

Research

Advanced Materials and Materials Genome—Review

Progress in Understanding Color Maintenance in Solid-State Lighting Systems

Maryam Yazdan Mehr^{1,2}, Willem Dirk van Driel¹, G. Q. (Kouchi) Zhang^{1*}

ABSTRACT In this paper, progresses of color maintenance, also known as color shift, in solid-state lighting (SSL) systems are thoroughly reviewed. First, color shift is introduced and a few examples are given from different real-life industrial conditions. Different degradation mechanisms in different parts of the system are also explained. Different materials used as lenses/encapsulants in light-emitting diode (LED)-based products are introduced and their contributions to color shift are discussed. Efforts put into standardization, characterizing, and predicting lumen maintenance are also briefly reviewed in this paper.

KEYWORDS light-emitting diode (LED), color shift, lumen depreciation, lumen degradation

1 General information

1.1 Introduction

Solid-state lighting (SSL) technologies and products are gradually penetrating daily life. An SSL system is composed of a light-emitting diode (LED) engine with an electronic driver or drivers, integrated in a housing that also provides optical functions, thermal management, sensing, and/or other functions. Knowledge of system reliability is crucial, not only for successful business in today's SSL products and applications, but also to gain a deeper scientific understanding that will enable improved products and application design in the future. System malfunction may be induced by the failure and/or degradation of any subsystem or interface. Most SSL system designs, which allow few failures of the subsystem/interface during the application period, can be achieved with significant cost reduction when system reliability is well understood by means of appropriate experimental and simulation techniques.

Color maintenance is a recently-appearing system failure. Color-maintenance problems are insidious, because they are poorly understood, and only appear after many hours of operation. The purpose of this paper is to describe current prac-

tice, that is, field issues, test results, and prediction capability, with color maintenance; and to recommend how to address LED color maintenance in our products. This paper presents:

- Examples of color-maintenance issues that have appeared in the field;
- The origins of color shift;
- Current prediction insights; and
- Standardization activities.

1.2 Terms and definitions

“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 Δxy 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. 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 [1, 2]. 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 [1], 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 [1, 2].

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

$$u' = \frac{4x}{-2x + 12y + 3} \quad (1a)$$

$$v' = \frac{9y}{-2x + 12y + 3} \quad (1b)$$

¹ Delft University of Technology, Delft 2600 AA, the Netherlands; ² Material Innovation Institute (M2I), Delft 2628 XG, the Netherlands

* Correspondence author. E-mail: G.Q.Zhang@tudelft.nl

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

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

Energy Star specifies that color maintenance must not exceed $\Delta u'v' = 0.007$ on the CIE $u'v'$ diagram, after 6000 h of operation.

“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.

“Color stability” describes how the entire spectrum changes over time. Although it is closely related to color maintenance, color stability encompasses more detail. The term “color maintenance” will be used in this paper.

2 Examples of color shift

This section describes several examples of field issues in which color shift has been indicated.

2.1 The L Prize LED lamp

Two hundred L Prize lamps were tested for 25 000 h at 45 °C. Testing has continued for 32 of these lamps and test hours now exceed 36 000 h (Figure 1). The L Prize lamps show that LED technology enables color shift (and lumen depreciation) to be quite small [3]. The average lumen maintenance for 200 lamps is over 100%, after 25 000 h. The average lumen maintenance at 36 000 h is 96.5% with respect to the maximum light output, which occurred after about 2000 h of operation. The average color maintenance, $\Delta u'v'$, is slightly above 0.001, or about one MacAdam step [3], both at 25 000 h and 36 000 h, as shown in Figure 2. (Two light sources observed simultaneously cannot be distinguished from each other by an average viewer, if the colors are within one MacAdam step of each other.)

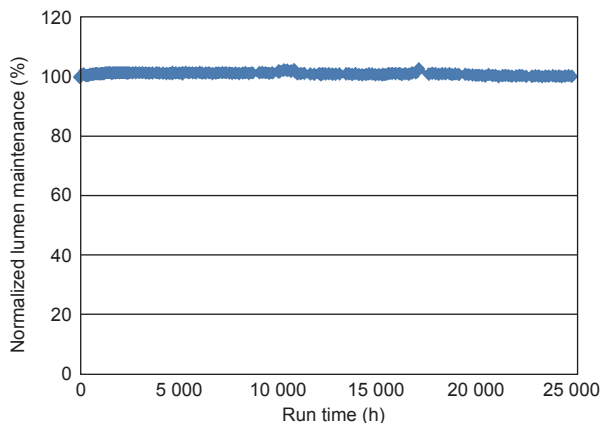


Figure 1. L Prize test results: Normalized lumen maintenance [3]. L Prize average lumen maintenance, as of 2013-04-29.

