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Failure modes and effects criticality analysis and accelerated life testing of LEDs for medical applications

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ABSTRACT

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 of the LEDs. 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 and 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, and GaN–DH–DC. 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.

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 Figs. 1a and 1b.

We used the Failure Modes and Effects Criticality Analysis (FMECA) tool to identify the critical LED 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. Materials and methods

2.1. Materials

Commercially available AlGaInP 640 nm MQW LEDs were used in this research. The structure and material combinations of similar LEDs have been previously reported [6,9,11,12].

2.2. Methods

AlGaInP LEDs were put on accelerated life test as described in Section 3. We also performed regression analysis of prior published

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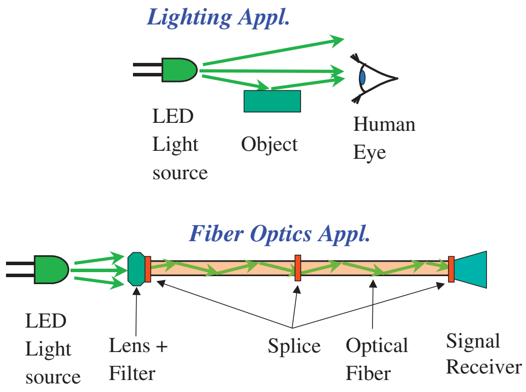

Fig. 1a. LED in lighting/Fiber Optics application. Ability of the optical receiver or human eye to detect presence or absence of light is important.

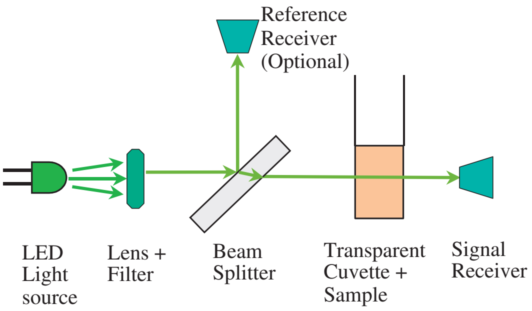

Fig. 1b. LED in medical diagnostic application. The precise value of light intensity is used to interpret patient results making the LED failure critical.

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 used to separate critical failure modes from the rest. The segregation is done based on the approximate probabilities of the failure modes and the severity of the outcomes. It 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

(a) Active layer [6,7,12] where electron–hole recombination occurs to emit light.
(b) P–N contacts [2] which provide electrical contact to the semiconductor chip.
(c) Indium tin oxide surface layer [16] used to improve current spreading and light extraction.
(d) Plastic encapsulation [21] which is a protective polymer layer and
(e) Packaging failures [2] such as bond wires and heat sink separation.

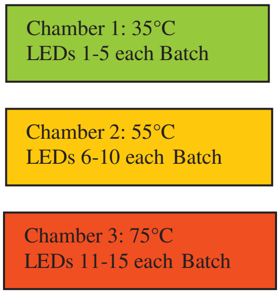

Fig. 2. Environmental test. AlGaInP LEDs were accelerated life tested simultaneously in three Environment Chambers. The LEDs were tested in batches with 15 LEDs in each batch.

A FMECA table is constructed and the criticality of the failure modes 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:

$$C_m = \beta\alpha\lambda t \tag{1}$$

3. Experimental

AlGaInP LEDs were accelerated life tested simultaneously in three Environment Chambers. The LEDs were tested in batches with 15 LEDs in each batch. See Fig. 2.

Per the need of the medical application in Fig. 1b, 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. See Fig. 3 for details of the timing diagram.

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. 4 for details.

4. Theory/calculation

4.1. Modeling for current and 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:

$$\mathrm{TTF} = A \cdot J^{-n} \tag{2}$$

where TTF is the time to failure in hours, J is LED current density in A/cm^2, A and n are +ve constants. Taking Ln on both sides:

$$\mathrm{Ln(TTF)} = \mathrm{Ln}A - n\mathrm{Ln} \cdot J \tag{3}$$

Eq. (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.

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

where T is the temperature in K, Ea is activation energy of the LED degradation, K is Boltzmann's constant, and B is the constant. We take a reciprocal of 'rate' to get 'time to failure' giving equation:

$$\mathrm{TTF} = Ce^{\left(\frac{Ea}{KT}\right)} \tag{5}$$

where TTF is the time to failure in hours, C is $1/B$ is another constant. Taking Ln on both sides: