AGEING OF LEDS: A COMPREHENSIVE STUDY BASED ON THE LM80 STANDARD AND THERMAL TRANSIENT MEASUREMENTS

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Abstract

The motivation of the work reported this paper was to investigate what kind of failures are likely to happen in LED based streetlighting luminaries. The work was carried out in the framework of the KÖZLED project of the Hungarian National Technology Research and Development Office. Therefore LM80 testing of nominal 1 W and 3 W white LEDs from different North-American, European and Asian manufacturers was started. The novelty of our experiments is that photometric/colorimetric and electrical measurements usual during LM80 tests were completed by in-situ thermal transient measurements from which thermal resistance data and information about the possible structural changes of the junction-to-ambient heat-flow path of all investigated LEDs were identified. We report on the experienced changes of the investigated LEDs and we also try to find correlation between the measured thermal properties and the electrical, photometric/colorimetric properties of the investigated LEDs.

Keywords: LM80 test, ageing of LEDs, LED reliability, thermal transient testing, thermal interface materials, structural analysis of heat-flow paths

1 Introduction

The investigation of ageing of LEDs is an important issue during the design LED luminaires in many application fields such as streetlighting where prescribed luminance level needs to be assured during the entire lifetime of the luminaire, under harsh environmental conditions. During the life span of LEDs, light intensity and chromaticity changes manifestly. There are different physical phenomena behind this, for example increasing thermal resistance results in higher junction temperature which manifests in reduction of light output. Therefore LED forward voltage and thermal resistance are supplementary data, which both predict the behaviour of LED during its life, therefore, need to be measured together with light output characteristics.

1.1 Motivation, initial studies

Work reported in this article was performed in the framework of a Hungarian consortium (KÖZLED) aimed at the development of a new LED based streetlighting luminaire family. One set of tasks in the project is the investigation of LED ageing, and based on the experimental data development of certain built-in self-diagnostic functions into the luminaires [1].

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 Figure 1). Degradation of these thermal interfaces such as delamination or material ageing results in increased thermal resistance, thus in higher junction temperature, which is among the reasons that lead to luminous flux reduction of LEDs during their life time or even to fatal failures.

End users of LEDs have no control over the quality of most of these thermal interfaces except the ones which are in connection with the assembly of the LEDs. This might be the LEDs' attachment to a substrate like a metal core printed circuit board (MCPCB) or the so called TIM2 layer – the thermal interface material used to reduce the interfacial thermal resistance between the MCPCB and the heat-sink (luminaire body).

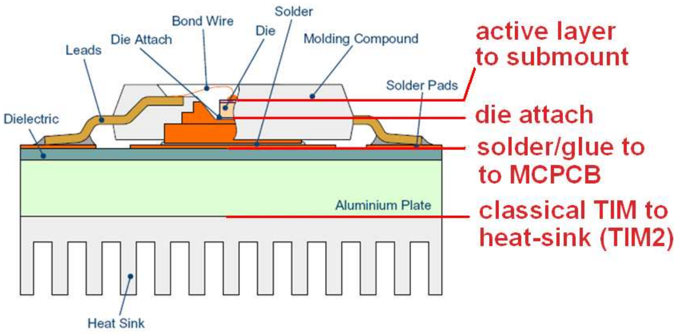


Figure 1. Different thermal interfaces in the junction-to-ambient heat-flow path of typical LED applications.

In failure analysis of packaged semiconductor devices thermal transient measurements followed by structure function analysis became a de facto standard non-destructive method of failure analysis [2]. The basic principle of this method is based on the JEDEC JESD51-1 standard [3]: first a large heating current is applied at the PN junction of the semiconductor device being tested. After the device heated up and reached its hot thermal steady-state, the PN junction is switched off from the heating current to a small measurement current abruptly and its forward voltage (as a temperature sensitive parameter) is measured and is used as an indicator of the junction temperature. The first measurement of the junction temperature should take place within a few micro-seconds immediately after the switching and it may be measured continuously – initially with a time resolution as of one micro-second, later on a logarithmically increasing time scale with at least ~100 data points in a decade of time – until the final, cool steady-state of the device is reached. With a subsequent post-processing algorithm (first publish in [2]) the *junction temperature transient* are converted to so called *structure functions.* They provide a *thermal capacitance vs. thermal resistance map* of the heat-conduction path from the PN junction of the device till the ambient. Any change in a measured structure function of a device with respect to a reference structure function indicates structural changes in the junction to ambient heat-flow path. This method can be used for failure analysis, TIM (thermal interface material) quality assessment or even to finding thermal metrics such as R_{thJC} – junction-to-case thermal resistance [4].

This principle was first applied for power LEDs in 2005 by the team of M. W. Shin [5] to study delaminations inside packages. In 2008 Trevisanello et al. reported on using thermal transient testing and subsequent structure function analysis in accelerated life-time tests of LEDs [6] and the method was recently successfully applied also in die attach quality assessment of high brightness LEDs after temperature and power cycling [7]. These applications of the thermal transient testing motivated us to use this technique also during LM80 testing of LEDs foreseen for application is streetlighting luminaires.

1.2 Test specifications, test setups

Conditions of LED luminous flux degradation measurements / life-time tests are described in the LM80 standard [8]. A detailed CFD analysis of a LED based streetlighting luminaire proved that the aging conditions defined in this standard (85 °C ambient temperature for the LEDs under test) were close to the expected operating conditions of the LEDs to be used in the field [1]. Figure 2 shows some details of this simulation study. The thermal model of the LEDs assumed in this simulation study was identified from combined thermal and radiometric measurements of selected LEDs [9].

During the implementation of the standard at the laboratory of the University of Pannonia additional specifications were also considered: namely, providing the possibility of in-situ measurement of the LEDs’ luminous flux and chromaticity as well as allowing in-situ thermal impedance measurements, without any need of removing the LED samples from the LM80 test chamber.

The application of the in-situ measurements originates from the results of prior LED stability studies performed at the University of Pannonia [10] where repeatability of luminous flux measurements was ±0.05% when mechanical assembly test LEDs mounted on a cold-plate remained intact between two subsequent measurements. The other reason for the in-situ measurements is that this way the thermal interface resistance between the LED assemblies and the test chamber's temperature controlled surface remained intact – not affecting the thermal measurements performed during our experiments. Figure 3 shows the open test chamber and the way how photometric/colorimetric and thermal measurements are done in-situ.

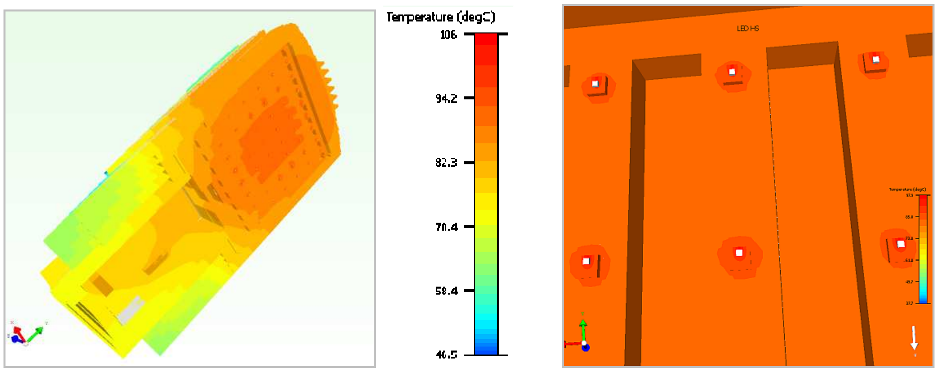


Figure 2. CFD thermal analysis results using the FloTHERM program for a LED based streetlighting luminaire confirm expected operating conditions of the LEDs investigated in LM80 tests.

a) b) c)

Figure 3. LM80 test chamber, a) 60 devices and the liquid circulator for temperature control, in-situ measurement of the b) light output, c) thermal impedance.

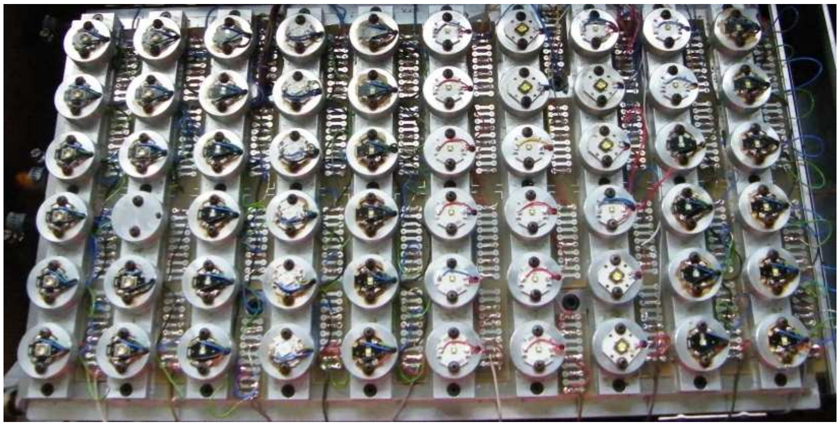
2 Test samples

Authors composed a sample set of LEDs from 6 vendors, including manufacturers from Europe, the USA and a “no-name” vendor from the Far-East. Conditions of LM80 standard are fulfilled during the ageing process, but several new methods are also applied. Each LED is soldered and mounted at the start of the aging process into its place and is never dismounted during the ageing process. Light intensity and chromaticity co-ordinates are measured in-situ (Figure 3b and 3c). Figure 4 shows the test chamber with the initial set of test LEDs installed. In column 1 and 2 samples from two different binning classes of the same LED type were installed. LEDs in columns 6 and 7 differed in their nominal correlated colour temperature (3000 K and 6000 K). In columns 1 through 7 nominal 1 W devices were installed, in column 8 we had nominal 3 W devices. In columns 9 and 10 LEDs similar to the ones in columns 3 and 5 were overdriven.

