative luminous flux

Ligh output drop likely due to increased R_{th} caused by TIM degradation, not by LED degradation

No change inside the LED package

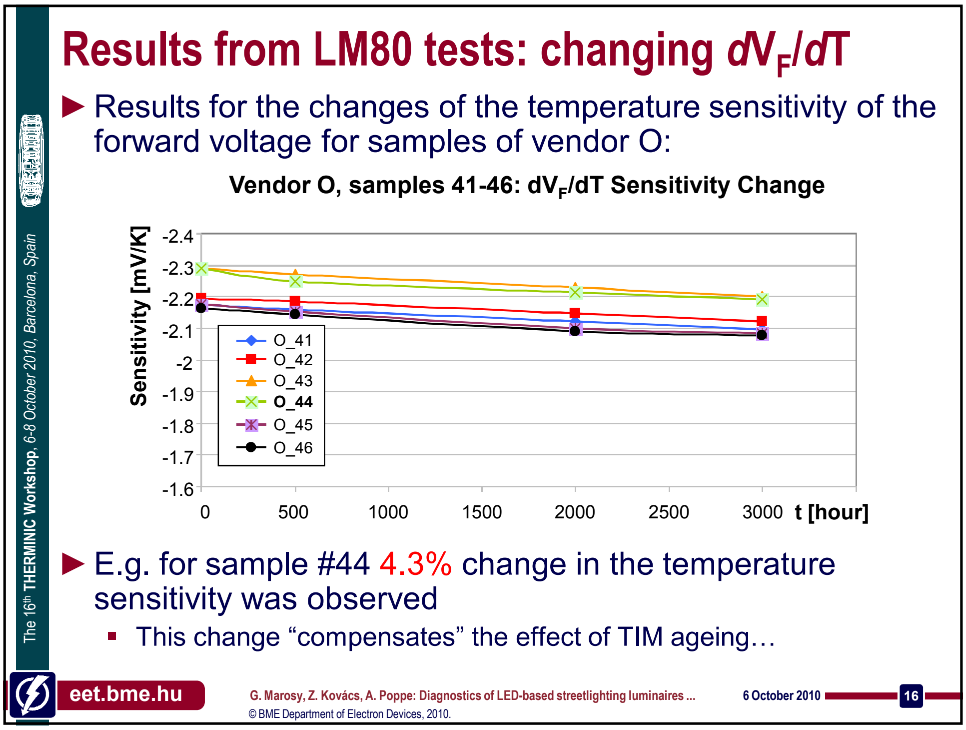
Structure functions taken at
0h, 500h, 1000h



Results from LM80 tests: with accurate dV_F/dT

- Results when accurate temperature sensitivity of the forward voltage is considered in thermal transient testing:

- Problems:
  - dV_F/dT sensitivity also changes in time
  - We have no means to calibrate

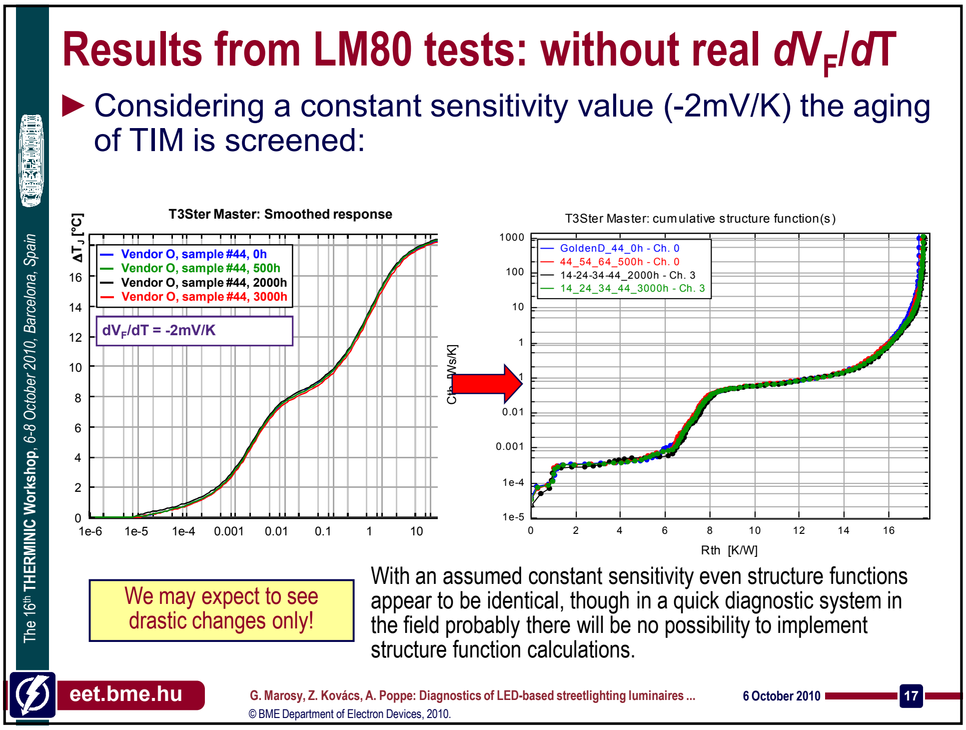


Results from LM80 tests: changing dV_F/dT

- Results for the changes of the temperature sensitivity of the forward voltage for samples of vendor O:

Vendor O, samples 41-46: dV_F/dT Sensitivity Change

- E.g. for sample #44 4.3% change in the temperature sensitivity was observed
  - This change "compensates" the effect of TIM ageing…

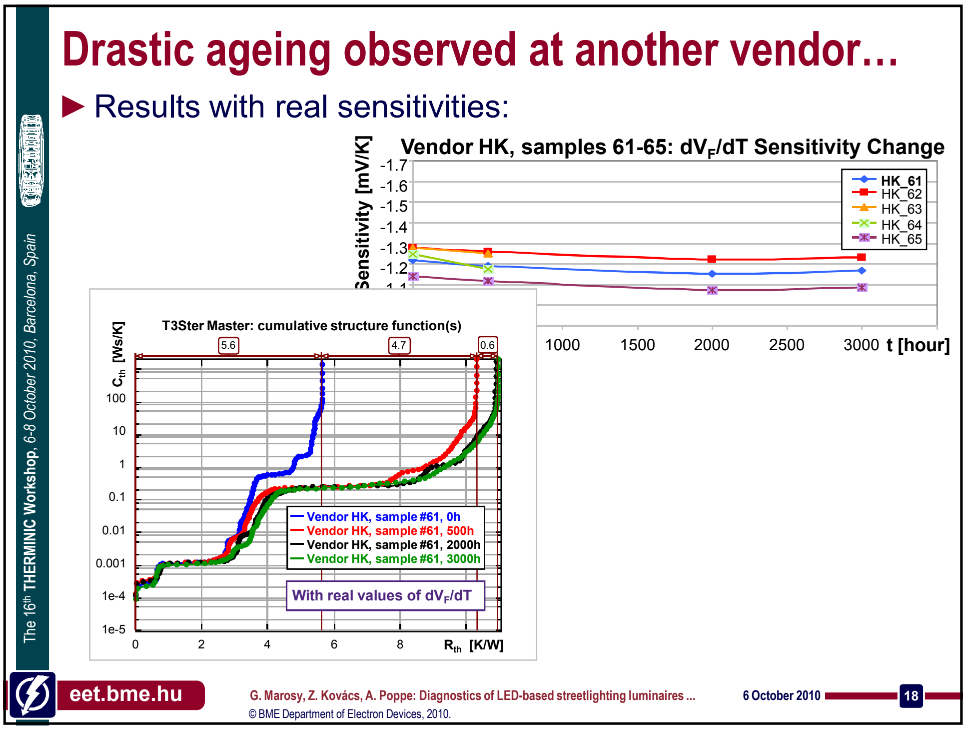


Results from LM80 tests: without real dV_F/dT

- ► Considering a constant sensitivity value (-2mV/K) the aging of TIM is screened:

We may expect to see drastic changes only!

With an assumed constant sensitivity even structure functions appear to be identical, though in a quick diagnostic system in the field probably there will be no possibility to implement structure function calculations.

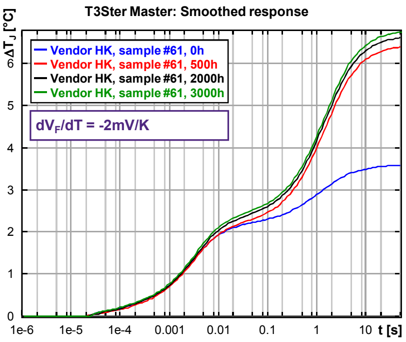


Drastic ageing observed at another vendor…

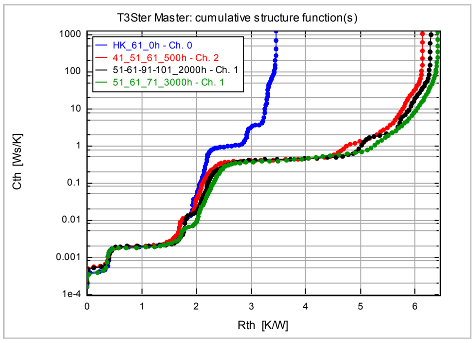
- ► Results with real sensitivities:

Drastic ageing observed at another vendor…

- ▶ Results considering an assumed constant sensitivity only:



Delamination of the LED/MCPCB interface as well as TIM ageing can be observed even from the measured raw forward voltage transients.



