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Robustness and reliability of high-power white LEDs under high-temperature, high-current stress

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ABSTRACT

High-power white LEDs for outdoor lighting were submitted to accelerated lifetime stresses to evaluate their robustness and reliability. LEDs featured a 2 mm^2 chip with 2 A absolute maximum current (I_{abs}) at 135 °C junction temperature. A first high-temperature, high-current robustness stress was performed at 1, 1.2, 1.4, 1.6 times I_{abs} for 50 hours. This stress caused a heavy decrease of optical power and a degradation of colorimetric properties of the LEDs stressed at currents exceeding I_{abs}. Optical analysis showed darkening of the phosphors and silicone and cracking of the lens. A second, long-term, stress was performed at 0.8 times I_{abs} at 45, 65, 85, 105 °C. This stress showed almost no lowering in flux for the samples stress at 45 and 65 °C, whereas samples stressed at 85 and 105 °C showed a decrease in flux from 2500 and 200 hours of stress, respectively, estimating a L90 lifetime of 5500 and 1500 hours. xy coordinates shifted proportionally to stress temperature. LEDs stressed at 85 °C and 105 °C eventually failed catastrophically, similarly to the high-current stress, with silicone and phosphors darkening and lens cracking. Raman analysis on high-current stressed LED lenses showed that poly(methyl,phenyl)siloxane was used as lens material. Stress induces higher luminescence of the silicone under Raman analysis. The cause of degradation is attributed to thermomechanical stress (cracking) and high-temperature silicone decomposition (darkening), possibly due to phosphors thermal quenching, causing a hot-spot just above the chip (confirmed by thermography), even if the junction temperature was within manufacturer specifications.

Keywords: LED, solid state lighting, reliability, silicone, failure.

1. INTRODUCTION

Solid state lighting revolutionized the way in which humanity perceive light, since white Light Emitting Diodes (LEDs) enabled to shape the light in ways that were not possible nor thinkable before. From the development of the first Gallium Nitride-based blue emitting diodes to its use, with phosphor-based conversion materials to emit white light, a very big advancement in both reliability and efficiency was made, with LEDs well exceeding efficiency of 150 lm/W and lifetimes of over 50000 hours.

LEDs are nowadays used in many applications, like indoor and outdoor lighting, automotive, as well as specific applications like horticulture and digital signage. However, due to their immersive presence, LEDs strongly impacts on human quality of life and care must be made when choosing the appropriate type of illumination for a certain application. Moreover, the reliability of illuminating system is crucial, since failures can manifest not only with a reduction of the luminous flux, but also with the variation on the colorimetric properties of the light sources, that is noticeable to the naked eye and could have a strong impact on the human perception[1].

In this paper we present the results of a series of stress performed on commercial white LEDs for outdoor illumination at high operating temperatures. We analyze the failures and their root causes by means of various techniques.

2. HIGH-CURRENT STRESS EXPERIMENT

A first experiment was performed of commercial white LED for outdoor lighting, with a die size of 2 mm^2, a nominal Correlated Color Temperature of 4000 K and an absolute maximum current (I_{max}) of 2.0 A at 135 °C junction temperature. 8 LEDs were soldered on the same metal core printed circuit board (MCPCB). The experiment consisted in a stress in which the LEDs were stressed at 4 different currents, 2 LEDs per each current, of 2.0 A, 2.4 A, 2.8 A, 3.2 A, i.e. from 1 to 1.6 times I_{max}, as shown in Figure 1, for 50 hours at 85 °C ambient temperature. Due to measurements issues, the data of only one LED stressed at 2.0 A is available, whereas for other conditions both LEDs data are available.

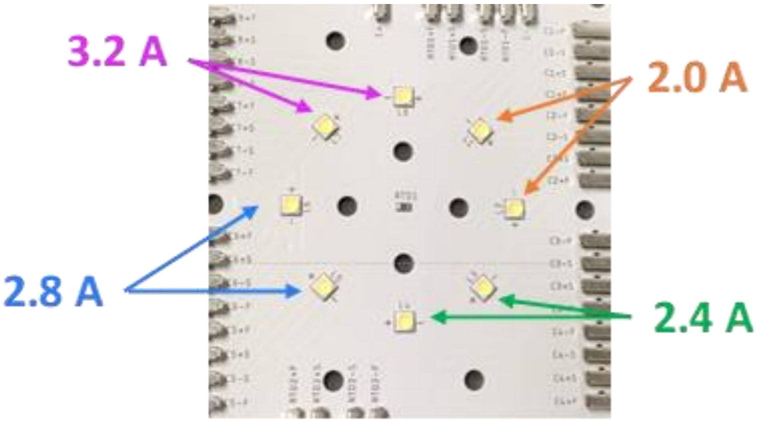

Figure 1 MCPCB with LEDs mounted and currents used for the step-stress experiments. 4 identical PCBs were used for long-term stress, all stressed at 1.6 A.

The LEDs were characterized by electrical measurements (not shown here) by a Keysight B2912A parameter analyzer and powers spectral density by means of a 65'' integrating sphere (LMS-650 by Labsphere) and an Ocean Optical USB2000+ spectrometer. The results of the measurements are shown in Figure 2: the LED stressed at I_{max} show almost no degradation in its optical power, whereas LEDs stressed at higher currents show a strong decrease in their optical power with a slight dependance on stress current.

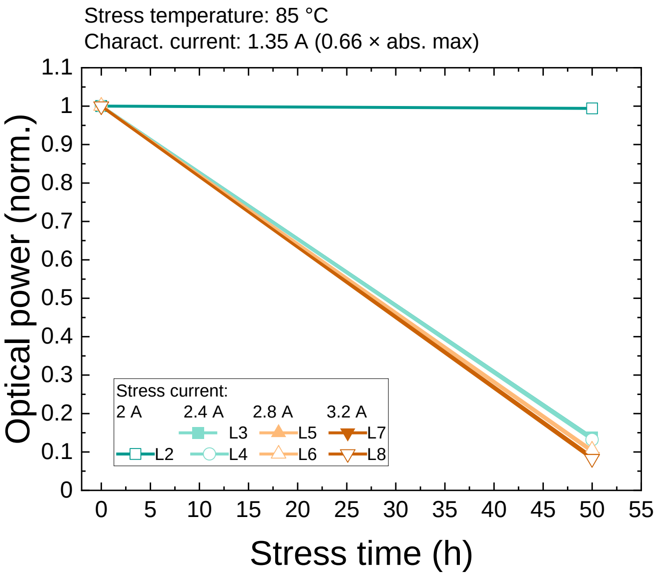

Figure 2 Optical power of the LEDs at the beginning and at the end of 50 hours high-current stress.

Colorimetric parameters were also evaluated by analysis of the PSDs (not shown here) and CIE 1931 xy coordinates were calculated and reported in Figure 3. It is possible to see that the LED stressed at nominal current has a small shift of the coordinates, whereas other LEDs have major shifts in different directions of the chromatic diagram.

