LED degradation
From component to system

Hamon, B.; van Driel, W.D.

DOI
10.1016/j.microrel.2016.07.014

Publication date
2016

Document Version
Accepted author manuscript

Published in
Microelectronics Reliability

Citation (APA)
Hamon, B., & van Driel, W. D. (2016). LED degradation: From component to system. *Microelectronics Reliability*, *64*, 599-604. https://doi.org/10.1016/j.microrel.2016.07.014

LED Degradation: From Component to System

B. Hamon[a], W.D. van Driel[b, c]

[a] *3 Philips Lighting, Miribel, France*
[b] *Philips Lighting, High Tech Campus, Eindhoven, The Netherlands*
[c] *Delft University of Technology, Delft, The Netherlands*

Abstract: Human civilization revolves around artificial light. Since its earliest incarnation as firelight to its most recent as electric light, artificial light is at the core of our existence. It has freed us from the temporal and spatial constraints of daylight by allowing us to function equally well night and day, indoors and outdoors. It evolved from open fire, candles, carbon arc lamp, incandescent lamp, fluorescent lamp to what is now on our door step: solid state lighting (SSL). SSL refers to a type of lighting that uses semiconductor light-emitting diodes (LEDs), organic or polymer light-emitting diodes (OLED / PLED) as sources of illumination rather than electrical filaments, plasma (used in arc lamps such as fluorescent lamps), or gas. SSL applications are now at the doorstep of massive market entry into our offices and homes. This penetration is mainly due to the promise of an increased reliability with an energy saving opportunity: a low cost reliable solution. An SSL system is composed of a LED engine with a micro-electronics driver(s), integrated in a housing that also provides the optical, sensing and other functions. Knowledge of (system) reliability is crucial for not only the business success of the future SSL applications, but also solving many associated scientific challenges. In practice, a malfunction of the system might be induced by the failure and/or degradation of the subsystems/interfaces. This paper will address the items to ensure high reliability of SSL systems by describing LED degradation from a component and a system perspective.

Keywords: Solid state lighting, reliability, degradation, LED systems

Corresponding author.
Willem.van.driel@philips.com
Tel: +31 (0) 6 50 123153

1. INTRODUCTION

Human civilization revolves around artificial light. Since its earliest incarnation as firelight to its most recent as electric light, artificial light is at the core of our existence. It has freed us from the temporal and spatial constraints of daylight by allowing us to function equally well night and day, indoors and outdoors. It evolved from open fire, candles, carbon arc lamp, incandescent lamp, fluorescent lamp to what is now on our door step: solid state lighting (SSL). SSL refers to a type of lighting that uses semiconductor light-emitting diodes (LEDs), organic or polymer light-emitting diodes (OLED / PLED) as sources of illumination rather than electrical filaments, plasma (used in arc lamps such as fluorescent lamps), or gas. As such, SSL is recognized as the second revolution in the history of lighting [1]. SSL applications are now at the doorstep of massive market entry into our offices and homes. This penetration is mainly due to the promise of an increased reliability with an energy saving opportunity: a low cost reliable solution. The SSL industry is expected to exceed €80 billion by 2020, which will in turn create new employment opportunities and revenues. A second reason is the promise of a long useful lifetime, with claims up to 80,000 hours [1]. Lifetime here refers to the period of time during which something is functional and is a derivate from the reliability performance of the product [2, 3]. Knowledge of reliability is crucial for the business success of SSL and we aim to achieve the same kind of knowledge as available in semiconductors [4]. In principle, all components (LEDs, optics, drive electronics, controls, and thermal design) as well as the integrated system must live equally long and be highly efficient in order to fully utilize the product lifetime, compete with conventional light sources and save energy. The link between LED reliability from a component [5, 6] and system objective is obvious: the higher the reliability of the components, the higher the system lifetime expectance.

It is currently not possible to qualify the SSL lifetime (10 years and beyond) before these products are available in the commercial market [7, 8, 9]. This is a rather new challenge since typical consumer electronics devices are expected to function for only 2-3 years. Predicting the reliability of traditional electronics devices is already very challenging due to their multi-disciplinary issues, as well as their strong dependence on materials, design, manufacturing and application. This will be even more challenging for SSL systems since they are comprised of several levels and length scales with different failure modes in each level. The tendency towards system integration, via advanced luminaries, System-in-Package approaches, and even heterogeneous chip on chip integrations poses an additional challenge on SSL reliability.

To add to the complexity, a functional SSL system comprise of different functional subsystems working in closed collaboration. These subsystems included the optics, drive electronics, controls and thermal design. Hence, there is also a need to address the interaction between the different subsystems [10, 11. Furthermore, an added challenge for system reliability is that accelerated testing condition for one subsystem is often too harsh for another subsystem [12]. Alternatively, even the highest acceleration rate possible for one subsystem may be too low to be on any use for yet another subsystem. New techniques and methodologies are needed to accurately predict the system level reliability of SSL systems. This would require advanced reliability testing methods since todays available standards are mainly providing the probability at which LEDs may fail within a certain amount of time. This paper will address the items to ensure high reliability of SSL systems by describing LED degradation from a component and a system perspective.

2. SSL RELIABILITY

New technologies, processes and materials will always introduce a series of new and unknown failure modes. In this particular case, the ones that are known from semiconductors are directly imported into the lighting products. Semiconductor failure modes are well described [4], but their relation to the quality and reliability of light is not known. LED-based products performance strongly relies to its lumen depreciation in which the light source gradually but slowly degrades over time. Experiences with these new modes need to be built using both life time tests and accelerated tests like HALT, MEOST and other techniques [13]. And need to be combined with a theoretical approach in order to describe product performance in application.

The lighting industry does not have the installed reliability testing base that is needed to cover the promised lifetimes. Even more, there are no test standards available with appropriate pass/fail criteria for the (key) components and/or SSL products [1]. Relationships with material and component suppliers need to be tightened, as is the case in the automotive industry [14], in order to share the responsibility for the product quality and reliability. In other words: a huge mind-set change is needed in reliability to make the market introduction of SSL application a big success.

Figure 1 gives an overview of the possible failure modes on different sub-levels in an SSL product, including LEDs and their optics [15 - 18].

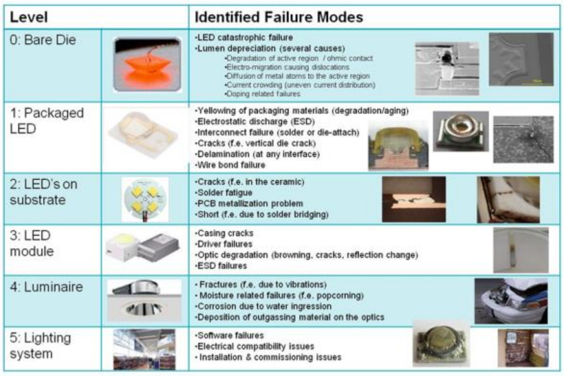

Figure 1: Solid state lighting failure modes [1].

In this paper we cover two main challenges that are needed to cover SSL Reliability:

1. Component Reliability

Component reliability refers to the performance over time of the individual key-components in a system. Each system can just last as long as it's lowest life component. Key-components in a SSL system are the LED package, the optics, drive electronics, controls, thermal design, connectors, sealants and other plastics. Currently, only the IES standards [19 - 21] are available to address the performance of the LED package components.

2. System Reliability

System reliability refers to the probability that a system, including all hardware, firmware, and software, will satisfactorily perform the task for which it was designed or intended, for a specified time and in a specified environment. Reliability modelling refers to the process of predicting or understanding the failure modes of a component or system prior to its implementation by using multi-physic techniques. Reliability prediction refers to forecasting the reliability performance of a component or system by using statistical techniques.

3. LED RELIABILITY

One of the main challenges in the study of LED reliability is the fact that a single failure mode is governed by multiple failure mechanisms [22]. For instance, the depreciation of the luminous flux, which is used as the main failure criterion [1], is affected by the degradations of the different part of the LED (chip, phosphor, and lens). The LED by itself can be described as a system. This system is composed of different sub-parts (die, electrical connections, package, phosphor, optical package). The degradation of each subpart as well as their interaction will impact the overall reliability of the LED. It is then challenging to discriminate the individual contributions of each sub-part degradation.

Considering the LED as a global component and its reliability as the general combination of the different sub-part degradation allows to make lifetime prediction for luminaire manufacturers. From an LED manufacturer point of view, having access to the individual contributions is a key point for improving the reliability of the LED package. In fact, such knowledge will allow to highlight the weak part of the component and focus R&D efforts on this part to increase the component reliability. Different methods can be considered to evaluate individual contributions of the different LED subparts.

Separate aging of the subparts such as silicone aging or phosphor aging can bring information regarding the different aging rates. However, separate aging might lead to optimistic results as it does not take into consideration the interaction between the different subparts (e.g. the degradation of plastic packages by the blue light of the LED die).

From an LED manufacturer point of view, the reliability improvement of a component can also be achieved using a comparative approach. In this approach, changes of LED subparts are gradually made (e.g. lens silicone change) and results of reliability tests compared to the original component. This approach allows to improve component reliability from one generation to another but require shorter reliability tests. In fact, duration of reliability tests such as HTOL are not compliant with development cycles. In addition, this approach can also lead to high efforts in cases where the subpart of the LED limiting the reliability is not clearly identified.

In our study, the evaluation component is a high power LED composed of:

- A 1mm² die based on Thin Film Flip Chip technology (flip-chipped on a ceramic substrate using gold-gold interconnect)
- Phosphor layer (over moulded on top of the die)
- Silicone lens

In the following parts, we will consider the die, interconnections and ceramic substrate as the chip and the phosphor layer and lens as the component's optical package. Samples have been aged using HTOL test in the conditions listed in Table 1. For each condition at least 16 samples are used.

Table 1: Aging conditions.

Aging current (mA)	**Aging ambient temperature (°C)**	**Aging duration (hours)**
700	120	6000
700	80	8000
700	100	4000
1000	100	4000

The objective of the following test is to differentiate the degradation of the chip from the one on the optical package in order to better target the reliability limiting part of the component. The proposed approach consist in a first place of evaluating the degradation of the aged components considering the global contribution of the different subparts. In a second step, the degradation of the chip itself is evaluated using the proposed approach. Finally based on the degradation of both component and chip, the degradation of the optical package is deducted.

Component degradation is obtained by comparing the optical power of the aged devices before and after aging. The choice of optical power depreciation over flux depreciation has been made to reduce the impact of the optical spectrum degradation on the resulting flux. The relative loss of optical power is defined as δ_{device}.

In order to evaluate the chip degradation, the optical package of the component as to be removed. The choice has been made to chemically remove the optical package in order to not imply mechanical stress during this process.

The optical power from the blue chip is then measured after aging and optical package removal. As this method is destructive, the initial optical power from the chip (blue light) cannot be directly measured on the aged samples. In order to evaluate this value, pristine samples have been used to correlate the optical power of the component with the optical power of the component without its optical package. Results of this correlation are presented in Figure 2.

Based on Figure 2, it is possible to assess the initial optical power without optical package before aging. This information allows to evaluate the contribution of the chip degradation (δ_{chip}).

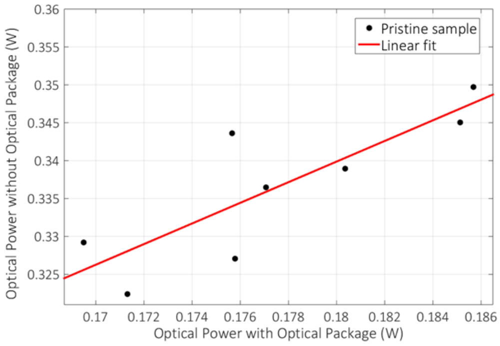

Figure 2: Correlation for the optical power of the component with the optical power of the component without its optical package.

Finally using δ_{device} and δ_{chip}, it is possible to calculate the contribution of the optical package degradation. In fact, it can be considered that δ_{device} results from the contribution of δ_{chip} and $\delta_{optical}$-package. Calculation of δ_{device}, δ_{chip} and $\delta_{optical}$-package has been processed following the approach described above. Results are consistent from one sample to another when aged in similar conditions. As a result, Figure 3 displays the average values of δ_{device}, δ_{chip} and $\delta_{optical}$-package obtained at the end of the aging tests.

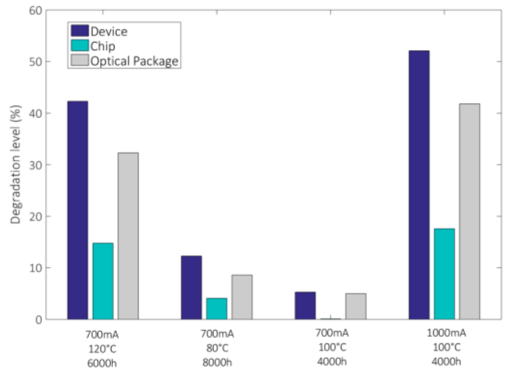

Figure 3 Degradation level (δ) for device / chip / optical package obtained for the different test conditions.

From Figure 3, it can be observed that for all aging conditions the degradation of the component is mainly governed by the degradation of the optical package. This means that in order to improve the reliability of this family of LEDs, focus has to be put on the improvement of the optical package reliability. To go further and in order to discriminate degradation from lens and phosphor layer, the proposed approach has been applied to two similar set of components aged in similar conditions but from different colour correlated temperature (CCT): one set of warm white LEDs and one set of neutral white LEDs. Results are displayed In Figure 4.

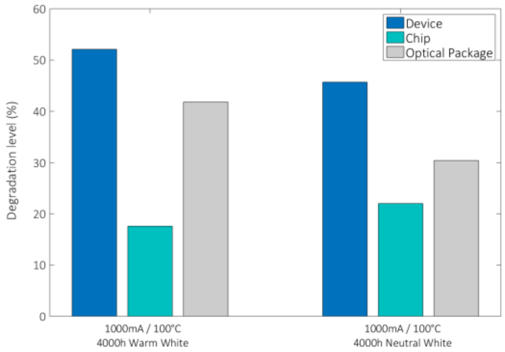

Figure 4: Degradation level (δ) for device / chip / optical package for warm white and neutral white LEDs aged in similar conditions.

As it can be seen from Figure 4, the degradation rate of the optical package is lower for the neutral white LEDs. As the lens is identical between warm and neutral white, the hypothesis that the phosphor layer is the limiting subpart of this architecture of LEDs from a reliability point of view can be made. As a consequence, for this component, reliability improvement should focus on improving the phosphor reliability.

Using this methodology, the different component of degradation δ_{Device}, δ_{Chip} and $\delta_{OpticalPackage}$ have been evaluated. The limitation of this methodology is that due to the optical package removal step, the results only provide "a photography" of the three degradations. In fact, the method is destructive and the sample cannot be aged anymore. As a consequence, in a future work, to follow the evolution of the three degradations, a large number of samples have to be aged and studied at different aging times.

Using this approach, the limiting subpart from a reliability point of view has been identified for this given LED architecture. It would be of interest in coming studies to apply this approach to other LED architectures in order to identify if the phosphor layer is always the limiting subpart of LED components.

4. SYSTEM RELIABILITY

One of our challenges is to master the reliability of different systems and their components, ranging from lighting in offices, around living houses to streetlight and total cities that needs to be lighted [1]. To add to the complexity, a functional SSL system comprise of different functional subsystems working in closed collaboration. These subsystems include the optics, drive electronics, controls and thermal design. Hence, there is also a need to address the interaction between the different subsystems. On top of that, manufacturing and processing may influence the eventual lifetime of the product. Figure 5 indicates how these items may interact.

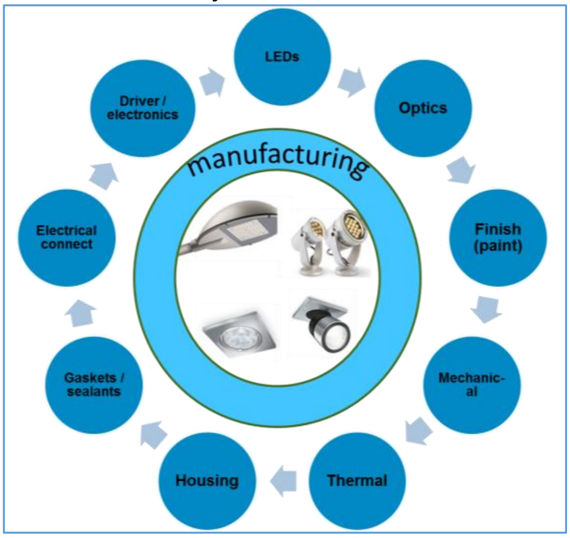

Figure 5: Lighting applications are full of interacting sub-systems, influenced by manufacturing.

On system level, there are two relevant 'over time' performance values to be considered: gradual and abrupt light output degradation, see Figure 6. Gradual light output degradation relates to the lumen maintenance of a luminaire over time. It tells you how much of the initial lumen output of the luminaire is maintained after a certain period of time. The lumen depreciation can be a combination of degradation of optical elements used, individual LEDs giving less light and individual LEDs giving no light at all. Abrupt light output degradation describes the situation where the LED based luminaire no longer gives any light at all because the system, or a critical component therein, has failed.

