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MODELLING OF POWER LEDS**

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A STEP FORWARD IN LIFETIME MULTI-DOMAIN MODELLING OF POWER LEDS

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Abstract

Simulation of the emitted total luminous flux of an LED-assembled luminaire at operating temperature is a multi-domain task since its operation can be described with the interaction of the electrical, thermal and optical domains. Multi-domain modelling of LEDs was the main target of a recent European H2020 project (Delphi4LED) in order to make the so called digital twins of LEDs widely available for industrial development purposes. One problem of these measurement based models is that they refer to fresh devices with 0h of real operation. It would be practical to try to simulate the multi-domain behaviour at any age of an LED. This article provides a description on the first attempts of using the recently refined Spice-compatible LED model for lifetime simulations, keeping in mind that in future reliability tests even the multi-domain model parameters can be used as aging indicators, possibly providing a deeper insight into LED aging than the present plain LM80/TM21 based luminous flux maintenance as standard metric of LED aging.

Keywords: multi-domain modelling, LED, characterization, digital twin, lifetime modelling, LED aging indicator

1 Introduction

The recent industrial trends are continuously pushing product development under digitalization to reduce time-to-market and development cost. This mostly means system level computer aided simulations with the so called digital twins (computer simulation models) of the real life components, like light sources, optical parts, heatsinks, etc. Power LED modelling is still an active research area; a recent European H2020 on LED characterisation and modelling (Delphi4LED, www.delphi4LED.eu) undertook to fulfil the growing industrial needs and aimed to generate the measured-data based digital twins of power LEDs. Besides many considerations like round-robin testing (Poppe 2017), product variability analysis (Bornoff 2018, Mérelle 2018, 2019), chip-on-board device modelling (Hegedüs 2019), etc. a question also arose: how could the electrical, optical and thermal parameter degradation of LEDs be modelled? How could a lifetime-lasting digital pair of an LED be generated? This exceeded the goals of the aforementioned H2020 research project but the solution is of an increasing interest as it offers many new options not only in LED reliability analysis but also in certain LED applications, like streetlighting, through possible improved reliability, lower power consumption and higher visual comfort during the whole lifetime of streetlighting luminaires.

Unlike incandescent and fluorescent light sources, the common failure mode of LEDs is not catastrophic failure. End-of-life criteria of SSL (Solid State Lighting) products are usually connected to the IES LM-80-08 approved test method (IESNA, 2008) that measures total luminous flux depreciation of LEDs. Measuring the continuously shifting forward voltage may be part of the life tests but it is still not required and therefore such measurements (or the results reporting) is often omitted. In addition, LM-80-08 (like any other common life testing method) is defined at predetermined ambient temperatures and does not consider any change in the dissipated power or the degradation of the heat flow path, i.e. the cooling capability of the LED, though such tests were already proposed as early as 2011 (Poppe 2011). In the lack of accurate lifetime models, streetlighting luminaires are usually designed by rules-of-the-thumb or by experimental data of existing prototypes.

The so called L70 or L50 means that the product lifetime ends when the luminous flux depreciation reaches down to 70% or 50% of the initial value. LEDs are usually driven by current sources where the current value is pre-defined at the design stage and is constant during the whole product lifetime. In case of automotive and streetlighting applications the forward current should be set in order to fulfil the minimum required light output level even until the specified end-of-life criteria (like L70 or even L90) are reached. Therefore, a design methodology resulting in constant light output performance throughout the whole product lifetime could further enhance efficacy and permanence of SSL devices (Hegedüs 2017). To achieve such a controlling scheme, the first step is generating the lifetime multi-domain model of the LEDs. As a base concept, the model should be suitable even for freely available circuit simulator software, that way trying to push the methodology into everyday development practice.

