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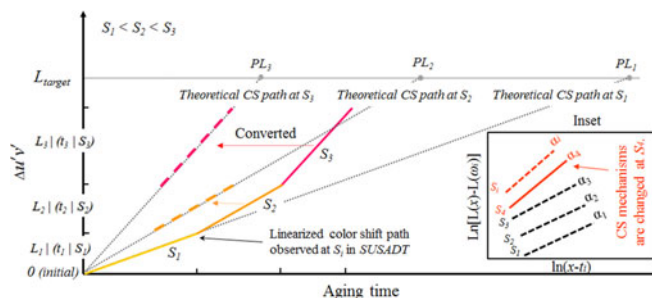
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Color Shift Modeling of Light-Emitting Diode Lamps in Step-Loaded Stress Testing

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Abstract: The color coordinate shift of light-emitting diode (LED) lamps is investigated by running three stress-loaded testing methods, namely step-up stress accelerated degradation testing, step-down stress accelerated degradation testing, and constant stress accelerated degradation testing. A power model is proposed as the statistical model of the color shift (CS) process of LED products. Consequently, a CS mechanism constant is obtained for detecting the consistency of CS mechanisms among various stress-loaded conditions. A statistical procedure with the proposed power model is then derived for the CS paths of LED lamps in step-loaded stress testing. Two types of commercial LED lamps with different capabilities of heat dissipation (CHDs) are investigated. Results show that the color coordinates of lamps are easily modified in various stress-loaded conditions, and different CHDs of lamps may play a crucial role in the various CS processes. Furthermore, the proposed statistic power model is adequate for the CS process of LED lamps. The consistency of CS mechanisms in step-loaded stress testing can also be detected effectively by applying the proposed statistic procedure with the power model. Moreover, the constant assumption in the model is useful for judging the consistency of CS mechanisms under various stress-loaded conditions.

Index Terms: Light-emitting diodes (LEDs), color shift (CS), reliability modeling, degradation mechanism.

1. Introduction

Light-emitting diodes (LEDs) are increasingly attracting attention because of their advantages over traditional light sources; these advantages are high luminous efficiency, controllable color performance, energy saving, and long lifetime [1]–[3]. Given their high junction temperature (T_j), LED products suffer from numerous problems, such as quantum efficiency droop, spectral shift,

and early decommissioning [4], [5]. The capabilities of heat dissipation (CHDs) of LED products can be improved by various thermal designs to minimize T_j , such as the designs of the heat sink for LED lamps, the substrate of the LED module, the thermal conduction path of the LED package, and the selection of a transparent molding compound [6], [7]. However, the inherent degradations to thermal conditions must be considered in analyzing the lifetime of LED products. Numerous decay mechanisms may be responsible for thermal degradation. Thus, the thermal reliability of LED products is currently a major topic in research.

Lumen degradation and color shift (CS) must also be considered in predicting the lifetime of LED products. The lifetime of an LED product is defined by the Illuminating Engineering Society (IES) under the standards LM-79 and LM-80. Reliability models focusing on the lumen decay process are developed to extrapolate the lifetime of LED lamp systems. Examples of such reliability models include an approach designed for reliability [8], a hierarchical life prediction model [9], a non-linear filter-based approach [10], a method based on a boundary curve method [11], and a procedure that uses the gamma process model [12]. Moreover, a simplified Eyring model considering the degradation of the epoxy lens and plastic package is introduced to predict the life of a lighting system under changing conditions [13]. Most of the existing reliability models are based on the lumen decay data derived from extended degradation testing.

Traditional constant stress accelerated degradation testing (CSADT) usually requires a long test duration, a complicated stress level selection process, large sample sizes, and high test costs. By contrast, the step-loaded stress testing method is characterized by special advantages, such as a short time for testing and a small sampling size; these advantages make this method suitable for LED products [14]–[16]. To reduce the duration of reliability assessment, a study applied step-up stress accelerated degradation testing (SUSADT) with a subsystem isolation method in evaluating the lifetime of LED lamps [15]. Given the complex system integration of LED lamps, the entire system is separated into several subsystems; thus, each individual subsystem can undergo a reliability test using the highest possible stress levels. Step-down stress accelerated degradation testing (SDSADT) based on the subsystem isolation method for LED lamps is further proposed with the goal of developing a solution to rapidly terminate the initial inherent activation phase of LED products [17]. The step-loaded stress testing is extremely effective in predicting the lifetime of LED lamp systems.

However, most of the extant research is focused on reliability modeling of the lumen output in predicting the lifetime of LED lamps or luminaires. The prediction of CS process also remains a challenging task for an accelerated testing, especially for step-loaded stress testing. Studies on the CS of LED package indicated that various mechanisms must be considered, such as the degradation of silicone lens, the interaction of the plastic materials on short-wavelength radiation, the browning of the phosphorous materials, the formation of oxidation products, and the composite corrosion or silver migration [18]–[26]. The CS mechanisms of a lamp are more complex and more sensitive to thermal stress than lumen decay mechanism in aging testing [27]. The degradation of polyethylene terephthalate reflective materials or polycarbonate materials in LED products [24], [28], [29] is the potential CS mechanism in lamp systems. Such degradation is worse under humid and thermal ambiances.

Reliability modeling is meaningful only when the LED products are tested with a unique decay mechanism in various stress-loaded conditions. The unique lumen decay mechanisms can be detected when the reliability modeling of step-loaded stress testing is based on the composite exponential model and the constant assumption in the model is proven effective [14], [15], [30]. However, analyzing the CS of LED products in the step-loaded stress testing is impossible because no proper statistical model of CS is available. The CS modeling of LED devices has been conducted, but no specific physical model is used as a statistical model for CS [31]–[34]. Although a statistical and non-linear dual-exponential model has been developed to describe the process of chromaticity state shift, the model is very complex to achieve the relationship between CS data and stress level [35]. Koh *et al.* [29] first demonstrated that a linear model can be applicable for the CS of LED devices, and Huang *et al.* [36] further described the CS as linear degradation by excluding the early degradation from the measured CS. However, the linear model is inadequate for detecting

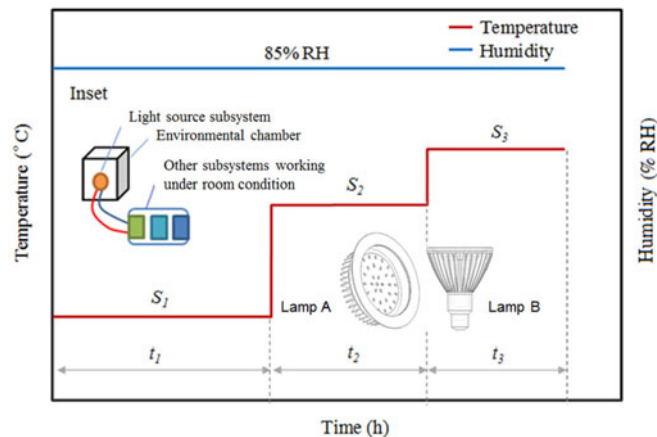


Fig. 1. SUSADT profile. (Inset) Test setup schematic. [15].

the consistency of CS mechanisms in various stress-loaded testing. Therefore, reliability modeling with an adequate statistical model for the CS process of LED lamps in step-loaded stress testing has become a meaningful task.

In this work, the color coordinate shift of LED lamps is investigated by running three stress-loaded testing methods, namely, SUSADT, SDSADT, and CSADT. A power model is proposed as the statistical model of the CS process of LED products. Accordingly, a constant assumption is obtained for detecting the consistency of CS mechanisms among various stress-loaded conditions. Then, a statistical procedure with the proposed model is derived for the CS paths of LED lamps in step-loaded stress testing. Two types of commercial LED lamps with different CHDs are investigated. Furthermore, the proposed power model is applied on three LM-80 test results of phosphor-converted white LED packages and modules as a validation step. The acceptable variation of CS mechanism constant for LED packages and modules is also analyzed.

2. Methodology

2.1. Testing Setup

This work involves two types of commercial 12 W LED indoor lamps with different CHDs; these lamps are LED down lamps (Lamp A) with 36 horizontal-chip InGaN/GaN LED packages in series and LED spotlights (Lamp B) with 6 flip-chip InGaN/GaN LED packages in series. Lamp B is composed of an LED module, a driver, an optical part, a heat sink, and a fixture. The driver in Lamp B is located inside the lamp and operates under 220 V input voltage and a constant output current. The driver in Lamp A is independent from the other parts. Given the complex system integration of LED lamps, the entire system is separated into several subsystems; each individual subsystem can undergo a reliability test using the highest possible stress levels [15]. This study assumes that the effect of drive current on LED lamps is steady and constant during operation. The SUSADT profile involves constant humidity (85% RH) and three-step thermal stresses (65, 85, and 95 °C). These stresses are reasonably determined on the basis of the highly accelerated decay testing (HADT) proposed in a previous work [37]. Following the procedure for measuring the pseudo-junction temperature (T_{pj}) of LED lamps [37], the T_{pj} values of Lamp A are roughly 73, 95, and 102 °C; the T_{pj} values of Lamp B that operates at 65, 85, and 95 °C are roughly 87, 103, and 112 °C. The duration of each stress phase is calculated using the accelerated factor with the same degradation quantity at each stress level. Tseng *et al.* [14] provided the detailed steps to calculate duration. Dwell times at S_1 , S_2 , and S_3 are $t_1 = 855$ h, $t_2 = 610$ h, and $t_3 = 535$ h, respectively. By contrast, the SDSADT profile uses the opposite order of thermal stresses (i.e., from high to low) and the same humidity (see Fig. 1). The outlines of Lamps A and B are also provided in the figure. CSADT with a constant thermal humidity condition (85 °C, 85% RH for roughly 2,000 h) for Lamps

A and B is implemented to compare the CS paths of the LED lamp modules by various stress–load test approaches including SUSADT, SDSADT, and CSADT.

A total of 10 LED lamps comprise each group of testing in this work; 30 spotlights and 30 down lamps are subjected to testing. The subsystem isolation method for LED lamps proposed in a previous study [15] is applied in SUSADT, SDSADT, and CSADT (see the inset of Fig. 1). The accelerated tests are implemented on the LED light engine (LED lamp module level) only. The LED light engine consists of a lamp case, secondary optical lens, a LED module, a thermal interface material, and a heat sink. The LED light engine is placed in a thermal chamber and connected to other subsystems outside the aging furnace. The optical parameters of the LED lamps are measured before and after the loading of each step-loaded stress. The samples are cooled down at room temperature (25 °C) for 2 h after their removal from the thermal chamber. The light parameters, such as lumen maintenance, chromaticity coordinate, and color rendering index, are measured with an integrating sphere (following the IES LM-79 test method) after lighting the samples for 30 min under the conditions of stabilization and temperature equilibrium.

2.2. CS Statistical Model for LED Lamps

The CS of LED light engines at any two positions (u_1', v_1') and (u_2', v_2') can be derived as follows [38]:

$$D u'v' = \sqrt{(u_1' - u_2')^2 + (v_1' - v_2')^2}. \quad (1)$$

From the statistical perspective, Koh *et al.* [29] first demonstrated that a linear model is applicable for the CS of LED devices by analyzing experimental and simulation data. Huang *et al.* [36] further described the CS ($\Delta u'v'$) as linear degradation by excluding the early degradation from the measured CS. The linear model can be expressed as follows:

$$L(t|S_i) = \beta_i t + L_0 \quad (1 \leq i \leq m) \quad (2)$$

where $L(t|S_i)$ is the CS amount ($\Delta u'v'$) of LED devices aged at thermal stress (S_i) for a duration t , L_0 is the projected initial, and β_i is the CS rate constant that depends on stress level S_i .

The monitored parameters, along with the same or similar decay mechanisms, must exhibit a regular change trend (i.e., obeying a fitting function with a satisfactory goodness of fit) [37]. Similarly, the new CS mechanisms of the same LED products can be detected when a selected statistical model is used to fit the CS paths from various stress-loaded conditions; the inherent constant of the model must exhibit an evident change under a satisfactory goodness of fit (>0.85). A power (α) constant on the time (t) is considered in the common exponential model as a parameter that is associated with the same decay mechanism of accelerated products in various stress-loaded conditions; this parameter describes the lumen decay path of LEDs [14], [15], [30]. In other words, $L(t|S_i) = \exp\{-\beta_i t^\alpha\}$. Following the similar consideration in the statistical model of CS path, the following power model for the CS process of LED products can be derived on the basis of (2):

$$L(t|S_i) = \beta_i t^\alpha + L_0. \quad (3)$$

The power α can also detect the stress limit in the reliability test [14], [37]. When $\alpha = 1$, the model is a linear model. Initial data point ($t = 0$) must be excluded during fitting the CS path to ensure that the power model is available. Normally, α depends on the product used and is constant and independent of stress. In this study, α is defined as a constant assumption, namely, a CS mechanism constant. In other words, the stress levels are within the stress range that induces the same CS mechanisms in LED lamps. Equation (3) can be simplified when the CS path starts from zero ($L_0 = 0$), as follows:

$$L(t|S_i) = \beta_i t^\alpha. \quad (4)$$

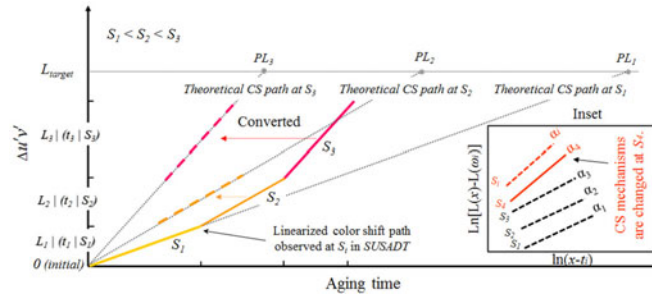


Fig. 2. Theoretical CS path in SUSADT. (Inset) Schematic for analyzing the consistency of CS mechanisms under various stress-loaded conditions.

The following Arrhenius reaction rate model is adopted to represent the relationship between β_i and thermal stress S_i [29], [39]:

$$\beta_i = A_0 \exp \left[\frac{E_a}{k_b(273 + S_i)} \right] \quad (5)$$

where A_0 is a fitted constant, E_a is the activation energy (in eV), and k_b is Boltzmann's constant (8.6173×10^{-5} eV/K).

Humidity stress is introduced as an acceleration factor in the thermal accelerated tests. Thus, Peck's model ($\beta = C \cdot e^{E_a/kT} \cdot H^{-\lambda}$) combined with the Arrhenius temperature reaction model ($\beta = C \cdot e^{E_a/kT}$) and the humidity reaction part ($H^{-\lambda}$) must be considered. Given that humidity stress is constant among all step-loaded thermal stresses in SUSADT or SDSADT, the humidity reaction part ($H^{-\lambda}$) is a constant; meanwhile humidity acceleration reactions are assumed the same in all stresses. Peck's model can then be presented with the Arrhenius reaction rate model [$\beta = (C \cdot H^{-\lambda}) \cdot e^{E_a/kT} = C_1 \cdot e^{E_a/kT}$]. The high-humidity reaction is changed to that of room humidity for calculating the real lifetime of LED lamps at room ambience. Prior to this process, the Arrhenius reaction rate model [see (5)] is adopted to represent the relationship between β_i and stress S_i .

2.3. Statistical Analysis of the CS Paths of LED Lamps in Step-Loaded Stress Testing

The color coordinate shift path of LED light engine over time is derived during SUSADT and SDSADT. The CS at any two positions (u_1', v_1') and (u_2', v_2') can be obtained using (1). The database of CS amount $(\Delta u'v')$ over time $\{[t, L_i(t)]\}$ can be derived. The CS rate of the tested light source is assumed to possess a "memory-less property" in step-loaded stress testing. In other words, the CS rate of the light source depends only on the ongoing stress and not on the history of the process. Thus, the linearized CS path observed at each stress S_i can be transferred to its theoretical CS path in SUSADT (see Fig. 2). The pseudo lifetime at S_i (PL_i) can then be achieved at the target CS amount (L_{target}). Similarly, when an opposite order of the thermal stresses is loaded in SDSADT [17], the theoretical CS path of SDSADT can also be achieved (Fig. 3).

