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Lifetime estimation of LED lamp using gamma process model

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ABSTRACT

The data for the light flux degradation and chromaticity shift of LED lamps exhibits a considerable amount of scatter due to intrinsic and extrinsic factors. In this study, some degradation models, such as the gamma process model, were reviewed in terms of uncertainties associated with the continuous, gradual, and monotonic nature of degradation. Statistically varying light flux degradation and chromaticity shift data in a test report from Lumileds were used as an example to demonstrate the use of the gamma process model. This model can describe the condition and lifetime as statistical distribution curves whose shapes vary with operation time. The service life was estimated as a median value, while the warranty life was estimated as a $B_{2.5}$ life for lumen degradation and B_{25} life for chromaticity shift from consideration of the optimal replacement life and percentile life.

1. Introduction

The light emitting diode (LED) has a broader application since the development of the blue LED in the 20th century, permitting radiation of the three primary colors of light. It has superior characteristics to conventional light sources in terms of energy savings (high efficiency), long life, small size, light weight, a wide variety of light colors, excellent on/off response, low emissions other than visible light, tolerance of low temperatures, containing no environmentally hazardous mercury (Hg), etc. These merits have allowed them to be used in various applications such as mobile devices, automotive applications, electronic goods and large outdoor displays. Recently, the use of high power white LEDs (HPWLEDs) in the area of lighting has been consistently researched and has increased the market share due to its advantageous eco-friendly features that are indispensable in helping prevent global warming [1–3].

The reliability of a system is based on the probability that, when operating under given environmental conditions, the system will perform its intended function adequately for a specified period of time [4]. Failure is the state or condition of not fulfilling a desired or intended function or not performing properly. The failure is classified into two categories; the functional failure not to perform intended function and the conditional failure of degrading below a predefined level. The common failure modes of HPWLEDs include catastrophic and wear-out failures. The probability of catastrophic failures, such as the light suddenly going off due to an open circuit is low especially for the InGaN types of LEDs without wire bonding interconnects. Lumen degradation and chromatic change correspond to wear-out failures [5]. Therefore, the lifetime of LEDs vis-à-vis this dominating failure must be estimated based on conditional failure because the luminous flux and the chromatic change gradually degrade to the failure level with operation time.

Lumen degradation is the dominant factor in LED lifetime. However, the chromaticity shift is another important performance attribute that can cause an LED lamp or luminaire to fail. While in some applications such as street lighting large color tolerances may be acceptable, color stability is very important for light sources in locations such as a museum or retail store where multiple lamps or luminaires are being used or where objects are being evaluated based on color such as in a hospital or factory [6]. Most attention has been paid to lumen depreciation, and the chromaticity state shift has been ignored.

There is a standard procedure to estimate useful life for light power. The LM-80-08, published by the Illuminating Engineering Society of North America (IESNA), estimates the lifetime of light sources using an exponential regression equation extrapolated to the failure level [7]. Although test methods for measuring the chromaticity characteristics have been recommended [8,9], there are no chromaticity state shift prediction methods in the specifications developed by the American National Standard Institute (ANSI) [10,11]. The traditional method to predict lifetime is regression analysis which estimates lifetime using a deterministic method. However, this deterministic method cannot reflect the statistical properties of degradation paths.

Generally, the degradation path varies according to intrinsic and extrinsic factors. The inhomogeneity of material is one of the intrinsic

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factors, while driving current, forward voltage, power dissipation, junction temperature, etc. for semiconductors, interconnects, and packages are some extrinsic factors [12–14]. The ambient and junction temperature influence the degradation of luminous flux most and the variation in the degradation rate caused by temperature variations results in a lifetime that follows a certain statistical distribution. Because LED lamps have a long lifetime and the collection of degradation data requires significant time and expense, the lifetime has been estimated using fitting data from accelerated lifetime tests to statistical distributions such as a Weibull distribution or a log–normal distribution. [15–18].

The variation in experimental data is caused by sampling and temporal uncertainty. The sampling uncertainty is an intrinsic aspect of the material and determines the path of degradation. The temporal uncertainty is an extrinsic factor that varies in a nondeterministic manner with operation time and it affects the rate of degradation. There is a large gap between the product lifetime estimated using statistical distribution and the actual application life due to not considering the measurement dynamics and uncertainties [19]. Because the stochastic process model can express temporal uncertainty as well as sampling uncertainty, it has been widely applied in lifetime estimations for construction materials, infrastructure, and metal fatigue. However, this model has still not been applied for lumen degradation or chromaticity shifts of LEDs.

