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Useful lifetime analysis for high-power white LEDs

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ABSTRACT

An accelerated degradation test is used to analyze the useful lifetime of high-power white light-emitting diodes (HPWLEDs) as the point at which the light output declines to 70% of the initial flux in lumens, called L_{70} In this study, the degradation-data-driven method (DDDM), including the approximation method, the analytical method, and the two-staged method, is used to analyze the useful lifetime of HPWLEDs. A response model based on an inverse power (exponential) law under different stresses is used to predict the useful lifetime under operating conditions. However, the degradation model for each HPWLED is usually fitted to an exponential function. In order to improve the fit accuracy, we present a bi-exponential model for the degradation curve of HPWLEDs. The estimation of the model parameters are easily obtained by using the nonlinear least square method. Through numerical examples, the results show that the bi-exponential model performs better than the exponential model based on the two-staged method. The extrapolation algorithm for L_{70} should be fitted to a bi-exponential extrapolation model and two-staged method.

1. Introduction

Lighting systems play a significant role in life, affecting visual conditions, comfort, health, well-being, and work performance [1–3]. Light-emitting diodes (LEDs) were developed in 1993 and have been continuously improved. LEDs have attracted increasing interest in the field of lighting systems owing to their having superior characteristics to conventional light sources in terms of guaranteed longer lifetime, lower power consumption, higher brightness and being less harmful [4]. These merits of LEDs forced them to be used for high-power applications, such as general lighting, back lighting (small to large size), strobe lighting (cell phones and cameras), automotive, and large outdoor displays [5].

In recent years, LEDs have been increasingly used in display back lighting, communications, medical services, signage, and general illumination [6–9] due to their small exterior outline dimensions, often less than 10 mm × 10 mm. LEDs, when designed properly, offer higher energy efficiency that results in lower power consumption (energy savings) with low voltage (generally less than 4 volts) and low current operation (usually less than 700 mA). LEDs can have a longer lifetime (50,000–100,000 h) [10] with better thermal management than conventional lighting sources (e.g., fluorescent lamps and incandescent lamps). LEDs provide high performance, such as ultra-high-speed response time (microsecond-level on–off switching), a wider range of controllable color temperatures (4500–12,000 K), a wider operating temperature range (20–85 °C), and no low-temperature startup problem [11].

As LEDs may have a much longer lifetime, and it is not practical to gather data for such long periods of time it is important to develop some rapid reliability assessment techniques and methods to predict LED light data accurately. Traditional reliability assessment techniques, like the failure mode mechanism and effect analysis (FMMEA), fault tree analysis (FTA), lifetime test or accelerated lifetime test (ALT), are always time and cost consuming during operation [12,13]. However, with highly reliability products, few failures may have occurred during reliability tests, meaning that we could not obtain enough lifetime data in short and reasonable time by using traditional reliability assessment techniques or ALT [14].

In this situation, collecting degradation data can overcome this problem and provide information to perform the reliability assessment. The degradation data can be collected under higher levels of stress and allow extrapolation of the reliability information under use conditions. This is called an accelerated degradation test (ADT). Therefore, using ADT is more attractive to alternative traditional reliability assessment techniques in processing failure time data, such as more reliability information and benefits in identifying the degradation path and providing effective maintenance methods before failures happen [15].

In general, LEDs do not fail catastrophically. However, their light output slowly decreases with operating time. The useful lifetime of

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an LED component or system is defined as the operating time (L, in hours) for the component or system to reach two performance criteria: time to 70% lumen maintenance ($L_{70\%}$) and time to 50% lumen maintenance ($L_{50\%}$) [16]. That is, the failure criterion can be defined as the 50% or 70% decrease in the emitted optical power, when compared with the initial level. The failure time is, accordingly, the time required to achieve that failure criterion. For general lighting applications, $L_{70\%}$ is considered and $L_{50\%}$ is used in other applications.

In this paper, we analyze the test data of LUXEON Rebel White LED devices from LUMILEDS, PHILIPS. The LUXEON Rebel White LED devices are one type of high-power white LEDs (HPWLEDs) with high luminous flux [17]. A typical high-power LED has a built-in heat sink, or slug, on which the GaN-based LED chip is placed and connected with two wires with the cathode and anode leads. In the case of HPWLEDs, the chip is uniformly coated with a layer of phosphor. The chip is then covered by a silicone gel and a lens is placed on top of it. The constructional details of the LUXEON Rebel White LED are showed in Fig. 1. We compare two different models to fit the data from luminous flux degradation testing based on the degradation-data-driven method (DDDM). Section 2 presents degradation models. Section 3 presents a general procedure for ADT to predict the lifetime of LUXEON Rebel White LEDs. Section 4 discusses the lifetime analysis of the two different models. Finally, Section 5 outlines the conclusions and discusses further research.

