Research Article Vol. 55, No. 22 / August 1 2016 / Applied Optics 5909

applied optics

Analysis of junction temperature and modification of luminous flux degradation for white LEDs in a thermal accelerated reliability test

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Received 29 April 2016; revised 29 June 2016; accepted 30 June 2016; posted 1 July 2016 (Doc. ID 264207); published 25 July 2016

An accelerated aging test is the main method in evaluation of the reliability of light-emitting diodes (LEDs), and the first goal of this study is to investigate how the junction temperature (Tj) of the LED varies during accelerated aging. The Tj measured by the forward voltage method shows an upward trend over the aging time, which gives a variation about 6°C–8°C after 3,000 h of aging under an ambient temperature of 80°C. The second goal is to investigate how the variation of Tj affects the lifetime estimation. It is verified that at a certain aging stage, as Tj increases, the normalized luminous flux linearly decreases with variation rate of microns (μ) (1/°C). Then, we propose a method to modify the luminous flux degradation with the Tj and μ to meet the requirements of a constant degradation rate in the data fitting. The experimental results show that with the proposed method, the accelerated lifetimes of samples are bigger than that of the current method with increment values from 8.8% to 21.4% in this research.

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

http://dx.doi.org/10.1364/AO.55.005909

1. INTRODUCTION

Over the past few years, white light-emitting diodes (LEDs) have infiltrated a number of lighting applications owing to their high efficiency, environmental benefits, and long lifetime. The white LEDs converted by blue chips and yellow phosphor are efficient devices with expected lifetimes exceeding tens of thousands of hours [1–4]. In order to demonstrate the performance, IES LM-80-08 [5] proposed a test composed of a minimum of 6,000 h at three different temperatures, which was so time-consuming that it created an obstacle for new products to be updated. By using the data acquired from the LM-80-08 test, IES TM-21-11 [6] proposed a method for estimating the LED lifetime $L_{70\%}$ defined as the time with a luminous maintenance of 70%. It was pointed out that the estimated $L_{70\%}$ should be within six times the test time, i.e., the maximum predicted $L_{70\%}$ was 36,000 h by a 6,000 h test. In 2008, the L-Prize competition [7] was set for promoting the production of LED retrofit light bulbs, and the average luminous maintenance for 31 samples of the winner was 95.6% after 40,890 h without catastrophic failures. Obviously, the 6,000 h test is far from being enough for these LED products. Due to LEDs with a long life span being significantly affected by the generated heat at the LED positive-negative (P-N) junction, Gu and co-workers [2,8], Ke *et al.* [3], and Su [9], respectively, took the elevated ambient temperatures of 70°C, 80°C, and 50°C as the constant accelerated stress for LED products to shorten the test time. Jian *et al.* [10], Tian and co-workers [11,12], Hu [13], and Cai and co-workers [14,15] shortened the test time by using a step-stress accelerated aging test with the ambient temperatures of 60°C–90°C, 25°C–105°C, 65°C–95°C, and 65°C–95°C, respectively.

The widely used method for LED junction temperature (Tj) estimation is called the forward voltage (V) method, which is based on the linear relationship of the forward V of LEDs with respect to the Tj [16–20]. Cain *et al.* [21] and Ye and Zhang [22] analyzed the uncertainty in Tj estimation introduced by the thermal transient effect (TTE) in the calibration of the V – Tj model. In practice, Tj is always substituted by the solder temperature (Ts) [5,23] or the temperature of LED pins (T-point) [2,8] for convenience. However, only the ambient temperature can be controlled to be at a steady level with a temperature chamber during the aging test, and the Tj, Ts, and T-point of LEDs may not always be at steady level. Gu and Narendran [2] found a change of a few degrees in the

T-point during a long-term performance of LEDs, leading to a deviation of the lumen degradation of LED arrays. Tj plays a significant role on the optical performance of LEDs such as lumen flux and chromaticity, and therefore, the effect of the variation of Tj during an aging test should be considered.

The lifetime of LEDs under normal operating conditions is normally projected by using the Arrhenius model [6,14,24] with the accelerated lifetime predicted in an accelerated aging test. The Arrhenius model describes the degradation rate of the light output of LEDs with respect to Tj, and the accelerated lifetime can be obtained by the exponential fitting of luminous maintenance [2,3]. It is noted that the fitting should be with a constant degradation rate, and therefore, an invariant Tj of LEDs during the accelerated aging is requested. As a result, if the Tj changes in the accelerated aging test, the measured luminous fluxes should be corrected to ensure the validity of applying the exponential fitting.

