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Humidity Effect on the Degradation of Packaged Ultra-bright White LEDs

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Abstract

Many ultra-bright light-emitting diodes (LEDs), especially the white LEDs, are being actively developed for solid-state lighting and many other commercial applications. Hence, it is important to evaluate and understand the failure mechanisms that affect the performance characteristics and lifetimes of these new LEDs. This study concerns the humidity effect on the degradation of GaN-based packaged white LEDs.

Under the accelerated humidity test, the LEDs showed a degradation of optical output. With the mixture statistical distribution analysis method, it is noted that the luminous flux degradation of the packaged white LEDs is dependent on more than two failure mechanisms. Two of the failure mechanisms are observed to follow the lognormal distribution. With detailed spectrum analysis and by employing the parameters extraction method, one of the two failure mechanisms that follow the lognormal distribution is observed to be caused by chip related failure due to the accumulated moisture in the encapsulation. For the other failure mechanism, phosphor degradation is noted to be the primary cause.

Introduction

LEDs are basically p-n junctions that produce light via a process called electroluminescence when electrical current is applied in the forward direction of the devices. Electroluminescence is the result of radiative recombination of electrons and holes in and near the semiconductor p-n junction. Today, the luminous efficacy of state-of-the-art high power LEDs has exceeded ~150 lm/W and for comparison, a conventional 60-100W incandescent lightbulb produces only about 15 lm/W, and standard fluorescent lights produce up to 100 lm/W [1]. Hence, solid-state lighting is now emerging as a energy efficient alternative technology to the conventional lighting source.

The very first solid-state LED was demonstrated approximately 100 years ago by Henry J Round, a British electrical engineer, while studying "cat's whisker rectifiers" fabricated from carborundum (an impure form of polycrystalline SiC). He discovered the emission of a remarkably broad range of colors including orange, yellow, green and blue from the region of the semiconductor near the metal point contact [2]. However, it was not until 1962 when the first practical LED made of a compound semiconductor alloy, gallium arsenide phosphide GaAsP, was developed [3]. Since then, compound semiconductors have provided the foundation for the commercial expansion of LEDs. The advances in material sciences then made possible the production of devices with ever-shorter wavelengths, producing light in a variety of colors.

Today, the most promising applications of high power solid-state LEDs is to produce white light with a broad spectrum. Generally, there are two methods of producing

white light using LED. One is to use individual LEDs that emit three primary colors – red, green, and blue. The other is to use a phosphor material to convert monochromatic light from a GaN-based chip to white light.

The white LEDs fabricated from GaN-based chips combined with yellow phosphors ($(Y_{1-a}Gd_a)_3(Al_{1-b}Ga_b)_5O_{12}:Ce^{3+}$ (YAG)) are commercialized in 1996 [4]. These phosphor-based white LEDs represented an innovation in solid-state lighting because they are very small, lightweight, having a long lifetime and are easy to operate. However, the luminous efficiency of the first white LEDs is only 5 lm/W at a forward-bias current of 20mA [5].

Today, the advances in material sciences, design and fabrication techniques have enabled white LEDs with lumen output that is sufficient to challenge traditional light sources in a number of applications [6]. Though these phosphor-based LEDs have led to a solid-state replacement of the fluorescent lamp, they have lower quantum efficiency and other phosphor-related degradation issues as compared to the complete conversion approach that uses a variety of independently controlled primary colored LEDs [7].

Most importantly, the phosphor-based white LEDs have yet to demonstrate the property of longevity, on the order of 50,000-100,000 hours, which is one of the key features of LEDs that has attracted the lighting community to this technology [8]. Although many studies have investigated the degradation of GaN-based LEDs and several research works have indicated that there is a set of physical mechanisms that may limit the reliability of GaN-based LEDs with respect to their lifetime values imposed by the application market, very few studies have actually studied the degradation of phosphor-based package white LEDs [9]. Based on the few conducted, epoxy yellowing caused by excessive heat at the p-n junction is cited as the primary reason for the rapid degradation of light output [10-11].

