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Budapest University of Technology and Economics
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LIFETIME MULTI-PHYSICAL MODELLING OF LIGHT EMITTING DIODES

Ph. D. thesis booklet

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Prologue: motivation and objectives

The spread of the switch to LED lighting is mainly due to the sufficiently increased efficiency and efficacy of LEDs. However, the use of LED light sources poses a number of technical challenges for designers and manufacturers. Adequate cooling of luminaires has become a key task, as the efficiency and life expectancy of LEDs decrease significantly as the temperature increases. Insufficient cooling not only puts the LEDs in a much more unfavourable operating point, but also accelerates the aging of the device, which further deteriorates the efficiency and increases the likelihood of sudden failure of the device. LED lamps and luminaires are still designed according to rules of the thumb in most cases, and although they are constantly reviewed and adjusted by many manufacturers based on thorough tests, purposeful design still has more and more benefits.

When discussing the thermal issues of LEDs, the ambient temperature is often determined, although the forwar voltage and luminous flux of LEDs depend on the temperature of the pn junction of the LED, which in turn is much warmer than their environment for today’s power LEDs. In many cases, manufacturer's data sheets also refer to the temperature dependence of the operating characteristics of the LEDs, but typically we do not get a complete, quantified picture of the temperature dependence even if the operating parameters are a function of the LED chip temperature. The main reason for this may be that the so-called isothermal forward current – forward voltage – radiant flux (luminous flux) characterization is a rather complicated and time-consuming procedure under the current standards. However, a suitable and detailed model is needed to perform simulations that can be used to consistently determine the operating temperature, luminous flux, forward voltage and power consumption of LED luminaires by replacing previous rules of the thumb.

The aim of my research work was to develop the foundations of an “Industry 4.0” design solution, which can be used to determine not only the temperature change, but also the control that eliminates the effects of elapsed operating time, i.e. the luminaire luminous flux can be kept constant throughout its life. This reduces the electrical consumption and increases the life expectancy. Last but not least, the visual comfort provided by the lamp is improved, as its luminous flux does not have to be overdesigned by 10-30% to compensate for the subsequent decrease in luminous flux.

At a constant forward current, the luminous flux of the luminaire decreases with increasing temperature. If the minimum luminous flux specified in the specification is to be provided in all conditions, the forward current of the LEDs shall be set according to the expected warmest temperature. This means that for street lighting luminaires, under continental climates, the luminaire will have an unnecessarily high luminous flux during most of the year, which will increase the electricity consumption of LEDs and accelerate their aging.

A similar situation is caused by the decrease in luminous flux due to the aging of the LEDs, which becomes more and more significant with the operating time. Remaining at street lighting as an area of application, in order to ensure the required illumination value at all times, the lamp must be overdesigned at the initial time so that its expected luminous flux remains above the critical value even until the planned replacement. This causes significant extra consumption over the entire operating time and faster degradation of the LEDs.

The basis of the researched procedure is the so-called LED multi-physical circuit simulation model that describes the electrical, thermal, and optical operating parameters and their interactions. The thermal compact model of the LED case is also part of the model, to which the thermal model of the respective cooling unit can be continuously connected. During the SPICE circuit simulation, the operating parameters of the LEDs mounted in the luminaire, the temperature of the pn junctions, the forward voltage and efficiency of the individual LEDs, as well as the radiant flux and the total luminous flux can be determined after specifying the input current and the ambient temperature.

In order to produce the LED model, it is primarily necessary to use the previously mentioned isothermal characteristics of the LED, from which the values of the model parameters can be determined by a suitable fitting method.

The most widely accepted method for aging LEDs is recorded in IES LM-80, and further extrapolation of the test results is possible using the TM-21-11 method - and the Arrhenius equation. With the help of these results and the initial multi-physical model of the LED, lifetime simulations can already be performed with some negligence, but in principle accurate results are provided by the time-dependent model parameters.

My research is based on the strongly temperature-dependent operation of power LEDs. Thorough measurement and design procedures can also further increase the efficiency and reliability of LED-based light sources. Examining and modelling life expectancy is also part of my research topic. The ultimate goal was to set up an LED model that can be used to determine the characteristic state of a luminaire at any time during its life cycle already in the luminaire design phase.

In my work, I considered the energy / power radiated by the LEDs; modelling of spectral power distribution and chromaticity parameters goes beyond the work currently described, the development of which is part of my future research plans.

The temperature-dependent operation and aging of the luminaires was studied in my work only with respect to the encapsulated LED; the examination of the LED driver circuit and the optics was not part of my study, so by ‘luminaire’ I mean the set of operating characteristics determined from the multi-physical modelling of the elapsed operating time of the LED enclosures that have the greatest influence on it.

List of the frequently used symbols

α, β	Fitting parameters of the Varshni formula
Φ_e	(Total) radiant flux, $\Phi_e = P_{opt}$, [W]
Φ_V	(Total) luminous flux, [lm]
K	Luminous efficacy (of radiation), $\mathrm{K} = \Phi_V / \Phi_e$, [lm/W]
λ_p	Peak wavelength, [nm]
λ	Wavelength, [nm]
η_e	Energy conversion efficiency, $\eta_e = P_{opt}/P_{el}$, [-] or [%]
τ	Thermal time constant (on linear scale), [s]
ω	Angular frequency, [Hz], [rad/s]

A	Pre-exponential factor of the Arrhenius-equation
c	Speed of light in vacuum (299 792 458 m/s)
C_{th}	Heat capacity, [Ws/K]
dt	Time taken during a reaction [s]
E_a	Activation energy [J] or [eV]
E_g	Banned-gap energy [J] or [eV]
F	Speeding factor calculated by the Arrhenius-equation [-]
h	Planck constant ($6.626070 \cdot 10^{-34}$ Js)
I_0	Saturation current of the Shockley-diode model, [A]
I_{0dis}	Saturation current of the I_{dis} forward current component of an LED, [A]
I_{0rad}	Saturation current of the I_{rad} forward current component of an LED, [A]
I_{dis}	Current component of an LED causing heat dissipation, [A]
I_{rad}	Current component of an LED causing radiation, [A]
I_F	Forward current of an LED, [A]
I_H	Heating current uring a thermal transient testing, [A]
I_M	Measuring current uring a thermal transient testing, [A]
k	Reaction rate coefficient (the unit depends on the rate of reaction)
k_B	Boltzmann constant ($1.380649 \cdot 10^{-23}$ J/K)
m	Ideality factor of the Shockley-diode model, [-]
m_{dis}	Ideality factor of the I_{dis} forward current component of an LED, [-]
m_{rad}	Ideality factor of the I_{rad} forward current component of an LED, [-]
n	Life stressor slope [-]
P_{el}	Electrical power of an LED, $P_{el} = I_F \cdot V_F$ [W]
P_{opt}	Total radiant flux, $P_{opt} = \Phi_e$, [W]
P_H	Heat dissipation, [W]
q	Unit charge ($1.602177 \cdot 10^{-19}$ C)
R_S	Series resistance of an LED, [Ω]
R_{th}	Thermal resistance, [K/W]

R_{thJA}	Junction-to-ambient thermal resistance, [K/W]
R_{thJC}	Junction-to-case thermal resistance, [K/W]
R_{thReal}	Optically corrected thermal resistance of an LED, [K/W]
S_m	Temperature sensitivity of the ideality factor, [1/K]
S_{RS}	Temperature coefficient of the series resistance, [Ω/K]
t	Elapsed operation time of an LED, [h]
T	Temperature, [°C]; or absolute temperature, [K]
T_A	Ambient temperature, [°C] or [K]
T_{cp}	Cold-plate temperature, [°C] or [K]
T_J	Pn junction temperature, [ºC] or [K]
T_{ref}	Reference temperature (arbitrarily chosen), [°C] or [K]
V_F	Forward voltage of an LED, [V]
V_{Ff}	Forward voltage measured near the sensor current, [V]
V_{Fpn}	Forward voltage of the internal pn junction of an LED, [V]
V_g	Banned gap potential, $V_g = W_g/q$ [V]
V_H	Forward voltage measured near the heating current [V]
V_T	Thermal voltage, $V_T = k \cdot T/q$ [V] ($\approx$ 26 mV at 300 K)
W_g	Banned gap energy [J] or [eV]
x	Changing reactant quantity
Z_{th}	Thermal impedance, [K/W]
$Z_{th}(t)$	Thermal impedance as the function of time, [K/W]