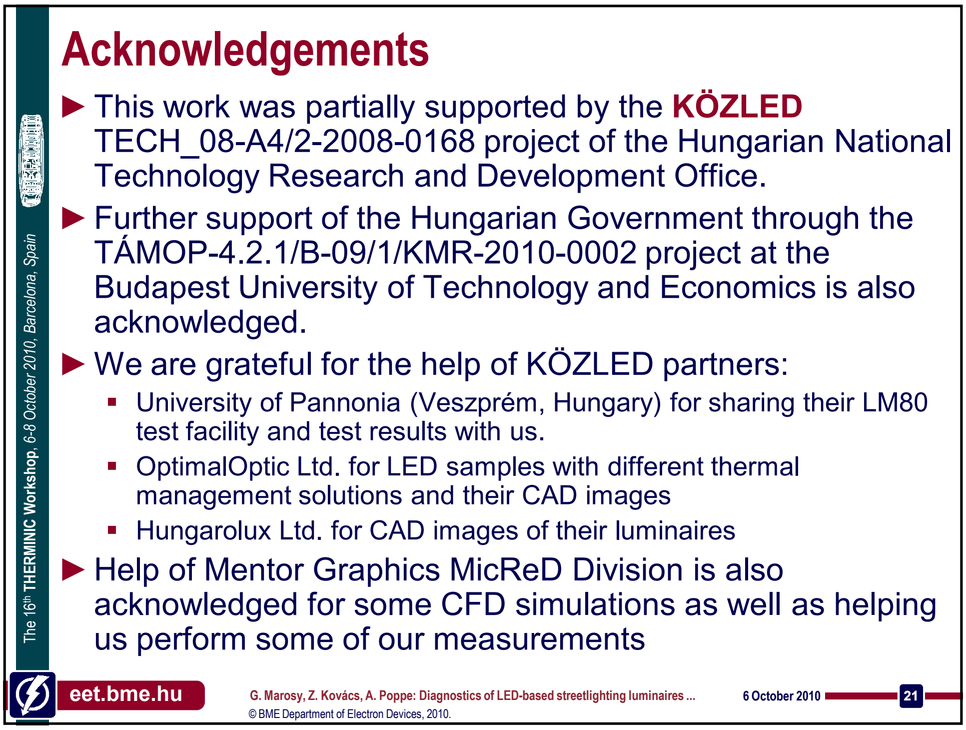
30 s measurement time is sufficient for this test, sufficient time resolution can be 0.1ms or even 1ms

Real life conditions are even harsher:

- vibration
- humidity
- temperature cycling

Conclusions

- ▶ We made an analysis of possible structural integrity issues in the junction to ambient heat-flow paths of LEDs to be used in streetlighting luminaires.
- ▶ Preliminary results of long term stability studies of LEDs suggest that in harsh environment we should expect degradation of the different thermal interfaces.
- ▶ If the degradation exceeds a given limit (resulting thermal resistance change bigger then variation of temperature sensitivity of the forward woltage), with built-in thermal transient measurement based diagnosis early warnings can be provided and maintenance of luminaires can be scheduled to avoid fatal breakdown.
    - Requirements for such testing circuitry are not too high, ~1ms time resolution seems to be sufficient ti detect LED/MCPCB or TIM2 delamination/ageing
    - No sophisticated data processing is required for such tests, it seems, raw forward voltage transients are sufficient



Acknowledgements

- This work was partially supported by the **KÖZLED** TECH_08-A4/2-2008-0168 project of the Hungarian National Technology Research and Development Office.
- Further support of the Hungarian Government through the TÁMOP-4.2.1/B-09/1/KMR-2010-0002 project at the Budapest University of Technology and Economics is also acknowledged.
- We are grateful for the help of KÖZLED partners:
    - University of Pannonia (Veszprém, Hungary) for sharing their LM80 test facility and test results with us.
    - OptimalOptic Ltd. for LED samples with different thermal management solutions and their CAD images
    - Hungarolux Ltd. for CAD images of their luminaires
- Help of Mentor Graphics MicReD Division is also acknowledged for some CFD simulations as well as helping us perform some of our measurements

András Poppe: Development of LED-based streetlighting luminaires in the KÖZLED project
Előadás.

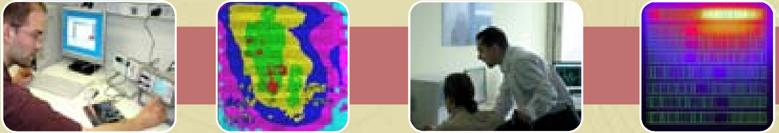
Elhangzott a szentpétervári Finommechanikai és Optikai Egyetem nemzetközi kapcsolatok osztálya által szervezett PhD szemináriumon 2010. november 22-én.

MŰEGYETEM 1782
Budapest University of Technology and Economics

Department of Electron Devices

Development of LED based streetlighting luminaires in the KÖZLED project

András Poppe



Introduction to the KÖZLED project

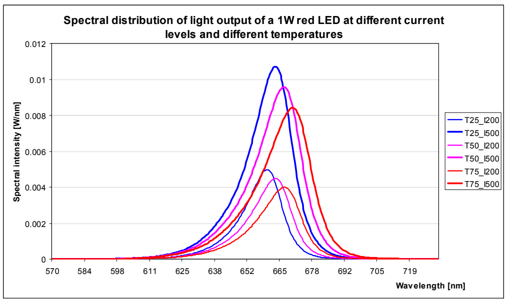
- The **KÖZLED poject** of the Hungarian National Technology Research and Development Office
  - Development of energy efficent LED based street lighting luminaires
- Our partners in the project
  - **HOFEKA** Ltd.: local manufacturer of street lighting luminaires (120+ years of expertise in Budapest)
  - **OptimalOptik** Ltd.: BME spin-off specialized in optics design
  - **HungaroLux** Ltd.: specialized in driver electronics for LED based lighting applications
  - **University of Pannonia** (Veszprém, Hungary): European center of excellence in lighting research

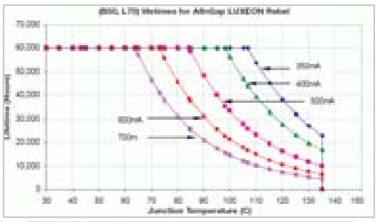
Motivation of the project

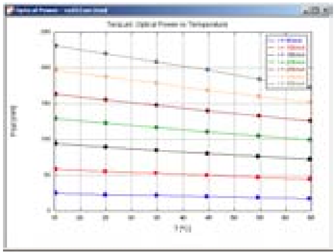
- ► Most of LED based street lighting luminaires do not comply with street lighting standards (EU/HU)
  - 20 different products were purchased and measured (using goniometry)
  - much difference from shape and uniformity of illumination
    - also a common issue in case of household retrofit solutions
- ► **Problems that we deal with within KÖZLED:**
  - Unrealiable binning of LEDs:
    - Luminous flux, color temperature measured at a temperature which is believed to be $T_j = 25^oC$ while LEDs' operational temperatures are much higher
  - Asses thermal performance of LED assemblies
  - Little information on reliability / life time data
  - What color temperature is the best for mesopic vision?

Why to deal with thermal issues?

- ► Reliability is connected to thermal issues
  - life time (failure mechanisms are thermally assisted)
  - mechanical stress
- ► Optical properties strongly depend on temperature
  - spectra
  - emitted flux / efficiency / efficacy



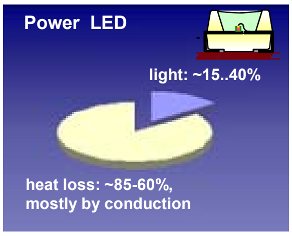




No doubt that **reliable thermal data** is a must for power LED based designs

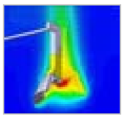
What is the real issue? Keep T_j low!

