LUMEN MAINTENANCE AND TREND PREDICTIONS FOR LIGHT-EMITTING DIODES USING REGRESSION ANALYSIS

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LUMEN MAINTENANCE AND TREND PREDICTIONS FOR LIGHT-EMITTING DIODES USING REGRESSION ANALYSIS

by

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LIST OF SYMBOLS

E_a	Activation energy
A	Ampere
k_B	Boltzmann constant
α	Decay rate constant
°C	Degree Celsius
$\mathbb{E}$	Expectation
exp	Exponential
I	Drive current
K	Kelvin
I_v	Luminous intensity output
L_p	Lumen maintenance life
log	Natural logarithm
ϕ	Normalised luminous intensity output
T_a	Operating ambient temperature of LED
T_j	Operating p-n junction temperature of LED
T_s	Operating solder point temperature of LED
B	Projected initial constant
$R_{\theta JS}$	Thermal resistance from junction to solder point
t	Time

LIST OF ABBREVIATIONS

ADT	Accelerated Degradation Test
AlInGaP	Aluminium Indium Gallium Phosphide
ChipLED	Chip Light-Emitting Diode
HTOL	High Temperature Operating Life Test
IES	Illuminating Engineering Society of North America
InGaN	Indium Gallium Nitride
LED	Light-Emitting Diode
MSE	Mean Square Error
RTOL	Room Temperature Operating Life Test

RAMALAN PENYENGGARAAN LUMEN DAN TREND UNTUK DIOD PEMANCAR CAHAYA MENGGUNAKAN ANALISIS REGRESI

ABSTRAK

Diod pemancar cahaya (LED) terkenal dengan kebolehpercayaan yang tinggi dan jangka hayat yang panjang. Jangka hayat LED amat bergantung kepada keadaan penggunaan seperti suhu operasi dan arus pemacu. Ujian jangka hayat terhadap setiap keadaan penggunaan adalah mahal dan tidak praktikal. Kajian terdahulu menggunakan persamaan Arrhenius dan model Black untuk menyiasat hubungan antara suhu operasi, arus pemacu dan jangka hayat pengekalan lumen. Namun, ramalan dengan menggunakan persamaan Arrhenius dan model Black adalah kurang tepat. Kajian ini bertujuan untuk menambah baik ramalan jangka hayat pengekalan lumen di bawah keadaan termal-elektrik yang berbeza dan model Eyring telah dicadangkan dalam kajian ini. Parameter model ditentukan dengan pendekatan regresi, yang memberikan kebagusan penyuaian model ramalan serta selang ramalan. Selain itu, satu kaedah untuk meramal trend penyusutan lumen bagi keadaan operasi yang berbeza berdasarkan model Eyring dan pendekatan regresi turut dibina. Hasil kajian menunjukkan jangka hayat and trend penyusutan lumen yang diramalkan oleh model Eyring lebih tepat berbanding dengan ramalan daripada persamaan Arrhenius dan model Black. Ralat peratusan ramalan jangka hayat pengekalan lumen model Eyring dengan menggunakan pendekatan regresi adalah kurang daripada 5%, sementara ralat purata kuasa dua ramalan trend penyusutan lumen adalah kurang daripada 6.82×10^{-4}.

LUMEN MAINTENANCE AND TREND PREDICTIONS FOR LIGHT-EMITTING DIODES USING REGRESSION ANALYSIS

ABSTRACT

Light-emitting diodes (LEDs) are known for their high reliability and long lifetime. Their lifetime is highly dependent on usage conditions such as operating temperature and drive current. It is costly and impractical to test the lifetime of LEDs on every usage conditions. Previous studies used the Arrhenius equation and Black's model to investigate the relationship of operating temperature, drive current and lumen maintenance life. However, the predictions using Arrhenius equation and Black's models were less accurate. This study aims to improve the prediction of lumen maintenance life under different thermal-electrical conditions and the Eyring model is proposed in this study. The model parameters are determined by regression approach, which provides the goodness of fit of the prediction model as well as the prediction interval. Apart from this, a method to predict lumen depreciation trend for different operating conditions based on the Eyring model and regression approach is also established. The findings show that the lumen maintenance life and lumen depreciation trend predicted by the Eyring model are more accurate compared to the predictions made by Arrhenius equation and Black's model. The percentage error of the lumen maintenance life predictions made by the Eyring model using regression approach is less than 5%, while the mean square error of the lumen depreciation trend made by the Eyring model using regression approach is less than 6.82×10^{-4}.

