

# 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

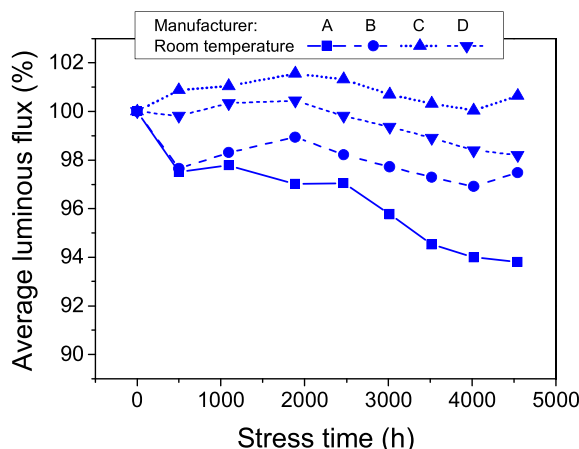


Fig. 1. Output optical power reduction of the light bulbs under test at room temperature.

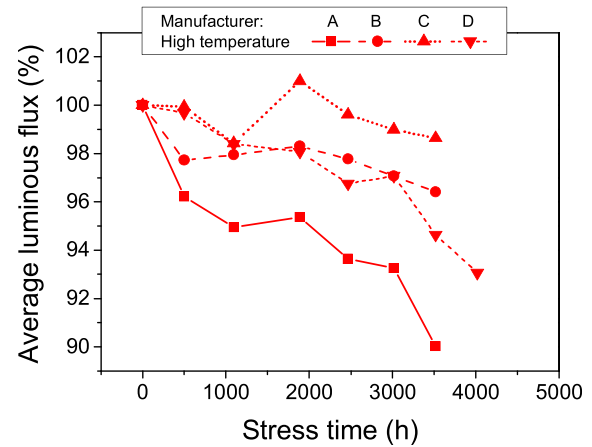


Fig. 2. Output optical power reduction of the light bulbs under test at high temperature.

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.

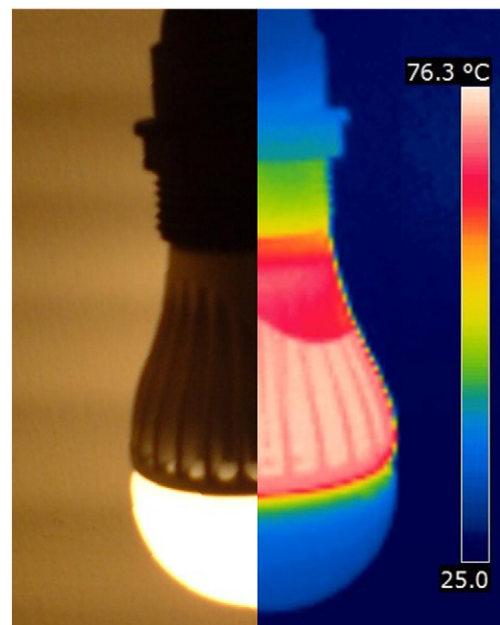
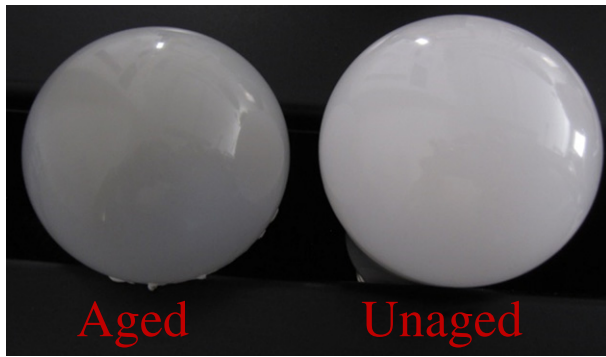


Fig. 3. IR thermogram of a RT light bulb during stress.



**Fig. 4.** Photograph of an unaged and aged (2500 h) diffusive bulb of manufacturer D. Darkening after stress is clearly visible.

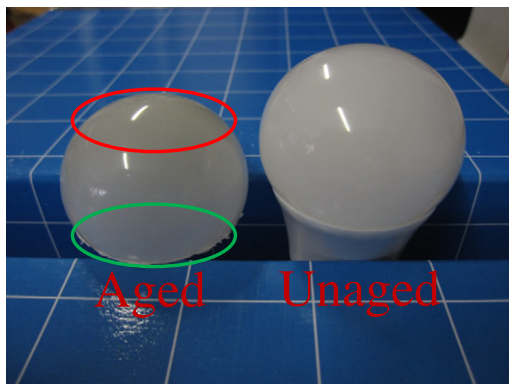
Fig. 6 describes the different amount of transmitted light between a darkened (red region in Fig. 5) and a clear (green region in Fig. 5) part of the same aged bulb under illumination with an Ocean Optics LS-1-CAL radiometric calibration lamp. The use of an external light source prevents any effect related to the LEDs or to their driver. The darkening effectively reduces the transmissivity of the dome and is therefore responsible for (at least part of) the decrease of the luminous flux.

