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Vos, T.; den Breeijen, P.; van Driel, Willem Dirk

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Chapter 1
Quality and Reliability in Solid-State Lighting: Qua Vadis?

T. Vos, P. den Breeijen, and Willem Dirk van Driel

Abstract In the past 4 years we have witnessed a change in quality and reliability to make the marked introduction of solid-state lighting (SSL) successful. LED penetration levels have reached values of 10–30%, depending on the application. The number and variety of LED packages and, thus, associated LED-based products, have significantly increased in the past years. Consequently, new processes and new materials are introduced which will introduce a new series of new and unknown failure modes in SSL products. The understanding of these failure modes is better understood, and the number has grown to beyond 50. The fingerprint is changing to failures that are due to interactions between components. First exercises with system level acceleration tests are presented, but it is important to derive acceleration models for these tests. Advanced reliability prediction capabilities are needed including algorithms and tools that couple the multi-physic and multiscale behavior of the SSL failure modes. The shift toward services will force the lighting industry to develop these capabilities in order to better address lifetime and reliability. Connected lighting will bring big data from live connections that can be used to determine the degradation level of the system. Both trends, service and connected, will bring yet another huge change in mind-set in the lighting industry when in concerns reliability: detailed understanding of failure mechanisms, usage scenarios, technology, and design will come together.

1.1 What We Predicted: A New Era in Lighting

In *Solid State Lighting Reliability: Components to System* we presented a chapter describing a brief history of quality and reliability, their interaction, and the impact for the change within the lighting industry into the solid-state era [1]. We mentioned

T. Vos • P. den Breeijen
Philips Lighting, HTC45, 5656 AE Eindhoven, The Netherlands
e-mail: tony.vos@philips.com; peter.den.breeijen@philips.com

W.D. van Driel (✉)
Philips Lighting, High Tech Campus, Eindhoven, The Netherlands

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

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that a huge mind-set change is needed in both quality and reliability to make the market introduction of solid-state lighting (SSL) applications a big success. Our final remark dealt with the challenge to embed known-good practices from industries such as semiconductors, automotive, military, and aerospace into the veins of the lighting designers. Let us in this paragraph reflect on what happened in the 4 years that elapsed; we focus on the reliability part and leave out the quality aspects of SSL. We first want to discuss three major observations from a market perspective that occurred in the past 4 years (our first chapter was published in 2013, see [1]).

First of all, in only 4 years of time we have seen a substantial change in the (traditional) lighting industry. The three major lighting companies in conventional technology, Osram, Philips Lighting, and General Electric (GE) Lighting, made substantial changes in their enterprise architectures. This is mainly due to the upcoming competition by other parties able to develop, manufacture, and sell LED-based products at competitive price levels. For example, the ascension of Chinese manufacturers in recent years has pushed down LED bulb prices considerably. The same trend occurred for professional luminaires, both for indoor and outdoor applications. In the past years GE, Osram, and Philips Lighting published a series of public announcements, just to highlight a few of them:

1. GE's 125-year-old lighting business has been the backbone of the organization's foundation since 1890 when Thomas Edison founded the company. In October 2015, GE announced it would be spinning off its commercial LED lighting business, solar energy, and energy storage devices into a new start-up company [2]. In 2016 GE said farewell to the compact fluorescent light, or CFL [3]. Here, the company announced in February 2016 that it would stop making and selling these bulbs by the end of the year.
2. German lighting giant Osram announced in 2015 to spin off of its lamps business into LEDVANCE. LEDVANCE encompasses Osram's lighting brand values in the conventional and LED lighting businesses sectors. Osram completed this organizational separation as of April 2016, while the legal separation was scheduled in July 2016 [4].
3. Royal Philips announced in 2015 to spin off its "historical" lighting business [5]. Effectively on January 2016, Philips Lighting ended up as an initial public offering (IPO), which will result in the listing of the lighting business on the Dutch bourse, and aims to sell at least 25% of its shares in the lighting company [6]. The Dutch conglomerate started making light bulbs 123 years ago, where Gerard Philips and his father Frederick founded one of the earliest makers of incandescent light bulbs in 1891. Besides this, Royal Philips also intends to divest in their LED components and automotive lighting business, named Lumileds.

