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Color shift acceleration on mid-power LED packages

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ABSTRACT

Mid-power LED packages are now widely used in many indoor illumination applications due to several advantages. Temperature stress, humidity stress and current stress were experimentally designed and performed to accelerate the color shift of mid-power LED packages and color shift mechanisms have been discussed based on the color shift results obtained from measurements. Conclusions could be drawn:

- Linear function fitting demonstrates a good linear relationship between color shift ($\Delta u'$ $\Delta v'$) and aging time almost for all the aging conditions. We can extrapolate the color shift $\Delta u'$ and $\Delta v'$ based on the fitted regression equations and then make the prediction for the total color shift $\Delta u'v'$.
- Current stress can induce a different failure mode. Peak intensity reduction analysis reveals that the current stress accelerates the degradation of LED die.
- Humidity test induced a substantial color shift both in u′ and v′. The u′ has an increased degradation rate after aging of 3000 h at 85%RH & 85 °C, there should be different degradation mechanisms during the whole humidity test. The molecular structure decomposition of silicone plates and then follows the silicone carbonization due to the long-term (3000 h) accumulated high localized temperature aging.

1. Introduction

Mid-power LED packages, whose electrical power rating ranges from 0.2 to 0.5 W are now widely used in many indoor illumination applications and in place of other high cost devices due to many advantages such as cost-effective, ease for simpler design for the distributed light system [1–3].

Several studies have been reported on the lumen output and degradation mechanisms of LED packages under different aging conditions [1–8]. There are also some studies on the color shift mechanisms. Meneghini and Zanoni et al. investigated InGaN/GaN based high brightness LEDs with high temperature or dc or pulsed stress, results shown that thermal treatment can induce a worsening of the chromatic properties of the devices. In most of the cases, white LEDs submitted to stress tests show significant modifications of their spectral characteristics during stress time and, in particular, a decrease in the ratio between the intensity of phosphor-related emission and the intensity of the main blue peak. Consequently, after stress, the chromatic properties of the devices can shift toward a bluish light. The degradation of the chromatic properties is usually ascribed to the browning of the material used for the encapsulation of the phosphors/chip system. The degradation can be also correlated to the partial carbonization of the reflective surface of the package: this effect may introduce a decrease in the efficiency of the light extraction process due to the reduced contributions of the light reflected by the package to the overall emission. Both these processes can modify the spectral content of the light emitted by the LEDs and induce modifications in the relative intensity of the blue and yellow emission peaks [9–14].

Davis et al. [15–19] examined chromaticity shift modes of the PAR38 lamps with four types of built-in LED packages, results shown the chromaticity shift is dominated by the characteristics of the LED packages. There are mainly four potential chromaticity-shift directions of a light source: blue shift, yellow shift, green shift and red shift. Huang et al. studied the color shift caused by the yellowing of package encapsulate for mid-power white light LED packages in the outdoor illumination applications with high humidity and high temperature (WHTOL) [20].

However, research on the color shift and mechanisms of mid-power LED packages for indoor illumination applications, especially for the

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color shift acceleration and prediction, is less published. To improve the light efficacy and miniature the package size for ease of secondary optical design as well as cost efficiency in many indoor applications, mid-power LED packages have reduced thermal and optical design compared to high-power LEDs: usually a Ag coated layer covering plastic housing is used but lack of dedicated thermal pad and optical element, which increased sensitivity of this type of LED packages toward environmental temperature. These characters will possibly induce a different degradation in color shift from other types. Since the color is important in some applications, although there is only one industry standard to define the color shift limit [21–23], it is important to predict the color shift for LED package designers and manufacturers.

The aim of this report is to investigate the color shift modes and mechanisms of mid-power LED packages caused by different acceleration stresses and propose an acceleration and prediction method for color maintenance. Temperature stress, humidity stress and current stress were experimentally designed and performed to accelerate the color shift of mid-power LED packages, and color shift mechanisms are discussed based on the color shift results obtained from measurements. A prediction method is proposed.

The experimental results and the proposed prediction method will be helpful in the mid-power LED package design and application, and also helpful in the color shift investigation and acceleration for the luminaire level products in which this class of LED packages is used.