When ω_i is defined as the start time of the CS path for stress S_{i+1} that produces the same CS amount at the end time of CS path under stress S_i , the CS relationship of stress S_{i+1} to S_i can be expressed as follows [14]:

$$L(\omega_{i+1}|S_{i+1}) = L(\omega_i + t_{i+1} - t_i|S_i). \quad (6)$$

On the basis of (4) and (6), the following equation can be derived:

$$\beta_{i+1} = \beta_i \left(\frac{\omega_i + t_{i+1} - t_i}{\omega_{i+1}} \right)^\alpha. \quad (7)$$

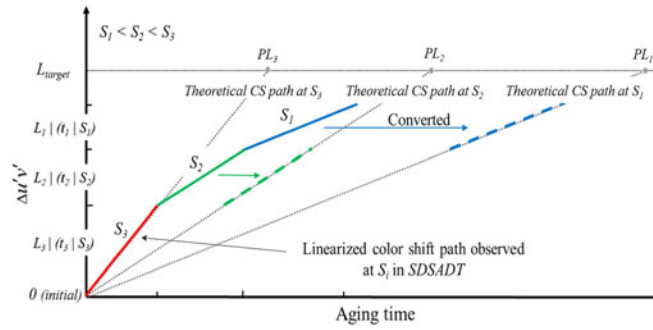


Fig. 3. Theoretical color shift path in SDSADT.

Thus, the following equations can be obtained using (4) and (7):

$$\ln(L_i(t)) = \begin{cases} \ln\beta_1 + \alpha \cdot \ln t, & (0 \leq t \leq t_1) \\ \ln\beta_1 + \alpha \cdot \left[\ln\left(\frac{t_1}{\omega_1}\right) + \ln(t + \omega_1 - t_1) \right], & (t_1 \leq t \leq t_2) \\ \dots\dots\dots \\ \ln\beta_1 + \alpha \cdot \left[\sum_{k=1}^m \ln\left(\frac{\omega_k + t_{k+1} - t_k}{\omega_{k+1}}\right) + \ln(t + \omega_m - t_m) \right], & (t_m \leq t \leq t_{m+1}, m \geq 2). \end{cases} \quad (8)$$

Furthermore, by defining $\chi = t + \omega_m$ ($\omega_0 = 0$) as the time on the theoretical CS path, (8) can be expressed as follows:

$$\ln[L_i(\chi) - L_{i0}(\omega_i)] = \begin{cases} \alpha \cdot \ln(\chi) + \ln\beta_1, & (0 \leq \chi \leq t_1) \\ \alpha \cdot \ln(\chi - t_m) + L_k, & (t_m + \omega_m \leq \chi \leq t_{m+1} + \omega_m, m \geq 1) \end{cases} \quad (9)$$

where $L_k = \ln\beta_1 + \alpha \sum_{k=1}^m \ln\left(\frac{\omega_k + t_{k+1} - t_k}{\omega_{k+1}}\right)$.

On the basis of (9), the process that evaluates the constant α associated with the CS mechanism in various stress-loaded conditions is simplified without considering the start time (ω_i) of the CS path for each stress S_i . The reason is that the initial CS amount $[L_{i0}(\omega_i)]$ is always known at each stress S_i . α at various stresses S_i can be obtained only by conducting linear fitting between $\{\ln[L_i(\chi) - L_{i0}(\omega_i)]\}$ and $[\ln(\chi - t_i)]$. In this paper, the CS amount $[L_i(\chi)]$ is exactly the CS of LED products in stress S_i , excluding the CS amount accumulated before S_i . Subsequently, the parameters β_i can also be fitted with (5) and (8) by minimizing the residual error of the least square estimator [14]. The steps for assessing the residual error and lifetime extrapolation on the CS of LED lamps are similar to the detailed steps on the lumen maintenance that are provided in [14] and [15].

Ensuring the controlled CS mechanism at each stress level is critical. The independent value of α at each stress level exactly denotes whether the thermal stresses selected for LED lamps are suitable for use in step-loaded stress testing. During the accelerated test at different stress levels, the change in the value of α (α_Δ , the slope) must be maintained within an acceptable range. As shown in the inset of Fig. 2, the CS mechanisms of LED products must be changed when α_Δ exceeds a given range. By maintaining the lumen decay mechanisms of LED products, the value of α_Δ based on the known composite exponential model is generally between 0 and 0.2 [14], [15]. In the present work, the acceptable range of α_Δ to maintain the unique CS mechanisms in accelerated testing for LED products is discussed. The proposed power model is expected to be effective and fast in detecting the change of CS mechanisms of LED products in various stress-loaded conditions. The CS data of two existing LM-80 test results [40], [41] released for commercial phosphor-converted white LED packages and modules are used to determine the acceptable variation of constant assumption α for LED products. In addition, one type of phosphor-converted white LED package with 100 mA drive current is tested in ambiances of 25, 55, and 85 °C for 6,000 h by following the LM-80 procedure in this work. The derived CS data are also analyzed.

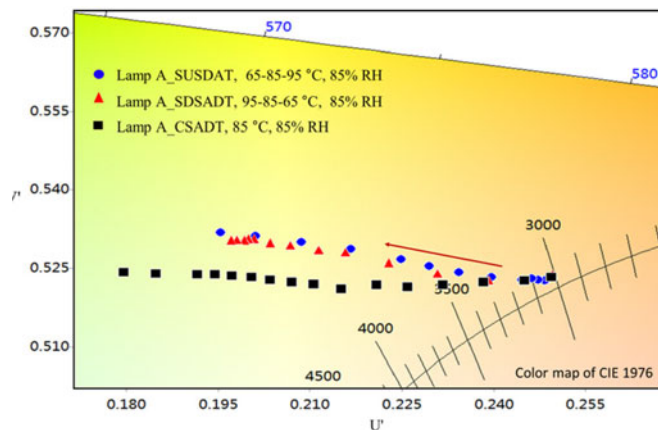


Fig. 4. Average color coordinate shift paths of Lamp A in various stress-loaded conditions on the color map of CIE 1976.

