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Overdriving reliability of chip scale packaged LEDs: quantitatively analyzing the impact of component

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Abstract

The objective of this study is to quantitatively evaluate the impacts of LED components on the overdriving reliability of high power white LED chip scale packages (CSPs). The reliability tests under room temperature are conducted over 1000 hours in this study on CSP LEDs with overdriving currents. A novel method is proposed to investigate the impact of various components, including blue die, phosphor layer, and substrate, on the lumen depreciation of CSP LEDs after aging test. The electro-optical measurement results show that the overdriving current can lead to both massive light output degradation and significant color shift of CSP LEDs. The quantitative analysis results show that the phosphor layer is the major contributor to the failure in early period aging test. For the long-term reliability, the degradations of phosphor and reflectivity of substrate contribute significantly on lumen depreciation. The proposed reliability assessment method with overdriving loadings can be usefully implemented for LED manufacturers to make a cost- and effective- decision before mass production.

Keywords: Chip Scale Package; Light Emitting Diodes; Overdriving reliability; Component impact

1. Introduction

Phosphor converted white light-emitting diode (LED) packages are the most typical light source in solid state lighting (SSL) applications [1]. The advancement of application design requires the next generation LED package design with small footprint and high lumen density [2]. The chip scale packaged (CSP) LED has been developed in order to fulfill these requirements. One of the extraordinary advantages of CSP LED is their high efficacy operating under high current injection [3, 4]. Compared to common SMD LED package, the structure of CSP LED is simplified by removing sub-mount and bonding wires, as shown in Figure 1. Only a flip-chip LED die and a light converting phosphor layer are kept. This simplified structure enables the volume reduction up to 80% compared with traditional SMD packages [5]. The thermal resistance of the CSP LED is about 2 ^{o}C/W, while that of traditional LED is 15~30 ^{o}C/W [6]. Yole Développement announced, "The combination of cost reduction and advanced packaging technologies, such as Flip Chip and Chip Scale Package, is changing the LED industry landscape, especially its supply chain" [7].

According to Haitz's law, SSL lamps will exceed all conventional mainstream lamps by factors of 2 to 10 times in efficacy by 2020 [8, 9]. To achieve higher luminous efficacy, CSP LEDs are driven under higher current density[10], especially under overdriving current. "Overdriving current" in this paper means the current is higher than the typical current of the product datasheet (normally is 350 mA [11]). However, the small-size interconnection pads induce the heat being concentrated in a small area, which is particularly sensitive to the reliability of the CSP LED when it is driven by overdriving current. Although the reliability of white LEDs has been attracted great interest by many research groups [12-28], there is limited report on the reliability of CSP LEDs under overdriving current.

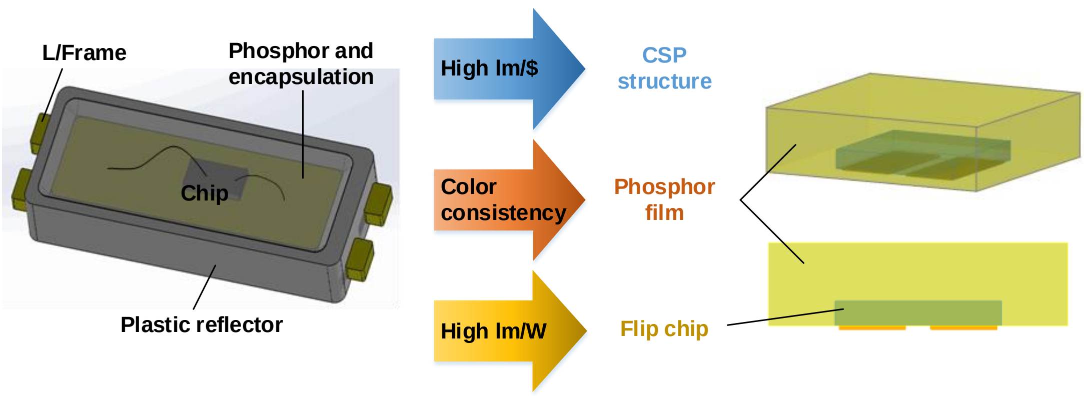

Figure 1. A SMD white LED package (left) compared to CSP LED (right)