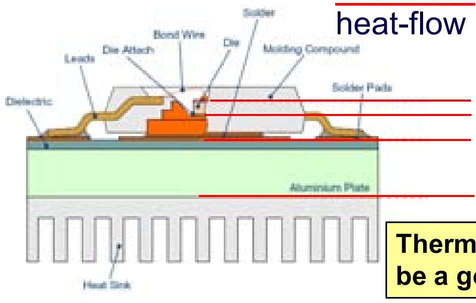
- In case of LEDs, heat-loss is mainly by conduction



- Heat-conduction is the initial part of the dissipation
- The luminaire is used as a heat sink, like in case of retrofit LED lamps

- There are different thermal interfaces present in the heat-flow path





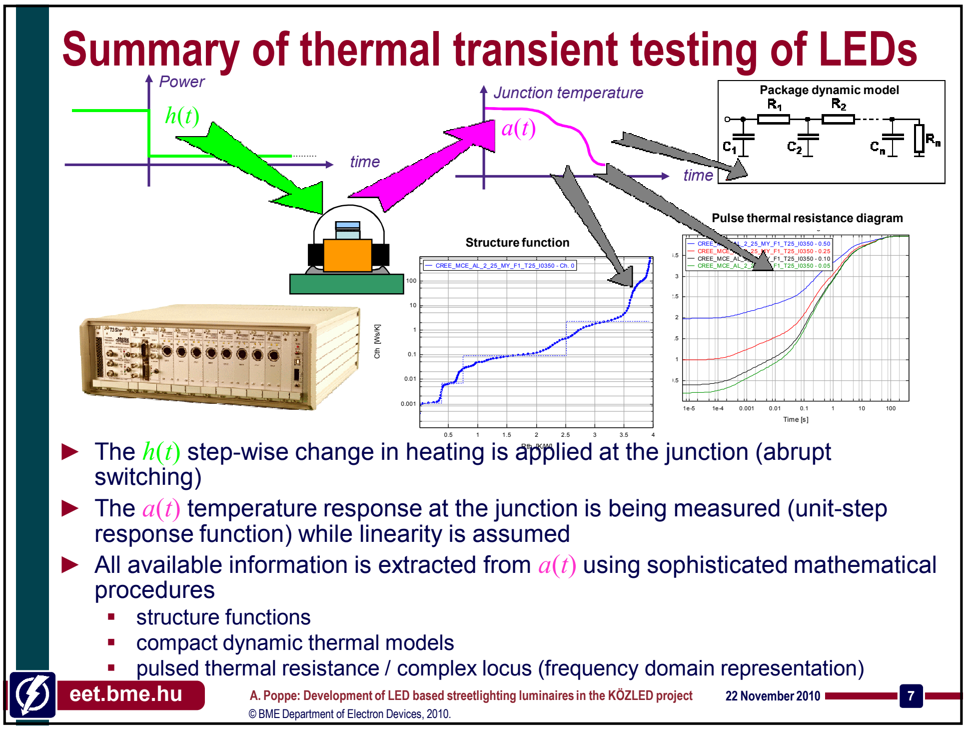
active layer to submount
classical die attach (TIM1)
solder/glue to MCPCB
classical TIM to heat-sink (TIM2)

Thermal transient testing proved to be a good testing tool for TIMs…

Test methods used in the KÖZLED project

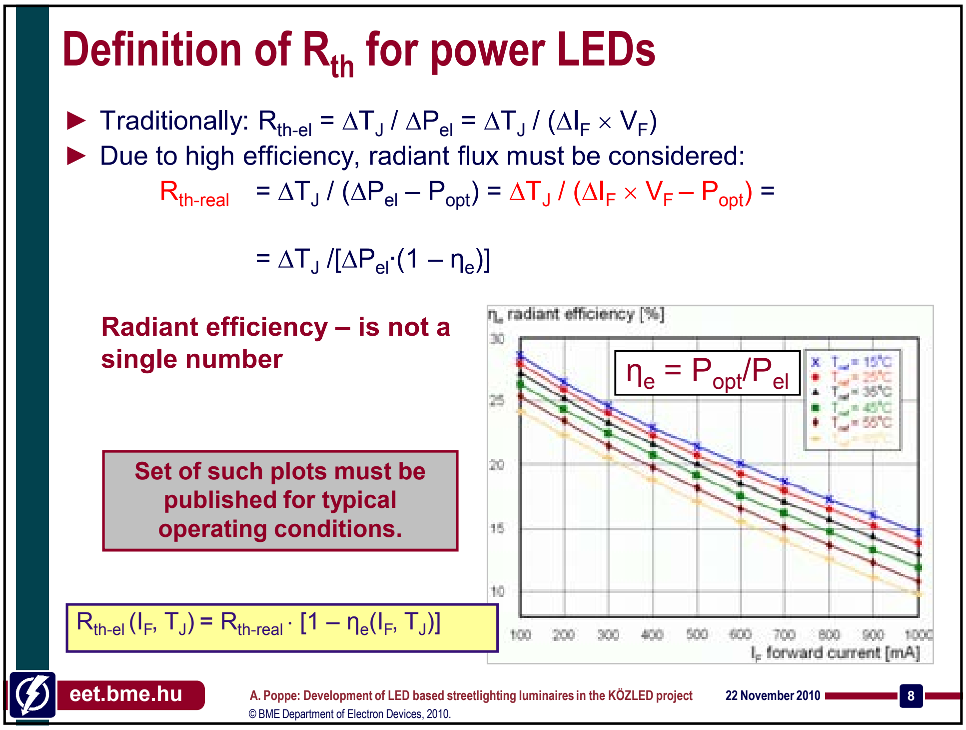
Prinicples of thermal transient testing

Combined thermal and radiometric testing of LEDs



Summary of thermal transient testing of LEDs

- ► The $h(t)$ step-wise change in heating is applied at the junction (abrupt switching)
- ► The $a(t)$ temperature response at the junction is being measured (unit-step response function) while linearity is assumed
- ► All available information is extracted from $a(t)$ using sophisticated mathematical procedures
  - structure functions
  - compact dynamic thermal models
  - pulsed thermal resistance / complex locus (frequency domain representation)



Definition of R_{th} for power LEDs

- ► Traditionally: $R_{th\text{-}el} = \Delta T_J / \Delta P_{el} = \Delta T_J / (\Delta I_F \times V_F)$
- ► Due to high efficiency, radiant flux must be considered:

$$R_{th\text{-}real} = \Delta T_J / (\Delta P_{el} - P_{opt}) = \Delta T_J / (\Delta I_F \times V_F - P_{opt}) =$$

$$= \Delta T_J / [\Delta P_{el} \cdot (1 - \eta_e)]$$

Radiant efficiency – is not a single number

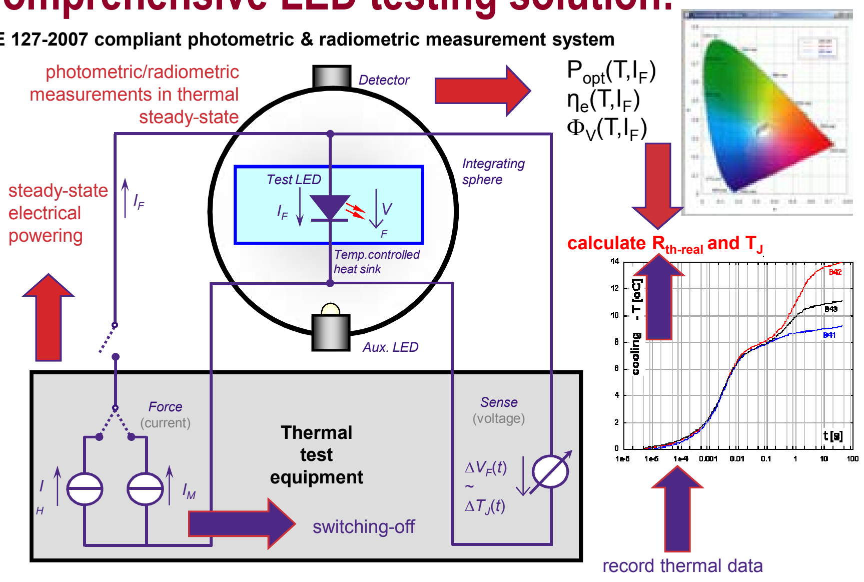
Set of such plots must be published for typical operating conditions.

$$R_{th\text{-}el}(I_F, T_J) = R_{th\text{-}real} \cdot [1 - \eta_e(I_F, T_J)]$$

$$\eta_e = P_{opt}/P_{el}$$

Comprehensive LED testing solution:

CIE 127-2007 compliant photometric & radiometric measurement system



JEDEC JSD51-1 static test method compliant thermal measurement system

---

Implementation in the commercial tools we used

Building D of the Budapest Infopark – hosting Mentor Graphics MicReD division

Span out of BME Department of Electron Devices in 1997

Joined FLOMERICS in 2005

Ackquired by Mentor Graphics in 2008

Factory division of Mentor Graphics; 100+ MicReD systems installed world-wide, established de facto standard in the SSL industry. Customers from SSL include