3. Results and Discussions

The benchmark samples without any stress loaded are subjected to optical measurements each time; this procedure is conducted to confirm that the room ambience and test setup are steady and the same as their initial states. The results of the optical measurements for the benchmark samples indicate that the average error of optical measurements from the ambience and test setup is $\leq 4\%$; the maximum errors of flux output are 3.19% and 4.78% for Lamps A and B, respectively; the maximum errors of color coordinate are 3.95% and 3.57% for the two lamps. When the possible errors from the inherent tester deviation ($\leq 2\%$) and an additional assumed deviation from the testing process ($\leq 2\%$) are considered, the confidence level of all the experimentally derived data in this study is approximately 90%.

3.1. CS Kinetics of LED Lamps

3.1.1. Color Coordinates Shift Paths of LED Lamps: The average color coordinate shift paths of Lamp A under the three testing conditions are plotted on the color map of CIE 1976 (see Fig. 4). The color coordinate ($u'v'$) shift paths of Lamps A in SUSADT, SDSADT, and CSADT clearly exhibit a common blue-shift process. By comparing with the effect of CSADT on the CS process, the CS mechanisms in all stress levels of step-loaded stress testing are extremely similar for Lamp A with strong CHD. Evidently, the cooling color temperature of lamps begins with 3000 K. By focusing on the step-loaded stress testing, the effect of stress order on the color coordinate shift path is minor; this finding indicates that the color coordinate shift rate and its mechanisms for Lamp A are only related to the ongoing loading stress; this result is associated with the results on lumen decay mechanisms [17].

The average color coordinate shift paths of Lamp B with weak CHD exhibit a two-phase law (Phase I and Phase II) for all aging conditions (see Fig. 5). The color coordinates first shift toward bluish light in Phase I, and then shift back toward yellowish light in Phase II. The CS kinetic of Phase I is associated with the CS process of Lamp A. The CS mechanisms of Lamp B are more sensitive to thermal stress than those of Lamp A. The result from HADT on Lamp B (see Fig. 6) provides a clear proportional relationship of thermal stress sensitivity to the ratio of yellow light to blue light. Thus, the stress order in the step-loaded stress testing shows an evident effect on the color coordinate shift path for Lamp B.

Evidently, the color coordinates of the lamps are easily modified in the three stress conditions, namely, SUSADT, SDSADT, and CSADT. Lamp A with strong CHD only experiences the bluish shift phase in various stress-loaded conditions, whereas Lamp B with weak CHD exhibits the two-phase CS process including the bluish shift phase (Phase I) and yellowish shift phase (Phase II).

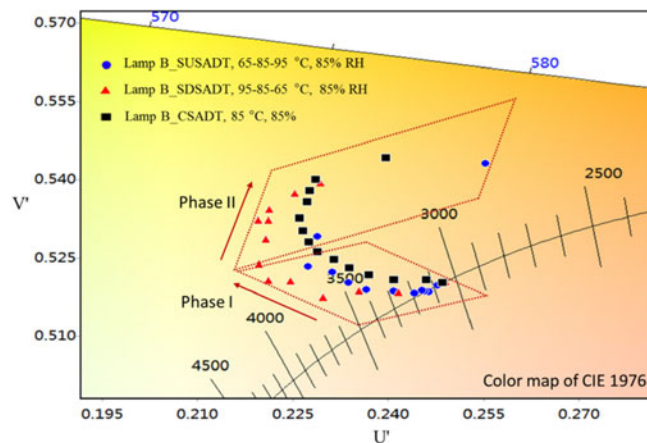


Fig. 5. Average color coordinate shift paths of Lamp B in various stress-loaded conditions on the color map of CIE 1976.

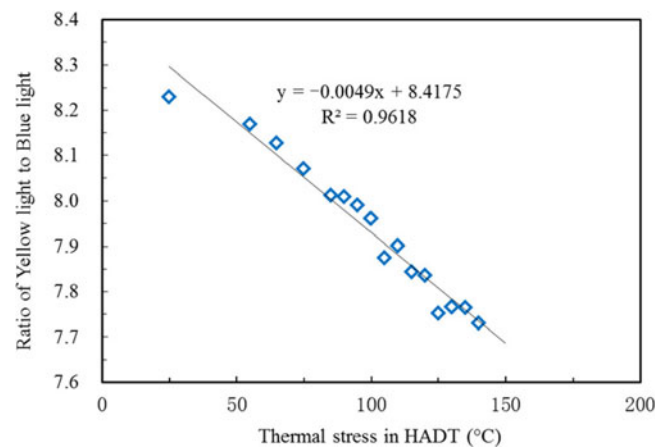


Fig. 6. Ratio of Yellow light to Blue light of Lamp B in HADT with the thermal stress of 12-hour dwell.

3.1.2. CS Mechanisms of LED Lamps: The typical spectrum of Lamp A (see Fig. 7) indicates that a significant modification occurs on the wavelength of yellow emission peak during the aging tests. Inset II of Fig. 7 analyzes the corresponding wavelength of yellow peaks normalized to the initial value in three stress testing conditions and validates the obvious change of yellow emission wavelength. The wavelength shift rate of yellow emission is only related to the ongoing stress conditions, and the final shift amount is unrelated to the stress order of step-loaded stress testing. The wavelength shift of yellow emission peak may be responsible for the color coordinate shift of Lamp A. Therefore, the spectral degradation of yellow emission plays a key role in the CS of Lamp A. As shown in Fig. 8 and its Inset II, the yellow emission of Lamp B in various stress testing methods experiences a similar decay process to that of Lamp A. The process is affected slightly by the weak CHD of Lamp B. Moreover, the blue emission peaks of Lamp A normalized to initial relative intensity (see Inset I of Fig. 7) exhibit an enhanced process prior to approximately 1000 h, and then maintain in a nearly stable process. However, the blue emission peaks of Lamp B with weak CHD show a rapid decay after the enhanced process. This phenomenon may be responsible for the two-phase CS process.

