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Early degradation of high power packaged LEDs under humid conditions and its recovery — Myth of reliability rejuvenation

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ABSTRACT

A sharp rise in lumen degradation was observed for packaged high power LEDs during the initial period of operation under high humidity and temperature conditions, and the degradation reaches a peak value, followed by a "recovery" in lumen output, a sign of reliability rejuvenation. The time to reach the peak degradation is shorter with higher relative humidity. Scanning acoustic microscopy (SAM) tomography is employed to study the effect of moisture at different time intervals. With the help of moisture diffusion modeling using ANSYS simulation, the phenomenon is found to be due to the increasing moisture absorption of silicone resulting in subsequent light scattering as light is emitting from the dice. The "recovery" is the result of moisture absorption by die attach material that sucks the moisture from the silicone. Thus the "recovery" of lumen degradation is actually associated with the degradation in the internal structure of the LED package which is not reversible. C-SAM results are in accordance with the simulation and experimental results. The implication of this finding on temperature–humidity test of high power LEDs is described, and the material parameters of silicone to reduce this initial degradation are also presented.

1. Introduction

High power LEDs are widely used in today's solid state lighting due to their high efficiency and longer lifetime, and their applications are expanding, with increasing applications in outdoor usage and marine industry. However, the lifetime for these LEDs in later applications seems to be much shorter [1].

While many works have been reported relating to LED degradation due to high temperature conditions or high junction temperature, and standards such as LM-80 and TM-21 have been established to evaluate the thermal stability of these high power LEDs, very few works are done on moisture related to LED degradation, and the test standard to evaluate their humidity reliability remains to be the industry's IPC/JEDEC standard J-STD-020D [2–4] which was developed for integrated circuits. Tan and Singh [5–6] reported that such JEDEC standard is not applicable to the study of humidity reliability of LEDs as the degradation mechanisms of LEDs at 85% RH and 85 °C are very different from the mechanisms under normal operating conditions.

Furthermore, in contrast to integrated circuits, rapid degradation of lumen during the early lifetime was observed for LEDs under humid conditions, and it was attributed to the moisture absorption of silicone and the subsequent light scattering by the entrapped moisture in silicone [7]. We perform similar experiments and find that such lumen degradation is actually recoverable as will be reported in this work. The physical principle underlying this recovery will be presented in this work, and the finding provides implication to the humidity reliability testing of high power LEDs.

2. Experimentation and results

The humidity test set-up and the measurement details can be found in the work of Tanand Singh [5]. A total of 40 high power packaged OSRAM golden dragon white LEDs are placed in a high temperature–humidity chamber (μ series from Isuzu) for accelerated life testing. The temperature of the chamber is kept at 85 °C while two RH levels, 95% and 85%, are used with a sample size of 20 at each RH level.

The measured luminous flux is tabulated versus time for all the LEDs and the percentage of luminous flux degradation versus time is plotted as a box plot curve for the 2 sets of LEDs at 95% RH and 85% RH respectively as shown in Figs. 1 and 2.

It is interesting to note that all the LEDs experienced a sharp decrease in the percentage luminous flux during the initial stages of testing, consistent with the previous work reported [7]. However, we also observe that the percentage luminous flux degradation reaches a peak value, and the degradation recovers thereafter. This initial lumen

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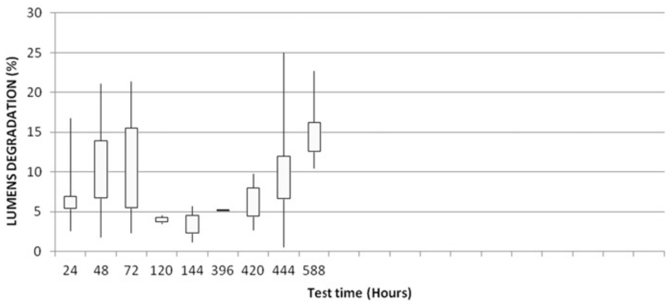

Fig. 1. Percentage luminous flux degradation vs time for the 95% RH set of LEDs.

degradation reaches peaks at 120 and 72 h for samples under 85% and 95% RH respectively. The peak degradation level is also higher at the higher RH condition.

As it was reported that the initial lumen degradation is due to the light scattering by the entrapped moisture particles in silicone, we would like to investigate the mechanism of the observed lumen recovery. Finite element modeling of moisture diffusion into the LED package is employed in this work for such investigation. However, before we employ finite element modeling, the possible number of degradation mechanisms must first be identified.