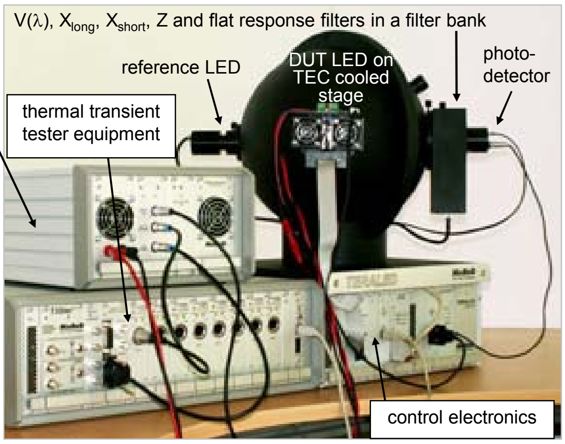
Lumileds, Phlips, Osram, Samsung, SSC, LG, Panasonic, Bridgelux, Sylvania, GE, Avago

Mentor Graphics®

MicReD Hardware

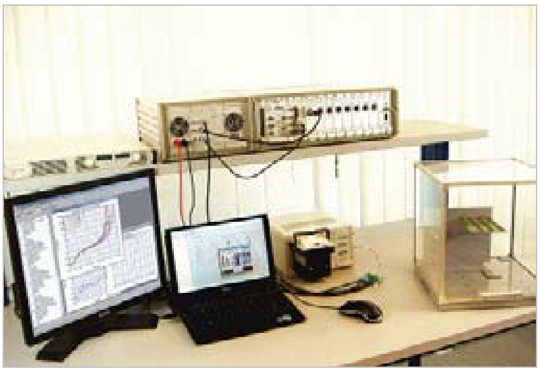
The Mentor Graphics MicReD implementation:

Special LED booster: allows high voltage across a LED line (overall forward voltage can reach 280V).



It can be added to the system in a plug&play manner if the voltage of the base tester is not sufficient.

T3Ster / booster / thermostat / SA chamber and T3Ster software "family" photo

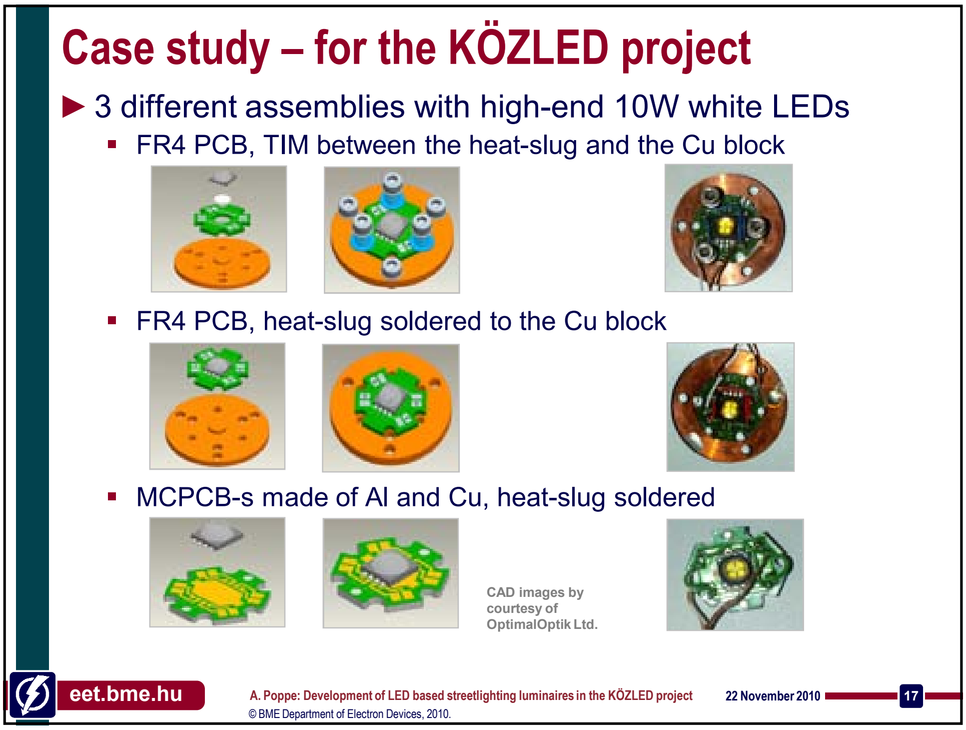


T3Ster-Booster: dual high current / 280 V safety and switching box / 280 V setup

Industrial Realization of LED Reliability Testing

- Automated measurements with high throughput (~1000 LEDs/hour)

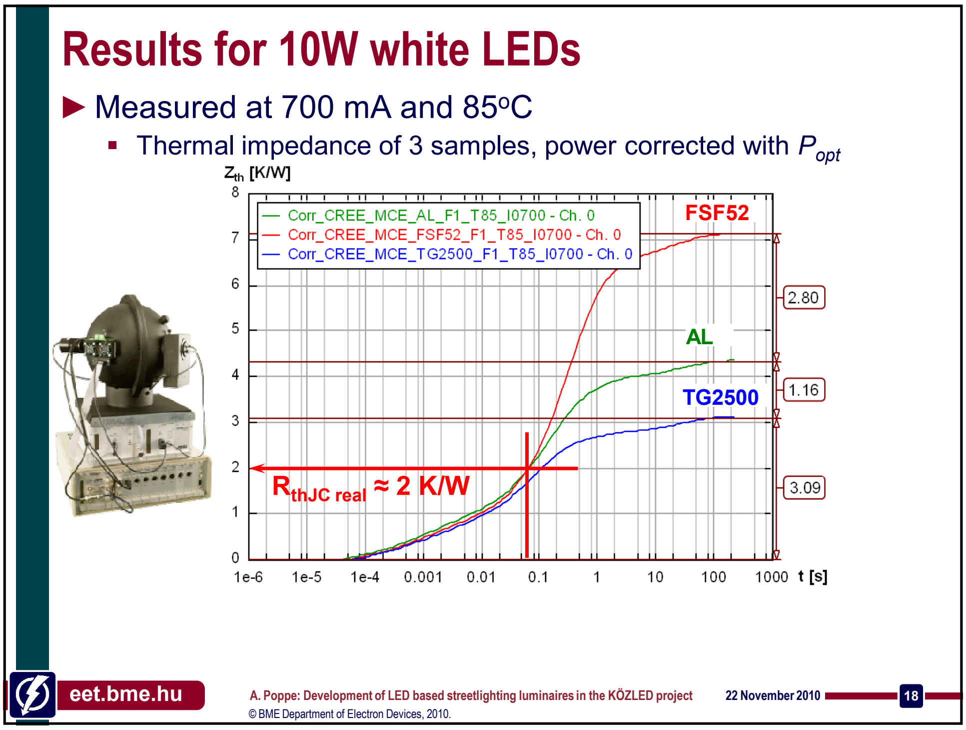
Results



Case study – for the KÖZLED project

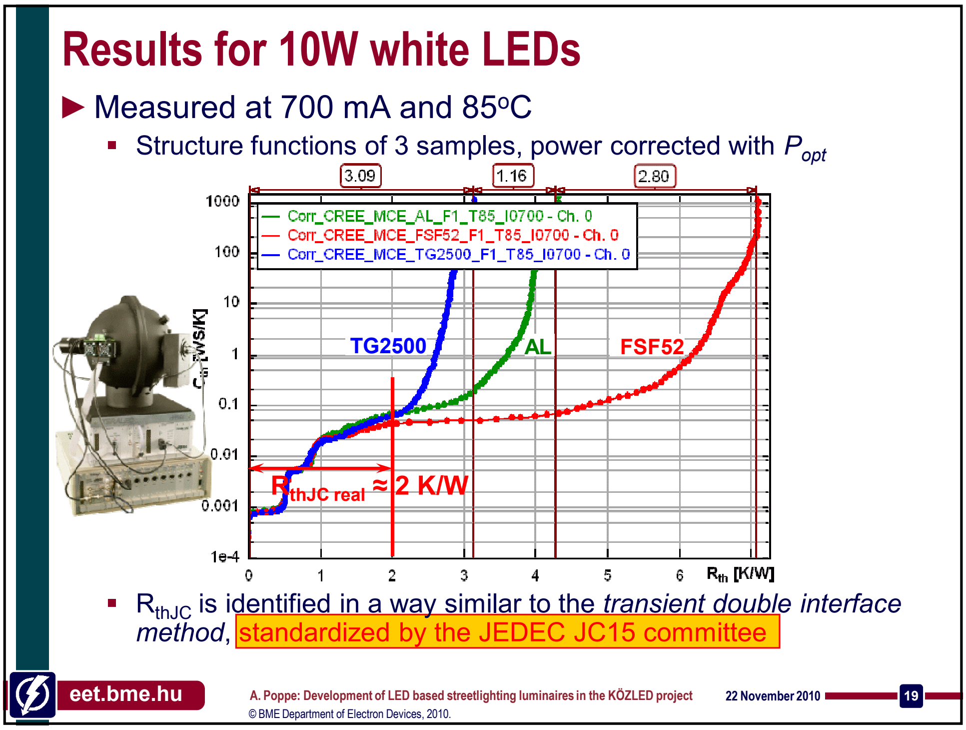
- ▶ 3 different assemblies with high-end 10W white LEDs
  - FR4 PCB, TIM between the heat-slug and the Cu block
  - FR4 PCB, heat-slug soldered to the Cu block
  - MCPCB-s made of Al and Cu, heat-slug soldered

CAD images by
courtesy of
OptimalOptik Ltd.