In this research, an accelerated aging test for 5 LED arrays lighted under the ambient temperature of 80°C is conducted. During the aging process, the sample is taken out of the temperature chamber for the measurements of the optical parameters and the Tj. To eliminate the influence of the variation of the Tj during accelerated aging on the lifetime prediction, we propose a method to modify the measured luminous flux by a pre-acquired luminous flux variation rate over the Tj. Then, the lifetime of the $L_{70\%}$ and the correspondent degradation rate of the accelerated aging test are obtained by the exponential fitting of the modified luminous maintenance. This way the influence of the variation of Tj is eliminated, and the acquired constant degradation rate is in response to the initial accelerated Tj.

2. THEORETICAL ANALYSIS

The exponential decay model is recommended as an appropriate empirical model to describe the luminous flux degradation of LEDs, as stated in Refs. [2,3]:

$$\Phi_t = \Phi_0 \times e^{(-\beta t)}, \tag{1}$$

where t is the aging time in hours, Φ_0 is the initial luminous flux (lm) of LEDs, and β is the degradation rate. The relationship of the degradation rate β with respect to the Tj can be described by the Arrhenius model given in Refs. [6,14,24]:

$$\beta = A \times e^{(-Ea/k\mathrm{Tj})}, \tag{2}$$

where A is a constant, Ea is the activation energy, and k is the Boltzmann constant (8.167E − 5 eV/K). Suppose β_1 and β_2 represent the degradation rate in a normal operating and accelerated aging condition, respectively. With the same luminous flux degradation in the two conditions, we have, according to Eq. (1),

$$\Phi_t/\Phi_0 = e^{(-\beta_1 t_1)} = e^{(-\beta_2 t_2)}, \tag{3}$$

where t_1 and t_2 are the operation time in the normal operating and accelerated aging conditions, respectively. Combining Eq. (2) with Eq. (3), we have the acceleration factor of AF which is given by

$$\mathrm{AF} = t_1/t_2 = e^{[(Ea/K)\times(1/\mathrm{Tj}_1 - 1/\mathrm{Tj}_2)]}, \tag{4}$$

where Tj_1 and Tj_2 are the initial Tjs of LEDs in normal operating and accelerated aging conditions, respectively. Thus, the lifetime of the LED in its normal operating condition can be obtained if Ea, Tj_1, Tj_2, and the lifetime in the accelerated aging condition are all known. In the actual accelerated aging test, the ambient temperature is usually controlled to be invariant throughout the test by temperature chamber. The Tj of Tj_2, however, inevitably varies as the aging time increases. This leads to a variation of the degradation rate of β_2, and thereby, an error in the prediction of the accelerated lifetime with Eq. (1), where the degradation rate is supposed to be a constant value corresponding to the initial Tj, is introduced.

It is noticed that in most studies and standards about the LED accelerated aging test, the optical parameters of LEDs are usually measured at an ambient temperature of 25°C, rather than at the elevated ambient temperature [3,5,11,15,25]. Thereby, the degradation rate of β_2 corresponding to the elevated ambient temperature is calculated with the luminous flux degradation measured at the ambient temperature of 25°C. For this testing method, we propose an approach to eliminate the error in the lifetime prediction caused by the variation of Tj during the accelerated aging.

First, the parameter of microns (μ) (1/°C), which is the normalized luminous flux variation rate with respect to the Tj of the LED, is determined experimentally. It is known that the luminous flux of the LED shows a downward trend as the Tj is increasing. At a certain aging stage, the decrease of the normalized luminous flux with respect to the Tj is supposed to obey a linear rule:

$$\Phi_{\mathrm{other}}/\Phi_{25} = \mu \times \mathrm{Tj}_{\mathrm{other}} + C, \tag{5}$$

where Φ_{25} is the luminous flux measured at ambient temperature of 25°C, Φ_{other} is measured at other ambient temperatures corresponding to the Tj of $\mathrm{Tj}_{\mathrm{other}}$, and C is a constant. We then suppose that at the ambient temperature of 25°C, the initial luminous flux and Tj of the LED are Φ_0 and Tj_0, respectively. After a period of accelerated aging time of t the luminous flux is Φ_t, and the Tj_t at the ambient temperature of 25°C. The variation of the luminous flux of $(\Phi_0 - \Phi_t)$ is attributed to the degradation of the LED and the variation of the Tj. The influence of the variation of Tj on the luminous flux can be written as $\Phi_t \times (\mathrm{Tj}_t - \mathrm{Tj}_0) \times \mu$. With the solved μ value, we can get a modified luminous flux of $\Phi_{t\mathrm{modified}}$, which is expressed as

$$\Phi_{t\mathrm{modified}} = \Phi_t - \Phi_t \times (\mathrm{Tj}_t - \mathrm{Tj}_0) \times \mu. \tag{6}$$

According to the exponential degradation of the luminous flux we have

$$\Phi_{t\mathrm{modified}}/\Phi_0 = e^{-\beta_2 \times t}, \tag{7}$$

where β_2 is the degradation rate corresponding to the initial Tj of Tj_2 at an elevated ambient temperature. This way the influence of the variation of Tj on the luminous flux degradation is eliminated.