The ratios of yellow light to blue light for Lamps A and B in various stress testing conditions are provided in Fig. 9. For Lamp A, the ratios for all loading conditions remain at a stable value with a slight fluctuation or decline. However, the color coordinates impressively degrade reasonably with

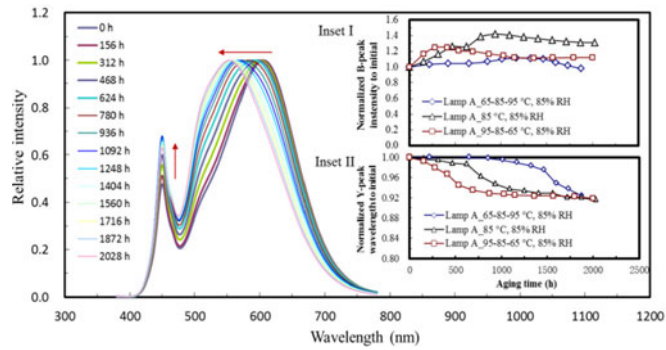


Fig. 7. Typical spectrum of Lamp A (Inset I) Blue peak (B-peak) decay paths during three testing conditions. (Inset II) Yellow peak (Y-peak) wavelength decay paths during three testing conditions.

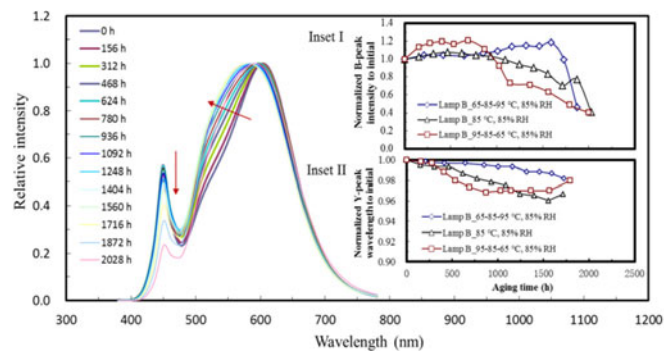


Fig. 8. Typical spectrum of Lamp B (Inset I) Blue: blue peak (B-peak) decay paths during three testing conditions. (Inset II) Yellow peak (Y-peak) wavelength decay paths during three testing conditions.

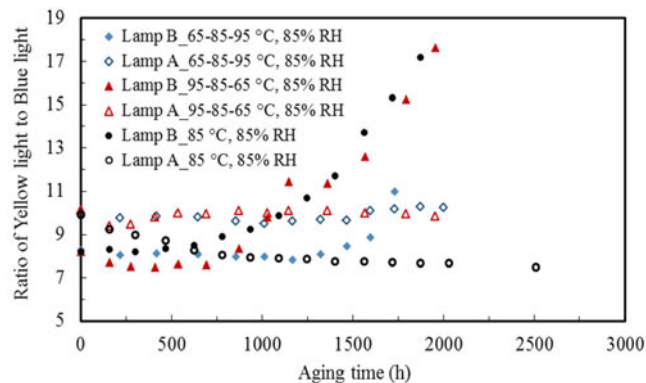


Fig. 9. Ratio of yellow light to blue light for Lamps A and B under various stress-loaded conditions.

bluish shift phase in aging testing while the spectrum of yellow emission shifts gradually toward the bluish light. Previous studies found some critical CS mechanisms, such as the degradation of the plastic lens because of the high temperatures reached by the LED devices and the interaction of the plastic materials with the short-wavelength radiation emitted by the LEDs [18]–[22], and the browning of the phosphorous material as a consequence of high-temperature treatment [20], [22]. The mechanisms of the subsequent browning of the LED module and optical parts in the lamp system [18], [42] cause the degraded spectral properties of yellow emission and worsen under humid and thermal ambiances; these mechanisms also result in the high sensitivity of the CS in

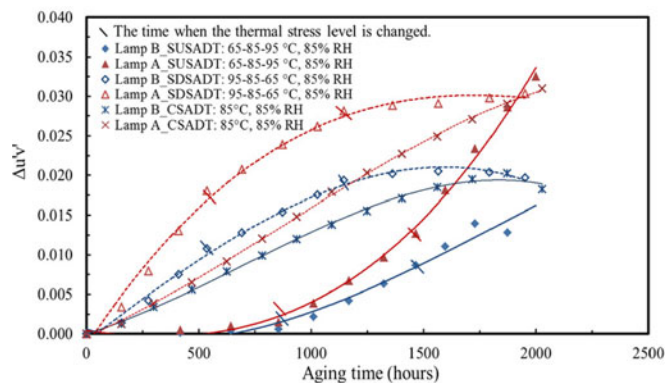


Fig. 10. CS paths of LED lamps in various aging tests.

lamp level. The considerable silicone decay of LED lens, beginning with a short wavelength [43], also aggravates the CS process despite the enhanced blue emission in the early stage.

For Lamp B, the ratios for all loading conditions increase dramatically after testing for roughly 1000 h. This result is associated with the two-phase CS process and the rapid decay process of blue emission peaks. A previous study indicated that the optical power of stressed flip-chip LEDs in Lamp B decreases significantly after the aging test and exhibits a close correlation with the drooped tunneling saturation current [17]. The degradation of blue emission chip may be responsible for the result of yellowish shift phase (Phase II) in Lamp B. Thus, the color coordinate shift process of Lamp B in various stress-loaded conditions presents the evident bending law; this law is induced mainly by the normal bluish shift phase related to the decay of yellow emission and the Phase II related to the gradual degradation of chip level.