Results for 10W white LEDs

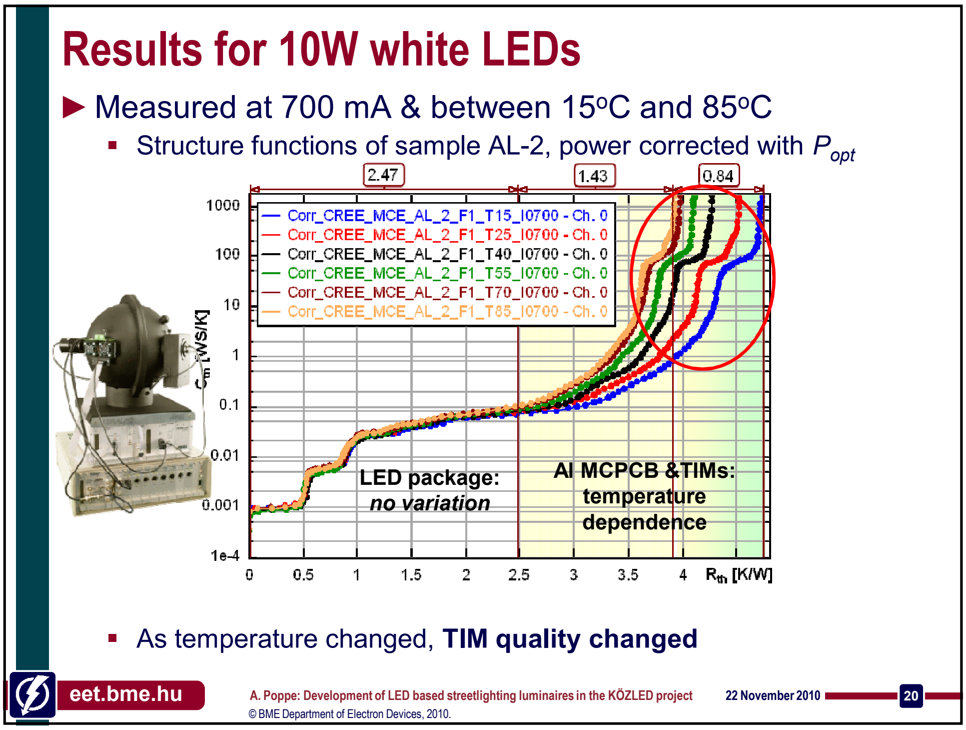
- ▶ Measured at 700 mA and 85°C
  - Thermal impedance of 3 samples, power corrected with P_{opt}



Results for 10W white LEDs

- Measured at 700 mA and 85°C
  - Structure functions of 3 samples, power corrected with P_{opt}

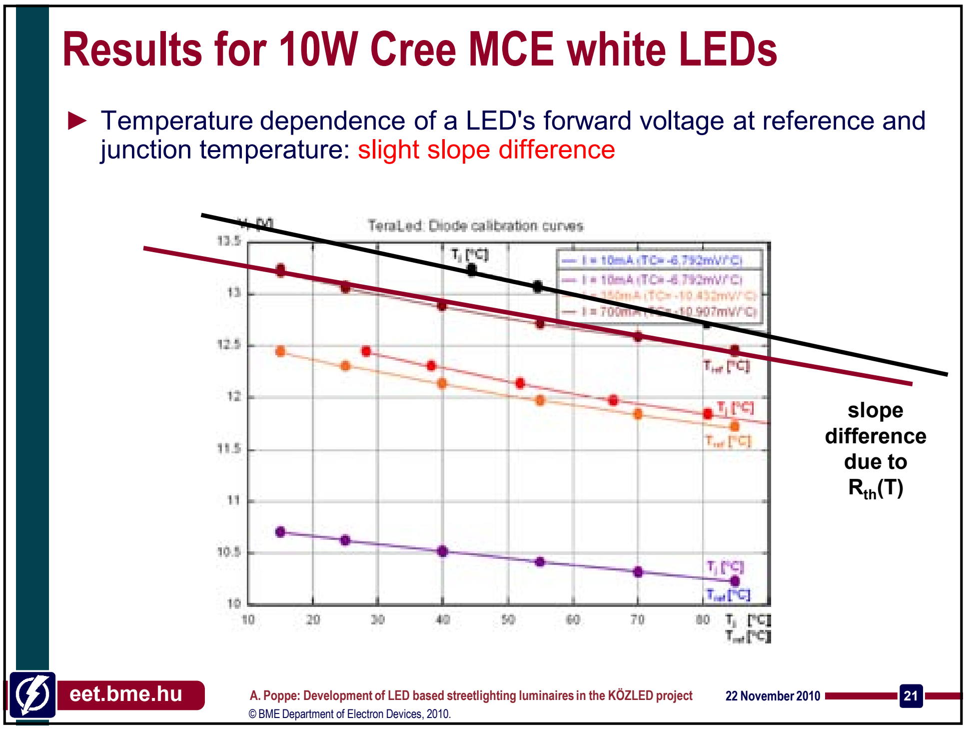
  - R_{thJC} is identified in a way similar to the *transient double interface method*, standardized by the JEDEC JC15 committee



Results for 10W white LEDs

- Measured at 700 mA & between 15°C and 85°C
  - Structure functions of sample AL-2, power corrected with P_{opt}

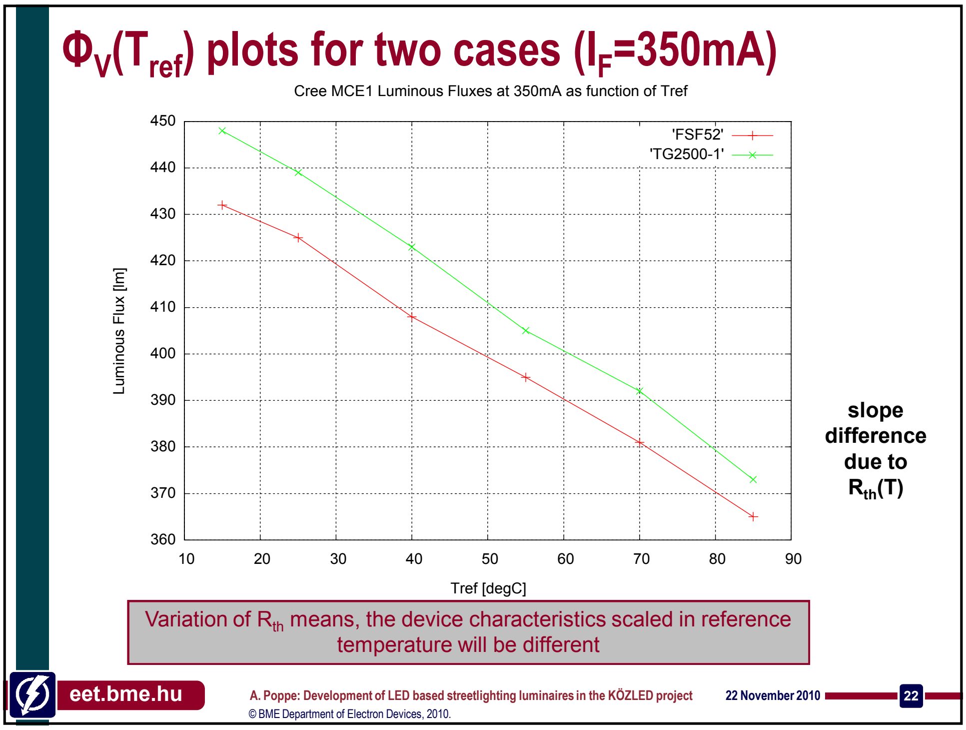
  - As temperature changed, **TIM quality changed**



Results for 10W Cree MCE white LEDs

- Temperature dependence of a LED's forward voltage at reference and junction temperature: slight slope difference