The remainder of this paper is organized as follows: Section 2 presents the materials and methods for the experiment set-up and testing. Section 3 provides results and discussions on the designed experiment. Finally, concluding remarks are presented in Section 4.

2. Materials and methods

Samples used in the investigation are widely used mid-power LED packages, 5630 with dimension $5.6 \times 3.0 \times 0.96$ mm^3, from a leading manufacturer in the industry. LED packages were mounted on metal core based plates as shown in Fig. 1.

Samples were divided into 3 different groups, and each group was subjected to a different aging condition, 25 °C (room temperature), 85 °C, or 85 °C & 85%RH. 25 °C is used here as a reference temperature to simulate the daily use condition, 85 °C is a temperature lift of 60 °C to investigate the temperature effect on color shift and 85 °C & 85%RH is for humidity test investigation. Each group has 2 sub-groups, and every sub-group has 5 samples, which were switched on with a different current, 75 mA or 225 mA during aging. Lighting status is shown in Fig. 2. Samples were taken out periodically and measured at room temperature with normal operation conditions by the same integrating sphere with a diameter of 0.5 m at 2pi mode. In this 2pi measurement mode, the LED package is placed at the centre of the integrating sphere so that rays directly going to the sphere spread a solid angle of 2pi sr or a hemisphere. Measurement errors have been minimized to within ±0.0005 by a strict control on the major error contributors as follows: 1) The ambient temperature is 25 ± 1 °C during test; 2) Every time in the measurement, only one person did the measurement, and the LED package was mounted and aligned to the same place; 3) The measurement data used in this paper is average of 3 times of measurement.

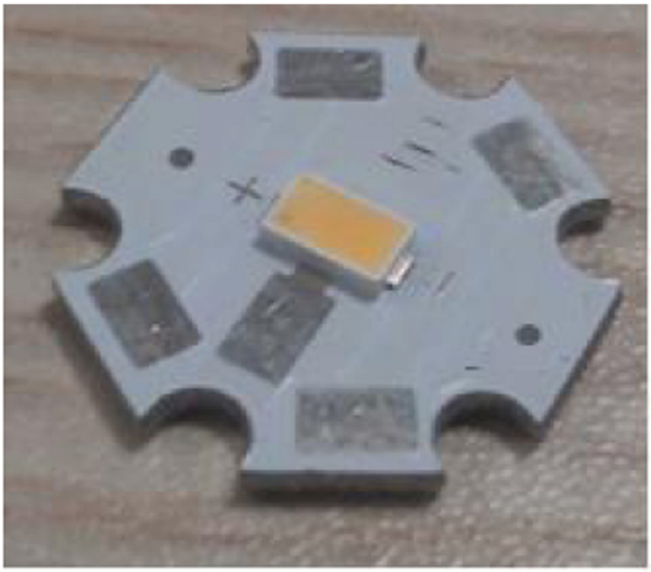


Fig. 1. LED package mounted on the metal core based plate.

3. Results and discussions

3.1. Results for the subgroup with loading current I = 75 mA

Chromaticity coordinates data was collected, u′ and v′ (loading current I = 75 mA) were normalized to their initial color points and shown in Fig. 3(a) and (b), respectively. Linear function model fitting demonstrates R^2 (a scalar measure of model significance) is greater than 80% for all the aging conditions, which reveals a good linear relationship between color shifts (Δu′, Δv′) and aging time. Negative slope reveals a trend of decrease or degradation both in u′ and v′ under all the aging conditions.

Two curves are plotted to fit the aging condition of 85%RH & 85 °C, because significant difference exists in the degradation rate between before 3000 h and after, the degradation rate is higher after 3000 h. Obviously, even in the first 3000 h, the aging condition of 85%RH & 85 °C demonstrates a degradation rate greater than the other conditions in absolute value, which indicates humidity has a much bigger acceleration effect in color shift. Similar phenomenon could be found in Fig. 4, where samples were subjected to a greater loading current as high as 225 mA during aging.

3.2. Results for the subgroup with loading current I = 225 mA

As mentioned, normalized u′ and v′ (aging current I = 225 mA) were shown in Fig. 4(a) and (b) respectively.

Similarly, linear model fitting results demonstrate that R^2 is greater than 80% for all the aging conditions, which reveals again good linear relationships between color shifts (Δu′, Δv′) and aging time.

