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Reliability of LED-based systems

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ABSTRACT

Reliability is an essential scientific and technological domain intrinsically linked with system integration. Nowadays, semiconductor industries are confronted with ever-increasing design complexity, dramatically decreasing design margins, increasing chances for and consequences of failures, shortening of product development and qualification time, and increasing difficulties to meet quality, robustness, and reliability requirements. The scientific successes of many micro/nano-related technology developments cannot lead to business success without innovation and breakthroughs in the way that we address reliability through the whole value chain. The aim of reliability is to predict, optimize and design upfront the reliability of micro/nano-electronics and systems, an area denoted as 'Design for Reliability (DfR)'. While virtual schemes based on numerical simulation are widely used for functional design, they lack a systematic approach when used for reliability assessments. Besides this, lifetime predictions are still based on old standards assuming a constant failure rate behavior. In this paper, we will present the reliability and failures found in solid-state lighting systems. It includes both degradation and catastrophic failure modes from observation towards a full description of its mechanism obtained by extensive use of acceleration tests using knowledge-based qualification methods. A use case will be presented in more details.

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 source. It is 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. 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.

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 [1,2]. The impact of this digitization is far beyond the impact on single products and extends to an ever-larger number of connected systems. Continuously, more intelligent interfacing with the technical environment and with different kind of users is being built-in by using more and different kind of sensors, (wireless) communication, and different kind of interacting or interfacing devices (Fig. 1).

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, they it maximizes the asset value for service providers and reduces the initial investment and risk of ownership for customers [8–10]. Smart LED-based products are rapidly entered the building market and widespread commercial and residential

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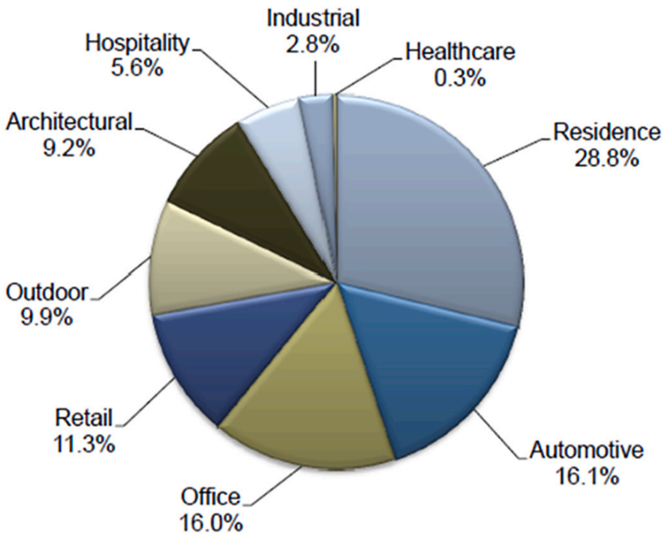


Fig. 1. Total LED lighting market: Percent revenue by applications, global, 2019.
(Taken from [1]; with permission.)

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.

From a reliability perspective, it all means that failure modes of LED-based products will simply need to be discovered and one should be able to understand which possible failure modes can occur or can be triggered. With the continuously 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 LED-based products. In this paper, we will describe our current understanding of the reliability and known failure modes in these products.

2. Failure modes in LED-based products

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 [11,12]. 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 [12,13]. There 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 [14]. 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 [15,16], does not exist in the Lighting industry.

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 [17]. 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 to the design and development of reliable product to prevent failure, 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 [17]. 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. 2, 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
  Following IEC62861 [16], 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. 3: organic material degradation. This failure is well described in an open access review paper [18].

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. Fig. 4 depicts the detection of new failure modes in a 10-year period. On average 10 new failure modes are discover 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 [19]. Eventually, a total number of approximately 130 unique failure modes are to be discovered.

Further data analysis is feasible as each unique failure modes is well described. Fig. 5 depicts a pareto of the number of failure modes per product type. Examples are:

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

Fig. 2. Summary sheet for failure modes, as part of the failure mode handbook.