Seven columns of LEDs were driven with a steady 350 mA forward current, three columns were supplied with 700 mA. The LEDs in the last three columns were overdriven – see Figure 4.

At the beginning of the tests reference samples from each vendors’ samples were comprehensively tested in a combined thermal and radiometric/photometric test setup recommended by emerging thermal test standards being developed by the JEDEC JC15 committee on thermal standards for semiconductor devices [9], [11], [12]. Figure 7 shows the test setup used to characterize the reference samples. The total flux measurement system [13] in this combined test setup complies with the CIE 127-2007 recommendations [14]. Detailed description of the testing procedure used is provided in [12].

This way initial data regarding temperature sensitivity of light output characteristics of the LED samples was obtained. These reference samples form the 11th column: they are also attached a similar cooling assembly (water cooled cold-plate with mounting and positioning platforms) which is kept at a constant 25°C temperature when they are measured.



Vendor:	USA1	USA1	USA1	EU	USA2		NONAME		USA1	USA2
Column:	1	2	3	4	5	6	7	8	9	10
I_F [mA]	350	350	350	350	350	350	350	700	700	700

Figure 4. The initial test samples and the applied forward currents

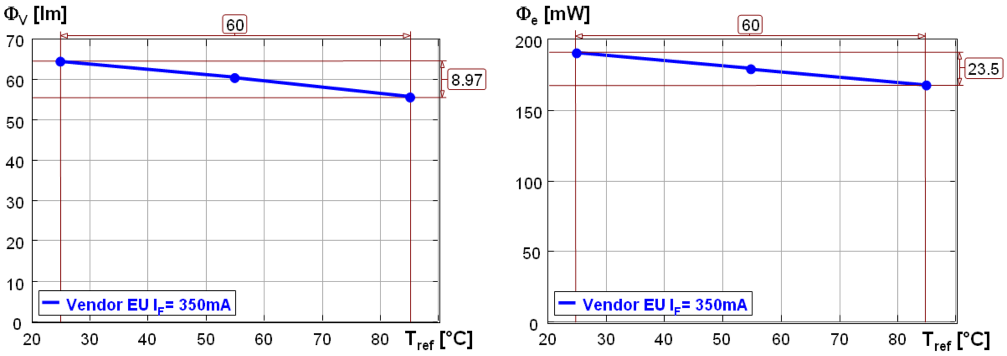


Figure 5. Temperature dependence of the luminous flux and the radiant flux of the reference sample from LED vendor “EU”, measured at 350 mA forward current.

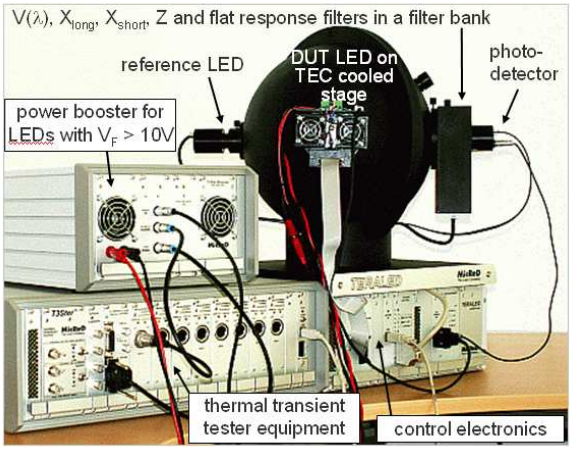


Figure 6. Temperature dependence of the luminous flux and the radiant flux of the reference sample from a European LED vendor, measured at 350 mA forward current.

During the ageing process the reference samples are switched off. As an example, in Figure 5 we present results of the luminous flux and radiant flux measurement for the reference sample from a European LED vendor. From the measurements performed at different temperatures the temperature sensitivity of the luminous flux and the radiant flux was identified. The corresponding values are 0.15 lm/°C 0.39 mW/°C, respectively.

At the time of writing this paper experiments at the University of Pannonia have reached over 6000 h of cumulative aging time. Besides measuring the change of the light output characteristics, change of forward voltage, change of the temperature sensitivity of the forward voltage and the change of the *junction-to-coldplate* thermal resistance of every LED was measured regularly.

3 Measurement of luminous flux and chromaticity

To monitor the degradation of the LED samples over the ageing period the light output change should be measured at regular time intervals. The measurements were carried out using an integrating photometer tube with a detector equipped with a V(λ) filter. The LEDs' back-plate temperature was set to the LM80 specified 25°C +/- 2°C (see Figure 4b).

The measured values are collected and stored on a PC, so the evaluation and correction of the measurement data can be carried out easily. White LEDs can have chromaticity shifts due to the different ageing characteristics of the exciter chip and of the phosphor layer; therefore a four channel integrating colorimeter tube was used to monitor the chromaticity of the different LEDs. The integrating tube in these measurements was similar to the one used for relative luminous flux measurements (Figure 3b). Alternatively a fiber optic array spectrophotometer (Ocean Optics S2000) was used to record the relative spectral power distribution of the different LEDs.

Both the test samples and the reference samples were measured. Through the luminous flux values measured for the reference samples measurement results obtained by the integrating tube (Figure 3b) and the total flux measurement system [13] (Figure 6) were connected.

4 Measurement of thermal and electrical properties

At regular time intervals thermal transient measurements of every LED samples installed in the LM80 test chamber was performed at the above mentioned back-plate temperature (25°C+/- 2°C $^{)}$, using a advanced thermal transient test equipment [15] – see Figure 3c. The measured thermal impedance diagrams were post processed and were turned into *structure functions*. During the thermal transient measurements the I_{H} *heating current* (provided by the test equipment during the test) was set equal to the nominal forward current used during the ageing process (350 mA or 700 mA, see Figure 4). The I_{M} *measurement current* (10 mA) used to capture the junction temperature cooling transients was also provided by the test equipment. The same measurement current was used for all LEDs. The current sources of the test equipment were carefully compared against the current sources used during the ageing process and the forward voltage measurements (see below).The length of the captured junction temperature transients varied between 60 s and 120 s – depending on the actual longest thermal time-constant of the LED being tested.

Forward voltages of LEDs have also been measured regularly at 10 mA forward current at temperature values of 25°C, 55°C and 85°C, using a high precision digital multi-meter (K-2000 from Keithley). These measurements were also used as K-factor (reciprocal of the temperature sensitivity of PN junctions' forward voltage) calibration for thermal impedance measurements.

5 Results and discussion

5.1 Relative luminous flux measurement results

The measured relative luminous flux values are summarized in the diagrams presented in Figure 7. In case of vendors "EU" and "USA 1" the light output dropped to approximately 90% of the initial value in 6000 h. In case of a certain LED type of vendor "USA 1" in the first 2000 h period an initial increase of the luminous flux was observed. The same initial increase was also observed in case of LEDs of vendor "USA 2". These LEDs have maintained their original level of light output. The high stability of these LED types is also supported by the results of thermal transient measurements (discussed later).

Samples of the no-name vendor have reached 70% of their initial luminous flux fairly quickly, therefore most of the samples were removed from the test before 2000 h – only a few samples survived 4500 h of ageing. According to the structure function analysis these LED samples suffered serious structural degradation (e.g. delamination) which will be discussed later.

The samples of vendor "NONAME" have been replaced by the latest LED types of vendor "USA 1". The elapsed ageing time for these samples is 1500 h .. 2000 h only – therefore results regarding of these samples are not reported here.

5.2 Chromaticity changes

Figure 8 provides summary of the colour coordinate and spectral power distribution changes for all LEDs of vendors “EU”, “USA 1” and “USA 2” observed until 6000 h of ageing.

In case of LEDs of vendor “USA 1” we observed significant shift of colour coordinates towards warmer white. This can also be observed in the measured spectral power distributions. According to measured spectra blue emission has dropped while emission in longer wavelength ranges has increased. This is perhaps due to degradation of the lens (also known as yellowing of the lens). This can be proven after completing our experiments by comparing transmission spectra of these test samples to the transmission spectra of the corresponding reference samples.

In case of vendors “EU” and “USA 2” high stability of colour coordinates and spectra can be observed. It is worth noting, that this stability – especially in case of vendor “USA 2” is paired with high stability of the relative luminous flux. In addition, as will be shown in the subsequent section, these LEDs also showed high stability from the point of view of thermal properties.