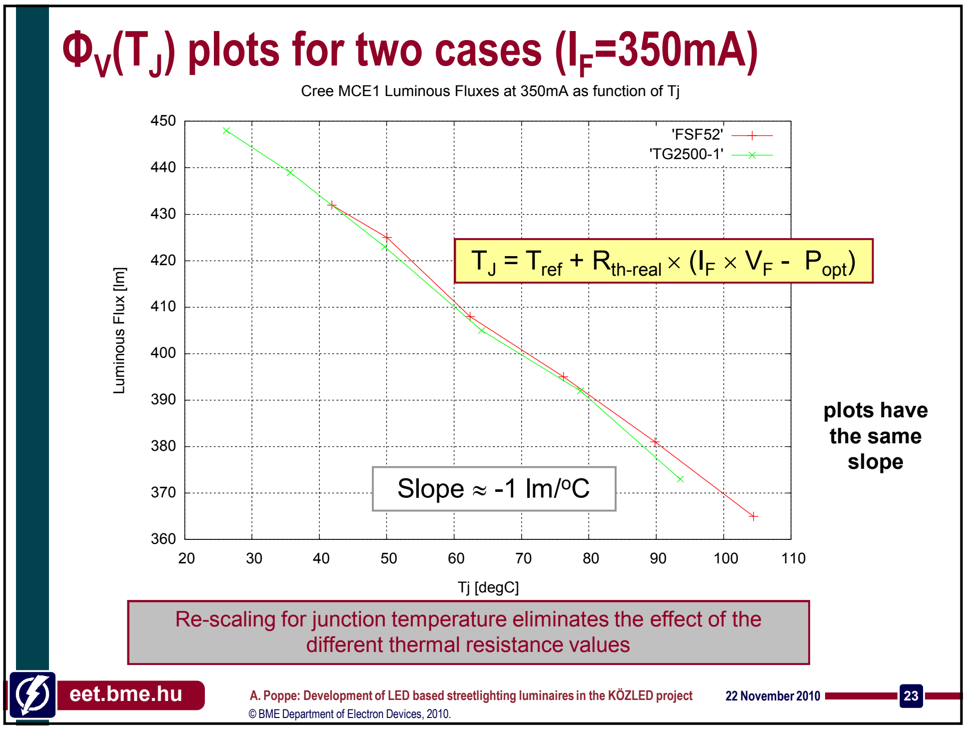
slope difference due to R_{th}(T)



$\Phi_V(T_{ref})$ plots for two cases (I_F=350mA)

slope difference due to R_{th}(T)

Variation of R_{th} means, the device characteristics scaled in reference temperature will be different



$\Phi_V(T_J)$ plots for two cases (I_F=350mA)

Cree MCE1 Luminous Fluxes at 350mA as function of Tj

$T_J = T_{ref} + R_{th\text{-}real} \times (I_F \times V_F - P_{opt})$

Slope ≈ -1 lm/°C

plots have the same slope

Re-scaling for junction temperature eliminates the effect of the different thermal resistance values

eet.bme.hu

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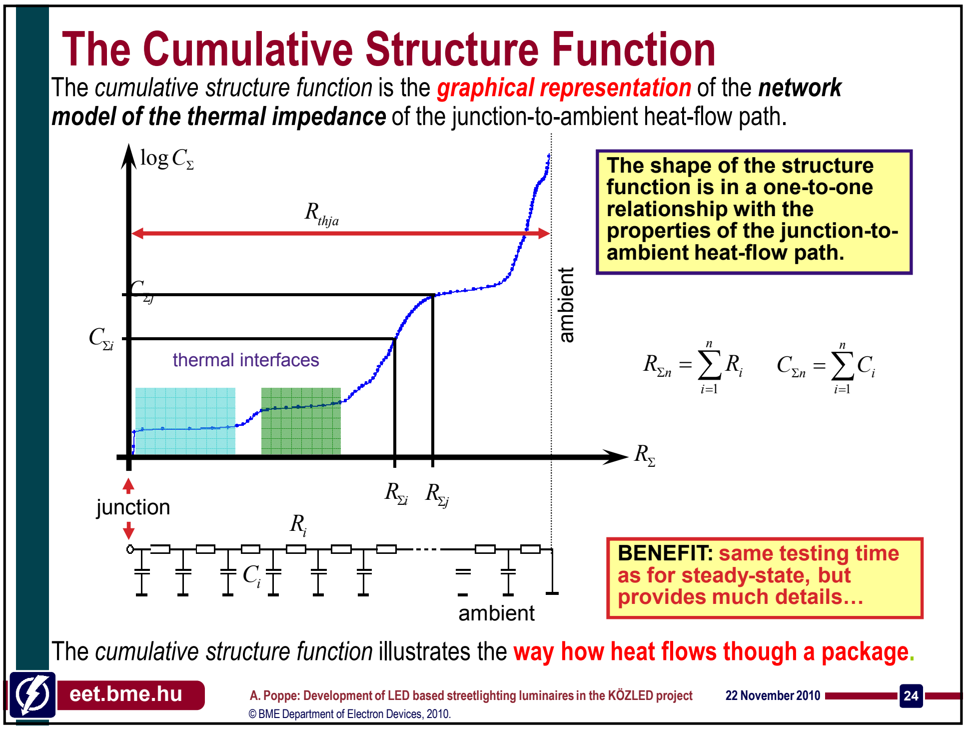

The Cumulative Structure Function

The *cumulative structure function* is the ***graphical representation*** of the ***network model of the thermal impedance*** of the junction-to-ambient heat-flow path.

The shape of the structure function is in a one-to-one relationship with the properties of the junction-to-ambient heat-flow path.

$$R_{\Sigma n} = \sum_{i=1}^{n} R_i \qquad C_{\Sigma n} = \sum_{i=1}^{n} C_i$$

BENEFIT: same testing time as for steady-state, but provides much details…

The *cumulative structure function* illustrates the way how heat flows though a package.

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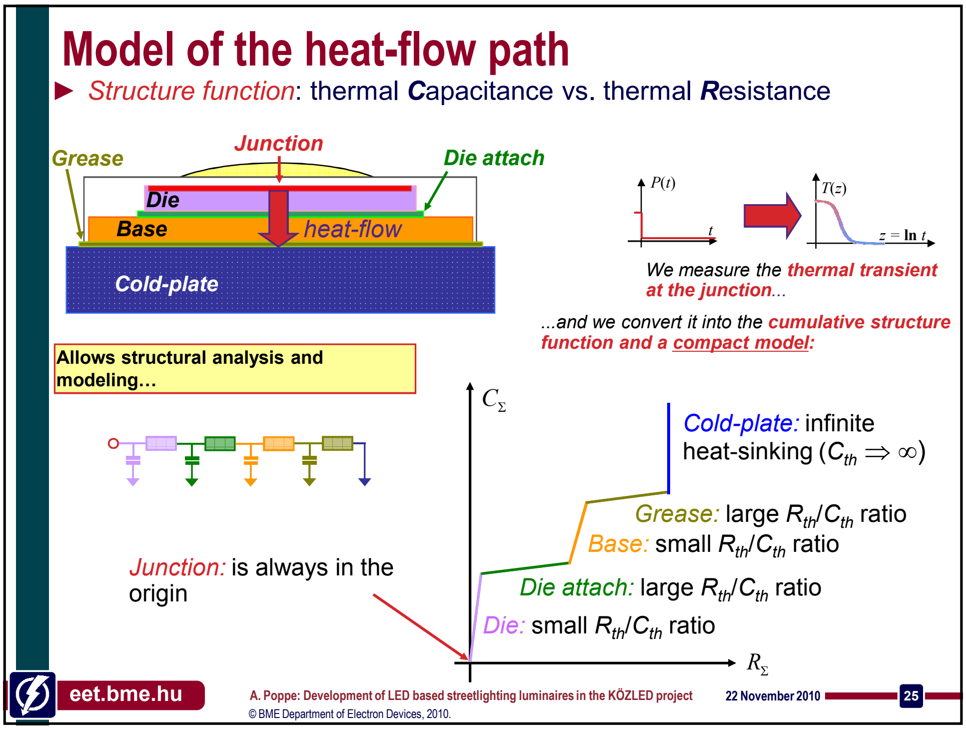


Model of the heat-flow path

- *Structure function*: thermal **C**apacitance vs. thermal **R**esistance

We measure the ***thermal transient at the junction****...*

...and we convert it into the ***cumulative structure function and a compact model:***