CHAPTER 1

INTRODUCTION

1.1 Introduction to Light-Emitting Diode

A light-emitting diode (LED) is a semiconductor device that emits light. The invention of LED has produced artificial lighting which is more efficient than the traditional incandescent bulb and fluorescent lamp. LEDs comparatively consume less energy, have longer lifetime and generally are more environmentally friendly. They have become the main choice for display backlights, luminaries as well as indicators. LEDs have brought colours and conveniences into our lives, and its significance is acknowledged even by the Nobel Prize committee. The 2014 Nobel Prize in Physics was awarded to the inventors of efficient blue light-emitting diodes that brought us bright and energy-saving white light source (The Royal Swedish Academy of Sciences, 2014). Figures 1.1 and 1.2 show LEDs in different packages.

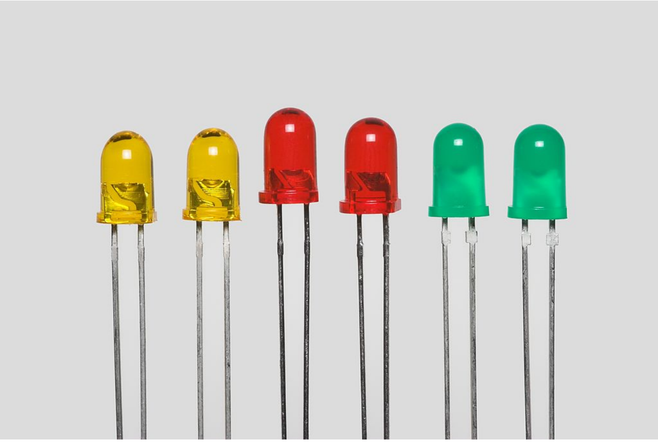


Figure 1.1. Through-hole 5mm LED in different colours (Afrank99, 2005).