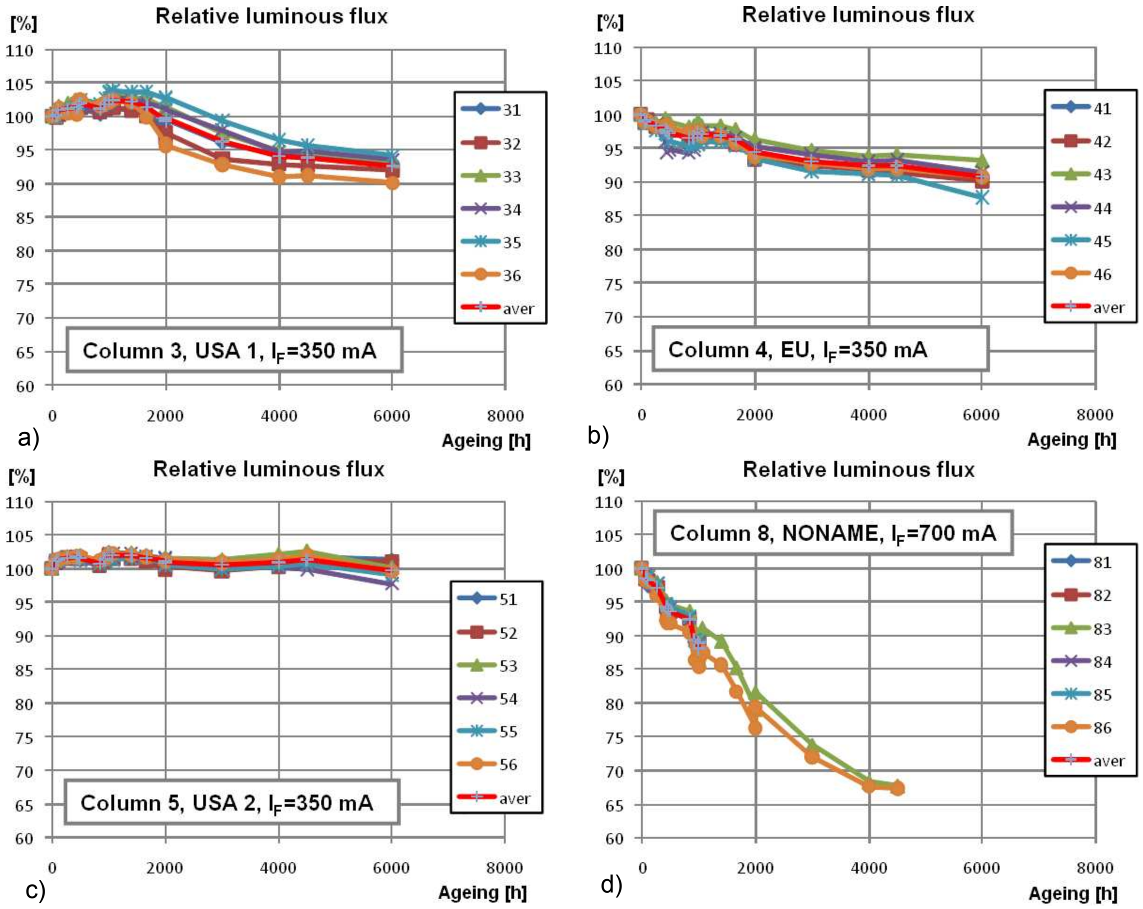


Figure 7. Summary of relative luminous flux measurement results for LED samples which reached 6000 h of ageing: a) vendor “USA 1” , b) vendor “EU”, c) vendor “USA 2”, d) vendor “NONAME”

5.3 Forward voltage changes

Figure 9 presents the change of the forward voltage LEDs from vendors “USA 1”, “USA 2”, and “NONAME”. The only conclusion one can draw is, that this property of LEDs changes in case of all vendors and one can hardly predict any tendency with ageing time. Some LEDs got stabilized, some others keep on changing. Figure 10 shows how the temperature sensitivity of the forward voltage changes. In case of the LEDs of vendor “EU” one can see a clear tendency of reduction of about 4.3% within the first 3000 h of ageing, but in case of vendor “NONAME” drifts change sign.