In fact, identification of the failure modes, especially quantitative analysis the impact of each component on the CSP LEDs, is essential for further improving CSP technology. Pecht's groups [12-14, 29, 30] predicted the reliability of high-power LEDs by using prognostics and health management method. Fan *et al.* [12, 31, 32] analyzed thermal, optical and electrical performance of LEDs with experiment and simulation after a high temperature accelerated degradation test. Cheng *et al.* [13] presented lumen degradation and chromaticity shift in glass and silicone based high-power LEDs under accelerated thermal tests. Most of their studies indicate that the blue die and the phosphor layer are the critical factors to determine the reliability of LEDs. In order identify which portion of LEDs is degraded, Wong *et al.* [3, 15] analyzed the change of spectral power distribution of the sample before and after aging test with non-destructive techniques according to IES LM-80-08 [33] and JESD 22-A101-C [34] standard. They found that the color shift of the blue die might not be the major factor because blue radiation makes little contribution to in the lumen. However, the effects of solder joint and substrate on the reliability of CSP LEDs are not considered. Besides, few studies have been conducted on analyzing the impact of components on the lumen depreciation of CSP LEDs.

In this study, the reliability tests under room temperature are conducted over 1000 hours on CSP LEDs with overdriving currents at first. Second, the components of the aged samples, including blue die, substrate and phosphor layer, are exchanged separately according to the proposed methodology. Then, the electro-optical performances of each sample are investigated. Finally, the impacts of individual components on the early-period and long-term reliability of CSP LEDs are quantitatively analyzed.

2. Experimental procedures

2.1 Methodology

Lumen depreciation of CSP LEDs is a complex process and is dependent on the interactions of multiple factors, including the effect of the aged solder joint, the degradation of blue die, the reflectivity change of substrate, and the degradation of phosphor layer. The effect of aged solder joint on the reliability can be ignored because CSP LEDs' soldering is in good condition after aging (see Section *3.1*). A sample of CSP LED is fabricated by bonding a blue die with a phosphor layer on a ceramic substrate. We quantitatively analyze the data of aged samples in two stages: the early period (24 hours) and the long-term aging (>1000 hours).

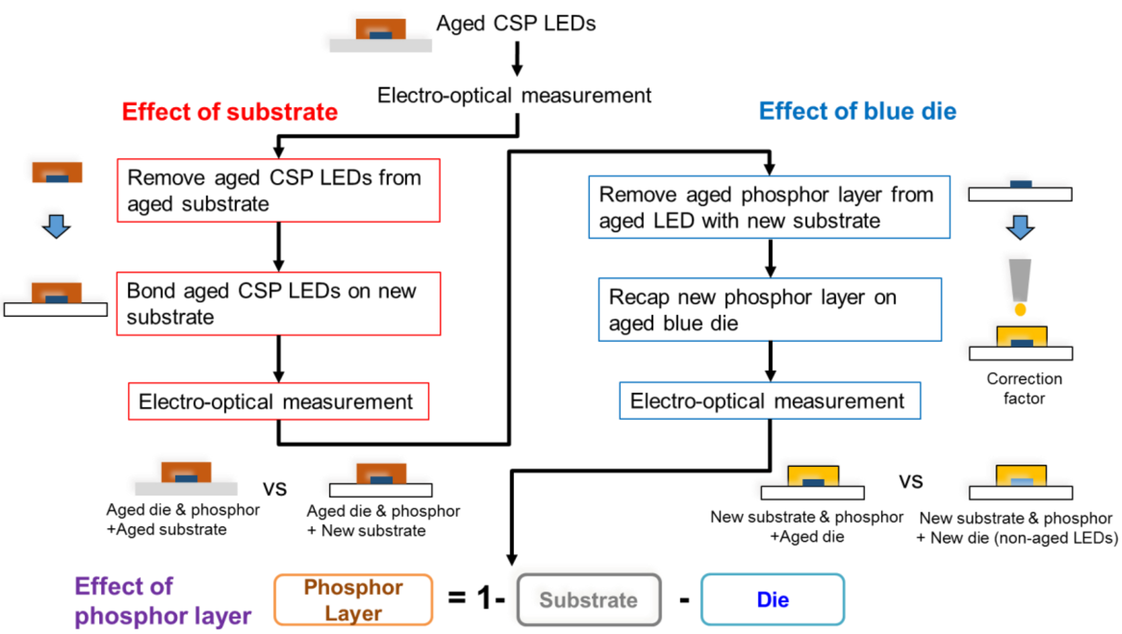

Figure 2. A series of experiments designed to investigate the impact of various components on the reliability of CSP LED after aging test.

Benefited from the simplified structure of CSP LED, we can exchange the individual component separately and avoid the interaction of the whole aged components. The processes are as follow:

1) Before the impact analysis of CSP LED's components, shear tests are conducted on the packages to analyze the mechanical strength of the package according to the JESD22-B117B standard [35]. The mean shear strength of the samples is about 1689 g, indicating that the CSP package mounted on the ceramic substrate can withstand the mechanical damages out of the environment.

2) The aged CSP LED is de-soldered from the aged substrate and bonded to a new substrate. Thus the impact of the substrate can be evaluated by the comparison of electro-optical parameters between the aged CSP LED with aged and new substrate.

3) For investigating the degradation of blue die, we remove the aged phosphor layer from the samples with new substrate. Then, a new phosphor is recapped on the aged blue die to reconstruct a complete package. After introducing a correction factor of recapping process, the impact of blue die can be estimated by calculating the difference in luminous efficacy between the recapped and non-aged LED.

4) The impact of the aged phosphor layer on the CSP LED is determined by subtracting the effect of substrate and blue die.

2.2 Experimental set up

One type of LED die with a dominant wavelength of 450 nm and dimension of 40 mil × 40 mil is chosen to prepare the CSP white LEDs. The phosphor layer is made by homogenously mixing phosphor with silicone and then thermally being impressed on the blue LED wafer. As shown in Figure 3, the LED wafer is segmented as individual CSP LED and then attached to a ceramic substrate with a silver surface by flip-chip technology via the solder SAC305. Six samples of each group are connected in series on a fixture with an aluminum heatsink. The samples are driven by typical (350 mA), double overdriving (700 mA) and maximum current (1000 mA) at room temperature (RT) for over 1000 hours [5, 10]. We measured the electro-optical characteristics at RT under 350 mA at different intervals. Thus the influence of driving current on the light output of CSP LEDs will be analyzed according to the experimental results.

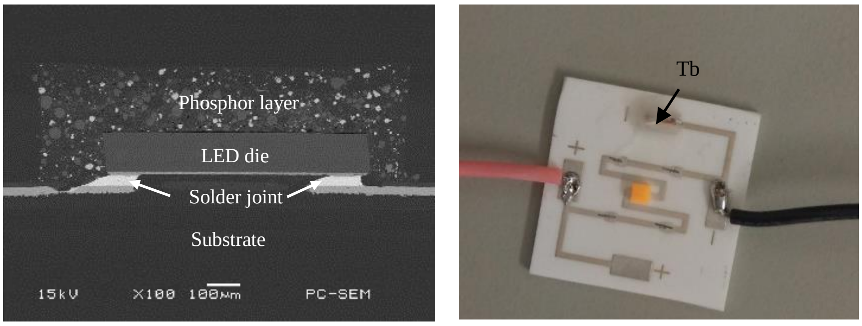

Figure 3. SEM image (left) and physical picture (right) of CSP LED mounted on a ceramic substrate

The testing and measurement methods and the failure criteria described above fulfill the IES LM-80-08 [33], JESD22-A101-C[34], LED Reliability Overview[36] and ENERGY STAR Program

Requirements for Lamps- Eligibility Criteria[37]. The lumen maintenance of the CSP LEDs over 1000 hours can be calculated by the following equation:

$$\tau = \frac{\eta_t}{\eta_0} \tag{1}$$

where η_0 is the luminous efficacy at aging time 0, η_t is the luminous efficacy at aging time t. And the color shift (*D*) is given by

$$D = \sqrt{(u' - u_0)^2 + (v' - v_0)^2} \tag{2}$$

where(u_0, v_0) is color coordinate at aging time 0 under CIE 1976, (u', v') is color coordinate at aging time t.