3. Identification of number of degradation mechanisms through a statistical technique

Akaike information criterion (AIC) [5,6,8–10] is employed to find the number of possible failure mechanisms during the initial degradation and at the end of the recovery stage. Simulated annealing (SA) in conjunction with the expectation–maximization (EM) is used to determine the probability of each unit belonging to each failure mechanisms. The detail of the method and its successful applications can be found in Refs. [5,8–10].

From the statistical method, we found that there is only one degradation mechanism in each stage as seen in Tables 1 and 2.

The shape parameters of the statistical distributions for the degradation mechanisms during initial degradation and at the end of recovery stage respectively are shown in Table 3, and it is clearly observed that the shape parameters are having different values, indicating that the two degradation mechanisms in the two stages are different as expected.

Knowing that there is only one degradation mechanism in each stage, we are ready to explore in-depth the physics of the degradation mechanisms at the two stages.

Table 1
Time to reach maximum initial degradation before recovery stage for each LED under 95% RH/85 °C and the probability of each unit that belong to the degradation mechanism. Unit # is arranged according to the increasing time to initial degradation.

Unit #	TTF (time to failure)	Inlier (I)/outlier (O)	Pr (FM 1)
4	24.00	I	1
5	24.00	I	1
8	24.00	I	1
10	48.00	I	1
12	48.00	I	1
13	48.00	I	1
15	48.00	I	1
17	48.00	I	1
1	72.00	I	1
2	72.00	I	1
6	72.00	I	1
9	72.00	I	1
11	72.00	I	1
14	72.00	I	1
19	72.00	I	1
20	72.00	I	1
16	96.00	I	1
18	96.00	I	1
3	120.00	I	1
7	144.00	I	1

4. Formulation of finite element modeling for moisture diffusion

A 2D finite element model is created using mechanical ANSYS 14 Parametric Design Language (MAPDL) software as shown in Fig. 3. The molding compound is silicone which is shown by the light blue color in Fig. 3. Red color represents LED die, and in between the LED die and copper (at the bottom) is the die attach which is shown as dark blue color. Bonding wires of the package is ignored for simplicity as they are believed to be not affecting the principle of lumen degradation recovery.

After the meshing of the 2D design, the material properties are assigned to each component of LEDs. The three most important parameters for the diffusion modeling are the moisture diffusivity D, moisture saturation concentration C_{sat} and moisture absorption and desorption times.

The moisture diffusion in water permeable body is given as [12]

$$\partial C/\partial t = D\left(\partial^2 C/\partial x^2 + \partial^2 C/\partial y^2 + \partial^2 C/\partial z^2\right). \quad (1)$$

As this equation is analogous to the heat diffusion equation, finite element modeling of moisture diffusion is usually done using thermal diffusion model with the following changes in the modeling parameters shown in Table 4 as derived and presented by Ma et al. [11].

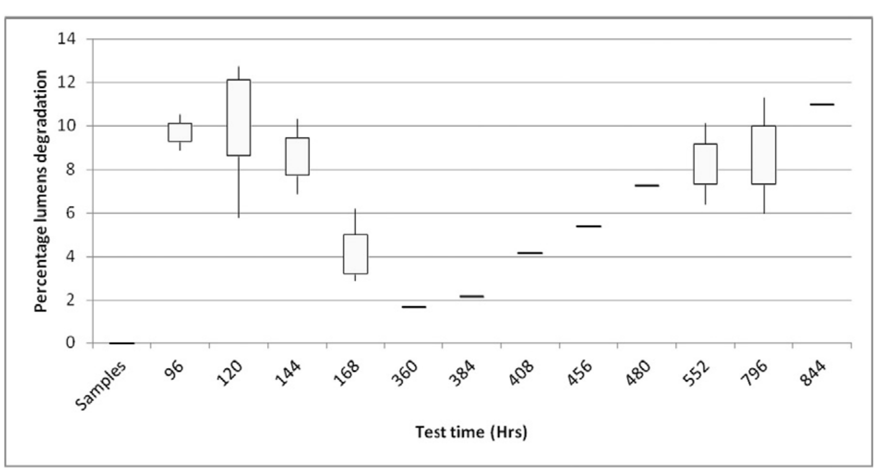

Fig. 2. Percentage luminous flux degradation vs time for the 85% RH set of LEDs.