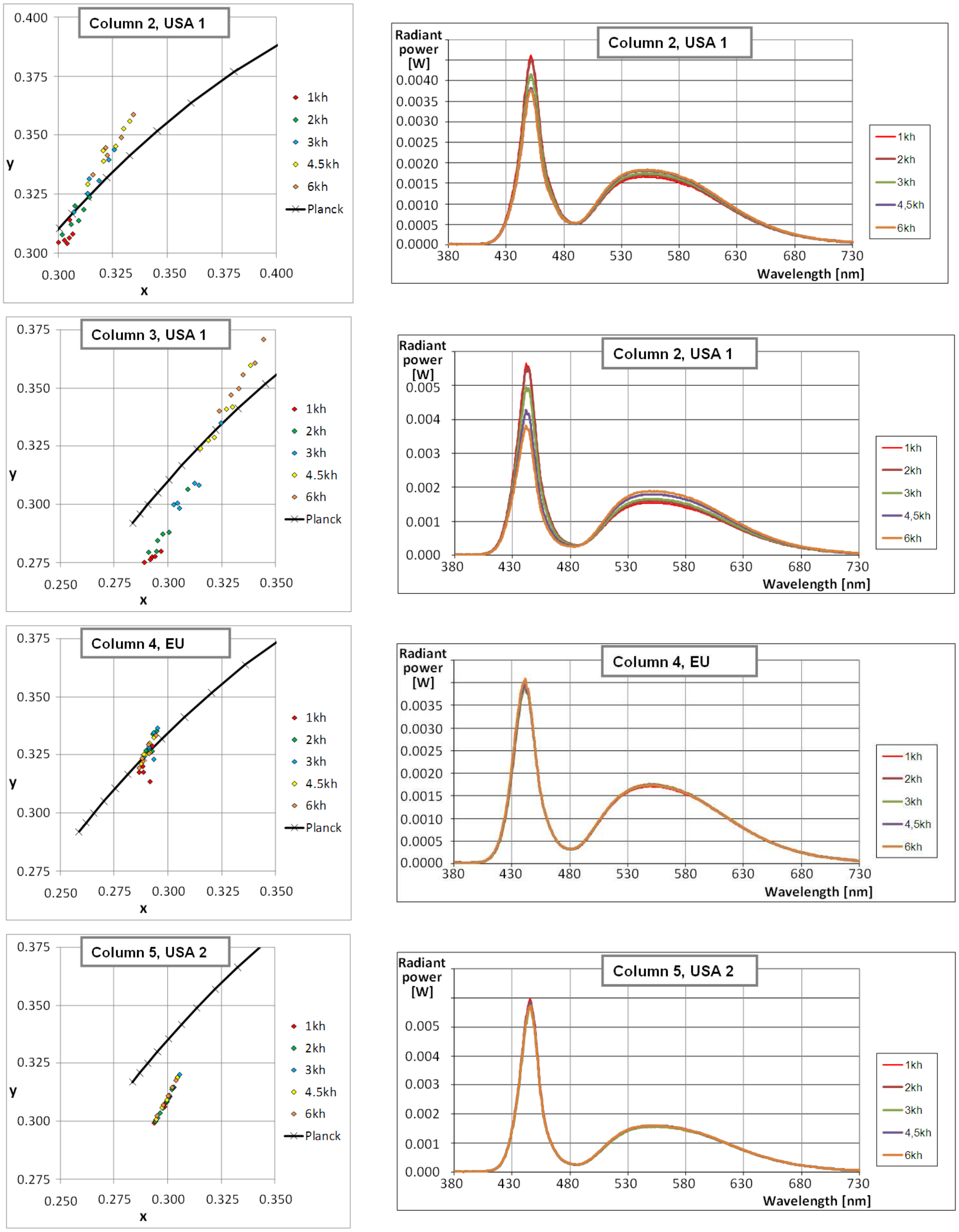


Figure 8. Summary of chromaticity and spectral power distribution changes of LED samples of vendors “USA 1”, “EU” and “USA 2” during 6000 h of ageing

5.4 Thermal resistance changes, structural changes in the heat-flow path

The measured thermal impedance curves were converted into structure functions from which all the essential elements of the junction-to-coldplate heat-flow path, like the LED chip itself, die attach, the solder/glue between the primary LED package and the MCPCB used for assembly and the TIM between the MCPCB and the temperature controlled solid surface of the test chamber (coldplate) can be separated, identified.