3. EXPERIMENTS

A. Accelerated Aging Test

In the accelerated aging, test five LED arrays from the same batch are selected as the samples. Each LED array is composed of thirty 0.15 W and GaN-based white LEDs converted by $\mathrm{Y_3Al_5O_{12}}$:Ce, as shown in Fig. 1. The electrical configuration of the arrays is as follows: thirty LEDs are divided into three

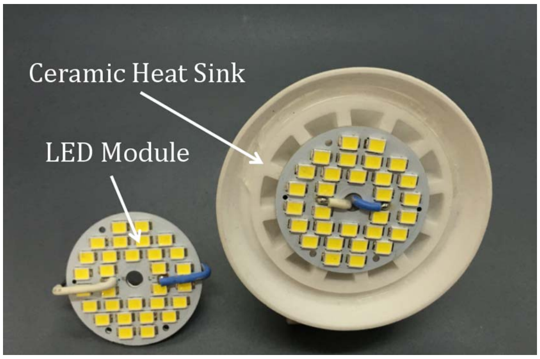

Fig. 1. Test sample with a ceramic heat sink attached.

groups connected in parallel, with each group consisting of ten LEDs connected in a series. The rated current of a single LED is 45 mA, and the rated current of the LED arrays is, therefore, approximately 135 mA, which is taken as the drive current in this research. The Tj of the samples is prevented from an excessive level by a ceramic heat sink with thermal grease attached.

In the aging process, the samples are placed in a temperature chamber at an ambient temperature of 80°C and lighted by a current of 135 mA. During the accelerated aging, the samples are taken out for optical parameter measurements at an intervals of 500 h. The measurement system mainly consists of a 1.5 m integrating sphere and a spectrometer from the Lan-Fei Company, as shown in Fig. 2. The sample is fixed in the integrating sphere at an ambient temperature of 25°C, and preheated for 20 min before the measurement. Then the Tj and the luminous flux are measured, respectively, with each measurement repeated five times. After the measurements, the sample is put back to the temperature chamber for further accelerated aging.

B. Measurement of Junction Temperatures

The forward V method is used for measuring the Tj of the samples at different aging stages. The relationship between the forward V and the Tj approximately obeys a linear rule [16–19], which is given by

$$V = K \times \mathrm{Tj} + B, \tag{8}$$

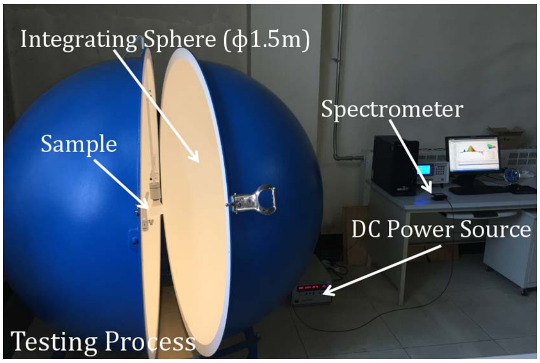

Fig. 2. Testing process, using an integrating sphere system with the 4π method.

where K (V/°C) is the V variation rate with respect to Tj and B is a constant. In the experiment, the unlighted sample is fixed inside a temperature chamber with the ambient temperature first controlled at 30°C. After 20 min, the sample reaches its thermal steady state where the Tj approximately equals the ambient temperature. Then, a repetitive current pulse with current of 135 mA, frequency of 1 kHz, and duty cycle of 50% (correspondent pulse width of 0.5 ms) is applied to the sample by pulse power. The first pulse response of the forward V is recorded, and the stable V during the last 0.2 ms period is taken as a reference. This is because there is a significant rising edge of V in the initial 0.3 ms.

To find out the impact of the current pulse on Tj during one cycle, we adjust the current pulse to be a frequency of 0.666 kHz and duty cycle of 33.3%. This current pulse is with the same pulse width of 0.5 ms as that in our actual experiments, but with a longer falling tail. Figure 3 shows the first two pulse responses of sample 1 at an ambient temperature of 30°C. It can be seen that in the pulse response exists a fast rising edge of 0.3 ms and a falling edge of 0.7 ms. The stable V before the rising edge (part A) and after the failing edge (part B) is 25.3203 and 25.3173 V, respectively. The variation of 0.0050 V is of such a low level that the impact of the current pulse on the LED Tj is negligible [18].

