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Reliability of LED-based Products is a Matter of Balancing Temperatures

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Abstract

Solid State Lighting (SSL) technologies and products are gradually pervading into our daily life. An SSL system is composed of a LED engine with a micro-electronics driver(s), integrated in a housing that also provides the optical, sensing and other functions. Knowledge of (system) reliability is crucial for not only the business success of the future SSL applications, but also solving many associated scientific challenges. In practice, a malfunction of the system might be induced by the failure and/or degradation of the subsystems/interfaces. Extra costs, in terms of additional efforts/designs/parts, have been considered in order to secure the guaranteed reliability performance of SSL system. Most of SSL system designs, which allow few failures of the subsystem/interface during the application period, can be achieved with significant cost reduction when the (system) reliability is well understood by proper experimental and simulation techniques. Our keynote will address the items to ensure high reliability and thermal management of SSL systems and set out the challenges for good thermal management, high performance, and reliable SSL systems.

1 Introduction

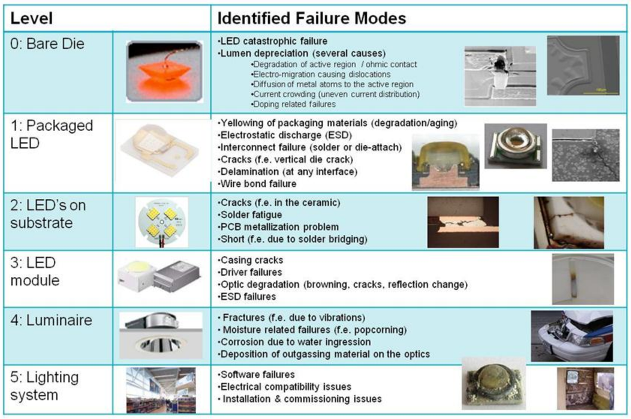
Solid state lighting (SSL) is recognized as the second revolution in the history of lighting. The main reason is the annual global energy bill saving of €300billion and a reduction of 1000MT of CO2 emission. As such, the SSL industry is expected to exceed €80 billion by 2020, which will in turn create new employment opportunities and revenues. A second reason is the promise of a long useful lifetime, with claims up to 80,000 hours. Lifetime here refers to the period of time during which something is functional and is a derivate from the reliability performance of the product. As with any products, the consistency and reliability of SSL systems need to be ensured before they can be adopted in any application. To add to the complexity, there is also a need to ensure that the cost of this technology needs to be comparable or even lower than the current technology for them to be adopted in these applications. Although SSL systems with low reliability requirements have already been developed, they can only be used in applications that operate in modest environments or in non-critical applications. For demanding applications in terms of environmental conditions such as automotive application, or where strict consistency is needed, such as healthcare applications and horticulture applications, the conventional lighting sources are currently still preferred until the reliability of SSL is proven in these applications. Therefore, knowledge of reliability is crucial for the business success of SSL, but is also a very scientific challenge. In principle, all components (LEDs, optics, drive electronics, controls, and thermal design) as well as the integrated system must live equally long and be highly efficient in order to fully utilize the product lifetime, compete with conventional light sources and save energy. The link between thermal design and reliability is obvious: the higher the temperature on the components and/or (sub) system, the lower the lifetime expectance. Thermal management is one of the key features to control the reliability of an SSL system.

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

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

2 SSL Reliability and Thermal Management

New technologies, processes and materials will always introduce a series of new and unknown failure modes. In this particular case, the ones that are known from semiconductors are directly imported into the lighting products. Semiconductor failure modes are well described [1], but their relation to the quality and reliability of light is not known. LED-based products performance strongly relies to its lumen depreciation in which the light source gradually but slowly degrades over time. Experiences with these new modes need to be built using both life time tests and accelerated tests like HALT, MEOST and other techniques [2]. And need to be combined with a theoretical approach in order to describe product performance in application



Level	Identified Failure Modes
0: Bare Die	·LED catastrophic failure ·Lumen depreciation (several causes) ·Degradation of active region / ohmic contact ·Electro-migration causing dislocations ·Diffusion of metal atoms to the active region ·Current crowding (uneven current distribution) ·Doping related failures
1: Packaged LED	·Yellowing of packaging materials (degradation/aging) ·Electrostatic discharge (ESD) ·Interconnect failure (solder or die-attach) ·Cracks (f.e. vertical die crack) ·Delamination (at any interface) ·Wire bond failure
2: LED's on substrate	·Cracks (f.e. in the ceramic) ·Solder fatigue ·PCB metallization problem ·Short (f.e. due to solder bridging)
3: LED module	·Casing cracks ·Driver failures ·Optic degradation (browning, cracks, reflection change) ·ESD failures
4: Luminaire	· Fractures (f.e. due to vibrations) · Moisture related failures (f.e. popcorning) ·Corrosion due to water ingression ·Deposition of outgassing material on the optics
5: Lighting system	·Software failures ·Electrical compatibility issues · Installation & commissioning issues

Figure 1: Solid state lighting failure modes [3].

The lighting industry does not have the installed reliability testing base that is needed to cover the promised lifetimes. Even more, there are no test standards available with appropriate pass/fail criteria for the (key) components and/or SSL products. Relationships with material and component suppliers need to be tightened, as is the case in the automotive industry, in order to share the responsibility for the product quality and reliability. In other words: a huge mind-set change is needed in reliability to make the market introduction of SSL application a big success. Within the SSL Reliability and Thermal Management domain, 4 challenges are identified:

- Component Reliability

Component reliability refers to the performance over time of the individual key-components in a system. Each system can just last as long as it's lowest life component. Key-components in a SSL system are the LED package, the optics, drive electronics, controls, thermal design, connectors, sealants and other plastics. Currently, only the IES standards [4 – 6] are available to address the performance of the LED package components.

- System Reliability

System reliability refers to the probability that a system, including all hardware, firmware, and software, will satisfactorily perform the task for which it was designed or intended, for a specified time and in a specified environment.

- Reliability Modelling and Prediction

Reliability modelling refers to the process of predicting or understanding the failure modes of a component or system prior to its implementation by using multi-physic techniques. Reliability prediction refers to forecasting the reliability performance of a component or system by using statistical techniques.

- Thermal Management

Thermal management refers the use of various temperatures monitoring devices and cooling methods, such as heat sinks and/or forced air flow, within a system, to control the overall temperature of components. The traditional incandescent light bulbs operate relatively predictably since the lamp characteristics and life are not affected by the luminaries' structure nor there is a need for strict operating temperature requirements. Furthermore, heat can be easily dissipated in the form of radiation. This scenario is completely different in LED technology as heat can only be removed to the surrounding via conduction or convection. Furthermore, due to the drive for high brightness LED, higher electrical currents are needed for driving brighter LEDs and this will cause significant heat generation in SSL systems. For example, the chip heat fluxes are expected to be in excess of 100W/cm2 by 2018 whereas microprocessors have an average heat flux of about 10-50W/cm2 (in 2008). This will have detrimental effects on the maximum light output, efficiency, quality, reliability and the lifetime of the SSL systems. Hence, thermal management is a key design consideration in terms of their cost and performance. Thermal management of systems strongly depends on the architecture, the materials, geometric dimensions and overall cooling strategy. The key challenges are:

- Advanced LED package thermal management methodologies
- Novel thermal architectures for SSL systems
- System level compact thermal modelling techniques
- Design for thermal management tools
- Standardization of thermal measurements

In the next paragraph we describe two cases where thermal management influences the component reliability performance.

3 Discoloring of Optical Components

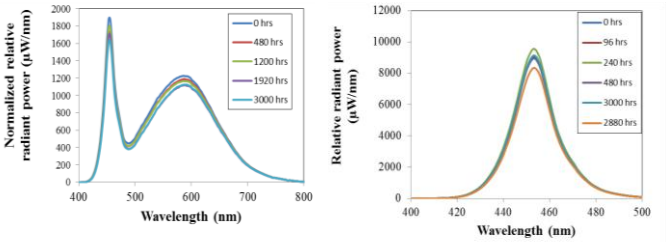
Temperature is a very significant controlling parameter in LED reliability. High temperature levels can damage the optical properties of the package and of the material used for the lens and remote phosphor [7-11]. This can result in a significant reduction in the luminous flux, emitted by the devices. Two types of 3 mm-thick plates which are the lens plate and remote phosphor in which the phosphor is laminated on the same lens are used in this study. The Correlated Colour Temperature (CCT) of remote phosphor is 4000 K. The samples were aged under high temperature stresses at 100, 120, and 140 ºC for 3000 h. Testing temperatures for accelerated lumen depreciation test is determined in such a way that the temperature does not go above the glass transition temperature of the plastics. Optical properties of thermally-aged plates were studied at room temperature, using an integrated sphere. Spectral power distribution (SPD) method is used to study the effect of high temperature stress test on the optical degradation of both PC lens and remote phosphor, i.e. Luminous flux depreciation. Reliability model for the life time assessment is based on an exponential luminous decay equation, where the time-to-failure can be calculated as [6],

$$\phi(t) = \beta \exp(-at) \tag{1}$$

where *Φ(t)* represents the lumen output, *α* is the rate of reaction or depreciation rate parameter, *t* is time and *β* is a pre-factor. When lumen output, Φ, is equal to 70%, *t* is time-to-failure [12]. The rate of reaction, *α*, is related to the activation energy of the reaction and to the ageing temperature as follows [6].

