Microelectronics Reliability 53 (2013) 435–442

Contents lists available at SciVerse ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Optimum design domain of LED-based solid state lighting considering cost, energy consumption and reliability

Bong-Min Song [a,1], Bongtae Han [a,*], Joon-Hyun Lee [b]

[a] Mechanical Engineering Department, University of Maryland, College Park, MD 20742, United States
[b] School of Mechanical Engineering, Pusan National University, Busan, South Korea

ARTICLE INFO

Article history:
Received 11 May 2012
Received in revised form 9 September 2012
Accepted 23 October 2012
Available online 1 December 2012

ABSTRACT

Design parameters of LED-based solid state lighting products are interdependent and the corresponding requirements are dictated by operating conditions. We propose a scheme to define optimum design domains of LED-based luminaires for a given light output requirement by taking cost, energy consumption and reliability into consideration. First three required data sets to define design domains are expressed as contour maps in terms of the forward current and the junction temperature (I_f and T_j): (1) face lumen and cost requirement as lumen/LED; (2) power consumption and energy requirement as luminaire efficacy (*LE*); and (3) reliability requirement as L70 lifetime. Then, the available domain of design solutions is defined as a common area that satisfies all the requirements of a luminaire. The proposed scheme is implemented for a wall wash light and the optimum design solutions are presented.

1. Introduction

Recently LED-based luminaires have emerged rapidly for commercial and residential applications. For a required light output, the optimum design of a LED-based luminaire can be achieved by considering cost, energy consumption and reliability.

Design considerations for LED-based luminaires are unique in that many design solutions are possible for the same required light output unlike the conventional light sources (e.g., compact florescent light, incandescent light, etc.). This is due to the well-known fact that the lumen output that each LED produces is a function of the driving current, I_f, as well as the junction temperature, T_j.

Fig. 1 illustrates the details. The luminous flux of LEDs increases as the driving current increases, but the corresponding luminous efficacy decreases at a higher driving current because the luminous flux is not linearly proportional to a driving current. More importantly, when a higher driving current is used, heat flux becomes proportionally larger, resulting in a higher junction temperature. This increased junction temperature not only decreases the luminous flux but also significantly affects the rate of lumen maintenance (i.e., life time). A lower driving current can be utilized if more LEDs are used in the light engine of a luminaire. Yet this is often not the most desired solution due to the high cost of LEDs.

In an LED-based luminaire design, all design parameters are interdependent and the corresponding requirements are dictated by operating conditions (I_f and T_j). This paper suggests a methodology to define the optimum design domains of LED-based luminaires considering cost, energy consumption and reliability. The required data sets to define design domains are described in Section 2. An application using the requirements of wall wash light is provided in Section 3.

2. Design considerations and required data sets

Optimum design of LED-based luminaires can be achieved by considering cost, energy consumption and reliability. These design parameters can be expressed as lumen/LED, luminaire efficacy, and L70 lifetime, respectively. Since they are a function of operating conditions, the parameters can be quantified in the domain of junction temperature (T_j) and forward current (I_f).

This section describes the three interdependent design parameters and defines the data sets required to obtain them. Test data obtained from a commercial phosphor converted LED are used to illustrate the concept.

2.1. Cost (lumen/LED)

The Department of Energy (DoE) of U.S. published the requirements for solid state lighting luminaires [1]. To deliver a required light output, two different approaches can be considered depending upon the nature of applications. For medical and military applications where stringent reliability requirements must be met, the required light output should be delivered at a junction temperature that is sufficiently low to satisfy the high reliability standards. For a given passively or actively-cooled luminaire, a low junction

* Corresponding author. Tel.: +1 3014055255.
E-mail address: bthan@umd.edu (B. Han).
[1] Participant in the University of Maryland/Pusan National University Joint Doctoral Program.

0026-2714/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.microrel.2012.10.010

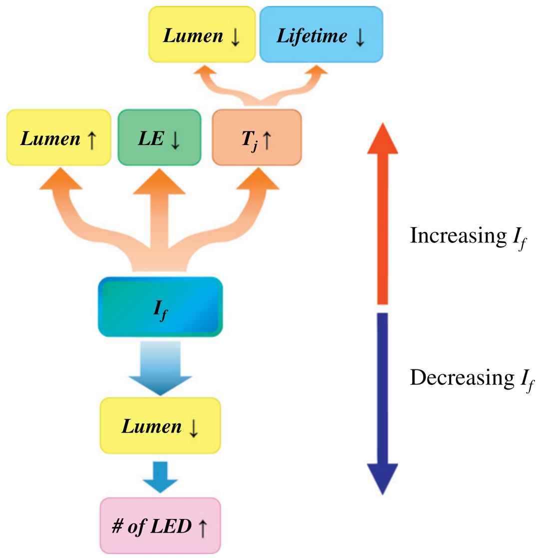

Fig. 1. Effect of I_f on performance of LED-based luminaire.

temperature can be achieved only by a low forward current level, which forces to employ as many LEDs as needed. For commercial and residential applications, however, LED-based luminaires should use only a minimum number of LEDs to be cost-effective and thus to be competitive with the conventional light sources. Therefore, the light output of a single LED at a specified condition is a very important parameter. Since the light output is a function of forward current and junction temperature, the light output has to be measured at various forward current and junction temperature conditions.

Fig. 2 shows an experimental setup used to acquire light output at different currents and junction temperatures. An LED (CREE XR-E) is mounted on a thermoelectric cooler (TEC) in an integrating sphere. The LED has a conformally coated phosphor layer on the chip and encapsulated with transparent silicone. The top part dome is glass. The package is surrounded with the aluminum reflector. The TEC controls the *solder point temperature*[2] of LED (T_s) and the integrating sphere (SMS-500: Labsphere) equipped with a spectroradiometer system measures the spectral power distribution (SPD) of the LED at the various operating conditions. The sampling interval of the spectroradiometer is 1 nm. The measurement range of wavelength is 360–1000 nm. The TEC is controlled by a thermal controller (LB 320: Silicone Thermal. Co. Ltd.) using an input provided by a *T*-type thermocouple directly mounted on the solder point surface. The setup can adjust the solder point temperature from −40 to 125 °C with a resolution of 0.1 °C.

The junction temperature can be estimated by the well-known forward voltage method [2]. The method is valid only when a pulsed current with a very short duration is used so that the junction temperature does not change during forward voltage measurement. For the SPD measurement, however, the spectroradiometer requires an integration time [3], which is usually much longer than the short pulse duration for the forward voltage method: a typical integration time for a full white light spectrum is 100–1000 ms. As a result, an additional increase of junction temperature is unavoidable during the SPD measurement.

In order to avoid this undesired error in junction temperature measurement, an LED is subjected to a steady-state condition inside an integrating sphere for accurate junction temperature measurement. With the 4π configuration in Fig. 2, a current is applied to the LED continuously until the solder point temperature reaches a preset value which is maintained by controlling the TEC. Once the solder point temperature is stabilized, the SPD and the forward voltage of the LED are measured simultaneously.

The SPDs have been measured at various solder point temperatures and forward currents: T_s from 65 to 125 °C with a constant interval of 15 °C and I_f from 300 to 1000 mA with a constant interval of 100 mA. The total number of measurements is 40. Typical SPDs obtained at T_s = 65 and 125 °C at I_f = 300 and 1000 mA are shown in Fig. 3. The radiant flux and the corresponding luminous flux obtained from all 40 measurements are shown in Fig. 4a and b, respectively. As expected, the luminous flux increases as the solder point temperature decreases under a constant current.

The measurement data obtained for solder point temperatures can be converted to the junction temperature domain through the relationship between junction temperature and solder point temperature, which can expressed as [4–6]:

$$T_j = T_s + P(1-\eta_P)R_{js} = T_s + I_f V_f (1-\eta_P)R_{js} \quad (1)$$

where T_s is the solder point temperature, P is the total electrical power consumption in W ($= I_f \cdot V_f$), η_p is the LED power efficiency (the radiant flux divided by the total electrical power input), I_f is the forward current, V_f is the forward voltage and R_{js} is the thermal resistance between the chip and the solder point (8 °C/W for the LED tested in this study [7]). It is important to note that power efficiency in Eq. (1) was often ignored in the thermal analysis of low power LEDs due to low efficiency [8,9]. For high power LEDs with typical power efficiency of 15–30%, the effect of the power efficiency must be considered in a thermal analysis.

The forward voltage is measured first as a function of solder point temperatures (Fig. 5a), from which the total electrical power consumption is determined. The results are shown in Fig. 5b. The power efficiency then can be determined simply by dividing the total power consumption by the radiant flux amount shown in Fig. 4a, and the results are shown in Fig. 6. The power efficiency varies significantly with the forward current.

The solder point temperatures in Fig. 6 can be converted to the corresponding junction temperatures using Eq. (1). The converted power efficiency as a function of junction temperature is shown in Fig. 7. It is worth noting that the power efficiency decreases almost linearly as the junction temperature increases and the rate of the power efficiency reduction remains the same regardless of the current.

The luminous flux data of Fig. 4b can be also presented in the junction temperature domain using Eq. (1) and the power efficiency data. The converted luminous flux data is shown in Fig. 8. From the data in Fig. 8, a contour plot of the luminous flux of a single LED in a domain of the forward current and the junction temperature can be determined (Fig. 9). The contour plot shows the distinctive characteristic of LED luminous flux, which depends on the junction temperature as well as the forward current.

2.2. Energy consumption (luminaire efficacy)

One of the key attributes of LED lighting is low power consumption. In other words, LED-based luminaire can deliver the same amount of luminous flux with lower power consumption compared to the conventional light sources. This property is expressed as *luminaire efficacy* [10], which is defined as the total lumens produced by a luminaire divided by the total wattage drawn by the power supply/driver, expressed in lumens per watt (lm/W); i.e.,

$$|LE|_{luminaire} = |LE|_{LED} \times F_{fixture} \quad (2)$$

[2] The "solder point" is the point at which the solder meets with a printed circuit board and LED leads. Some LED manufactures refer to "case temperature but referring to the solder point temperature is more precise.