Reliability and Failures in Solid State Lighting Systems

Driel, W. D. van; Jacobs, B. J. C.; Onushkin, G.; Watte, P.; Zhao, X.; Davis, J. Lynn

DOI
10.1007/978-3-030-81576-9_7

Publication date
2022

Document Version
Final published version

Published in
Reliability of Organic Compounds in Microelectronics and Optoelectronics

Chapter 7
Reliability and Failures in Solid State Lighting Systems

W. D. van Driel, B. J. C. Jacobs, G. Onushkin, P. Watte, X. Zhao, and J. Lynn Davis

1 Introduction

The penetration of LED-based products has significantly increased in the past years [1–6]. Here, an LED-based product is an apparatus that distributes, filters, or transforms light transmitted from one or more LED light sources. It can be seen as a system that includes all the parts necessary to support, fix, and protect light sources and (where necessary) circuit auxiliaries, along with the means to connect them to the supply but not the light sources themselves. The global LED lighting market grew by 3.2% from 2018 to almost 60BEuro in 2019 [1]. It is expected that the market will grow at a compound annual growth rate (CAGR) of 2.8% largely based on the expected growth in healthcare and industrial applications [1]. Several reports in the past years [4–6] predict that, compared to conventional incandescent, halogen, fluorescent, and high-intensity-discharge white-light sources, the rate of LED market penetration will increase steadily, rising to 75–85% percent by 2030 (see Fig. 7.1). This prediction year-on-year is adapted with the latest prediction values rather 75% [6] than 85% [4], see Fig. 7.1.

Figure 7.2 depicts the total LED lighting market by the percentage revenue for these applications in 2019. Application-wise, lighting for health and wellbeing will drive the market for LED lighting in the coming period. Healthcare, industrial, and

W. D. van Driel (✉)
Signify, HTC7, Eindhoven, The Netherlands

Delft University of Technology, Delft, The Netherlands
e-mail: willem.van.driel@signify.com

B. J. C. Jacobs · G. Onushkin · P. Watte · X. Zhao
Signify, HTC7, Eindhoven, The Netherlands

J. L. Davis
RTI International, Research Triangle Park, Durham, NC, USA

W. D. van Driel, M. Yazdan Mehr (eds.), *Reliability of Organic Compounds in Microelectronics and Optoelectronics*,
https://doi.org/10.1007/978-3-030-81576-9_7

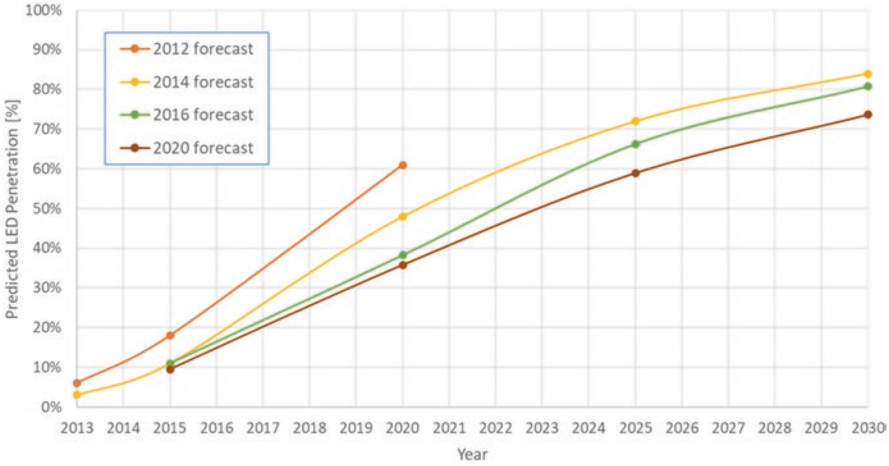

Fig. 7.1 Predicted LED penetration levels as a function of year (taken from [4–6]; with permission)

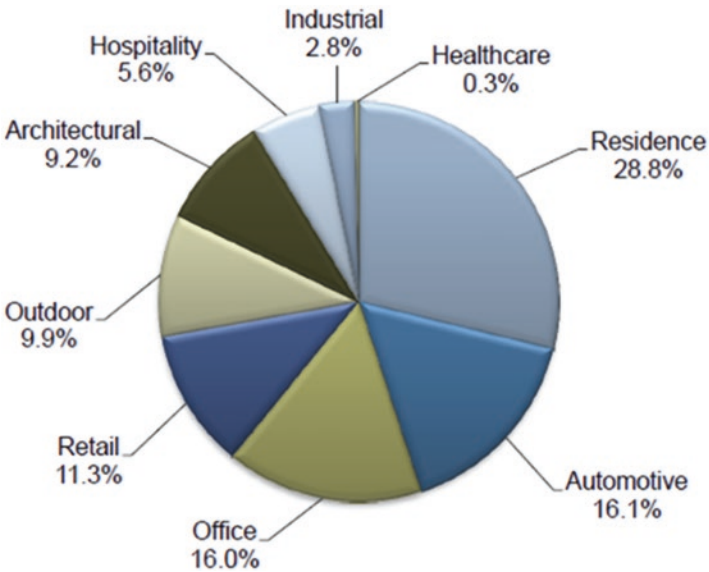

Fig. 7.2 Total LED Lighting Market: Percent Revenue by Applications, Global, 2019 (taken from [1]; with permission)

office segments will be the major adopters of such lighting in the future. Architectural lighting solutions or products are used in all applications, including outdoor lighting for city beautification and urban lighting displays. Smart cities have the capability to transform daily life and IoT plays a key role in the development of smart cities.

Major global economies and developing economies have invested heavily in smart city development. Accompanied with the LED penetration, the lighting industry also experiences an exponential increasing impact of digitization and connectivity of its lighting systems [1, 7]. The impact of this digitization is far beyond the impact on single products and extends to an ever-larger amount of connected systems. Continuously, more intelligent interfacing with the technical environment and with different kinds of users is being built-in by using more and different kinds of sensors, (wireless) communication, and different kinds of interacting or interfacing devices.

New business models, like Light as a Service (LaaS) and/or Pay-per-Lux (PPL), are widely adopted that repurpose LED lights and make them re-usable. LaaS and PPL provide a cost-effective lighting solution for LED applications by shifting from an “asset ownership” model to an “as a service” model. These systems save upfront costs associated with installing energy-saving lighting. By planning for longevity rather than a “fit and forget” approach, it provides the most efficient and cheapest lighting possible – which encourages the uptake of energy-saving lighting. At the end of the contract, products can be returned to the production process again, reusing the raw materials, optimizing recycling, and reducing waste. As such, it maximizes the asset value for service providers and reduces the initial investment and risk of ownership for customers [8, 9, 10]. Smart LED-based products have rapidly entered the building market and widespread commercial and residential LED adoption will be centered on smart LEDs. Ease of use, aesthetic value, and affordable cost are enablers for the quick adoption of smart LEDs. IoT-enabled LED lighting will continue to drive the growth of connected buildings and related services.

The use of information from above-mentioned connected sources can be described as a revolution named big data. With big data, data analytics from live connections of “intelligent” systems can be used to determine the system prognostics. Due to these changes in technology, the next generation of product data will be much richer in information [11]. From a reliability perspective, it all means that the service life of LED-based products will simply increase and 10–15 years will be normal. In that extensive time frame, one should be able to understand which possible failure modes can occur or can be triggered. With the continuous introduction of new processes and new materials this is not without challenges as these will introduce a new series of new and unknown failure modes in connected LED-based products. In this chapter, we will describe our current understanding of the reliability and known failure modes in these products.

2 Customer View: Catastrophic vs Degradation Failures

Failure modes in LEDs are well described in the literature. Pecht and Chang discuss thirteen different types of failure mechanisms of LEDs based on previously published papers and opinions of experts in the LED industry [12, 13]. These failure modes are dislocations, die cracking, dopant diffusion, electromigration, overstress, electro-static discharge (ESD), carbonization, delamination, yellowing, cracking, thermal quenching, and solder joint failure. Extensive work on the LED epitaxial degradation level was done by the group of Prof Zanoni, from the Electronics University of Padova [14, 15]. Their work concentrates on light output degradation due to nonradiative recombination at epitaxial defects and shifted electrical parameters due to increased reverse leakage currents. According to their findings, the lifetime and performance of LEDs are limited by crystal defect formations in the epitaxial layer structure. Crystal defects are mainly generated in contacts and in the active regions and result in a reduction in the lifetime of non-equilibrium electron-hole pairs and an increase in multi-phonon emissions under high drive currents. Multi-phonon emissions result in strong vibration of defect atoms and reduce the energy barrier for defect motions such as migration, creation, or clustering. Another great overview of LED failure modes was given by Caers and Zhao [16]. They distinguish catastrophic and degradation failure modes on all LED product levels ranging from LED package to LED products to LED systems. Unfortunately, a document like JEP122F, Failure mechanisms and models for semiconductor devices [17], does not exist in the Lighting industry.

It is correct to distinguish failure modes having a catastrophic or degradation behavior in LED-based systems. Here catastrophic refers to:

> *a catastrophic failure is a sudden and total failure from which recovery is impossible.*

and degradation refers to:

> *A failure which is gradual or partial; it does not cease all function but compromises that function. It may lower output below a designated point, raise output above a designated point or result in erratic output. A degraded mode might allow only one mode of operation. If left unattended, the degraded mode may result in a catastrophic failure.*

Figure 7.3 illustrates the different failures in a LED-based system. Degradation may not only be reflected by a reduction in light output, it may also change the color output. The general approach in the industry is that degradation due to lumen maintenance is the basis for commercial claims of LED-based products. LED lifetime specifications are based on the time to, e.g., 70% (L70) or 80% (L80) of light output degradation at application temperatures. Here, IES LM-80-08 [18] serves an approved method for measuring lumen maintenance of LED lighting sources. And the IES standard TM-21-11 [19] provides a guideline for lifetime prediction of LED devices. On system level, however, Fig. 7.3 illustrates that the further reason for degradation effects can be either due to differential light output reduction, by catastrophic failures of single LED package, by degradation of the optical materials in the system, and even by many more causes.

IEC62681 [20] clearly state that LED-based systems depend generally on how balanced its principal components are in terms of their reliability. It is not only the LED components that determine product performance, but also other parts (or components) of the LED product play an equally important role. The technical document specifies the accelerated tests for each other parts, e.g., electronics, mechanical parts, that need to be conducted to determine the reliability of the system. Each other part or component may "equally" contribute to the failure as such.

For the case where catastrophic and degradation failure modes are considered simultaneously, system simulation techniques do exist [21]. Pettit and Young [22]

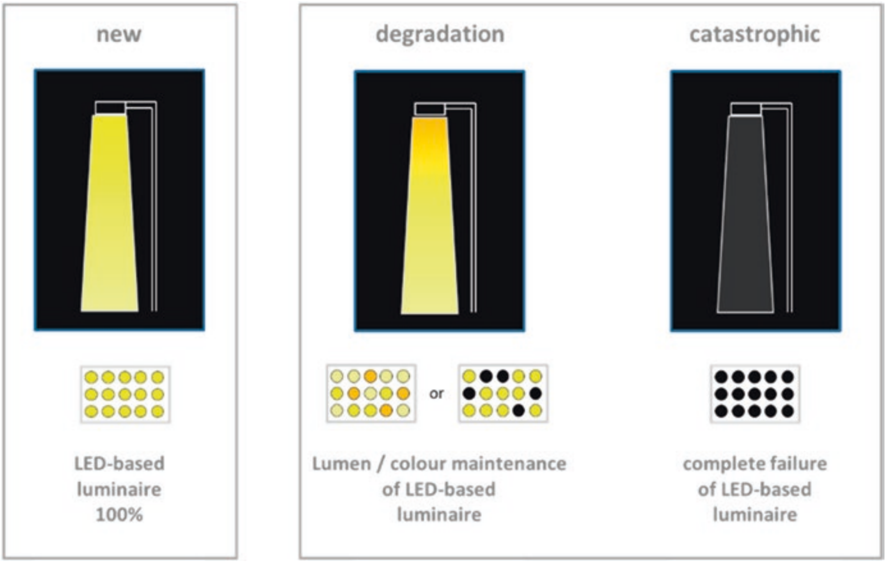

Fig. 7.3 Degradation and catastrophic failures can have unexpected effects on the lighting function

developed Bayesian procedures for simultaneously analyzing the lifetimes of failed units during the test and the degradation measurements of un-failed units observed at the end of the test. This work can be extended to the case of accelerated testing and repeated measures. Schuld et al. presented different system-level techniques to calculate the joint reliability by, e.g., Monte Carlo techniques [23]. Certainly, more work is available on this topic, but this is not our interest in the chapter.

To summarize the above: from an observation point of view, two effects can be noted by the user, being catastrophic of degradation failure, but the further substantiation of this observation can be more complex. Again, Fig. 7.3 illustrates this point.

3 From Observation to Malfunctioning

As mentioned above, the user will either notice a total or a degraded loss of the lighting function. The true root cause of that observation is not so straightforward and is determined by the components in the system. LED-based systems are composed of [20]:

- LED package and interconnects (the lightsource), e.g.
  - High-, mid-, or low-power LEDs
  - Solders, SAC or a-like
  - PCBs like FR4, CEM3, MCPCB

- Optical materials, e.g.
    - Polycarbonate (PC)
    - Polymethylmethacrylaat (PMMA)
    - Silicones
- Electronic subassemblies, e.g.
    - Drivers
    - Controllers
- Cooling systems, e.g.
    - active (e.g., fans)
    - passive (e.g., thermal interface material);
- Construction materials, e.g.:
    - Mechanical parts: connectors (e.g., screws, clips), wires
    - Housing: metal casing, plastic boxes
- Digital solutions, e.g.
    - Software
    - Data storage
    - Sensors
    - Wireless connectivity

Field quality control is a process by which entities review the quality of all factors involved in product installation. Field quality engineers regularly inspect, e.g., on yearly basis, installations toward possible failures and/or malfunction of the product. Products that do not fulfill the specified function anymore are send back to the supplier, in our case this will be the manufacturing site. At the manufacturing site the product in inspected and those components that have failed are registered in a cloud-based database. Figure 7.4 shows the pareto made from this database from an installation of >10 M pieces sold, in a time frame of 5 years, and a failed quantity of 19 k pieces (reflecting 0.2%). Percentage-wise the failures per component are listed as:

- Lightsource 23.4%
- Optical materials 4.3%
- Electronics 34.0%
- Cooling system 0.3%
- Construction materials 34.7%
- Digital solution 3.3%

Most of the failures are either due to the electronics or due to the construction materials. Lightsource malfunction is third in the row, the other 3 components occur significantly less. Field quality engineers also report out the reason for the

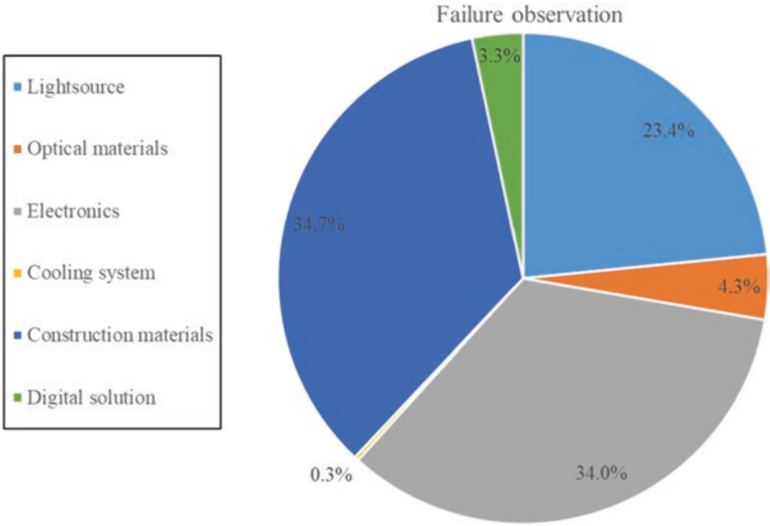

Fig. 7.4 Pareto's of Quality control (QC) is a process by which entities review the quality of all factors involved in production

Table 7.1 Further substantiation of the component malfunctioning

Component	Substantiation of field issue
Lightsource	Bad contact; broken; burnt / overheated; damaged; flickering; inoperative; missing; not controllable / programmable; out of expectation; randomly off; visual defect (aspects); wrong color; wrong light level
Optical materials	Visual defect (aspects); wrong; broke; damaged; loose; missing
Electronics	Bad contact; burnt / overheated; damaged; fallen; flickering; ingress of water/ dust; inoperative; missing; not controllable / programmable; out of expectation; randomly off; wrong light level; wrong programming
Cooling system	Damaged; deformed
Construction materials	Broken; damaged; deformed; ingress of water/dust; missing; bad contact; burnt / overheated; loose; bad mounting; ingress of water/dust; out of expectation; oxidation/corrosion; visual defect (aspects); wrong dimensions; bad machining; fallen
Digital solution	Broken; inoperative; out of specification; missing data; out of expectation

product malfunctioning. Table 7.1 lists further substantiation of the reason for the product malfunctioning. It ranges from missing, to broken, to lose, to fallen, to wrong color. For construction materials, the list is extensive and an item like "wrong dimensions" may also appear as reason. Clearly, the below substantiation does not.

4 From Malfunctioning to Root Cause

Physics-of-failure, also known as reliability physics, is a technique that leverages the knowledge and understanding of the processes and mechanisms that induce failure to predict reliability and improve product performance [24]. The most used definition is:

> *The process of using modeling and simulation based on the fundamentals of physical science (physics, chemistry, material science, mechanics, optical) to predict reliability and prevent failures.*

It helps to understand system performance and reduce decision risk during design and after the equipment is fielded. This approach models the root causes of failure such as fatigue, fracture, wear, and corrosion. An approach able to design and develop reliable products to prevent failures, based on the knowledge of root cause failure mechanisms. The concept is based on the understanding of the relationships between requirements and the physical characteristics of the product and their variation in the manufacturing processes, and the reaction of product elements and materials to loads (stressors) and interaction under loads and their influence on the fitness for use with respect to the use conditions and time.

The application of this concept to solid-state lighting products is founded on the conviction that the failure of LED-based products is governed by optical, mechanical, electrical, thermal, and chemical processes. As such, potential problems in new and existing technologies can be identified and solved even before they occur, by understanding the possible failure mechanisms [24]. For LED-based systems, the concept is used, and results are carved in the so-called Failure Mode Handbook. This handbook consists of summary sheets for each newly discovered failure mode, see Fig. 7.5, detailing out:

- Failure mode description

Short description of the failure mode, what is the observation? Accompanied, if possible, with a picture.

