Accelerated life test of high luminosity AlGaInP LEDs

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ABSTRACT

Specific tests to assess reliability of high luminosity AlInGaP LED for outdoor applications are needed. In this paper tests to propose a model involving three parameters: temperature, humidity and current have been carried out. Temperature, humidity and current accelerated model has been proposed to evaluate the reliability of this type of LED. Degradation and catastrophic failure mechanisms have been analyzed. Finally we analyze the effect of serial resistance in power luminosity degradation.

1. Introduction

In a previous paper [1] we analyzed a temperature humidity accelerated life model for high luminosity LEDs. In this paper we have made a step further and we propose a life model that involves three parameters: temperature, humidity and current. We have carried out seven new tests in different conditions in order to validate the model that allows us to evaluate the influence of the three parameters: current, humidity and temperature. Failure analysis have been done.

2. Samples and test procedure

LEDs samples are in standard package T–1 ¾ (5 mm) with transparent epoxy AlInGaP LEDs (red, 626/630 nm wavelength), maximum DC Forward Current 50 mA and Luminous Efficacy (IF = 20 mA) 155 lm/w. Leads of the LEDs are mild steel, solder dipped and a gold wire is used to connect the metal contact on the top of the LED die to the adjacent pin. A ball bond is formed on top of the LED die and a wedge bond is used to attach the wire to the adjacent pin. Die is attached to the base of the reflector, with electrically conducting epoxy Fig. 1.

In this analysis we have carried out accelerated tests on high luminosity light emitting diodes (LEDs) in a pressure cooker chamber [2] at different temperatures, humidities and currents, see Table 1. The tests have been planned in order to have tests with one parameter (i.e. temperature) with three different values (120 °C, 130 °C and 140 °C) and the other two parameters fixed (i.e. RH = 85% and I = 40 mA). In this way it is possible to analyze the influence of the parameter that varies:

(a) Temperature tests, three different temperatures and fixed current and humidity.
(b) Current tests, three different currents and fixed humidity and temperature.
(c) Humidity tests, three different humidity and fixed temperature and current.

During the tests each LED is driven with an independent current source. Power luminosity was measured every 24 h at a constant current of 20 mA. Voltage–current curves of each diode were also measured at a temperature of 20 °C using a Peltier element to maintain the temperature constant.

3. Results

3.1. Failure definition

Failures in LEDs were classified as catastrophic and degradation: Catastrophic failures are sudden and drastic changes in the operating characteristics of an LED, resulting in total loss of useful performance. In these tests only one type of catastrophic failures have been observed, open circuit failure, which is detected in real time when the polarization resistance voltage drops to zero.

Degradation failures occur when the power luminosity decays below a predefined power luminosity value [3]. In this work, the failure threshold was set in accordance with the value proposed by ASSIST, LEDs will fail by degradation if power luminosity decays below 70% initial power [4]. The 130 °C and 140 °C tests have more degradation failures than 120 °C tests, and this indicates that temperature is the determining factor in this type of failure.

3.2. Temperature tests

Three temperature accelerated tests, 120 °C, 130 °C and 140 °C with the same drive current, 40 mA, and humidity, 85%RH, have been done in order to analyze the temperature influence in the life of the LEDs. One failure was observed in the 130 °C test, at 18 h, occurred by LED terminal failure, resulting from the cracked plastic

Fig. 1. LED sample.

Table 1
Test conditions.

Temperature (°C)	Current (mA)	Humidity (%)	Test duration (h)
120	40	85	276
130	40	85	153
140	40	85	75
120	20	85	384
120	30	85	384
120	40	70	339
120	40	60	507

Table 2
Weibull parameters and median for temperature tests.

T (°C)	Sample size	Number failures	Weibull shape parameter	Weibull scale parameter	Median (h)
120	15	15	2.19	147.78	125.08
130	15	14	2.18	83.1	70.29
140	15	15	2.37	43.81	37.55

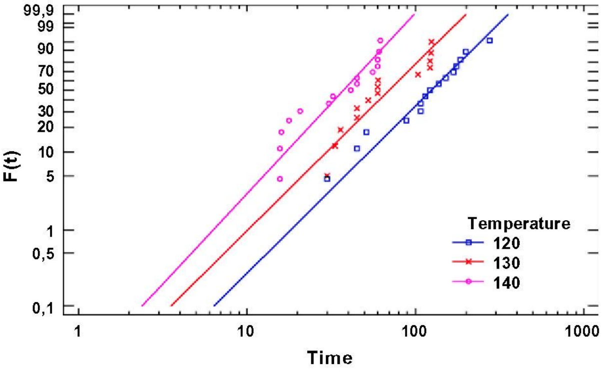

Fig. 2. Weibull plot for temperature tests.

(this one was censored). In the other two tests (120 and 140 °C) all failures were catastrophic by open circuit. Table 2 gives the Weibull shape, scale, and median parameters for three tests. Parameter estimation was evaluated with Maximum Likelihood Estimation Method with 95% confidence level.

Fig. 2 shows the Weibull plot for failures under different temperatures for the same current and humidity conditions. Weibull plots have similar slopes according the same failure mode (open circuit).

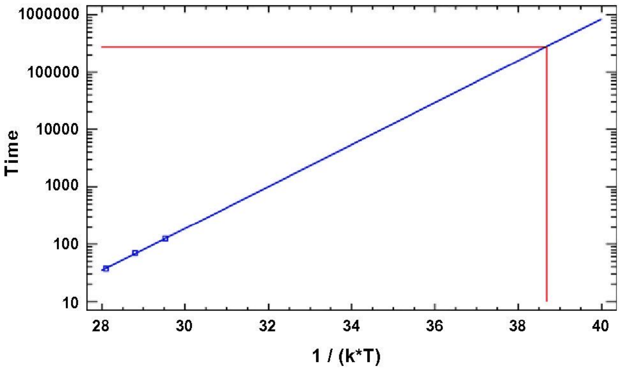

Fig. 3. Arrhenius plot.

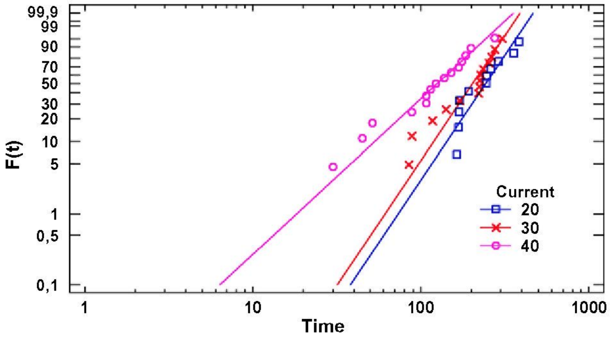

Fig. 4. Weibull plot for current tests.

We have represented the medians in Arrhenius plot Fig. 3, obtaining an activation energy of 0.84 eV. Similar values have been reported by Lacey et al. [5] and Altieri-Weimar et al. [6] in similar devices. The vertical line represents the median life at room temperature, 27 °C.

Eq. (1) represents the model for the failure of 50% of devices (median) according to the Arrhenius–Weibull model at RH = 85% and $I = 40$ mA.

$$t_{50\%} = 2.08 * 10^{-9} e^{\frac{0.84}{KT}} \quad (1)$$

where T is the temperature in °K; k is the Boltzmann constant.

3.3. Current tests

Three tests were conducted at constant humidity (85%RH) and temperature (120 °C) with different drive current (20, 30 or 40 mA). In the 20 mA test four LEDs fail at 7, 66.5, 118.75 and 128 h by terminal failures. This failure mechanism is similar to the failure observed for the 130 °C-40 mA-85% test. Fig. 4 shows the Weibull plot for these tests, and Table 3 gives the Weibull parameters derived from these plots. Parameter estimation was evaluated with Maximum Likelihood Estimation Method with 95% confidence level.

Although beta parameter is not the same for all the accelerated tests, it is necessary to consider that all of them are in a relatively small range, between 2.2 and 3.5, being all the tests in the aging stage of the life. There are other authors that have wider beta ranges with the same failure mechanism [7–9]. These beta parameter differences could be explained due the small sample size, 15 LEDs in each experiment. Furthermore we have analyzed all the failed LEDs and we have found that all the catastrophic failures

Table 3
Weibull parameters and median for current tests.

Current (mA)	Sample size	Number failures	Weibull shape parameter	Weibull scale parameter	Median (h)
20	15	11	3.53	270.32	243.69
30	14	14	3.53	225.37	203.16
40	15	15	2.19	147.78	125.08

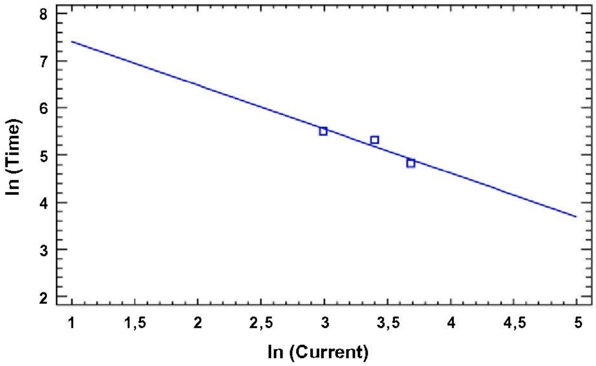

Fig. 5. Inverse Power Law plot.

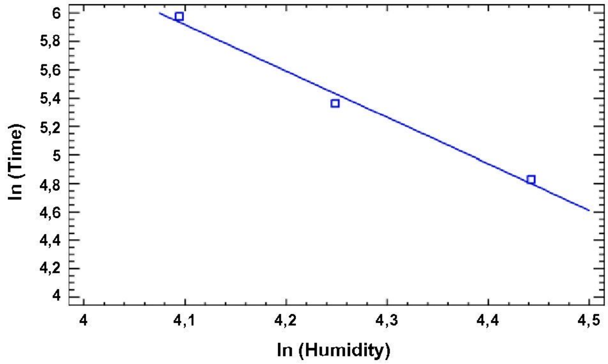

Fig. 7. Peck plot.

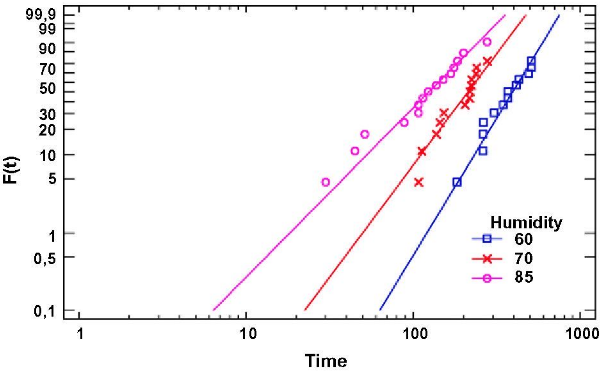

Fig. 6. Weibull plot for humidity tests.

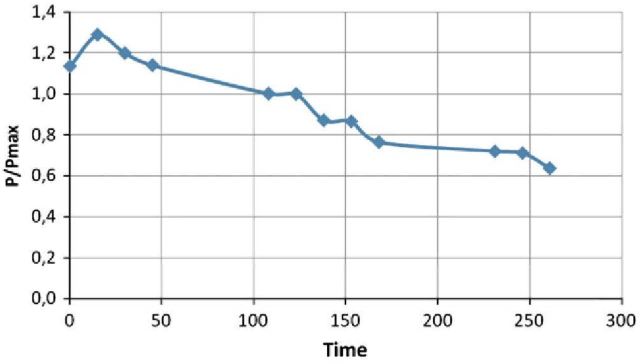

Fig. 8. Average relative power luminosity evolution vs time (h) (120 °C 85%RH 40 mA).

Table 4
Weibull parameters and median for humidity tests.

Humidity (%RH)	Sample size	Number failures	Weibull shape parameter	Weibull scale parameter	Median (h)
60	15	13	3.58	435.97	393.55
70	15	13	2.90	241.93	213.26
85	15	15	2.20	147.78	125.08

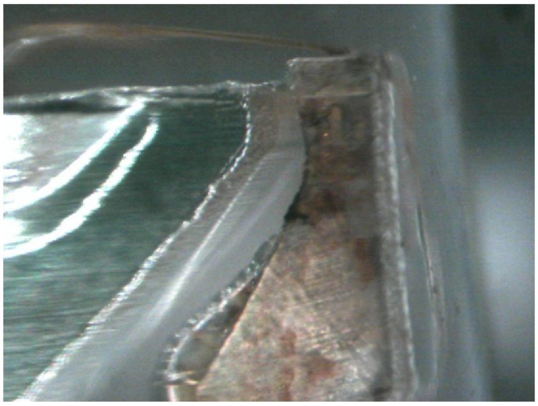

Fig. 9. Anode oxidation due humidity penetration.

are open circuit caused by anode oxidation due humidity penetration, see Section 4.

The median life, for tests at 120 °C and RH = 85% and varying current, were analyzed by the Inverse Power Law and Exponential Relationships models. The best results were obtained using the Inverse Power Law Relationship, as shown in Fig. 5, yielding a n value of 0.928. The value of n parameter depends on several factors as the type of the device, failure definition and materials. Although in the literature there are a wide range of *n* values (0.5–8.1) [10,11], the value of n generally ranges between 1 and 2 [12]. The *n* value evaluated in this work is slightly lower than 1 and therefore is in the lower part of the range. We attribute this low value due the failure mechanism presents in these tests is enhanced mainly by humidity and in a second term by current.

Eq. (2) represents the model for the failure of 50% of devices (median) according to Inverse Power Law Relationship–Weibull at RH = 85% and T = 120 °C.

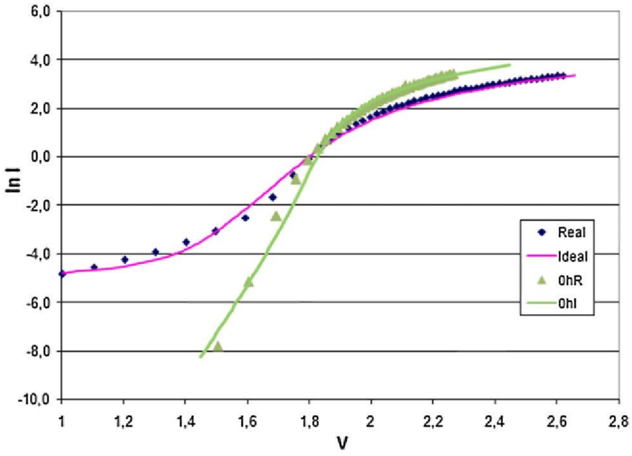

Fig. 10. *IV* curves at 0 h and just before failure.

$$t_{50\%} = \frac{4165}{I^{0.928}} \tag{2}$$

where I is the drive current.

3.4. Humidity tests

Tests were conducted at constant temperature (120 °C) and current (40 mA) with varying relative humidity (60%, 70% or 85%). Fig. 6 shows the Weibull plot for these tests, and Table 4 gives the Weibull parameters derived from these plots evaluated by means of Maximum Likelihood Estimation (MLE). The median life, for tests at constant temperature and current, were analyzed by Peck's Law Relationship [13] models Fig. 7.

Eq. (3) represents the model for the failure of 50% of devices (median) at $I = 40$ mA and $T = 120$ °C. according to Peck–Weibull model. The obtained n value, 3.26, is in the wide range of n data reported in the literature [14], between 2.5 and 5, depending on the materials used in the package.

$$t_{50\%} = 244.8 * 10^{6} * \left(\frac{1}{H}\right)^{3.26} \tag{3}$$

where H is the relative humidity.

3.5. Complete model for temperature, humidity and current

We can generalize this model due there is one unique test (120 °C/40 mA/85%RH) that is common to the three test groups (temperature, humidity and current) that allow us to evaluate the constant of Eq. (4). From Peck, Inverse Power Law and Arrhenius models median life follow the next equation:

$$t_{50\%} = 0.123 * \frac{1}{H^{3.26}} * \frac{1}{I^{0.928}} * e^{\frac{0.84}{KT}} \tag{4}$$

From this equation it is possible to evaluate the median life under different working conditions. Assuming normal working conditions of 27 °C, 30 mA and RH 75%, the median life is 59.6 years.

4. Failure analysis

In this section failure mechanisms of LEDs will be analyzed. During the tests LEDs have been working in a pressure cooker chamber and periodically the devices have been tested outside the chamber in order to analyze their performance and the failure mechanism by the following techniques:

Table 5
Initial RS values and before catastrophic failure (130 °C 85%RH 40 mA).

LED		RS (Ω)	Time of last measurement before catastrophic failure (h)	$P(t)/P_{\max}$
L1	Initial RS value	12		
	RS before catastrofic failure	21	55	0.679
L2	Initial RS value	15		
	RS before catastrofic failure	15	95	0.749
L3	Initial RS value	12		
	RS before catastrofic failure	14	65	0.848
L4	Initial RS value	7		
	RS before catastrofic failure	8.5	40	0.944
L5	Initial RS value	9		
	RS before catastrofic failure	11	40	0.817
L6	Initial RS value	10		
	RS before catastrofic failure	10	75	0.836
L7	Initial RS value	10		
	RS before catastrofic failure	15	30	0.9621
L8	Initial RS value	10		
	RS before catastrofic failure	12	45	0.926
L9	Initial RS value	15		
	RS before catastrofic failure	17	55	0.737
L10	Initial RS value	12		
	RS before catastrofic failure	14	50	0.697
L11	Initial RS value	11		
	RS before catastrofic failure	16	70	0.696
L12	Initial RS value	10		
	RS before catastrofic failure	13	40	0.891
L13	Initial RS value	9		
	RS before catastrofic failure	11	65	0.817
L14	Initial RS value	10		
	RS before catastrofic failure	10	15	1
L15	Initial RS value	8.5		
	RS before catastrofic failure	11	20	0.974

(a) Power luminosity of each LED has been measured in order to evaluate how power luminosity degrades with time and if LEDs fail catastrophically or by degradation. As it has been explained in Section 3.1, LEDs will fail by degradation if power luminosity decays below 70% initial power [4].
(b) *I–V* curves of each LED have been measured at controlled temperature periodically outside the pressure chamber. Main objective of these measurements is to analyze the device parameter evolution during the test by means of *I–V* curve electrical stimulation. In order to evaluate LED device parameters in this work it has been used the same equivalent circuit proposed by Fujii et al. [15] that consists on a diode with a series resistance and a parallel resistance.
(c) Microscopic optical inspections have been made to all LEDs in order to analyze the failure mechanism.

In order to evaluate if LEDs fail catastrophically or by degradation we have analyzed the power luminosity evolution. Related with power luminosity all the LEDs follow a similar evolution: during the first hours of the accelerated tests power luminosity increases and after that, power luminosity degrades Fig. 8. This power luminosity evolution has been observed by other authors [16–18]. Related with failure analysis we have observed two types of failures:

(a) In some cases power luminosity decayed below failure degradation definition and LEDs fail by means of degradation.
(b) In other cases power luminosity decayed abruptly due a catastrophic failure.

Both types of failures have been analyzed by means of microscopic optical inspection and I–V curves measurement.

Related with microscopic optical inspection we have observed that both types of failures have the same cause: there is an oxidation in the anode wire bonding; see Fig. 9, that in many cases ended with an open circuit failure. It is necessary to take into account that tests have done in a high humidity ambient that enhances humidity intrusion in the encapsulation. With respect to encapsulation degradation, voids in the encapsulation were observed by optical microscopy imaging in almost all the LEDs. No discoloration or cloudiness of the encapsulation epoxy was observed.

Anode wire bonding oxidation will affect in the degradation stage also to I–V curve by means of an increase of the series resistance associated to the contact. Series resistance affect to *I–V* curve in the higher currents range. We have analyzed *I–V* curves by means of electrical simulations and from these simulations we have observed that device parameters have degraded during the test Fig. 10, by means of an increase of series resistance [19] and leakage current (parallel resistance decreases). This increase of the ohmic leakage current can be ascribed to the thermally activated interaction between LEDs surface and the surrounding material, generating surface conductive paths in parallel to the junction [3]. This degradation of device parameters could be explained by the oxidation process that increases the resistance of anode wire bonding contact and the chip leakage current [15].

In table 5 it have been shown the series resistance obtained from the *I–V* curve just in the initial instant (third column first line) and just before the catastrophic failure (third column second line). The last column indicates the relationship between power luminosity in the measurement just before catastrophic failure and maximum power luminosity. From the data of this table it can be seen that in all the LEDs, except L6, there is a relationship between power luminosity degradation and an increase of series resistance. A decrease of parallel resistance and/or decrease of recombination current could explain this power luminosity degradation of L6 [20].

Therefore failure mechanism in both types of failures is due the same cause: humidity penetration inside the encapsulation that oxidizes the anode wire bonding. During the first hours due this oxidation series resistance of the device increases and LEDs power luminosity degrades. After a time the oxidation causes that wire bonding breaks failing catastrophically the LED.

5. Conclusions

The main conclusions of these tests are:

- We observed chip and encapsulation degradation prior to open circuit (catastrophic failure).
- With respect to encapsulation degradation, voids in the encapsulation were observed by optical microscopy imaging in almost all the LEDs. No discoloration or cloudiness of the encapsulation epoxy was observed.
- Related with catastrophic and degradation failures both of them are due the cause: oxidation in the anode wire bonding; that in many cases ended with an open circuit failure.
- There is a relationship between power luminosity degradation and an increase of series resistance.
- The Arrhenius model is being determinate with an activation energy of 0.84 eV, Inverse Power Law factor of current is 0.92 and Peck's factor is 3.26.

Complete model predicts a median life of 2,034,995 h of continuous operation under normal working conditions of 60%RH, 20 mA and 25 °C.

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