As a result, the Tj can maintain its original value of the ambient temperature, and the forward V corresponding to the Tj of 30°C is obtained. Repeating the above procedures under different ambient temperatures, the corresponding forward Vs are acquired, and the values of K and B in Eq. (8) can be solved by a linear fitting. In this research, six ambient temperatures from 30°C to 130°C, with an interval of 20°C, are chosen to get the calibration curve of the Tj with respect to the forward V of the sample. With the established V – Tj model, the Tj of the sample in a given state can be obtained by measuring the forward V of the sample.

Figure 4 shows the pulse responses of sample 1 under different Tj s. It can be seen that as the Tj raises from 30°C to 130°C, the corresponding forward V drops from 30.4411 to 28.0312 V. With the data in Fig. 4, a linear fitting of the V – Tj is obtained and is shown in Fig. 5. The variation of the forward V over the Tj is in a good linearity with the R-square (coefficient

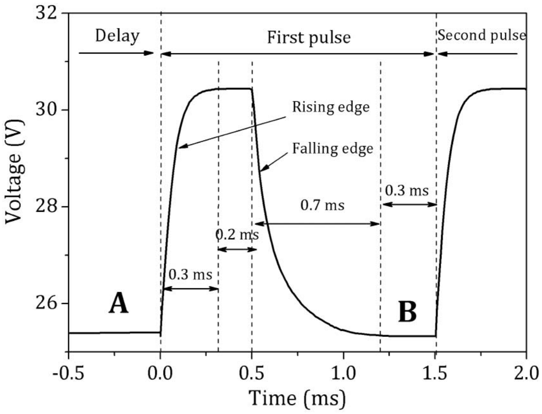

Fig. 3. First two pulse responses of sample 1 under 30°C with a current pulse frequency of 0.666 kHz and a duty cycle of 33.3%.

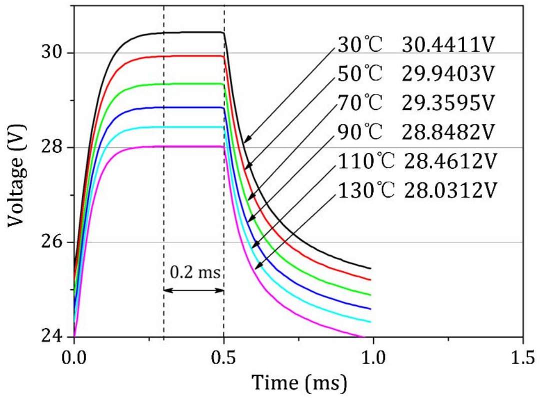

Fig. 4. Pulse response of sample 1 under different Tj with a current pulse frequency of 1 kHz and a duty cycle of 50%.

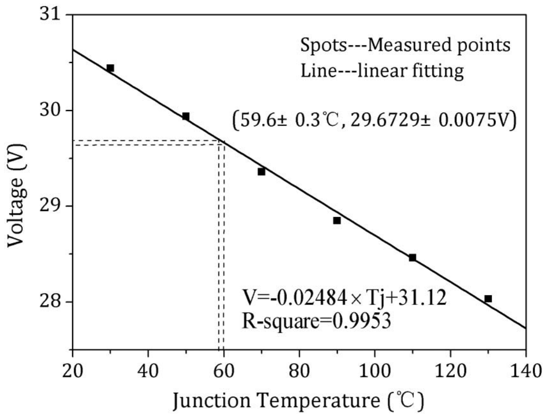

Fig. 5. Linear fitting results of Tj and forward V for sample 1.

of determination of regression) of 0.9953. The slope of the fitting, representing the K value, is −0.02428 V/°C. Before aging, the forward V of sample 1 at the ambient temperature of 25°C and with the rated current of 135 mA is measured to be 29.6729 ± 0.0075 V. The correspondent Tj is then calculated to be 59.6 ± 0.3°C by using the calibration curve.

C. Measurement of μ

The setup and apparatus for measuring the luminous flux of the sample under different Tjs are shown in Fig. 6. The sample and a reflective cup are fixed inside a temperature chamber. The reflective cup is just facing a window of the chamber to ensure that most of the luminous flux of the sample can pass through the window. The window is made of evacuated double glazing to achieve thermal isolation at this part of the chamber. Outside the chamber, a 0.5 m integrating sphere and a spectrometer are used for the collection and measurement of the luminous flux. The integrating sphere is placed with its side opening closely connected to the window.

In the experiment, the sample is lighted by the rated current of 135 mA with the chamber temperature at 25°C for 30 min before the measurement. Then, the luminous flux of the sample is measured with the spectrometer. Simultaneously, the forward V of the sample is measured. With the acquired V – Tj model in Section 3.B and the value of the forward V, the correspondent Tj is obtained. Repeating the above procedure under different chamber temperatures, a set of normalized luminous fluxes of the sample over the Tj is acquired. Seven chamber temperatures from 25°C to 85°C with an interval of 10°C are applied.