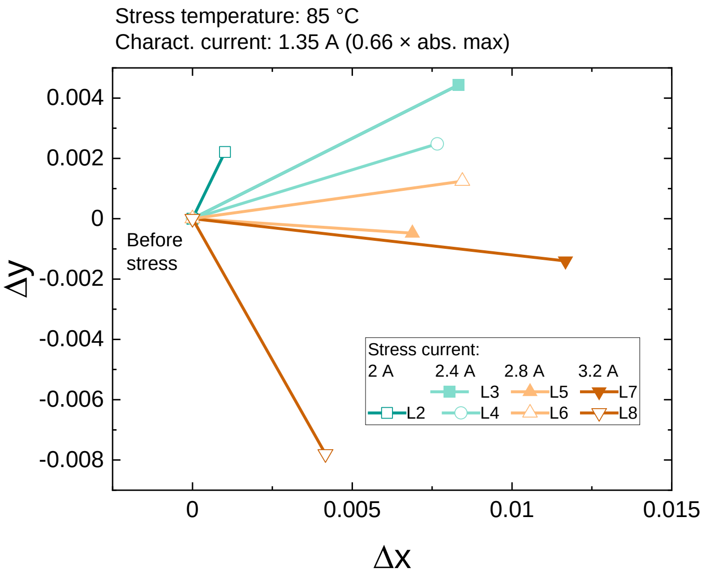

Figure 3 Shift of the CIE 1931 xy coordinates of the LEDs after stress with respect to the unstressed LEDs.

The reason of these heavy changes in optical power and chromatic shift is clear by looking at Figure 4: the LEDs stressed at currents higher than absolute maximum exhibit a heavy darkening of the lens, almost independent from the stress current. Some devices were cross-sectioned to obtain an image of the device. From this analysis, it is clear how the silicone darkened near the phosphors layer, and this layer itself detached from the die.

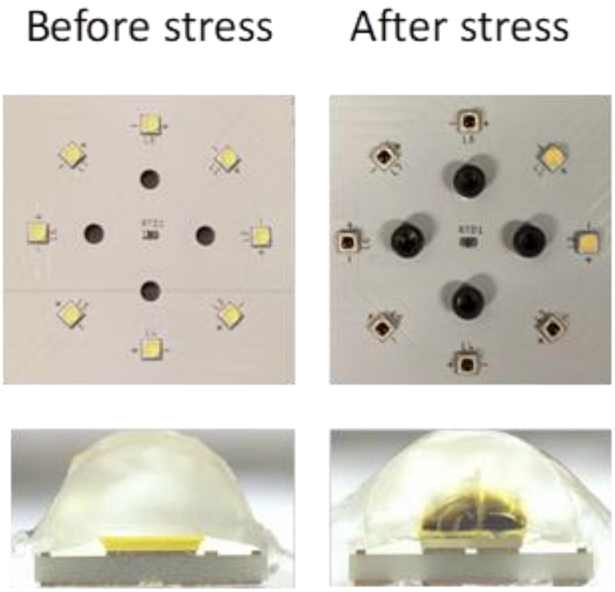

Figure 4 Optical images of the LEDs on the PCB before and after stress (top) and cross section of one unstressed LED and of one LED stressed at 2.8 A (bottom).

Raman spectroscopy was performed on the silicone dome lens to understand the type of material and the degradation mechanism and it is reported in figure Figure 5. Raman analysis was performed by means of a 785 nm laser (Sol instruments) and a MS750 series Monochromator-spectrograph at room temperature. By the spectra of the unstressed LED it is possible to understand that the silicone is a poly(methyl,phenyl)siloxane due to the presence of phenyl group peaks at 1000 cm^{-1} and 1030 cm^{-1} [2–4]. LED stressed at 2.0 A, that does not exhibit optical degradation, has a Raman spectrum nearly identical to the unstressed LED, confirming that silicone did not degrade. LED stressed at 2.4 A exhibit a strong increase in luminescence, that partially hide the Raman peaks.