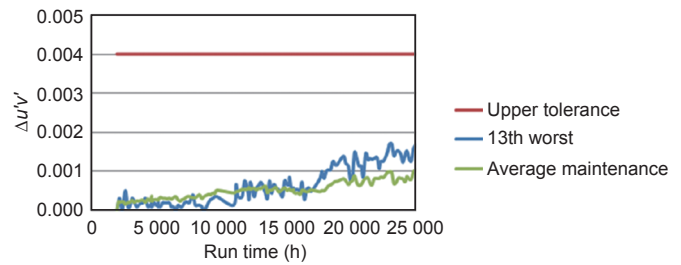


Figure 2. L Prize test results: Color shift. Chromaticity maintenance: 13th worst performing lamp.

Controlling color shift in an L Prize lamp was particularly complicated, because two LED colors were used (red and blue) in addition to a remote phosphor. When two colors of LEDs are used, they will have different temperature dependence and different degradation rates. Both of these factors will cause color maintenance to be poorer than for a light source made from a single LED color. Still, it is possible to create a stable light source, as shown in the figures above. In some cases, color-maintenance issues appear after several years of lamp service. Because the market has the impression that LED lamps “live forever,” failures like color shift are particularly irksome.

2.2 Reports from the Smithsonian Institution

At the US Department of Energy (DOE) R&D workshops in 2011 and 2013, Scott Rosenfeld, a curator at the Smithsonian Institution, reported color-consistency (2011) and color-maintenance (2013) problems with LED lamps [4, 5]. Clear color change can be observed in Figure 3. Reported color shifts at the museum were as large as $\Delta u'v' = 0.027$ (27 steps), after only 10 000 h of operation! Some of the reported color shifts are too large to comply with the Energy Star specification that color shift should be less than 0.007 at 6000 h of operation.

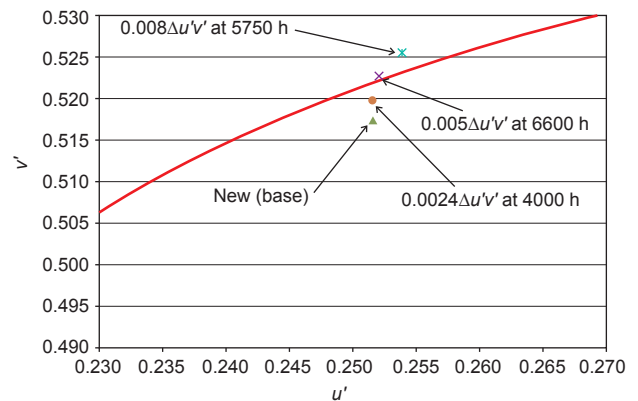


Figure 3. Results from the Smithsonian Institution [4, 5]. PAR30/3000K with Cree XPE chip and Themistor, manufacture #1, lamp types A and B.

2.3 Pacific Northwest National Laboratory

DOE-funded project at the Pacific Northwest National Laboratory (PNNL) [6–8] gives an excellent overview of color maintenance. A gateway project conducted at the Smithsonian Institution, involving several lamps from six different

lamp types, indicated that many of the lamps failed the Energy Star requirement that $\Delta u'v'$ should not exceed 0.007 before 6000 h of life. The graph in Figure 4 is taken from Ref. [6] and summarizes the results of several Commercially Available LED Product Evaluation and Reporting (CALiPER) studies on many different products. This figure demonstrates that color shift can show quite different behavior for different lamps. A study of 17 A lamps operated for 8000 h at 45 °C showed that 3 out of 8 Energy Star lamps failed to meet the 6000-hour Energy Star requirement for color shift. With such erratic behavior, one might expect difficulty in predicting color maintenance.

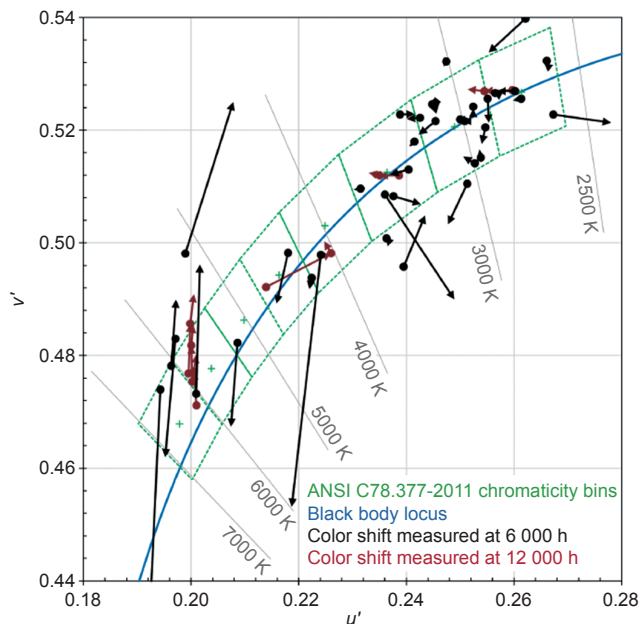


Figure 4. Results from the DOE-funded project [6].

Table 1. Lamps used in the CALiPER Retail Lamps Study [7].

ID	Brand	Model	Rated lifetime (h)	Energy star qualified
13RT-01	3M	RRA19B3	27 500	
13RT-02	Bulbrite	LED12A19/0/30K/D	50 000	Yes
13RT-03	Cree	BA19-08027OMF-12DE26-1U100	25 000	
13RT-04	EcoSmart	ECS A19 WW 60WE 120	25 000	
13RT-05	Feit Electric	A19/OM800/LED	25 000	Yes
13RT-06	GE Lighting	LED13DA19/830, 65386	25 000	Yes
13RT-07	Insignia	NS-LED60FB	25 000	Yes
13RT-08	LEDnovation	LEDH-A19-60-1-27D-IO-E	50 000	Yes
13RT-09	MaxLite	SKBO10DLED30	25 000	Yes
13RT-10	Philips Lighting	BC11A19/AMB/2700 DIM120V	25 000	Yes
13RT-11	Great Value	GVRAS11W27KND	25 000	
13RT-12	Satco	LED/9.8W/2700K/120V	25 000	
13RT-13	Switch	Switch 60/ A22141FA1-R	25 000	
13RT-14	OSRAM Sylvania	LED12A19/DIM/O/827/HVP/	25 000	Yes
13RT-58	Cree	BA19-08027OMN-12DE26-1U100	25 000	
BK13RT-15	Philips Lighting	EL/mdT2 13W 6/4 (819798)	12 045	Yes
BK13RT-17	Philips Lighting	43A19/EV 120V 6/4	1 000	

2.4 The CALiPER Retail Lamps Study

The CALiPER Retail Lamps Study reports on the lumen and chromaticity maintenance of LED lamps that are operated in steady-state conditions [7]. This report documents the long-term performance of 15 of the LED A lamps from CALiPER's third study of lamps that are available in retail stores. Specifically, the report focuses on lumen and chromaticity maintenance relative to benchmark halogen and compact fluorescent lamps (CFLs). Table 1 lists the commercial lamps that were studied and tested.

The results include data on lumen maintenance for 15 commercial LED lamps, as well as the color maintenance of these LED lamps compared to conventional technologies. Figure 5 shows that from an average color-maintenance point of view, LED technology does not differ much from CFL and halogen benchmarks.

Figure 6 shows the average chromaticity maintenance for each lamp model. The three worst are the CREE, MaxLite, and Great Value lamps. These three do not meet the Energy Star specifications. The CREE lamp did not even make 1000 h before its color exceeded seven steps.

The CALiPER report also investigated the relationship between lumen maintenance and chromaticity maintenance, as shown in Figure 7. Overall, there was a correlation between lumen depreciation and color shift, but no detailed investigations toward the mechanism were presented.