- Root cause/failure mechanism

What is the true cause of the failure mode, which physical mechanism is behind it?

- Solutions

What are possible solutions, how can one prevent the failure modes, what are the design rules to be obeyed?

- Lifetime model/acceleration

Under give testing conditions, what acceleration factors can be reached and what (lifetime) model is applicable.

- Testing method

Date:	index	
Failure mode description	**Root cause / failure mechanism**	**Solutions**
Lifetime model / accelerators	**Testing methods**	**Reference to technical documents and experts**

Fig. 7.5 Summary sheet for failure modes, as part of the failure mode handbook

Date: June 2016	Organic material degradation	
Failure mode description	**Root cause / failure mechanism**	**Solutions**
Optical material discolors to get yellowish color.	• Thermal degradation of encapsulants induced by high junction temperature between LED die and lead frame • Thermal degradation of exit window induced by high temperatures • Photo degradation of encapsulants induced by UV radiation from LED dies and outdoor radiation • UV degradation of plastic materials • Thermal oxidation	• Higher grade lens material • Lower temperature • Apply UV coating • Reduce exposure to UV radiation
Lifetime model / accelerators	**Testing methods**	**Reference to technical documents and experts**
Temperature and UV radiation exposure (with Intensity I) are accelerators.	• HTSL • UV exposure • Refer to QS-000221 Optical Material Reliability Release Procedure	• Web search will reveal significant amount of references. • Work from PhD Maryam Yazdan Mehr • PR-TN 2017/00088 Color maintenance of LED-based products - Towards a system level prediction method • QS-000221 Optical Material Reliability Release Procedure *Experts: Willem van Driel, Boudewijn Jacobs, Guido Crick, William Yao* *External: Eurofins EHV*

Fig. 7.6 Summary sheet for the failure mode organic material degradation

Following IEC62861 [20], *or alike, which (accelerated) test provokes the failure mode?*

- Reference to technical documents and experts

Internal or external document and/or experts are mentioned as touchpoints for further details.

A pre-filled example is shown in Fig. 7.6: organic material degradation. This failure is well described in an open access review paper [25].

Since 2011 the physics-of-failure concept is applied to LED-based products and systems. Both accelerated testing results prior to commercial release and actively monitoring field response (see the former paragraph) have yielded a total number of 88 unique failure modes since then. Figure 7.7 depicts the detection of new failure modes in a 10-year period. On average 10 new failure modes are discovered per year. As it is expected, due to the growing maturity level of solid-state lighting products, this trend will once flatten out, the data is fitted with the Goel-Okumoto maturity growth model. This model is well-known for predicting the reliability of software [26]. Eventually, a total number of approximately 130 unique failure modes is to be discovered.

Further data analysis is feasible as each unique failure modes is well described. Figure 7.8 depicts a pareto of the number of failure modes per product type. Examples are:

- LED package

Browning of LED silicone, Chip moisture corrosion, Dome melting/deforming, LED Vf shift, Silver mirror corrosion, Sticky silicone dome

- LED product

BOM outgassing, Color shift, Driver induced LED failures, Zener burn-out,

- LED system

Battery failure, Software reliability, Surge issues, Water ingress.

Table 7.2 lists the classification toward the component that failed and how it failed, either in a catastrophic manner or if any signs of degradation yielded to its failure. The numbers clarify the following:

- Degradation is a dominant failure mechanism within solid-state lighting products. This by itself is not a surprise as these products are intended for long-term usage.

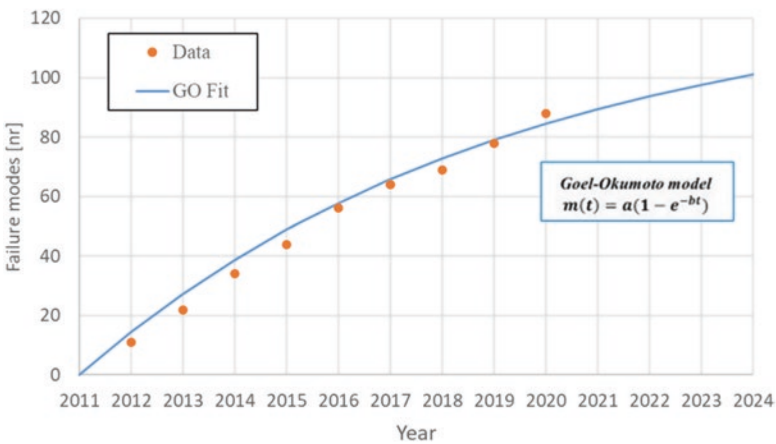

Fig. 7.7 Number of unique failure modes as function of years

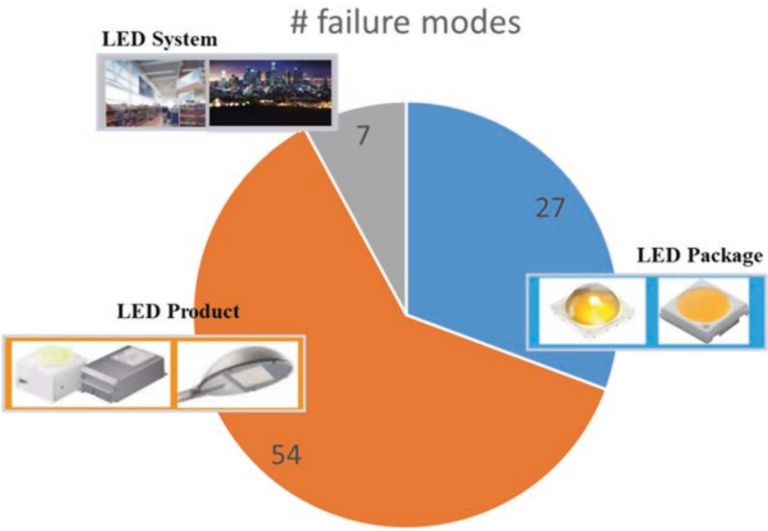

Fig. 7.8 Pareto for the number of failure mode vs product type

Table 7.2 Failure mode classification towards component, catastrophic, and degradation

Component	Catastrophic	Degradation	Total
Lightsource	16	16	32
Optical materials	3	10	13
Electronics	12	11	23
Cooling system	0	2	2
Construction materials	5	10	15
Digital solution	2	1	3
Grand Total	39	49	88

- As seen in the field response, the components that contribute the most to product failure are the lightsource, the electronics, and the mechanical construction.
- Failure modes in digital solutions (sensors, software) remain low and it is expected that this number will grow in the coming years due to the extension of the connected portfolio.
- Failure modes in the cooling system seem rare, which was also concluded from the 5-year field response (see Fig. 7.4).
- In comparison with the 5-year field response data, the optical material degradation surprisingly pops up in our physics-of-failure concept. Degradation is leading for this component with discoloration, yellowing, browning, and corrosion as long-term events to occur.

In summary, whatever is observed by the user, after further substantiation to component level and physics-of-failure root cause may lead to a surprisingly complex failure mechanism. The number of failure modes increases over time, not only due to newly introduced technologies but also because degradation mechanisms start to appear after 5–10 years. Figure 7.9 illustrates the before-mentioned approach. In next paragraphs, several failure modes will be further described.

5 Degradation Failure: Lumen Decay by Absence of Oxygen

In homes, available sockets like the E19 and E27 are to be replaced by an LED alternative. These are named LED Lamps. Per today, the penetration is in the area of 50–80% depending on the region and country and further cost reduction is a must to increase the acceptance of this new technology. LED Lamps development is currently in the process of significant cost reduction in materials, component design, and manufacturing. The use of glass instead of molded plastic is seen as a cost-efficient alternative for lamp housing. Besides that, glass is used in conventional bulbs meaning leverage of the existing manufacturing lines. As such, several major lighting companies did investigate the concepts for glass LED bulbs [27]. The products that are currently available on the market are depicted in Fig. 7.10.

The ongoing cost reduction of LED bulbs led to the re-use of the installed manufacturing base used in conventional lighting. As mentioned above, glass is re-introduced. These bulbs, in general, have a general design which is depicted in Fig. 7.11. They resemble typical convention E27 sockets, but in this case the inner part of the glass bulb consists either of a printed circuit board (PCB) with LEDs

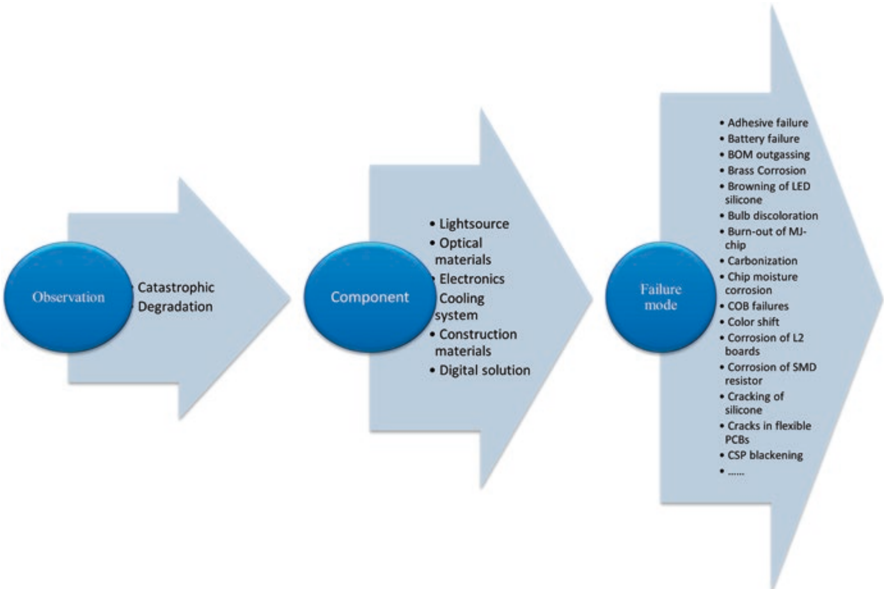

Fig. 7.9 From observation to failure mode

Fig. 7.10 Examples of glass LED bulbs, (**a**) transparent with filaments, (**b**) not transparent with an LED light source on PCB