$$a = A\exp\left(\frac{-E_a}{KT}\right) \tag{2}$$

where *A* is a pre-exponential factor, *Ea* is the activation energy (ev) of the degradation reaction, *K* is the gas constant, and *T* is the absolute temperature (K). Figure 2 illustrates the spectral power distribution (SPD) of both lens and remote phosphor plates for the case of thermal ageing at 140 °C. It is obvious that there is a reduction in blue light transmission (450 nm) and also the phosphor conversion yellow light (600 nm).



a B

Figure 2: Spectral power distribution (SPD) of a) Remote Phosphor, and b) Lens, aged at 140 ºC

One can see that the reduction in the blue peak has almost the same trend in both lens and remote phosphor.

Figure 3 illustrates more details of the effects of thermal-stress on the performance of remote phosphor and lens. This figure shows the evolution of the normalized flux intensity and the degradation rate of the phosphor plates and lens plate. Clearly, the degradation rate shows a significant dependence on the stress temperature level in both plates, the higher the ageing temperature, the higher the lumen depreciation and the degradation kinetics. It is also noticeable that the extent of degradation in remote phosphor plates is more than that of lens plates.

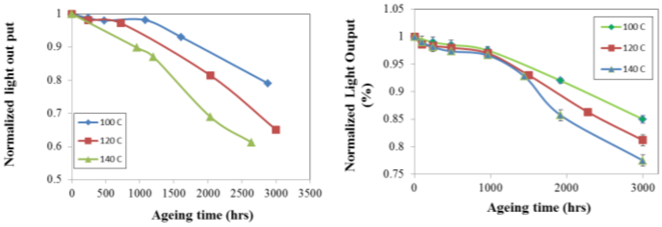


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Figure 3: Normalized flux of a) remote phosphor plates, and b) Lens at 100 up to 140 °C

According to the alliance for solid state illumination system and technology (ASISST) standard, lifetime of LEDs is defined as time to reach 70% of its initial lumen output [12].The lumen output is extrapolated to higher depreciation by the model that is explained in our previous paper [13]. Table 1 illustrates the calculated values for the reaction rate (a) or ageing kinetics for each temperature for remote phosphor plates and lens. Obviously, by increasing the temperature the reaction rate becomes faster, inferring that shorter time is needed to reach the same level of lumen depreciation.

Table 1: Reaction rate a for remote phosphor plates A and lens at temperature up to140 °C

Temp (C)	Remote Phosphor	Lens
40	1.03E-05	1.97E-06
60	2.15E-05	4.73E-06
80	4.12E-05	1.03E-05
100	7.38E-05	2.0 E-05
120	1.24E-04	4.0 E-05
140	2.0E-04	6.5E-05

Thermal-ageing test also have some important effects on the CCT. The variation of CCT during high temperature stress test is shown in Figure 3. It is seen that CCT decreases by increasing the thermal ageing time. One can also notice that the higher the ageing temperature, the higher the degradation kinetics. The reduction in CCT follows the same kinetics as the luminous flux decay and can therefore be ascribed to the thermally activated degradation mechanism discussed above. The reduction in color temperature suggests that the degradation of the remote phosphor plates has consequences not only on the light conversion efficiency of phosphor but also on the discoloration of the BPA-PC.

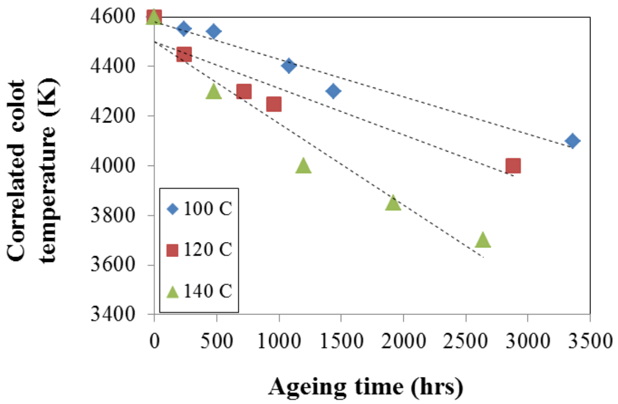

Figure 3: Correlated colour temperature (CCT) variation during high thermal-stress tests

4 Discussion and conclusions

SSL reliability is a challenging task, mainly due to

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

With the current pace of SSL industry development, there is an urgent need to address the (long-term) design for reliability of SSL systems. No question about it that thermal management will be a key challenge in meeting this need.

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