

## Reliability and Lifetime Assessment of Optical Materials in LED-Based Products

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# Chapter 5

## Reliability and Lifetime Assessment of Optical Materials in LED-Based Products

M. Yazdan Mehr, Willem Dirk van Driel, and Guo Qi Zhang

**Abstract** Lumen depreciation is one of the major failure modes in light-emitting diode (LED) systems. It originates from the degradation of the different components within the system, including the chip, the driver, and the optical materials (i.e., phosphorous layer). The kinetics of degradation in real-life applications is relatively slow, and in most cases, it takes several years to see an obvious deterioration of optical properties. A highly accelerated stress testing (HAST) setup and a methodology to extrapolate the results to real applications are therefore needed to test the reliability of LED package and lens materials. Employing HAST concept in LED industry is inevitable due to the necessity of assessing the reliability of new products in a short period of time. This chapter aims at briefly explaining the degradation mechanism of optical components in LED package and how they contribute to the lumen depreciation of the LED package. The concept of HAST and the way the reliability of LED packages can be assessed will also be explained.

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## 5.1 LED and the LED Landscape

Solid-state lighting (SSL) technology is known as a revolutionary invention in the history of lighting industry. Light-emitting diodes (LEDs) are used as source of illumination in solid-state lighting systems. The first practical LED, made from GaAsP semiconductor, was invented in 1962 [1]. The blue LED (GaN semiconductor) was then invented in 1993 [2]. The first commercial white LED was introduced to the market in 1997, using blue LED [3]. Since then the LEDs have become a credible alternative and competitor to incandescent and fluorescent lamps. Recently due to technological improvements of the LED designs, the high-brightness LEDs (HB LEDs) with higher output lumen flux are introduced to the market. The multiple benefits of LEDs, including compactness, output, and color adjustment, and the continuous increase in their performance have made them competitive to fluorescent lamps and tubes. One of the advantages of LEDs over conventional lighting systems is its relatively longer lifetime. A common incandescent lamp has an average lifetime of around 1,000 h, whereas the fluorescent lighting technology has an average lifetime of about ten times longer than incandescent light, which is around 10,000 h. The present LED lighting devices have an average lifetime of around 25,000 h with the potential of reaching up to 50,000 h lifetime. In addition LEDs are increasingly becoming an eco-friendly technology. Longer lifetime means less materials waste and less release of toxic materials. Another important environmental benefit of LEDs is their comparatively lower energy consumption. The electrical energy consumption for lighting in big cities is about 25% of the total consumed electrical energy. It is estimated that in 2013, the lighting industry was responsible for 17% of energy consumption in the USA. Figure 5.1 illustrates the prediction of the lighting energy consumption in the USA till 2030. One can see that the expected saving due to the replacement of LEDs will be 15% in 2020 and 40% in 2030 [4].

Due to the comparatively lower energy consumption of LEDs and their longer lifetimes, compared to traditional light sources, the total lifetime cost of LEDs will be much lower than the traditional lighting technologies. LEDs have also higher efficiency, compared to other light sources [5, 6]. This makes lighting systems, based on LEDs, a great new solution for lighting applications. The internal quantum efficiencies of green and blue LEDs are around 20–40% and 40–60%, respectively [7]. The maximum theoretical efficiency of combining blue LED and yellow phosphor is around 50% [8, 9]. However, the commercial white LEDs, used in different applications, have normally lower power conversion efficiency [2].

In order to define the quality of LED lighting, three qualitative measurements are usually applied. The first one is efficiency of light, known as efficacy, which is usually defined by lumens/watt (lm/W). Light sources with higher efficacy have obviously higher energy efficiency. The second measurement of the lighting quality is the color rendering index (CRI). CRI is a quantitative measure of the ability of a light source to reproduce the colors of various objects faithfully in comparison with an ideal or a natural light source. The last qualitative measurement is the lifetime

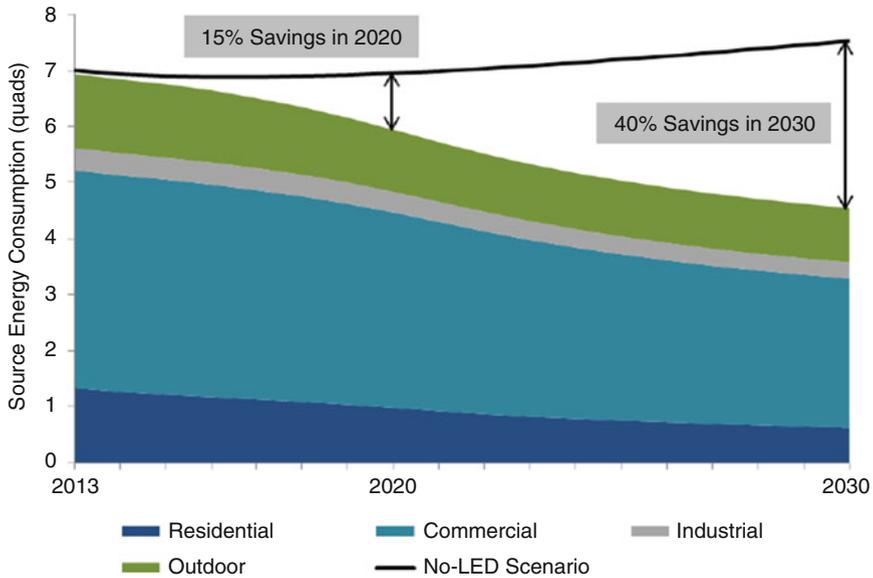


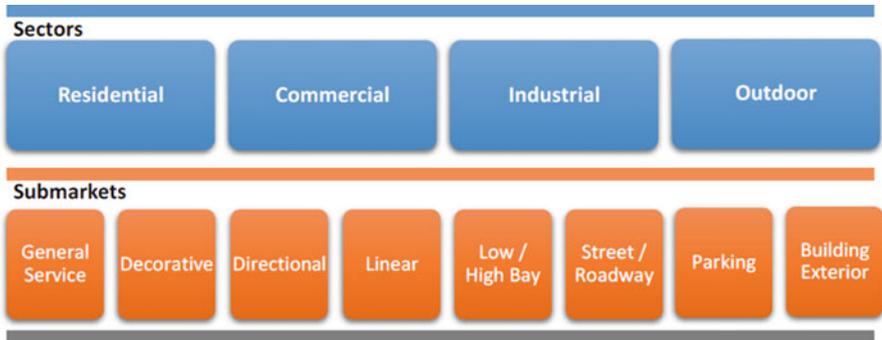
Fig. 5.1 Total US lighting consumption prediction (2013–2030) [4]

Table 5.1 Efficacy, CRI, and lifetime of common light sources [10]

Light source	Efficacy (lm/W)	CRI	Lifetime (hours)
Incandescent (120 V)	14.4	100	1,000
Compact fluorescent	51	80	10,000
High-pressure mercury	34	50	24,000
High-pressure sodium	108	22	24,000
LED	130–220	>80	50,000

which is a reliability parameter of the light source. It represents the working time of such light source within the lighting specification. Table 5.1 presents examples of the optical characteristics for common light sources. One can see that the overall properties of LED technology are better than those of other light sources.