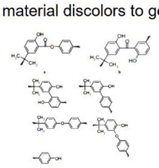
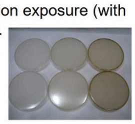
Date: June 2016	index **Organic material degradation**	
Failure mode description	**Root cause / failure mechanism**	**Solutions**
Optical material discolors to get yellowish color. 	• Thermal degradation of encapsulants induced by high junction temperature between LED die and lead frame • Thermal degradation 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.  $Af = (\frac{I}{I_0})^n \exp(\frac{E_a}{K}(\frac{1}{T_{reference}} - \frac{1}{T_{test}}))$	• 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*

Fig. 3. Summary sheet for the failure mode organic material degradation.

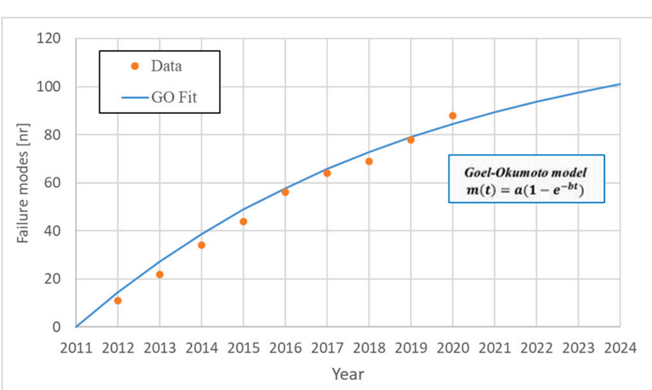


Fig. 4. Number of unique failure modes as function of years.

- 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 1 lists the classification towards 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.

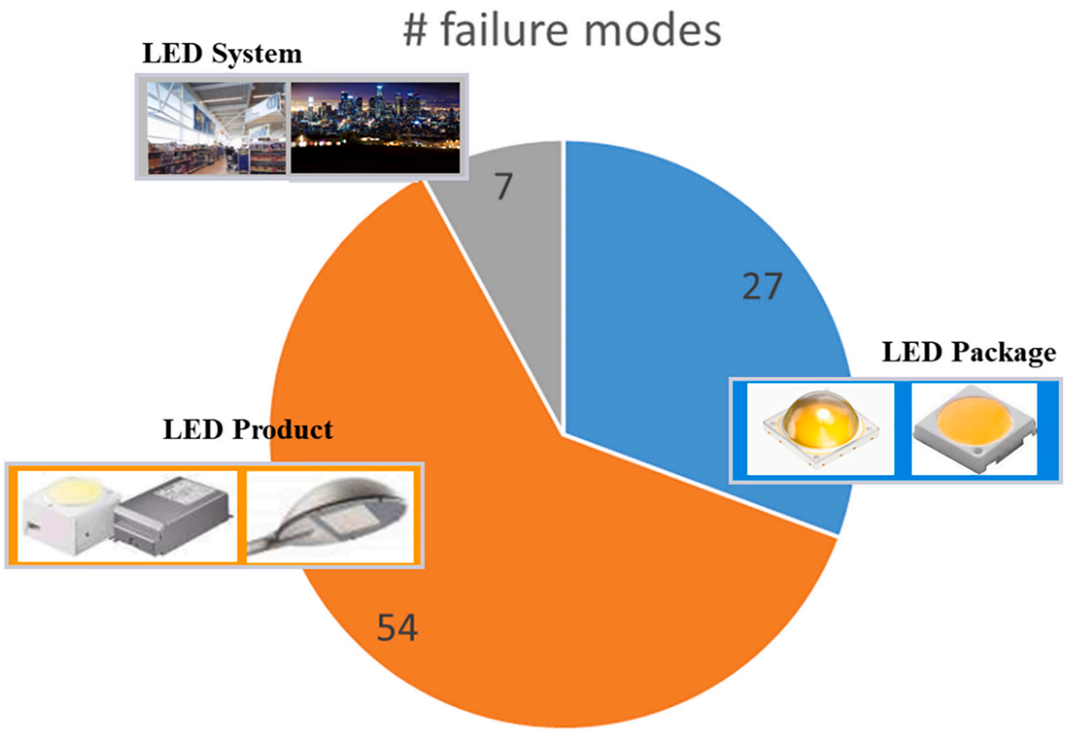


Fig. 5. Pareto for the number of failure mode vs product type.

Table 1
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

- 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.
- For the optics, degradation is a leading failure mode 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. In the next paragraph a degradation failure mode example is presented.