3. Results and discussions

3.1 Effect of aged solder joint on the efficacy of CSP LEDs

The solder joint cannot affect the light output of LEDs directly because it located in the backside of LED die. However, low quality of solder joints, such as voids in the solder layer and the interfacial intermetallic compounds (IMC), may block the thermal path of the whole package and finally lead to insufficient reliability of the device[38, 39]. Therefore, we investigate the voids in the solder layer of one CSP LED by X-ray before and after aging test at 1000 mA under harsh environment (85°C & 85% relative humidity(RH)), as shown in Figure 4. Slight change of void ratio means that the change of package's thermal resistances is small. Moreover, the interfacial Ag-Sn intermetallic compounds between solder joint and metal pad are investigated by scanning electron microscope (SEM), as shown in Figure 5. After aging for 1000 hours, the morphology and thickness variation of IMC is not obvious.The thermal conductivity of SAC305 and Ag_3Sn IMC are 35 W/m·K [39] and 34.1 W/m·K [40] with the thickness of 30μm and 3μm, respectively. It indicates that the thermal conductivity of solder joint has no significant drop after aging test. In summary, the aged solder joint has insignificant influence on the efficacy of CSP LEDs.

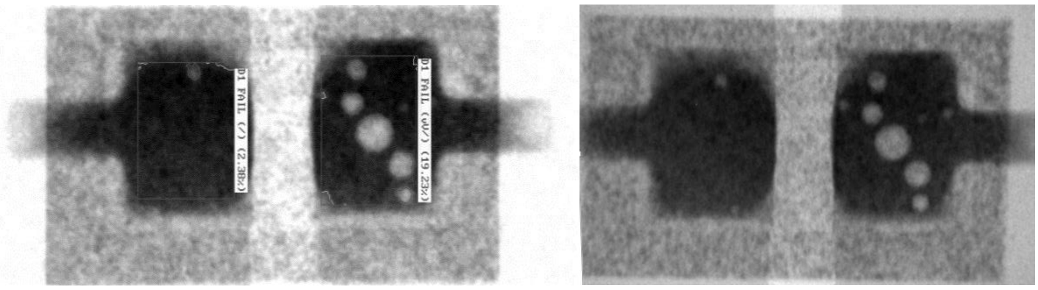

Figure 4. X-ray morphology of solder joint of one CSP LED at the aging time of 0 hour (left) and 300 hours (right) under 85°C & 85%RH environment

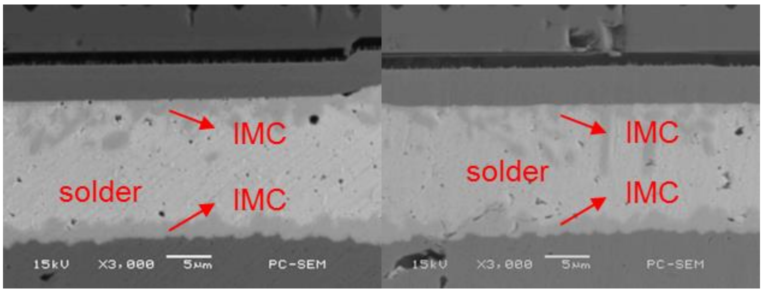

Figure 5. SEM images of solder layer of one CSP LED at the aging time of 0 hour (left) and 1000 hours (right) under 85ºC & 85%RH

3.2 Effect of de-soldering and recapping process on the efficacy of CSP LEDs

The electro-optical characteristics of the sample fabricated from de-soldering and recapping process may have discrepancy to the non-aged sample. High soldering temperature will damage the structure of LED chip and induce dramatically luminance decrease. Thus we de-soldered a non-aged CSP LED from the original substrate and then solder the chip back to the original substrate. The luminous efficacy is almost the same after de-soldering, indicating that the impact of de-soldering process on the efficacy of CSP LEDs can be neglected. For analyzing the variation between the non-aged CSP LED and recapped one, we removed the aged phosphor from the aged CSP LED completely and cleaned the residues on the aged die with alcohol. The recapped sample is fabricated from a new blue die dipped with the phosphor that used in non-aged CSP LED. A small shift of the blue peak in Figure 6 indicates that the recapping process has a small effect on the LED die. The shift of the phosphor peak is the main variation of the recapping process. The electro-optical parameters of the non-aged and recapped CSP LEDs are measured and summarized in Table 1. The difference in efficacy is 3.7 lm/W and the corresponding percentage declining by 3.78%.