Because of all benefits explained above, there can be a wide variety of applications for which LEDs are potentially perfect choices. This rapid progress in adopting LED lighting is well seen in the England’s Palace in center room chandelier, where all 25 W tungsten lamps were removed and a low voltage system controlling 2.8 W LED lamps were installed initiating an energy saving in excess of 80% [5]. There are many more examples obviously. LED lighting is not only adopted for general indoor lighting applications. In fact, the largest applications of colored and white LEDs are for automobile interior and exterior lighting, backlighting for mobile devices and small- and middle-sized liquid crystal displays (LCD), single and traffic lighting, and LED display. These applications now

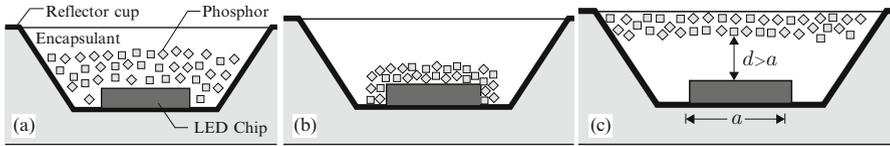


**Fig. 5.2** Market domains for LED lighting [4]



**Fig. 5.3** Three examples for different applications of LED-based products

account for about 90% of the LED needs. Figures 5.2 and 5.3 show some market domains and examples of the application for SSL devices for indoor lighting, outdoor/street lighting, and automotive lighting.



**Fig. 5.4** (a) Proximate phosphor distributions, (b) conformal proximate phosphor distributions, and (c) remote phosphor distribution [9]

## 5.2 White Light LEDs

Currently there are several technologies, used to produce white light in high-power LED systems [11–13]. These methods are mainly based on combining different LED chips with different colors to generate high color rendering index (CRI) and tunable colors. These methods can be listed as follows:

- A blue chip and two color phosphors such as green and red phosphors
- An ultraviolet (UV) chip and three-color phosphors in which the UV light excites the three-color phosphors (red, green, and blue) to generate white light with a high CRI
- A blue chip and yellow phosphor in which the yellow phosphor is excited by a blue radiation, producing white light by mixing of nonabsorbed blue light

LEDs, made by combining the blue-emitting diode chips with phosphor, are the most commercially available white LEDs due to their high efficiency. In this system, the phosphor layer can be either deposited directly on the chip or incorporated into a lens disc [14–17]. The spatial phosphor distribution in white LED lamps strongly influences the color uniformity and efficiency of the lamp. One can distinguish between proximate and remote phosphor distributions [14–17]. In proximate phosphor distributions, the phosphor is located in close proximity to the semiconductor chip. In remote phosphor distributions, however, the phosphor is spatially removed from the semiconductor chip. Proximate phosphor distributions and remote phosphor distribution are schematically shown in Fig. 5.4a–c, respectively. A general weakness of proximate phosphor distributions is the absorption of light by the semiconductor chip. Phosphorescence emitted toward the semiconductor chip can be absorbed by the chip. The reflectivity of the semiconductor chip and metal contacts is generally not very high. This negative point of proximate phosphor distributions can be avoided by remote phosphor distributions in which the phosphor is spatially placed apart from the semiconductor chip. In such remote phosphor structure, it is less likely that phosphorescence is absorbed by the semiconductor chip due to the separation between the semiconductor chip and the phosphor.

## 5.3 Failure Mechanisms in LEDs

The failure of LEDs can be attributed to three regions in the system; semiconductors, interconnections, and the package [18–21]. The die-related failures include severe light output degradation, burned/broken metallization on the die, lattice

defects, die cracking, dopant diffusion, and electromigration. The interconnect failures of LED packages are electrical overstress-induced bond wire fracture, metallurgical interdiffusion, and electrostatic discharge, which leads to catastrophic failures of LEDs. Package-related failures are mostly due to the degradation of polymeric materials and result in an optical degradation, color change, and severe discoloration of the encapsulant/lens materials.

## 5.4 Aging of Optical Materials and Origins of Color Shift

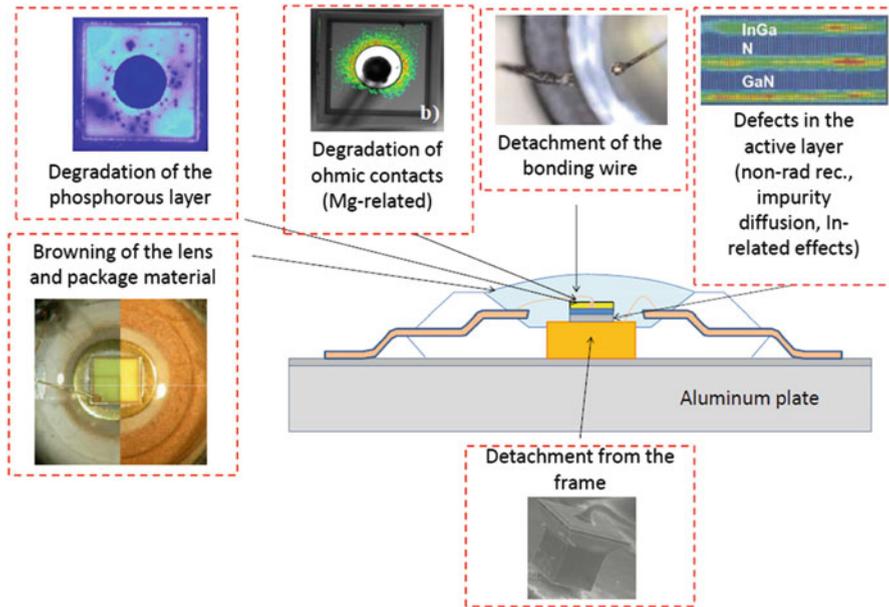
There are many technical challenges for LEDs to be considered as viable lighting sources. Among them, the light extraction efficiency and the light output degradation are key issues, which turn out to be all related to the packaging materials. LEDs have to often operate in different temperatures and environments with high level of humidity. Moisture, ionic contaminants, heat, radiation, and mechanical stresses can also be highly detrimental to LEDs and may lead to device failures. Almost all microelectronic devices are encapsulated by plastics. LEDs are also encapsulated to prevent mechanical and thermal stress shock and humidity-induced corrosion and oxidation [22]. Details of package-related failures and the relative solutions are given in Table 5.2 and shown schematically in Fig. 5.5. Most important challenges for packaging materials to be dealt with are to increase the light extraction efficiency, minimize the heat generated, extract more heat out of the package, and make the package more heat and UV resistant.

To sum up, the below mentioned requirements are essentially needed to improve the performance of the packaging materials and therefore enhance the lifetime of LEDs:

- High refractive index
- Excellent electrical properties
- Good chemical resistance

**Table 5.2** Materials challenges and solutions for packaging high-power LEDs [22]

Challenges	Problems	Packaging material solutions
Light extraction	Refractive index mismatch between LED die and encapsulant	High refractive index encapsulant
		Efficient lens/cup design
Thermal yellowing	Thermal degradation of encapsulants induced by high junction temperature between LED die and lead frame	Modified resins or silicone-based encapsulant
		Low thermal resistance substrate
UV yellowing	Photodegradation of encapsulants induced by UV radiation from LED dies and outdoor radiation	UV transparent encapsulant
Stress/delamination	Failure of wire bond and die attach caused by the CTE mismatch among encapsulant, LED die and lead frame	Low CTE and modulus encapsulants
		Excellent adhesion and CTE matching materials between the surfaces



**Fig. 5.5** Schematics of some common failure reasons in LED systems [11]

- Low water absorption (high resistance to moisture)
- Good adhesion to package components
- Mechanical strength
- Good UV and thermal resistance

