applied optics

Comparison of online and offline tests in LED accelerated reliability tests under temperature stress

HONG-LIANG KE,[1,2] LEI JING,[1] QUN GAO,[1] YAO WANG,[1,2] JIAN HAO,[1,2] QIANG SUN,[1,*] AND ZHI-JUN XU[1]

[1]Department of Optoelectronics Research and Development Center, CIOMP, Chinese Academy of Sciences, 3888 Eastern South Lake Road, Changchun, Jilin 130033, China
[2]University of Chinese Academy of Sciences, No. 19A Yu-quan Road, Beijing 100049, China
*Corresponding author: pirlo2008snooker@126.com

Received 8 July 2015; revised 15 October 2015; accepted 16 October 2015; posted 20 October 2015 (Doc. ID 245440); published 17 November 2015

Accelerated aging tests are the main method used in the evaluation of LED reliability, and can be performed in either online or offline modes. The goal of this study is to provide the difference between the two test modes. In the experiments, the sample is attached to different heat sinks to acquire the optical parameters under different junction temperatures of LEDs. By measuring the junction temperature in the aging process (T_{j1}), and the junction temperature in the testing process (T_{j2}), we achieve consistency with an online test of T_{j1} and T_{j2} and a difference with an offline test of T_{j1} and T_{j2}. Experimental results show that the degradation rate of the luminous flux rises as T_{j2} increases, which yields a difference of projected life $L_{70\%}$ of 8% to 13%. For color shifts over 5000 h of aging, the online test shows a larger variation of the distance from the Planckian locus, about 40% to 50% more than the normal test at an ambient temperature of 25°C.

OCIS codes: (000.2190) Experimental physics; (350.4800) Optical standards and testing.

http://dx.doi.org/10.1364/AO.54.009906

1. INTRODUCTION

Due to the long lifetime of LED products, elevated stresses such as temperature, humidity, and current are usually used in accelerated reliability tests to obtain the accelerated lifetime of an LED, which is essential for projecting the product's life under rated conditions. To calculate the temperature-dependent reactions, the Arrhenius [1] model is always used to describe the degradation behavior of light output affected by temperature stress. It is worth noting that the degradation behavior should be measured in the corresponding temperature stress, which means that the junction temperature of the LED in the testing process should be consistent with that in the aging process. To achieve this, Narendran and Gu [2–4] proposed an online test method by designing a life-test chamber that could keep the ambient temperature constant and also act as a light-integrating box for continuously measuring the light output.

It is not easy to realize the online test, since an LED is always at an elevated temperature during the accelerated aging process; the test equipment usually cannot endure harsh experimental conditions and also should be calibrated at regular intervals throughout the life test to remove the detector drift error. Most of the present tests are offline tests in which the samples must be taken from the experimental environment for optical parameter measurements at normal conditions and put back afterward. In the offline test, however, the junction temperature of the LED in the aging process is not consistent with that in the testing process. IES LM-80-08 [5] recommends acquiring the data under 25 ± 1°C at least once every 1000 h over the minimum lumen maintenance test period (6000 h). Cai and Zhang [6] indicated that the sample needed 2 h for thoroughly cooling down and at least 15 min for preheating to accurately obtain the optical parameters. So, considering the number of data points and the time consumed for each test, 100–300 h are often taken as the test interval in most studies [1,6,7].

In the accelerated reliability test of an LED under temperature stress, to the best of our knowledge there has been no report about the effectiveness of an offline test, although the degradation of the LED should be measured with the online test method. In this paper, we provide a method to accomplish online and offline tests of the same LED sample. To obtain the optical parameters at different junction temperatures, the sample is attached to different heat sinks and the testing process is done at an ambient temperature of 25 ± 1°C. The online and offline tests are then, respectively, achieved when the junction temperature in the testing process is consistent with and different from that in the aging process. The degradation of the luminous flux and the shift of chromaticity coordinates are adopted as evaluation criteria.

2. EXPERIMENTS

In this research, the diode forward voltage method [8,9] is used to measure the junction temperature of T_{j1} in the aging process and T_{j2} in the testing process. The test samples are white LED modules. Three different kinds of heat sink (ceramic, aluminum, and air) are successively attached to the sample in the testing process to get different T_{j2}. Figure 1 is the case that the sample is attached to different heat sinks in the measurement of the junction temperature. To achieve a steady junction temperature, the variation of T_{j2} is recorded in the initial several minutes to confirm the time for the LED warming up with different heat sinks. As shown in Fig. 2, at the ambient temperature (T_a) of 25°C and with a rated current of 135 mA (DC), the junction temperature of the sample reaches its steady state of 119.5°C–121.5°C after 135 s with the air heat sink. It is, respectively, 425 s and 600 s with the ceramic heat sink and the aluminum heat sink. Obviously, when a better heat sink is used a longer preheating time is needed to achieve the thermal equilibrium state.