3 Origins of color shift

Any source of lumen depreciation is likely to be a source of color shift as well, since the light output degradation is not generally completely uniform across the entire spectrum. Different degradation in different parts of the spectrum will inevitably lead to color changes, though the amount of color

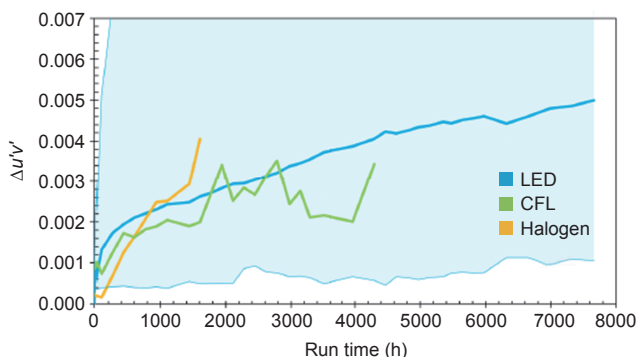


Figure 5. Average change in chromaticity for each source type, with the range of change shaded for the 15 LED lamp models. On average, the LED products demonstrated similar amounts of color shift compared to the other technologies over the same time period [7].

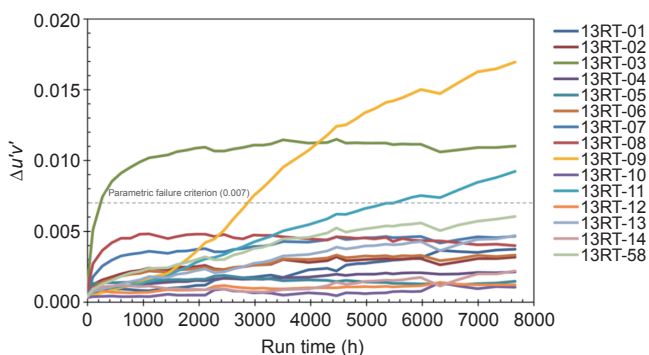


Figure 6. Average chromaticity maintenance for each LED model. Some of the LED products exhibited rapid color shift, CREE (dark green), MaxLite (yellow), and Great value (turquoise), while others maintained exceptionally consistent chromaticity [7].

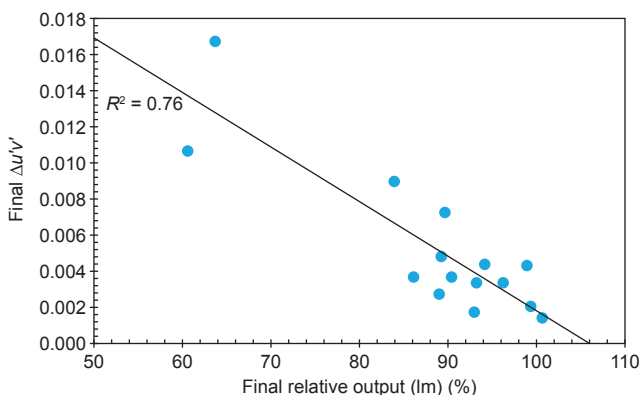


Figure 7. Final average color shift versus final average lumen maintenance [7].

shift may be small [8–12]. The most common origins of color shift in LED-based products are described below. Table 2 lists various mechanisms within an LED-based product that may affect the color of the light emitted by that LED over time [7].

3.1 Material degradation

This section explains encapsulant- and phosphor-related degradations.

3.1.1 Encapsulant degradation

LEDs have to operate in environments with different tem-

Table 2. Origins of color shift [19].

Color-shift root cause	Examples
Material degradation	<ul style="list-style-type: none"> Degradation of the direct optical path from LED die to air Degradation of reflective surfaces within the LED component Degradation of the optical materials within the system, whether MCPET, white solder resist, polycarbonate, or PMMA
External contaminants	<ul style="list-style-type: none"> Contaminations in the direct optical path, such as browning of the optical path due to VOCs or residual flux after reflow on the exterior of the LED package Change in the reflective surface properties of materials within the LED component, including, for example, tarnishing of silver Carbonization due to lack of oxygen Sedation of particles onto any optical surface, such as onto the silicones
Interface delamination	<ul style="list-style-type: none"> Separation between different material interfaces, such as substrate and optical path materials Material cracking, for example, in the MCPET reflector due to brittleness

Notes: MCPET—micro cellular polyethylene terephthalate; PMMA—polymethyl methacrylate; VOC—volatile organic compounds.