These are just a few of the announcements we have seen passing in the past 4 years. It indicates that the transition from conventional lighting into SSL truly resulted into a new era for the lighting industry.

Secondly, SSL has the promise of an increased reliability with an energy-saving opportunity, and we mentioned in the first chapter that SSL applications are now at the doorstep of massive market entry. But what are then the current volumes and penetration levels of LED-based products in the different application domains, and did they significantly increase? This question is answered by the DOE reports Energy Savings Forecast of Solid-State Lighting in General Illumination [7, 8]. There are seven iterations of the *Energy Savings Forecast of Solid-State Lighting in General Illumination*. Just recently, the 2016 report was published [8]. Here we only discuss this report and the one from 2014 [7]. LED lighting is projected to gain significant market penetration. Of the eight submarkets examined, they forecast that LEDs will grow most rapidly in the street and roadway and general service submarkets in terms of the percentage of total lumen-hour sales. Scenarios estimate the expected future adoption of LEDs based on historical data and the current trajectory for the technology. In the 2016 report, LEDs are predicted to comprise over 90% installed penetration by 2025 and nearly 100% by 2035. When one compares the 2016 forecast with the earlier one in 2014, it can be noted that the penetration is a bit slower. Take, for example, the street and roadway submarket, already a popular area for LED upgrades. In the 2014 report, LEDs are predicted to reach 83% market share of sales by 2020 and nearly 100% by 2030 [7]. In the 2016 report these values are 60% and 88%, with a 100% not to arrive before 2035 [8].

Penetration projections dating from December 2012 forecasted that LEDs will reach a level of 84% in 2020. This number represents the estimated LED market penetration between 2010 and 2020. In 2014, light-emitting diodes were expected to reach a penetration into the lighting market of approximately 11%.

Figure 1.1 depicts these three projections indicating the fact that LED penetration is growing rapidly but not as fast as one once thought. Following these

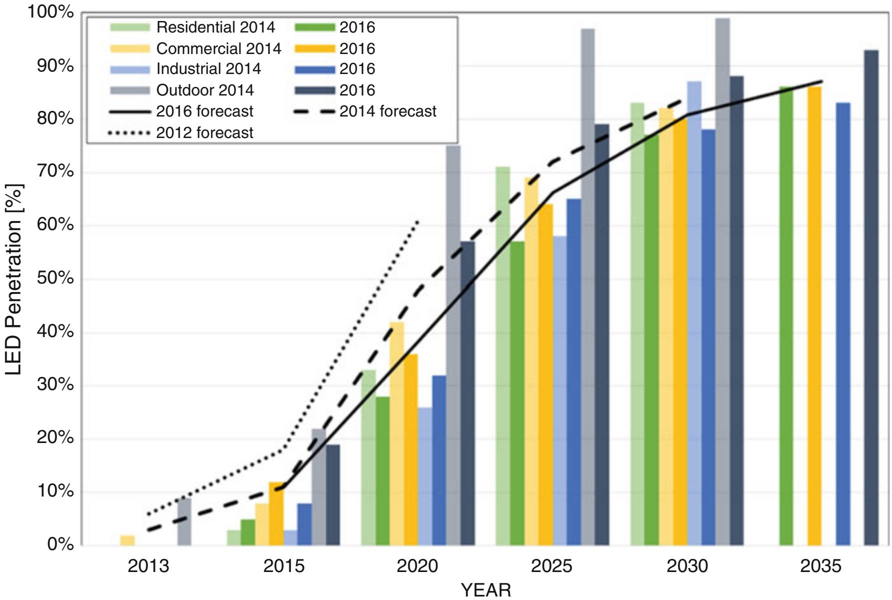


Fig. 1.1 LED penetration levels in four applications; *blue line* indicates overall trend (DOE data from [7, 8], 2012 data from [9]; with permission)

projections, the 2013 and 2017 numbers are <10 % and 20–30 %, respectively. It means a 2–3 times increase since 4 years. Remind that these are projections, and signals from countries and/or companies should underline them. For example, in June 2015 it was reported that Japan was the first country in the world to use LED lighting and with penetration rates for the home market exceeding 90 % [9]. GE's announced LED revenues soared 77 % during the second quarter in 2016 [3]. Philips Lighting announced LED lighting sales grew strongly by 27 % and now account for 50 % of the overall lighting sales [10]. But be aware that booming revenue figures in the LED business can be misleading as sharp price declines for LED-based products impact the margins on these products.

The third observation is the following one. The number and variety of LED packages and LED arrays have significantly increased in the past 4 years. This is mainly due to the fact that the LED supplier landscape is exploding; see Fig. 1.2 for just a snapshot. High-power LEDs are replaced by mid-power LEDs in the consumer products, chip-on-boards (COBs) were introduced, and low-power LEDs are currently introduced. The power consumption ranges from low-power LEDs that operate at less than 0.05 watts per package to COB that can consume over 50 watts per module. However, an agreed or standardized package outline for all these LED variants still does not exist. In the semiconductor industry, JEP95 is a compilation of some 1,800 pages of outline drawings for microelectronic packages including

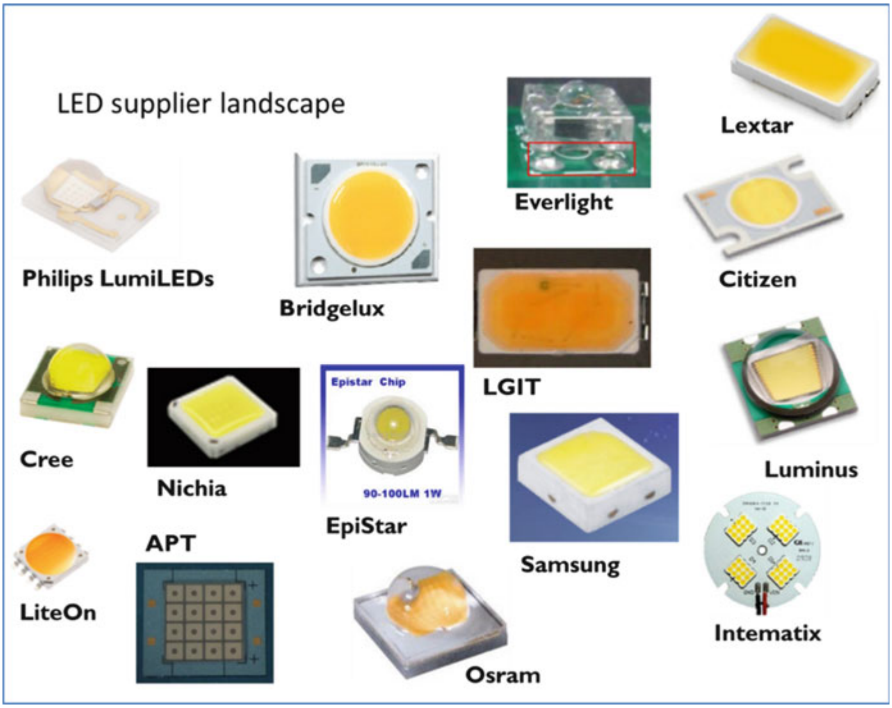


Fig. 1.2 The LED supplier landscape is exploding. Just a short list of companies providing LED packages. It resulted in an increased variety of LED packages

transistors, diodes, DIPS, chip carriers, and package interface BGA outlines in both inch and metric versions [11]. It facilitates easier product design and second sourcing of particular package types. In the LED industry the inexistence of such a standard (read, agreement) means that where one LED supplier offers a 2×3 mm ^{2} leadless package, it can completely differ from another supplier. The consequence of this is a corresponding increase in the number of LED replacement lamps and LED luminaires that are available. Also here, we see an explosion of offered solutions and products. And, consequently, new processes and new materials which will, as we wrote in [1], always introduce a series of new and unknown failure modes.

1.2 What Is the Current Status?

Since 2013, the understanding of the degree to which LED drive current and operating temperature affect product reliability is better understood. Failure modes, mainly originating from the semiconductor industry, are better understood and under control. Better designs are the positive outcome; however, still a wide range of design choices to meet specific application and market needs are required, hence a potentially wide range of product reliability. On top of that, other sub-systems and components in a luminaire, e.g., sensors and controls, introduce other potential failure modes which will affect and may actually dominate the determination of its reliability. In 2014, the Lighting Industry Alliance LED Systems Reliability Consortium (LSRC) identified potential failure modes for SSL products. The LSRC members scored the failure modes they most frequently observed [12]; the resulting Pareto plot is shown in Fig. 1.3. Failure of the light source, in this case LEDs, is only 20 %. This result underlines our earlier statements:

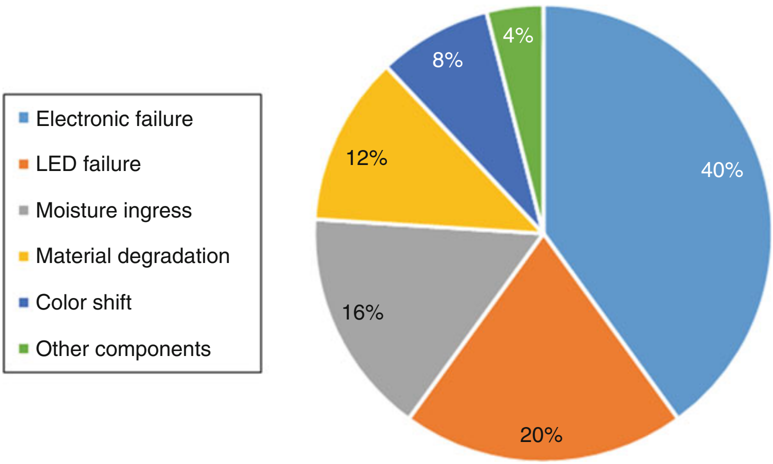


Fig. 1.3 Pareto plot of scored failure modes by the LSRC (Data from [11], with permission)

> There is a clear shift in the reliability budget for SSL applications: with the introduction of SSL it is no longer the light source that is the limiting factor for the product life.

In 2013, we mentioned that the amount of failure modes for SSL products would easily be larger than 30 [1]. They would partly be inherited from the semiconductor industry, as described in JEP122F [13]. In those days we did not know the effect of such failure modes on to the specifics of a SSL system. Simply due to the fact that the relation of them to the quality of light was unknown. Take, for example, the failure mode *wire bond fatigue*. In JEP122F [13] it is described as a:

> Wire bonds can break under temperature cycle, the mechanism are well modeled by Coffin-Manson or Paris power law models.

For LED-based products, however, we learned that the effect of a wire bond failure can have a more complex effect on a system level:

1. A wire bond failure leads to an open electrical structure.
2. It is quite common to design serial strings of LEDs; thus, if one fails, then the total string is giving no light.
3. In parallel designs with serial LEDs strings this will lead to black spots in the product.

Figure 1.4 schematically represents this situation in the middle picture: if single LEDs fail, the light distribution will be affected, either by showing blacks spots, by changing the color, or by a decreased lumen output. Other typical semiconductor failure modes, such as fatigue and/or interfacial failures, may lead to the same effects [14].