In this research, the average junction temperature after preheating is taken as the reference. This is, respectively, 72.5°C (ceramic), 59.6°C (aluminum), and 119.8°C (air). Obviously, the highest T_{j2} is 119.8°C with the air heat sink, so we choose 120°C as the junction temperature of T_{j1} in the aging process.

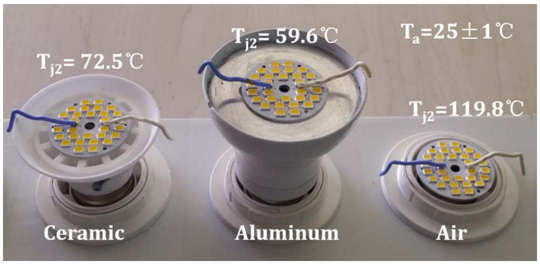

Fig. 1. Sample attached to different heat sinks.

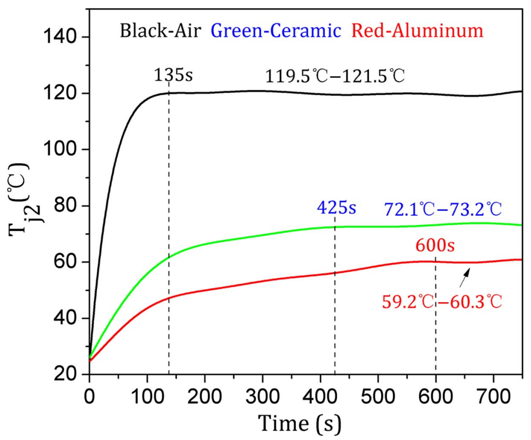

Fig. 2. Variation of T_{j2} of LED during warming up with different heat sinks.

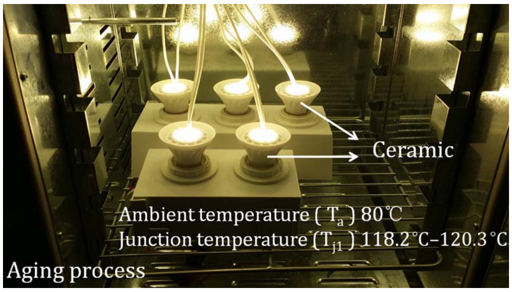

Fig. 3. Aging configuration, five samples with the ceramic heat sink placed in a temperature chamber under 80°C.

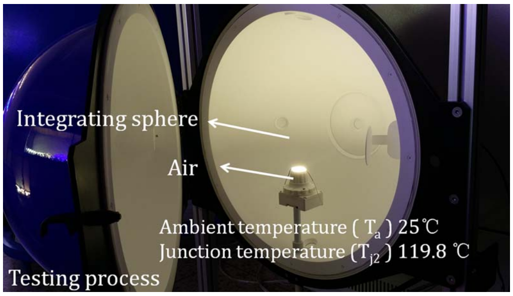

Fig. 4. Testing process using an integrating sphere system at an ambient temperature of 25°C with the 4π method.

Figure 3 shows the aging experimental configuration. Five samples with the ceramic heat sink are placed in a temperature chamber under 80°C, and the measured junction temperatures of T_{j1} are in a range from 118.2°C to 120.3°C. During the aging process, the samples are removed into an integrating sphere for the measurement of optical parameters at T_a of 25°C every 250 h, as shown in Fig. 4. It is clear that T_{j1} in the aging process can be approximately the same as with T_{j2} in the testing process with the air heat sink, which is about 120°C. Therefore, the measurement of the LED output corresponding to the online test process can be obtained in this case. Obviously, the test process with the ceramic or aluminum heat sink is the result of the offline test in which T_{j1} in the aging process is different from T_{j2} in testing process.

Table 1 lists the operating conditions of the aging process, online test process, and offline test process. Due to the annealing influence, the LED initially experiences a rapid change before settling into a steady decline over time. So, before beginning the experiment, the samples are lit by a rated current at 25°C for 1000 h, for an initial seasoning.