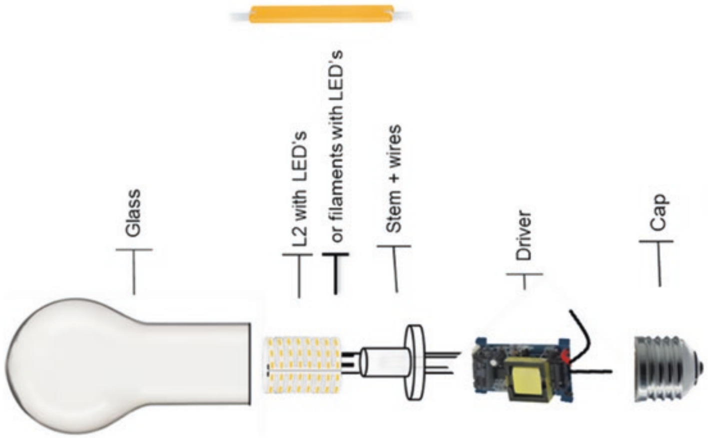

Fig. 7.11 Architecture of glass LED bulbs. Either with L2's or with filaments

mounted on top (l2) or of a filament with LEDs mounted on a substrate and covered with phosphor-embedded silicone. Several concepts are possible for the LED engine consisting of different PCB or substrate types (CEM, metal, glass), different LED technologies (mid-power or low power). The LED engine is mounted on top of a stem, placed into the glass which is sealed at the bottom. As such, the LEDs are placed in an enclosed environment with no direct (chemical) contact with the outer world. Furthermore, glass is highly transparent, cheap, and fire safe.

Glass LED bulbs' performance strongly relies on its lumen depreciation in which the light source gradually but slowly degrades over time. For thermal reasons, the LEDs are placed in an enclosed environment that is filled with helium. This enclosed environment is sealed from outside meaning no natural flow of gasses may occur. A drawback of the design is severe discoloring of the LEDs over life in absence of oxygen. The root cause for this discoloring can be two folded:

- Yellowing/browning: degradation of silicone lenses due to photo-oxidation [28–30]
- Carbonization: discoloration at the epitaxial–silicone interface by (volatile) organic compounds [12, 25]

This problem can be overcome by dosing a mixture of oxygen and helium, typically 10–20% O_2/He. The drawback of this measure is less cooling. As the dosed oxygen is consumed over lamp life, an optimum mixture should be found coping with the trade-off:

Sufficient cooling ↔ sufficient lifetime

Here, the lifetime is reached below lumen maintenance values <70% which may occur once the oxygen is consumed. For determination of the proper trade-off setting, knowledge on both thermal management in O2/He mixtures and oxygen depletion is needed.

The heat transport inside the glass LED bub is a combination of convection in the gas mixture and thermal radiation between the surfaces. The convective transport is depending on the gas mixture composition, while the radiation transport depends on the surface emission coefficient. The gas mixture is not taking part in the radiation transport. The heat transport is analyzed with a CFD simulation model (ANSYS CFX) of the bulb geometry. In this model, the gas mixture is described as an ideal mixture with temperature-dependent properties. The thermal resistance from "heat spreader" (substrate or PCB) to ambient, $Rth_{hs\text{-}amb}$, is calculated with the model. It is based on the average surface temperature of the engine. The goal of the simulations is to investigate the impact of various gas mixture compositions on the $Rth_{hs\text{-}amb}$ value within the same geometry.

Lifetime tests involve lamps put on traditional burning racks, see Fig. 7.12. In these tests, bulbs are operated in a well-controlled environment with constant ambient temperature at 25C, 35C, and 45C, respectively. Accelerated tests included dedicated degradation experiments under flushed N_2 or He environment, without any presence of oxygen. During the O_2 lifetime test, the gas mixture composition is measured at several moments. The results of these tests showed that during lifetime:

- the pressure in the glass LED bulb is decreasing
- the amount of O_2 is decreasing, while CO_2 is increasing
- the amount of He (mol/m^3) is almost constant.

The consumption of O_2 appeared to be a rather complicated process as there are many different hydrocarbons, from several sources inside the lamp located at positions with different temperatures. Here, a scientific description of the physical-chemical processes will not be discussed rather we present degradation models that describe the O_2 depletion in terms of design and application parameters. For the gas analysis, at least one glass LED bulb is measured to obtain the initial oxygen

Fig. 7.12 Lifetime tests with glass LED bulbs put into traditional burning racks

concentration level before the lifetime test is started. The tested bulbs are taken out for gas analysis at different test times. Since the gas analysis is a destructive analysis, all gas analysis results are from different bulbs. The gas measurements were performed on a mass spectrometer. Before the measurement, the lamp is brought in a stainless (pre-cleaned) cracker and purged with ultra-pure argon for at least 1 hour with a purge flow of several litters/minute. After the initial purge time, the cracker has been connected to the mass spectrometer and the composition of the argon filling gas has been analyzed. After another 30 min purge time, the lamp has been broken in the Argon environment. The composition of the gas is calculated by using the calibration factors of the Mass Spectrometer. Results are calculated without the Argon content and normalized to 100%. During the lifetime test, as mentioned before, with the decreasing O_2 and the increasing CO_2, the gas pressure inside the lamps decreases while the volume of He increases, see Fig. 7.13. To make the calculation of the $_{O2}$ concentration after burning consistent with the initial situation before the test, the "absolute" O_2 concentration is calculated by correcting for He following this relationship (in volume %):

$$O_{2\_abs} / O_{2\_measured} = He_{initial} / He_{measured} \tag{7.1}$$

The first step in our analysis is to correlate the failure criterium (L70) to the value of O_2 concentration. For that purpose, survivals and none-survivals are analyzed toward remaining O_2 levels, results are listed in Table 7.3. In the table, bulbs 1 to 4

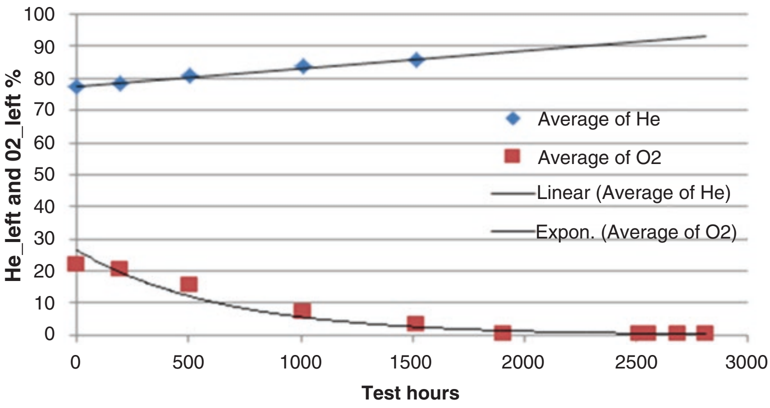

Fig. 7.13 Trends of measured O_2 concentration and He volume during operational life test

Table 7.3 Estimated minimum oxygen levels to keep the bulb in the L70 target

Nr	P [W]	O_2 initial [%]	O_2 after test [%]	L70 criterium
1	60	21	0.40	Pass
2	60	10	0.38	Pass
3	60	11	0.64	Pass
4	40	2	0.66	Pass
5	60	20	0.07	Fail
	60	20	0.08	Fail

showing more than 0.4% O_2 concentration give still enough lumen output while numbers 5 and 6 with the amount of O_2 concentration below 0.1% give weak lumen output below the target. Therefore, the needed O_2 concentration to prevent severe degradation is between 0.1% and 0.4%.

The O_2 consumption is determined by reacting with organic volatiles or VOC by: $C_xH_y + O_2 \rightarrow CO/CO_2$, a well-known reaction. Here, the O_2 consumption can be expressed as:

$$-d\frac{[O2]}{dt} = k.[O2].[VOC] \tag{7.2}$$

Assuming the level of VOCs in the glass bulb is fixed for any fixed design, the above equation is equivalent as

$$\int^{[O2]_i} \frac{d[O2]}{[O2]} = \int -k.dt \tag{7.3}$$

Assuming k is constant during whole lifetime, the above equation is integrated to

$$[O2] = [O2]_i \cdot e^{-kt} \tag{7.4}$$

or:

$$\mathrm{t} = -\ln\left(\frac{[O_2]}{[O2]_i}\right)/k \tag{7.5}$$

where

k: reaction rate [1/hr]
t: lamp burning time [hrs]
$[O_2]$: oxygen content [%]
$[O_2]_i$: Initial oxygen content [%].