1 Compensation of temperature dependence with multi-physical LED model

1.1 Temperature dependence of LEDs and luminaires

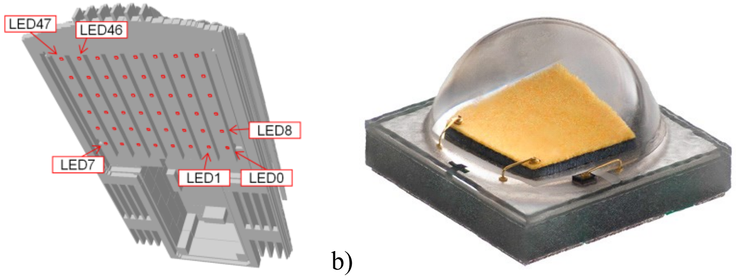
The forward voltage, efficiency and efficacy of LEDs, which are typically powered by a current generator, all decrease as the pn junction temperature increases, so they consume less electrical power and convert even less of it into light. This should be taken into account when designing street lighting luminaires, i.e. the luminaire must provide the minimum required luminous flux even at the warmest ambient temperature expected. If a luminaire operates at a constant forward current, its value (and / or the number of LEDs installed in the luminaire) shall be determined so that its luminous flux remains satisfactory even at the expected warmest operating temperature. However, for most of the year, light emissions will be higher than necessary (especially at cold winter nights).

Looking at the phenomenon described above from the other direction, it can be seen that as the environment cools, the consumed power of the LEDs increases and their light utilization improves, which can be appropriately exploited by careful design. Accurate knowledge of the temperature dependence of the LEDs used in the luminaire and the system-level simulation of the luminaire make it possible to accurately determine the operating luminous flux of the luminaire as a function of the ambient temperature and the forward current of the LEDs. This way, a forward current control scheme can be defined that provides constant luminous flux operation to compensate for the effects of changes in ambient temperature. This not only saves a significant amount of electrical energy, but also increases the reliability and life of the luminaire.

1.2 Determining the operating luminous flux with an LED model

Hungaro Lux Light Kft. provided us with a physical sample of the PearlLight 48G luminaire with full functionality (Figure 1.1. a)) and two more samples of the LED modules used in the luminaire (Figure 1.1. b)). The multi-physical characterization of the obtained LED samples was performed according to the JEDEC JESD 51-5x family of standards. The combined thermal compact model of the LED case and the supporting MCPCB could be extracted directly from the measurement results. To determine the model parameters, I made my own semi-automatic calculator in MS Excel environment.

The luminaire system-level simulations were performed in the SPICE-compatible ELDO electro-thermal circuit simulation environment. The results of the performed simulations were arranged in a two-dimensional matrix according to the ambient temperature and the forward current values, and I searched for a suitable interpolation solution to convert the simulation results for the discrete values into a continuous function. The array of characteristics obtained as a result of the simulations and the control scheme compensating for temperature changes are shown in Figure 1.2.



a) b)

Figure 1.1. a) Detailed 3D MCAD model of the PearlLight 48G luminaire, and b) CREE XP-G2 LED used in the luminaire.

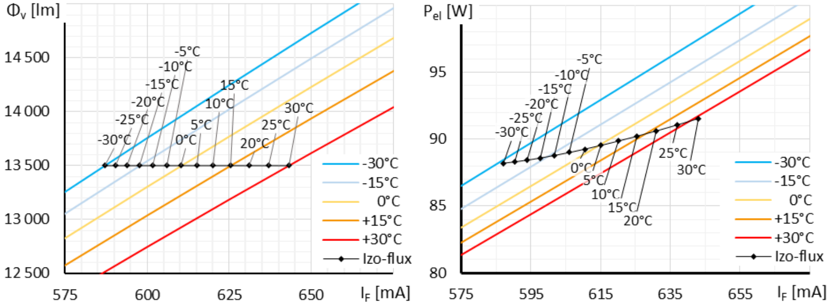


Figure 1.2. Simulated and interpolated characteristics of the total luminous flux and electrical power of the PearlLight 48G luminaire as a function of ambient temperature and forward current. In the figures, the so-called iso-flux range is marked separately.

1.3 Verification of simulation results by field measurements

The correctness of the simulation results was confirmed by field and laboratory measurements under both operating schemes. In-situ field measurements of the luminaire were performed at two locations.

The primary purpose of the field measurements was to compare the actual behaviour of the luminaire with estimates made by simulations. After the field measurements, the luminaire was also measured in a WEISS WK 340/70 climate chamber, where the measurement set-up remained undisturbed and intact during the temperature change, allowing consistent optical measurements of the temperature-dependent operation.