Table 1. Aging Process, Online Test and Offline Test Process

	T_a (°C)	Heat Sink	T_j (°C)
Aging	80	Ceramic	118.2–120.3
Online	25	Air	119.5–121.5
Offline 1	25	Ceramic	72.1–73.2
Offline 2	25	Aluminum	59.2–60.3

3. RESULTS AND ANALYSIS

A. Degradation of Luminous Flux

The luminous flux of the LED decreases over time, and can be represented by an exponential decay model [3]

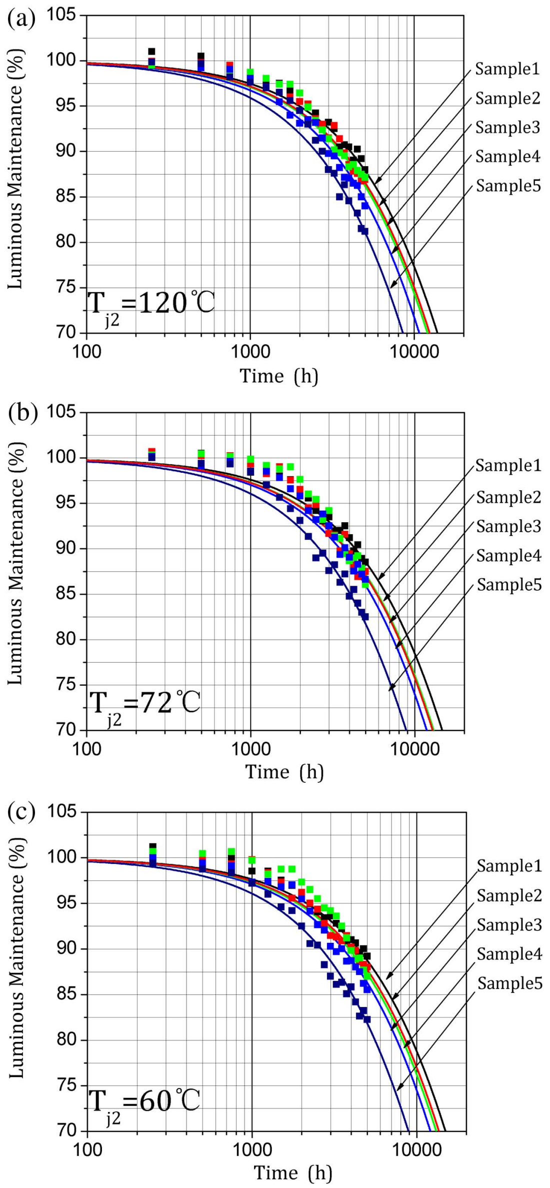

Fig. 5. (a) Luminous flux degradation as a function of time under a T_{j2} of 120°C, (b) results under a T_{j2} of 72°C, and (c) results under a T_{j2} of 60°C.

$$\Phi = \Phi_0 \times e^{-\alpha t}, \tag{1}$$

where α is the degradation rate, t is the aging time in hours, and Φ_0 is the initial luminous flux (lm). Figure 5(a) shows the normalized luminous flux as a function of time, with the curves fitted by the exponential decay model under a junction temperature T_{j2} of 120°C in the testing process. Figs. 5(b) and 5(c) are the fitting curves under junction temperatures of 72°C and 60°C, respectively. It is shown that the degradation rate α and the RMSE (root mean squared error) of the fittings are different for different junction temperatures of T_{j2} in the testing process, as listed in Table 2. The value of the RMSE at a T_{j2} of 120°C is between 0.03 and 0.04, which is lower than that at a T_{j2} of either 72°C or 60°C. This implies that the result tested at a T_{j2} of 120°C has a higher fitting degree of the exponential model than that of 72°C or 60°C.

As seen in Fig. 6, the degradation rate α shows a decreasing trend as T_{j2} is decreasing. The values of α in sample 4 are 3.33E-5 under a T_{j2} of 120°C, 3.02E-5 under 72°C, and 2.95E-5 under 60°C. The projected life of $L_{70\%}$, which is the time when Φ degrades to 70% of its initial value, can be obtained by Eq. (1) with the value of α. The calculated $L_{70\%}$ is listed in Table 2, and the curves of normalized $L_{70\%}$ (to its initial value) as a function of T_{j2} are illustrated in Fig. 7. It can be seen that most of the curves approximately obey a linear rule, except for that of sample 2. The difference of $L_{70\%}$ between junction temperatures of 120°C and 60°C is 7.9% for sample 1, 10.0% for sample 2, 9.2% for sample 3, 12.9% for sample 4, and 4.5% for sample 5.

In summary, due to the differences in junction temperature in the testing process, the degradation rate α is different, which makes the projected life $L_{70\%}$ different. In this research, the differences of $L_{70\%}$ are from 8% to 13% for the five samples.

B. Color Shift

The chromaticity of white light can be expressed by CCT (correlated color temperature) and Duv (distance from the Planckian locus) [10]. The variation of chromaticity coordinates along the direction of the Planckian locus can be evaluated by the CCT, and the Duv shows the variation along the direction perpendicular to the Planckian locus.

Figure 8 illustrates the chromaticity coordinates of sample 1 after 0, 1000, 2000, 3000, 4000, and 5000 h of aging, which is measured under junction temperatures T_{j2} of 120°C and 72°C, respectively. ANSI [10] sets a range of chromaticity coordinates for white LEDs with CCT of 3350 K, as ABCD shows in Fig. 8. In this range, CCT is 3350 ± 217 K and Duv is 0.000 ± 0.006. Energy Star [11] provides that the Duv

Table 2. Degradation Rate α, RMSE of Fitting and Projected Life $L_{70\%}$

	T_{j2} = 120°C			T_{j2} = 72°C			T_{j2} = 60°C		
	α	RMSE	$L_{70\%}$ (h)	α	RMSE	$L_{70\%}$	α	RMSE	$L_{70\%}$
Sample 1	2.58E−5	3.25E−2	13820	2.43E−5	6.32E−2	14680	2.39E−5	7.23E−2	14920
Sample 2	2.88E−5	2.25E−2	12380	2.78E−5	7.12E−2	12830	2.62E−5	7.31E−2	13610
Sample 3	2.97E−5	3.86E−2	12010	2.74E−5	8.59E−2	13020	2.72E−5	8.53E−2	13110
Sample 4	3.33E−5	3.65E−2	10710	3.02E−5	6.52E−2	11810	2.95E−5	8.56E−2	12090
Sample 5	4.19E−5	3.96E−2	8510	4.03E−5	5.95E−2	8850	4.01E−5	4.21E−2	8890

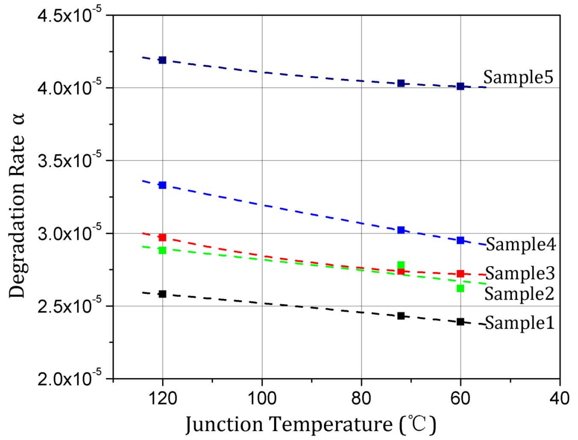

Fig. 6. Degradation rate α as a function of T_{j2}.

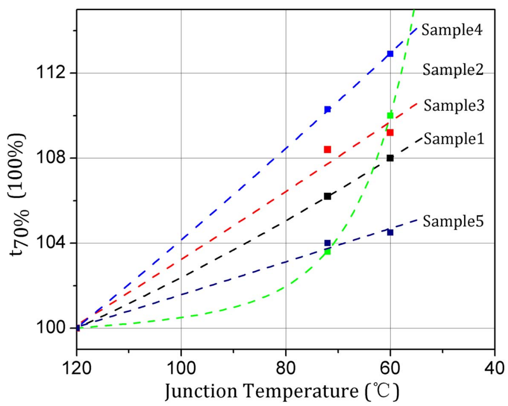

Fig. 7. Projected life $L_{70\%}$ as a function of T_{j2}.

tolerance should be within 0.007 over a 6000 h nonaccelerated aging period for LED products.

It can be seen from Fig. 8 that the color shift is mainly along the direction perpendicular to the Planckian locus over time, which implies that the variation of Duv has a greater effect than CCT for this sample. Table 3 lists the variation of the Duv of five samples over 5000 h under junction temperatures T_{j2} of

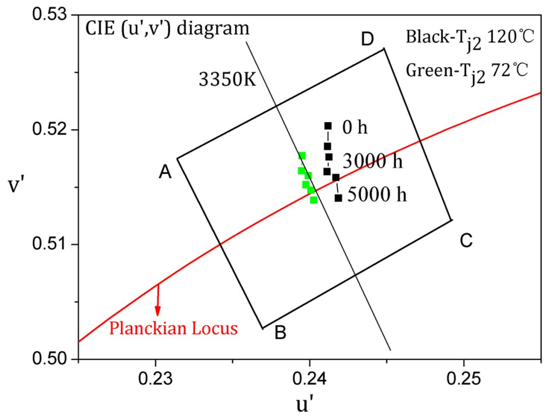

Fig. 8. Color shift of sample 1 over 5000 h on a CIE (u', v') diagram.

Table 3. Variation of Duv Over 5000 h

	Duv (0–5000 h)		
	120°C	72°C	120°C–72°C
Sample 1	0.0065	0.0043	0.0022
Sample 2	0.0072	0.0048	0.0024
Sample 3	0.0068	0.0045	0.0023
Sample 4	0.0071	0.0051	0.0020
Sample 5	0.0075	0.0052	0.0023

120°C and 72°C. It is shown that the Duv measured under a T_{j2} of 120°C is approximately 0.0022 larger than that of 72°C.

Normally, the sample is mounted with aluminum or other heat sink in a real lighting system. In this case, the junction temperature of the sample is approximately 60°C–80°C in its normal working condition. Therefore, the color shift measured at a T_{j2} of 72°C is in agreement with the existing criteria for lifetime evaluation for LED products. Although the test done at a T_{j2} of 120°C gives a bigger variation of Duv, about 40%–50%, the result can still provide a reference for lifetime prediction.

In this acceleration test, the color shifts measured at a T_{j2} of 120°C and 72°C are both within the range of ABCD. However, this acceleration test does not show a bigger variation of Duv than 0.007 in Energy Star's nonacceleration test. It may be due to the ignorance of the 1000 h needed for an initial seasoning in which the Duv may change rapidly, or "0.007", which was set by ANSI in 2008, may be a bigger value for current LED products.

4. CONCLUSIONS

To compare the online and offline test methods in an accelerated reliability test of an LED under temperature stress, the sample is attached to different heat sinks to obtain different junction temperatures in the testing process. The online test is achieved when the junction temperature in the testing process is consistent with that in the aging process. Otherwise, the testing process is regarded as an offline test.

Experimental results show that the result of the online test has a higher exponential fitting degree of luminous flux degradation. The degradation rate decreases as T_{j2} decreases, which makes the projected life $L_{70\%}$ of the LED module in online tests different from that in offline tests. The differences are from 8% to 13% for five samples. For color shift, the shifting direction of chromaticity coordinates over time is mainly along the direction perpendicular to the Planckian locus. During 5000 h aging, the values of Duv of the five samples in the online test show a variation range from 0.0065 to 0.0075, which is approximately 40%–50% larger than that in the offline test.

This study is limited to a type of single phosphor ($Y_3Al_5O_{12}$:Ce) converted white LEDs. The correlations of the experimental results in the two testing modes given in Figs. 5 and 8 are valid only for this type of LEDs. It is noted that especially for the color shift, the correlation may be significantly different for different types of LEDs. Therefore, to achieve a more accurate characterization of LEDs more experiments for other types of LEDs should be done. This is our future work.

Funding. Chinese Academy of Sciences (CAS) (KZCC-EW-102); 863 Program (2013AA03A116, 2015AA03A101).

REFERENCES

1. Y.-H. Yang, Y.-F. Su, and K.-N. Chiang, "Acceleration factor analysis of aging test on gallium nitride (gan)-based high power light-emitting diode," in *14th IEEE Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)* (2014).
2. N. Narendran and Y. Gu, "Life of LED-based white light sources," J. Disp. Technol. **1**, 167–171 (2005).
3. Y. Gu and N. Narendran, "White LED performance," Proc. SPIE **5530**, 119–124 (2004).
4. N. Narendran, "Solid-state lighting: failure analysis of white LEDs," J. Cryst. Growth **268**, 449–456 (2004).
5. Illuminating Engineering Society, "Approved method: measuring lumen maintenance of LED light sources," LM-80-08 (2008).
6. M. Cai and G. Q. Zhang, "Accelerated testing method of LED luminaries," in *International Conference on Thermal, Mechanical & Multi-physics Simulation & Experiments in Microelectronics & Microsystems* (2012), pp. 16–18.
7. S. Koh and G. Q. Zhang, "Product level accelerated lifetime test for indoor LED Luminaires," in *14th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems* (2013).
8. H. Ye, "Thermal transient effect and improved junction temperature measurement method in high-voltage light-emitting diodes," IEEE Electron Device Lett. **34**, 1172–1174 (2013).
9. A. Keppens, "High power light-emitting diode junction temperature determination from current voltage characteristics," J. Appl. Phys. **104**, 093104 (2008).
10. American National Standard: specifications for the chromaticity of solid state lighting products, ANSINEMAANSLG C78.377 (2008).
11. http://www.energystar.gov/ia/partners/product_specs/program_reqs/archive/IntegralLEDLampsCriteria_V1.1_AMENDED_22MAR10_FINAL.pdf, ENERGY STAR Program Requirements for Integral LED Lamps–Partner Commitments (2011).