The weak CHD of Lamp B may be responsible for the abnormal performance on the CS process. As illustrated in Fig. 9, the previous durations for SUSADT, SDSADT, and CSADT are roughly 1300, 700, and 600 h, respectively. For Lamp B, the existing degradation accumulated from previous stress-loaded testing suddenly deteriorates under the weak CHD associated with the tight lamp structure in the rest stress testing. The effects of long-term experiment on the decay of blue chip are evident [23]. Therefore, an evident bending law is found in the color coordinate shift paths of Lamp B. By contrast, for Lamp A, given the adequate heat spread capacity, the existing degradation from the beginning to the end gradually continues. Moreover, the color coordinates shift law maintains well in the modification of yellow emission.

3.2. Analysis on the CS Mechanisms Consistency of LED Lamps

On the basis of Equation (1), the CS ($\Delta u'v'$) paths of various aging tests can be derived (see Fig. 10). Evidently, the CS of Lamp A with strong CHD is mostly independent on the historical loaded stresses; this finding is associated with the wavelength shift of yellow emission peak (See Inset II of Fig. 7). Meanwhile, by using the failure threshold of 0.007 ($\Delta u'v' = 0.007$) released for packages and modules from IES LM-80-08, all stressed lamps must fail within only roughly 1200 h or earlier in all stress conditions. Thus, the sensitivity of CS mechanisms in LED lamp level to stress conditions is much higher than that in LED package or module level. The CS path observed at each stress S_i in step-loaded stress testing can be converted to its theoretical CS path with the assumption that the CS rate depends only on the ongoing stress. The theoretical CS paths converted from the actual paths observed in SUSADT are shown in Fig. 11. PL_i can then be obtained at a target CS amount on each theoretical CS path.

By using the proposed power model, the independent value of α at each stress level for Lamp A is achieved only by conducting linear fitting with high goodness of fit ($R^2 > 0.92$) between the CS amount $\{\ln[L_i(\chi) - L_{i0}(\omega_i)]\}$ and time $[\ln(\chi - t_i)]$ based on (9) (see Fig. 12). Considering all thermal stress conditions in 85% RH, the inherent constant α fluctuates with the maximum α_{Δ} value

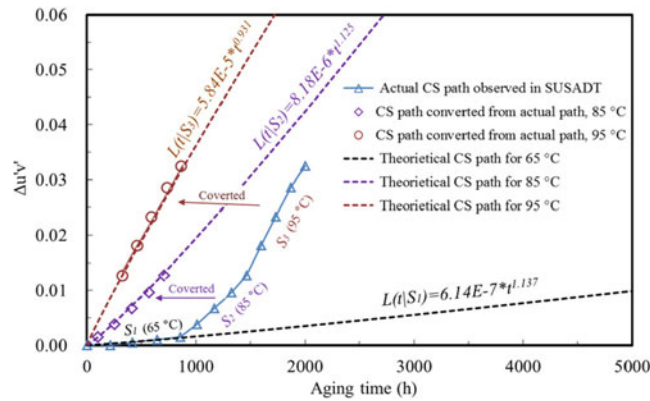


Fig. 11. Theoretical CS paths converted from actual observed paths.

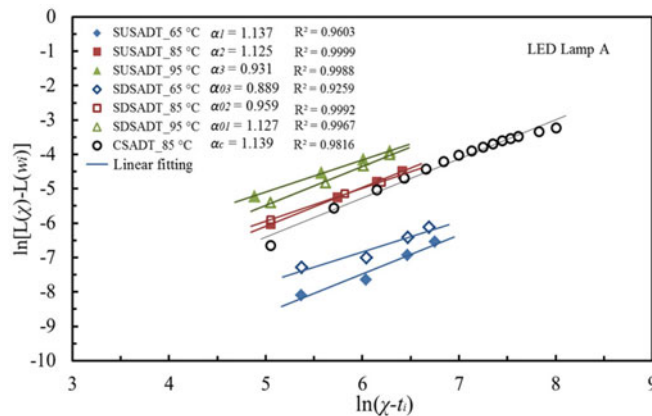


Fig. 12. Analysis on CS mechanism constants of Lamp A with the proposed power model.

of 0.208, excluding α_{03} (0.889) at the third stress (65 °C) of SDSADT. When the change in the value of α is limited below 0.25 for controlling the unique CS mechanisms of Lamp A, the effects of all stress conditions, excluding the third stress of SDSADT on the CS kinetic, are consistent. The mechanism constant α_{03} at the third stress of SDSADT changes with the minimum α_{Δ} value of 0.042 and the maximum α_{Δ} value of 0.25 in a warning range. This range is regarded as within a warning boundary that indicates that the CS mechanism is deviating and dangerous. Similarly, the independent value of α at each stress level for Lamp B is achieved using (9) (see Fig. 13). As discussed in Section 3.1, the sudden decay mechanisms of blue LED chip are combined into the CS process. Accordingly, the data at the third stress (95 °C) of SUSADT and the last stress (65 °C) of SDSADT cannot be fitted. The constant α at rest stress conditions are received with high goodness of fit ($R^2 > 0.89$). Evidently, the received inherent constants α validate the consistency of CS mechanisms of Lamp B with the maximum α_{Δ} value of 0.247 when the change in the value of α is limited below 0.25. In addition, although the linear model [29], [36] can fit the actual observed paths from the step-loaded stress testing and can be converted to theoretical CS paths, the linear model without a mechanism constant which is independent of stress conditions cannot detect the consistency of CS mechanisms in various stresses; thus, the reliability modeling of CS process with the linear model in the step-loaded stress testing is impractical.

