

Failure causes and mechanisms of retrofit LED lamps



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ABSTRACT

This paper describes one of the first studies of the degradation of retrofit light bulbs based on white GaN light emitting diodes. The results indicate that the lifetime of LED lamps depends mostly on the stability of the driver and optical elements, rather than on the degradation of the LED chips, that have a stable output over stress time. By comparing lamps from four different manufacturers stressed at room and high temperature, we found that (i) long-term stress causes a change of the chromatic properties of the lamps, which is ascribed to the degradation of the phosphors or to the inner LED reflector; (ii) during aging the LED driver may degrade gradually and/or catastrophically, causing a reduction of the output optical power, or a complete failure; (iii) proper thermal management and heat dissipation reduce the degradation rate; (iv) spectral transmissivity measurements and visual inspection reveal the degradation of the diffusive optical elements, which is induced by the short wavelength side of the LED emission spectrum.

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1. Introduction

White LEDs based on blue GaN chips and yellow phosphor conversion are efficient devices whose reliability and stability was proved up to tens of thousands of hours [1,2]. In order to exploit this performance, several countries and associations are promoting the production of LED retrofit light bulbs, able to fit in a common Edison screw socket, whose most renowned example was the “L Prize” competition run in 2008 by the United States Department of Energy with a US\$10 million prize fund [3].

Retrofit light bulbs are now commonly sold in stores. Given the higher initial cost, it is important to ensure that their intensity and chromatic properties remain stable over the usable lifetime to take advantage of the reduced power consumption and longer lifetimes compared to traditional incandescence or fluorescence lamps [4].

Although several papers have analyzed the degradation of chip LEDs over high temperature [5,6], high current [7,9] and reverse-bias [7–13] stress, to date no paper has described the long-term degradation of complete lamps.

This paper presents one of the first studies of the degradation mechanisms of commercially-available lamps; the results allow us to identify the critical parts of the overall system, and to correlate failure modes with specific failure mechanisms. We found that (i) the operating temperature accelerates the degradation processes, which are related to (ii) the darkening of the plastic diffusive bulb, to (iii) the

change in the chromatic properties of the inner phosphor and/or reflector and to (iv) the degradation of the LED driver.

2. Experimental details

Commercially-available retrofit light bulbs from four different manufacturers (A to D in the following) were submitted to lifetime tests at room temperature (RT) and accelerated tests at higher temperature (HT). The analyzed lamps have a luminous flux between 765 and 810 lm, and a correlated color temperature of 2700–3000 K. The actual stress temperature varies due to the different driving and heat dissipation strategies adopted by the manufacturers, on average the temperature of the HT lamps is 15 °C higher than the RT lamps. Table 1 reports a comparison of the average temperatures in different regions of the light bulb for each manufacturer and test temperature (room temperature or high temperature). These temperatures were measured by using a FLIR Systems i50 infrared thermal camera. During the stress the lamps are biased in their normal operating condition, i.e. screwed in a socket and connected to a mains wall plug.

At each stress step we carried out a complete optical and spectral characterization in a 1.5 m diameter Labsphere LMS-650 integrating sphere by using an Ocean Optics USB2000 spectrometer. We performed a radiometric calibration of the whole setup in order to obtain an accurate distribution of the optical power at different wavelengths and the correct power spectral density in International System (SI) units. Moreover, after every stress period we measured the electrical power consumption of the complete system, i.e. the power absorbed by the LED driver from the electrical distribution network in order to operate the LEDs, was measured by means of a Rohde & Schwarz HAMEG HM8115-2 power meter.

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Table 1

Operating temperatures of different lamp regions for each manufacturer during stress at room temperature (RT) or high temperature (HT).

Stress condition		Bulb (°C)	Heatsink (°C)
RT	A	38.1	82.6
	B	35.2	75.3
	C	39.2	64.4
	D	36	88.1
HT	A	42.6	98.5
	B	38.1	89.1
	C	42	80.7
	D	38.4	99.8

3. Degradation kinetics

Figs. 1 and 2 report the degradation kinetics of the output optical power for all the samples under test at room temperature and at high temperature, respectively. Each line represents the average trend of all the lamps from the same manufacturer stressed at the same external temperature. The reliability under typical operating conditions is high, a 6% drop after 4500 h in the worst case and almost no degradation for manufacturer C. These figures highlight a general improvement of the systems if compared to preliminary reports on the degradation of retrofit bulbs produced during previous iterations of the technological process [14], and can support additional research in order to obtain further improvements and widen the target market of these lighting engines.

The output luminous flux is affected by a faster decay during the HT stress for all the manufacturers under analysis. This suggests the important role of temperature as a degradation accelerating factor, which was reported for LED chips [9], phosphors [7] and reflector [15]. We measured the temperature distribution in the bulbs by means of IR thermography, whose results are presented in Fig. 3 alongside an optical photograph. We can see that, even if the diffusive bulb differs lightly from room temperature, the heat dissipation features reach very high temperatures (75 °C or more). We can expect a junction temperature for the LEDs higher than this value, which can pose reliability issues for the whole system, since LEDs are rated for maximum values up to 150 °C [16].

By comparing these degradation kinetics with the average stress temperatures reported in Table 1, we can notice a strict correlation between the amount of optical power reduction and the temperature reached by the whole lamp during the stress. The heatsinks designed by manufacturer C (and, to a minor extent, by manufacturer B) feature a large number of voids that can enhance the air flow through the bulb body and enhance more effectively the thermal exchange between

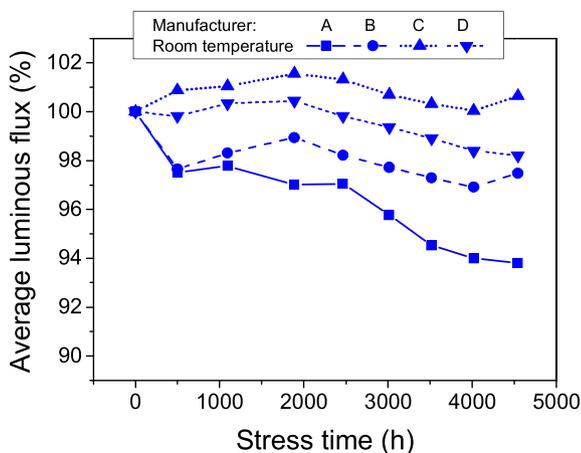


Fig. 1. Output optical power reduction of the light bulbs under test at room temperature.

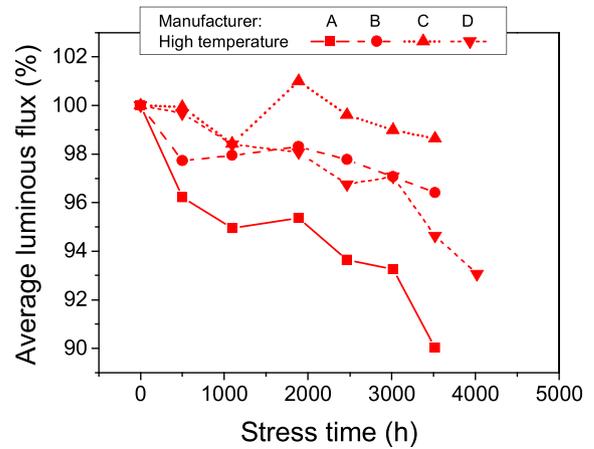


Fig. 2. Output optical power reduction of the light bulbs under test at high temperature.

the hot parts and the external ambient. This reflects in a lower operating temperature, as reported in Table 1, and in a higher reliability (see Figs. 1 and 2), therefore this may be a good design solution in order to improve the lifetime of the system.

4. Diffusive bulb darkening

We detected a progressive darkening of the diffusive bulb over stress time for lamps of manufacturer D. In Fig. 4 an untreated bulb is compared to a dome stressed for 2500 h. Both bulbs are from the same lamp set, in the figure the aged one is smaller because it was cut from the main body in order to expose the underlying LEDs for visual inspection. A variation of the color is clearly visible, which is non-uniform over the dome surface. Since the effect is stronger at the center and weaker at the borders, the degradation is probably related to the short-wavelength radiation flowing through the diffusive bulb, whose intensity is higher in the direction normal to the surface of the LED due to the typical Lambertian emission profile. We can probably exclude temperature as the sole cause, since its highest value can be found at the edges of the dome (see Fig. 3) which are the parts affected the least by the darkening, as reported in Fig. 5.

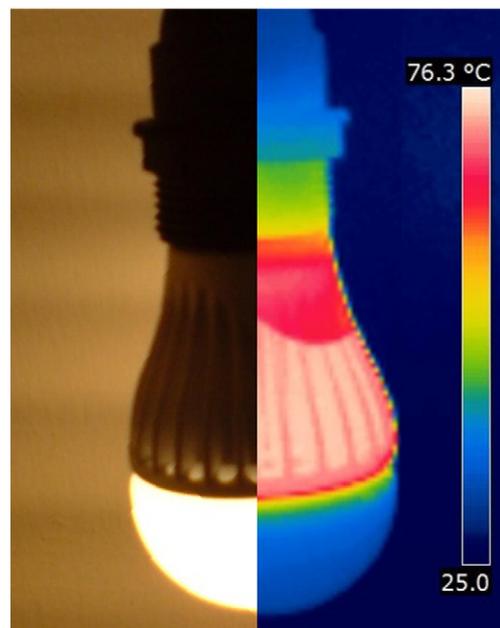


Fig. 3. IR thermogram of a RT light bulb during stress.

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