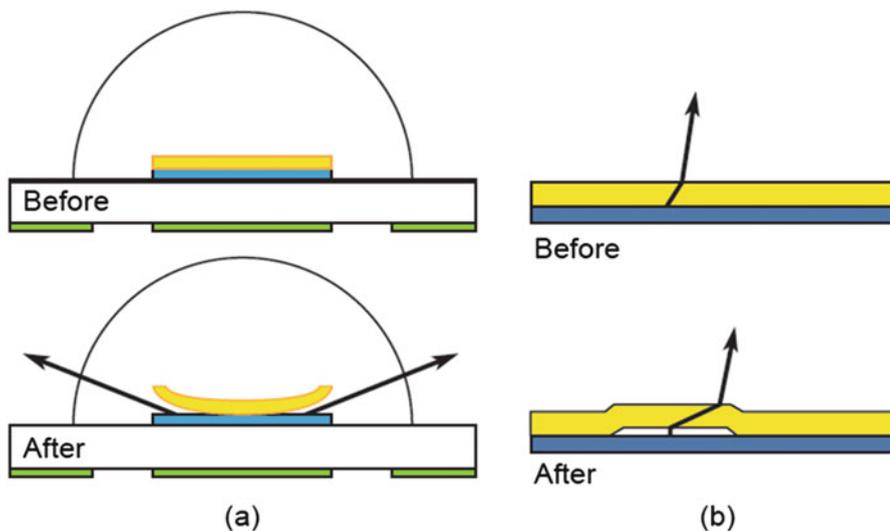
Some of the most important degradation reasons of optical packages, which result in the aging of optical materials, will be explained in details here.

### 5.4.1 Contaminations

LEDs are susceptible to failures due to contaminations from several sources. A particular concern is the presence of sulfur-containing compounds which can cause darkening of the silver mirror that is frequently used beneath LEDs to increase package optical efficiency. Contamination and impurities can also accelerate the oxidation reaction of the polymer and therefore accelerate the kinetics of degradation.

### 5.4.2 Interface Delamination

Figure 5.6 shows the effects of the delamination of a phosphor coating applied directly to the LED in a high-power package. For case A, the phosphor has peeled



**Fig. 5.6** Curling (a) and delamination (b) of phosphor-coated LED package [23]

up from the edges of the LED, allowing more blue light to escape and causing an overall shift toward blue. It may also cause spatial nonuniformity. Such an LED will emit more blue light to the sides and more yellow light on the optical axis. For case B, the phosphor has lifted from the LED in the non-edge portion of the device. In this case, the average path length for a blue photon through the phosphor increases. With longer path length, the chance of capture in the phosphor increases and more blue light is absorbed in the phosphor and converted to lower wavelengths, shifting the color toward yellow. Lamps using remote phosphor are less susceptible to many of the effects described above, because delamination is not a concern and because the remote phosphor is generally at a lower temperature than phosphors embedded in an LED package.

Mid-power LED packages can also show signs of delamination. Mid-power packages frequently use combinations of metals, silicones, and epoxies that have coefficients of thermal expansion. The adherence of these materials strongly depends on the process and on environmental stresses, including humidity and temperature. If any interface delaminates, the scattering internal to the package will change, and color shift is likely.

### 5.4.3 *Discoloration*

LEDs are encapsulated to prevent mechanical and thermal stress shock and humidity-induced corrosion [24–27]. Encapsulants, used in an LED packages, include plastics, epoxies, or silicones. These materials can discolor over time.

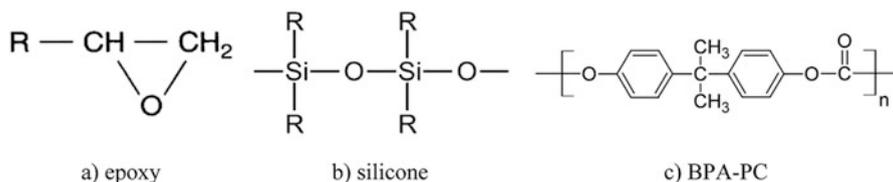
**Fig. 5.7** BPA-PC plate after discoloration [24]



One example is shown in Fig. 5.7 in which the aged sample (in yellow) is compared with the as-received sample (in white) [24]. This is from a bisphenol-A polycarbonate (BPA-PC) plate of 3 mm thickness, used as a substrate in remote phosphor configuration. This yellowing will certainly shift color and deteriorates optical output of the system. Among different polymers that are commonly used as encapsulants and lenses, the details of three important ones are explained below.

**Epoxy Resin.** The majority of encapsulant/lens materials used today belongs to the thermosetting polymers, based on epoxy resins. Epoxy resins have been widely used as encapsulant materials in LED packages because of their combination of low cost, ease of processing, and excellent thermal, electrical, mechanical, and moisture barrier properties [28, 29]. Epoxies are also widely used as die-attach adhesives, laminates for printed wiring boards, and underfill adhesives for flip-chip and transfer-molding compounds for plastic-encapsulated microcircuits (PEMs). Epoxy resins are based on the epoxy group, a strained three-membered carbon-oxygen ring structure, as shown in Fig. 5.8a. Epoxy resins, however, have two disadvantages as LED encapsulants. One disadvantage is that cured epoxy resins are usually hard and brittle owing to their rigid cross-linked networks. The other one is that epoxy resins degrade under exposure to radiation and high temperatures, resulting in chain scission and discoloration, due to the formation of thermo-oxidative cross-links. Among different degradation mechanisms in epoxy in optical systems, discoloration and yellowing are the most common failure mechanisms, resulting in a reduction in the transparency of the encapsulants/lens and a decrease in the LED light output [29].

**Silicone.** Is a material with enhanced optical, toughness, and thermal stability properties that can be used to replace epoxy. Silicone is a unique type of polymer in the sense that its structure is semi-organic. Because of its combination of organic groups (methyl, vinyl, etc.) with an inorganic backbone (Si–O), silicone exhibits unique properties such as higher purity, stronger stress absorbing, better high and



**Fig. 5.8** The chemical structure of different polymers that are commonly used as encapsulants and lenses

low temperature stability, and more excellent biocompatibility than other polymers. Also, silicone maintains its excellent electrical properties at high temperatures and under humid environments [30]. The general formulation of silicone is shown in Fig. 5.8b. However, the disadvantages of silicone are its lower glass transition temperature ( $T_g$ ), larger coefficient of thermal expansion (CTE), and poorer adhesion to the housing. One possible way to improve the thermal and mechanical properties of silicone is to use a siloxane-modified LED transparent encapsulant. The siloxane compounds improve the bond energy of the polymer chains to mitigate chain scission by increasing the cross-link density [31].

**Polycarbonate.** Is a thermoplastic and is the third most widely used material for LED encapsulants. It has high impact strength, high heat resistance, and high modulus of elasticity. It has been used in various applications, and its application in different domains has increased tremendously in recent years [31–33]. The general formulation of BPA-PC is given in Fig. 5.8c. Similar to epoxy resins and silicones, polycarbonate is prone to yellowing and discoloration under exposure to radiation at elevated temperatures. This results in a decreased light output due to decreased encapsulant/lens transparency. Polycarbonate degrades by an oxidation process that is strongly dependent on the exact composition of the polycarbonate, the presence of additives, and the loading (i.e., temperature and light). More information can be found in Refs. [35–43].