The proposed statistic power model is suitable for the CS of LED lamps, and the consistency of CS mechanisms in step-loaded stress testing can be evaluated effectively by the proposed statistic procedure with the power model. The constant assumption of α in the power model is useful for

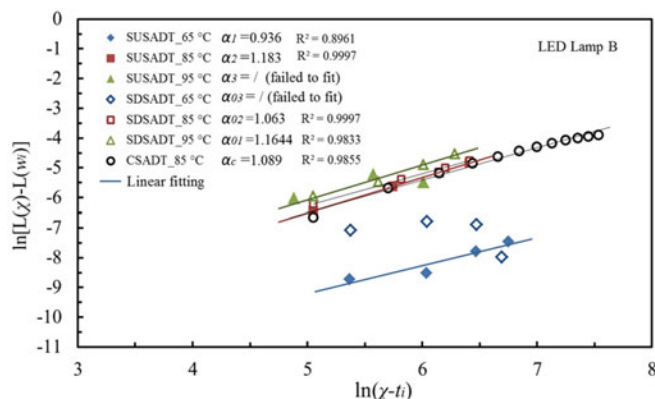


Fig. 13. Analysis on CS mechanism constants of Lamp B with the proposed power model.

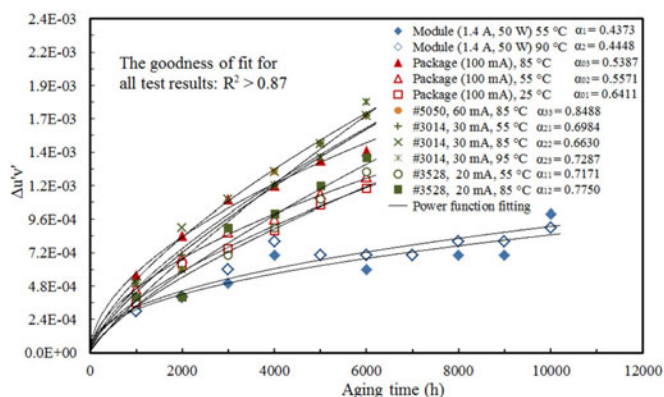


Fig. 14. CS paths and CS mechanism constants of LED packages and modules.

determining the expected consistency of CS mechanisms in various stress-loaded conditions. The acceptable change range of α_{Δ} for LED lamps in accelerated testing depends mainly on the structure and CHD of lamps. The results imply that the acceptable range of α_{Δ} for the CS of selected lamps is limited within 0.25 ($\alpha_{\Delta} \leq 0.25$). In addition, this study suggests that the maximum acceptable range of α_{Δ} is not exceeding 0.3 for LED lamps.

3.3. Applications and Validation of the Proposed Power Model on LED Packages and Modules

The proposed power model is applied to the CS data of phosphor-converted white LED packages and modules to validate its performance (see Fig. 14). Moreover, the constant assumption of α in the power model is analyzed to determine the acceptable variation of constant assumption α for LED packages and modules. Two groups of CS data in existing LM-80 test results are analyzed in Fig. 14. For Test Result #1[40], three types of LED packages with low drive current including 20, 30, and 60 mA are tested for 6000 h. The tested types are LED packages #5050, #3014, and #3528. For Test Result #2 [41], one type of 50 W LED module with high drive current of 1.4 A is tested for 10,000 h. One type of commercial phosphor-converted white LED package with 100 mA drive current (#100C) is subjected to the ambiances of 25, 55, and 85 °C for 6,000 h; the derived CS data are provided in Fig. 14. The CS data over aging time in each stress condition are plotted and fitted with the proposed power function model. The results indicate that the proposed power model is adequate, and the goodness of fit is more than 0.87 for all test results. The CS mechanism constant

of α for the same LED package and module tested in various stress-loaded conditions changes slightly with small maximum α_{Δ} , such as 0.03, 0.058, 0.102, and 0.0075 for the LED packages #3014, #3528, #100C, and the 50 W LED module. Thus, the acceptable CS constant range of $\alpha_{\Delta} \leq 0.2$ can be reasonably defined for the CS process of LED package and module. In addition, the linear model without considering the early degradation [36] is used to fit all test results. The minimum goodness of fit is 0.74, which implies that the proposed power model is more applicable to the CS of LED devices than the linear model.

Compared with the constant assumption of α ($\alpha_{\Delta} \leq 0.25$) on LED lamps, the control range of CS mechanism consistency on LED package and module is more rigorous. As concluded in the previous sections, the CS mechanisms of LED lamps mainly depend on yellow emission maintenance in aging tests when the mechanism of CS process is unique. The degradation of yellow emission is usually ascribed to the degradation of the plastic materials, the browning of the phosphorous materials, and subsequent browning of the LED module and optical parts in the lamp system under humid and thermal ambiances. Thus, the acceptable range of α_{Δ} for LED lamps is enlarged when considering the high sensitivity of CS kinetics to stress ambience.

4 Conclusion

The color coordinates of lamps are easily modified in three stress-loaded conditions, namely, SUSADT, SDSADT, and CSADT. The color coordinate shift process presents an evident two-phase bending law for the lamps with weak CHD. This law is induced mainly by the gradual decay of yellow emission, which is only related to the ongoing loading stress and unrelated to the historical loaded stress. The sudden degradation of blue chip also contributes to the two-phase bending law. The different CHDs of LED lamp A and B may be responsible for the various CS processes. The analysis results show that the proposed statistic power model is suitable for the CS process of LED lamps. Furthermore, the consistency of CS mechanisms in step-loaded stress testing can be detected effectively by applying the proposed statistical procedure with the power model. The constant assumption of α in the power model is useful for judging the consistency of CS mechanisms in various stress-loaded conditions. The acceptable change range of α_{Δ} for the CS mechanisms LED lamps in accelerated testing depends mainly on the structure and CHD of lamps. The results from analyzing the CS data of three LM-80 tests indicate that the acceptable range of α_{Δ} for LED lamps is usually larger than that for LED packages and modules because of the high sensitivity of the CS kinetics of lamps to stress conditions.

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