peratures and humidity, ranging from indoor conditions to outdoor conditions. Moisture, ionic contaminants, heat, radiation, and mechanical stresses can be highly detrimental to LEDs and may lead to device failures. More than 99% of recently manufactured microelectronic devices are encapsulated by plastics. LEDs are encapsulated to prevent mechanical and thermal stress shock and humidity-induced corrosion [8–12]. Encapsulants used in an LED package include plastics, epoxies, or silicones. These materials can discolor over time. The example in Figure 8 [8], for 3 mm bisphenol-A polycarbonate (BPA-PC), used as a substrate in remote phosphor plate, shows strong yellowing over time. This yellowing will certainly shift color. Among the different polymers that are used as encapsulants and lenses, the details of three important ones are explained below.



Figure 8. BPA-PC discoloration.

Epoxy resin. The majority of encapsulant/lens materials used today are 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 [13, 14]. 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 Figure 9.

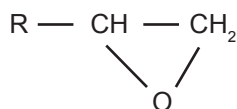


Figure 9. The chemical structure of the epoxy functionality.

Transparent epoxy resins are generally used as LED encapsulants. However, epoxy resins have two disadvantages as LED encapsulants. One disadvantage is that cured epoxy resins are usually hard and brittle owing to rigid cross-linked networks. The other 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 the different degradation mechanisms in epoxy and encapsulant plastics 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 [13].

Silicone. 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 low temperature stability, and more excellent biocompatibility than other polymers. Also, silicone maintains its excellent electrical properties at high temperatures and under humid environments [15]. The general formulation of silicone is shown in Figure 10.

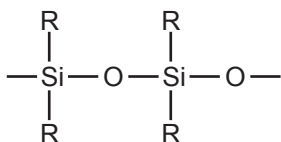


Figure 10. The chemical structure of silicone.

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 [14].

Polycarbonate. Thermoplastics based on polycarbonate are the third most widely used material for LED encapsulants. BPA-PC is an engineering thermoplastic with 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 [15–17]. The general formulation of BPA-PC is given in Figure 11.

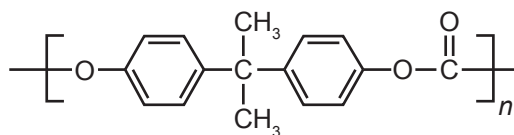


Figure 11. The chemical structure of BPA-PC.

Like epoxy resins and silicones, the main disadvantages of polycarbonate are 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 inhibitors (which reduce the yellowing from ultraviolet (UV) exposure), and the loading (i.e., temperature and light). More information can be found in Refs. [18–27].

3.1.2 Phosphor degradation

Phosphor materials (used in all white LEDs) can degrade over time, leading to color shift. In some cases, it is not the phosphor material, but the position of the phosphor with respect to the LED that changes over time, allowing more or less blue light to be emitted. Deterioration of the binder material, which binds the phosphor to the LED die, may cause phosphor particles to detach, leading to an increase of scattering and an associated color shift.

3.2 Contamination

LEDs are susceptible to contamination 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. More details can be found in Ref. [21].

3.3 Interface delamination

Figure 12, taken from Ref. [6], shows the effects of the delamination of a phosphor coating applied directly to the LED in a high-power package. For Figure 12(a), the phosphor has peeled 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 non-uniformity. Such an LED will emit more blue light to the sides and more yellow light on the optical axis. For Figure 12(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.

Mid-power LED packages can also show signs of delamination. Mid-power packages frequently use combinations of metals, silicones, and epoxies that have quite different material properties (i.e., different coefficients of thermal expansion). The adherence of these materials strongly depends on the process and on environmental conditions like moisture

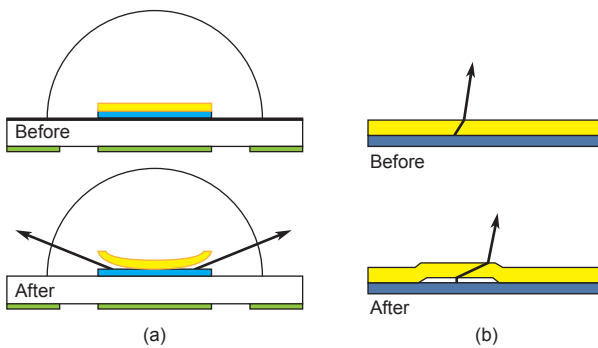


Figure 12. (a) Curling and (b) delamination of phosphor coated LED package.

and temperature. If any interface delaminates, the scattering internal to the package will change, and color shift is likely.