Thesis I.

I have developed a new multi-physical method to determine the constant total luminous flux control scheme of LED luminaires. Based on archive meteorological data, with the help of simulations I examined the advantages of the control scheme in terms of operating luminous flux and electrical consumption. The operation of the control scheme was verified by field and laboratory measurements of a real street lighting luminaire.

The method can be applied to any luminaire, given the LED models and the compact thermal model of the luminaire housing. In the case of existing luminaires, the method makes it possible to forecast electrical consumption.

Related publications: [J1], [J2], [B1], [C1], [C2], [C3], [C4]

2 Constant luminous flux operation taking into account aging in the sense of LM-80

A control scheme that compensates for device aging is now available from many light source manufacturers. Regarding the implementation of CLO ("Constant Light Output" or "Constant Luminous flux Output"), manufacturers typically provide a rather concise description, based on which they typically determine the operating time-dependent forward current scheme based on the LM-80 measurement results of the LEDs, according to which the LED driver circuit is pre-programmed. In this case, the method saves a significant amount of electricity without having to overdesign the initial luminous flux of the installed lamp or without the luminous flux of the aged lamp already leading to insufficient illumination. Apparently, however, it is manufacturer-specific how the forward current of LEDs is increased as a function of operating time.

Modelling the luminous flux of outdoor luminaires is not obvious, because the pn junction temperature of LEDs depends on the current weather – temperature, air movement, humidity etc. The results of the TM-21 extrapolation can only be applied at a constant forward current and a constant pn junction temperature. In order to determine the degree of aging at a variable temperature (and optionally at a variable forward current), the reaction rate coefficient must be replaced by the Arrhenius equation (or an appropriately extended form) in the differential form of the reaction rate equation:

$$-\frac{d\Phi}{dt} = \Phi \cdot k = \Phi \cdot A \cdot exp\left[\frac{-E_a}{k_B \cdot T_J}\right] \cdot I_F^n \tag{2.1}$$

where I already calculate the aging based on the T_J chip temperature of the LEDs. By rearranging the above relationship and integrating both sides, the change in the emitted optical parameter between any two time instances can be determined:

$$\int_{\Phi_1}^{\Phi_2} \frac{1}{\Phi} d\Phi = -\int_{t_1}^{t_2} A \cdot exp\left[\frac{-E_a}{k_B \cdot T_J}\right] \cdot I_F^n \, dt \tag{2.2}$$

where the chip temperature of the LEDs depends directly on the temperature of the luminaire and indirectly on the weather conditions, i.e. T_J can be written as a function of the elapsed operating time t. The value of the forward current is constant in most applications, but with any “smart” luminous flux regulation / control solution, this simplification can no longer be used. In the case of a control scheme that also compensates for changes in the ambient temperature, the forward current I_F is primarily a function of T_J, which can ultimately be written as a function of the elapsed time due to weather conditions.

The determination of a control scheme that provides a constant luminous flux for the entire service life can only be done by rough estimation during installation, especially in the case of smart solutions that also monitor traffic. In principle, monitoring the luminaire temperature and determining the aging of the LEDs in-situ gives a more accurate value.

Equation (2.2) can be greatly simplified by considering the chip temperature of the LEDs (and thus the value of the forward current) to be constant, and the calculations are performed only in discrete time steps. We can also do this because the main thermal time constants of luminaires typically fall in the order of 10 minutes.

Assuming that the operating time only degrades the efficiency of the device (but, for example, the temperature-dependent parameters do not change), then the quotient of the light emission values for different operating points but at the same time instance can be considered constant:

$$\frac{\Phi_2}{\Phi_2'} = \frac{\Phi_3}{\Phi_3'} = \frac{\Phi_4}{\Phi_4'} = \ \dots \ = Konstans$$

thus, the rate of aging at different operation points is proportional and normalizable. I defined the concept of lifetime-budget: let η_t be a ratio expressed in %, which describes the operating time dependent state of the LED as an efficiency parameter. Its initial value is 100% or equal to the zero-hour value (i.e. β) of the curve fitted to the LM-80 measurements. The actual luminous flux of an LED can be determined by multiplying the operating point dependent luminous flux value with the remaining lifetime-budget. The remaining lifetime can be determined by accumulating the discrete time step model as:

$$\eta_{t\_i+1} = \eta_{t\_i} \cdot exp\left[-k_{T_J,I_F} \cdot \Delta t\right]$$

where η_{t_i} and η_{t_i+1} are the lifetime-budgets I have defined for the previous and next steps, k_{T_J,I_F} is the reaction rate coefficient taken at the operating point, and Δt is the elapsed time in between the calculations at t_2 and t_1.