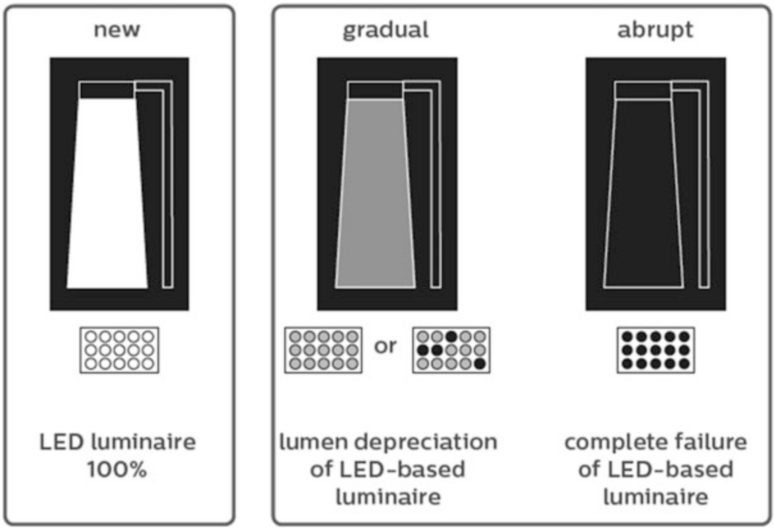


Fig. 1.4 Failures in LEDs can have unexpected effects on the lighting function

In the past 4 years, the industry learned how semiconductor failures interact within lighting products. Note that some of them could not be captured before affected products entered the market. This is quite logical if you consider the introduction of a totally new technology. The consumer product safety commission [15] lists the number of unsafe products that have entered the market. Searching for those that contain LEDs results in approximately 19 cases in the past 4 years. Main reasons are (i) impact hazard, (ii) burn hazard, or (iii) shock hazard. The largest one, that is, the one with the highest amount of affected products, comes from a large LED manufacturer, recalling >700,000 LED T8 lamps in the USA and Canada due to the risk of burn hazard [16].

Obviously plenty of failure modes do not lead to unsafe products. They are detected during the design phase of SSL products. Extensive testing, by using accelerated conditions, will reveal weaknesses in to-be-launched products [17]. Figure 1.5 depicts a so-called word cloud with failure modes in SSL products as seen in 2013 (gray) and appearing in the period after until 2016 (black). Here, the word size reflects the impact, which is common for such pictures. Figure 1.6 depicts the same

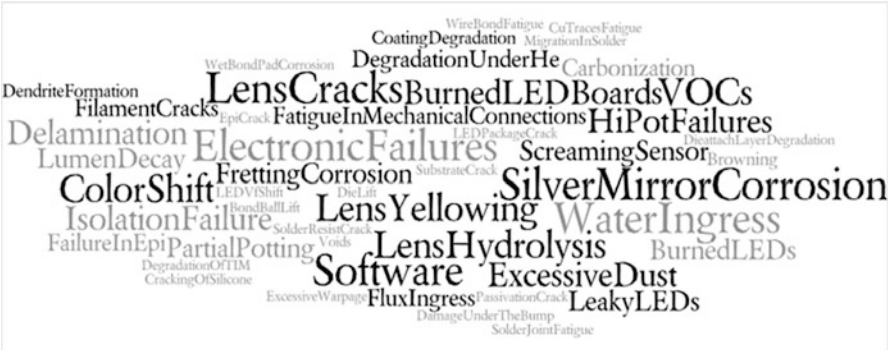
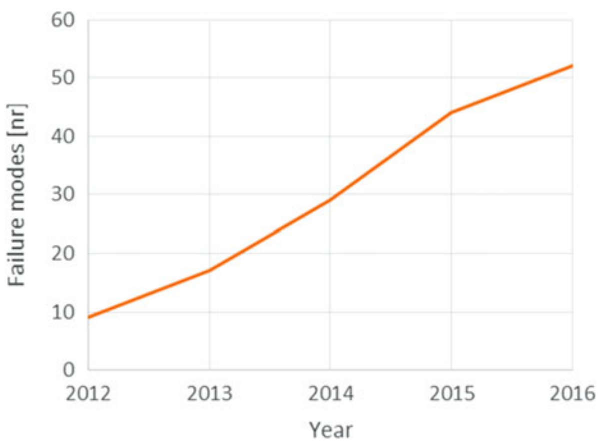


Fig. 1.5 Failure modes in SSL products: as seen in 2013 (*gray*) and appearing in the period after until 2016 (*black*). Word size reflects the impact

Fig. 1.6 Number of failure modes in SSL products versus the year detected



information in a more traditional kind of showing them: a line graph for the number of failure modes in SSL products versus the year detected. What can be seen in these figures is that since the past 4 years the amount of failure modes has more than doubled. Also our earlier forecast of >30 failure modes [1] was easily achieved, and a number of >50 are met. On average ten new failure modes per year were found, but this growth seems to decline in the last years. In semiconductor industry it is believed that one new failure mode is expected per year [18]. Here, the fingerprint changed from single mode failures to those that are due to interactions between components making it difficult to detect the root cause. Looking at the past 4 years, the SSL industry is slowly but gradually moving to that pace.

