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DOI
10.1109/EuroSimE.2018.8369897

Publication date
2018

Document Version
Accepted author manuscript

Published in
2018 19th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems, EuroSimE 2018

Citation (APA)
Sun, B., Fan, J., Fan, X., & Zhang, G. (2018). A probabilistic physics-of-failure reliability assessment approach for integrated LED lamps. In *2018 19th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems, EuroSimE 2018* (pp. 1-5). IEEE. https://doi.org/10.1109/EuroSimE.2018.8369897

2018, EuroSIME, DOI: 10.1109/EuroSimE.2018.8369897

A Probabilistic Physics-of-Failure Reliability Assessment Approach for Integrated LED Lamps

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Abstract

This work studies the effect of randomness of LED's lumen depreciation on reliability of the entire LED lamp. An integrated LED light bulb is selected as carrier of the proposed method. A PoF based lumen depreciation model and electronic-thermal simulations are introduced for reliability prediction. The normal distribution is used to describe the statistical distribution of LEDs. The probabilities of the driver's catastrophic failures and lumen can then be obtained by Monte Carlo simulations by considering the increase of lamp's temperature. The effect of the lumen depreciation to the entire lamp is studied with two scenarios: constant light mode and constant current mode.

1. Introduction

For an integrated LED lamp, the driver is considered as one of the major reliability bottlenecks of LED lamps [1, 2]. The driver's temperature interacts with LED's lumen depreciation [3]. With the decay of luminous flux, the LED light source will generate more heat, leading a temperature rise of the driver. LED lumen depreciation is not only a degradation process, but also with a certain randomness. In a constant junction temperature, the average values of lumen maintenance degrades exponentially [4]. The randomness of the LED's lumen depreciation and color shift are usually described by stochastic process based models, such as Gamma process [5] and Wiener process [6]. A Six sigma DMAIC approach is used for life test for white LEDs [7]. The real operation conditions have been considered by an LED life prediction method [8]. As a smart control technology, the constant light output method has been developed to compensate lumen depreciation of LED light sources. In such an operation mode, the output power of the LED driver can be increased in order to keep the light output unchanged. Due to the increased current, the constant light output brings a huge temperature rise to LED lamps [9]. Current, few of reliability assessment method takes LEDs' impact from on driver reliability into consideration.

In recent years, probabilistic physics-of-failure based methods have been proposed for reliability assessment of electronic systems [10]. For instance, a life prediction method of turbine discs has used the probabilistic PoF framework to combine PoF models and uncertainty quantification [11]. A probabilistic PoF model, which integrates the Weibull distribution and the Monte Carlo method, has been developed for component reliability assessment [12]. Since both the failure mechanism and uncertainty can be considered, the Probabilistic PoF methodology could be used for reliability prediction of LED driver in an integrated lamp.

This work studies the effect of randomness of LED's lumen depreciation on reliability of the entire LED lamp. An integrated LED light bulb is selected as carrier of the proposed method. A PoF based lumen depreciation model and electronic-thermal simulations are introduced for reliability prediction. The normal distribution is used to describe the statistical distribution of LEDs. The probabilities of the driver's catastrophic failures and lumen are obtained by Monte Carlo simulations by considering the increase of lamp's temperature. The effect of the lumen depreciation to the entire lamp is studied with two scenarios: Constant Light mode (CLM) mode and Constant Current mode (CCM).

2. Assessment Method

A. General Methodology

Fig.1 displays the assessment methodology which integrates the electronic thermal simulation with Monte Carlo simulations to obtain failure probability of the entire LED lamp. For a given LED lamp, PoF-based simulations are applied to obtain the temperature distribution and lumen maintenance of the lamp. The LED degradation model provides simulation parameters at each time point. Circuit simulations calculate power distribution. System-level thermal simulations are conducted to determine the temperature distribution under operating conditions. Details of the electronic-thermal simulation can be found in previous studies [13, 26]. Then, the Monte Carlo simulations suppose that the basic efficacy of the LED light source follows the normal distribution. According to such a distribution, electronic thermal simulations are repeats to obtain distributions of the lumen maintenance and temperatures. Then, the reliabilities of the LED light source and the driver are calculated by using the simulation results. Finally, the reliability of the entire LED lamp can be obtained.