## 5.5 Yellowing of Encapsulant/Lens

In previous section the yellowing of polymeric materials and their sensitivity to yellowing were briefly explained. In this section the chemical reasons for the yellowing will be explained in more details. The main reasons of discoloration and yellowing are believed to be continued exposure to wavelength emission (blue/UV radiation), excessive temperature, and the presence of phosphor. Photodegradation of polymer materials usually takes place as a result of increasing the molecular mobility of the polymer as well as the introduction of chromophores as an additive into the molecule, both of which have absorption maxima in a region where the matrix polymer has no absorption band [41]. Photodegradation also depends on exposure time and the amount of radiation. The chemistry of degradation processes in

polycarbonates has been studied extensively over the past few decades [41–43]. In BPA-PC the reasons, underlying the photodegradation, have been attributed to two different mechanisms: photo-Fries rearrangement and photooxidation. Rivaton et al. [41] reported that the photo-Fries rearrangement reaction is more likely to occur at wavelengths shorter than 300 nm, whereas photooxidation reactions are more important when light of longer wavelengths (>340 nm) is used. On the other hand, Diepens et al. [44] argued that the photo-Fries rearrangement products are also formed, when samples are exposed to wavelength longer than 300 nm. Formation of both photo-Fries and oxidation products results in the yellowing and decrease in the transmission of BPA-PC plates [41–44]. In photo-Fries rearrangement reactions, carbonyl groups are rearranged to products of phenyl salicylate (L1), dihydroxybenzophenone (L2), and L3 which are shown in Fig. 5.9. L3 units are formed when CO–O band scission leads to decarbonylate or decarboxylate before further radical recombination or hydrogen abstraction. Rivaton et al. [41] postulated that at wavelengths longer than 340 nm, where the photooxidation reaction is dominant, side-chain oxidation, ring oxidation, and ring attack reactions are likely to take place. The side-chain oxidation in BPA-PC, however, is reported to be more probable [41–44]. To start the oxidation process, initiating of free radicals is required [42]. Lemaire et al. [43] and Factor et al. [45] demonstrated that photo-Fries products can be oxidized easily and act as a source of intrinsic photooxidation. Diepens et al. [44], however, showed that the increase in

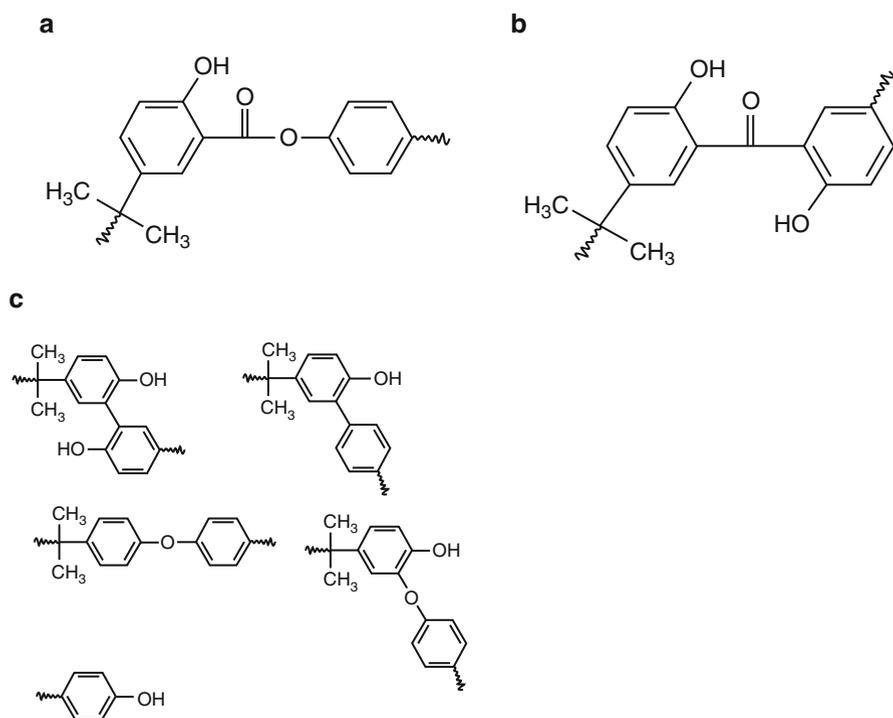


Fig. 5.9 Photo-Fries rearrangement products (a) L1, (b) L2, and (c) L3 [43]

photo-Fries rearrangement rate does not increase the oxidation rate, meaning that the photo-Fries reaction does not initiate the oxidation of polycarbonates.

Thermal degradation mechanisms and its effects on the optical and chemical properties of pure BPA-PC plates at 100, 120, and 140 °C are extensively studied by the author. Thermal aging of BPA-PC lens could significantly deteriorate the optical properties of LEDs. Rearrangement and oxidation in polycarbonate could result in discoloration and yellowing of BPA-PC encapsulant materials [35–38]. Discoloration due to the formation of oxidation products and rearrangement products or a combination of them could result in a decrease in the transmission of BPA-PC plates. Depending on the temperature, the degradation mechanism could be altered. It is believed that the higher the temperature, the more important the influence of rearrangement products on yellowing is [35]. Davis et al. [46] reported that the Fries rearrangement reaction is more likely to occur at high temperatures and under vacuum conditions. Rearrangement reaction in BPA-PC results in phenyl salicylate, diphenyl carbonate, phenol, and some other similar products [35]. Thermal oxidation products are more commonly reported as the main mechanism of yellowing of BPA-PC at low temperatures in the presence of oxygen [35–37]. Rivaton et al. [41] postulated that side-chain and ring oxidations are likely to take place during thermal degradation. Factor [45] showed that the main reason for discoloration and yellowing of thermally aged BPA-PC is the formation and subsequent oxidation of phenolic end groups, as is schematically shown in Fig. 5.10.