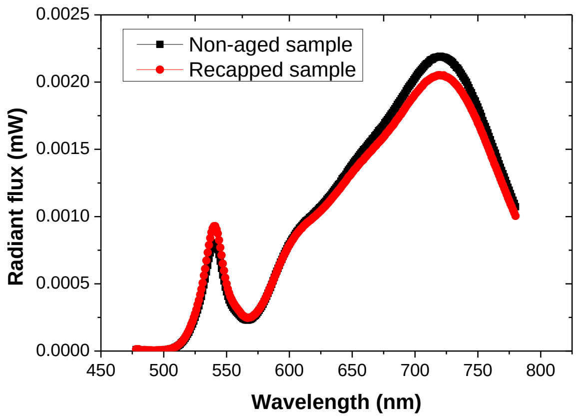

Figure 6. Spectral change between the non-aged and recapped CSP LEDs

Table 1. Comparison of Electro-optical parameters of non-aged and recapped CSP LEDs

Sample	Input power(mW)	Radiation flux (mW)	Luminous flux (lm)	Efficacy (lm/W)	u’	v'
Non-aged LED chip	1080	344.4	105.9	98.0	0.2574	0.5297
Recapped phosphor	1070	330.0	100.9	94.3	0.2547	0.5254
Difference	10	14.4	5.0	3.7	0.0027	0.0043
% change	0.93%	4.18%	4.72%	3.78%	-	-

3.3 Lumen maintenance and color shift of CSP LEDs under different current density

The lumen maintenance and color shift of samples over 1000 hours at RT are shown in Figure 7. All the plots are based on the mean values of the six test samples. At RT, the lumen maintenance and color shift remain relatively constant under 350 mA and 700 mA. However, sudden lumen depreciation (drops ~73%) and color shift (~0.1227) occur at 24 hours under 1000 mA, while the lumen maintenance drops ~42% with the color shift of ~0.0052 after 1000 hours. Obviously, overdriving current can definitely deteriorate the reliability of CSP LEDs. To find out the reason of sharp degradation in the first 24 hours and recovery later under 1000 mA, it is necessary to quantitatively analyze the data of aged samples in the early period and the long-term aging.

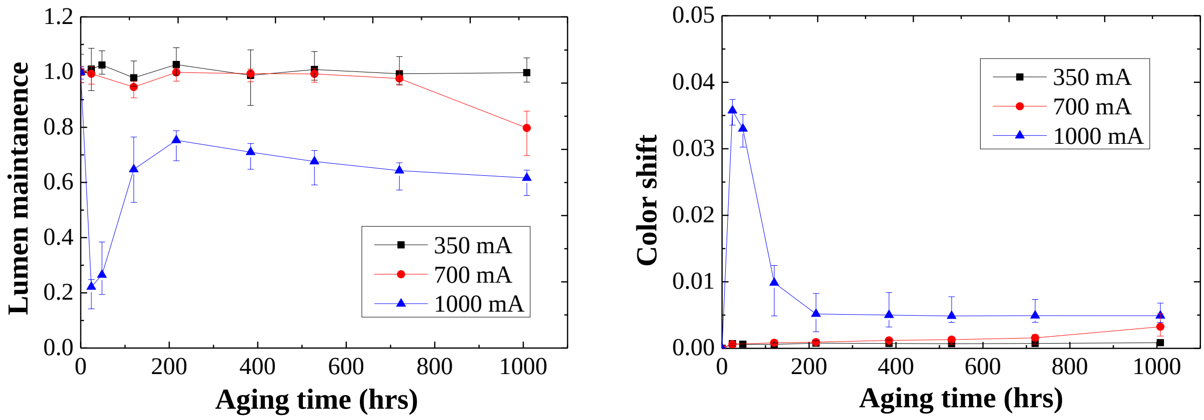

Figure 7. Lumen maintenance and color shift of CSP LEDs under RT aging as a function of time

3.4 Quantitative analysis of the impact of aged components in early period aging

To further understand the cause of lumen depreciation in early period of aging test, the electro-optical parameters are measured at 0 and 24 hours and summarized in Table 2. The radiation flux drops 71.41% from 322.1 mW to 92.1 mW. The efficacy decreases by 73.25% from 92.81 lm/W to 24.83 lm/W. As shown in Figure 8, the color shift is larger than 10 sdcm, the blue (from 380 to 480 nm) and the phosphor peak (from 480 to 780 nm) in the spectrum decreases. A small shift to the smaller wavelength of the blue peak and large shift of the phosphor peak is observed, indicating that the change both in the die and phosphor is possible.

