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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 with-out 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/nanoelectronics 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.

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 [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, 5, 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.

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 discusses thirteen different types of failure mechanisms of LEDs based on previously published papers and opinions of experts in the LED industry [7, 8]. 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 [9, 10]. 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 [11]. 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 [12], 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 [14]. 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.*

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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 [14]. 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 Figure 1, 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.

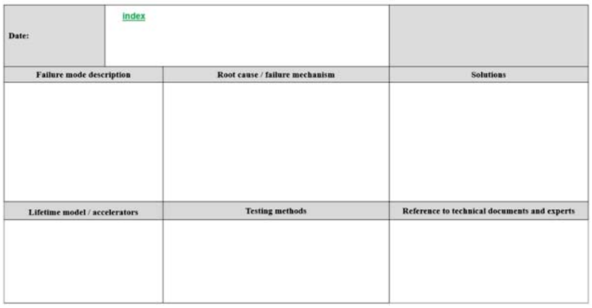
- Testing method

Following IEC62861 [13], or alike, which (accelerated) test provokes the failure mode?

- Reference to technical documents and experts

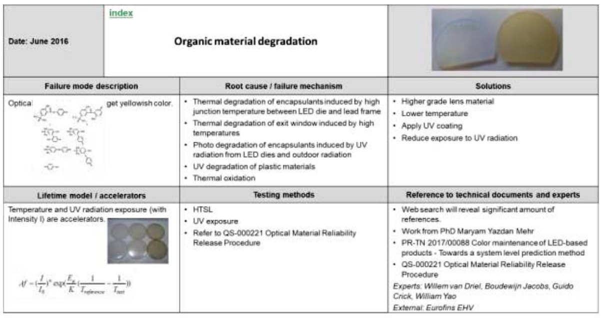
Internal or external document and/or experts are mentioned as touchpoints for further details.

A pre-filled example is shown in Figure 2: organic material degradation. This failure is well described in an open access review paper [15].



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

Figure 1: 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**
Optica[l] ... 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, Guido Crick, William Yao* *External: Eurofins EHV*

Figure 2: Summary sheet for the failure mode organic material degradation.

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 3 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 [16]. Eventually, a total number of approximately 130 unique failure modes is to be discovered.

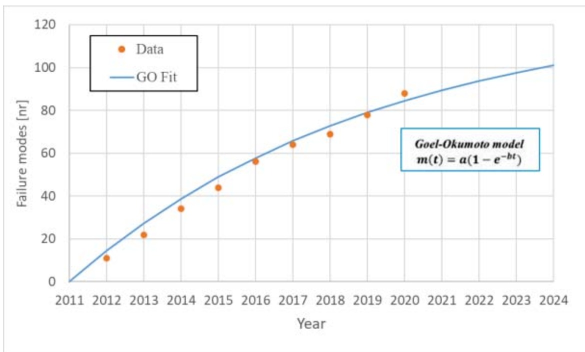


Figure 3: Number of unique failure modes as function of years.

Further data analysis is feasible as each unique failure modes is well described. Figure 4 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 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.
- 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.

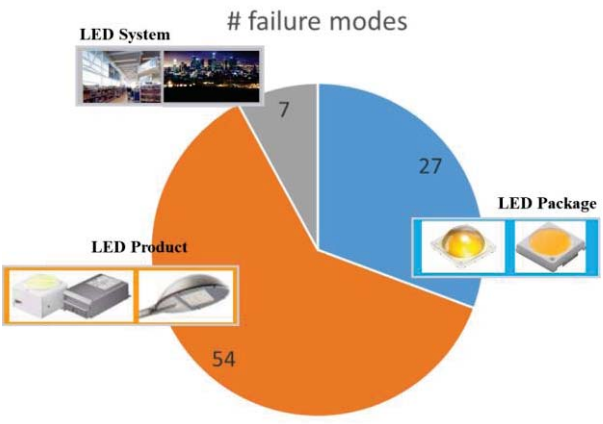


Figure 4: Pareto for the number of failure mode vs product type.

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

3. 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.

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