Allows structural analysis and modeling…

Junction: is always in the origin

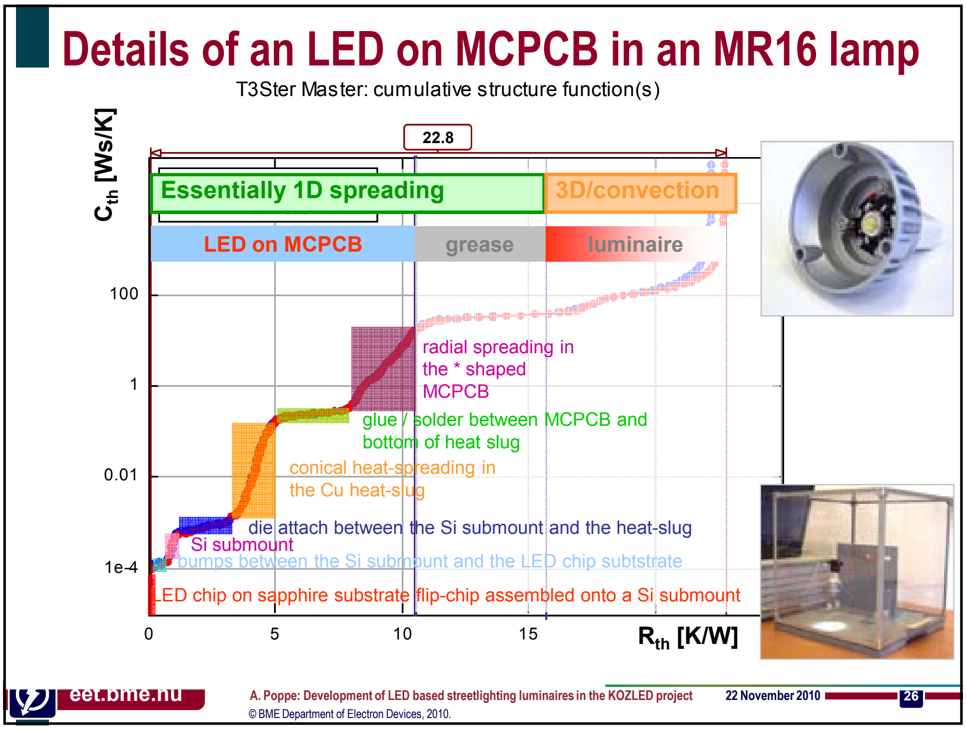
Cold-plate: infinite heat-sinking ($C_{th} \Rightarrow \infty$)

Grease: large R_{th}/C_{th} ratio

Base: small R_{th}/C_{th} ratio

Die attach: large R_{th}/C_{th} ratio

Die: small R_{th}/C_{th} ratio



Details of an LED on MCPCB in an MR16 lamp

T3Ster Master: cumulative structure function(s)

Essentially 1D spreading

3D/convection

LED on MCPCB

grease

luminaire

radial spreading in the * shaped MCPCB

glue / solder between MCPCB and bottom of heat slug

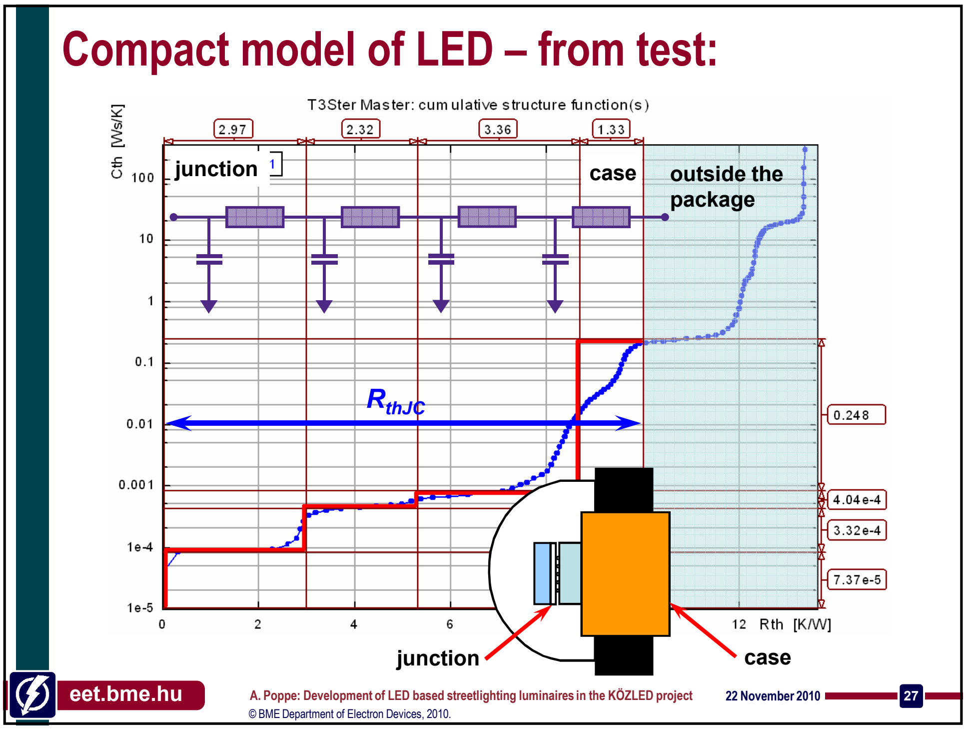
conical heat-spreading in the Cu heat-slug

die attach between the Si submount and the heat-slug

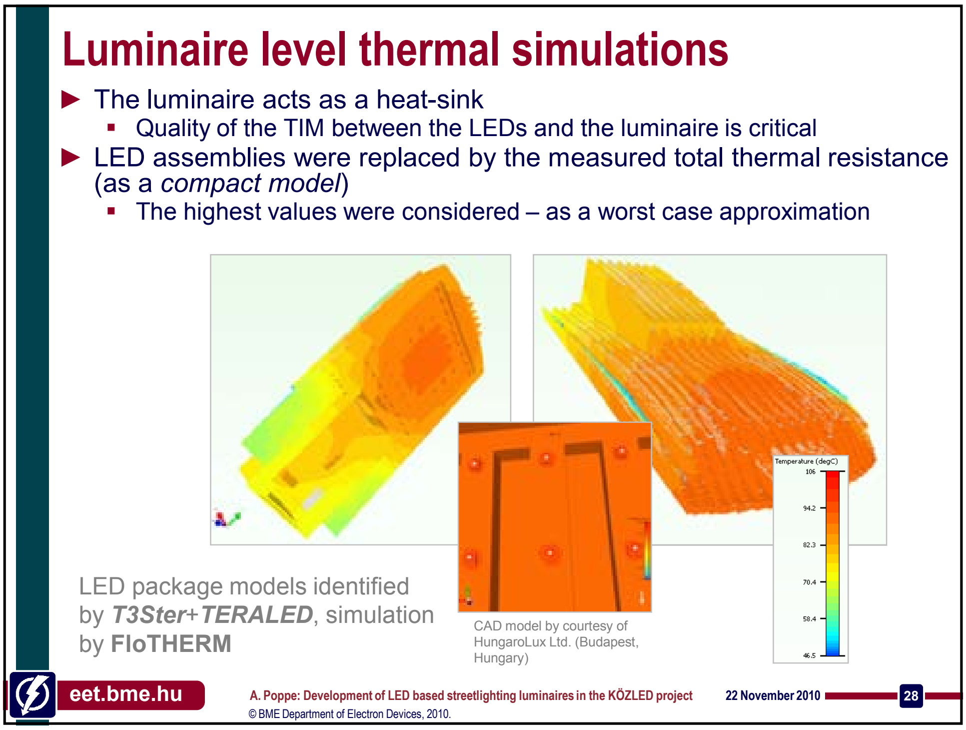
Si submount

bumps between the Si submount and the LED chip substrate

LED chip on sapphire substrate flip-chip assembled onto a Si submount



Compact model of LED – from test:

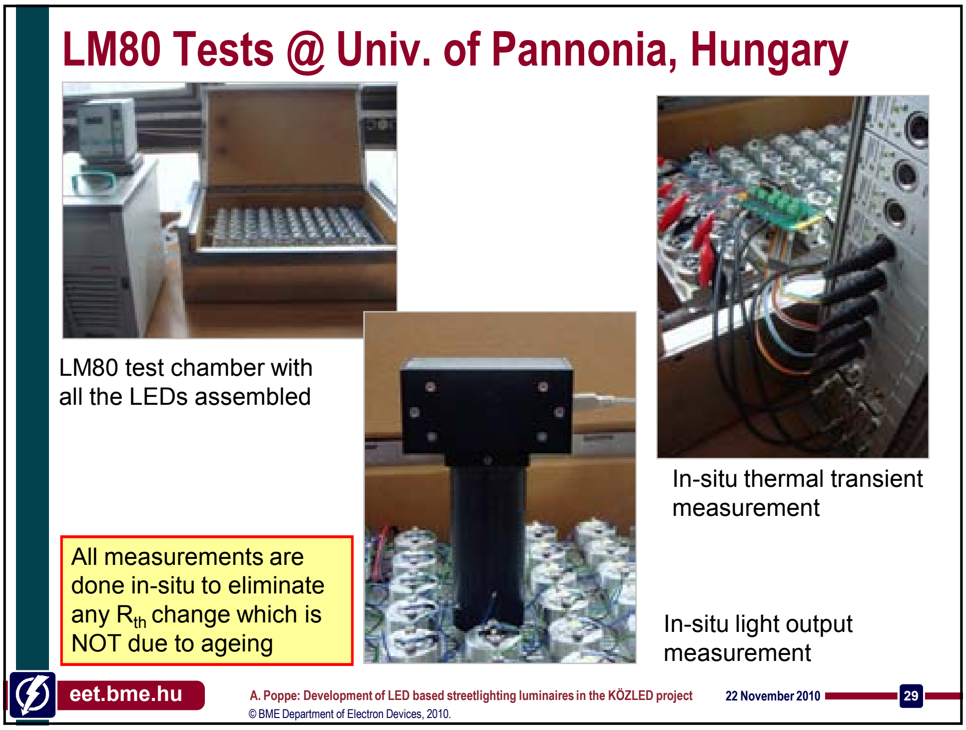


Luminaire level thermal simulations

- The luminaire acts as a heat-sink
  - Quality of the TIM between the LEDs and the luminaire is critical
- LED assemblies were replaced by the measured total thermal resistance (as a *compact model*)
  - The highest values were considered – as a worst case approximation