In order to estimate the effect of the darkening on the chromatic properties of the lamp, we normalized the curves of Fig. 6 and the lamp spectrum provided by the manufacturer at their highest value. We can then divide the curves of the two dome parts by the curve of the lamp and obtain the percentage variation of the transmissivity, relative to its maximum value. By subtracting the two relative transmissivities we can estimate the spectral distortion induced by the darkening process, reported in Fig. 7. As can be seen, the degradation of the dome causes not only a reduction of the absolute transmissivity but also a distortion of the transmitted spectrum, leading to a change in the chromatic properties of the lamp.

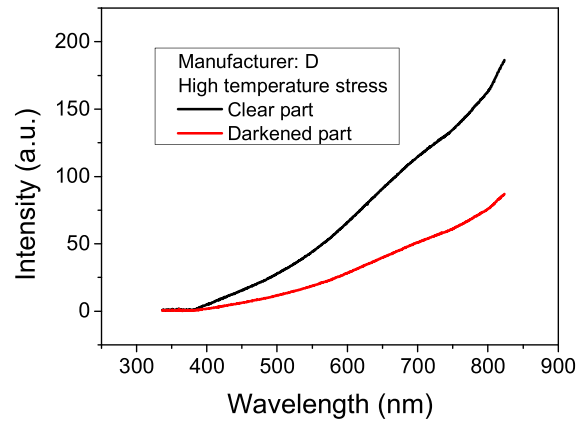
## 5. Chromatic variation

For lamps of group “A”, the most frequent degradation mechanism is the variation of the relative contributions in the output spectra; a representative example is shown in Fig. 8, which indicates that stress induced a variation of the chromatic properties, caused by the faster decay of the emission in the yellow region of the spectra.

This decay may originate from three different mechanisms: a change in the spectral response of the diffusive bulb (see above), the decrease in the phosphor conversion efficiency or the oxidation/darkening of the inner reflector. The diffusive bulb may probably be ruled out, since no



**Fig. 5.** Photograph of an unaged and aged (2500 h) diffusive bulb of manufacturer D. Different amounts of darkening are pointed at by the green oval (low darkening) and by the red oval (high darkening).



**Fig. 6.** Transmitted light in two regions of the bulb with different darkening levels. Light source: radiometric calibration lamp.

relevant darkening is detected in lamps of group “A”, contrary to the case of group “D”. Moreover, we found that its influence is stronger at shorter wavelengths (see Fig. 7), whereas in Fig. 8 the larger variation occurs at longer values.

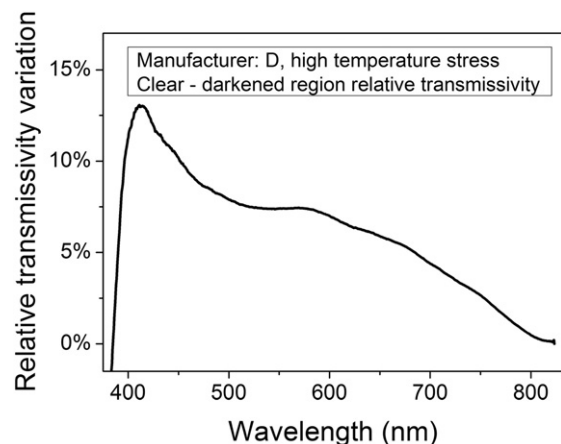
It is important to point out that the emission at 455 nm, which corresponds to the blue chip, does not significantly vary, suggesting that the GaN-based LED remains stable and does not affect the reliability of the system, even at the very high temperatures reached during operation.

Fig. 9 reports the variation of the correlated color temperature (CCT), a quantity describing the equivalent temperature of the black body which most closely resembles the output spectra. Since the yellow contribution is decreasing, the CCT is gradually increasing toward hotter (and then bluish) equivalent black bodies. The increased CCT could be a problem since it produces a “colder” perceived light, which could not be acceptable in home application and lead to the early substitution of a still functioning lamp.

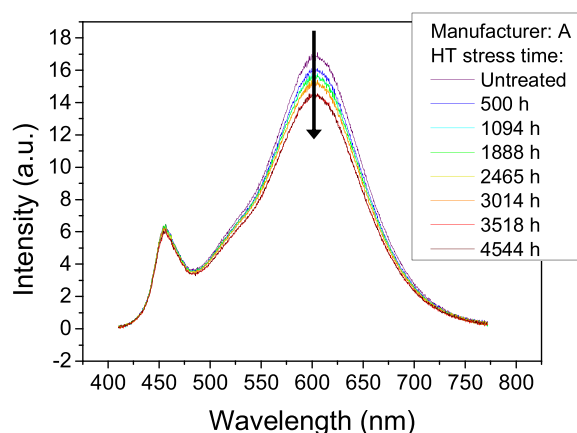
## 6. Driver performance

The last light bulb subsystem which affects the lamp performance is the LED driver, i.e. all the additional circuitry required in order to convert the electrical power drawn at high voltage from the mains to a lower level compatible with the limited maximum operating voltage and current of white LEDs.

In lamps of manufacturer D the output optical power closely follows the variation of the electrical power consumption, as shown in Fig. 10.



**Fig. 7.** Variation of the normalized transmitted spectra comparing two regions of the bulb with different darkening levels. Light source: radiometric calibration lamp.

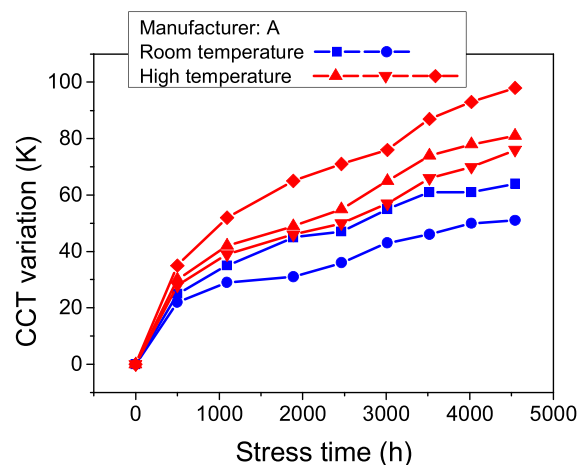


**Fig. 8.** Spectral variation over stress time. The reduction of the yellow peak is responsible for the variation of the chromatic properties, whereas the output of the LED chip (peak at 455 nm) remains stable.

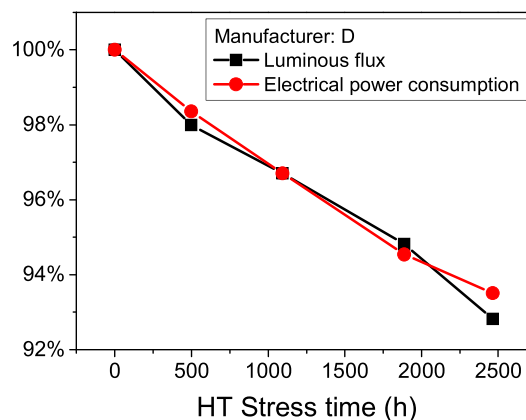
This effect suggests that the reduced emission is not related to a damage of the LED chip or to a change in chromatic properties of the phosphors or diffusive bulb, but depends on a lower amount of electrical power available to be converted into light. The same effect is present also in devices from other manufacturers, but in those cases it is one of the causes for the reduced luminous flux rather than the main degradation mechanism.

In one case the lamp underwent an early failure. Visual analysis of the driver highlighted the driver as the failed part (see Fig. 11). The red oval circles an electrolytic capacitor with a visible crack in the outer insulating layer. This is the usual appearance of damage due to electrolyte evaporation, probably caused by power line surges or electrical overstress. Its burst was so strong as to cause the burning of the encasing material, which appears darkened (red arrow) rather than white as in the other regions. The blue arrow points out the expected color of the filling material when the burned region is removed.

All these problems confirm that, if we take into account the very different voltage levels, the reduced space available and the high operating temperature, proper design of the LED driver is a crucial feature for a reliable light bulb.



**Fig. 9.** Variation of the correlated color temperature during aging. Lamps stressed at high temperature are affected by a stronger degradation.



**Fig. 10.** Correlation between the decrease of the output optical power and the reduced electrical power consumption in one of the light bulbs under test.

## 7. Conclusions

Lifetime tests carried out on commercial retrofit LED light bulbs confirm the important role of the temperature as an accelerating factor for the degradation and of a correct and accurate thermal management in order to avoid damage.

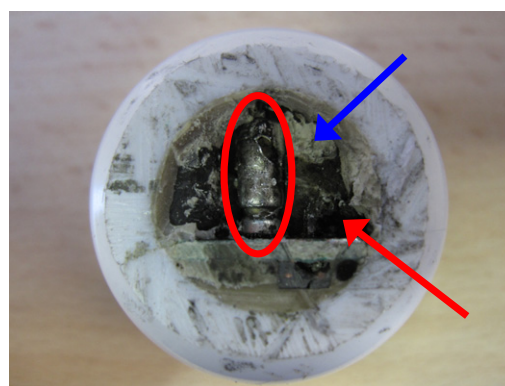
The main mechanisms which can lead to the decrease of the performance are:

- (i) the darkening of the diffusive bulb, that reduces the overall transmissivity of the dome and produces a distortion of the emitted spectrum, therefore altering the perceived chromatic quality;
- (ii) the variation of the chromatic properties of the phosphors and/or of the reflector, which reduces the efficiency of the lamp and causes a strong change in the correlated color temperature (CCT);
- (iii) the alteration of the performance of the LED driver, which can lead to early failures if not accurately designed due to power line surges or electrical overstress.

All these effects concur in limiting the overall reliability of the system, whose expected lifetime is tens of thousands of hours in typical operating conditions.

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**Fig. 11.** Photography of a failed LED driver.

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