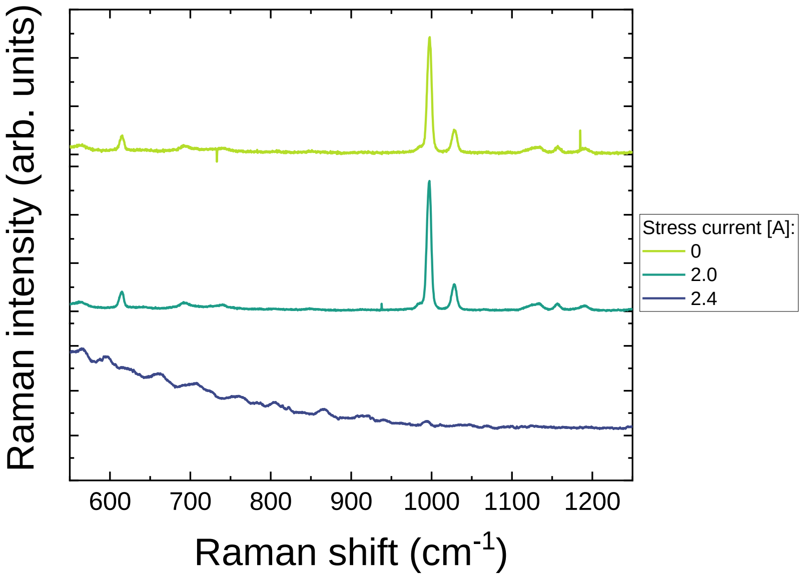

Figure 5. Raman spectra of the silicone of LEDs unstressed, stressed at 2.0 A and stressed at 2.4 A.

3. LONG TERM STRESS

Having noted that currents (even slightly) higher than absolute maximum caused LED catastrophic degradation, a long-term stress at a moderate current (1.6 A, i.e. 0.8 times I_{max}) was performed at 4 different temperatures of 45 °C, 65 °C, 85 °C, 105 °C, on 4 different PCBs of the same type shown in Figure 1, with 8 LEDs per PCB to have a statistical significance. Junction temperatures were evaluated by forward voltage mapping method[5] and ranged from around 95 °C to around 155 °C. The optical power measured during the stress is reported in Figure 6. It is possible to note 3 different behavior: a plateau region, shown by devices stressed at 45 °C and 65 °C during the whole stress and by the devices stressed at 85 °C up to around 3000 hours; a gradual degradation of around 15 %, shown by devices stressed at 85 °C from 3000 hours to 7000 hours and by devices stressed at 105 °C from the beginning of the stress up to 2000 hours; a third phase of catastrophic degradation, similar to the one observed during the high-current stress, at 2000 hours for the stress at 105 °C and at 7000 hours for the stress at 85 °C. Note that only 4 LEDs out of 8 stressed at 85 °C failed catastrophically: this can be seen by looking at the very large error bar, due to the two populations of (almost) undegraded and degraded LEDs.

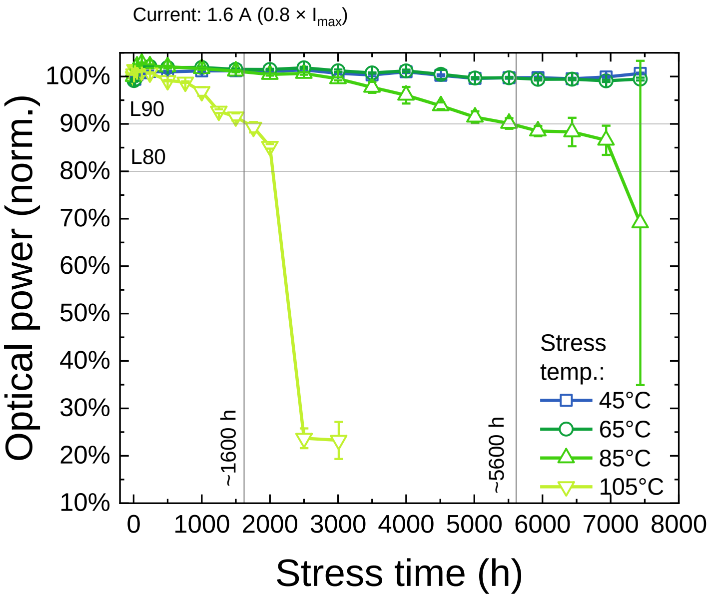

Figure 6 Optical power measured during long term stress. The error bars represent the standard deviation of the 8 LEDs..

Similarly to what observed during the high-current stress, also colorimetric properties (reported in Figure 7) are affected by degradation: LEDs that did not fail have a slight shift toward yellow-green region of the diagram, whereas LED stressed at 105 °C have a blueshift.