Compared to constant forward current operation, the proposed method can save a significant amount of electrical power, in addition the life expectancy is significantly increased. The relevant simulation results are summarized in Table 2.1.

	Constant forward current	Constant luminous flux	Benefits of the "smart" lamp
Time to L(90) [hours]	64,4k hrs.	83k hrs.	+29%
	16,7 years	21,4 years	+4,7 years
Power consumption til. 64.4k hrs.	130,8 kWh	112,8 kWh	-13,7%
Power consumption in the 1st year	7,9 kWh	6,5 kWh	-17,7%

Table 2.1. Simulation results on the benefits of using a constant luminous flux control scheme.

Thesis II.

I have developed a new theory, which can be used to describe the current state of the LEDs, i.e. the aging process, as a function of the operating temperature and forward current during the whole operating time, using the standard LM-80 measurement results of the LEDs. With the help of this, I created a theoretical model for a constant total luminous flux control for the entire LED life, which takes into account the effects of both the temperature changes and aging.

Sub thesis II./A

Based on archive meteorological data, I estimated the power saving potential of an LED street lighting luminaire under a constant luminous flux control scheme for the entire LED lifetime, as well as the resulting LED lifetime increase.

Sub thesis II / B

I have defined the concept of lifetime-budget, which describes the state of an LED as a function of the elapsed operating time. I have proposed to determine the wear of LED luminaires controlled by a constant total luminous flux scheme based on the lifetime-budget.

Related publications: [J3], [J4], [B2], [C5]

3 The modified multi-physical LED model

One of the goals of the Delphi4LED project was to provide an LED model that is also available to small and medium-sized enterprises to facilitate digital luminaire design. However, the multi-physical LED model used in Thesis 1 is specifically adapted to circuit simulation environments with both thermal parameter and equation sets. Also suitable for such electro-thermal simulations, the SPICE netlist compatible platform is, for example, the ELDO I also use. The annual license fee for the program for professional applications is very high and therefore cannot be considered as a widely available tool for players in the lighting industry.

Implementation of the multi-physical LED model previously developed at BME EET was redefined. A key element of this was the request of the project partners that the model should be suitable for incorporation into a thermal simulation program at the level of equations, assuming a constant forward current, following a relaxation simulation scheme.

The previous multi-physical LED model is a so called voltage-controlled model that requires electro-thermal supplementation of the built-in diode model of standard SPICE-type circuit simulation programs. However, from the SPICE-type circuit simulation programs more widely used in the industry, only ELDO has such a model. The LED model corresponding to the request of Delphi4LED partners assumes a so called current-driven model. Such a model, supplemented by electro-thermal effects, relying on a standard set of SPICE components, can be implemented as a macro-model in any SPICE-type circuit simulation program.

3.1 The modified model

The model used for Thesis I consists of two main parts: the circuit describing the electrical and optical operation of the LED chip and the thermal model. In the modified model, I separated the electrical and optical branches of the LED chip, so the new model already consists of three separate parts (Figures 3.1. A), b) and c).

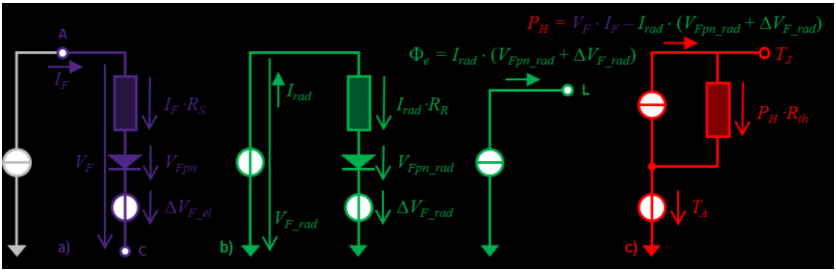


Figure 3.1. a) Outline of the electrical branch, b) the optical branch, and c) the thermal model. The gray curtent generator is external element, not part of the model.