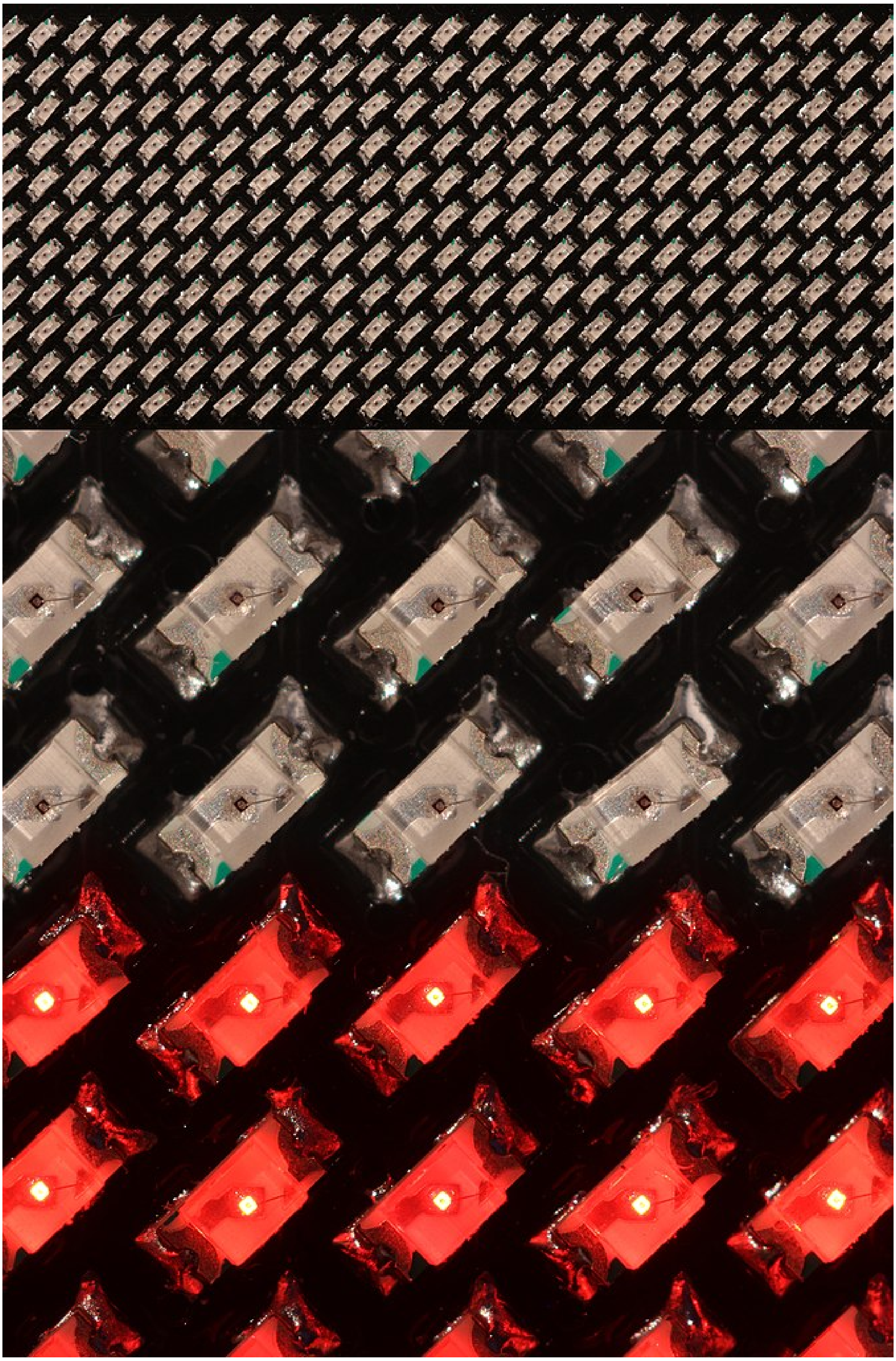


Figure 1.2. Composite image of a 11x44 LED matrix display using surface mount device LEDs. Top: A little over half of the 21x86 mm display. Center: Close-up of 0.8x1.6mm LEDs in ambient light. Bottom: LEDs in their own red light (Nyström, 2018).

LEDs are semiconductor devices that emit light when an electrical current is injected into it. They emit light by the radiative recombination of injected electrons and holes through the p-n (positive-negative) junction. When an electrical current passes through the LED, the valence electrons of the semiconductor are excited and they jump from the valence band to the conducting band. These electrons will eventually lose energy and return from the conducting band to the valence band. As illustrated in Figure 1.3, radiative recombination occurs when an electron from the conduction band directly combines with a hole in the valence band and releases a photon, which produces light in an LED (Fukuda, 1991).

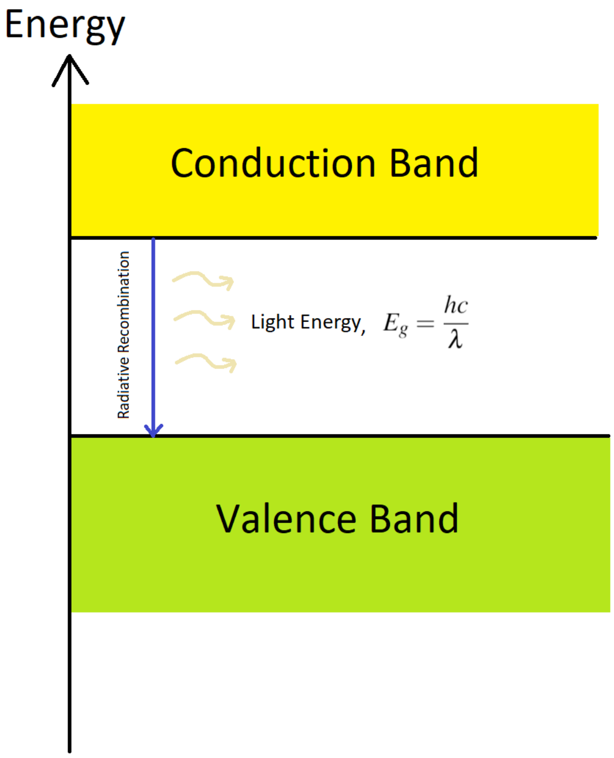


Figure 1.3. Energy band diagram. Radiative recombination occurs when an electron from the conduction band combines with a hole in valence band to release light energy (Fukuda, 1991).

LED devices are produced in various forms and packages. For example, Figure 1.1 shows traditional through-hole LEDs which are usually used as indicators. Figure 1.4 shows a chip LED (ChipLED) package mounted directly on a printed circuit board. ChipLED packages are small LED packages commonly used for automotive and consumer applications.