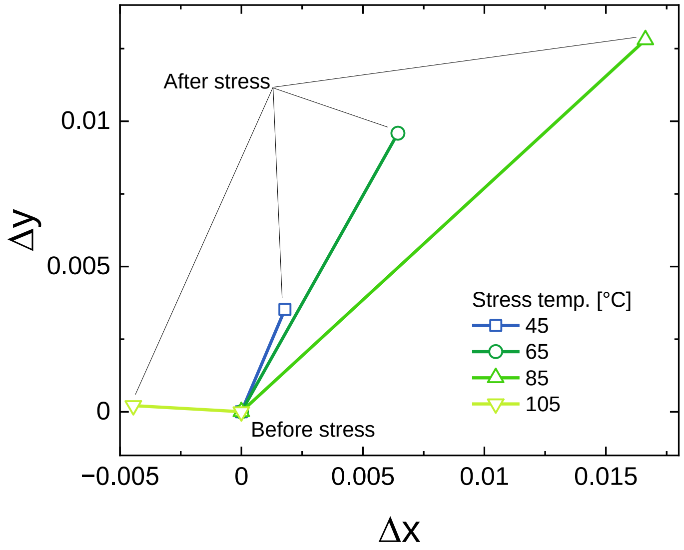

Figure 7 Shift of the CIE 1931 xy coordinates of the LEDs after stress with respect to the unstressed LEDs.

4. ANALYSIS OF DEGRADATION

By analyzing the outcomes of the high-current stress and of the long term stress it is possible to hypothesize several mechanisms that concurred to LED failures. During high current stress, high temperatures due to the very high currents possibly initiated silicone thermal degradation mechanisms, maybe eased by the lowering in efficiency of the phosphors at high optical powers[6,7]. In particular, it is reported that a typical silicone degradation pathway is the phenyl group decomposition due to Si-O bonds breaking and formation of cyclic oligomers at temperatures higher than 150 °C[8,9], and, at even higher temperatures, the breaking of Si-phenyl bounds and thermal oxidative degradation clearly visible with the darkening[10].

During long-term stress, these phenomena take place during a long amount of time. In particular, at 45 °C and 65 °C stress ambient temperatures silicone temperature is not sufficient to initiate degradation. At higher ambient temperatures, the (relatively) low temperature degradation takes place. This leads to a decrease in optical power emitted by the LED due to increased absorption, that in its turn increases silicone temperature in a runaway process that eventually leads to the conditions to initiate higher temperature degradation processes, causing the darkening of the silicone and the failure[11–13]. An additional increase in temperature due to solder degradation during the stress could be investigated in future works.

5. CONCLUSIONS

Commercial LEDs for outdoor lighting were analyzed at high currents and during a moderate current, long term stress experiment. During the high current stress at 85 °C ambient temperature, LEDs stressed at currents higher than absolute maximum rating failed after 50 hours with a strong decrease in optical power and a visible darkening of the lens. LEDs were then stressed at a current lower than absolute maximum at 4 different ambient temperatures. LEDs stressed at 45 °C and 65 °C were almost undegraded, whereas LEDs stressed at 85 °C and 105 °C catastrophically failed after 7000 and 2000 hours, respectively. Cross section of the devices showed phosphors delamination and silicone darkening. By Raman spectroscopy the silicone material was determined to be poly(methyl,phenyl)siloxane, that has several degradation mechanisms at different temperatures. High current stress (higher than absolute maximum) causes very high temperatures that lead to a fast thermal degradation of the silicone, along with phosphors delamination due to thermomecanical stresses. Long term stress leads to the activation of a first low temperature degradation mechanism, that causes increased absorption and in its turn increases silicon temperature, eventually ending in catastrophic failure of the device.

These experiments highlight the importance of using LEDs in the proper conditions, even if they are commercial state-of-the-art devices, since optical materials are rather delicate and an improper design of the solid state lighting system could lead to reliability issues in a relatively short timeframe.

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