Using the lifetime tests listed above we have predicted the lifetime of glass bulbs as a function of temperatures and oxygen concentration. Here, we assume the reaction rate follows the well-known Arrhenius model:

$$k = k_0 e^{-E_a/RT} \tag{7.6}$$

with:

k0: constant [1/hr]
Ea: activation energy [eV]
T: absolute temperature [K].

In order to predict the lifetime of glass LED bulbs, we have determined E_a and K_0 by fitting the below equation to the experimental data:

$$\mathrm{t} = -\ln\left(\frac{[O_2]}{[O2]_i}\right)/\left(k_0 e^{-\frac{E_a}{RT}}\right) \tag{7.7}$$

Figure 7.14 depicts such a fitted curve for the case of an initial O_2 level of 20%, tested at an ambient temperature of 35C. The data is well described within a confidence interval of 95%.

For all variations we tested, the activation energy was found to be between 0.37 eV and 0.58 eV. The influence of temperature and initial O_2 level is depicted in Fig. 7.15. When the target lifetime of the bulb is 10khrs, these plots will give the design guidelines in order to achieve those values.

In summary, the O_2 consumption in glass LED bulbs can be modeled and understood from a physical point of view and is directly related to the lifetime of the product.

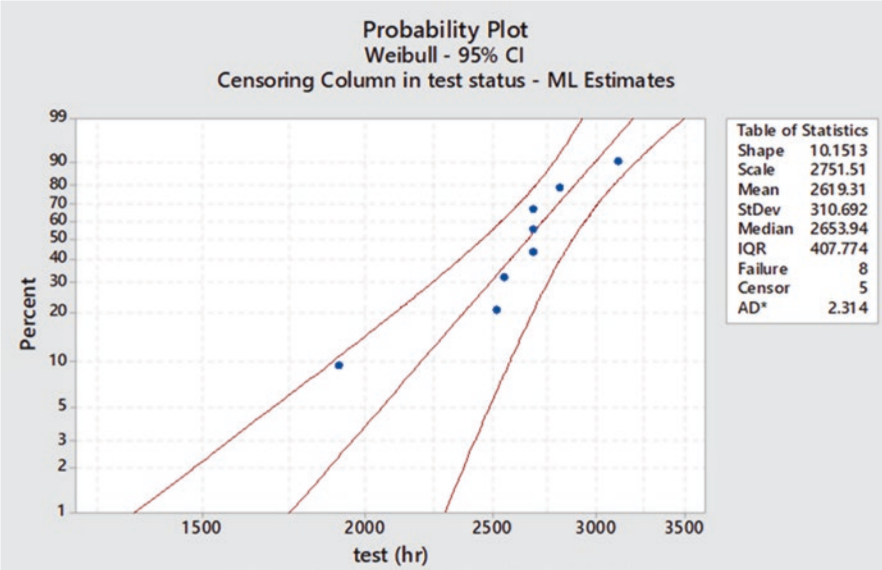

Fig. 7.14 Weibull plot of tested O2 consumption lifetime for 60 W, 20% [O2]-96 mA-35C ambient temperature

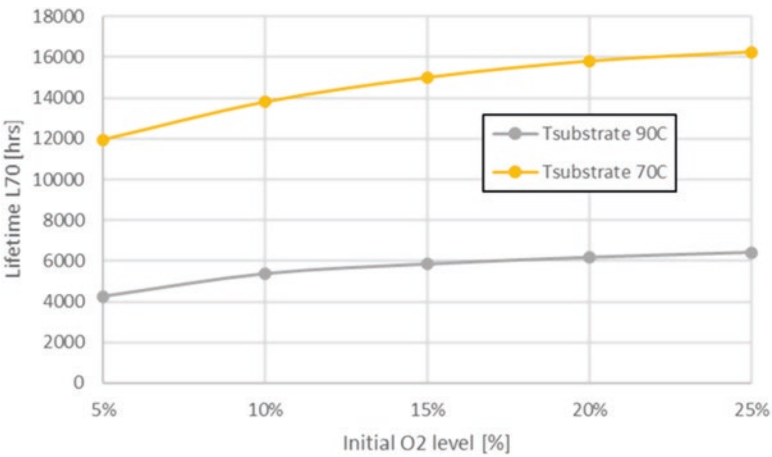

Fig. 7.15 Lifetime as a function of temperature and initial O_2 level

6 Degradation Failure: Color Maintenance

A recently appearing system failure mode in LED-based products is color maintenance. Color maintenance problems are insidious, because they are poorly understood, and only appear after many hours of operation [31, 32]. Lumen maintenance failure of SSL products is generally characterized by L70 life or 70% degradation of the lumen output. However, no failure criterion for color maintenance has been defined specifically in the application field except that ENERGY STAR® program mandates that Δu'v' at 6000 hours of operation should not exceed 0.007 [18], which is perhaps the only industry-wide criterion. It is a reasonable starting point but may not be strict enough to ensure very high-quality lighting, especially since the lifetimes of LED products routinely far exceed 6000 hours [2, 3]. Poor color maintenance can be a substantial problem in applications where color quality is important, including museum and gallery lighting, architectural facade lighting, retail display lighting, healthcare lighting, hospitality applications, cove and wall wash lighting, down lighting in commercial and residential applications [33–35].

Color maintenance is analogous to lumen maintenance and is the change in chromaticity of a light source with respect to the chromaticity at the beginning of the lamp's life. It is typically measured as Δxy or Δu'v', in the CIE color coordinate systems [36, 37]. Energy Star specifies that color maintenance must not exceed Δu'v' = 0.007 on the CIE u'v' diagram, after 6000 hours of operation. This is a liberal allowance for color shift, and we expect that LED-based products should do better than this to maintain a positive perception in the marketplace.

Color consistency is the variation in chromaticity, at the start of product life, among a population of products. For example, a product may be made from LEDs that are binned to fall within 3 MacAdam [36] steps of a target chromaticity. The LEDs have a color consistency of 3 steps. Color consistency can also be defined in terms of xy or u'v'. The color consistency of lamps built from these LEDs may be worse than three steps, because of temperature variations, current variations, or other factors. Color stability describes how the entire spectrum changes over time, and is closely related to color maintenance, but encompasses more detail. Color maintenance will be used in this paragraph, an example is shown in Fig. 7.16. Origins of color maintenance are listed in Table 7.4 [31, 38].

What we need to develop color maintenance predictions on system level are:

- System-level approach that can combine (known) component-level color shift functions.
- An approach that can deal with the product (optical) design.
- Test data on component, sub-component, and system level to validate and verify the system level predictions.

So far there has been one attempt published that is able to do product-level prediction in this area [32]. Davis' method also considers changes in the LEDs and the optical components (i.e., lenses and reflectors) of the luminaire. In addition, the relative impacts of lens and reflector degradation will depend on the design of the

Fig. 7.16 Example of color maintenance drift for an indoor installation

Table 7.4 Origins of color maintenance

Color maintenance Root cause	Examples
Material degradation	Degradation of direct optical path from LED die to air Degradation of reflective surfaces within the LED component Degradation of the optical materials with the system, be it MCPET, white solder resist, poly carbonate or PMMA.
External contaminants	Contaminations in the direct optical path such as browning of the optical path due to VOCs or residual flux after reflow on the exterior of the LED package. Change in the reflective surface properties of materials within the LED component, including, for example, tarnishing of silver. Carbonization due to lack of oxygen. Sedation of particles onto any optical surface, for example, onto the silicones.
Interface delamination	Separation between different material interfaces such as substrate and optical path materials. Material cracking, for example, in the MCPET reflector due to brittleness.

luminaire. This phenomenon can be studied by using optical simulation tools for nearly any luminaire design. This simulated or "virtual" luminaire approach, which is illustrated here, involves designing a luminaire in the simulation tool that includes the selection of the initial optical properties of the lenses and reflectors. Then, the properties of these materials can be degraded in a systematic manner, and the impacts on luminaire performance can be determined. For this analysis, any luminaire design can be modeled for any expected physical parameters, including size and optical cavity depth. Aging of materials used in luminaire could be easily accommodated in the simulation by attenuating the optical properties of the materials. For example, the impact of a 10% drop in lens transmittance can be simulated by reducing normalized lens transmittance by 10%. Transmittance is normalized by the initial transmittance of the pristine material. By systematically changing the design parameters and simulating aging of the optical surfaces by introducing new values for normalized transmittance and reflectance, a model can be created to determine the change in luminous flux produced by the luminaire during aging. A simple power-law model of the form shown in the equation below captures the impact of optical materials degradation on lumen maintenance for the LED device:

$$\Phi_{tot}(t) = \Phi_{init} F_{LEDs} \left[L(t)\right]^m \left[R(t)\right]^n \tag{7.9}$$

where

- Φ_{tot} = Total luminous flux from the luminaire at time t
- Φ_{init} = Initial luminous flux from the luminaire at time zero. This value is also the product of the luminous flux from the light engine and the luminaire efficiency.
- F_{LEDs} = Lumen maintenance factor of the LED at time t
- $L(t)$ = Change in the normalized lens transmittance $[\%T(t)/\%T(t = 0)]$ at time t
- m = Design-dependent factor for the lens as determined from the simulation
- $R(t)$ = Change in the normalized reflector reflectance $[\%R(t)/\%R(t = 0)]$ at time t
- n = Design-dependent factor for the reflector as determined from the simulation.