The advantage of this approach is that the incorporation of controlled voltage generators (ΔV_F generators) makes it possible to take into account the electro-thermal effects so that the roughly logarithmic $V_F(I_F)$ characteristic of the LED is standardized (i.e. not ‘electro- thermal') diodes.

3.2 Applications that support modelling

Most of the parameters of the modified multi-physical LED model presented in the previous chapter cannot be determined analytically, therefore I extended the calculator made in MS Excel environment to a parameter matching automaton using Visual Basic macros. The runtime of the parameter matching algorithm for 40 operation points on a dual-core and dual-threaded (i.e. quad-core for MS Excel operation) mid-range Intel processor is approximately 60 min.

3.2.1 Mass production of LED model parameter sets

For the Delphi4LED project, I created a separate starting engine for the production of parameter sets of 850 LED models, which I ran using 24 desktop PCs of the department's computer lab. The production of the complete model set thus took approximately one and a half days. During model matching, error of the forward voltage and radiant flux in the upper forward current decade (typically in the range of 100 mA… 1000 mA) for the basic models is less than 0.5% and 1.5%, respectively. The luminous flux matching error is 1.65% for the white, red, and amber LEDs, while 11.4% for the royal blue LEDs.

To present the large number of LED models, I created a separate application also in MS Excel environment, where some of the necessary macros were already available to me.

Thesis III.

I have developed a new multi-physical LED model that can be implemented in any SPICE-based circuit simulation environment that does not directly support electro-thermal simulations.

To determine the parameter sets of the new multi-physical LED model, I created a reliable parameter matching automaton. With the parameter sets best suited to the new LED model, the inaccuracy of the simulated characteristics in terms of forward voltage and radiant flux within a forward current decade is less than 0.5% and 1.5%. These errors are within the standard deviation of the unique characteristics of an LED population of 5-10 samples. I proposed the definition of nominal parameter sets describing the characteristic operation of a larger population of each LED type.

Related publications: [J5], [C7], [C8], [C9], [C10], [C11], [C12]

4 The time-dependent multi-physical LED model

The aim of Thesis II. was to create a device model, which basically describes the aging process of LEDs, even under real operating conditions, based on the LM-80 measurement results, but also taking into account the continuous change of the operating point. However, the model cannot be implemented in SPICE-based circuit simulation environments (its facilitation was not a consideration during the model development), or in the case of more complex thermal systems it is not directly suitable for describing thermal cross-effects without whole luminaire aging studies. For the preparation of a lifetime LED model supporting system-level simulations, such as computer-aided design (virtual prototype production), I examined the possible operating time dependence of some parameters of the multi-physical LED model presented in Thesis III.

4.1 Lifetime modelling of Seoul 2525 LEDs

From the point of view of examining the time evolution of the model parameters, it may be much more advantageous to set the desired luminous flux reduction value instead of pre-determining the test time. Using previous experiences, I launched another LM-80-based test, during which I examined the aging of 18 Seoul 2525 blue-emitting, mid-power LEDs.

The LM-80 based test of the LED samples was performed at the ambient temperature of 70 °C and at the prescribed 55 °C and 85 °C. At each chamber temperature, I used three different forward currents, 220 mA, 260 mA, and 300 mA, respectively (the latter being the maximum allowed forward current of the LED type). For the 18-piece sample set, this represented 2 samples per test condition. This is not sufficient for the TM-21-11 extrapolations, but my goal was to develop the theoretical background, and the set 30% reduction in radiated power made further extrapolations unjustified. The design behind the 3 × 3 boundary condition arrangement was to make the results suitable to model both the forward current and pn junction temperature.

4.2 Results of the LM-80-08 based test

The LM-80 based lifetime test was discontinued after the elapsed time of 1735 hours due to the high failure rate; by this time, 14 of the 18 LED samples were already faulty, and 2 of the remaining 4 operational LEDs had contact failures.

The radiated power values measured during the test are illustrated in Figure 4.1. In addition to the high failure rate of LEDs, the most important finding is that there is a different aging trend for the three chamber temperatures. From the measurement results, it can be seen that the samples belonging to the lowest chamber temperatures aged the fastest. One possible explanation for this, based on a previous humidity resistance test, was that higher relative humidity may have developed at lower chamber temperatures, which may have accelerated the aging of the LEDs. This may also have caused a different aging pattern; while the other chamber temperatures show a characteristic exponential decrease, the deterioration of light emission is consistently logarithmic at an aging temperature of 55 °C.