Finally we raised the question that the promising lifetime numbers of 50.000 and higher burning hours are great, but how does one cover that? It needs accelerated test conditions both on product and component level which is a totally new approach for the lighting industry. A first exercise in this direction was performed by the LED Systems Reliability Consortium [19] by conducting the so-called Hammer Tests. The Hammer Test was to serve as a highly accelerated stress test (HAST) method that would produce failures in SSL luminaires in a reasonable test period (defined as less than 2,000 h of testing). It was set up solely to provide insights into potential failure modes in SSL products. One loop of the Hammer Test consists of four stages of different environmental stresses, and each stage was modeled after common stress tests used in the microelectronics industry. Cumulatively, one loop of the Hammer Test lasted for 42 h, with each stage presenting a stress comprising variations in heat and humidity. Electrical power was cycled on and off during the Hammer Test and provided an extreme stress environment for the luminaires. The acceleration factor of the test was estimated at 30 or higher, depending on the actual application conditions. The testing protocol was exposed to seven commercial SSL luminaires. The results were very surprising [19]. The failures typically occurred in the driver circuit, and the 611 tested LEDs endured nearly 1 million hours of cumulative exposure with only four failures. These findings reinforce the need to consider a systems-level approach, including LEDs, drivers, optics, and other components.

1.3 What's Next: SSL Reliability, Qua Vadis?

Quo vadis is Latin for *where are you going?* According to the legend, it was the apostle Peter who first used these words, by then in a more religious meaning. Here we want to highlight the topics in the coming years that are important in the context of SSL reliability.

The first item worthwhile mentioning is acceleration models. There is a significant need for the creation of appropriate acceleration models for the SSL failure modes mentioned in the previous chapter. We can use the existing models, such as Arrhenius, Coffin-Manson, Norris-Landzberg, Peck, and/or Generalized Eyring, but they need to be tuned to lighting products. A working group in the International