Regarding color maintenance of LEDs, TM35 describes the projection of long-term chromaticity coordinate shift of LEDs [39]. Ignoring these effects of taking them as a given, Eq. 7.9 can be recast into a model for luminaire optical efficiency degradation as shown in the following eq.

$$LE(t) = LE(t = 0)\left[L(t)\right]^m \left[R(t)\right]^n \tag{7.10}$$

where

- $LE(t)$ = Luminaire efficiency at time t
- $LE(t = 0)$ = Initial luminaire efficiency

The parameters m and n consider the impact of the luminaire design on the relative contributions of lens and reflector aging upon degradation in luminaire efficiency. For example, for a 2 × 2 m^2 troffer design, m is approximately 2 and n is approximately 0.5 [32], indicating that the degradation of the lens has a much greater impact on changes in luminaire efficiency and be extension chromaticity stability than the degradation of the reflectors. However, for luminaires with smaller apertures and proportionally deeper optical mixing cavities, the value of n can equal or surpass the value of m, indicating that reflector degradation has a significant impact on overall luminaire efficiency changes in some designs. Conceptually, the value of n can be thought of as being proportional to the likelihood that light emitted by an LED at the base of an optical cavity will strike the reflector in that optical cavity and be impacted by reflector degradation. Consequently, the impact of reflector degradation on lumen maintenance and chromaticity stability can be reduced by shrinking the optical mixing cavity, but this may also change the distribution and homogeneity of the light emitted by the luminaire.

A more generic approach for deducting the product design parameters m and n is based on the so-called view factor method [38]. To help illustrate this approach, a schematic diagram of light paths for a LED-based product is shown in Fig. 7.17. Each exchange of light in the light paths can be considered as a contribution to color maintenance.

As the color maintenance of the light out of the product is the result of those coming from the LEDs, reflector, PCB, and optics, the interaction between these optical elements needs to be included. A complete ray tracing model will result in a too complex model to be used by designers and reliability engineers. The view factor approach assumes that a certain fraction of the light emitted or reflected by an optical part is radiated to another part (or even itself again). Each part that reflects light can also give this light a small color shift or spectral change.

The set of equations describing the light interaction between the 4 optical elements is as follows:

$$\begin{pmatrix} \Phi_{\text{i to LEDs}} \\ \Phi_{\text{i to pcb}} \\ \Phi_{\text{i to housing}} \\ \Phi_{\text{i to exit}} \end{pmatrix} = \begin{pmatrix} F_{L-L} & F_{p-L} & F_{h-L} & F_{e-L} \\ F_{L-p} & F_{p-p} & F_{h-p} & F_{e-p} \\ F_{L-h} & F_{p-h} & F_{h-h} & F_{e-h} \\ F_{L-e} & F_{p-e} & F_{h-e} & F_{e-e} \end{pmatrix} \begin{pmatrix} \Phi_{\text{i from LEDs}} \\ \Phi_{\text{i from pcb}} \\ \Phi_{\text{i from housing}} \\ \Phi_{\text{i from exit}} \end{pmatrix} \quad 7.11$$

Here the letter i denotes how many interactions (= reflections) the light has already undergone. The matrix with the numbers F is the view factor matrix, and as we assume that all light emissions and reflections have Lambertian distribution, the view factor matrix is independent of i. The sum of the elements in each column is equal to 1. The part "housing" could also be described as the "reflector". Part of the

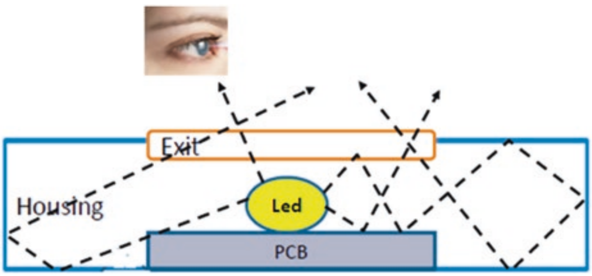

Fig. 7.17 Schematic diagram of light paths representing the view factor approach

light hits upon each optical element is also reflected again. This can be expressed in the next equation:

$$\begin{pmatrix} \Phi_{\text{i+1 from LEDs}} \\ \Phi_{\text{i+1 from pcb}} \\ \Phi_{\text{i+1 from housing}} \\ \Phi_{\text{i+1 from exit}} \end{pmatrix} = \begin{pmatrix} R_L & & & \\ & R_p & & \\ & & R_h & \\ & & & R_e \end{pmatrix} \begin{pmatrix} \Phi_{\text{i to LEDs}} \\ \Phi_{\text{i to pcb}} \\ \Phi_{\text{i to housing}} \\ \Phi_{\text{i to exit}} \end{pmatrix} \quad 7.12$$

At each reflection R the light can undergo a color change. This color change can be described in two ways:

- color shift Δx and Δy, independent of the color point (spectrum) of the incoming light
- spectral change, the reflectivity depends on the wavelength of the light

Method 2 is more realistic, but in that case the spectra of the light need to be included in the calculations. In case of small color changes (small changes of the spectrum upon reflection) and low reflectivity's *R* (fast damping), method 1 can be good enough. Therefore, this method is preferred. We note the initial condition:

$$\begin{pmatrix} \Phi_{\text{0 from LEDs}} \\ \Phi_{\text{0 from pcb}} \\ \Phi_{\text{0 from housing}} \\ \Phi_{\text{0 from exit}} \end{pmatrix} = \begin{pmatrix} \Phi_{\text{LEDs}} \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad 7.13$$

And then the light coming out of the lamp/luminaire by means of transmission through the exit window:

$$\Phi_{\text{from exit}} = (1 - R_e - A)\Phi_{\text{to exit}} \quad (7.14)$$

where *A* stands for absorption and the light is summed over enough *i*. The transmission of the light can also be accompanied with a color change of the light. As the light out of the module is also calculated, the approach also gives the optical efficiency as output so it can be used to estimate the optical efficiency.

For 2 common geometries, a rectangular and an axis symmetric product, the view factors for the users are known [40], following the conservation law and reciprocity, see Fig. 7.18:

$$\sum_j F_{\text{from } i \text{ to } j} = \sum_j F_{ij} = 1$$

$$A_i F_{ij} = A_j F_{ji} \quad (7.15)$$

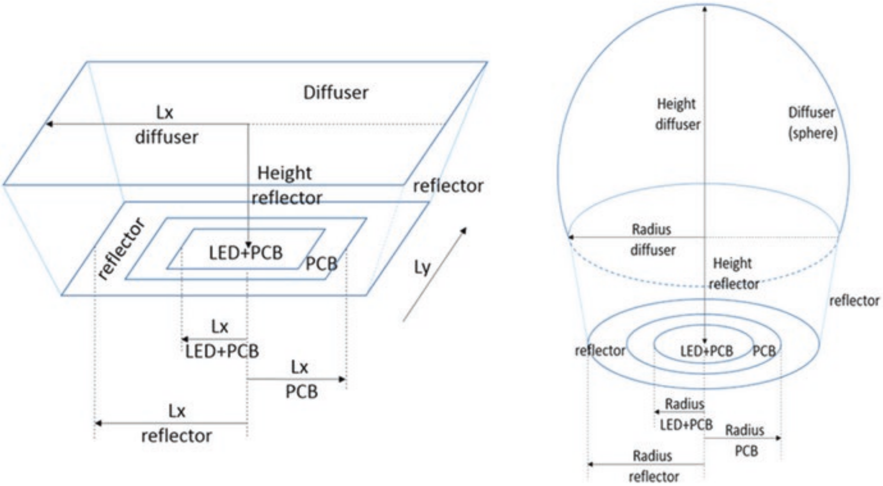

Fig. 7.18 Rectangular product geometry (left) vs axis symmetric product geometry (right)

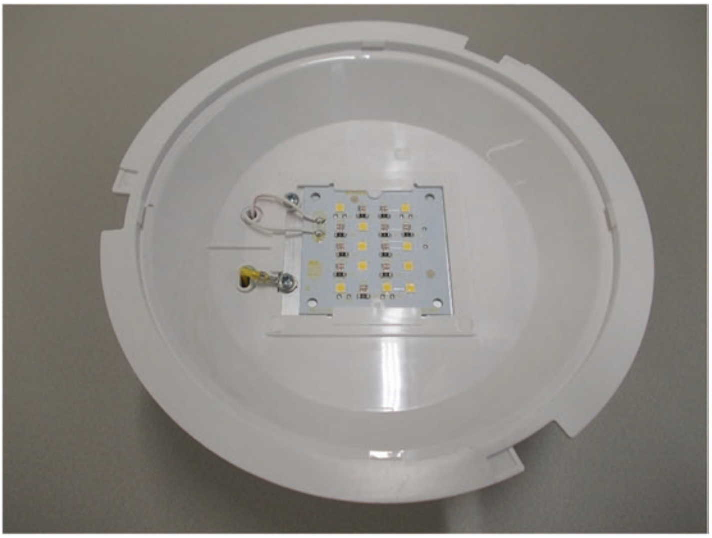

Fig. 7.19 Photo of carrier product with the diffusive flat exit window taken out

The carrier product used for validation of the approach is depicted in Fig. 7.19. It perfectly fits in the "axis symmetric" shape of which the view factors can be easily calculated, see Table 7.5. Most of the light coming from the LEDs will travel through the diffuser (91.7%). Reflection from the PCB is not negligible (13.2%). For purpose of validation, the carrier product is tested at elevated temperatures of 110C and 120C. All optical materials will degrade over time. Regarding the aging of these plastics, the correlation between aging time and aging temperature is

Table 7.5 Calculated view factors for the carrier product

View factor [%]		From			
TO		LEDs	PCB	Reflector	Diffuser
	LEDs	0.0	0.0	0.1	0.8
	PCB	0.0	0.0	1.2	13.2
	Reflector	8.3	8.9	20.9	86.0
	Diffuser	91.7	91.1	77.8	0.0
	SUM	100	100	100	100

described by the principle of time-temperature superposition or equivalently introducing the effective time variable:

$$\Delta t_{eff} = \Delta t / a_T$$

$$a_T = \exp\left[\frac{\Delta H}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{7.16}$$

where T is the temperature in Kelvin (T_0 the reference temperature), R the gas constant 8.314 J/mol.K, and ΔH the activation energy, used to fit the data at several temperatures (i.e., sensitivity to temperature).