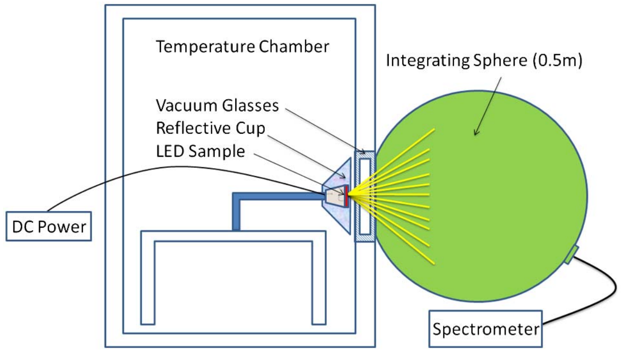

Fig. 6. Sketch map of the experiment for measuring the luminous flux at different Tj.

Table 1 lists the experimental results for sample 1 before the accelerated aging. It can be seen that as the ambient temperature rises from 25°C to 85°C, the Tj rises from 59.6°C to 123.5°C, and the luminous flux drops from 276.0 to 235.4 lm.

Table 1. Forward Voltage, Junction Temperature and Luminous Flux of Sample 1 at Different Ambient

Ambient Temperature (°C)	Voltage (V)	Tj (°C)	Luminous Flux (lm)
25	29.6729 ± 0.0075	59.6 ± 0.31	276.0 ± 0.7
35	29.3888 ± 0.0068	71.3 ± 0.28	268.2 ± 0.8
45	29.1873 ± 0.0072	79.6 ± 0.30	262.8 ± 0.6
55	28.9275 ± 0.0056	90.3 ± 0.23	254.7 ± 0.7
65	28.6289 ± 0.0085	102.6 ± 0.35	249.1 ± 0.6
75	28.4177 ± 0.0061	111.3 ± 0.25	244.0 ± 0.5
85	28.1214 ± 0.0055	123.5 ± 0.23	235.4 ± 0.6

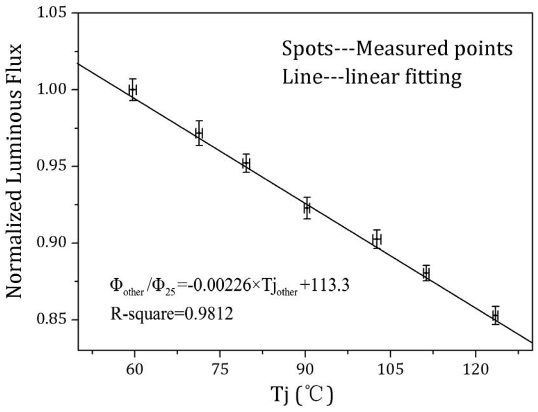

Fig. 7. Fitting result of normalized luminous flux over Tj for sample 1 before accelerated aging.

The normalized luminous flux with respect to the Tj is then fitted according Eq. (5), and the fitted result is shown in Fig. 7. The R-square of this linear fitting is 0.9812, and the slope is −0.00226/°C, which means that the normalized luminous flux decreases 0.00226 as the Tj increases 1°C. Therefore, the μ is taken as −0.00226/°C in this case.

4. RESULTS AND ANALYSIS

A. Degradation of Luminous Flux

The data of the luminous maintenances and the exponential fitting curves for the five samples, during 3,000 h of aging, are shown in Fig. 8. Each data point is normalized by its initial value. It can be seen that after 3,000 h of aging, the normalized luminous fluxes of the samples drop to 86.6%, 86.3%, 85.5%, 89.9%, and 89.7%, respectively. The degradation rates of β acquired from the fittings are −4.83E − 5, −5.57E − 5, −5.06E − 5, −3.44E − 5, and −3.53E − 5, respectively. The accelerated lifetime of $L_{70\%}$, which is the time when Φ_t degrades to 70% of its initial value, can be obtained by Eq. (1) as

$$L_{70\%} = \frac{(-\ln 0.7)}{\beta}. \tag{9}$$

With the values of β, the accelerated lifetimes of $L_{70\%}$ of the samples are calculated, which are 7,470, 6,480, 7,150, 10,190 and 10,420 h, respectively.

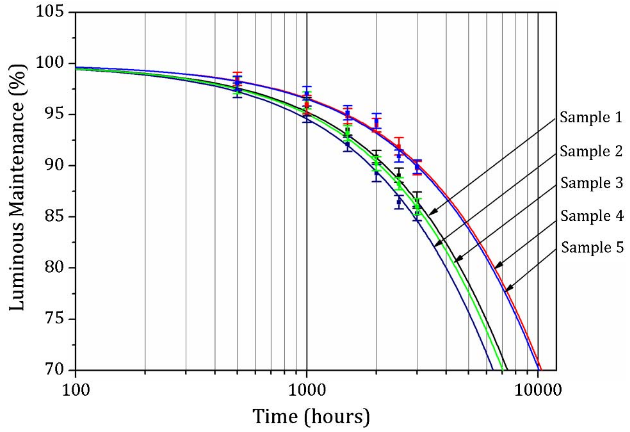

Fig. 8. Luminous maintenance for the five samples.

Table 2. Linear Fitting Results for Sample 1 at Different Aging Stages

Aging Time (h)	Linear Fitting	R-square
0	V = −0.02484 × Tj + 31.12	0.9953
500	V = −0.02052 × Tj + 30.99	0.9974
1,000	V = −0.01813 × Tj + 30.79	0.9952
1,500	V = −0.01603 × Tj + 30.79	0.9981
2,000	V = −0.01412 × Tj + 30.56	0.9971
2,500	V = −0.01253 × Tj + 30.53	0.9958
3,000	V = −0.01181 × Tj + 30.40	0.9962

B. Results of Tj

In this section, we refer to the procedure of the measurement of Tj described in Section 3.B. Figure 9 shows the V − Tj calibration data of sample 1 after the aging time of 0, 500, 1,000, 1,500, 2,000, 2,500, and 3,000 h, respectively, as well as the linear fitting curves. Table 2 lists the linear fitting expressions

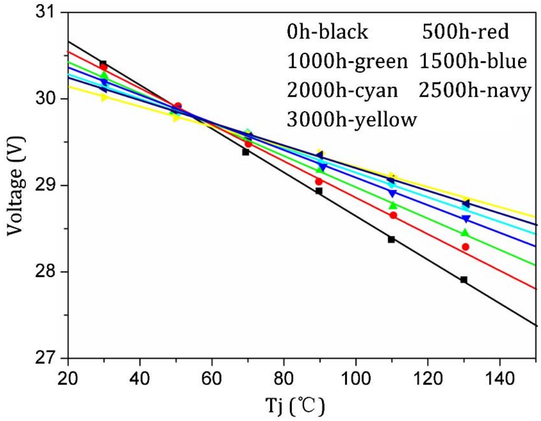

Fig. 9. V − Tj calibration results of sample 1 at different aging stages.

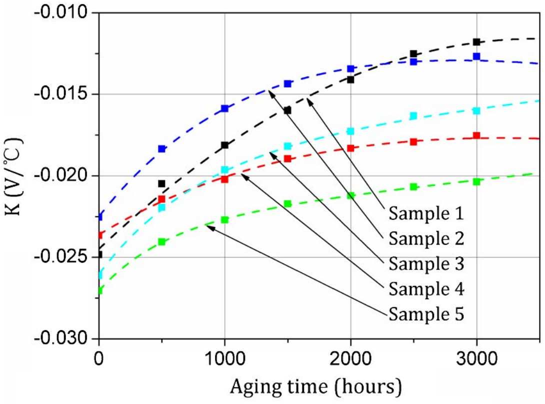

Fig. 10. Slope K as a function of aging time for the five samples.

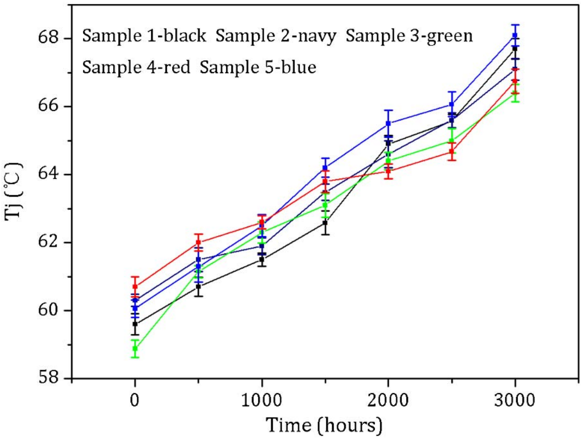

Fig. 11. Tj as a function of aging time under an ambient temperature of 25°C.