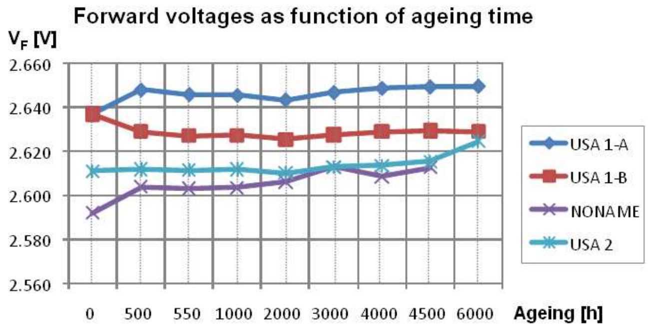


Figure 9. Forward voltages (measured at 25°C / I_F=10 mA) vs. ageing time

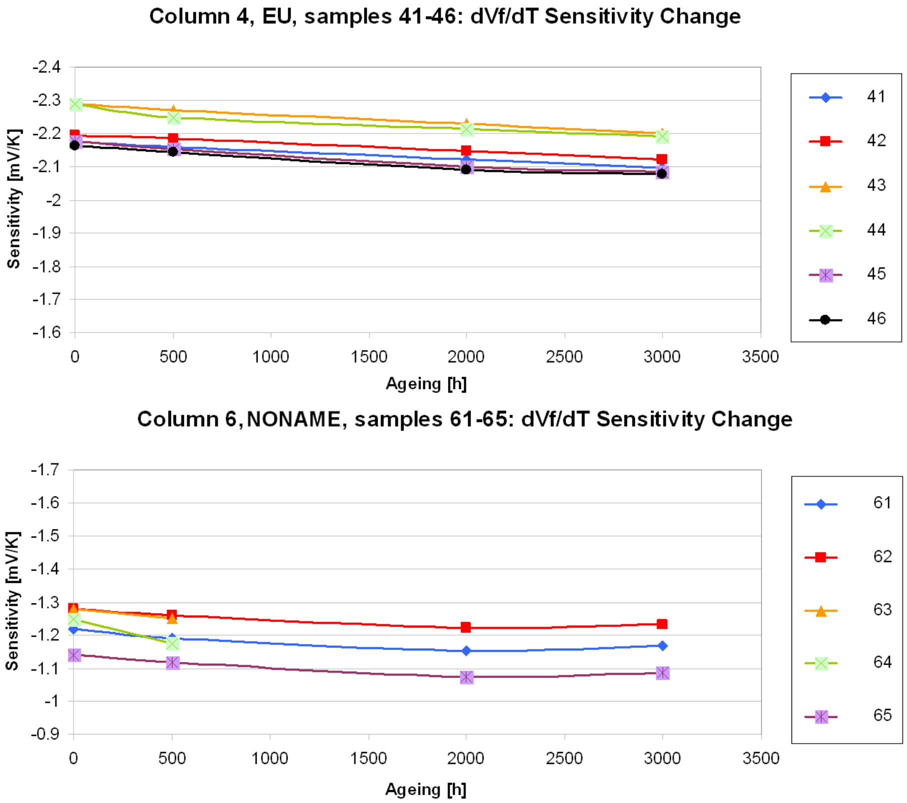


Figure 10. Temperature sensitivity changes of the forward voltage of some sample LEDs from vendors “EU” and “NONAME” as function of ageing time.

As a result of regular thermal transient measurements during our experiment we could observe structural degradation both within the LED package and outside the LED package. The most characteristic changes we observed were delamination of the LED package from the MCPCB and the degradation of the applied TIM. Figure 11 provides snapshots for LED samples which are considered “best” performing from the point of view of light output stability devices (samples of vendors “EU” and “USA 2”) as well as for the worst devices of vendor “NONAME” (which in the meanwhile were removed from our experiment. In Figure 11a a slight thermal resistance increase can be observed – the main contributor to this increase is at the end of the junction-to-coldplate heat-flow path, which is the thermal interface material (conventional thermal grease in this case) between the MCPCB and the test chamber. This increase of 0.9 K/W with respect to the original value of 15.1 K/W means about 6% change of the total thermal resistance. Looking at Figures 11a and 11b (structure function of the reference device from the same group) one can conclude, that besides this degradation of the TIM layer the shapes of the structure functions are fairly identical, suggesting high level of structural stability of packages of vendor “EU”. The same high level of structural stability can be seen in Figure 11d. The scatter in the measured thermal resistance in case of sample #54 of vendor “USA 2” remained less than 1.5% during 6000 h of ageing.