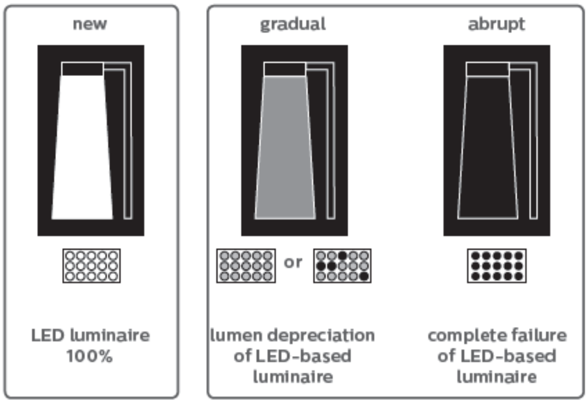

Figure 6: Over time performance of a LED-based system.

Gradual light output degradation follows an exponential decaying function [21]

$$\Theta(t) = \exp(-\alpha t^{\beta}) \quad (1)$$

where:

- t is time in hours;
- $\Theta(t)$ is the normalized luminous flux output at time t;
- α is the decay rate constant derived by a least squares curve-fit;
- β is the shape parameter.

This acceleration model for α follows as [23]:

$$\alpha = C \exp\left(\frac{-E_a}{k_B T_s}\right) I^n \quad (2)$$

where:

- C is a pre-exponential factor;
- E_a is the activation energy (in eV);
- T_s is the in-situ absolute temperature (in K);
- k_B is the Boltzmann's constant (8.617385x10-5 eV/K).
- I is the current;
- n is a life-stressor slope.

Using long term LM-80 testing [20] for each individual product a model is fitted to predict L80 values, the time when 80% of the initial lumen output is remaining, and turn degradation values into failure times. One of the most important questions arising from a degradation experiment is how many hours an accelerated degradation experiment should last for gathering proper data to allow one to make inference about the product lifetime under the normal use condition. Here, we focus on the convergence of the quantile estimators (such as B10 or B50) to decide whether we are able to make this inference [23]. A Maximum Likelihood (ML) procedure is used to estimate B10 (50) under certain use conditions (T, I). Lognormal and Weibull distributions are both appropriate models to fit the (estimated) lifetime data. Figure 7 demonstrates this method for LM-80 data sets coming from high-power (HP) LEDs and reveals convergence after 11khrs test time. At that point of test time, the acceleration model parameters are fitted to be: C = 8.1; n = 0.38; Ea = 0.10eV; s = 0.33.

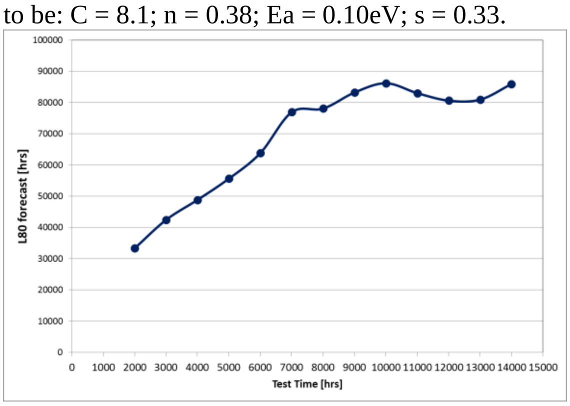

Figure 7: Predicted gradual output degradation as function of test time revealing C = 8.1; n = 0.38; E_a = 0.10eV; s = 0.33.

5. Discussion and conclusions

SSL reliability is a challenging task, mainly due to:

- The large amount of unknown failure modes and mechanisms, and lack of field data.
- The technological gap to physically describe these mechanisms.
- Non-existing optimal acceleration test methods and/or standards.
- The requested high lifetime levels.

With the current pace of SSL industry development, there is an urgent need to address the (long-term) design for reliability of SSL systems. In this paper we have addressed the impact of LED degradation from a component and a system perspective.

ACKNOWLEDGEMENTS

The research leading to this paper received funding from the European Union's Seventh Framework Program (FP7/2007-2013) for DEWI Dependable Embedded Wireless Infrastructure Joint Undertaking under grant agreement 621353 and from specific national programs and/or funding authorities.