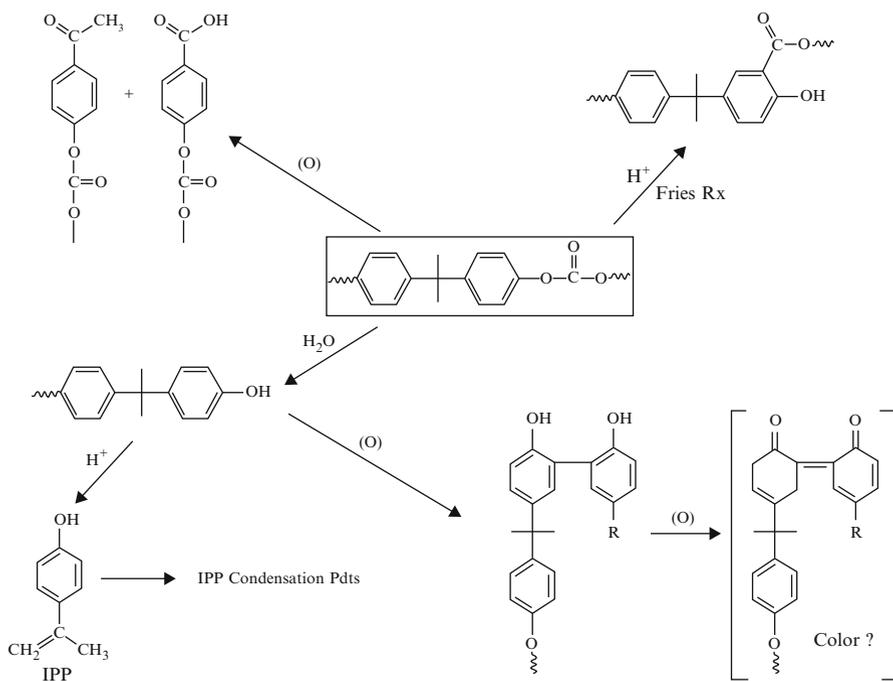


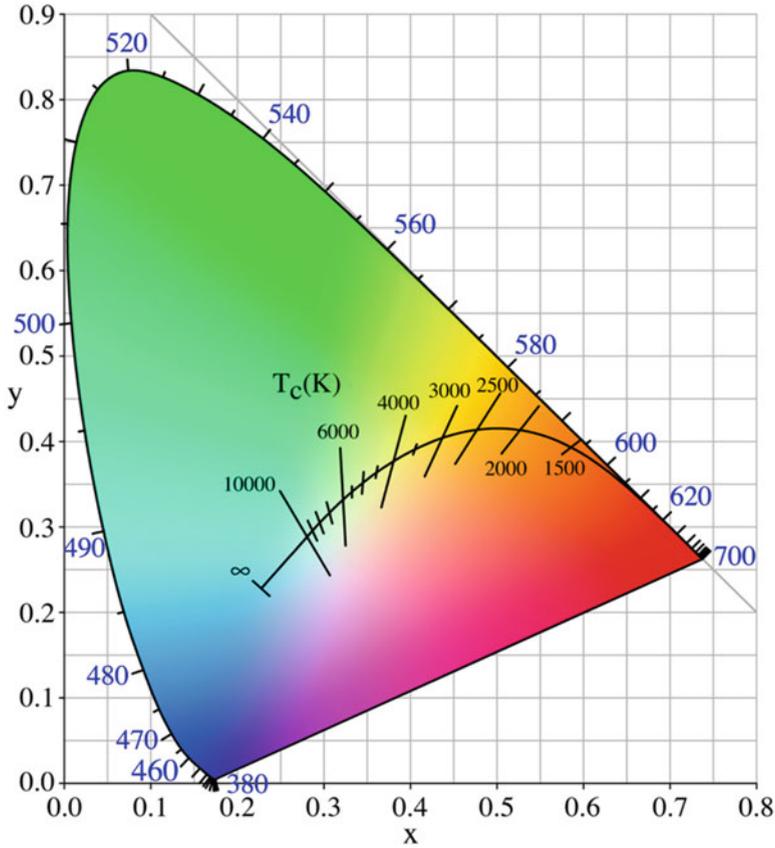
Fig. 5.10 Proposed pathway for the thermal oxidation of BPA-PC [43]

The temperature, leading to degradation, is a combination of junction temperature, ambient temperature, and LED self-heating [16]. Narendran et al. [16] reported that the degradation was affected by junction heat and the amount of short-wavelength emissions. It was shown that the thermal effect has greater influence on the yellowing than the short-wavelength radiation. Besides, it is revealed that a portion of the light circulated between the phosphor layer and the reflector cup would also contribute to the increasing of the temperature, causing yellowing [16]. Barton and Osinski [47] showed that a temperature of around 150 °C was sufficient to change the transparency of the epoxy and decreasing the light output of LEDs. Localized heating, produced by phosphor particles during light conversion, has also an effect on the encapsulant/lens discoloration [43]. It was shown that although phosphor is a necessary component to produce white light, the presence of phosphor causes a decrease in reliability. Phosphor thermal quenching decreases light output with the increase of the non-radiative transition probability due to thermally driven phosphorescence decay. Phosphor thermal quenching means that the efficiency of the phosphor is degraded when temperature rises. It is generally required that phosphors for white LEDs have low thermal quenching by a small Stokes shift to avoid changes in the chromaticity and brightness of white LEDs [34].

## 5.6 Terms and Definitions of Color Shifting

“Color maintenance” is analogous to lumen maintenance and is defined as 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  $\Delta_{xy}$  or as  $\Delta u'v'$  in the Commission Internationale de l’Eclairage (CIE) color coordinate systems. The chromaticity coordinates of a source provide a numerical representation of the color of the light. The three most common chromaticity diagrams, with their coordinates, are the CIE 1931 ( $x, y$ ), the CIE 1960 ( $u, v$ ), and the CIE 1976 ( $u', v'$ ). The ( $x, y$ ) coordinates are the most frequently reported. Figure 5.11 shows the CIE 1931 ( $x, y$ ). Every color is represented by unique ( $x, y$ ) coordinates. The CIE system is the most common method of characterizing the composition of any color in terms of three primaries [48, 49]. Artificial colors, indicated by  $X, Y,$  and  $Z$  coordinates, also called tristimulus values, can be added ( $X + Y + Z = 1$ ), to produce real spectral colors. The chromaticity coordinates,  $x, y,$  and  $z$  [48], are the ratios of the  $X, Y,$  and  $Z$  coordinates of the light to the sum of the three tristimulus values. It is necessary only to consider the quantity of two of the reference stimuli in order to define a color, since the three quantities ( $x, y, z$ ) are always made to sum to 1. Thus, the ( $x, y$ ) coordinates are commonly used to represent a color [48, 49].

The ( $u', v'$ ) coordinates are related to the ( $x, y$ ) coordinates by the following equations:



**Fig. 5.11** The CIE 1931  $x, y$  chromaticity space, also showing the lines of constant correlated color temperature

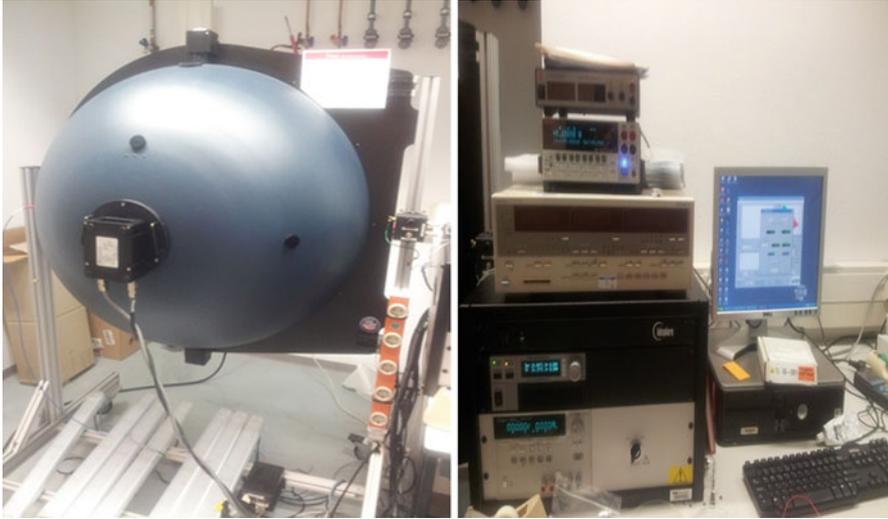
$$U' = \frac{4x}{-2x \times 12y \times 3} \tag{5.1a}$$

$$V' = \frac{9y}{-2x \times 12y \times 3} \tag{5.1b}$$

Based on Eq. 5.1a and 5.1b, the coordinates  $\Delta u'v'$ , which define the color shift at any two positions (0 and 1), can be calculated using the following formula:

$$\Delta u'v' = \sqrt{(u'_1 - u'_0)^2 + (v'_1 - v'_0)^2} \tag{5.2}$$

Energy Star specifies that color maintenance must not exceed  $\Delta u'v' = 0.007$  on the CIE  $(u', v')$  diagram, after 6,000 h of operation.