Each part in the carrier product is aged during a period of approximately 4000 hrs. Color changes in terms of coordinates Δx and Δy are found to follow:

$$\Delta x = \Delta x_t \left(\frac{t}{t_0}\right)^{n_x}$$

$$\Delta y = \Delta y_t \left(\frac{t}{t_0}\right)^{n_y}$$

where t denotes time, t_0 a reference time, an example is given in Fig. 7.20.

Each part in the carrier product exhibits its own degradation. Figure 7.21 depicts the testing results after approximately 4000 hrs at elevated temperatures in terms of changes in color coordinates (the arrow gives the direction). Notice that the LED color changes are opposite in direction from the optical parts.

With the given color maintenance view factor approach, predictions of both the lumen decay as the color shift were made. Now the temperature-dependent (effective time) models for color shift, lumen decay, reflection, and transmission change are used. As a function of time and temperature the parameters of the LEDs, PCB, reflector, and exit window can be calculated. Results are depicted in Figs. 7.22 and 7.23. From these figures we read that the LED color shift starts faster than the color shift due to yellowing of the PCB, reflector, and exit window. In the end the

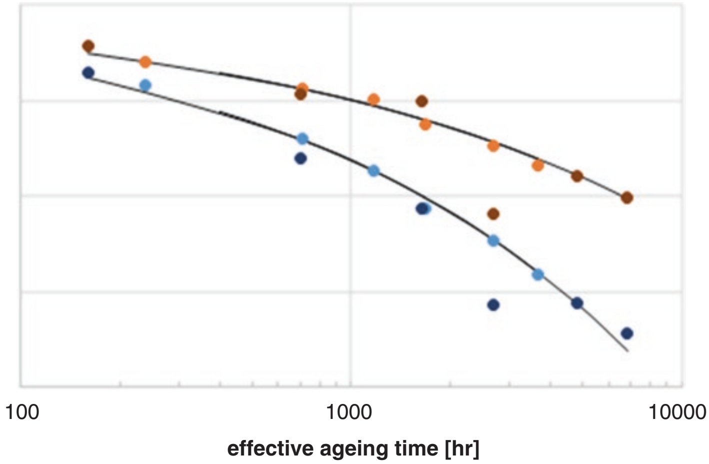

Fig. 7.20 Measured x (blue) and y (orange) color shifts for 2 carrier products with a reflector but without the diffuser

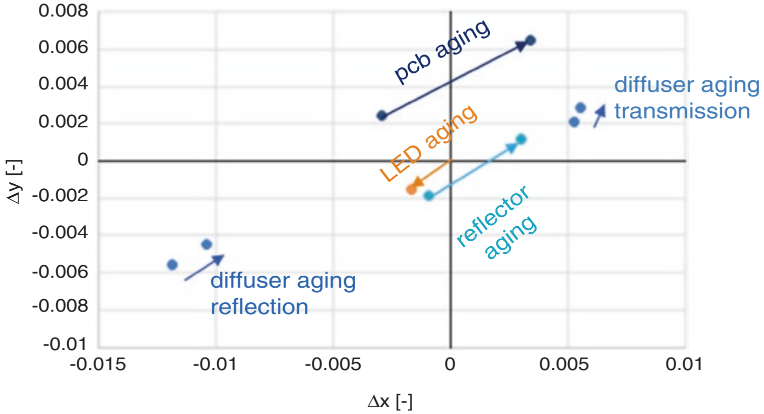

Fig. 7.21 Colors changes after ~4000 hrs testing in the product parts depicted in x, y color coordinates, indicated with an arrow

yellowing "wins" even with 90 °C LED temperature and 70 °C reflector and exit window temperature. As the LED color shift is toward blue, the product color point first moves a bit toward blue and later moves in the opposite direction toward yellow. The result is that if the LEDs would give a fixed color (no aging) the color shift of the product will be larger. One can also see that lumen decay due to deteriorating of the optics is small compared to the lumen decay caused by the LED degradation.

When one asks which criterion is limiting, lumen decay (80%) or color shift (7 SDCM), then Fig. 7.23 shows that lumen decay is most critical. But if one thinks of

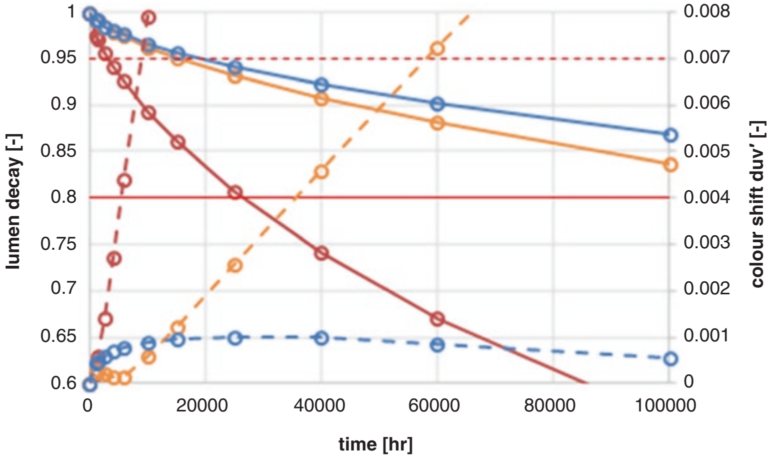

Fig. 7.22 Calculated uv' color shift (dotted line) and lumen decay (solid line) as a function of aging time. Red: all parts 110 °C; Orange: all parts 90 °C; Blue: LEDs 90 °C, PCB 80 °C, reflector & exit window 70 °C

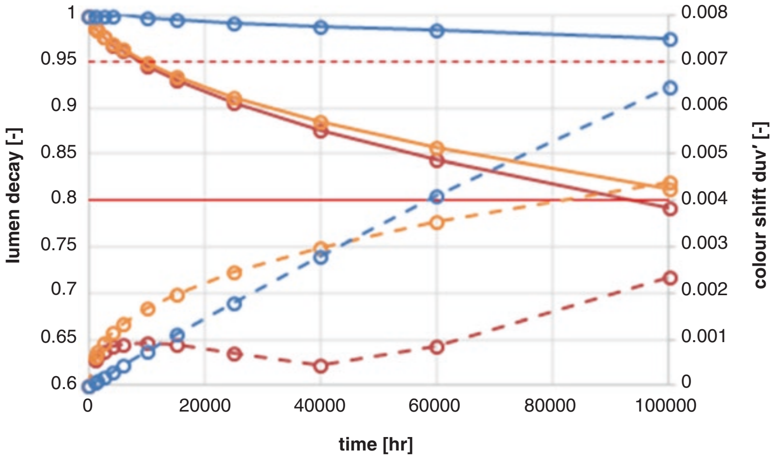

Fig. 7.23 Calculated uv' color shift (dotted line) and lumen decay (solid line)as function of (aging) time; LEDs 100 °C, PCB 90 °C, reflector & exit window 80 °C. Red: all parts aging; Orange: only LED aging; Blue all but LED aging

stricter specified products with only 2 SDCM color shift allowed then the 80% lumen decay and the 0.002 uv' color shift occur both at ~90 khr.

In summary, we presented the results of this newly developed method, including the validation experiments that were executed in other to compare predictions with reality. The results indicate that:

- Color maintenance in LED-based products is a combination of color maintenance in LEDs, optical materials, and the construction itself.
- Temperature is the main driver for the color maintenance.
- The optical materials play an equally important role in controlling the amount of color maintenance.

For fixed constructions, color maintenance on system level is just a balance between the LED and the optical materials.

7 Final Remarks

In the past ten years we have witnessed a substantial change in the lighting industry. Traditional companies have changed their strategy and upcoming competition has pushed down prices for LED-based products considerably. LED penetration levels increased so as the diversity of commercially available replacement products. New processes and materials were introduced, and consequently new failure modes appeared. This trend has continued in the past four years as the lighting industry is getting connected and large amounts of user data are being analyzed. New components are needed to deliver this functionality (sensors, actuator IoT modules) and, as such, the diversity from an architectural point of view will also increase. In this chapter, we have presented the currently known reliability and failures found in these solid-state lighting systems. It includes both degradation and catastrophic failure modes from observation toward a full description of its mechanism obtained by extensive use of acceleration tests using knowledge-based qualification methods. A total number of 88 failures modes are found, from which 60% are related to degradation. This indicates the importance of monitoring the degradation process in these products, as longer lifetimes and warrantees are industry targets. As such, gradually but slowly the term reliability in the lighting industry will be replaced by availability and "smart" maintenance will distinguish good from bad products.