2. Degradation models

Accurate lifetime estimates for a high brightness LED operating in specified conditions is a very important task for LED manufacturers. The current practice of LED manufacturers is to measure the light output after a certain number of hours, such as 6000 h in an ADT [18–22]. The procedure of the IES TM-21-11 method can be found in TM-21 working group [22]. The useful lifetime $L_{70\%}$ is defined as the point at which the LED light output has declined to 70% of its initial flux in lumens. The extrapolation algorithm for lumen maintenance testing ignores data from the first 1000 h, and uses data from the last 5000 h of the test. The data are then fit to a model using a least square curve method. However, Fan, Yung, and Pecht [14] reported that by applying the "6 times rule" required in IES TM-21-11, both projecting results exceed the 6 times limitation (like $L_{70\%}$ (6 k) > 36,000 h). Therefore, more test time and more lumen maintenance data are required to estimate lumen lifetime under these test conditions for the LUXEON Rebel White LED device. Another drawback of IES TM-21–11 is that as it does not consider the variance of each test unit, so little reliability information for this device, including mean time to failure (MTTF), confidence interval (CI), and reliability function and so on, could be obtained.

Levada et al. [23] presented the accelerated life tests of GaN LEDs under two different packaging schemes (plastic transparent encapsulation and pure metallic) using a Weibull-based statistical model. The results show that metal packaged devices exhibit a longer lifetime than lamp devices. Shen et al. [24] investigated an accelerated life test for HPWLEDs based on spectroradimetric measurement using an exponential model. Ishizaki et al. [25] developed a robust high-power LED module that could operate at junction temperatures of up to 140 °C. The failure time, defined as a 50% decrease from the initial light level, was longer than 40,000 h. Jeong et al. [26] performed an accelerated life test of an InGaN LED backlight module for the front display of a refrigerator. Han and Narendran [27] presented an accelerated life test method for LED drivers that used electrolytic capacitors at the output stage by monitoring the output current ripples at different elevated operating temperatures. Pan and Crispin [15] investigated the degradation process of LEDs used as a light source in DNA sequencing machines. The degradation path is based on a nonlinear model proposed by Fukuda [28]. Wang and Chu [29] reported that the exponential model is better than the nonlinear model as the fit for the degradation path of light bars as a light source in laptops.

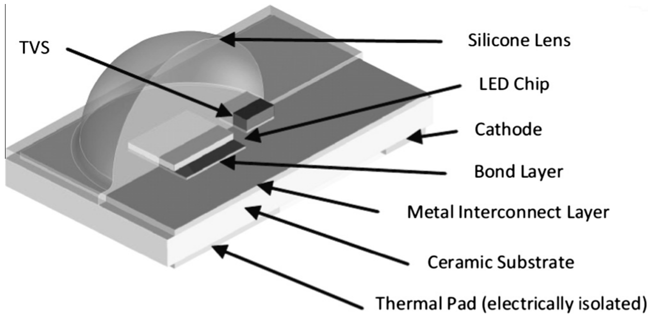

Fig. 1. The constructional details of LUXEON Rebel White LED [17].

However, several failure mechanisms for LEDs can be categorized into temperature dependent packaging (e.g. epoxy and phosphor), semiconductor (e.g. growth of dislocation and metal diffusion), and stress (e.g. thermal overload and electrostatic). Therefore, other models might be suitable to fit the degradation data. In addition, the parameter estimates of the model can be obtained using evolutionary algorithms, such as the genetic algorithm, particle swarm optimization, and differential evolution.

Fukuda [28] reported that the degradation modes can be classified as several types such as dislocations that affect the inner region, metal diffusion and alloy reaction that affect the electrode, solder instability (reaction and migration) that affects the bonding parts, separation of metals in the heat sink bond, and defects in buried hetero-structure devices. Models based on the current flowing during ambient temperature operations can be used to predict the LED lifetime in different accelerated degradation stress tests.

For the degradation life test of LEDs, the extrapolation function uses an exponential model, which is called model-1 and is given by

$$D(t_j) = \beta_1 e^{-\beta_2 t_j} + \varepsilon(t_j) \tag{1}$$

where $D(t_j)$ is the actual degradation path of a LED at j test time referred to as t_j, β_1 is a fixed effect parameter that describes population characteristics, β_2 is a random effect parameter that describes the decaying characteristic according to the diversity of the raw materials, production processes, component dimensions, and $\varepsilon(t_j)$ is a normal distribution with zero mean and unknown variance $\varepsilon(t_j) \sim N(0, \sigma^2)$.

The extrapolation function, using a bi-exponential model proposed by Bae et al. [30], is called model-2 and is given by

$$D(t_j) = \phi_1 e^{-\gamma_1 t_j} + \phi_2 e^{-\gamma_2 t_j} + \varepsilon(t_j) \tag{2}$$

where $D(t_j)$ is the actual degradation path of a LED at j test time referred to as t_j, φ_1 and φ_2 are parameters of fixed effects that describe population characteristics, and γ_1 and γ_2 are parameters of random effects associated with the diversity of the raw materials, production processes, component dimensions, $\varepsilon(t_j)$ is a normal distribution with zero mean and unknown variance $\varepsilon(t_j) \sim N(0, \sigma^2)$.

The estimates of the parameters in Eqs. (1) and (2) can be determined by the nonlinear least square method (NLS) and standard particle swarm optimization (SPSO) from the R Development Core Team [31].

3. A general procedure for ADT

In this section, the DDDM is briefly presented, including three methods: the approximation method, the analytical method, and