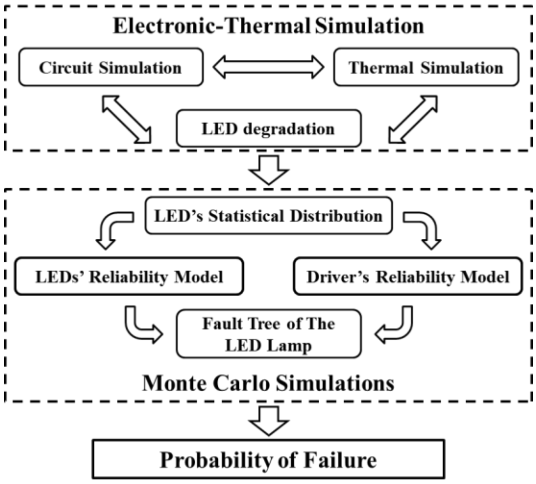

Fig. 1 Block diagram of the Proposed Reliability Assessment Method

B. PoF Modeling

Fig.2 displays the selected driver. In this circuit, the control IC U1 is considered as the critical components. In the circuit simulation, a virtual feedback device is used to achieve two operation modes: the constant current mode (CCM) and the constant light mode (CLM). The feedback device can adjust the output current to achieve invariant lumen output in the CLM.

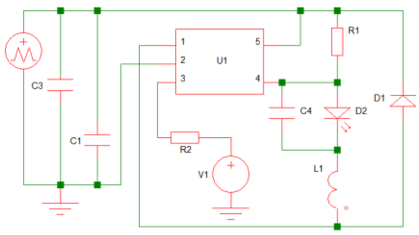

Fig. 2 The Selected Buck Driver

A temperature-dependent depreciation model for LED light source is considered in circuit simulations. The lumen maintenance $\Phi(t)$ can be described as a function of the ever-changing junction temperature $T_j(t)$ and current $I_{LED}(t)$:

$$\Phi(t)=\begin{cases}\eta_0\cdot\dfrac{B_e I_{LED}(t)^2}{A_e+B_e I_{LED}(t)+C_e I_{LED}(t)^2}\cdot V_f\cdot e^{-\int_0^t \beta[T_j(x)]\cdot dx} & (T_j<T_{MAX}) \\ 0 & (T_j\geq T_{MAX})\end{cases} \quad (1)$$

where η_0 is the basic efficacy, A_e and C_e are the linear and the 3rd-order non-radiative recombination rates, B_e is the radiative recombination rate, V_f is the forward voltage, T_{MAX} is the maximum junction temperature of the selected LEDs and β is the depreciation rate.

Fig.3 displays the selected LED lamp, which consists of a bulb cover, LED light source, heat sink, a driver and other relevant parts. The original driver in this lamp is replaced by the selected driver for the purpose of the study in this paper.

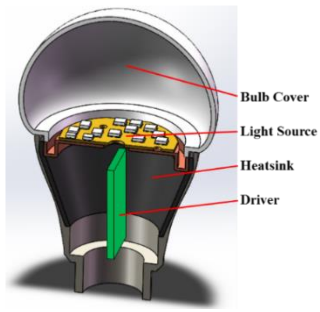

Fig.3 The Model of the selected LED Lamp.

System level thermal simulations are conducted to calculate the LEDs' junction temperature T_{LED} and driver's temperature T_D. The driver (the green part in Fig.3) is considered as homogenous material with heat from the driver distributed evenly on surface. The heat comes from both the LEDs and the driver's components. Thermal power of the LEDs $P_{th,LED}$ can be obtained by:

$$P_{th,LED}=P_{LED}-P_{Opt}\cdot\Phi(t) \quad (2)$$

where, P_{LED} is the input power and P_{Opt} is the initial optical power of the LED light source. The details of the PoF models mentioned above can be found in the literature [13, 14].

C. Reliability Models

This work focuses on the catastrophic failures of critical components of the driver. Failures of the driver distribute randomly during operation. This work regards the control IC U1's failure as the failure of the driver. Thus, failure probability density of the driver $f_D(t)$ can be obtained by the following function[13]:

$$f_D(t)=f_D[T_{j,IC}(t)]=\lambda_{IC}\cdot e^{\frac{-E_{a,IC}}{\kappa\cdot T_{j,IC}(t)}} \quad (3)$$

where, $T_{j,IC}$ is the junction temperature, λ_{IC} is basic failure probability density, $E_{a,IC}$ is the activation energy. In this work, $T_{j,IC}$ can be calculated via thermal simulations. According to the empirical models [13], λ_{IC} = 4.12×10^{-7} and $E_{a,IC}$=0.7eV. Expressed by the differential equation, the survival probability of the entire system $R_D(t)$ can be obtained by [14]:

$$R_D(t)=e^{-\int_0^t f_D(x)\cdot dx} \quad (5)$$

For constant current mode, this work considers the lumen maintenance $\Phi(t)$ as the failure criterion of the LED light source. LEDs' lumen maintenance not only degrades with time, but also has a certain distribution. For large number of LED light sources, the basic efficacy η_0 at time zero follows the normal distribution:

$$\eta_0 : N(1,\alpha) \quad (5)$$

where the standard deviation α can be measured by experiments. Therefore, the probability density for any η_0 can be expressed by:

$$p[\eta_0] = \frac{1}{\sqrt{2\pi}\alpha} e^{-\left(\frac{\eta_0 - 1}{\sqrt{2}g\alpha}\right)^2} \quad (10)$$

At each time point, the lumen maintenance degrades with time and follows a certain distribution. The $\Phi(t)$ ≤70% is defined as the threshold. Therefore, the reliability of the LED lamp is at time t:

$$R_{Lamp}(t) = \int_{0.7}^{1} p[\Phi(t)] \cdot R_D(t) \cdot d\Phi(t) \quad (6)$$

For constant light mode, the junction temperature $T_j(t)$ is used as the failure criterion instead of the unchanged $\Phi(t)$. When $T_j(t)$ exceeds its maximum value, the LED is considered burn out and give zero light output. With the lumen depreciation process, the junction temperature increases with time and follows a certain distribution at each time point. The $T_j(t) = 423$K is defined as the maximum junction temperature. Similarly, the reliability of the LED lamp is at time t:

$$R_{Lamp}(t) = \int_{0}^{423} p[T_j(t)] \cdot R_D(t) \cdot dT_j(t) \quad (7)$$

3. Case Study and Discussions

A. Scenario Design

This work considers three scenarios: the constant light mode (CLM), the constant current mode (CCM) and the combined operation mode. In the CLM, LEDs' driving current can be adjusted to achieve invariant light output; In the CCM, the current from the driver to the LED light source remains unchanged. The details of the results will be discussed below.

B. Constant Light Mode

Fig.4 displays the LED's driving current in the constant light mode. To compensate the lumen depreciation of the light source, the driver increases the output current exponentially. The mean value, upper bound and lower bound of LED's current rise to about 539mA, 725mA and 464mA in about 9000 hours respectively.

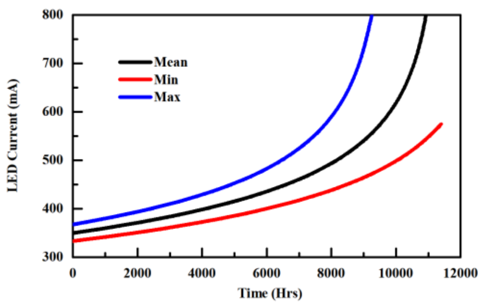

Fig.4 Driving Current of the LED Light Source in CLM

Fig.5 shows the junction temperature of the LED light source in constant light mode. The mean value, upper bound and lower bound of the junction temperature exceed 423K at about 9350 hours, 10250 hours and 7650 hours respectively.

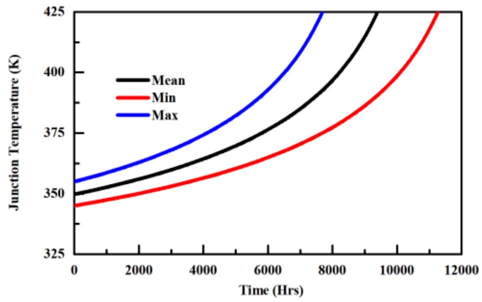

Fig.5 Junction Temperature of the LED Light Source in CLM

Fig.6 displays cumulative probability curves as functions of the junction temperature for each time point in the constant light mode. At zero hour, the junction temperature distribution follows normal distribution. Lumen depreciation rate increases with the junction temperature. A higher junction temperature at zero hour brings a faster depreciation rated, leading greater junction temperature increment with the lumen depreciation. Therefore, distributions of the junction temperature distribution no longer follow normal distributions as the lumen maintenance degrades with time.

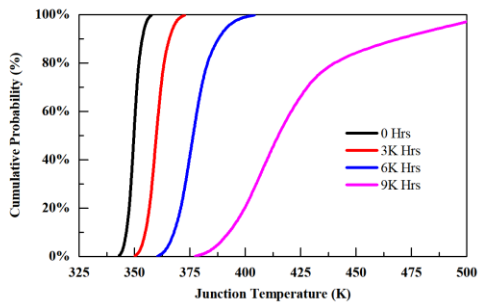

Fig.6 Cumulative Probability vs Junction Temperature of The LED Light Source in CLM

Fig.7 shows the driver's temperature in constant light mode. The mean value, upper bound and lower bound of the junction temperature increase about 21K, 53K and 12K in about 9000 hours respectively.