Similar to any other optical and electronics components, the packaged white LEDs are subjected to moisture containing environment in many of their applications. However, few works have been reported on the study of the moisture effects on packaged white LEDs, despite the fact that humidity test is common to all the packaged integrated circuit. In this work, the high temperature-humidity (85°C - 85% RH) aging test based on industry IPC/JEDEC standard [12] is used to evaluate the reliability of the packaged white LEDs with respect to their optical output properties.

Experiment Procedure

To examine the humidity effect on the degradation of the phosphor-based GaN LEDs, 24 units of commercial packaged ultra-bright white LEDs, each of power rating of 1W, are used. A major disadvantage with such high brightness LED is its tremendous heat dissipation. Hence, special attention to the thermal management is required to ensure a reliable and

successful experiment. Shown in Fig. 1, each of the packaged white LEDs is first attached to a 20mm × 20mm × 1mm copper heat sink base via thermal silver paste, cured at 120°C for 15mins.

Fig. 1. Packaged white LED attached with copper heat sink.

The final stage of thermal management is provided by carefully spacing and securing the individual LEDs onto a 150mm × 125mm × 1mm copper board using M3 screws and nuts as illustrated in Fig. 2.

Fig. 2. Packaged white LEDs attached with heat sinks mounted on a copper board.

The packaged white LEDs mounted on the copper board are then placed in a life-test humidity chamber designed for high temperature and humidity. The test condition is set at 85°C and 85% RH in accordance to the industry IPC/JEDEC standard [12]. During the humidity test, all the LEDs are switched off so as to prevent heat generated during the on state to evaporate the moisture trapped in the encapsulation.

At specific intervals, the LEDs are removed from the humidity chamber to have their luminous intensity measured. Due to practical consideration, the intervals are fixed at 210 hours, 373 hours, and 515 hours. During these intervals, it is important to ensure that all the optical measurements are accomplished within four hours so as to minimize the evaporation of the moisture from the LEDs to the ambient environment.

The total luminous flux (in lumen) is often used as an objective measure of the useful power emitted by an LED, and is defined as the summation of spectral flux (in W/nm) at all optical wavelengths from 380nm to 780nm weighted by luminous efficiency function (human eye sensitivity curve). With the spectral data available, the color rendering index (CRI) and correlated color temperature (CCT) of the packaged white LEDs could also be determined.

To examine the optical degradation of the packaged white LEDs, an optical measurement system consisting of a spectroradiometer and an one-meter integrating sphere is set up to measure the total luminous flux (2π forward flux in this case) of the LEDs. The spectral flux responsivity of the measurement system is calibrated at the start and the end of the measurement of LEDs to achieve high measurement accuracy.

For the calibration process, a spectral irradiance (in $\text{W/m}^2/\text{nm}$) standard lamp is positioned at 500mm from the aperture of the integrating sphere. The spectral flux introduced into the sphere is calculated from the known spectral irradiance value of the standard lamp and the opening area of the aperture. To ensure that the optical output is stabilized, the standard lamp is lit up for at least five minutes before the spectral flux reading of the lamp at every wavelength is measured. Baffles with opening areas slightly larger than the aperture are placed between the integrating sphere and the lamp to reduce the stray light. The calibration reading is taken five times before the average is tabulated for the total luminous flux computation. The calibration setup is shown in Fig. 3.

Fig. 3. Schematic diagram of calibration set-up.

During the optical measurement, the copper board is attached to a specially designed stand by L-shaped brackets as shown in Fig. 4. The stand is designed in such that the position of the copper board could be adjusted in the x, y and z directions, hence allowing each of the attached LEDs on the copper board to be placed exactly at the aperture hole of the integrating sphere.

Fig. 4. Optical measurement set-up.

As recommended by the manufacturers of the packaged white LEDs, the LED under test is powered up with the nominal current of 350mA using a control circuit board. The control circuit board is designed such that the current provided to the LEDs is maintained constant over a wide range of input voltages. A stabilization time of 30secs is incorporated to ensure consistency and accuracy of the measurements taken. The simplified schematic diagram illustrating the overall experimental set-up is summarized in Fig. 5.

Fig. 5. Schematic diagram of experimental set-up.