**Fig. 5.12** Integrated sphere (IS), widely used to measure yellowing index

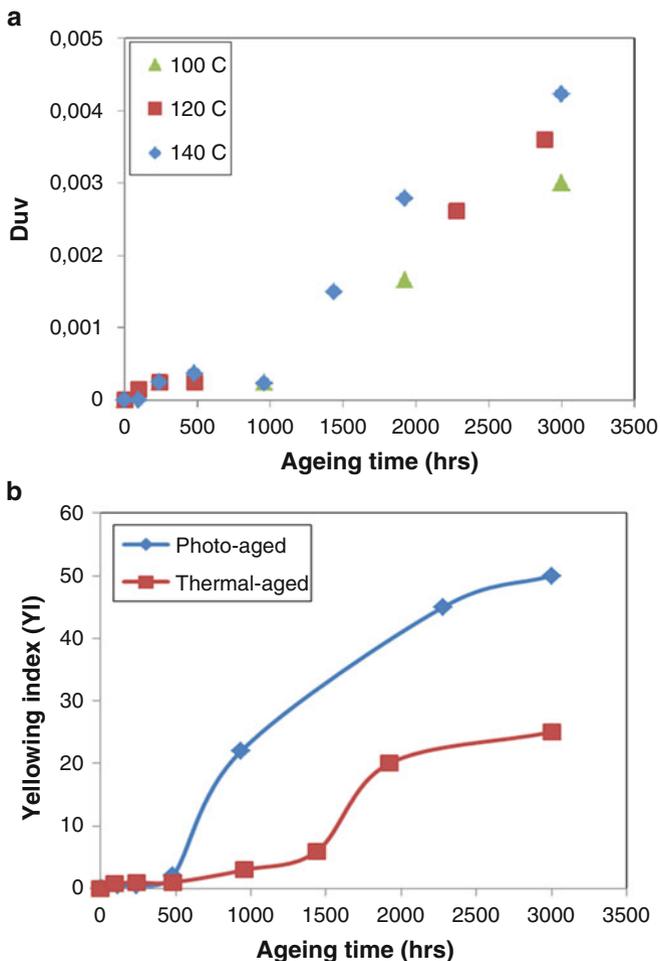
“Color consistency” is the variation in chromaticity at the start of a lamp’s life among a population of products. For example, a product may be made from LEDs that are binned to fall within three *MacAdam* steps of a target chromaticity. These LEDs have a color consistency of three steps. Color consistency can also be defined in terms of  $(x, y)$  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.

The spectral power distribution (SPD) and the yellowing index (YI) of the aged plates, measured by integrated sphere, are always good measures of the yellowing extent in samples. The integrated sphere, shown in Fig. 5.12, is an optical device consisting of a hollow spherical cavity with its interior covered with a diffuse white reflective coating, with small holes for entrance and exit ports. It is typically used with some light source and a detector for optical power measurement. The yellowing index (YI) is calculated according to ASTM D1925 [50] with the following equation:

$$YI = \frac{100 (1.28X \text{ CIE} - 1.6Z \text{ CIE})}{Y \text{ CIE}} \quad (5.3)$$

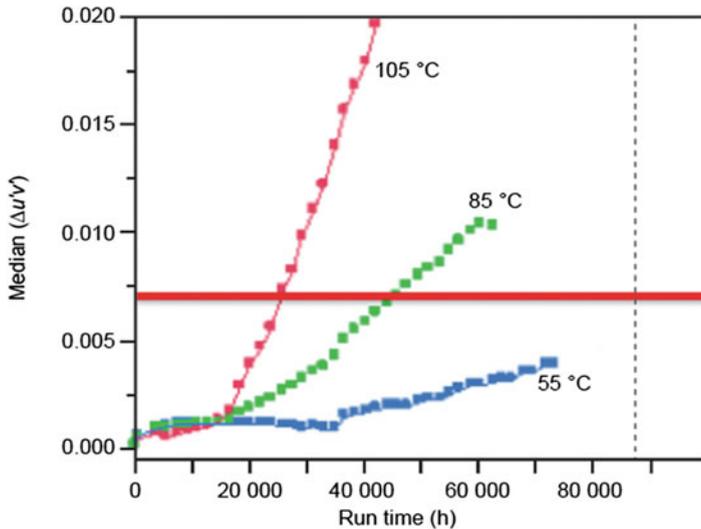
where  $X$  and  $Y$  are the tristimulus values in (CIE) standard.

Figure 5.13 depicts the color shift ( $\Delta u'v'$ ) of the BPA-PC specimens at different loading conditions as well as the yellowing index (YI) of BPA-PC plates as a function of exposure time under thermal and thermal plus blue light stress, as example. Obviously there is no major color shift during the incubation stage, whereas the color shift during the degradation stage is linearly proportional to the



**Fig. 5.13** Examples of (a) color shift of BPA-PC plate, aged at different temperatures, and (b) variation in YI of BPA-PC plates exposed to different stresses [37]

testing duration. Also Fig. 5.13b shows the temperature itself could cause the yellowing. However, one can see that the blue light has a significant contribution to the yellowing. The presented results in Fig. 5.13 are from the aging test, done on industrially pure BPA-PC, which is used as a lens and as a substrate for phosphor in remote phosphor LEDs. Details of the test are already published [37]. In commercial samples, the main reason for yellowing is thermal aging. For this reason, thermal aging can be used to accelerate degradation mechanisms in order to study color shift. It is already reported that by increasing the temperature, the kinetics of discoloration becomes faster [37–39].



**Fig. 5.14** Color shift in a high-power LED package [24]

Any of the degradation processes above is influenced by temperature and other stresses. Color shift will be accelerated by higher current or higher temperature. For example, Fig. 5.14 [24] shows a dramatic increase in the rate of color shift as the LED junction temperature is increased. In this particular case, the color shift begins only after about 15,000 h, so lamps, produced from these LEDs, would only begin to show strong color shift after being installed for about 2 years, if operated 24 h per day.