3.4 System-level degradation

On a system level, other parts may also play an optical role by either reflecting or transmitting light, and therefore may also contribute significantly to color shift if they degrade. For example, white solder resist deposited on printed circuit boards may become yellow over time. A micro-foamed PET light-reflective sheet, or MCPET, used in diffusers, may become brittle. Over time it may show signs of cracks, which also change the diffraction of light. Secondary optics in LED sources can also degrade, causing color shift, if improper materials or thermal design are used. The lamps studied in Ref. [6] did not show large color shift attributable to secondary optics. Measurements before and after removal of the secondary optics did not yield large color differences, indicating that the secondary optics were not contributing to color shift. This result does not mean that all lamps have no color shift induced by degradation in the secondary optics. Care in the design of the entire optical path is required to avoid degradation of any of the elements, whether plastic optics, reflecting foils, or other components. Outdoor applications, where optics are exposed to UV light from the sun, weather, and insects, may be more susceptible to degradation of secondary optics.

4 Acceleration factors

Many of the change mechanisms mentioned in the previous section are strongly correlated with the actual stress conditions of the materials used in an LED-based product. In particular, elevated operating temperatures in combination with high photonic/radiometric energy can have a substantial impact on the long-term color stability of white LED components.

4.1 Role of temperature and current

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, Figure 13 [25] 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 two years, if operated 24 h per day. Predictions based on the first few thousand hours would reveal no such shift.

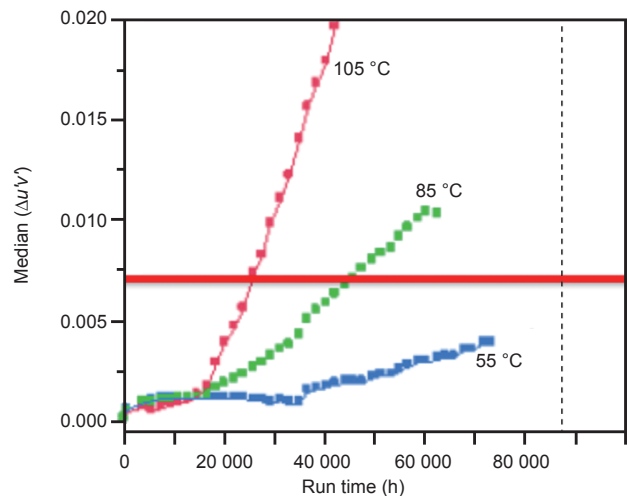


Figure 13. Color shift in a high-power LED package [8].

Lamps using remote phosphor are less susceptible to many of the effects described in the previous section, because delamination is not a concern, and because the remote phosphor is generally at a lower temperature than phosphors embedded in an LED package. The energy difference between blue absorbed photons and photons emitted by the phosphor is emitted as heat in the phosphor. If thermal management is insufficient in the remote phosphor, overheating and damage in the remote phosphor and its substrate can occur. Many other sources of temperature shift can occur. For example, the adhesives that bind the LED to the submount may degrade, increasing thermal resistance and LED-junction temperature, or the solder that binds the LED-package electrical and thermal contacts to a printed circuit board may fatigue and crack, reducing contact area and increasing thermal resistance and LED-junction temperature. LED color also shifts in reversible ways when the current or temperature is changed. Changes in the driving electronics that result in a different LED driving waveform (whether deliberate or as the result of degradation of the electronics) can also lead to color shift. Changes in ambient temperature generally cause reversible color shifts. Changes with temperature and current are of particular concern in light sources that contain more than one LED color, because the different LED colors are likely to have a different dependence on temperature and current. In this case, even though the color of the individual LEDs may shift insignificantly with the temperature/current change, the fact that the amount of light from the different LEDs changes differently can result in much larger color shifts in the combined light.

LM-80 is a method for measuring lumen depreciation and maintenance developed by the Illumination Engineering Society (IES) to enable comparison between LEDs from different manufacturers. LM-80 data includes color measurement. Thus, any LED qualified for use in Energy Star products will have color maintenance data available for at least 6000 h. This data may be helpful in determining if a particular LED pack-

age is likely to have a color maintenance issue. Figure 14 plots LM-80 data for two typical high-power packages at 85 °C. The color maintenance looks reasonable at currents less than 1000 mA. However, drastic color shift is apparent at 1000 mA. Can LM-80 data like this be used to predict color-maintenance problems? Data in Figure 14 extends only to 85 °C, which is a relatively low temperature, and may be a warning sign in itself (other LED manufacturers report data to 105 °C, 120 °C or higher) [8]. Data at higher temperatures might have revealed the color-maintenance problem with these LEDs more clearly.

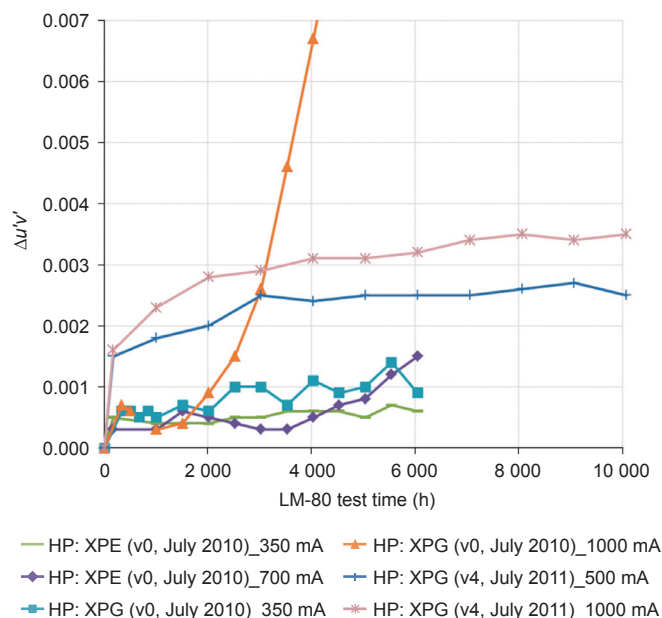


Figure 14. Data from high-power LED packages [8].

4.2 Role of photonic energy

In addition to thermal effects, the main reason for the discoloration and yellowing of optical materials within LED-based systems is continued exposure to wavelength emission (blue/UV radiation). Photo-degradation of the polymer materials used for LEDs usually takes place as a result of increasing the molecular mobility of the polymer and/or introducing chromospheres as an additive into the molecule. Both changes result in absorption maxima in a region where the matrix polymer has no absorption band [25]. Photo-degradation 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 [26–28]. In BPA-PC, the chemistry underlying photo-degradation has been described in two different mechanisms: the photo-Fries rearrangement and photo-oxidation. The relative importance of these two mechanisms depends on the irradiation wavelengths applied. Previous investigations show that the photo-Fries rearrangement reaction is more likely to occur at wavelengths shorter than 300 nm, whereas photo-oxidation reactions are more important when light of longer wavelengths (> 340 nm) is used [26–28]. When light with wavelengths longer than 340 nm is used, the dominant photo-degradation reaction is reported to be side chain oxidation [27].

In addition to the effects of light, the yellowing and degradation of package materials is largely dependent on temperature, which is a combination of junction temperature, ambient temperature, and LED self-heating [9]. Narendran et al. [11] reported that degradation was affected by junction heat and the amount of short wavelength emissions. It was shown that the thermal effect has a greater influence on yellowing than short-wavelength radiation. Figure 15 depicts the color shift ($\Delta u'v'$) of the specimens at different loading conditions. There is no major color shift during the incubation stage, whereas the color shift during the degradation stage is linearly proportional to the testing duration [22].

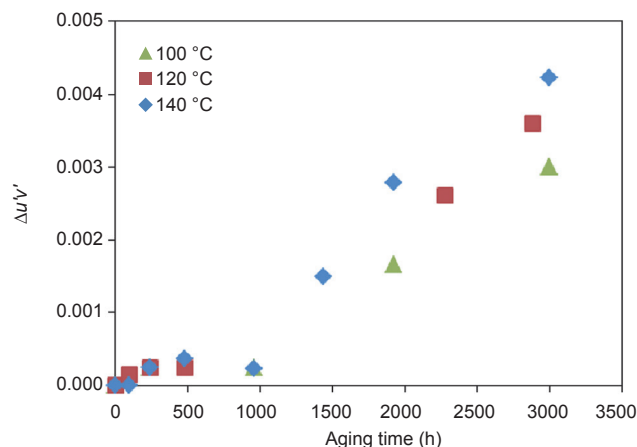


Figure 15. Color shift of BPA-PC plate, aged at 100 °C, 120 °C, and 140 °C for different thermal aging times [22].

