Degradation of AlInGaP red LEDs under drive current and temperature accelerated life tests

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A B S T R A C T

AlInGaP LEDs are widely used in illumination applications as automotive and signalization due their low consumption and high durability. In order to verify the high durability data it is necessary to consider not only catastrophic failures but also degradation. In this work LEDs degradation at different temperature and drive current accelerated tests have been analyzed. In all the tests we have carried out an exponential degradation trend have been observed. Temperature and drive current influence in degradation rate and reliability have been evaluated.

1. Introduction

AlInGaP red LEDs are widely used in illumination applications as traffic lights and automotive. AlInGaP LEDs do not usually fail by means of catastrophic failures but intensity luminosity degrades with time causing device failure. Degradation rate depends on working (intensity current) and ambient conditions (temperature and humidity). LEDs manufacturers do not usually give degradation data related with all these parameters that can be the great interest in order to select LEDs working conditions and maintenance procedure. An analysis of LEDs intensity luminosity degradation and reliability with respect temperature and drive intensity current has been carried out in this work.

2. Tests

Commercial 5 mm AlInGaP red LEDs have been tested at different drive current (0 mA, 10 mA, 20 mA, 30 mA and 40 mA) and ambient temperatures (130 °C, 150 °C and 180 °C) in a temperature climatic chamber. Degradation of 15 LEDs have been analyzed in each of the 15 tests (five drive intensity currents at three different temperatures) in order to evaluate degradation rate and reliability at the different working and ambient conditions.

The recommended drive current is 20 mA and therefore LEDs life will be accelerated by means of temperature and drive current stresses. Climatic chamber is in a benign humidity ambient and therefore degradation related with moisture will not be taken into account in these tests. Main objectives of these tests are to analyse the influence of temperature and drive current in the intensity luminosity degradation and reliability of these LEDs.

3. Intensity luminosity degradation

In this work we have analyzed the intensity luminosity degradation for the different working and ambient conditions. The intensity luminosity time evolution is similar in all the tests and can be summarized as follows:

- During the first hours, this time depends on the acceleration test, intensity luminosity increases with time as it can be seen in Fig. 1. This trend has been observed by other authors in AlInGaP LEDs [1,2] and is attributed to a defect annealing that reduces defect concentration and improves intensity luminosity.
- After that, intensity luminosity degrades in all the LEDs. The degradation rate depends on working conditions (drive current) and ambient conditions (temperature) but in all the tests LEDs degradation follows an exponential trend as it can be seen in Fig. 2. From this figure it is important to remark that LEDs without drive current also degrade in an exponential trend. In these tests an encapsulated browning is observed in the LEDs. This encapsulated browning is enhanced with temperature.

This exponential trend has been observed in different optoelectronic devices [3–9] and can be expressed with the following equation:

$$P(t) = P_0 e^{-\frac{t}{\tau}} \qquad (1)$$

The time constant, τ, is the time at which intensity luminosity decays below 0368 times the initial value.

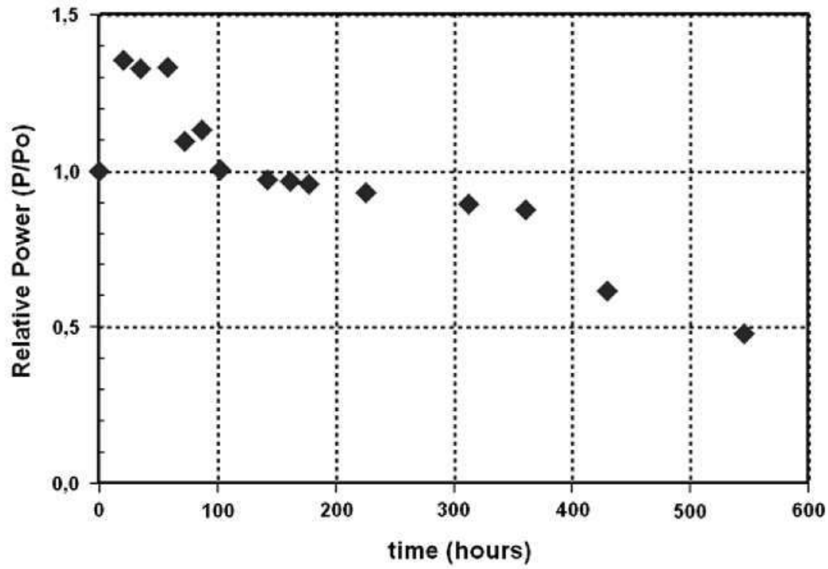

Fig. 1. Intensity luminosity evolution with respect time (30 mA and 150 °C).

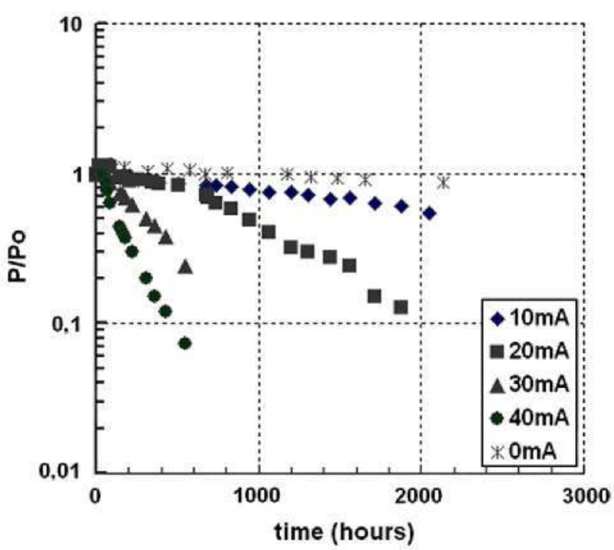

Fig. 2. Time evolution of relative average intensity luminosity (logarithm scale) of LEDs working at different intensity currents (tests at 150 °C ambient temperature).

3.1. Temperature influence in luminosity degradation

In this section temperature influence in degradation and reliability will be analyzed for the different tests. LED junction temperature [10] will be considered as the temperature parameter that affects to device reliability and degradation. Junction temperature is higher than ambient temperature due LED power consumption during working conditions. The increased temperature depends on the LED drive intensity current being higher when drive intensity current is higher. Junction temperature has been evaluated inside the climatic chamber by means of the voltage–temperature characteristics in the diode forward *I–V* curve [11,12] in two different climatic chamber conditions (natural and forced convection). Junction temperature in the two different climatic chamber conditions at 150 °C ambient temperature and the different intensity currents have been measured and summarized in Table 1.

The temperature difference between junction and ambient temperature depends directly on dissipated power by means of device thermal resistance. LED thermal resistance [13–15] is defined as the ratio of the difference in temperature to the power dissipated:

Table 1
LED junction temperature for the different drive intensity currents and 150 °C ambient temperature.

Intensity current (mA)	10	20	30	40
T_j (°C) natural convection	154.0	160.6	164.1	169.0
T_j (°C) forced convection	153.7	157.4	161.7	166.4

$$R_{th\ j-a} = \frac{T_j - T_a}{P_d} \tag{2}$$

being P_d the dissipated power of the LED equal to the product of forward voltage and forward current.In order to evaluate LED thermal resistance we have represented $T_j - T_a$ with respect P_d for natural and forced convection ambient in Fig. 3. Also it has been represented the linear regression assuming $T_j = T_a$ when $P_d = 0$ in order to evaluate thermal resistance. In the case of natural convection evaluated thermal resistance is very similar to thermal resistance supplied by manufacturer, 240 °C/W. In the case of forced

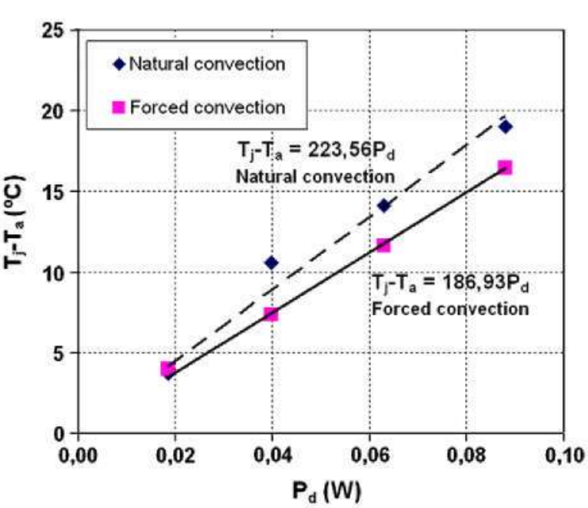

Fig. 3. Experimental $T_j - T_a$ vs. P_d. Linear regression assuming $T_j = T_a$ when $P_d = 0$.

convection calculated thermal resistance is roughly between 15% and 20% lower. Based on this analysis we have evaluated junction temperature at the different test conditions.

On the other hand the exponential trend degradation for the different tests has been also evaluated. As it can be seen in Fig. 4 for the different intensity currents τ parameter follows an Arrhenius relationship according to:

$$\tau = Ce^{\frac{E_A}{KT_j}} \tag{3}$$

being E_A the energy activation, T_j the junction temperature, and C a constant that depends on current intensity working condition.

From Fig. 4 an energy activation of 1.5 ± 0.1 eV has been obtained by least squares method for all the drive current working conditions. The C constant parameter of the Arrhenius plot has been also obtained for the different drive current ant it will be analyzed in the following section. This Arrhenius relationship has been observed by other authors in GaN [5,7], InGaAsP [8] and AlGaInP [9,16] LEDs.

3.2. Drive intensity current influence in luminosity degradation

C parameter has been evaluated by other authors [17] obtaining an exponential trend between C parameter and drive intensity current. In order to analyze if our data follows this trend we have represented in Fig. 5 the logarithm of C values obtained from Fig. 4 with respect drive intensity current. As it can be seen in Fig. 5a very good fit is obtained.

An exponential trend of C parameter with respect I have been obtained and therefore τ parameter depends on junction temperature and drive intensity in the following way:

$$\tau = Ke^{-\alpha I}e^{\frac{E_A}{KT}} \tag{4}$$

To obtain the influence of temperature and intensity current in degradation rate is very useful for maintainability planning in traffic lights or automotive applications.

4. Failure analysis

In all the tests there were very few catastrophic failures, caused at high drive intensity current and high temperature, that have not

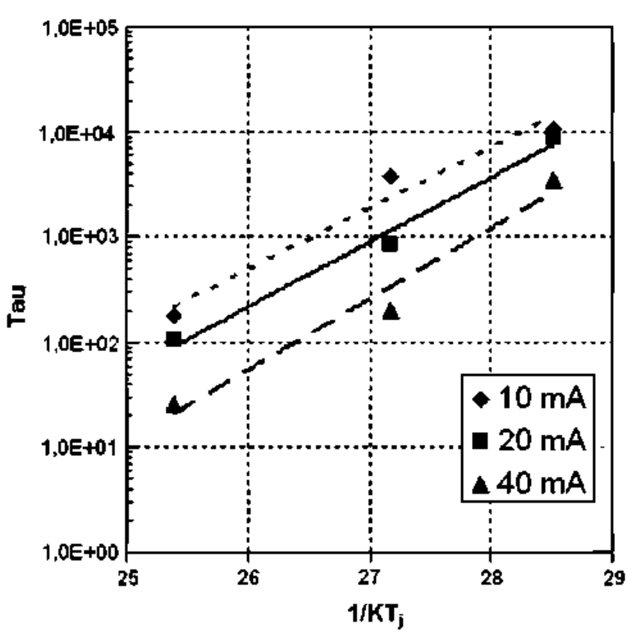

Fig. 4. Arrhenius plot of degradation time.

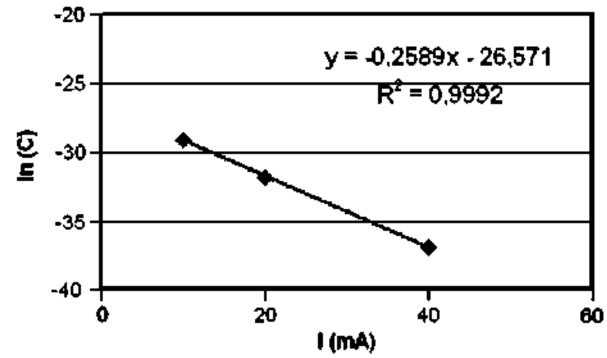

Fig. 5. ln(C) with respect drive intensity current.

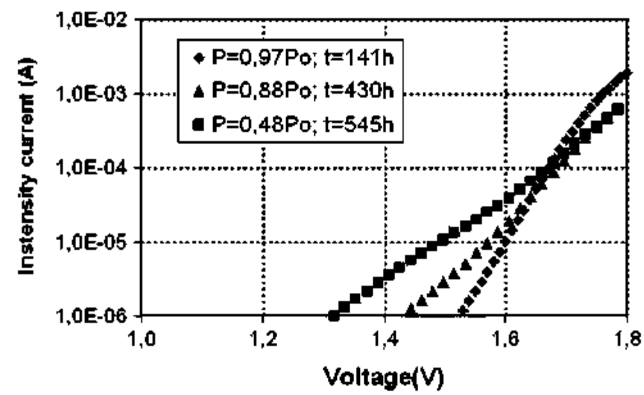

Fig. 6. I/V curve evolution of a LED working at 30 mA and 150 °C.

been analyzed in this paper. On the other hand most of LEDs fail by degradation of their intensity luminosity. Degradation has been analyzed by means of optical inspection and I/V curves measurement. Main results related with failure analysis shows that LEDs degradation is caused mainly two reasons:

- Epoxy browning that is mainly enhanced with temperature.
- LED chip degradation that is observed by means of I/V curve time evolution. LED chip degradation is mainly observed in LEDs that have been working at high intensity drive currents. In Fig. 6 can be seen LED $I–V$ curves time evolution in 30 mA/150 °C test. As it can be seen in the Figure I/V curve degrades in two different ways: at low forward voltages there is an increase of non radioactive recombination current caused by defects generation in the active layer [1,18,19]. At higher forward voltages a decrease of current is observed that is attributed to an increase of device series resistance [5].

5. Reliability analysis

AlInGaP LEDs fails basically by means of power luminosity degradation. In order to analyse LEDs reliability it is necessary to define degradation failure. Failure is defined in the same way as Alliance for Solid-State Illumination Systems and Technologies (ASSIST) proposes for illumination applications, when power luminosity decays below 70% of initial power luminosity [20]. Based on this failure definition we have evaluated the reliability for all the tests by means of Weibull function.

From Fig. 7 we have evaluated the Weibull parameters that have been summarized in Table 2.

Temperature influence has been analyzed temperature by means of Arrhenius law obtaining an activation energy between

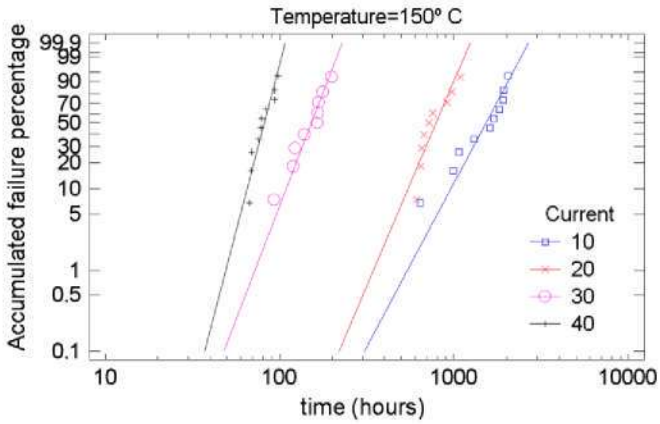

Fig. 7. Weibull distribution function of 150 °C ambient temperature tests (10 mA, 20 mA, 30 mA and 40 mA).

Table 2
Weibull parameters of 150 °C test (10 mA, 20 mA, 30 mA and 40 mA).

Current intensity (mA)	10	20	30	40
Shape parameter, β	4.1	5.1	5.6	8.3
Scale parameter, η (h)	1660	847	163 h	85 h

1.2 and 1.5 eV depending on intensity current. This activation energy agrees with the obtained in the degradation rate data.

Intensity current influence has been evaluated by means of inverse power law obtaining a n value of 2:

$$\mathrm{MTTF}(I_1) = \mathrm{MTTF}(I_o)\left(\frac{I_o}{I_1}\right)^2 \tag{5}$$

Based on these estimations we have evaluated MTTF at the considered working conditions, 65 °C/20 mA, obtaining a value of 3×10^6 h. This value is in the same range than others reported in the literature for AlInGaP LEDs [9,21] but higher than others in high humidity ambient [22]. It is necessary to take into account the benign humidity conditions of the tests.

6. Conclusions

Main conclusions of this work are the following:

- Degradation is the main failure mechanism of AlInGaP LEDs. AlInGaP LEDs degradation has two different steps: during the first hours intensity luminosity increases with time and after that decays following an exponential trend.
- The exponential trend of all the tests has been analyzed. An Arrhenius trend for temperature and exponential for intensity current has been obtained.
- Degradation causes has been identified as epoxy and chip degradation by means of optical inspection and I/V curve.
- An epoxy browning has been observed in all the LEDs that it is enhanced in the high temperature tests.
- LED chip degrades by means of an increase of non radioactive recombination current and series resistance. This degradation is enhanced with intensity current.
- Reliability has been evaluated by means of Weibull distribution obtaining a MTTF value of 3×10^6 h for 65 °C/20 mA working conditions.

References

[1] Strubel K, Linder N, Wirth R, Jaeger A. high brightness AlGaInP light-emitting diodes. IEEE J Select Topic Quantum Electron 2002;8:321–32.
[2] Grillot PN, Krames MR, Zhao H, Teoh SH. Sixty thousand hour light output reliability of AlGaInP light emitting diodes. IEEE Trans Dev Mater Reliab 2006;6:564–74.
[3] Ott M. Capabilities and reliability of LEDs and laser diodes, What's new in Electronics, vol. 20(6); 2000.
[4] Xie J, Pecht M. Reliability prediction modeling of semiconductor light emitting device. IEEE Trans Dev Mater Reliab 2003;3:218–22.
[5] Meneghini M, Trevisanello L, Meneghesso G, Zanoni E. A review on the reliability of GaN-based LEDs. IEEE Trans Dev Mater Reliab 2008;8:323–31.
[6] Narendran N, Gu Y, Freyssiner JP, Yu H, Deng L. Solid-state lighting: failure analysis of white LEDs. J Cryst Growth 2008;268:449–56.
[7] Ishizawki S, Kimura H, Sugimoto M. Lifetime estimation of high power white LEDs. J Light Vis Env 2007;31:11–8.
[8] Yamakoshi S, Abe M, Komiya S, Toyama Y. Degradation of high radiance InGaAsP/InP LEDs at 1.2–1.3 μm wavelength. Int Electron Dev Meet 1979;25:122–5.
[9] Lacey JDG, Morgan DV, Aliyu YH, Thomas H. The reliability of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ visible light-emitting diodes. Qual Rel Eng Int 2000;16:45–9.
[10] White Mark, Cooper Mark, Chen Yuan. Impact of junction temperature on microelectronic device reliability and considerations for space applications. Integrated reliability workshop final report, 2003 IEEE international; 2003. p. 1–4.
[11] Ryu Han-Youl, Ha Kyoung-Ho, Chae Jung-Hye, Nam Ok-Hyun, Park Yong-Jo. Measurement of junction temperature in GaN-based laser diodes using voltage–temperature characteristics. Appl Phys Lett 2005;87:03506.
[12] Keppens A, Ryckaert WR, Deconinck G, Hanselaer P. High power Light-emitting diode junction temperature determination from current–voltage characteristics. J Appl Phys 2008;104:093104.
[13] Standard EIA/JESD51-1 integrated circuits thermal measurement method – electrical test method (single semiconductor device); December 1995.
[14] Park J, Shin M, Lee CC. Measurement of temperature profiles on visible light-emitting diodes by use of a nematic liquid crystal, an infrared laser. Opt Lett 2004;29:2656–8.
[15] Kim L, Choi JH, Jang SH, Shin MW. Thermal analysis of LED array system with Heat pipe. Thermochim Acta 2007;455:21–5.
[16] Altieri-Weimar P, Jaeger A, Lutz T, Stauss P, Streubel K, Thonke K, et al. LEDs. J Mater Sci: Mater Electron 2008:S338–41.
[17] Narendran N, Bullough JD, Maliyagoda N, Bierman A. What is useful life for white LEDs? J Illum Eng Soc 2001;30:57–67.
[18] Pursiainen O, Linder N, Jaeger A, Oberschmid R, Streubel K. Identification of the aging mechanisms in the optical and electrical characteristics of light-emitting diodes. Appl Phys Lett 2001;79:2895–7.
[19] Yanagisawa T. Estimation of the degradation of InGAN/AlGaN blue light-emitting diodes. Microelectron Reliab 1997;37:1239–41.
[20] Taylor J. Industry alliance proposes standard definition for LED life. LEDs Magazine 2005;April:9–11.
[21] Dutta K, Ueda K, Hara K, Kobayashi K. High brightness and reliable AlGaInP-based light-emitting diode for POF data links. IEEE Photon Technol Lett 1997;9(12).
[22] Nogueira E, Vázquez M, Núñez N. Evaluation of AlGaInP LEDs reliability based on accelerated tests. Microelectron Reliab 2009;49:1240–3.