Results and Discussions

The box-plot shown in Fig. 6 illustrates the degradation of the total luminous flux of the LEDs as a function of time. From the plot, it is obvious that due to the prolonged humidity test, the optical output of the packaged white LEDs declined steadily through time. Degradation in the total luminous flux is an important failure phenomenon experienced in all LEDs. Hence, in this case, it is important to determine the underlying physical mechanisms that affect the performance of packaged white LEDs under the humidity effect. Using the measured data, an in-depth analysis of the degradation in the optical output of the LEDs could be carried out.

Fig. 6. Degradation of light emission of packaged white LEDs after prolonged humidity test.

In order to analyze the data systematically, the measured luminous flux of the individual LEDs is plotted as a function of time. With these graphs, the time to degradation (TTD) for the LEDs at 5%, 10%, 15% and 20% are computed as shown in Table 1.

Table 1. Time to degradation for packaged white LEDs at 5%, 10%, 15% and 20%.

Packaged White LED	Time to Degradation (Hour)			
	5%	10%	15%	20%
Sample #1	59.3	98.7	139.6	188.8
Sample #2	74.6	127.9	189.9	230.1
Sample #3	21.4	44.8	78.7	99.5
Sample #4	10.2	27.5	43.1	58.6
Sample #5	221.4	268.8	309.6	352.1
Sample #6	219.6	257.8	277.7	301.2
Sample #7	N.A	N.A	N.A	N.A
Sample #8	237.5	479.3	N.A	N.A
Sample #9	117.4	N.A	N.A	N.A
Sample #10	92.4	203.7	294.5	N.A
Sample #11	318.4	397.5	419.3	455.5
Sample #12	136.7	192.4	250	301.2
Sample #13	352.4	N.A	N.A	N.A
Sample #14	N.A	N.A	N.A	N.A
Sample #15	406.5	422.1	479.3	491.1
Sample #16	80	N.A	N.A	N.A
Sample #17	381.4	408.6	431.2	442.5
Sample #18	18.6	21.4	38.7	59.3
Sample #19	357.4	382.1	420.5	459.6
Sample #20	17.6	40	48.3	109.2
Sample # 21	300	373.4	435.7	487.6
Sample #22	18.3	39.1	51.4	72.3
Sample #23	340.5	380	440.3	500
Sample #24	240.6	261.1	300	325.2

The Akaike information criterion (AIC) is then used to verify the number of failure mechanisms in the given set of measured data [13-14]. A global maximization algorithm,

namely the simulated annealing (SA) in conjunction with the expectation-maximization (EM) algorithm is then employed for the mixture statistical distribution [13-14].

Table 2. Packaged white LEDs with degradation rate that followed lognormal distributions.

	Failure Mechanism A	Failure Mechanism B
Packaged White LED	Sample #1	Sample #11
	Sample #2	Sample #21
	Sample #3	
	Sample #20	
	Sample #22	

Upon the analysis, it is noted that the luminous flux degradation of the packaged white LEDs is due to more than one failure mechanisms of which two of them follows lognormal distribution. Fig. 7 shows the degradation rate of the two failure mechanisms that follow the lognormal distribution, namely failure mechanism A and failure mechanism B. The degraded units of the packaged white LEDs that belong to the two failure mechanisms are summarized in Table 2.

Fig. 7. Separation of failure mechanisms in humidity test of packaged white LEDs.

From Fig. 7, the degradation rates for the two failure mechanisms are observed to be distinct. The degradation rate for failure mechanism A is noted to increase rapidly within the first 100 hours of the accelerated humidity test. As for failure mechanism B, the plot indicates a much slower degradation rate for the initial 300 hours of the accelerated humidity test, before raising swiftly, having almost the same degradation rate of failure mechanism A.

For the phosphor-based packaged white LEDs, the GaN-based chips emitted the blue light at around 465nm. The incorporated phosphor is then used to convert part of the blue light into yellow light at roughly 500-700nm. By combining the blue and yellow light, the human eyes then perceive this combination of lights as a white light. By tabulating the ratio of the intensity at the blue wavelength to that at the yellow wavelength, the two failure mechanisms that follow lognormal distribution are further investigated.

Fig. 8. Blue to yellow spectrum intensity ratio of the emitted light for failure mechanism A showing the degradation is related to the GaN-based chips.