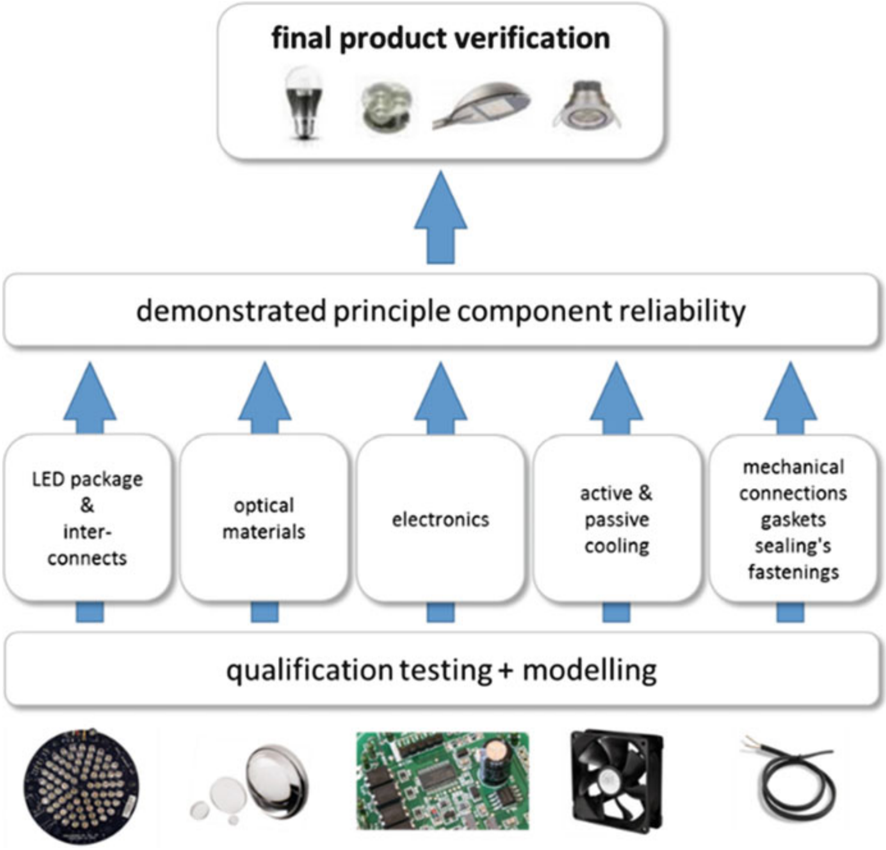


Fig. 1.7 Principal component reliability testing and demonstration on final product level

Electrotechnical Commission (IEC), known as IEC62861 [20, 21], has initiated the work to create a so-called guide to principal component reliability testing for LED light sources and LED luminaires. The group started in 2013, and a final version will appear in due time. Figure 1.7 depicts the principle behind this activity. The guide specifies minimum stress test-driven qualification and reliability requirements for the principal components of LED products. The purpose is to give guidance establishing a level of reliability for which a product is specified. What the exact level is depends on the product specification and depends on the application profile. Acceleration models are needed to project the accelerated test conditions to the application profiles. The publication of this document will certainly give a boost to the required creation of acceleration models.

A second point worthwhile to mention is concerning predictive reliability modeling capabilities. This does not only need advanced modeling theories, algorithm, and tools but also coupling of them and inclusion of the time factor in order to fulfill the reliability demand. Figure 1.8 depicts the currently available toolset for

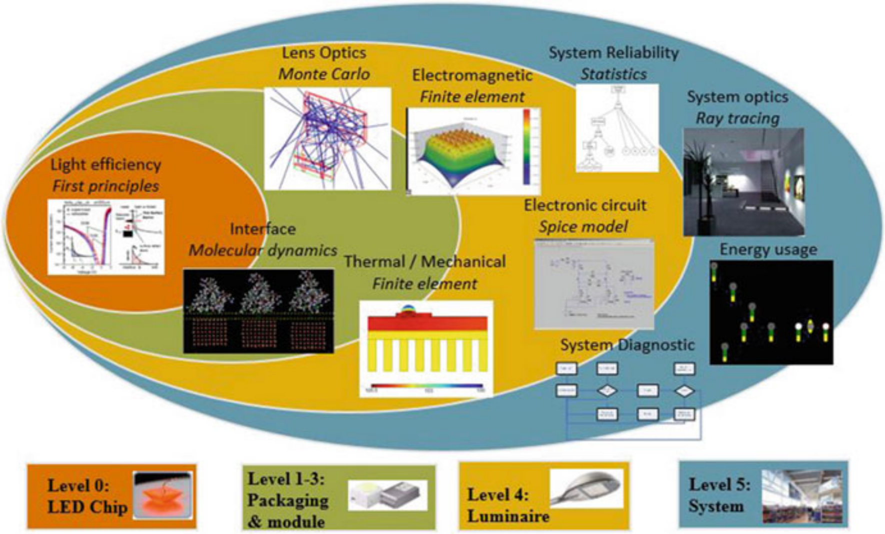


Fig. 1.8 The prediction landscape for SSL products. Coupling and inclusion of time are needed to cover reliability predictions (Courtesy by C.A. Yuan, [22])

SSL product reliability among the different levels from LED chip, package, to complete system. Clearly, tools do exist and are used by academia and industry, but direct coupling of them and inclusion of time need further attention.

Although finite element modeling (FEM) is a well-established technique for predicting thermomechanical behavior of product/process [18], they are not specifically developed for applications and needs of SSL systems. GaN chip is already manufactured to feature size down to several micrometer and nanometer, and also modeling the light output of GaN requires knowledge from across different field such as quantum efficiency and their interaction between different loading conditions. Hence, beyond-continuum mechanics modeling tools such as multiscale modeling tool that will incorporate both molecular dynamics and quantum mechanics need to be developed.

On top of this no coupling of available FEM techniques with traditional ray-tracing tools exists. For packaging and module-level modeling, FEM is a well-established technique for predicting thermomechanical behavior of the LED packages. However, since the performance of LEDs is highly dependent on the light quality, there is a need to develop techniques that could predict the light behavior in the optical system as the package degrades. The multiscale modeling platform (MMP) is part of the EU Multiscale Modeling Cluster of FP7-funded projects on multiscale modeling for nano-materials and systems by design [22]. This cluster unifies EU projects that have the ambition to develop an open, integrated, and multipurpose numerical nano-design environment. The cluster is intended to enable knowledge exchange, foster adoption of novel approaches for multiscale modeling and provide a platform for harmonizing standardization or interoperability. The first results of this EU project were presented in 2016 at the EuroSimE conference [23, 24]. Tapaninen et al. [25] presented a test case for coupling two physical aspects of an LED, optical and thermal, using specific simulation models coupled through an open-source platform for distributed multi-physics modelling. They showed how to connect a Mie theory-based scattering calculator with ray tracing. Alexeev et al. [24] followed this approach by connecting a ray-tracing model for the light conversion in LightTools® to a thermal model in ANSYS®. Tarashioon et al. [26] introduced a multi-physics reliability simulation approach for solid-state lighting (SSL) electronic drivers. This work explored the system-level degradation of SSL drivers by means of applying its components' reliability information into a system-level simulation. An automatic coupling between electrical simulations in SPICE® with thermal simulations was established in order to perform thermal-electrical reliability predictions. Sun et al. [27] continued this work by improving the thermal part through automatic coupling with ANSYS®. These multi-physics modeling attempts are needed to cover the grand challenge for reliability modeling in SSL, simply because all failure modes and mechanisms, such as electronic drift, browning, coating degradation, color shift, lumen decay, water ingress, corrosion, etc., are results of strong multidisciplinary interactions. More effort should be spent on the development of sophisticated (multi-physics and multiscale) models, efficient numerical algorithms, and user interfaces, code integration methods, as well as advanced computational techniques.

A last important point is the fact that several lighting companies are shifting toward services and/or are increasingly integrating their products and services to offer "integrated solutions." Shifting toward services is attractive because they provide a continuous revenue stream. It has become the new way for some of the world's leading companies to achieve success, e.g., IBM, GE, and Ericsson [28]. Innovating with services brings challenges for high-technology industries or traditional goods industries [29, 30]. One of these challenges is related to reliability and lifetime [31]. Here, lifetime can be thought of as the time by which the product reaches end of life. As such, the service contract length is determined based on the product lifetime, and reliability is replaced by dependability: a measure of system's availability, reliability, and maintainability [32]. A high reliability will always lead to a high availability, but a system with low reliability can still have a very high availability. In the latter case, appropriate scheduling of maintenance will be key for the service overall performance and thus its success.

Next to the shift toward services, as a result of the continuous growth in the utility of disruptive technologies, companies are also enabled to shift more toward an information-based environment [33]. As a result of a radical transformation in the SSL industry – the adoption of digital technology and LED – traditional lighting is shifting toward connected lighting. Hardware is increasingly becoming a source of information with the introduction of, e.g., sensors. The use of information from all these sources can be described as a revolution named *big data*. Big data will cause a fundamental change in the basic reliability concepts. In a classical reliability approach the results from (accelerated) tests are used to obtain conservative bounds of failure rates. With big data, data analytics from live connections of "intelligent" systems can be used to determine degraded performance. This will trigger scheduled maintenance and/or replacement of the (sub)system. Service in the lighting industry will move into the prognostics regime where a detailed understanding of failure mechanisms, usage scenarios, technology, and design comes together.

1.4 Final Remarks

In the past 4 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 will continue 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. Gradually but slowly, the term reliability will be replaced by availability, and "smart" maintenance will distinguish good from bad products.

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