Negative slope reveals a trend of decrease in u′ during aging under all conditions, while presences of positive slope indicates a trend of increase in v′ after a short certain period of aging at room temperature or 85 °C, shown in Fig. 4(b).

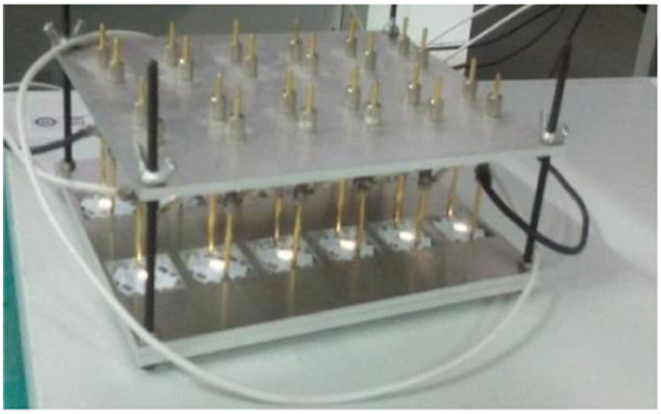
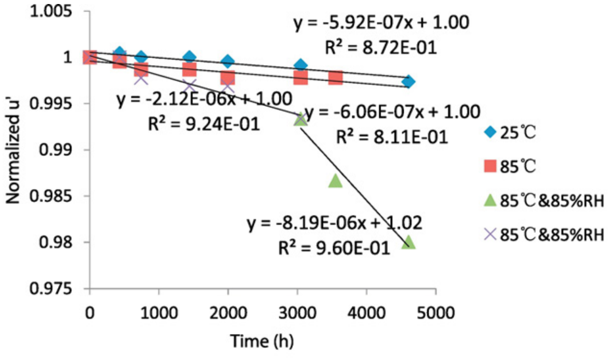
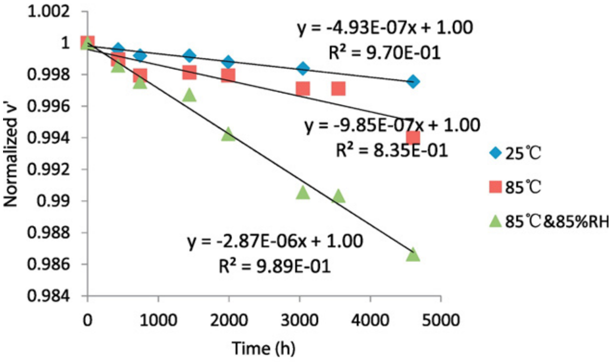


Fig. 2. LED packages switched on during aging.

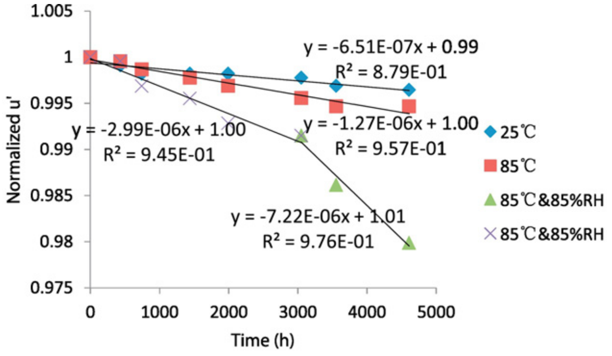


(a) Normalized u'

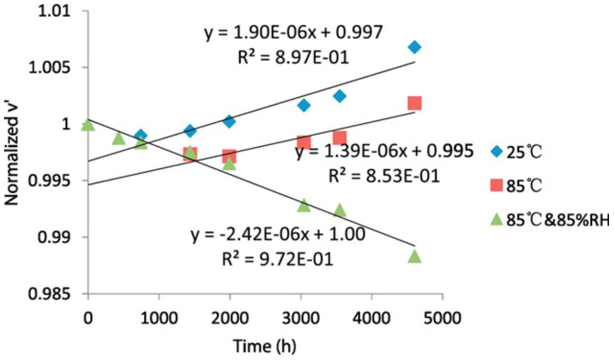


(b) Normalized v'

Fig. 3. Normalized u′ and v′ and linear function fitting with different aging conditions (loading current I = 75 mA).



(a) Normalized u'



(b) Normalized v'

Fig. 4. Normalized u′ and v′ and linear function fitting with different aging conditions (loading current I = 225 mA).

3.3. Discussions

To further understand this color shift phenomenon, the spectral power distributions (SPDs) have been checked for all the samples aged under different aging conditions. Both blue light peak intensity and yellow light peak intensity were gradually reduced during aging, but no obvious shift of peak wavelength was found, which is probably the reason that color shift (Δu′, Δv′) has a linear relationship with duration of operation. An example, shown in Fig. 5, demonstrates the relative flux intensity distributions of one sample aged at 85%RH & 85 °C for different periods of time.

Since the color shift is caused by the change of the ratio of blue to yellow light, peak intensity reduction could be used to further investigate the color shift mechanisms with different aging conditions. Relative peak intensity reductions of blue light and yellow light for the samples after aging of 3500 h are shown in Fig. 6. After aging at 85 °C for 3500 h, the reduction of blue peak intensity of the subgroup with high loading current (225 mA) is several times higher than the other subgroup with low loading current (75 mA), compared to a slight increase in the reduction of yellow peak intensity, thus leading to a different change of the ratio of blue to yellow light. That's why we observed a trend of increase in v′ after a certain period of aging in Fig. 4(b), compared to a decrease in Fig. 3(b). The emission at ~450 nm corresponds to the blue chip (LED die). The blue light peak reduction during aging at 85 °C is mainly associated with the degradation of the LED die. The junction temperature will be increased with the stress current, and the lifted junction temperature will accelerate the degradation of the LED die and hence induce the increase of blue light peak intensity reduction. Another factor is the conversion efficiency change of phosphor or phosphor oxidization. The lifted junction temperature by stress current will further heat the LED package and worsen the conversion efficiency of phosphor or even oxidize the phosphor and thus accelerate the reduction of the yellow light peak intensity.

There seems to be a different phenomenon for the samples aged at room temperature. When the stress current is increased to 225 mA during aging, the blue light peak intensity reduction becomes less. That's probably because the acceleration of current is not significant at low temperature and less blue light conversed to the yellow light during aging, and the phosphor conversion efficiency has not been worsen, or even become better. Subgroup to subgroup variation is also a factor.

Obviously, after humidity stress test, both the blue peak intensity and the yellow peak intensity have been reduced substantially for both stress currents. That's why we observed a rapid decrease in u′ and v′ in Figs. 3 and 4. The higher stress current has a more significant reduction in blue light peak intensity, which is consistent with the observation of aging at 85 °C. Since the u′ has an increased degradation rate after aging of 3000 h at 85%RH & 85 °C, there should be different

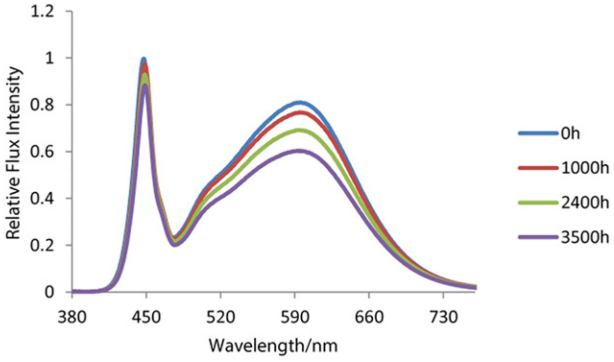
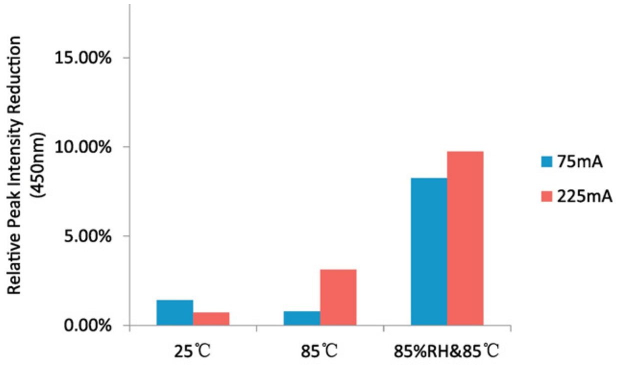
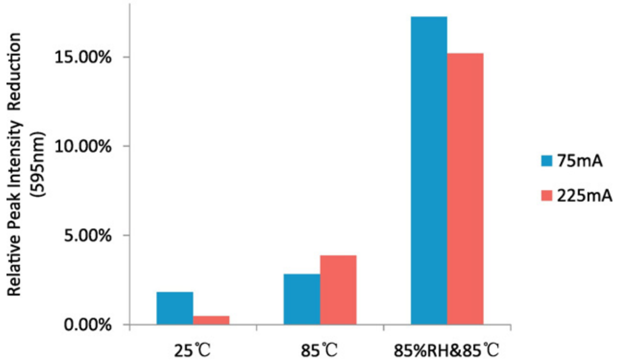


Fig. 5. SPDs of LED packages under different aging conditions.



(a) Blue light peak intensity reduction



(b) Yellow light peak intensity reduction

Fig. 6. Relative light peak intensity reduction after aging for 3500 h with different conditions.

degradation mechanisms on color shift during the whole aging period. Blue chip deterioration, phosphor oxidation and molecular structure decomposition in silicone plates contribute to the color shift in the first stage; while in the second stage, probably silicone carbonization appeared due to long-term accumulated high localized temperature aging. As reported earlier in Huang and Tan's works [3,21], when the moisture has been penetrated deep into the package layer, normal operation is not likely to drive out the moisture, and probably a blue light over-absorption is induced by water particle scattering, which could cause a localized temperature lift as high as 300 °C and hence induced silicone carbonization very soon. In our aging test, probably this lifted temperature is not that high due to a comparatively moderate humidity aging condition. According to Huang's investigation [3], assuming the lifted temperature is around 250 °C, it will induce the molecular structure decomposition and cause the transmittance change of silicone plates. It is believed that the following silicone carbonization will appear because of the long-term (3000 h) accumulated high localized temperature aging. Fig. 6 shows the yellow light peak intensity has been reduced even more as compared to the blue light peak intensity after aging of 3500 h, one reason is the converted yellow light went through a longer path than the blue light before emitting the package, contributing to a higher degradation rate [20].

Since differences exist between the mechanisms of color shift under different stress conditions, we should be careful when we choose an acceleration method. For example, when the LED package is used in the dry environment, if the humidity test is used as an acceleration stress, it will induce a substantial reduction in color shift since new factor such as transmittance change has been involved. In the normal operation, when the current is used as an acceleration factor, it will lead to a different color shift trend in v′. Nevertheless, the acceleration is possible if we can find the correlation of acceleration between different stresses.

Color shift is complex, what we care is more about the prediction. Since there is likely an linear relationship between color shift (Δu′ and Δv′) and duration of operation, we can extrapolate the color shift Δu′ and Δv′ based on the fitted regression equation and then make the prediction for the total color shift Δu′v′.

4. Conclusions

Temperature stress, humidity stress and current stress were experimentally designed and performed to accelerate the color shift of mid-power LED packages and color shift mechanisms have been discussed based on the color shift results obtained from measurements. Conclusions could be drawn as below.

1) Linear function fitting demonstrates a good linear relationship between color shift (Δu′, Δv′) and aging time almost for all the aging conditions. According to the investigation of SPDs, both blue light peak intensity and yellow light peak intensity gradually decreased during aging, but no obvious shift of peak wavelength was found, which probably is why the linear relationship exists. We can extrapolate the color shift Δu′ and Δv′ based on the fitted regression equations and then make the prediction for the total color shift Δu′v′.
2) Negative slope reveals a trend of decrease in u′ during aging under all conditions, while presences of the positive slope indicates a trend of increase in v′ during aging at room temperature or 85 °C when the stress current is lifted to 225 mA, which indicates the current stress can induce a different failure mode. Peak intensity reduction analysis reveals that the current stress accelerates the degradation of LED die.
3) Humidity test induced a substantial color shift both in u′ and v′. The u′ has an increased degradation rate after aging of 3000 h at 85%RH & 85 °C, there should be different degradation mechanisms on color shift during the whole humidity test. Further analysis reveals that the molecular structure decomposition of silicone plates and then follows the silicone carbonization due to the long-term (3000 h) accumulated high localized temperature aging.

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