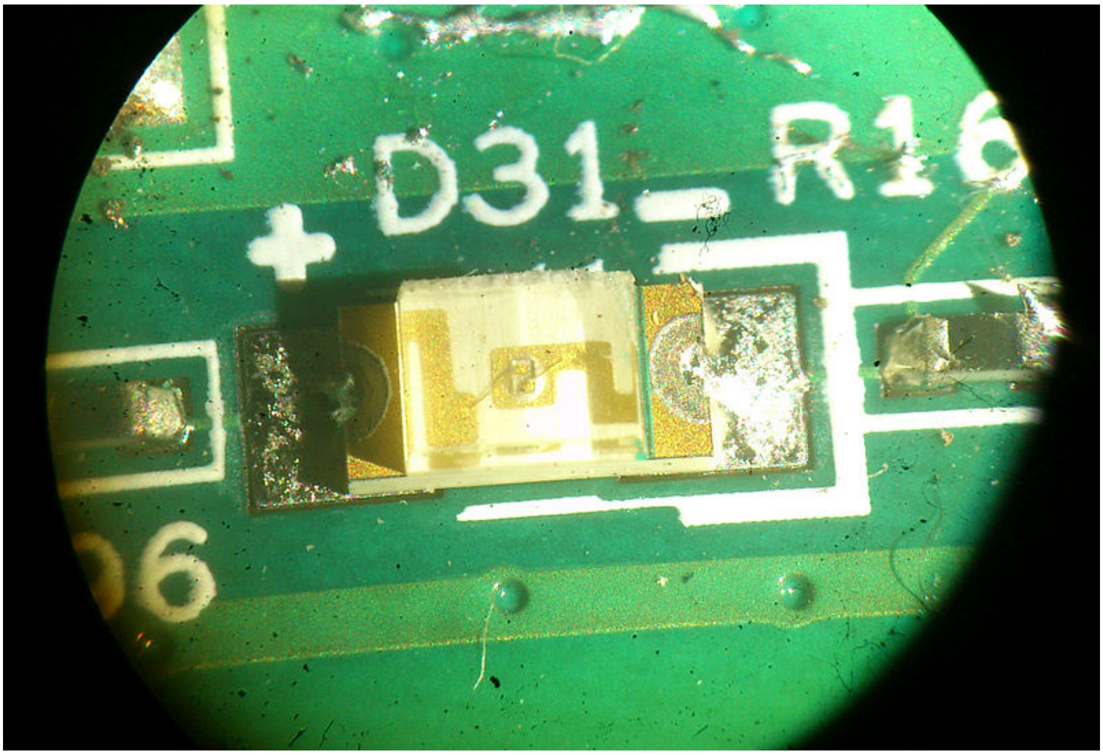


Figure 1.4. ChipLED mounted on a router printed circuit board (Sdk16420, 2020).

Figure 1.5 shows a cross-sectional diagram of a ChipLED package, marking the major components of an LED. The *die*, or known as the chip, is the semiconductor chip that emits light. The light travels through the *encapsulation* and out to the surrounding. The encapsulation is also used to protect the semiconductor chip from physical contact and moisture. The die sits on the electrically inductive die-attached epoxy that keeps the die attached on the lead frame. The *lead frame* is connected to one end of the electrical contact point, either the cathode or the anode. On the other hand, the *gold wire bond* connects the die to another lead frame which is another end of the electrical contact point.

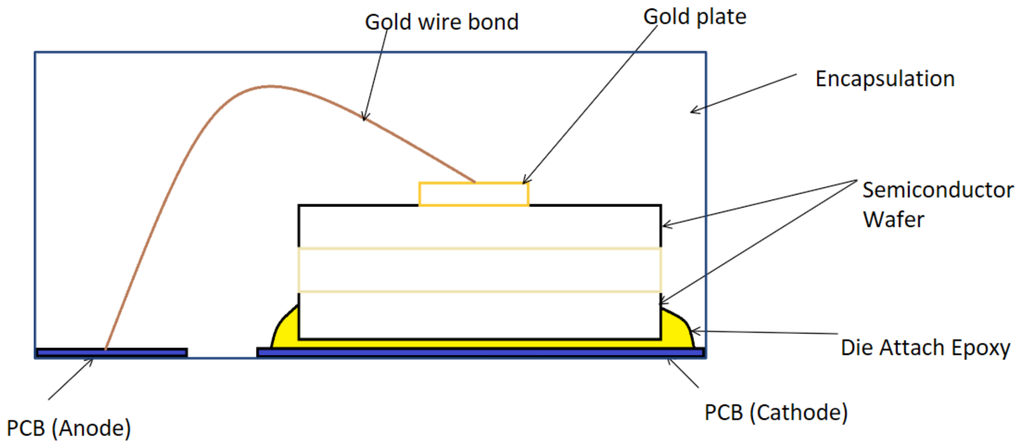


Figure 1.5. Cross-sectional diagram of a ChipLED package.

The amount of light emitted is quantified as the brightness of the LED, or formally, *luminous intensity* I_v, measured in candela (cd) (JEDEC Solid State Technology Association, 2000). The visible radiation power emitted by the LED is known as the *luminous flux*, Φ measured in lumen (lm). Luminous intensity can be measured by using a photometer, whereas luminous flux can be measured by using a photometer attached in an integrating sphere. The colour of the LED is defined by the emission wavelength, and the relationship is defined by

$$\lambda = \frac{hc}{E_g}, \tag{1.1}$$

where

λ = wavelength of LED,

h = Planck's constant (4.136×10^{-15} eV·s),

c = speed of light and

E_g = energy of bandgap.