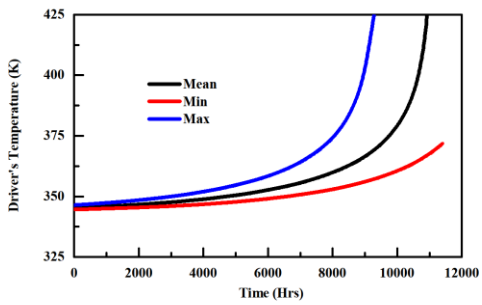

Fig.7 Driver's Temperature in CLM

Fig.8 displays reliability curves of the driver. In 9000 hours, the mean value, upper bound and lower bound of reliability of the driver drop to 50.06%, 56.86% and 27.95% respectively.

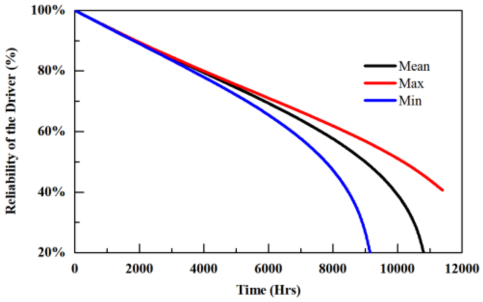

Fig.8 Driver's Reliability in CLM

C. Constant Current Mode

Fig.9 shows the junction temperature curves in constant current mode. The mean value, upper bound and lower bound of the junction temperature increases about 9.6K, 9.5K and 9.6K in 12000 hours respectively.

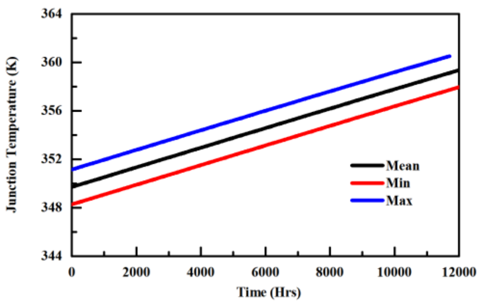

Fig.9 Junction Temperature of the LED Light Source in CCM

Fig.10 shows the lumen maintenance in constant light mode. The mean value, upper bound and lower bound of the lumen maintenance drop below 70% at about 13060 hours, 14840 hours and 11400 hours respectively. Compare with the constant light mode, lifetimes of constant current mode are 40%, 44% and 49% longer. Obviously, the constant light mode is hard to extend lifetime of the LED lamp, but maintains its optical performance.

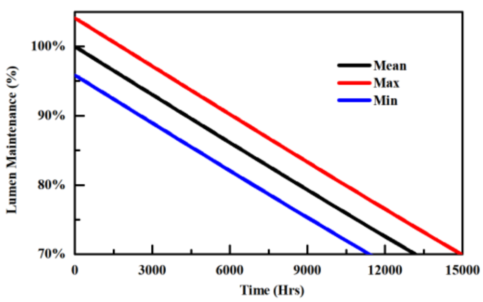

Fig.10 Lumen Maintenance in CCM

Fig. 11 shows the reliability degradation curves of the lamp in both the constant light mode and the constant current mode. The lamp's reliability curves in the constant light mode and the constant current mode degrade to about 5% in 12000 hours and 15000 hours. The driver's failure is dominant before 8000 hours in the constant light mode and 12000 hours. After these two points, failures of both LED light source and driver contribute to the lamp's reliability degradation, leading the lamp's reliability drops much faster than before. The reliability curves of the CLM and CCM almost overlap with each other before 5000 hours due to low temperature increments. With the lumen depreciation and thus increase of lamp's temperatures, reliability of the CLM decreases faster than the CCM. Therefore, the constant light mode is not approach to improve reliability of the LED lamp, but a method to maintain its optical performance.

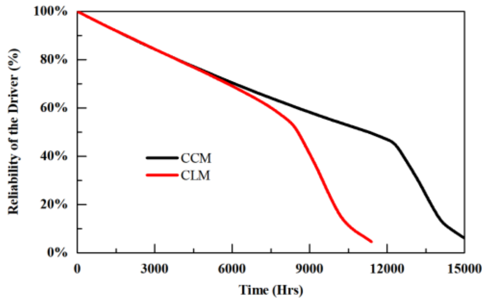

Fig. 11 Reliability of the LED lamp in CCM

4. Conclusions

This work studies the effect of randomness of LED's lumen depreciation on reliability of the entire LED lamp. An integrated LED light bulb is selected as carrier of the proposed method. A PoF based lumen depreciation model and electronic-thermal simulations are introduced for reliability prediction. The normal distribution is used to describe the statistical distribution of LEDs. The probabilities of the driver's catastrophic failures and lumen can then be obtained by Monte Carlo simulations by considering the increase of lamp's temperature. The effect of the lumen depreciation to the entire lamp is studied with two scenarios: constant light mode and constant current mode.

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