2 Methodology

The multi-domain LED model developed at our department (Poppe 2013, 2015, 2016) and refined in the recent H2020 project (Poppe, 2019) is based on the so called isothermal forward current – forward voltage – radiant flux (i.e. *iso-flux* or *iso I-V-L*) measurements. It implies that the optical and electrical operating parameters are calculated according to the pn-junction temperature of the light emitting diode which provides high accuracy and flexibility of the simulations. The operating or *hot-state* pn-junction temperature is calculated by the compact thermal model of the LED package which can be further extended by the compact thermal model of the cooling assembly. This makes the model capable of performing system level simulations of the whole luminaire, appropriately calculating the light output of the device at any forward current and ambient temperature conditions (Martin 2019).

Aging tendencies of LEDs (like interconnection, package or chip scale degradations) can be revealed by the above mentioned isothermal measurements. By periodically performing the characterisation as the life test time elapses, the multi-domain models of the aging LED can be generated to reveal the model parameter shifts over time. Figure 1 shows the shift in the iso I-V-L characteristics of a natural white phosphor-converted high power LED from a well-recognised vendor.

Figure 1 – Lifetime dependent isothermal I-V-L characteristics of a high power LED

Isothermal characterisations can be performed with the combined thermal and radiometric/photometric measurement setup proposed by the JESD51-5x family of measurement standard of JEDEC (JEDEC 2012a, 2012b, 2012c, 2012d) and the connecting CIE guidelines (CIE 2007, 2017). Under the current regulations of JEDEC the time needed for such measurements is around 10 to 20 minutes per a single operating point. Therefore, a well detailed characterisation of one LED sample may require a full working day.

In the Delphi4LED project, in connection with another national project on LED aging indicators more than 100 power LEDs were characterised and modelled. For this purpose, an automated global parameter fitting process was developed to handle such volumes of measured data. This

parameter fitting process was later performed on a sample LED set that was exposed to an LM-80-08 based life testing process; the samples were aged on the ambient temperature of 85 °C at the forward current of 1 A for 8000 hours. In the first 6000 hours detailed isothermal characterisation was performed on 5 samples (Figure 1 shows the results of sample #1).

3 Results

3.1 Results of the iso I-V-L characterisation and modelling

The aforementioned global parameter fitting was performed on the lifetime-variant iso I-V-L characteristics of the 5 LED samples. In the first run the algorithm run independently for each sample / aging-time combinations, providing the *elapsed time independent best fit*. Figure 2, Figure 3 and Figure 4 show the achieved Shockley model parameters of the electrical (indicated with the lower index “el”) and optical (indicated with the lower index “rad”) model parts after the first run. The resulted model parameters are very close to each other for the different samples and even the trends against the elapsed lifetime are very similar.

Figure 2 – Modell parameters as the function of elapsed lifetime: saturation currents

Figure 3 – Modell parameters as the function of elapsed lifetime: ideality factors

Figure 4 – Modell parameters as the function of elapsed lifetime: series resistances

An average device model may be considered by adding supplementary boundary conditions (or constraints) during the global fitting process and the *elapsed time dependent best fit* can be achieved. After re-running the algorithm in such way the difference between the model parameters of the individual samples becomes even smaller. Nevertheless, the results must be considered cautiously due to the fact that the exponential nature of the Shockley diode equation makes the model extremely sensitive to the ideality factor; in the absence of an adequate number of samples one can easily gain misleading values for the lifetime extrapolations. From Figure 2, Figure 3 and Figure 4 it is obvious that the time dependence of the model parameters cannot be represented by a single trend line due to the inflexion point at around 1000-1500 hours. Also, deviation of the zero-hour saturation currents both in the electrical and in the optical models is around 10 orders of magnitudes which comes again from the exponential nature of the diode equation.

3.2 Results of the LM-80-08 compliant measurements

Besides the time-consuming isothermal I-V-L characterisation of the selected 5 samples, the LM-80-08 prescribed measurements were also performed on the full set of 10 samples. The life testing standard states that optical parameters should be measured at the drive current applied during the aging process, at $25\text{ °C} \pm 2\text{ °C}$ ambient temperature, and the data collection should be performed at least of every 1000 hours. During our testing not only optical but electrical and thermal measurements were also done at the given drive current and ambient temperature, even with much higher temporal resolution than required by the standard. This allows to have a detailed look at the “time evolution” of the electrical and optical parameters. Figure 5, Figure 6 and Figure 7 show the captured radiant flux and forward voltage along with the calculated radiant efficiency values as the function of elapsed lifetime. In the figures it is clearly visible that the samples show very similar trends over the time; by averaging the individual curves (that way decreasing any measurement noise and sample-independent deflections) these trends can be better highlighted.