3. 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 [20,21]. 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 $\Delta u'v'$ at 6000 h of operation should not exceed 0.007 [22], 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 h [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 [23–25].

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 $\Delta u'v'$, in the CIE color coordinate systems [26,27]. Energy Star specifies that color maintenance must not exceed $\Delta u'v' = 0.007$ on the CIE u′v′ diagram, after 6000 h 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 [26] 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. 6. Origins of color maintenance are listed in Table 2 [20,28].

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

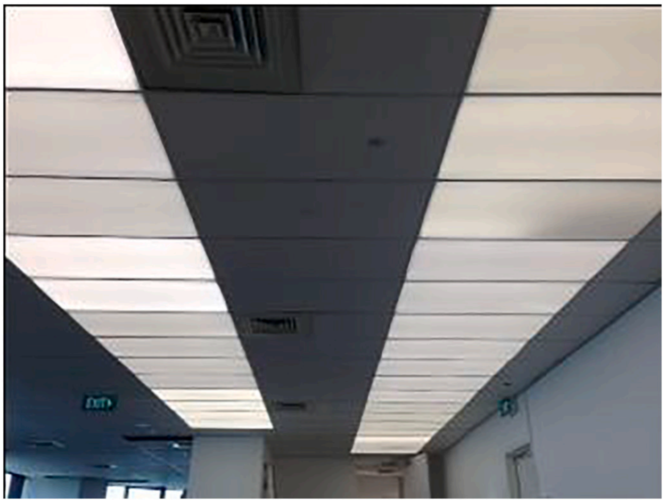


Fig. 6. Example of color maintenance drift for an indoor installation.

Table 2
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.

- 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 [21]. The 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 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:

$$\Phi_{tot}(t) = \Phi_{init} F_{LEDs} [L(t)]^m [R(t)]^n \quad (1)$$

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 [29]. Ignoring these effects of taking them as a given, Eq. (1) can be recast into a model for luminaire optical efficiency degradation as shown in the following equation.

$$LE(t) = LE(t=0) [L(t)]^m [R(t)]^n \quad (2)$$

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 $2 \times 2\ m^2$ troffer design, m is approximately 2 and n is approximately 0.5 [23], 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 [28]. To help illustrate this approach, a schematic diagram of light paths for a LED-based product is shown in Fig. 7. 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

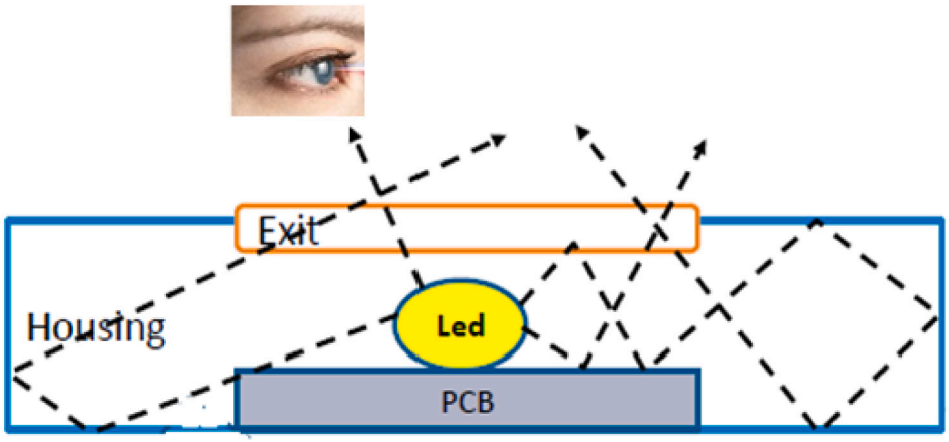


Fig. 7. Schematic diagram of light paths representing the view factor approach.

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:

$$\begin{pmatrix} \Phi_{\text{i to LEDs}} \\ \Phi_{\text{i to pcb}} \\ \Phi_{\text{i to housing}} \\ \Phi_{\text{i to exit}} \end{pmatrix} = \begin{pmatrix} F_{L-L} & F_{p-L} & F_{h-L} & F_{e-L} \\ F_{L-p} & F_{p-p} & F_{h-p} & F_{e-p} \\ F_{L-h} & F_{p-h} & F_{h-h} & F_{e-h} \\ F_{L-e} & F_{p-e} & F_{h-e} & F_{e-e} \end{pmatrix} \begin{pmatrix} \Phi_{\text{i from LEDs}} \\ \Phi_{\text{i from pcb}} \\ \Phi_{\text{i from housing}} \\ \Phi_{\text{i from exit}} \end{pmatrix} \tag{3}$$

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

$$\begin{pmatrix} \Phi_{\text{i+1 from LEDs}} \\ \Phi_{\text{i+1 from pcb}} \\ \Phi_{\text{i+1 from housing}} \\ \Phi_{\text{i+1 from exit}} \end{pmatrix} = \begin{pmatrix} R_L & & & \\ & R_p & & \\ & & R_h & \\ & & & R_e \end{pmatrix} \begin{pmatrix} \Phi_{\text{i to LEDs}} \\ \Phi_{\text{i to pcb}} \\ \Phi_{\text{i to housing}} \\ \Phi_{\text{i to exit}} \end{pmatrix} \tag{4}$$

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 spectrum of the light needs 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:

$$\begin{pmatrix} \Phi_{\text{0 from LEDs}} \\ \Phi_{\text{0 from pcb}} \\ \Phi_{\text{0 from housing}} \\ \Phi_{\text{0 from exit}} \end{pmatrix} = \begin{pmatrix} \Phi_{\text{LEDs}} \\ 0 \\ 0 \\ 0 \end{pmatrix} \tag{5}$$

And then the light coming out of the lamp/luminaire by mean of transmission though the exit window:

$$\Phi_{\text{from exit}} = (1 - R_e - A)\Phi_{\text{to exit}} \tag{6}$$

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 [30], following the conservation law and reciprocity, see Fig. 8:

$$\begin{aligned} &\sum_j F_{\text{from } i \text{ to } j} = \sum_j F_{ij} = 1 \\ &A_i F_{ij} = A_j F_{ji} \end{aligned} \tag{7}$$

The carrier product used for validation of the approach is depicted in Fig. 9. It perfectly fits in the "axis symmetric" shape of which the view factors can be easily calculated, see Table 3. 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 material will degrade over time. Aging of these plastics, the correlation between aging time and aging temperature is described the principle of time-temperature superposition or equivalently introducing the effective time variable:

$$\begin{aligned} &\Delta t_{eff} = \Delta t / a_T \\ &a_T = exp\left[\frac{\Delta H}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \end{aligned} \tag{8}$$

where T is the temperature in K (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 h. Color changes in term of coordinates Δx and Δy is 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. 10.

Each part in the carrier product exhibits its own degradation. Fig. 11 depicts the testing results after approximately 4000 h 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,

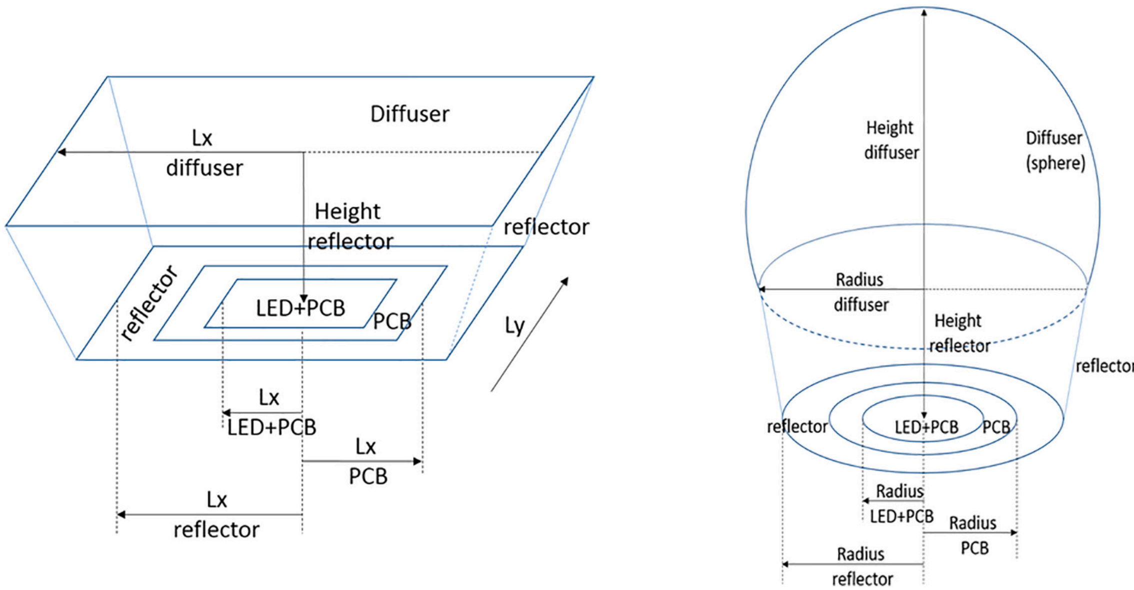


Fig. 8. Rectangular product geometry (left) vs axis symmetric product geometry (right).

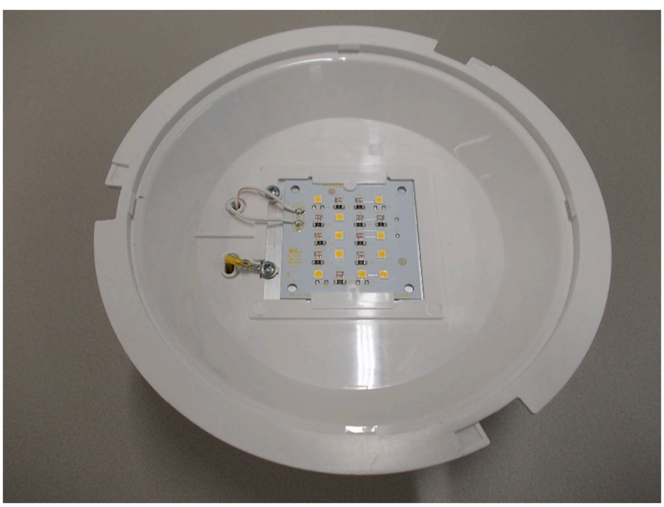


Fig. 9. Photo of carrier product with the diffusive flat exit window taken out.

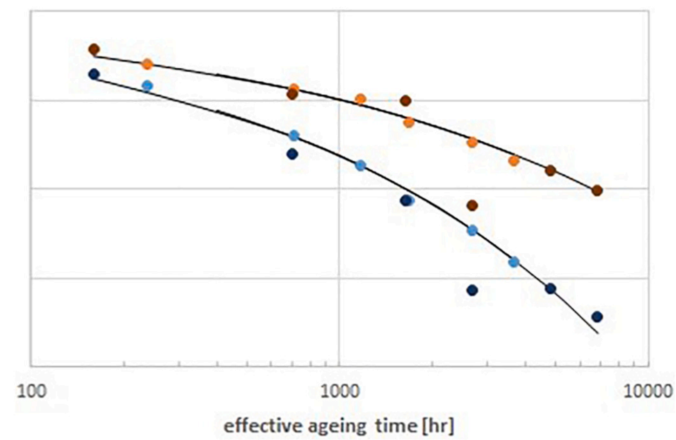


Fig. 10. Measured x (blue) and y (orange) color shifts for 2 carrier products with a reflector but without the diffuser. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Calculated view factors for the carrier product.

View factor [%]		From			
		LEDs	PCB	reflector	diffuser
To	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

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. 12 and 13. 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 yellowing “wins” even with 90 °C LED temperature and 70 °C reflector and exit window temperature. As the LED color shift is towards blue, the product color point first moves a bit towards blue and later moves in the opposite direction towards 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. 13 shows that lumen decay is most critical. But if one thinks of 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 develop 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.

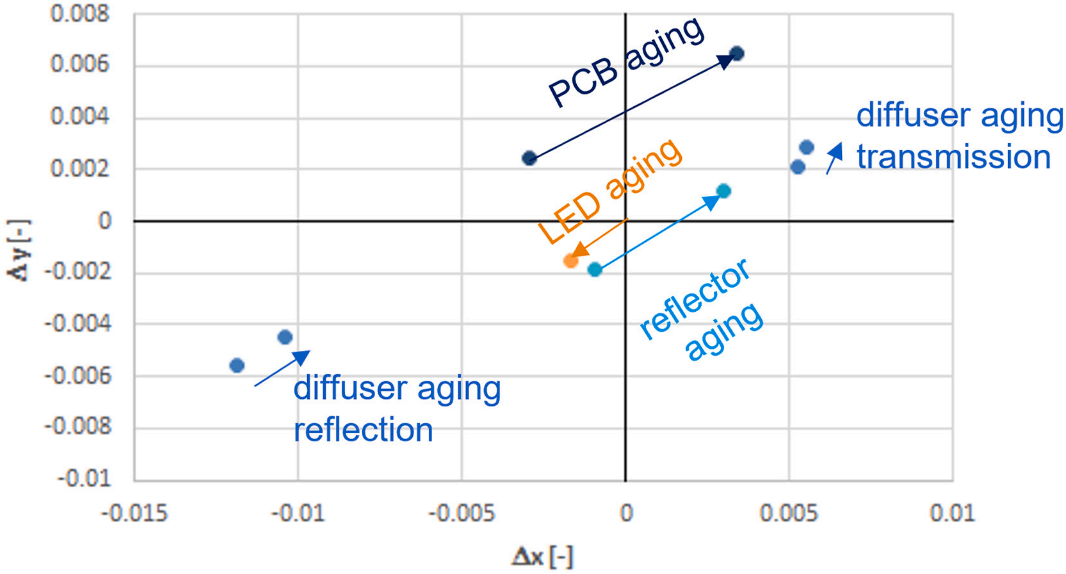


Fig. 11. Colors changes after ~4000 h testing in the product parts depicted in x, y color coordinates, indicated with an arrow.

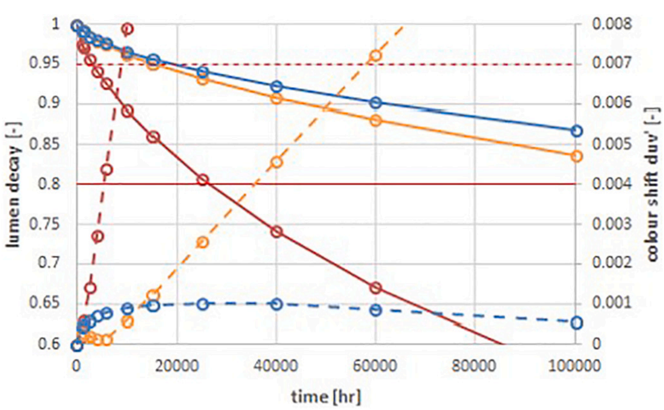


Fig. 12. Calculated uv′ color shift (dotted line) and lumen decay (solid line) as function of aging time. Red: all parts 110 °C; orange: all parts 90 °C; blue: LEDs 90 °C, PCB 80 °C, reflector & exit window 70 °C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

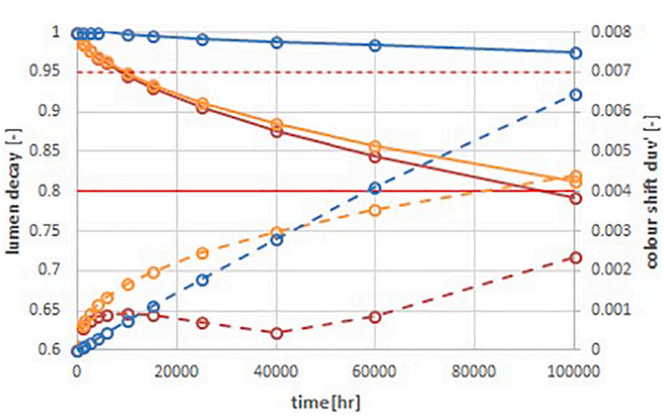


Fig. 13. Calculated uv′ color shift (dotted line) and lumen decay (solid line) as function of (aging) time; LEDs 100 °C, PCB 90 °C, reflector & exit window 80 °C. Red: all parts aging; orange: only LED aging; blue all but LED aging. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion & conclusions

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 is 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 paper, 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 towards 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.

CRediT authorship contribution statement

Willem D. van Driel: methodology, writing–original draft preparation
B. Jacobs: conceptualization, writing–review and editing, investigation
P. Watte: conceptualization, writing–review and editing, investigation
X. Zhao: conceptualization, writing–review and editing, investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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