REFERENCES

[1] W.D. van Driel, X.J. Fan, Solid State Lighting Reliability: Components to Systems, ISBN 978-1-

4614-3066-7, 31 August 2012, Springer, 617 pages.
[2] James McLinn, A short history of reliability, The Journal of Reliability Information, January 2011, pp 8 – 15.
[3] J.H. Saleh, K. Marais, Highlights from the early (and pre-) history of reliability engineering, Reliability Engineering and System Safety 91 (2006) 249–256.
[4] JEP122F, Failure mechanisms and models for semiconductor devices, JEDEC Solid State Technology Association, November 2010.
[5] M. H. Chang, D. Das, P. V. Varde and M. Pecht, Light-emitting Diodes Reliability Review, Microelectronics Reliability, vol. 52, no. 5, pp. 762-782, May 2012.
[6] M. Meneghini, A. Tazzoli, G. Mura, G. Meneghesso, and E. Zanoni, A Review on the Physical Mechanisms That Limit the Reliability of GaN-Based LEDs, IEEE Trans. Electron Devices, vol. 57, no. 1, pp. 108-118, Jan. 2010.
[7] N. Narendran, J. D. Bullough, N. Maliyagoda, and A. Bierman, "What is Useful Life for White Light LEDs?," Journal of the Illumination Engineering Society, vol. 30, no. 1, pp. 57-68, Jan. 2001.
[8] N. Narendran and Y. Gu, "Life of LED-Based White Light Sources," IEEE/OSA Journal of Display Technology, vol. 1, no. 1, pp. 167-171, Sept. 2005.
[9] N. Narendran, Y. Gu, L. Jayasinghe, J. P. Freyssinier, and Y. Zhu, "Long-term Performance of White LEDs and Systems," in Proceedings of First International Conference on White LEDs and Solid-state Lighting, Tokyo, Japan, Nov. 2-30, 2007, pp.174-179.
[10] P. S. Almeida, D. Camponogara, M. D. Costa, H. Braga, and J. M. Alonso, "Matching LED and Driver Life Spans: A Review of Different Techniques," IEEE Ind. Electron. Mag., vol. 9, no. 2, pp. 36-47, June 2015.
[11] S. Tarashioon, W.D. van Driel, G.Q. Zhang, Multi-physics reliability simulation for solid state lighting drivers, Microelectronics Reliability Volume 54, Issues 6–7, June–July 2014, Pages 1212–1222.
[12] W. B. Nelson, Accelerated Testing: Statistical Models, Test Plans, and Data Analysis (Wiley Series in Probability and Statistics), ISBN 0-471-52277-5, 1990.
[13] P. Lall and H. Zhang, "Assessment of Lumen Degradation and Remaining Life of Light-Emitting Diodes," J. Electron. Packag., vol. 137, no. 6, pp. 021002-10, June 2015.
[14] F. Franceschini, D. Maisano, Standardization of quality and reliability tests in the auto-parts industry: a structured approach concerning thermal systems, Total Quality Management and Business Excellence 26(11):1-13, December 2014.
[15] M. Meneghini, M. Dal Lago, N. Trivellin, G. Meneghesso, E. Zanoni, Thermally Activated Degradation of Remote Phosphors for Application in LED Lighting, IEEE transaction on device and materials reliability,vol.13, march 2013
[16] M. Yazdan Mehr, W.D. van Driel, K.M.B Jansen, P. Deeben, G.Q. Zhang, Lifetime Assessment of Plastics Lenses used in LED-based Products. Journal Microelectronics Reliability 2013.
[17] M. Yazdan Mehr, W.D. van Driel, G.Q. Zhang, Accelerated life time testing and optical degradation of remote phosphor plates, Microelectronics Reliability, Volume 54, Issue 8, August 2014, Pages 1544-1548.
[18] M. Yazdan Mehr, W.D. van Driel, K.M.B. Jansen, P. Deeben, M. Boutelje, G.Q. Zhang, Photodegradation of bisphenol A polycarbonate under blue light radiation and its effect on optical properties, Optical Materials, Volume 35, Issue 3, January 2013, Pages 504-508
[19] IES LM-79-08: Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products.
[20] IES LM-80-08: Approved method for measuring maintenance of Led light sources.
[21] IES TM-21-11: Projecting Long Term Lumen Maintenance of LED Light Sources.
[22] B. Hamon, LED Reliability: Mechanisms and Modelling, PhD Thesis, France 2014.
[23] W.D. van Driel, M. Schuld, B. Jacobs, F. Commissaris, J. van der Eyden, B. Hamon, Lumen maintenance predictions for LED packages, Microelectronics Reliability (2016), http://dx.doi.org/10.1016/j.microrel.2016.03.018.