Table 3. μ values of Five Samples at Different Aging Stages

	μ (1/°C)							
	0 h	500 h	1,000 h	1,500 h	2,000 h	2,500 h	3,000 h	Average
Sample 1	−0.00226	−0.00256	−0.00241	−0.00235	−0.00229	−0.00242	−0.00221	−0.00236
Sample 2	−0.00212	−0.00235	−0.00225	−0.00208	−0.00235	−0.00225	−0.00215	−0.00220
Sample 3	−0.00222	−0.00201	−0.00210	−0.00208	−0.00200	−0.00213	−0.00223	−0.00211
Sample 4	−0.00219	−0.00245	−0.00241	−0.00236	−0.00234	−0.00221	−0.00212	−0.00230
Sample 5	−0.00231	−0.00221	−0.00240	−0.00245	−0.00238	−0.00250	−0.00238	−0.00238

of sample 1 at different aging states. It can be seen that the slope K of the fitting increases as the aging time increases. It is −0.02484, −0.01063, and −0.01181 V/°C after 0, 1,500, and 3,000 h of aging, respectively. The fittings are all in good linearity with a R-square higher than 0.995. For the other four samples, the V – Tj calibration data and the corresponding linear fitting are similar to that of sample 1. Figure 10 shows the slope of K as a function of aging time for the five samples. It can be seen that K increases dramatically from 0 to 2,000 h for each sample, and then increases smoothly after 2,000 h.

After the V – Tj calibration, the forward Vs of the samples under the rated current and ambient temperature of 25°C are measured at different aging stages, and the corresponding Tjs are calculated with the calibration results. Figure 11 shows the variations of the Tj with respect to the aging time for the samples. It can be seen that the Tj increases as the aging time increases. The increments of the Tj of the five samples after 3,000 h of aging are 8.1°C, 7.6°C, 6.9°C, 6.0°C, and 8.1°C, respectively.

C. Results of μ

In this section, we refer to the procedure to obtain the μ value described in Section 3.C. Table 3 lists the values of μ after 0, 500, 1,000, 1,500, 2,000, 2,500, and 3,000 h of aging for the five samples. It can be seen that the μ value varies in a range from −0.00256/°C to −0.00221/°C, with an average of −0.00236/°C during 3,000 h of aging for sample 1. The average values of μ for the other four samples are −0.00222/°C, −0.00211/°C, −0.00230/°C, and −0.00238/°C, respectively.

D. Modification of the Luminous Flux Degradation

With the data of the luminous maintenances given in Section 3.A, the values of Tj given in Section 3.B and the μ values given in Section 3.C, we can get the corresponding modified luminous fluxes according to Eq. (6). With the acquired modified luminous maintenances, the degradation rate of β_2 can be obtained according to Eq. (7), and the corresponding modified lifetime of $L'_{70\%}$ according to Eq. (9) as well. Figure 12 shows the data of the modified luminous fluxes and the exponential fitting curves for the five samples. The degradation rates of β_2 are −4.39E − 5, −5.03E − 5, −4.21E − 5, −3.12E − 5 and −2.82E − 5, respectively, and the lifetimes of $L'_{70\%}$ are 8,130, 7,090, 8,470, 11,430, and 12,650 h, respectively.

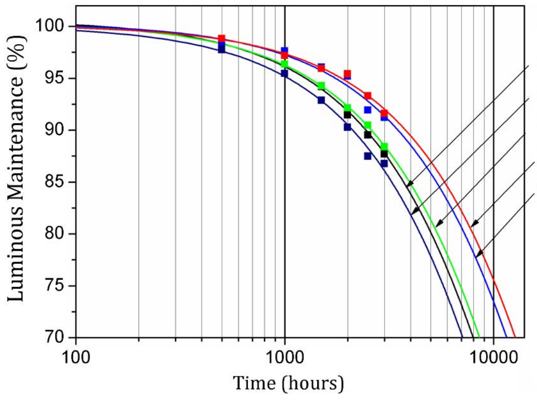

Fig. 12. Modified luminous maintenance for the five samples.

Figure 13 shows the comparison between the lifetime of $L_{70\%}$ in part 4A and the modified lifetime of $L'_{70\%}$. It can be seen that the modified lifetime of $L'_{70\%}$ is always bigger than the lifetime of $L_{70\%}$. The difference is 660 (8.8%), 610 (9.4%), 1,320 (17.7%), 1,700 (12.2%), and 2,230 h (21.4%), respectively, for the five samples. This can be explained as follows: $L'_{70\%}$ is the lifetime with the degradation rate corresponding to the initial Tj at an elevated ambient temperature, and $L_{70\%}$ is the lifetime with the degradation rate corresponding to a Tj higher than its initial value due to the increase of Tj over an accelerated aging time. According to the Arrhenius model, the higher the Tj is, the larger the degradation rate. Therefore, the lifetime $L_{70\%}$ is always underestimated.

