Long-term degradation mechanisms of mid-power LEDs for lighting applications

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ABSTRACT

This paper reports the results of a reliability investigation performed on four different groups of commercially available mid-power white LEDs. In order to determine the robustness of this continuously growing class of lighting devices we arranged an experiment of accelerated aging: the four groups of LEDs (from different manufacturers) were submitted to a series of stress tests in environmental chambers with set-point temperatures ranging from 45 °C to 105 °C, in accordance to the IES LM-80-08 lumen maintenance measurement standard. The experimental data gathered all along the 4000 h of stress accumulated up to now suggest the presence of multiple degradation mechanisms that may limit the useful lifespan of the light-emitting diodes under test. In particular we observed the following phenomena: i) a decay of the luminous flux; ii) an increase in the reverse and forward leakage current; iii) the worsening of the chromatic properties of the emitted light; and iv) the presence of a thermally activated degradation mechanism. The results provide a first insight into the reliability of those widely used LEDs; the results on the temperature-dependence of the degradation kinetics can be used as a guideline for the thermal design of modern distributed-light lamps.

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1. Introduction

Over the last years, Solid State Lighting (SSL) gained a considerable market share over conventional light sources like halogen, incandescent or Cold-Cathode Fluorescent (CCF) lamps. Thanks to the superior lifetime, efficiency and color rendering capabilities of GaN-based white light-emitting diodes (LEDs), this lighting approach is set to be the reference standard for the nearest future.

A modern LED lamp designed for general lighting purposes usually features a small number of High-Brightness devices (HB-LED) located in an appropriate frame, whose structure and material composition are the result of rigorous thermal and optical analyses finalized to maximize both the heat and light extraction from the source devices. Typically, these are state-of-the-art LEDs, supported by a solid background of reliability studies and equipped with a thermally advanced (ceramic) package. In the last few years, however, the need for cost reduction and for a simpler design of distributed light systems pushed towards the implementation of the so-called mid-power LEDs in place of the less cost-effective HB devices.

Those mid-power LEDs, whose (electrical) power rating ranges from 0.2 to 0.5 W, generally offer a good trade-off between lumen output and cost. This comes at the price of a reduced thermal and optical design of the package, which usually features a plastic housing that lacks of an optical element and, in some cases, of a dedicated thermal pad. Thus, despite the lower power dissipation, the increased sensitivity of this class of LEDs towards environmental temperature may turn out to be a major reliability issue.

The aim of this paper is to analyze the degradation mechanisms that limit the reliability of mid-power LEDs subjected to a high-temperature operating regime. To this aim, we arranged an accelerated aging experiment which revealed the following phenomena: 1) a strong and generalized decay of the luminous flux for junction temperatures above 120 °C; 2) an increase in the reverse and forward leakage current; 3) the worsening of the chromatic properties of the emitted light; and 4) the presence of a thermally activated degradation mechanism.

The experimental results reported below and the proposed interpretation represent the first attempt to address the reliability of this rapidly emerging class of white LEDs; this topic is not covered by previous literature reports.

2. Experimental details

The mid-power LEDs analyzed within this paper have been selected based on the following criteria: a color temperature of 3000 K, a nominal current of 100 ± 20 mA and a Color Rendering Index (CRI) > 80. Four families of LEDs (which from now on will be referred to as groups A, B, C and D) fabricated by four different leading manufacturers were chosen. Three of the four groups (namely A, B and C) were selected within the highly popular 5630 (5.6 × 3.0 mm) class of mid-power LEDs, while the fourth one, group D, presents a smaller-sized package (2.0 × 0.8 mm) inherited from the typical devices designed for backlighting purposes.

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Four single devices of each group were connected in series on a MCPCB (Metal-Core PCB) which was tightly anchored to an aluminum heatsink; a thin graphite layer served as thermal interface material. The peculiar series connection was adopted to provide a good signal-to-noise ratio during L–I measurements performed with our optical characterization setup, which will be described later on. The electro-optical characterizations were carried out on the whole series, therefore only one effective sample per group and per stress condition was analyzed.

3. Thermal characterization and stress conditions

In order to define the thermal behavior of the four different LEDs’ families under analysis, we carried out a complete thermal characterization on untreated samples. The junction-temperatures were estimated following the diode’s “forward voltage method” proposed by Xi and Schubert [1]. The results, summarized in Fig. 1, show the following facts: a) a quite good thermal resistance for the 5630 package-based samples (specific values range from about 9 to 20 °C/W); b) a thermal disadvantage of D group’s LEDs, due to the absence of a dedicated thermal pad and the reduced thermal design of the device; c) an almost linear relationship between environmental stress temperature and junction-temperature, whose maximum value of 152 °C is reached from group D samples stressed at Tamb = 105 °C. For this stress temperature, the four families of devices were operating outside the SOA (Safe-Operating Area) for Tj advised from the manufacturers (see Table 1).

Together with electrical over-tress (EOS) events [2], the elevated temperatures reached by modern GaN-based light-emitting diodes during operation are still the major limiting factor for their long-term reliability [3], both at chip or at package level. With the aim of testing the robustness of the mid-power LEDs under analysis against thermally activated and/or current driven degradation mechanisms, the devices were actively stressed at nominal current inside climatic chambers whose temperatures were set at 45, 65, 85 and 105 °C. The stress cycles were regularly interrupted in order to perform a complete electrical and optical characterization. For the latter we exploited a fully power and wavelength-calibrated setup constituted of a 65″ large integrating sphere (model LMS-650 from LabSphere) fiber-coupled to an Ocean Optics USB2000+ spectrometer. A Keithley 2614B source-meter provided the polarization for the samples. On the other hand, the voltage–current characteristics were measured through an HP4155A parameter analyzer, whose accuracy, even if affected by the non-ideal connection system used, let us spot current variations down to the pA range (see Fig. 4).

The measurement and stress methodologies described above fulfill the common IES LM-80-08 lumen maintenance measurement standard.

4. Results of the accelerated aging experiment

The degradation kinetics of the analyzed LEDs are reported in Fig. 2. Linear lifetime extrapolation for a 10% decrease of the output flux produced expected values of useful device life between 2500 and 5000 h: considering that a common market requirement for a TTF70% (usually referred to as L70) stands around 40,000 h, we can state that our
samples, probably, are not suited to be operated at junction temperatures above 120 °C, which, as already pointed out, is the average upper bound of the SOA for the LEDs under test. The aforementioned lifetime values are intended to be used only for the evaluation of activation energies, not for an accurate estimation of the expected lifetime of the device: not only this would require more data points, i.e. more hours of stress, but also a more sophisticated extrapolation algorithm, like the widely adopted IESNA TM-21.

As we can see from Fig. 3, the kinetics of flux decay are highly temperature dependent, which suggest the presence of a temperature activated degradation process. Nonetheless, the luminous flux trends provide a useful guideline for an appropriate design of the lamp thermal management, which should guarantee a maximum junction-temperature below the extrapolated critical level. In order to identify the physical mechanisms responsible for the flux decay, a deep investigation about the degradation of the chromatic and electrical characteristics was carried out. For the LEDs of group A, the increase in forward leakage current shows an approximately linear correlation with the flux decay, as reported in semi-log scale in Fig. 6.

Since one of the main electronic transport processes in the low forward bias region is trap-assisted tunneling [4], and since the rate of non-radiative recombination is directly proportional to the concentration of defect-related deep-levels inside the energy gap, the experimental data suggest the presence of an ongoing process of crystal defect generation inside the active region of the device. The observed phenomenon showed a remarkable temperature dependence.

Another relevant variation of the current–voltage characteristic was exhibited by D group LEDs (Fig. 5). The reverse leakage current of those devices experienced a temperature-dependent increase over time. Since leakage current strongly depends on the density of defects, a gradual worsening of crystal quality is to be expected [5,6].