The ratio of the intensity of blue to yellow wavelength of the packaged white LEDs classified under failure mechanism A is illustrated in Fig. 8. It shows that all the plots decrease monotonically and indicates that the luminous flux degradation due to the blue emission is more severe, and hence it is likely to be GaN-based chip related failure.

If failure mechanism A is indeed chip related failure, it seems to be contradicted to its degradation rate profile observed in Fig. 7. This is because in general circumstances, degradation is unlikely to be healed if it is a chip related failure. The seemingly decreasing degradation is likely related to the moisture being driven out from the encapsulation due to the increased heat generated from the degraded GaN-based chip during the on state, and thus the increase in the light output due to the decrease of the moisture content in the encapsulation compensate the decrease in the light output due to the chip related degradation. This renders a slower decrease in the light output as observed in Fig. 7.

Fig. 9. Blue to yellow spectrum intensity ratio of the emitted light for failure mechanism B showing the degradation is related to the phosphor degradation and GaN-based chips.

Fig. 9 shows the ratio of the intensity of blue to yellow wavelength of the packaged white LEDs classified under failure mechanism B. The plot shows that the ratio increases until 10% degradation before it starts to decrease as in the case of failure mechanism A. The increase in ratio indicates the degradation of the yellow emission is more severe, and hence

it is likely to be the phosphor degradation. After 10% degradation, the mechanism changes to be as that of failure mechanism A, i.e. GaN-based chip related failure.

The two failure mechanisms deduced from the mixed statistical distribution and spectrum analysis methods are further investigated using the parameters extraction method. As the behaviour of the LED is similar to a p-n junction, determining the importance parameters of the GaN-based LED, such as the ideality factor (n), series resistance (R_s) and saturation current (I_s), could revealed useful information with regards to the degradation of the packaged white LEDs.

The integration based parameters extraction method derived by Tan et. al. [15] is employed on an unstressed packaged white LED, and the LEDs that have been classified under failure mechanisms A and B. Table 3 summarizes the extracted n , R_s and I_s values for the LEDs.

Table 3. Summary of the n , R_s and I_s values for the packaged white LEDs experimented.

Packaged White LED	n	R_s (Ω)	I_s (A)
Unstressed	5.131	0.554	2.405E-11
Failure Mechanism A			
Sample #1	7.997	0.998	1.482E-09
Sample #2	7.343	0.761	9.181E-09
Sample #3	7.110	0.707	4.604E-08
Sample #20	8.512	1.432	5.007E-07
Sample #22	7.331	0.792	7.819E-08
Failure Mechanism B			
Sample #11	6.677	0.650	1.150E-10
Sample #21	5.410	0.635	9.110E-11

From Table 3, it can be seen that the n value for the unstressed packaged white LED falls within the range that has been reported of 2.0 to 7.0 [16-19]. However, the values of the extracted parameters of the packaged white LEDs that are classified under failure mechanism A are found to be much higher than that of the unstressed LED, further confirm that failure mechanism A is indeed chip related. Additional evidence can also be seen from the reverse saturation current of the pn junction.

On the other hand, the values of the extracted parameters of the packaged white LEDs that are classified under failure mechanism B are very much similar to those of the unstressed LED. Based on the results, the chip related failure as a cause for failure mechanism B could now be ruled out. This implied that the optical degradation of the LEDs is caused primarily by the degradation of phosphor.

Conclusions

In summary, 24 units of commercial packaged ultra-bright white LEDs, each of power rating of 1W, are subjected to humidity testing. As a consequence of the humidity effect, the LEDs showed a degradation of optical output. With the mixture statistical distribution analysis method, it is noted that the luminous flux degradation of the packaged white LEDs is dependent on more than one failure mechanisms. The degradation rate of the two failure mechanisms that followed lognormal distributions are analyzed based on their blue to yellow spectrum intensity ratio.

With the spectrum analysis and parameters extraction methods, it is deduced that the degradation for failure

mechanism A is related to the chip failure due to the accumulated moisture in the encapsulation. For failure mechanism B, degradation of phosphor is responsible for the optical degradation. The physics of the chip related failure due to moisture is to be investigated further. The nature of the phosphor degradation due to moisture is also of importance and should be investigated further.

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