Weibull distribution [10,26,27] is used for analyzing the obtained $L_{70\%}$ and $L'_{70\%}$, and the corresponding failure probability of samples with respect to the aging time t can be expressed as

$$F(t) = 1 - \exp\left(-\left(\frac{t}{\eta}\right)^{m}\right), \tag{10}$$

where m and η represent the shape parameter and characteristic lifetime, which can be solved by the corresponding likelihood function. As the failure probability is equal to 50%, the medium lifetime $\tau_{0.5}$ of samples is calculated to be

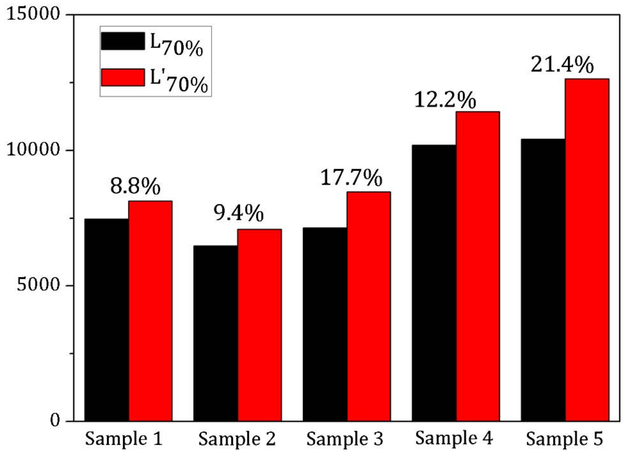

Fig. 13. Comparison between $L_{70\%}$ and $L'_{70\%}$ for the five samples.

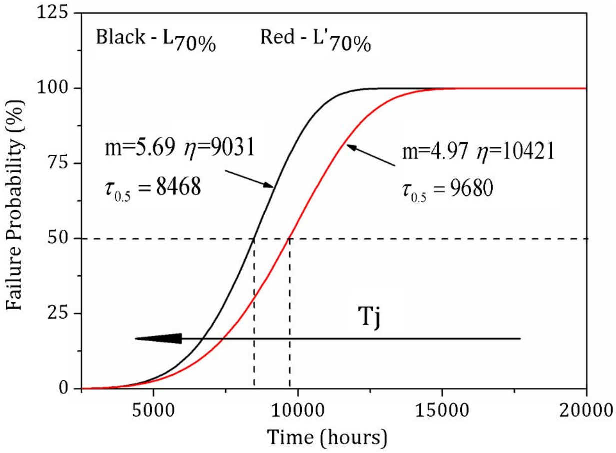

Fig. 14. Failure probability curves of the Weibull distribution derived from $L_{70\%}$ and $L'_{70\%}$.

$$\tau_{0.5} = \eta(\ln(2))^{\frac{1}{m}}. \quad \textbf{(11)}$$

The obtained $L_{70\%}$ and $L'_{70\%}$ in Fig. 13 are respectively analyzed under the Weibull distribution, and the calculated $F(t)$ and $\tau_{0.5}$ are shown in Fig. 14. It can be seen that m and η are 5.69 and 9,031 h, respectively, for $L_{70\%}$ and 4.97 and 10,421 h, respectively, for $L'_{70\%}$. Then, the medium lifetime of $\tau_{0.5}$ is calculated, which is 8,468 h for $L_{70\%}$ and 9,680 h for $L'_{70\%}$. The error in the medium lifetime estimation with the current method is underestimated by 12.5%.

5. CONCLUSIONS

An accelerated aging test of LED white arrays at an ambient temperature of 80°C is conducted to investigate the influence of the variation of Tj during the aging test on lifetime prediction. The forward V method is used to estimate the Tjs of the samples at different aging stages. The slope K of the V – Tj calibration increases over time with values of −0.02484 V/°C initially and −0.01181 V/°C after 3,000 h of aging for sample 1. The calculated Tj increases about 6–8°C for the samples under the testing condition with an ambient temperature of 25°C.

We have verified that at a certain aging stage, the decrease of normalized luminous flux with respect to Tj obeys a linear rule with the luminous flux variation rate of μ. After a period of aging, the value of μ can be acquired by a linear fitting of the luminous flux over Tj.

We have proposed a method to modify the luminous fluxes obtained at different aging stages to meet the requirement of the luminous flux degradation mode, l which is with a constant degradation rate corresponding to the initial Tj. In the modification, the Tj and the value of μ are used. It is shown in a comparison with the lifetimes of $L_{70\%}$ that the modified lifetimes of $L'_{70\%}$ are 8.8%, 9.4%, 12.2%, 17.7%, and 21.4%, respectively, longer for the five samples.

As a starting point, the scope of this study is limited to the LED array composed GaN-based white LEDs converted by $Y_3Al_5O_{12}$: Ce (10 wt. % relative to epoxy). For other mixture concentrations and phosphor converted white LEDs, the variation of Tj must be experimentally determined. This will be our focus future work.

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

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