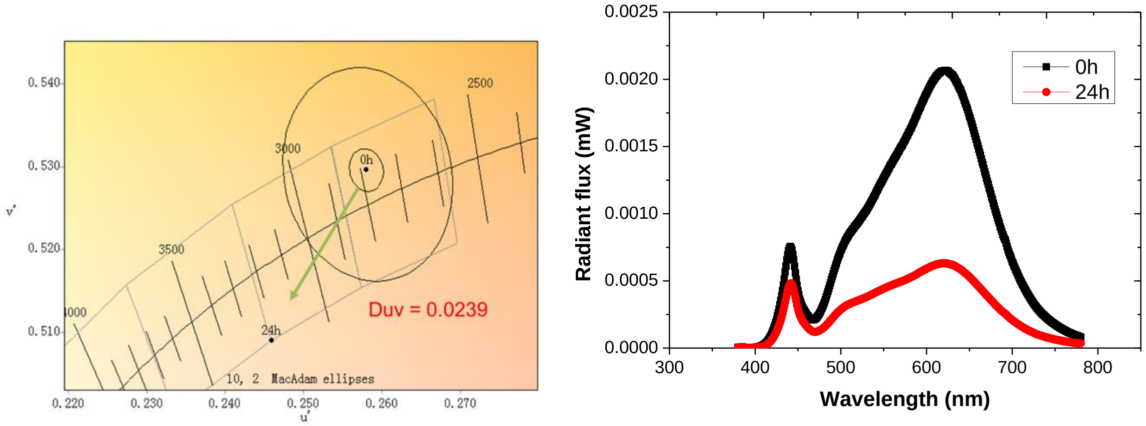

Figure 8. Color shift (left) and spectral change (right) of CSP LEDs under early period aging test

Table 2. Electro-optical parameters of CSP LEDs at the 0 and 24 hours.

Sample	Input power (mW)	Radiation flux (mW)	Luminous flux (lm)	Efficacy (lm/W)	u'	v'
0hr	1069	322.1	99.24	92.81	0.2580	0.5296
24hrs	1070	92.1	26.94	24.83	0.2459	0.5090
Difference	+1	-230.0	-72.30	-67.98	-0.121	-0.0206
% Change	0.09%	-71.41%	-72.85%	-73.25%	D=0.1227	

According to the quantitative analysis method, the aged samples are de-soldered from the substrate and bonded to new substrates with the identical configuration. As listed in Table 3, the difference of efficacy of LED chips between the aged substrate and the new substrate is merely 0.06 lm/W (-0.24%), which is within the measurement error. It means that the substrate aging has an insignificant impact on lumen depreciation of the CSP LEDs during the 24 hours operation.

Table 3. Electro-optical parameters of aged LED with aged/ new substrate in early period aging.

Sample	Input power (mW)	Radiation flux (mW)	Luminous flux (lm)	Efficacy (lm/W)	u'	v'
Aged LED + aged substrate	1085	92.1	26.94	24.83	0.2459	0.5090
Aged LED + new substrate	1072	90.78	26.55	24.77	0.2465	0.5096
Difference	-13	-1.32	-0.39	-0.06	0.0006	0.0006
% Change	-1.20%	-1.43%	-1.45%	-0.24%	D=0.0008	

For the study on the impact of blue die, the aged phosphor layer is removed from the aged die with the new substrate, and recapped with a new phosphor layer. The electro-optical parameters of the samples are measured and summarized in Table 4. The difference in the efficacy between the non-aged LED (new blue die with new phosphor layer) and the recapped LED (aged blue die with new phosphor layer) is 10.51 lm/W. The corresponding percentage change is 11.32%.

Table 4. Electro-optical parameters of non-aged LED and recapped LED in early period aging.