Two degradation cases are presented, O_2 consumption in glass LED bulb and color maintenance in LED-based products. The developed algorithms describe the degradation processes in detail and, thus, can be used for monitoring the product lifetime [41].

Acknowledgments This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 876659. The JU receives support from the European Union's Horizon 2020 research and innovation programme and Germany, Austria, Slovakia, Sweden, Finland, Belgium, Italy, Spain, Netherlands, Slovenia, Greece, France, and Turkey.

References

1. Frost & Sullivan, 2020 Annual Update of Global LED Lighting Market, September 2020
2. W.D. Van Driel, X.J. Fan (editors), Solid State Lighting Reliability: Components to System. 01/2013; ISBN 978-1-4614-3067-4 Springer New York
3. W.D. Van Driel, X.J. Fan and G.Q. Zhang (editors), Solid State Lighting Reliability: Components to System Part II. 06/2017; ISBN 978-3-319-58174-3 Springer New York
4. Navigant Consulting, Inc., Energy Savings Forecast of Solid-State Lighting in General Illumination Applications, report prepared for the U.S. Department of Energy, September 2016
5. Estimated LED penetration of the global lighting market from 2010 to 2020, available at http://www.statista.com/statistics/246030/estimated-led-penetration-of-the-global-lighting-market/ (last visited on 8/25/2016)
6. Market penetration predicted for white light, freely available at http://edisonreport.com/files/7613/7631/7460/SSL_Energy-Savings_Predictions.pdf (last visited on 10/16/2020)
7. D. Schenkelaars, W.D. van Driel, M. Klompenhouwer, I. Flinsenberg, R. Duijve, Towards Prognostics & Health Management in Lighting Applications, European Conference of the Prognostic and Health Management Society 2016, open access journal, available at: http://www.phmsociety.org/node/2090/, Volume 7, Page count: 7, 2016
8. T. Tuunanen, H. Cassab, Service process modularization: reuse versus variation in service extensions. Journal of Service Research (2011) 1094670511413912
9. L.L. Berry, V. Shankar, J. Turner Parish, S. Cadwallader, T. Dotzel, Creating new markets through service innovation. Sloan Management Review **47**(2) (2006)
10. J. Björkdahl, M. Holmén, Editorial: Business model innovation–the challenges ahead. International Journal of Product Development **18**(3/4), 213–225 (2013)
11. Meeker, William Q. and Hong, Yili, Reliability Meets Big Data: Opportunities and Challenges (2013). Statistics Preprints. Paper 82. http://lib.dr.iastate.edu/stat_las_preprints/82
12. Michael G. Pecht, Moon-Hwan Chang, Failure Mechanisms and Reliability Issues in LEDs, In: W.D. Van Driel, X.J. Fan (editors), Solid State Lighting Reliability: Components to System.. 01/2013; ISBN 978-1-4614-3067-4 Springer New York
13. M-H. Chang, D. Das, P. V. Varde, and M. Pecht, Light Emitting Diodes Reliability Review, Journal of Microelectronics Reliability, Article in Press, 2011, https://doi.org/10.1016/j.microrel.2011.07.063
14. G. Meneghesso, S. Leveda, E. Zanoni, G. Scamarcio, G. Mura, S. Podda, M. Vanzi, S. Du, I. Eliashevich, Reliability of Visible GaN LEDs in Plastic Package. Microelectronics Reliability **43**, 1737–1742 (2003)
15. C. De Santi, D. Monti, P. Dalapati, M. Meneghini, G. Meneghesso, E. Zanoni, Reliability of Ultraviolet Light-Emitting Diodes, in *Light-Emitting Diodes, Solid State Lighting Technology and Application Series 4*, ed. by J. Li, G. Q. Zhang. https://doi.org/10.1007/978-3-319-99211-2_11
16. J.F.J.M. Caers, X.J. Zhao, Failure Modes and Failure Analysis, in *Solid State Lighting Reliability: Components to System*. 01/2013; ISBN 978-1-4614-3067-4, ed. by W. D. Van Driel, X. J. Fan, (Springer, New York)
17. JEP122F, Failure mechanisms and models for semiconductor devices, JEDEC publication, March 2009
18. IES LM-80-08: Approved method for measuring maintenance of Led light sources, 2019
19. IES TM-21-11: Projecting Long Term Lumen Maintenance of LED Light Sources, 2019
20. IEC/TS 62861 Ed. 1: Guide to principal component reliability testing for LED light sources and LED luminaires, technical specification (under creation)
21. S.-H. Kim, S.-I. Sung, Modeling and analysis of the catastrophic failure and degradation data. Microelectronics Reliability (2020) in press
22. L.I. Pettit, K.D.S. Young, Bayesian analysis for inverse Gaussian lifetime data with measures of degradation. Journal of Statistical Computation and Simulation **63**(3), 217–234 (1999). https://doi.org/10.1080/00949659908811954

23. M.H. Schuld, B.F. Schriever, J.W. Bikker, Solid State Lighting System Reliability, in *Solid State Lighting Reliability: Components to System*. 01/2013; ISBN 978-1-4614-3067-4, ed. by W. D. Van Driel, X. J. Fan, (Springer, New York)
24. M. Pecht, A. Dasgupta, *Physics-of-failure: An approach to reliable product development, Proceedings Integrated Reliability Workshop* (1995). https://doi.org/10.1109/IRWS.1995.493566
25. M. Yazdan Mehr, A. Bahrami, W.D. van Driel, X.J. Fan, J.L. Davis, G.Q. Zhang, Degradation of optical materials in solid-state lighting systems. International Materials Reviews **65**(2), 102–128 (2020). https://doi.org/10.1080/09506608.2019.1565716
26. W.D. van Driel, J.W. Bikker, M Tijink, A Di Bucchianico, Software Reliability for Agile Testing, Mathematics 2020, 8(5), 791; https://doi.org/10.3390/math8050791
27. J.D. Hooker, W. Schaaf, J. Achten, W. Vinckx, L. Derhaeg, Development of Advanced Gas-Cooled 'LED Filament' Lamps, Proceedings LS14 conference, 2014
28. H.M. Le Huy, V. Bellenger, J. Verdu, Thermal oxidation of anhydride cured epoxies. 1--mechanistic aspects. Polymer Degradation and Stability **35**, 77–86 (1992)
29. H.M. Le Huy, V. Bellenger, M. Paris, J. Verdu, Thermal oxidation of anhydride cured epoxies II Depth distribution of oxidation products. Polymer Degradation and Stability **35**, 171–179 (1992)
30. X. Buch, M.E.R. Sha, Thermal and thermo-oxidative ageing of an epoxy adhesive, Polymer Degradation and Stability. **68**, 403–411 (2000)
31. M. Yazdan Mehr, W.D. van Driel, G. Q. (Kouchi) Zhang, Progress in Understanding Color Maintenance in Solid-State Lighting Systems. Engineering **1**(2), 170–178, ISSN 2095-8099 (2015). https://doi.org/10.15302/J-ENG-2015035
32. J.L. Davis, Color shift in LEDs and SSL luminaires, presentation at the 2014 DOE Solid-State Lighting Manufacturing R&D Workshop, San Diego, CA, May 8, 2014
33. J.L. Davis, Solid-state lighting luminaire reliability, presentation at Delft University, Delft, the Netherlands, April 10, 2014
34. J.L. Davis, K. Mills, M. Lamvik, R. Yaga, S.D. Shepherd, J. Bittle, N. Baldasaro, E. Solano, G. Bobashev, C. Johnson, A. Evans, *System reliability for LED-based products, in Proceedings of the 2014 15th International Conference on Thermal, Mechanical, and Multi-physics Simulation and Experiments in Microelectronics and Microsystems (IEEE EuroSimE)* (Ghent, Belgium, 2014)
35. J.L. Davis, M. Lamvik, J. Bittle, S. Shepherd, R. Yaga, N. Baldasaro, E. Solano, and G. Bobashev, Insights into accelerated aging of SSL luminaires, Proceedings of SPIE: LED-based Illumination Systems. 8835 (2013) 88350L-1–88350L-10
36. D.L. MacAdam, *Color Measurement, Theme and Variations*, 2nd edn. (Springer-Verlag, New York, 1985)
37. Y. Ohno, Color quality, In: W.D. Van Driel, X.J. Fan and G.Q. Zhang (editors), Solid State Lighting Reliability: Components to System Part II. 06/2017; ISBN 978-3-319-58174-3 Springer New York
38. L.U. Guangjun, W.D. van Driel, X. Fan, J. Fan, G.Q. Zhang, LED based Luminaire Color Shift Acceleration and Prediction, in *Solid State Lighting Reliability: Components to System Part II*. 06/2017; ISBN 978-3-319-58174-3, ed. by W. D. Van Driel, X. J. Fan, G. Q. Zhang, (Springer, New York)
39. IES – TM-35, Projecting Long-Term Chromaticity Coordinate Shift of LED Packages, Arrays, and Modules, 2019
40. JOHN R. HOWELL, A catalog of radiation heat transfer configuration factors, available at www.thermalradiation.net, (last visited on 25/11/2020)
41. M.S. Ibrahim, J. Fan, W.K.C. Yung, A. Prisacaru, W. Van, X. Fan, G. Zhang, Machine Learning and Digital Twin Driven Diagnostics and Prognostics of Light-Emitting Diodes. Laser & Photonics Reviews, 2000254 (2020). https://doi.org/10.1002/lpor.202000254