LED package models identified by ***T3Ster+TERALED***, simulation by **FloTHERM**

CAD model by courtesy of HungaroLux Ltd. (Budapest, Hungary)



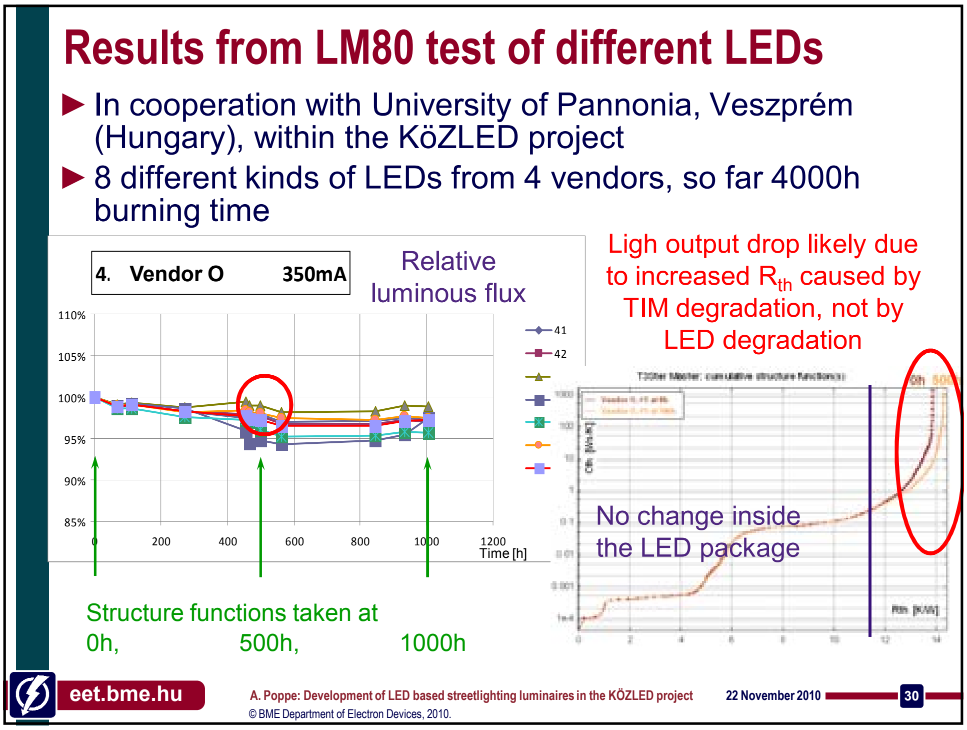
LM80 Tests @ Univ. of Pannonia, Hungary

LM80 test chamber with all the LEDs assembled

All measurements are done in-situ to eliminate any R_{th} change which is NOT due to ageing

In-situ thermal transient measurement

In-situ light output measurement



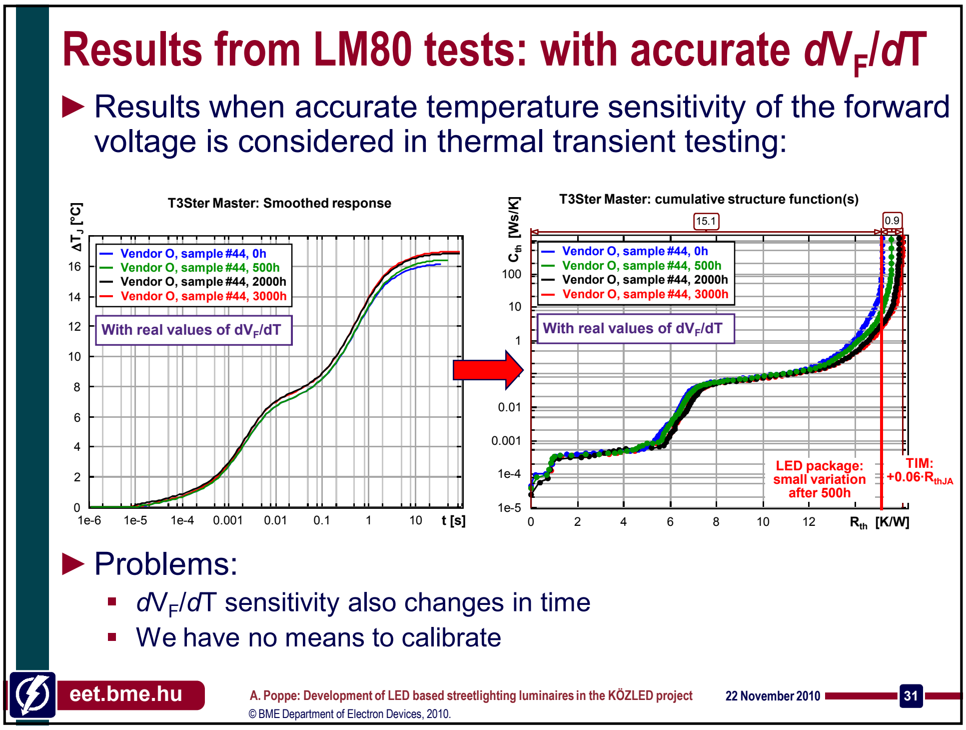
Results from LM80 test of different LEDs

- ▶ In cooperation with University of Pannonia, Veszprém (Hungary), within the KöZLED project
- ▶ 8 different kinds of LEDs from 4 vendors, so far 4000h burning time

Ligh output drop likely due to increased R_{th} caused by TIM degradation, not by LED degradation

No change inside the LED package

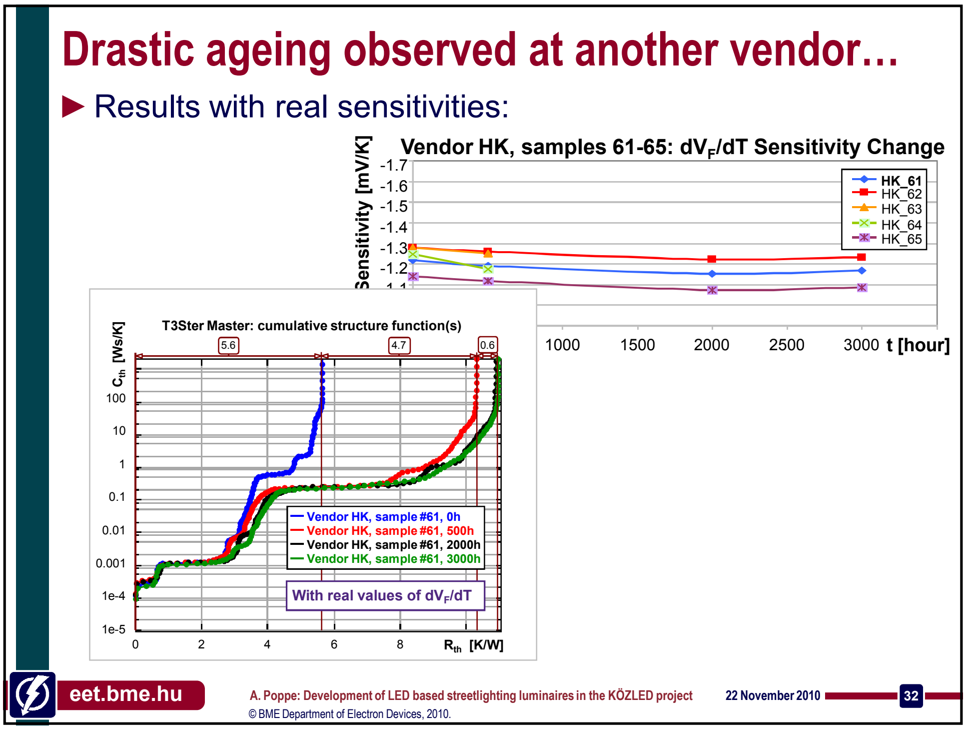
Structure functions taken at 0h, 500h, 1000h



Results from LM80 tests: with accurate dV_F/dT

- ► Results when accurate temperature sensitivity of the forward voltage is considered in thermal transient testing:

- ► Problems:
  - dV_F/dT sensitivity also changes in time
  - We have no means to calibrate



Drastic ageing observed at another vendor…

- ► Results with real sensitivities: