Student Paper

Failure Modes and Effects Criticality Analysis and Accelerated Life Testing of LEDs for Medical Applications

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While use of LEDs in fiber optics and lighting applications is common, their use in medical diagnostic applications is not very extensive. Since the precise value of light intensity will be used to interpret patient results, understanding failure modes [1-4] is very important. We used the Failure Modes and Effects Criticality Analysis (FMECA) tool to identify the critical failure modes. FMECA involves identification of various failure modes, their effects on the system (LED optical output in this context), their frequency of occurrence, severity and the criticality of the failure modes. The competing failure modes/mechanisms were degradation of: active layer (where electron-hole recombination occurs to emit light), electrodes (provides electrical contact to the semiconductor chip), Indium Tin Oxide (ITO) surface layer (used to improve current spreading & light extraction), plastic encapsulation (protective polymer layer) and packaging failures (bond wires, heat sink separation). A FMECA table is constructed and the criticality is calculated by estimating the failure effect probability (β), failure mode ratio (α), failure rate (λ) and the operating time.

Once the critical failure modes were identified, the next steps were generation of prior time to failure distribution and comparing with our accelerated life test data. To generate the prior distributions, data and results from previous investigations were utilized [5-33] where reliability test results of similar LEDs were reported. From the graphs or tabular data, we extracted the time required for the optical power output to reach 80% of its initial value. This is our failure criterion for the medical diagnostic application. Analysis of published data for different LED materials (AlGaInP, GaN, AlGaAs), the Semiconductor Structures (DH, MQW) and the mode of testing (DC, Pulsed) was carried out. The data was categorized according to the materials system and LED structure such as AlGaInP-DH-DC, AlGaInP-MQW-DC, GaN-DH-DC, GaN-DH-DC etc. Although the reported testing was carried out at different temperature and current, the reported data was converted to the present application conditions of the medical environment. Comparisons between the model data and accelerated test results carried out in the present are reported. The use of accelerating agent modeling and regression analysis was also carried out. We have used the Inverse Power Law model with the current density J as the accelerating agent and the Arrhenius model with temperature as the accelerating agent. Finally, our reported methodology is presented as an approach for analyzing LED suitability for the target medical diagnostic applications.

Keywords:
FMECA, LED, Medical application, Accelerated Life Testing

1. Introduction

High power LEDs are used in Fiber Optic Communications and Lighting Applications. In such an application, the ability of the optical receiver or human eye to detect presence or absence of light is important. In a medical diagnostic application, the precise value of light intensity is used to interpret patient results making the LED failure critical. Even a 20% decrease in light output will be considered a failure. See figures 1.1a and 1.1b below

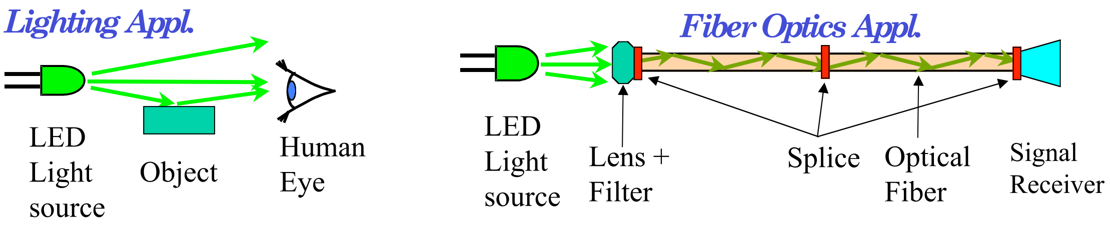

Fig. 1.1a LED in Lighting / Fiber Optics Application

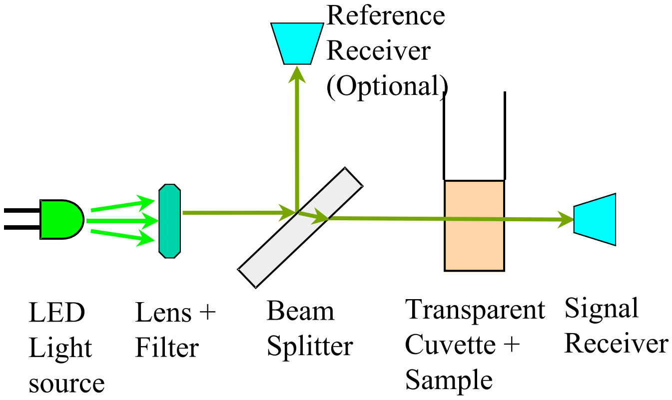

Fig. 1.1b LED in Medical Diagnostic Application

We used the Failure Modes and Effects Criticality Analysis (FMECA) tool to identify the critical failure modes. We then put the LEDs on accelerated life test at elevated temperature and pulse current. While the LEDs were on test, we performed a regression analysis of prior published data. Based on the results of the accelerated life test, we refined the FMECA.

2. Material and Methods

2.1 Materials

Commercially available AlGaInP 640nm LEDs were used in this research. The exact structure and material combinations have been previously reported ( ).

2.2 Methods

AlGaInP LEDs were put on accelerated life test as described in section 3. We also performed Regression analysis of prior published data for AlGaInP, GaN and GaAlAs LEDs and this is described in section 4. We used FMECA to perform risk analysis for use of LEDs in a medical diagnostic application as described below.

FMECA is a bottom up approach, which identifies failure modes at a component level (LED in this context), and analyzes the system level effects (failure or partial failure of the medical diagnostic instrument in this case). The competing failure modes/mechanisms were degradation of: active layer (where electron-hole recombination occurs to emit light), P-N contacts (provides electrical contact to the semiconductor chip), Indium Tin Oxide surface layer (used to improve current spreading & light extraction), plastic encapsulation (protective polymer layer) and packaging failures (bond wires, heat sink separation). A FMECA table is constructed and the criticality is calculated by estimating the failure effect probability (β), failure mode ratio (α), failure rate (λ) and the operating time (t). Criticality is given by equation (1) shown below:

$$C_m = \beta\alpha\lambda t \qquad (1)$$

3. Experimental

AlGaInP LEDs were Accelerated Life Tested simultaneously in 3 Environment Chambers. The LEDs were tested in batches of 15 LEDs each. See Fig 3.1.

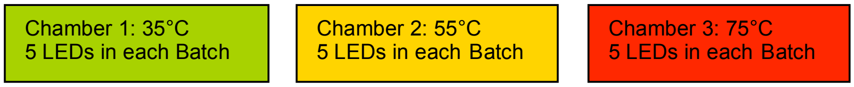

Fig 3.1 Environmental Test

Per the need of the medical application, the LEDs were driven in burst mode where each burst consists of 100 pulses. A single pulse corresponds to the time during which light passes though a single medical test sample as shown in Fig 1.1b. See Fig 3.2 for details of the timing diagram.

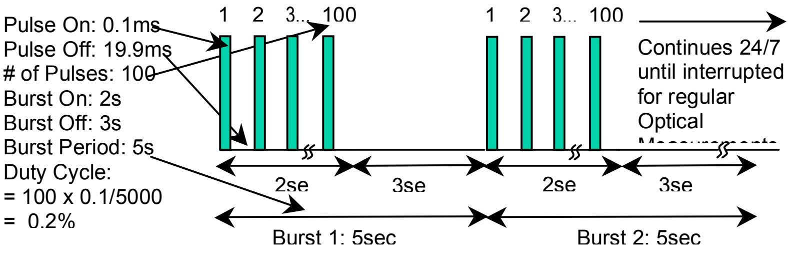

Fig 3.2 Pulse/Burst mode timing

The test is automated by using test software, data acquisition/control boards and constant current LED driver boards. The test SW makes the data acquisition board generate the necessary pulses which trigger the LED driver board. The peak current through the LED is maintained constant while it is on. A separate signal conditioning circuit also measures the forward voltage Vf across the diode which is fed back to the test SW to be written to a database. At regular intervals, the LEDs were removed from the chambers and were characterized electrically and optically (using a Spectro-radiometer). See fig 3.3 for details.

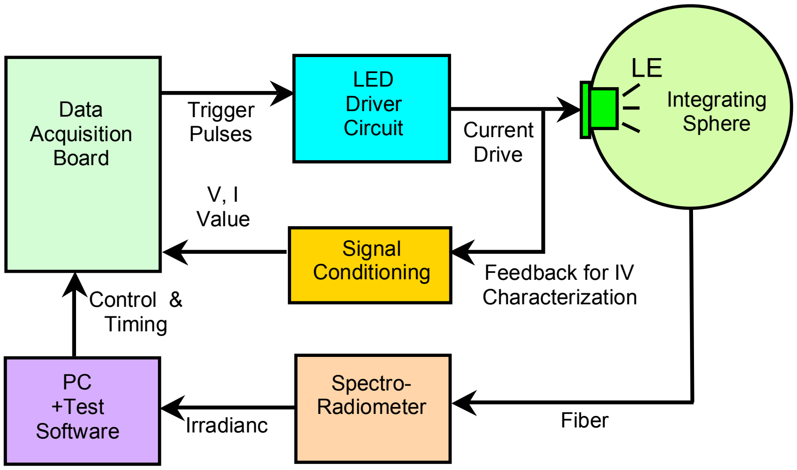

Fig. 3.3 Setup for LED Characterization

4. Theory/calculation

4.1 Modeling for Current & Temperature Acceleration

We have used Inverse Power Law (IPL) model with current density J as the accelerating variable. Since the prior published data spans over decades, use of current density (instead of current) normalizes the effect of die size increase to a great extent. The IPL is given as

$$TTF = A.J^{-n} \qquad \text{- (2)}$$

Where TTF=Time to failure in hrs, J=LED Current density in Amps/cm^2, A & n are +ve constants. Taking Ln on both sides,

$$Ln(TTF) = LnA - nLn.J \qquad \text{- (3)}$$

Equation 3 gives a straight line relationship where '-n' is the slope and J is the accelerating variable. The negative slope implies that as the current density increases, the TTF decreases.

For temperature acceleration, the Arrhenius reaction rate model was used.

$$Rate = Be^{-\left(\frac{Ea}{KT}\right)} \qquad \text{- (4)}$$

Where T=Temperature in °K, Ea=Activation energy of the LED degradation, K=Boltzmann's constant, B=constant. We take a reciprocal of 'rate' to get 'time to failure' giving equation

$$TTF = Ce^{\left(\frac{Ea}{KT}\right)} \qquad \text{- (5)}$$

Where TTF=Time to failure in hrs, C=1/B is another constant. Taking Ln on both sides,

$$Ln(TTF) = LnC + \frac{Ea}{KT} \qquad \text{- (6)}$$

This is a straight line relationship where Ea is the slope and 1/KT as the accelerating variable. The positive slope implies that as temperature increases, 1/KT and TTF decreases.

4.2 Regression Analysis of Prior Published Data

Previously published data [5-33] in which LEDs were put on long term reliability tests were identified. From the graphs or tabular data, we extracted the time required for the optical power output to reach 80% of its initial value. This is our failure criterion for the medical diagnostic application. Analysis of published data for different LED Materials (AlGaInP, GaN, GaAlAs), the Semiconductor Structures (DH, MQW) and the mode of testing (DC, Pulsed) was carried out. We had to categorize the data for combinations such as AlGaInP-DH-DC, AlGaInP-MQW-DC, GaN-DH-DC, GaN-DH-DC etc. Further, their testing was done at different temperature and current. This data was converted to application conditions of the medical environment. This required the computation of acceleration factors.

From equation 2, Acceleration Factor for Inverse Power Law Model is given by

$$AF_1 = \frac{TTF_{Use}}{TTF_{Acc}} = \left(\frac{J_{Acc}}{J_{Use}}\right)^n \qquad \text{- (7)}$$

From equation 5, Acceleration Factor for Arrhenius Reaction Rate Model is given by

$$AF_2 = \frac{TTF_{Use}}{TTF_{Acc}} = e^{\frac{Ea}{K}\left(\frac{1}{T_{Use}}-\frac{1}{T_{Acc}}\right)} \qquad - (8)$$

We used the Ea value provided/estimated from the published article or assumed it (0.43eV based on MIL-HDBK-217C). Ea would be the same for same LED data in a specific article. Similarly, if any article had data at different J (but same temperature), we estimated the n value. For all other articles, where Ea or n was unavailable, we used iterative regression as follows. Using equation 8, we converted all TTF data to use Temperature T_{Use}. We used linear regression for equation 3 to estimate n. Using this 'n' value and equation 7, we now re-converted all TTF data to use current density J_{use}. We now used linear regression for equation 6 to improve our estimate of Ea. It is quickly evident that normalizing the data for temperature, affects the regression analysis for n and normalizing the data for current density, affects the regression analysis of Ea. Thus an iterative approach was used to get best possible regression fits thereby accommodating the effects of both current density and temperature.

Overall Acceleration Factor is given by

$$AF = AF_1 x AF_2 = \left(\frac{J_{Acc}}{J_{Use}}\right)^n e^{\frac{Ea}{K}\left(\frac{1}{T_{Use}}-\frac{1}{T_{Acc}}\right)} \qquad - (9)$$

We used equation 9, published data and use conditions of the medical device application (i.e. temperature = 35°C and current density = 21.6Amps/sq^2) to get the TTF distributions (given in table 5.2) for AlGaInP-DH-DC, AlGaInP-MQW-DC, GaN-DH-DC, GaN-DH-DC etc.

5. Results and Discussion

5.1 Accelerated Life Testing (ALT)

ALT of the LEDs in Pulse mode was conducted at 3 temperatures (35°C, 55°C and 75°C) and 2 Peak currents (483mA=418.1A/cm^2 and 725mA=627.2A/cm^2). The optical power decreased with time due to degradation of the LED chip as well as the encapsulation. See Fig 5.1a and Fig 5.2b. The rate of degradation followed a logarithmic function in agreement with Yanagisawa et al [31]. 20% degradation was considered failure for the medical application. For LEDs that did not reach 20% degradation in a reasonable time (suspend data), a logarithmic function was used to extrapolate TTF. Using regression analysis of ALT data, the activation energy 'Ea' was found to be 1.15eV and 'n' for IPL was 4.48. Note that a few LEDs showed extremely low degradation rates. Since the focus was FMECA, such 'non-failing' LEDs were ignored in our analysis.

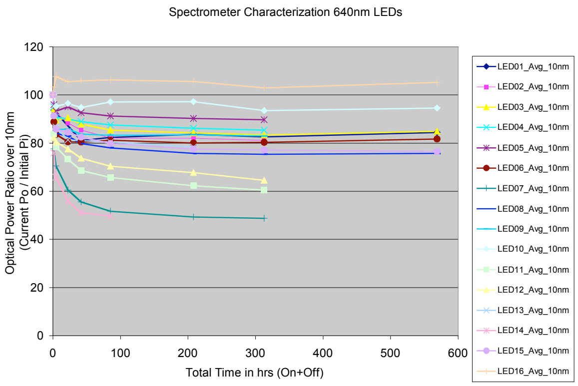

Fig 5.1a ALT for Batch2, 483mA

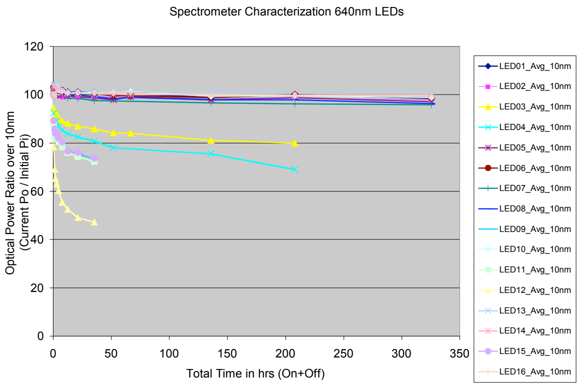

Fig 5.1b ALT for Batch3, 725mA

The most obvious failure mode was found to be encapsulation degradation. See Fig 5.1.c

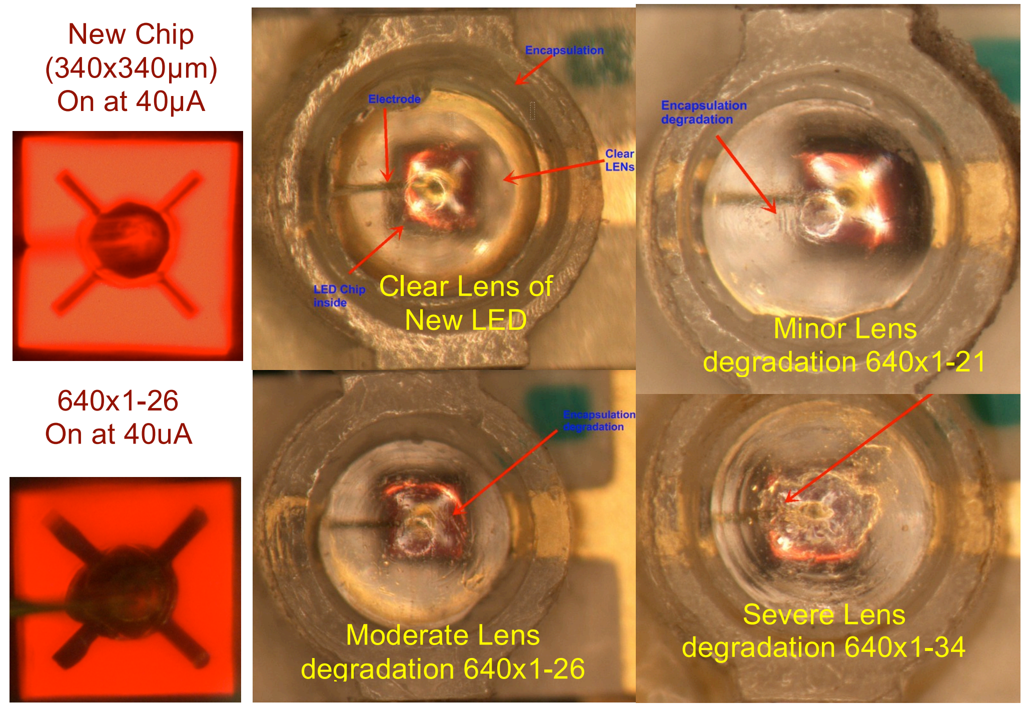

Fig 5.1.c Photos of Minor, Moderate & Severe Lens degradation

From the Vf vs. Time and Optical power vs. time graphs, it was also observed that in the LEDs that did fail, the chip degradation dominated the initial period whereas the lens degradation continues during the entire period of the test. See Fig 5.1.d. In some cases, there was a change in spectral performance after the ALT. See Fig 5.1.e for details. The peak wavelength decreased by 2nm (0.3%). The optical power drop at 650nm was higher than that at 630nm.

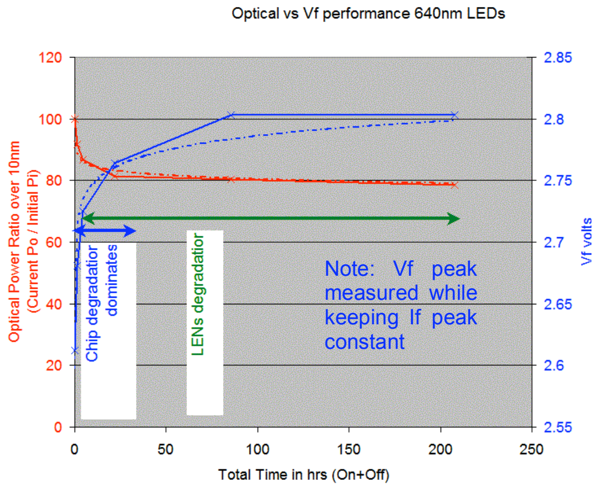

Fig 5.1.d Chip (Vf) vs. Lens degradation

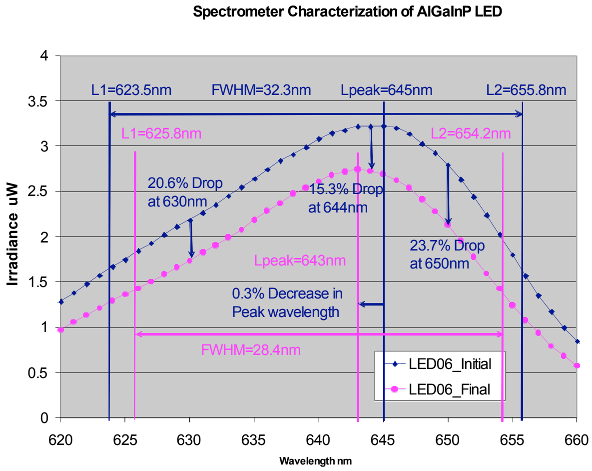

Fig 5.1.e Spectral performance after ALT

5.2 Regression Analysis of Prior Published Data

Iterative Regression Analysis of prior published data was done for various combinations as given in Table 5.2 which shows the ‘n’ and ‘Ea’ values estimated. The last 2 columns give the parameters for Weibull and Logarithmic distribution fit. Accelerated Life Test data in pulse mode is also included as Sr. # 5 for comparison with Prior published DC driving data in Sr. # 2. The activation energy ‘Ea’ and ‘n’ value during ALT are comparable. However, the time to failure predicted by ALT is much higher compared to published data. We believe that this is due to the extremely low duty cycle (0.2%) at which the LEDs were driven during ALT to simulate the medical diagnostic application.

Sr. #	**LED Material-Structure-Driving**	**‘n’ for IPL**	**Act. energy eV**	**Weibull**		**Lognormal**	
				α	β	μ	σ
1	AlGaInP-DH-DC	1.68	0.67	2.76E4	0.50	9.1	2.30
2	AlGaInP-MQW-DC	5.08	0.82	7.82E5	0.89	13	1.25
3	GaN-DH-DC	2.69	0.50	Not enough data		Not enough data	
4	GaN-MQW-DC	2.02	0.20	1.61E5	0.57	11.0	2.06
5	ALT: AlGaInP-MQW-Pulsed (0.2%)	4.48	1.15	1.55E9	0.50	20.0	2.50

Table 5.2 Regression Analysis of Prior Published Data

See Fig 5.2.a and 5.2.b for graphical equivalent for Sr. #2 in Table 5.2

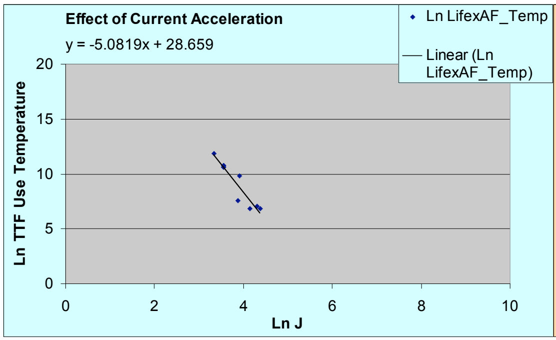

Fig 5.2.a Effect of J: AlGaInP-MQW-DC

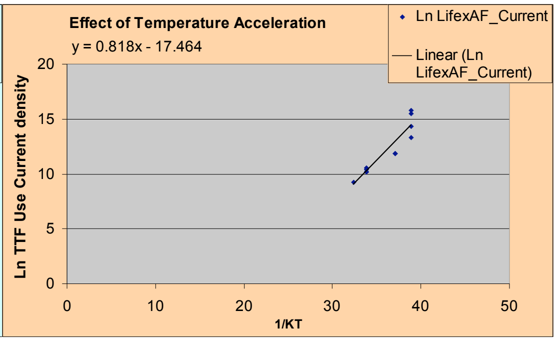

Fig 5.2.b Effect of Temp: AlGaInP-MQW-DC

5.3 FMECA for Medical Diagnostic Instrument

During our initial FMECA (based on our literature review and our knowledge or the medical diagnostic instrument), we estimated packaging heat sink de-lamination and degradation of the active region as the critical failure modes. After we performed ALT, we now believe that plastic encapsulation and active region degradation as the critical failure modes. Either of these failure modes will cause system level effects such as excessive drift requiring unscheduled calibration and delayed medical test results. See Table 5.3 for details.

Sr.#	Failure Modes/Mechanisms	Causes	Local Effects at LED level	System Effects in Medical equipment	Severity	Failure Effect Probability (ß)	Failure Mode Ratio (a)	Failure Rate	Operating Time (T) in hrs	Criticality #
1	Packaging failure (Heat Sink)	Heat sink de-lamination	- Decrease of optical output - Local heating effects	- Unscheduled module replacement - Delayed medical test results	3	0.4	0.3	1.8E-11	31500	6.7E-08
2	Degradation of plastic encapsulation	- Discoloration - Carbonization - Polymer degradation at high temperature	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	3	0.6	0.7	1.8E-11	31500	2.3E-07
3	Degradation of ITO layer	- Loss of Oxygen from ITO - De-adhesion	- Decrease of optical output - Non-uniform light emission	- Unscheduled module replacement - Delayed medical test results	4	0.3	0.1	1.8E-11	31500	1.7E-08
4	Packaging failure (Bond Wires)	- Electro-migration of bond wires - Burnout due to excessive current - Void formation at the solder metal stem - Reaction of solder metal with package electrodes	- Abrupt LED failure	- Unscheduled module replacement - Delayed medical test results	4	0.9	0.1	1.8E-11	31500	5.0E-08
5	Degradation of active layer	- Dislocation growth - Metal diffusion in AlGaInP - Heating effects of AlGaInP active region resulting in enhanced current injection	- Gradual decrease of optical output	- Excessive drift requires unscheduled calibration - Delayed medical test results	4	0.6	0.6	1.8E-11	31500	2.0E-07
6	Degradation of P-N metal contacts	- Interdiffusion	- Change in IV characteristics	- Design will accommodate minor changes in IV characteristics	5	0.4	0.2	1.8E-11	31500	4.5E-08

Table 5.3 FMECA table after Accelerated Life Test

6 Conclusions

FMECA approach, widely used for risk analysis, has been successfully applied to LED reliability and physics of failure investigation. In this study, we used FMECA to understand the criticality of LED failure modes when used in a medical diagnostic application. The FMECA was repeated and refined after conducting accelerated life testing of LEDs. Degradation of the plastic encapsulation and the active region were found to be the critical failure modes. These failures could cause unscheduled calibration of the diagnostic instrument and would cause delay in patient medical test results.

To simulate the medical diagnostic application, LEDs were driven in pulse/burst mode during Accelerated Life testing. The degradation rate was found to be logarithmic and this was used to estimate TTF of suspend data. LEDs not failed during ALT were excluded from the analysis since the focus was FMECA. For the LEDs that did fail, the chip degradation and specifically, active layer degradation dominated the initial period whereas the lens degradation was continuous during the entire period of the test. In a fraction of the tests, there was a change in spectral performance after the ALT. Where the peak wavelength decreased by 2nm (0.3%) changes in the active region were speculated to be the major cause. Where the optical power drop at 650nm was higher than that at 630nm, changes in the plastic encapsulation were suggested.

From the graphs or tabular data in prior published articles, we extracted the time required for the optical power output to reach 80% of its initial value. Iterative Regression Analysis was carried out to estimate the activation energy 'Ea' and 'n' for IPL. The activation energy 'Ea' and 'n' value during ALT are comparable. However, the time to failure during ALT is much higher compared to published data. We believe that this is due to the extremely low duty cycle (0.2%) at which the LEDs were driven during ALT to simulate the medical diagnostic application.

7 Acknowledgements

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