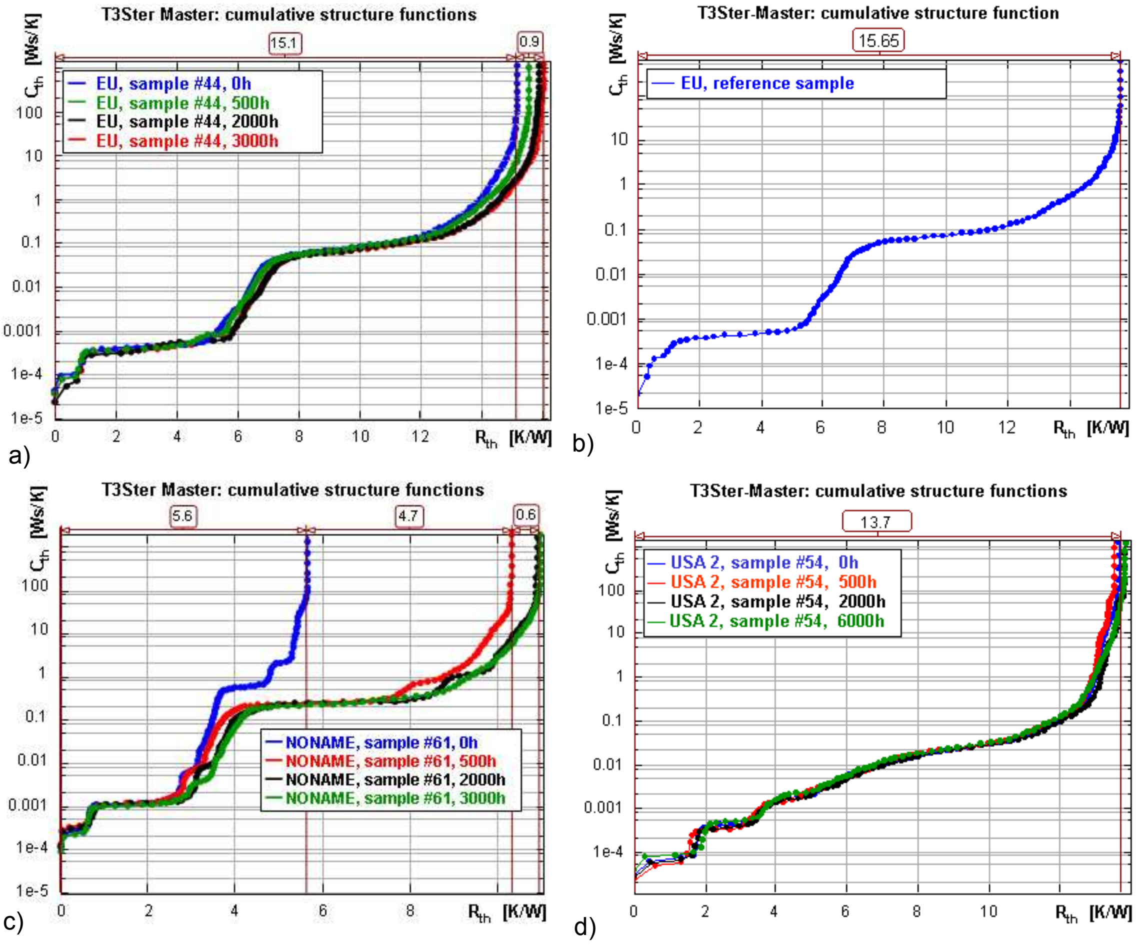


Figure 11. Structure functions obtained for certain LEDs of vendors “EU”, “USA 2” and “NONAME”: a) results between 0 h and 3000 h for sample #44 of vendor “EU”, b) reference sample from vendor “EU” taken at 0 h, c) results between 0 h and 3000 h for sample #61 from vendor “NONAME”, d) results for sample #54 of vendor “USA 2” obtained between 0 h and 6000 h.

Though according to Figure 7c sample #54 of vendor “USA 2” deviated the most from the group average of the relative luminous flux, this deviation can not be explained by thermal resistance increase during the ageing process.

In case of LED sample #61 of vendor “NONAME” huge increase of the total thermal resistance is indicated by the structure functions – see Figure 12c. This increase took place within 500 h of ageing time. Since the initial sections of the structure functions in Figure 11c co-inside (corresponding to the LED chip and the die attach), probably the delamination of the LED package from the MCPCB took place. Between 500 h and 2000 h the same TIM ageing took place as seen in Figure 12a for sample #44 of vendor “EU”.

TIM degradation observed in Figure 11a) is obviously independent from the aging of the investigated LED product but in this particular case its effect on the junction temperature is only about 1°C. Considering the temperature sensitivity of the luminous flux of the corresponding reference sample (0.15 lm/°C) the luminous flux decrease due to this TIM ageing would be less then 0.2% - much less than the measurement accuracy.

6 Conclusions

In order to achieve the highest possible accuracy during LM80 tests, all light output measurements were performed in-situ. Also, in-situ thermal transient measurements are performed with which structural changes during the ageing process can be explored.

So far (until 6000 h of ageing) only LEDs from a no-name vendor failed, but at LEDs of one of the vendors yellowing of the lens seems to appear according to measured chromaticity data. There are two LED types which show high level of stability. LEDs of vendor “USA 2” and “EU” still keep their relative luminous flux very close to 100%, and 90% respectively; their spectral power distribution is also fairly constant and according to the structural analysis performed by thermal transient testing the mechanical structure of these LEDs is also very stable. Drastic structural changes shown by structure functions however, seem to be in correlation with LED failure.

Forward voltages and their sensitivity with respect to temperature also change in time but based on our measured data we hardly can draw any conclusion.

Acknowledgements

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