Sample	Input power (mW)	Radiation flux (mW)	Luminous flux (lm)	Efficacy (lm/W)	u'	v'
Non-aged LED (New blue die + New phosphor)	1070	322.1	99.24	92.81	0.2580	0.5296
Recapped LED (Aged blue die + New phosphor)	1068	297.9	87.91	82.3	0.2554	0.5245
Difference	-2	-24.2	-11.33	-10.51	-0.0026	-0.0051
% change upon aging	-0.19%	-7.51%	-11.41%	-11.32%	D=0.0057	

3.5 Quantitative analysis of the impact of aged components in long-term aging

To analyze the cause of lumen depreciation in long-term aging test, the electro-optical parameters of aged CSP LEDs are listed in Table 5. The radiation flux decreases by 40.56% from 323.5 mW to 192.3 mW. The efficacy reduces by 42.13% from 89.59 lm/W to 51.85 lm/W. Figure 9 shows that the color shift by 5 sdcm is mainly in v' coordinate. The decrease in v' can be due to less blue light irradiation caused by degradation of die, change in the phosphor/silicone material, or ineffective light extraction induced by delamination between the die/phosphor interface [3]. Besides, a small shift of the blue peak and a large shift of the phosphor peak is observed from the spectrum. Moreover, the depreciation rate of phosphor under long-term aging test is lower than that of the early period aging test.

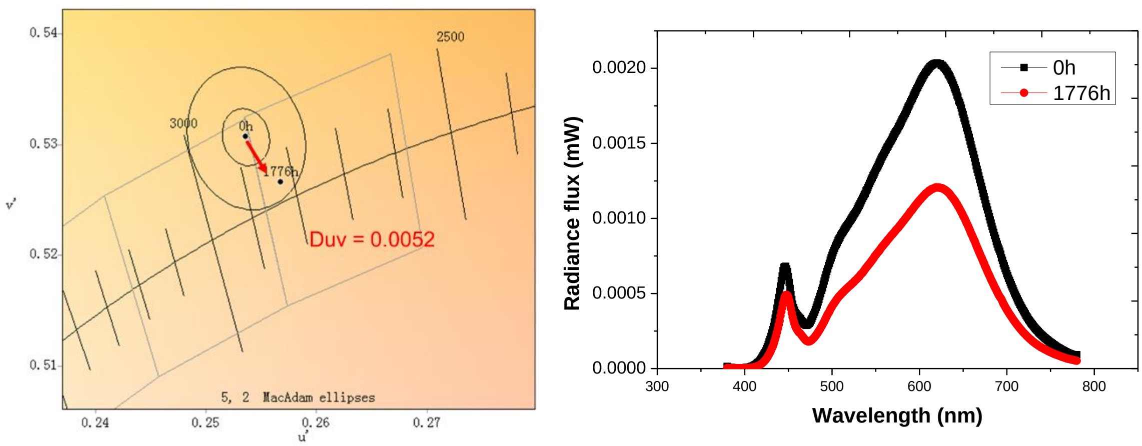

Figure 9. Color shift (left) and spectral change (right) of CSP LEDs under long-term aging test

Table 5. Electro-optical parameters of samples at the 0 and 1776 hours.

Sample	Input power (mW)	Radiation flux (mW)	Luminous flux (lm)	Efficacy (lm/W)	u'	v'
0hr	1134	323.5	101.54	89.59	0.2536	0.5307
1776hr	1137	192.3	58.97	51.85	0.2568	0.5266
Difference	3	-131.2	-42.57	-37.74	0.0032	-0.0041
% Change	0.26%	-40.56%	-41.92%	-42.13%	D=0.0052	

The impact of three components on the reliability of CSP LEDs in long-term aging is quantitatively analyzed and summarized in Table 6 and Table 7. The difference in efficacy between the aged and new substrate is merely 9.7 lm/W (-18.71%). The substrate aging has a substantial effect on lumen depreciation in long-term testing. The difference in the efficacy between the non-aged and recapped LED is 4.82 lm/W. The corresponding percentage change is 5.38%.

Table 6. Electro-optical parameters of aged LED with aged/ new substrate after long-term aging.