The emission spectrum of an LED depends on the bandgap energy of the semiconductor. For example, indium gallium nitride (InGaN) is a semiconductor material which emits blue light. It has higher bandgap energy and a shorter wavelength in the visible electromagnetic spectrum. Aluminium gallium indium phosphide (AlInGaP) which has a lower bandgap energy produces light in the red and orange spectrum, which has a longer wavelength in the visible spectrum. Aluminium gallium arsenide (AlGaAs) has the lowest bandgap energy. It emits light in the infrared spectrum, which is not visible by our naked eye (Fukuda, 1991). If an LED consists of an InGaN die and the encapsulation contains yellow phosphor, the phosphor will convert the blue light emitted by the InGaN die into white light, resulting in a white LED.

1.2 Operation and Thermal Effect of LED

Figure 1.6 shows an LED soldered and attached to a printed circuit board. The printed circuit board is connected to the power supply and controller. When current flows through the die, part of the electrical energy is converted into light energy if the recombination of electron and holes successfully radiates light energy.

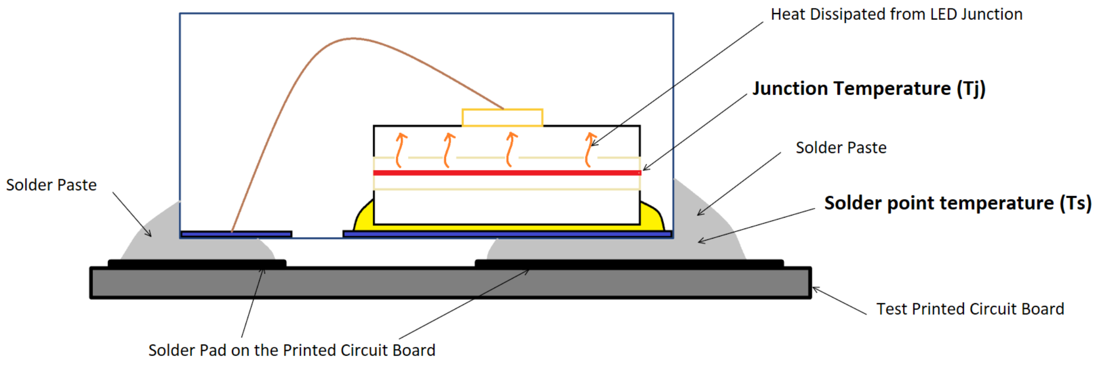


Figure 1.6. LED package soldered to the printed circuit board.

However, the rest of the electrical energy is converted into heat energy. The heat produced by the die causes self-heating in LED packages. Most of the heat that is generated in the die will travel downwards directly into the lead frame, rather than going through the gold wire bond or dispersing through the encapsulation. The area of contact between the die and the lead frame is larger than the area of contact between the die and the wire bond, hence rate of thermal conduction to the lead frame is higher. Since the thermal conductivity of the encapsulation is much lower compared to the metal lead frame, most heat produced will flow towards the lead frame.

As heat energy is produced, it contributes to a higher temperature in the LED package compared to the surrounding temperature. The surrounding temperature is known as *ambient temperature*, T_a. The temperature at the centre of the die is defined as the *junction temperature*, T_j. The centre of the die marks the highest temperature of the LED package.

In order to understand the thermal properties of the LED package, junction temperature is essential (Wang & Chu, 2012). However, there is no direct and non-intrusive way to measure the junction temperature of the LED. Instead, *solder point temperature*, T_s can be used to estimate the junction temperature by using the following formula:

$$T_j = T_s + P_H \times R_{\theta JS}, \tag{1.2}$$

where P_H is the dissipated power in the LED measured in W and $R_{\theta JS}$ is the junction-to-solder-point thermal resistance measured in K/W (JEDEC Solid State Technology Association, 2012). If significant amount of the electrical power, P_{elec} is converted into optical power P_{opt}, the power dissipation is defined as:

$$P_H = P_{elec} - P_{opt} = I_f \times V_f - P_{opt}, \tag{1.3}$$

where the electrical power is the product of the forward current I_f and the forward voltage V_f. Figure 1.6 also shows the location of the junction temperature T_j and solder point temperature T_s.

Heat energy dissipated from the LED junction is considered as wasted energy, and the heat trapped in the LED package generally accelerates the degradation process of LED. Degradation of LED and the measures taken to quantify such degradation will be explained in the next section.

1.3 Degradation of LED

Although LEDs are said to have a long lifespan of 50,000 hours and low failure rate (Fan, Yung, & Pecht, 2011), they age and degrade gradually. Signs of aging and degrading include change in colour and progressive dimming. These undesired changes usually happen when there are structural changes of the components in the LED. For instance, the chemical structure of the epoxy encapsulation changes after being exposed to light rays. The encapsulation will gradually become cloudy and yellowish, thus blocking light rays from leaving the encapsulation. Hence, the LED becomes dimmer and changes colour.

These signs of ageing are known as *degradation* of LED. There are other causes and effects that degradation can do to the LED. In order to quantify the dimming of LED, the luminous intensity (or luminous flux) have to be measured over a period of time using a photometer (or photometer attached in an integrating sphere). One of the standard degradation indicators that gauges the level of degradation of an LED is the *normalised luminous intensity*. The *normalised luminous intensity* is the fraction of luminous intensity remaining as compared to the initial luminous intensity of the LED. In mathematical formula, the normalised luminous intensity ϕ is defined as

$$\phi = \frac{I_{v0} - I_v}{I_{v0}}, \tag{1.4}$$

where I_v is the remaining luminous intensity output and I_{v0} is the initial luminous intensity output. The normalised luminous intensity is a standard and effective comparison of the degradation level of LEDs, as all LEDs have different initial luminous intensity output. On the other hand, the *normalised luminous flux*, or the fraction of luminous flux remaining as compared to the initial luminous flux of the LED is often used as degradation indicators too. *Lumen maintenance*, p is the maintained percentage of the initial luminous flux/intensity output, or equivalently, $p = \phi \times 100$. For example, normalised luminous intensity output of 0.7 is equivalent to lumen maintenance of 70%.

The *lumen maintenance life*, L_p is the elapsed operating time which an LED maintains $p\%$ lumen maintenance (usually $p = 70$ or $p = 50$). In other words, L_p is the time to $p\%$ lumen maintenance. For example, the lumen maintenance life L_{70} is the time to 70% lumen maintenance. The *lumen depreciation trend* is defined as the function of time that describes the lumen degradation path of the LED.

Figure 1.7 shows an example of normalised luminous intensity output of an LED plotted against time, as the normalised luminous intensity output drops gradually. However, it is tedious to measure the luminous intensity until significant degradation occurs. Moreover, the degradation behaviours differ under different operating conditions. For example, Figure 1.8 shows that LEDs degrade faster when drive current and operating temperature is higher. In other words, LEDs degrade faster on stricter conditions (higher drive current or operating temperature), and degrade slower on milder conditions (lower drive current or operating temperature). Hence, it is essential to test and model the degradation behaviour for reliability purposes as well as to obtain accurate prediction of the lumen maintenance life of an LED.

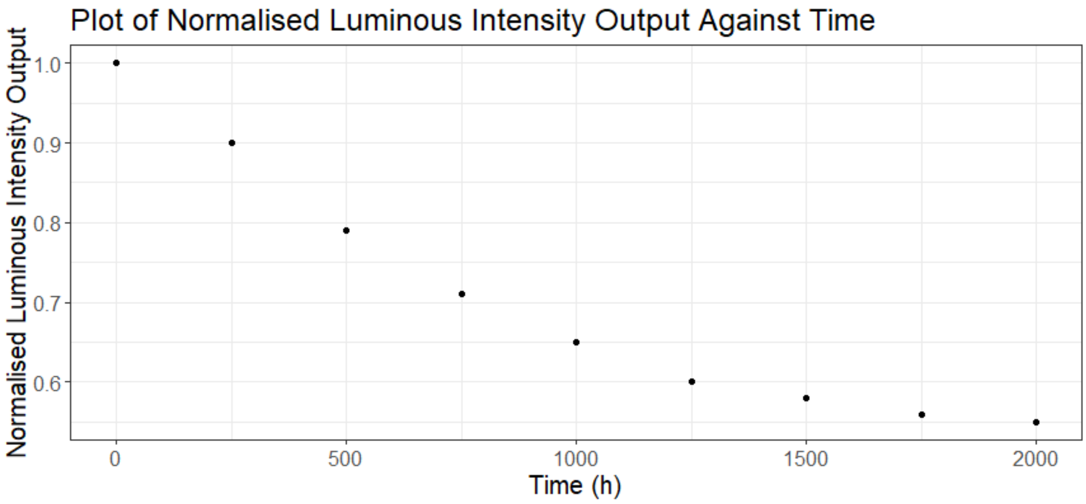
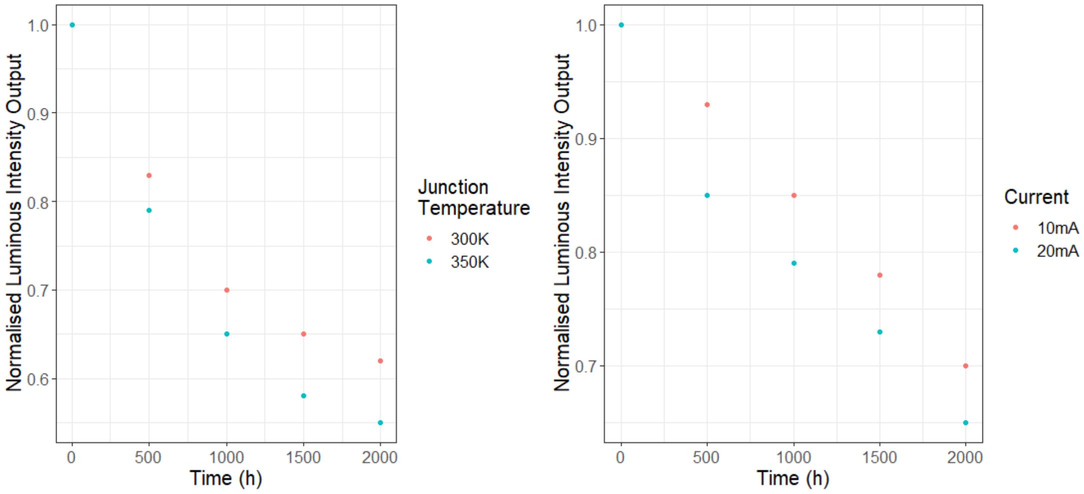