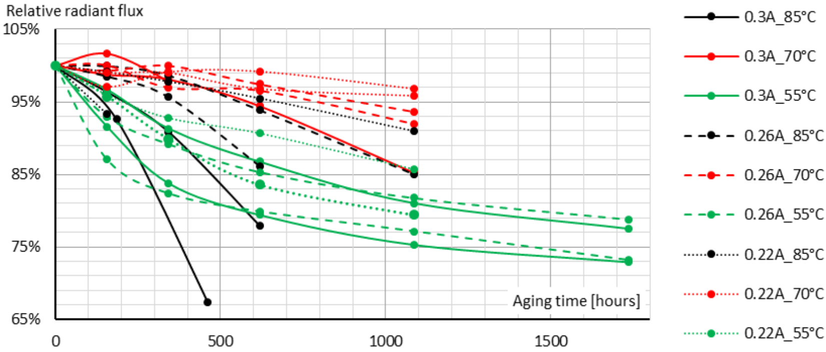


Figure 4.1. Relative values of the radiant flux.

Due to the high failure rate and the nature of the measured results, multi-physical modelling of the pn junction temperature and forward current dependence of the aging was not possible. Next, I modelled the two functional samples and checked the correctness of the models. Both samples belonged to the 55 °C ambient temperature and 300 mA forward current test parameters.

4.3 Lifetime-dependent multi-physical LED model: Version 1

The formula-like relationships describing the physical processes causing the aging of the samples are not yet known, so in order to produce the model that best fits the measurement results, I tried different functions according to the elapsed time during the global parameter fitting procedure. To do this in an automated way, in MS Excel environment, I created a calculator using Visual Basic macros, which calculated the deviation from the measurement results with model parameters corresponding to the assumed time functions.

The saturation current, ideality factor and series resistance values obtained from the automated parameter matching show a significant dependence on the operating time. Using the finished model, I ran a series of simulations, the results of which I compared with the real measurement data. Based on this, the simulation error is 0.5% on average and the largest deviation from the measurements is 1.2%. This level of accuracy of the model is due to the quadratic and logarithmic approximations of the saturation current and the ideality factor, which allow the model to fit well with the measurement results of both the initial burn-in phase and the subsequent operating time.

However, further simulations at higher time resolutions revealed that the model becomes completely inconsistent between 1 and 100 h of operating times. This is also due to the time functions of the Shockley diode equation parameters: the increase in saturation current and ideality factor shifts the simulation results in the opposite direction, and the initial sudden rise of the logarithmically modelled ideality factor is not compensated by the flat initial slope of saturation current, so an unwanted negative highlighting appears in the final results. Therefore the model can only be applied in a consistent manner after the first 100 hours of operation.

4.4 Lifetime-dependent multi-physical LED model: Version 2

For the remaining two LED samples, I continued the LM-80-based test, while reviewing the time functions of the parameters of the multi-physical model used previously. After an extensive "trial and error" type of investigation, I decided to sensitize only those parameters of the model to the operating time that move the simulation results in the same direction, and the other parameters – in the first approximation – I considered to be constant. The biggest simulation error was found in the initial burn-in phase in each case, so I finally omitted the initial phase from the model fitting process, which significantly simplified the multi-physical model.

After leaving the initial burn-in phase, the voltage shift can be modelled using a simple series resistance that increases linearly with time, while keeping the parameters used in the Shockley diode equation (saturation current and ideality factor) constant. This also means that the value of the voltage generator supplying the optical model (which is equal to the voltage at the internal pn junction) does not depend on the operating time, i.e. in this way the electrical and optical aging of the LED can be modelled completely separately. The time function of the decrease in light emission determined in the sense of LM-80 can be directly applied to the saturation current of the diode of the optical branch, while its ideality factor and series resistance remain constant.

At 4340 hours of the LM-80 based test of the Seoul 2525 LEDs, I re-characterized the S07 and S11 samples earlier returned to the test with the help of the department's LED test station. The radiant flux and forward voltage results obtained during the control measurement and simulated using the models described in the previous section are shown in Figures 4.2. and 4.3.