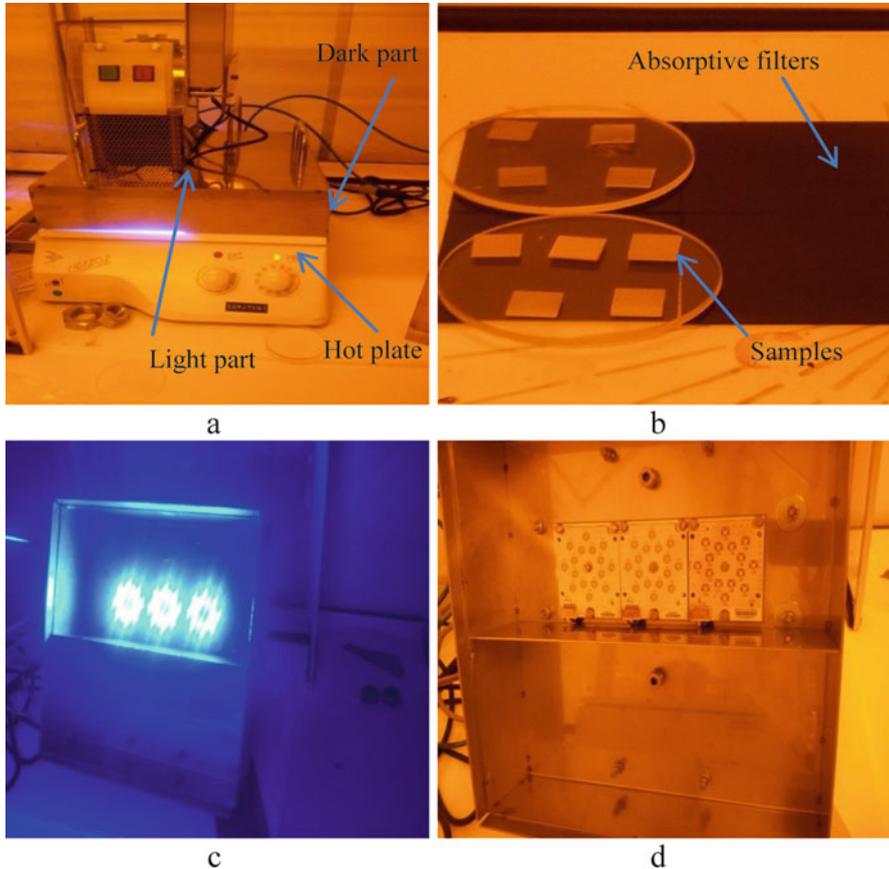
## 5.7 Reliability Performance of LEDs

Reliability is the probability that a system will perform its intended function under stated conditions for a specified period of time without failures [51]. By this definition, reliability is a measure as a function of time and, thus, a quantity. The LED domain, despite exciting innovations, motivated by technological developments, has still challenges regarding lack of information regarding the failure mechanisms and reliability. The relative low reliability information is an obstacle to the acceptance of LEDs in traditional applications. Consumers of LEDs expect that the industry guarantees the lifetime of LEDs in the usage conditions. LED lifetime is measured by lumen maintenance, which is how the intensity of emitted light tends to weaken over time. Other parameters such as chromaticity coordinate values ( $x$  and  $y$ ) and correlated color temperature (CCT) are also important. The Alliance for Solid-State Illumination Systems and Technologies (ASSIST) defines LED lifetime based on the time to 50% or 70% of light output degradation at room temperature [25]. In order to increase the quality of LEDs, it is important to know the main reason of lumen depreciation in a reasonable experimental time periods.

LED manufacturers usually perform tests in the product development cycle during the design and development phases to predict the lifetime of LED. The term reliability prediction is historically used to denote the process of applying mathematical models and data for the purpose of estimating field reliability of a system before empirical data are available [52]. These predictions are used to evaluate design feasibility, compare design alternatives, identify potential failure areas, trade off system design factors, and track reliability improvement. In order to predict LED lifetime, it is needed to carry out accelerated life tests at high temperatures and monitor the light output during the test. Modeling of acceleration factors (*AF*) is generally used to predict the long-term lifetime of LED packages at specific usage conditions [18]. Typical qualification tests of LEDs are categorized into operating life tests and environmental tests by using industrial standards such as *JEDEC* or *JEITA* and *LM-803* [53–55].

## 5.8 Highly Accelerated Stress Test (HAST) Setup

A highly accelerated stress testing (HAST) setup was developed in our previous works to study the effects of both blue light intensity and the thermal stress on the lifetime and the kinetics of aging of phosphor plates used in SSL luminaires. This work is a significant step forward and an improvement of our previously applied accelerated test methodology [36], where the only applied stress factor was thermal stress. Application of both thermal stress and light intensity in HAST setup makes the kinetics of degradation much faster. Figure 5.15 shows an overview picture of the HAST system including all components. The core of the HAST consists of a blue light source with wavelength of 450 nm and a working surface. Blue light sources were Philips modules, with each module containing 18 high-power LED packages. Samples were placed on the working surface and were directly aged under blue light radiation. The working surface in this setup is a hot plate, and absorptive filters are placed between the samples and the hot plate in order to prevent the reflection of light by the surface of the hot plate. The hot plate should constantly be calibrated by an IR camera. The temperature on the surface of the hot plate should also be perfectly homogenous, with the difference not being more than 5 °C all over the plate. The blue light source is composed of a mechanical assembly that holds the light source at a desired distance from the hot plate. In order to change the light intensity, the distance between the samples and the blue light source can be changed. The homogeneity of the light source across the samples can be checked by photometer at different distances and times. In one set of experiments, three temperatures of 80, 100, and 120 °C are used and samples are aged up to 3,000 h. The samples were remote phosphor plates of 3 mm thick with correlated color temperature (CCT) of 4,000 K and color rendering index (CRI) of 80. The luminescent powder mix for this sample was made of YAG powder with 3.3% Ce content and 1.5% nitride red phosphor, doped with CaSN-Eu. The blue light in this study was radiated on the sample with different light intensities of 825, 3,300, and



**Fig. 5.15** Highly accelerated stress testing (HAST) setup, with (a) frontal view in off state (*top left*); (b) samples on the absorptive filter (*top right*); (c) the blue LED light source (*bottom left*); and (d) frontal view in off state (*bottom right*)

13,200 W/m<sup>2</sup>. The change in the spectral power distribution (SPD) was used as a measure to monitor the optical degradation of remote phosphors.

Optical properties of photoaged plates, i.e., luminous flux depreciation and CCT of plates, were studied at room temperature, using an integrated sphere. In addition, color shifting in the aged specimens was also monitored. More details about the experiment and the results can be found in our previously published works [37].

## 5.9 Reliability Models

TM-21 is a Technical Memorandum being developed by an Illuminating Engineering Society (IES) technical committee. TM-21 does project the lumen maintenance of an LED source (package/array/module), which can then be used to project the

**Table 5.3** Lumen maintenance life projections in standard TM-21 [55]

Model	Decay rate	Closed form solution	Comment
1	$\frac{dI_v}{dt} = k_1$	$I_v = I_v^0 + (t - t^0)$	
2	$\frac{dI_v}{dt} = k_2 I_v$	$I_v = I_v^0 \exp[k_2(t - t^0)]$	
3	$\frac{dI_v}{dt} = k_1 I_v + k_2 I_v$	$I_v \left( I_v^0 + \frac{k_1}{k_2} \right) \exp[k_2(t - t^0)] - \frac{k_1}{k_2}$	Model 1 + Model 2
4	$\frac{dI_v}{dt} = \frac{k_3}{t}$	$I_v = I_v^0 + k_3 \ln \left( \frac{t}{t^0} \right)$	
5	$\frac{dI_v}{dt} = k_1 + \frac{k_3}{t}$	$I_v = I_v^0 + k_1(t - t^0) + k_3 \ln \left( \frac{t}{t^0} \right)$	Model 1 + Model 4
6	$\frac{dI_v}{dt} = k_4 I_v^2$	$I_v = \frac{I_v^0}{1 + I_v^0 k_4 (t - t^0)}$	
7	$\frac{dI_v}{dt} = k_5 \frac{I_v}{t}$	$I_v = I_v^0 (t/t^0)^{k_5}$	
8	$\frac{dI_v}{dt} = k_2 I_v + k_5 \frac{I_v}{t}$	$I_v = I_v^0 \exp[k_2(t - t^0)] (t/t^0)^{k_5}$	Model 2 + Model 7
9		$I_v = I_v^0 \exp \left[ - \frac{(t - t^0)}{k_6} \right]^{k_7}$	

expected lumen output of the source as part of a system [55]. Table 5.3 shows the proposed reliability model in TM-21 for different applications.

The simplest form of ratability model, which can be applied in many cases for the lifetime assessment of remote phosphor plates, is based on an exponential luminous decay equation, where the  $\Phi$  can be calculated as [55]:

$$\Phi(t) = \beta \exp(-\alpha t) \quad (5.4)$$

with  $\phi(t)$  being the lumen output,  $\alpha$  is degradation reaction rate or depreciation rate parameter,  $t$  the aging time, and  $\beta$  a pre-factor. When lumen output,  $\Phi$ , is equal to 70%,  $t$  is time to failure [12]. In the HAST experiments, where the light intensity is also used as an extra acceleration factor, the *Eyring* relationship, given below, is a more appropriate equation [55]:

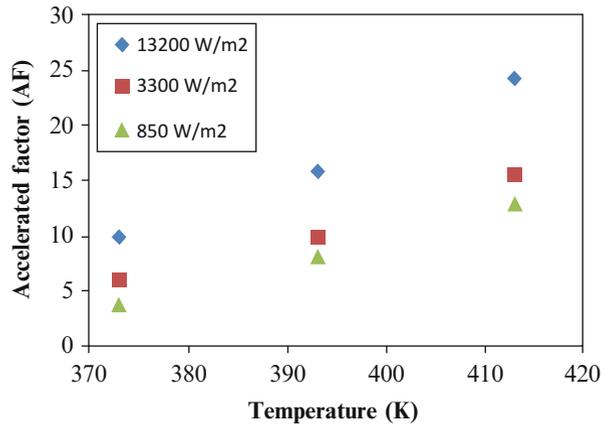
$$R = \gamma_0 (I)^n \exp \left( \frac{-E_a}{KT} \right) \quad (5.5)$$

where  $R$  is the reaction rate,  $\gamma_0$  is the pre-exponential factor,  $I$  is the intensity of blue light,  $n$  is the constant factor,  $E_a$  is the activation energy (eV) of the degradation reaction,  $K$  is the Boltzmann gas constant (eV/K), and  $T$  is the absolute temperature (K). In one of our studies, the aging temperatures of the hot plate were adjusted at 80, 100, and 120 °C. However, by radiation of light, the temperature of phosphor plates increased up to 2, 10, and 20 °C for 825, 3,300, and 13,200 W/m<sup>2</sup> intensities, respectively. The increase of the temperature by radiation of light was measured by a thermometer with an accuracy of  $\pm 0.5$  °C. This temperature increase should then be always taken into consideration in calculations.

Thermal stress tests have also some significant effects on the CCT. The variation of CCT during aging at high temperature stress test for remote phosphor plates is shown in Table 5.4. It is obvious that by increasing the thermal aging time, the CCT decreases.

**Table 5.4** CCT for remote phosphor plates at a temperature of 80–120 °C after 3,000 h aging

Light intensity (W/m <sup>2</sup> )	825	3,300	13,200
80	4,410	4,370	4,300
100	4,120	4,000	3,900
120	4,050	3,900	3,720

**Fig. 5.16** Acceleration factor of photothermal-aged at 120 °C

### 5.9.1 Effect of Light Intensity on the Acceleration of Aging Test

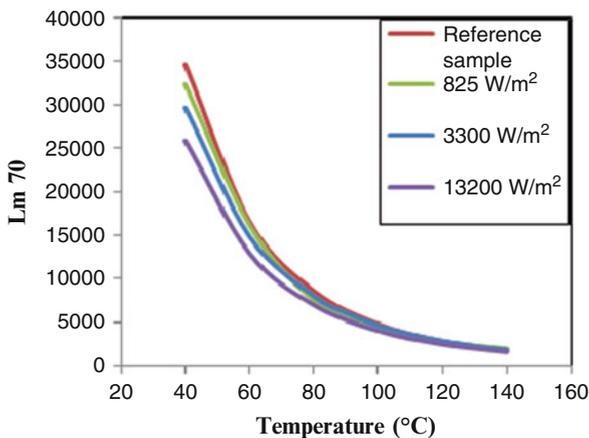
Using generalized Eyring equation [37], the acceleration factor of the tests at different stresses can be calculated. Acceleration factor is a measure of how much faster the test is performed at a certain testing condition, compared to normal behavior at real working conditions. Obviously the higher the acceleration factor, the faster and the more efficient (in terms of needed time for the experiment) the experiments. This factor is defined by the following equation:

$$Af = \left(\frac{I}{I_0}\right)^n \exp\left(\frac{E_a}{K}\left(\frac{1}{T_{\text{reference}}} - \frac{1}{T_{\text{test}}}\right)\right) \quad (5.6)$$

where  $T_{\text{Reference}}$  is reference temperature, which is assumed to be 80 °C which is closer to reality,  $T_{\text{test}}$  is the testing temperature,  $I$  is the intensity of blue light which is 13,200 and 3,300 W/m<sup>2</sup>, and  $I_0$  is the reference light intensity which is considered to be 850 W/m<sup>2</sup>. The acceleration factors of remote phosphor at aging temperature of 80–120 °C with radiation of light with intensities 825, 3,300, and 13,300 W/m<sup>2</sup> are given in Fig. 5.16.

The radiation of light accelerates the kinetics of the aging of remote phosphor. The increase in the acceleration factor by the radiation of light indicates the effect of light intensity (see Eq. 5.5). Using Eq. 5.5, the power factor,  $n$ , is found to be equal to 0.2. The acceleration factors of remote phosphor at aging temperature of

**Fig. 5.17** Time to failure (70% lumen decay) of remote phosphor at different temperatures for light intensities of 825, 3,300, and 13,200 W/m<sup>2</sup>



120 °C with radiations of 825, 3,300, and 13,300 W/m<sup>2</sup> light and dark experiment are 1.01, 1.2, and 1.9 for blue light radiations of 825, 3,300, and 13,200 W/m<sup>2</sup>, respectively. The increase in acceleration factor by radiation of light indicates the effect of light intensity (see Eq. 5.5).

### 5.9.2 Effect of Light Intensity on the Time to Failure of Remote Phosphor

The temperature of phosphor during service can increase up to 100 °C [24]. However, it is more logical to use 80 °C as reference temperature, which is more an average value over the whole year. The kinetics of lumen depreciation to 30% of its initial value can be calculated using Eq. 5.1a and 5.1b, equating  $\phi$  to 0.7, knowing that  $a$  can be obtained from Eq. 5.2. Figure 5.13 illustrates the time to failure (70% lumen decay) of remote phosphors, calculated at different temperatures for the photothermal aging, where the aging temperature was 120 °C. Data for the reference sample (thermally aged at 120 °C without light radiation) is added for the sake of comparison [36]. It is shown that the lifetime, defined as 30% lumen depreciation at 40 °C, is around 35 khrs, for the lowest energy power, which has almost the same lifetime as thermally aged phosphor. The lifetime of the phosphors with higher power energy is 25 khrs (Fig. 5.17).

## 5.10 Concluding Remarks

This chapter reviews the research done on the failure mechanisms and reliability of optical materials in LED systems. Different types of failures at the package level are discussed and introduced. Different operational and environmental stresses,

including junction temperature, contaminations, humidity, operation temperature, and UV light, might cause lumen decay and failure of LEDs. Among different failure modes, thermal degradation is the most severe one. If thermal management is insufficient in the remote phosphor, overheating and damage in the remote phosphor and its substrate can occur. For instance, the adhesives that bind the LED to the submount may degrade due to thermal weakening. Thermal loads result in thermal fatigue of solders in LED package as well. More importantly, thermal aging results in faster kinetics of yellowing and discoloration. With that said, thermal stress is frequently used for accelerated testing of LEDs. In this chapter a new acceleration test method for LED remote phosphors is introduced in which the effect of light intensity (in addition the temperature) on the kinetics of aging can be monitored. The results illustrated that there is a direct relation between the light intensity and the loss in conversion efficiency of remote phosphor. In fact, by increasing the light intensity, the conversion efficiency of remote phosphor decreases. Among different proposed lumen maintenance models, proposed in TM-21, the generalized Eyring equation is the right choice for the HAST setup. It is shown that the lifetime, defined as 30% lumen depreciation at 40 °C, is approximately 35 khrs, for the lowest energy power, which has almost the same lifetime as thermally aged phosphor. The lifetime of the phosphors with higher power energy is predicted to be 25 khrs. Although great effort was put into predicting lumen maintenance, resulting in the LM-80 and TM-21 standards, little has been done to address color maintenance. Few (or no) LED package manufacturers provide warranties on color maintenance. It is an absolute necessity to have a widely accepted method of predicting color maintenance and reliability of LED packages.

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