Figure 1.7. Typical normalised luminous intensity output degradation over time.



(a) Operating Temperature

(b) Drive Current

Figure 1.8. Different pace of lumen intensity depreciation of LED under different thermal-electrical conditions.

1.4 Degradation Tests

To understand the behaviour of product degradation in different conditions, *degradation tests* are introduced where samples of LED are put under operating conditions and environments that simulate the actual usage conditions. Operating environments include different surrounding temperatures and humidity. During these degradation tests, the luminous intensity and colour spectrum of the LED samples will be measured and recorded as degradation test data.

However, LEDs are highly reliable components. Hence, it is impossible to record significant degradation over a short period, and it is not practical to measure their degradation on every operating condition and environment as the tests are often time and cost consuming. Instead, these LEDs are forced to degrade faster by testing at tougher conditions than intended application conditions. Shorter testing time makes it easier to obtain adequate degradation data for analysis. Mathematical models and statistical methods are usually used to analyse these data in order to understand how this product behaves over a long period. For instance, mathematical models are used to *estimate lumen maintenance life* from the tested operating conditions. These estimated lumen maintenance life from tested conditions are used to *predict the lumen maintenance life* and to *predict the lumen depreciation trend* of the LED running at other milder operating conditions. The predictions are done using mathematical models as well. This testing methodology is known as *accelerated testing theory* (Tobias & Trindade, 2012).

Accelerated degradation testing theory is widely practised on LEDs to understand the degradation mechanism at a faster rate. The fundamental assumption of this theory is that the LEDs operating under right levels of elevated stress will have exactly the same failure mechanism as the LEDs operating under normal stress. For instance, if the chemical structure of the encapsulation changes at normal usage condition, the same type of changes should happen on elevated stress but at a faster rate.

Standard degradation tests have been proposed by the Illuminating Engineering Society of North America (IES) in TM-21-11 (Illuminating Engineering Society of North America, 2011) and LM-80-08 (Illuminating Engineering Society of North America, 2008). They have proposed standard methods for data collection, specifically addressing the standards of condition for the degradation test. An exponential decaying function is fitted to the test data to estimate lumen maintenance life of LED running on the tested condition. Then, Arrhenius model is used to predict the lumen maintenance life and lumen depreciation trend of LED running on different operating temperatures.

1.5 Problem Statement

The research was done with Company X. Company X has been using two methods: in-house methods (known as substitution method) and the method prescribed by IES on TM-21-11 to predict lumen maintenance life of an LED running under different thermal-electrical conditions. Company X is also using the TM-21-11 method to predict lumen depreciation trend. Specifically, given a pair of operating temperature and drive current, what is the lumen maintenance life and lumen depreciation trend of the LED device? However, these methods used by Company X produce significant prediction errors as compared to actual usage.

Company X needs more accurate and reliable methods for lumen maintenance life and lumen depreciation trend prediction in order to fully understand the degradation behaviour of their products. Accurate and reliable prediction will boost customers' confidence on their products.