The yellowing index (YI), which shows the amount of discoloration, of BPA-PC plates was also measured as a function of exposure time under thermal and thermal plus blue-light stress, as shown in Figure 16. This figure shows the YI of the sample, exposed to 140 °C without irradiation of blue light, together with the YI of the photo-aged sample (at 140 °C). Obviously, the temperature itself could cause the yellowing. However, one can see that the blue light has a significant contribution to the yellowing. This aging test was done in almost pure BPA-PC, which is used as a lens and as a substrate for phosphor in remote-phosphor LEDs, in order to clarify the chemical reason for color changing in BPA-PC; details of the test are already published [19]. In commercial samples, light has a lesser effect on discoloration due to the use of heat stabilizers, and the main reason for yellowing in these samples is thermal aging. For this reason, thermal aging is used to accelerate degradation mechanisms in order to study color shift. It is already reported that by increasing the temperature, the rate of discoloration is faster [19–23]. In our next work, the effect of light on the aging of remote phosphor and color shift, and possible solutions for reducing the rate of color shift, will be studied extensively.

Thermal aging at 85 °C for up to 3000 h was also done for PMMA, which is used as a secondary optics. It has been shown that there is no significant aging for PMMA materials under any implemented aging stress for up to 3000 h at 85 °C [28].

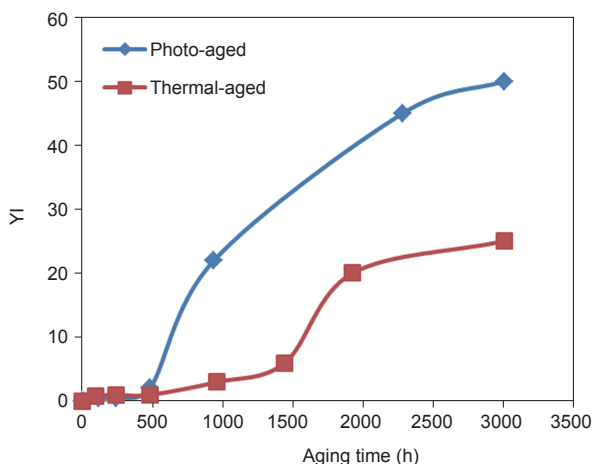


Figure 16. Variation in YI of BPA-PC plates exposed to blue light, at different aging times.

5 Standardization activities

Although great effort was put into characterizing and predicting lumen maintenance, resulting in the LM-80 and TM21 standards, little has been done to address color maintenance. Few (or no) LED-package manufacturers provide warranties on color maintenance. Some light-source manufacturers provide warranties on color maintenance, but these are likely to be limited to the time of LM-80 testing. (Longer warranties are of doubtful value, because predictions of color shift do not exist.) It is desirable to have a method of predicting color maintenance, to avoid the types of customer problems described above, if such a method can be determined. IES has defined several working groups related to color. The intention is to study, evaluate, and report on the effects of color and on color rendering in relation to the art and science of illumination. In addition, IES has begun a working group to define a procedure for color-maintenance prediction. The group, SO412SC “Projecting Long-Term Color Point Stability of LED Packages,” has not yet begun work. One reason for the delay, given by the chairman, is that LED manufacturers are not willing to share color-maintenance data. The stated purpose of the working group is to project long-term color point stability for white LED packages only, using LM-80 data. It is not intended to apply to colored LEDs, organic light-emitting diodes (OLEDs), or remote-phosphor systems. There is currently no activity either in International Electrotechnical Commission (IEC) (Europe) or in Industry Standard Architecture (ISA) (China).

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Compliance with ethics guidelines

Maryam Yazdan Mehr, Willem Dirk van Driel, and G. Q.

(Kouchi) Zhang declare that they have no conflict of interest or financial conflicts to disclose.

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