This paper will focus on the use of the gamma process model to estimate the lifetime of LED lamps. The condition and lifetime distribution variations with time will be presented as a gamma distribution whose shape parameter is time varying. The representative values will be examined to determine whether they represent the service life. By reviewing the optimum replacement period and percentile life, the warranty life will be presented as a value and percentile life.

2. Test device and test condition

In this paper, a LUXEON® Rebel white LED from Lumileds (shown in Fig. 1) was chosen as the research object. The indium gallium nitrogen (In GaN) chip is united on the metal interconnect layer and a ceramic substrate with high thermal conductivity (>20 W/m K) was used to improve heat dissipation. The electrically isolated copper thermal pad was united at the bottom of the LED to conduct the heat generated from the chip. The fluorescent material coated above the chip converts blue light to white light. The LED chip was packaged with chip-on-board technology to improve the optical, electrical, and thermal features [20].

The lumen degradation and the chromaticity shift data were taken from DR03: LM-80 Test Report [21], they were collected according to the standard test procedure proposed by IES LM-80-08. The test condition of data used in this paper is shown in Table 1.

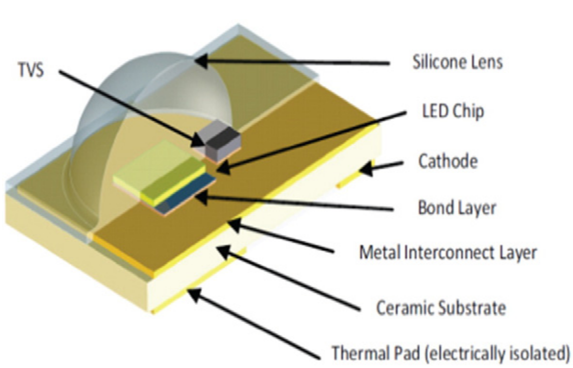

Fig. 1. Details of LUXEON® Rebel LED [20].

Table 1
Test conditions according to IES LM-80-08.

Terms		Test conditions
Testing duration		10,000 h
Data collection interval		Minimum of every 1000 h
Input current		350 mA
Temperature	Test	55 °C
	Case	60 °C
	Ambient	64 °C
Relative humidity		18%
Checking chromaticity change		Each measurement interval

3. Degradation characteristics and failure criteria

3.1. Degradation characteristics

The failure mode of a high-power white LED lamp is classified into open failure, short failure, luminous flux degradation, and chromatic change. The open and the short failure mainly arise due to electric shock or a flaw in the manufacturing process; however, the possibility of failure is very low. LED experiences a decrease over lighting time in the amount of emitted optical power and the degradation speed is affected by high temperatures and electrical current stress [12,22–24]. The optical degradation is accumulated gradually and is thermally stabilized at the time of initial use. Thereafter, it decreases to the conditional failure level [13]. Corrosion, heat, and excess current are the main cause of luminous flux degradation, and this occurs gradually over the long period of operating time. The chromatic change of light occurs due to the discoloration of epoxy from heat and excess current, the change of spectrum due to junction temperature, the imbalance between transformed and untransformed light from chips and YAG fluorescent substances [6,14].

3.2. Failure criteria

It is necessary to define conditional failure criteria and to estimate the failure time and parameters of the lifetime distribution. Generally, the rated life of a lamp is considered to be the time when half of the lamps have failed to go on. The lifetime of traditional electric lamps—such as incandescent, halogen, fluorescent, and metal halide lamps—is defined as rated life and the failure mode is functional failure. In contrast, the lifetime of an LED lamp is defined as service life (or useful life) when the luminous flux decreases to a predefined conditional failure level.

The Alliance for Solid State Illumination Systems and Technologies (ASSIST), a group led by the Lighting Research Center (LRC), recommends defining service life as the point at which output has declined by 70% of the initial lumens (L70 concept) for general lighting. This concept is based on research that found that the majority of occupants in a space will accept light level reduction of up to 30% with little notice, particularly if the reduction is general.

The Illuminating Engineering Society of North America (IESNA) published the LM-80-08, the standard document on the lifetime test for LED lamps. The Department of Energy (DOE) and the Environmental Protection Agency (EPA) added an LED lighting category to the Energy Star program which is a certificate system for highly efficient and highly eco-friendly products. The LM-80-08 is very similar to the lifetime assessment guideline for LED lamps suggested in the ASSIST program. The Energy Star program requires that lifetime assessment tests be performed using the test procedure described in the LM-80-08.

Both ANSI and the ENERGY STAR® program of the DoE accept the failure criteria for general luminaires whereby the change of chromaticity over the first 6000 h of lamp operation shall be within 0.007 on the CIE 1976 (u′, v′) diagram [25]. This means that the Euclidian distance