Although, radiant and total luminous flux are the main interest, these values come from the electric consumption and the conversion efficiency of the LED; in case of constant current driving the multiplication of the forward voltage and the radiant efficiency directly specifies the radiant flux value. In Figure 6 it can be seen that the forward voltage changes its trend at around 2500 hours and even a small shift can be found at around 4000 hours. Contrarily, the radiant efficiency has a peak at around 1250 hours and also a slight but abrupt change in its slope around 2500 hours. These altogether imply that different phenomena play the most significant roles with varying weight in the early aging or “burn-in” period of the LEDs. This fact is in accordance with the extrapolation technique of the TM-21-11 technical memorandum (IES, 2011) that uses only the last 5000 hours for the extrapolation when the test duration is less than 10000 hours, above which the last half of the data is used. Also, according to the LM-80-08 standard, the length of the whole life testing is not less than 6000 hours, and the preferred length is much rather 10000 hours, due to further possible changes in the aging trends.

Figure 5 – Measured and averaged light output parameters as the lifetime elapses

Figure 6 – Measured and averaged forward voltage values as the lifetime elapses

Figure 7 – Radiant efficiency of the individual samples and their average as the lifetime elapses

3.3 Results evaluation and future work

These findings suggest, that results below 2300 hours should be omitted during the parameter extrapolation of the multi-domain LED model. On 3 measurement points however, finding and fitting the appropriate curves cannot be done accurately and reliably. To explore the real time dependence functions of the parameters, the most preferable end-of-test criteria would be

reaching the pre-defined total luminous flux depreciation level while periodically performing isothermal I-V-L characterisation on the samples. With this purpose a new life testing was launched at our department on 18 mid power LEDs of a well-recognised vendor. The samples are exposed to an LM-80-08 based test, at the case temperatures of the specified 55 °C and 85 °C and at the arbitrarily chosen 70 °C. At each case temperature, three different forward currents are applied: 220 mA, 260 mA and 300 mA which is the absolute maximum allowed forward current of this LED type (the value is 150 mA). This means only 2 samples per each aging condition (case temperature / forward current) which is insufficient for TM-21-11 extrapolations but the captured iso I-V-L curves are expected to provide enough input data for lifetime modelling attempts. The new aging test has already passed the first 1000 hours and L70\B50 is supposed to be reached within the next 2-3000 hours.

**Figure 8 – a) The recently launched LM-80-08 based test setup;
b) three of the samples assembled in the standard LM-80-08 aging chamber**

4 Conclusions

Iso-flux characterisation of LEDs is the key to accurate modelling. The Delphi4LED project has already conducted extensive study for generating measured-data based compact LED models to serve the most recent industrial needs for the complete digitalisation of luminaire development. Completed with the efforts of a smaller scale national research project on LED aging, preliminary investigations were also done as a step forward in lifetime multi-domain modelling of power LEDs. The first experimental results presented here suggest that the hypotheses of that project were correct: parameters of multi-domain chip level LED models change with elapsed LED aging time, thus, these parameters can also be used as aging indicators besides the present industry standard luminous flux maintenance (IESNA 2008, 2011) and thermal structure functions (Poppe 2011).

Aging trends of the tested samples are very similar to each other, however, well-defined lifetime dependence of the model parameters could not be revealed yet. Still, the gained experiences were necessary to specify the next research directions and showed that during the investigations a specified total luminous flux depreciation should be reached instead of pre-defining the testing length. A new LM-80-08 based life test has already been launched under extensive operating conditions to reveal both the forward current and temperature dependence of the parameter aging.

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