Moreover, in the forward conduction region, those LEDs registered a maximum increase of the forward voltage of about 63 mV, well above the average 30 mV gained from the other samples under analysis. The forward voltage increase was found to be temperature dependent and well correlated with the gradual rise of the series resistance, as shown in Fig. 7. This suggests a partial degradation of the ohmic contacts and/or a resistivity increase of the quasi-neutral regions due to the high current density [7] and temperature of the operating regime. Such behavior, which may be the result of a “current-crowding” phenomenon [8], is critical when LEDs are employed in modules, where the voltage increase of a single device lowers the limited voltage headroom of the current driver by an amount nVF, where n is the number of devices in series.

Group D LEDs suffered from a noticeable chromaticity shift, which, for instance, led to a maximum 55 K increase of the CCT point within the whole 4000 h period of aging. The chromatic degradation process takes place mostly during the first stress hours, after which the yellow to blue emission peak ratio suddenly slows its decay. This phenomenon is clearly visible in Fig. 8. A similar behavior, but with different time...
constants, was experienced from the samples stressed at lower temperatures (Fig. 10): the strict correlation between stress temperature and the kinetics of the observed chromatic shift suggests the presence of a thermally activated degradation process, which probably involves the plastic package [9], the yellow phosphors [10] or the encapsulating material [11].

The simultaneous presence of a high-temperature environment (>100 °C) and of a low-wavelength optical radiation is a well-known condition that triggers both the decay of the phosphor conversion efficiency and the worsening of the optical properties of the polymeric encapsulants. As a matter of fact, those materials tend to assume an amorphous phase above their "glass-transition" temperature (Tg), which not only promotes the discoloring by VOCs (Volatile Organic Compounds) but also reduces their optical transmissivity in the low-wavelength range. Since our samples did not seem to suffer from this "red shift", and since the power-normalized spectra of untreated samples showed a remarkably different phosphor composition for D group LEDs, the "blue shift" of the chromaticity point, which affected in a relevant way only the aforementioned devices, is probably due to a conversion efficiency loss of the phosphor species.

One last package-related degradation mechanism, which was not considered so far, is the tarnishing of the Ag reflective coating [12]. This metallic layer, covering the lead frame and/or the plastic housing, is usually employed in mid-power LEDs in order to increase the overall light extraction efficiency. However, sulfur and chlorine-rich pollutants, released from different sources, may diffuse through the silicone encapsulant and react with the Ag atoms, forming Ag2S and AgCl complexes. This may lead to an unrecoverable chromaticity shift and/or a decay of the emitted optical power. In order to evaluate this hypothesis, we de-processed the stressed samples with a depolymerizer agent and compared them with untreated samples. Visual inspection did not reveal any particular sign of sulfurization, though in-depth analyses, like EDS, may provide us more accurate results.

Inspection of the de-processed devices belonging to the other three groups did not reveal proofs of degradation either, except for the samples of group A. As we can see in Fig. 11, those two-dice based LEDs showed a little darkening of the chip area near the lower surface contact. While this may be an evidence of an ongoing current crowding process, no correlation with the (slight) forward-voltage increase was found.

As additional analysis, we tried to estimate the activation energies of the registered lumen decay processes. From the L90 lifetime data, we extrapolated energy values of the degradation process ranging from 0.38 to 0.6 eV. The Arrhenius plots, reported in Fig. 12 for group C devices, did not show any bending for high temperature values, which suggests that no new processes were activated for junction-temperatures above 120 °C.
5. Conclusions

In summary, within this paper, we have presented the first extensive study of the degradation mechanisms of mid-power white LEDs. The results allowed us to identify the following degradation processes: generation of defects within the active region of the devices, worsening in the optical properties of the package/phosphor system, and the degradation of the electrical characteristics of the devices. The degradation process was found to be thermally activated with activation energies in the range from 0.38 to 0.6 eV.

References


Fig. 12. Arrhenius plot of the 90% TTF (Time To Failure) for C group’s LEDs. The failure criterion, which corresponds to a 10% decrease of the luminous flux at nominal current, has been chosen in order to guarantee the best possible coherence between the (linearly) extrapolated lifetime and the experimental data acquired so far, whose linear fit is represented by the red line showed above.