Sample	Input power (mW)	Radiation flux (mW)	Luminous flux (lm)	Efficacy (lm/W)	u'	v'
Aged LED + aged substrate	1137	192.3	58.97	51.85	0.2568	0.5266
Aged LED + new substrate	1156	236.7	71.15	61.55	0.2525	0.5155
Difference	-19	-44.4	-12.18	-9.70	0.0043	0.0111
% Change	-1.67%	-23.09%	-20.65%	-18.71%	D=0.0119	

Table 7. Electro-optical parameters of non-aged LED and recapped LED after long-term aging.

Sample	Input power (mW)	Radiation flux (mW)	Luminous flux (lm)	Efficacy (lm/W)	u'	v'
Non-aged LED (New blue die + New phosphor)	1134	323.5	101.5	89.59	0.2536	0.5307
Recapped LED (Aged blue die + New phosphor)	1146	312.66	97.03	84.77	0.2513	0.5216
Difference	12	-10.84	-4.47	-4.82	-0.0023	-0.0091
% change upon aging	1.06%	-3.35%	-4.40%	-5.38%	D=0.0094	

3.6 Discussions

The degradation of the blue die is supposed to be the most important factor leading to the dropped performance of LEDs in aging testing due to the increasing Tj of LEDs under high driving currents[16] and the effect of “efficiency droop” of LED packages[41]. However, the effect of phosphor degradation is proved to be the key parameter contributing to the lumen depreciation and color shift in this work, which is listed in Table 8. The phosphor doped in silicone plays a decisive role in the early aging process for the lumen depreciation, which contributes to 84.22% of efficacy drop in RT with substrate of 0.33% and blue die of 15.45%. For the long-term testing, the aging of phosphor (42.82%) and the dropped reflectivity of the substrate (44.41%) contribute significantly in lumen depreciation under 1000 mA. It indicates that the sharp drop in the first 24 hours and recovery later of the light output largely depend on the degradation of phosphor layer.

The degradation of phosphor layer in the early stage is more like the phenomena of phosphor thermal quenching[38, 42]. It means that the efficiency of the phosphor is degraded when temperature rises under high driving current. Also, phosphor layer degradation due to the seriously absorption of blue lights by the package encapsulant is another contributor to lumen depreciation and color shift. The light output decreases with the increase of the non-radiative transition due to thermally driven phosphorescence decay[38, 42]. After that, the phosphorescence decay is gradually stable and followed by a "recovery" in lumen output. It is induced by the recovery/self-healing of encapsulant materials[43, 44]. However, it has not yet been fully understood, which should be further studied in the future. For the substrate, it has been aged slightly at first 24 hours but degraded seriously after 1776 hours. The possible reason is that the degradation of the substrate is a gradual process, which tends to affect lumen efficacy greatly after long-term aging.

Table 8. Summary of the impact of aged components in early period and long-term aging test.

	24 hrs, 1A		Long-term (>1000hrs), 1A	
	% change efficacy	Relative %	% change efficacy	Relative %
Substrate	-0.24	0.33	-18.71	44.41
Blue die	-11.32	15.45	-5.38	12.77
Phosphor layer	-61.69	84.22	-18.04	42.82
Total	-73.25	-	-42.13	-

*Total% change efficacy = % change from substrate + % change from blue die + % change from recapping + % change from phosphor layer (% change from recapping = 3.78%)

4. Conclusion

In this work, overdriving reliability tests are conducted over 1000 hours on CSP LEDs with overdriving currents under room temperature. A novel method based on the electro-optical measurement is proposed to quantitatively analyze the impact of components on lumen depreciation of aged CSP LEDs samples. Combined with the proposed method and the electro-optical data, the results could be summed up as follows: i) overdriving current can definitely deteriorate the reliability of CSP LEDs, because the lumen maintenance of test samples drop 42.13% with serious color shift after aging 1000 hours. ii) the degradation of phosphor layer is the major contributor to the lumen degradation failure of CSP LEDs in early period aging, which contributes to 84.22% of efficacy drop. It is caused by the thermal quenching of phosphor, which decreases light output with the increase of the nonradiative transition probability due to thermally driven phosphorescence decay. For the long-term reliability tests, the degradation of phosphor and the dropped reflectivity of substrate contribute significantly to lumen depreciation.

Acknowledgements

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