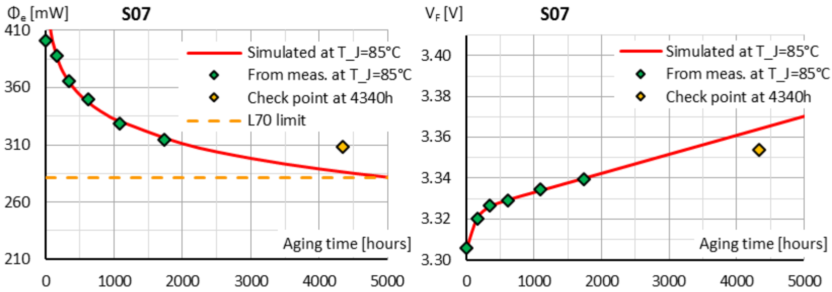


Figure 4.2. Comparison of measured and simulated radiant flux and forward voltage values of sample S07.

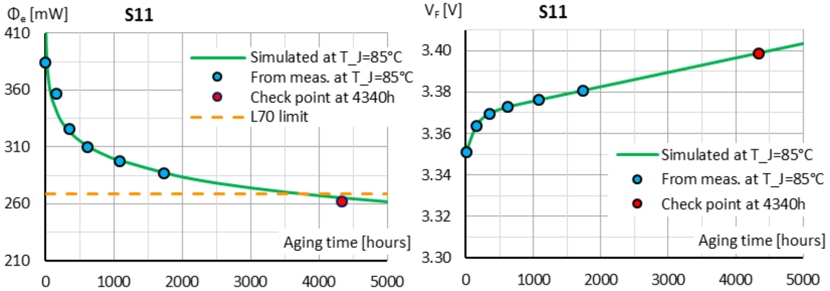


Figure 4.3. Comparison of the measured and simulated radiant flux and forward voltage values of sample S11.

Thesis IV.

The chip-level multi-physical LED model according to Thesis III. was further developed for two LED types in such a way that it appropriately describes the operating pn junction temperature, forward voltage and radiant flux values after the initial burn-in period as a function of the elapsed operating time.

Related publications: [J1], [J2], [J4], [C13], [C14]

5 Summary

The main purpose of my research work was the development of an “Industry 4.0” based design solution which can be used to determine a controlling scheme that eliminates the effects of both the temperature changes and that of the elapsed operating time, i.e. the total luminous flux of the luminaire can be kept constant throughout its lifetime. This reduces the electrical consumption and also increases the expected product lifetime. Last but not least, the visual comfort provided by the luminaire is improved, as its luminous flux does not have to be overdesigned by 10-30% in order to pre-compensate for the subsequent luminous flux decrease.

To compensate for the effects of temperature changes I have developed a new method based on the available multi-physical LED model and the related system-level simulation theory. I have created the circuit simulation model of a real street-lighting luminaire. With both field and laboratory measurements I verified the new method of keeping the luminous flux at a constant level in the short term, with the help of the largest and one intermediate specimen of the luminaire family. Virtually integrating the compact thermal model of the luminaire with the model of another power LED type aged in our department, I performed preliminary, system level studies to estimate the effects of LED aging.

In order to model the luminous flux reduction over the lifetime of LEDs first I used the LM-80 and TM21-11 methods base test results as these two documents describe the most commonly applied lifetime test and extrapolation methods worldwide applied. I examined the modelling possibilities in detail, based on which I developed a method to implement a lifetime lasting constant luminous flux operation mode, which can be implemented by the luminaire manufacturers with minor negligence even on the basis of data sheet values received from LED manufacturers. The additional circuits required for this are minimal and can be found in almost any “smart” called luminaire. The method I propose compensates for both the effects of temperature and the aging of the LEDs. However, during my work I did not deal with changes in the LED driver and optical components of the luminaire.

By reworking the existing multi-physical LED model, I created a new model that can be implemented in SPICE-based circuit simulation environments that do not directly support the performance of electro-thermal simulations. I created an automated application to generate the parameter sets of the reworked LED model, which I also used in the Delpi4LED project for the mass production of the parameter sets.

To produce an LED model that also allows system-level lifetime simulations, I continued the previous LM-80-based LED aging test. As the results of these did not allow the suitable generation of the model, I launched a new series of tests, based on which I created two elapsed lifetime dependent multi-physical LED models. These, together with the experience gained during my work, provide a good basis for modelling the lifespan of additional LED types too.

Publications – Journal papers

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