1.6 Research Rationale

Accurate and practical mathematical models are crucial for predicting the reliability of LEDs. Although LED typically does not fail catastrophically during use and it can provide very long usable life, over time the luminous intensity of LED will slowly decline. Eventually, the light produced by the LED depreciates to a level where it is no longer considered adequate for usage. Hence, the industry needs to be able to predict the useful lifetime and lumen depreciation trend of LEDs accurately in order to understand the estimated time for replacement, as well as for the consumers to be able to make informed decisions on the return of investment of adopting new technology.

1.7 Research Objectives

This study focuses on developing methods for lumen maintenance life and lumen depreciation trend prediction of LED under thermal-electrical stress. The objectives of this study are:

1. to propose a mathematical model for lumen maintenance life prediction of LED under thermal-electrical stress and a method to determine the model parameters with better prediction accuracy, and
2. to propose a procedure to predict the lumen depreciation trend over time under different thermal-electrical conditions.

1.8 Research Questions

The research questions for this study, based on the research objectives are as follows:

1. Given a set of degradation data of LED running under thermal-electrical stress, what mathematical model can be used to predict lumen maintenance life more accurately as compared to previous methods? How to determine the model parameters?
2. How to predict the lumen depreciation trend over time under different operating current and temperature?

For example, given a set of degradation data,

1. How does the mathematical model proposed predict the lumen maintenance life for a specific operating condition?
2. How to predict a lumen depreciation trend of LED running on a specific operating condition?

1.9 Significance of the Study

This study provides a lumen maintenance life prediction model for thermal-electrical stress with better prediction accuracy. Furthermore, this study also presents a procedure to predict the lumen depreciation trend. These predictions are important in evaluating the longevity of an LED product and to improve degradation test routine of LED.

Besides, this study allows Company X to improve their lumen maintenance life and lumen depreciation trend prediction on their products. The method developed in this study allows them to benchmark their products against competitors. This method eliminates the need to test the LEDs at every operating conditions requested by the consumers, hence reducing costs and time to carry out reliability tests. A robust method to assess the reliability of LED boosts consumers confidence. Consumers will be able to make informed decisions in terms of the performance of the LED products, as well as to make an accurate estimation of the return on investment if they are considering using the LED products.

1.10 Organisation of Thesis

Existing literature on lumen maintenance life and lumen depreciation trend prediction will be reviewed and summarised under Chapter 2. The approach proposed to address the research questions will be presented in Chapter 3. The experimental setup, data measurements and approaches of data analyses will also be laid out. Chapter 4 will include results of data analysis and discussion of the results. This thesis ends with the conclusions in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter begins with the discussion of existing literatures related to the degradation mechanism of LEDs and the contributing factors are reviewed. Then, the relevant industry test standards used to predict the lumen maintenance life and lumen depreciation trend under various operating conditions are presented. The strengths and weaknesses of these standards and methods are assessed.

2.2 A Review of Literature Related to Degradation of LED

Although LEDs are long-lasting, they are subjected to degradation or even catastrophic failures. Degradation effects include decrease in brightness, shift in emission wavelength and increase in forward voltage. Table 2.1 shows the common failure and degradation mechanisms of the sub-components of LEDs (Huang et al., 2017). For example, the yellowing of encapsulant caused by thermal stress will reduce the transparency of the encapsulant, hence reducing the brightness of the LED. Electrical overstress will lead to chip/die deterioration and higher operating LED junction temperature. The additional heat produced will lead to degradation of the encapsulation and cause it to be more opaque, hence reducing light output from the LED chip.

Huang et al. (2017) and Fukuda (1991) described the contributing factors which caused LED degradation, i.e., thermal-stress, electrical-stress and hygromechanical

Table 2.1

Degradation, degradation mechanisms, and the triggering factors of the degradation mechanisms in LED.

Sub-component degradation	Degradation mechanism	Triggering factors
Chip deterioration	Crystal defects, dopant diffusion, Ohmic contact deterioration	Thermal-mechanical stress, electrical overstress, thermal stress
Encapsulant carbonisation/ yellowing	Decrease in transparency	Thermal stress, photodegradation, electrical overstress
Package housing yellowing	Decrease in reflectivity	Thermal stress, photodegradation
Lead frame deterioration	Copper diffusion, metal recrystallization, contamination	Thermal-mechanical stress, hygromechanical stress, harmful elements
Phosphor degradation	Reduced quantum efficiency caused by thermal quenching of phosphor	Thermal stress

Note: Adapted from *Degradation Mechanisms of Mid-power White-Light LEDs* by Huang et al. (2017).

(surrounding/ambient humidity) stress. These factors are related to the LED operating temperature, drive current and the surrounding humidity. In general, higher operating temperature and higher drive current cause the LED to degrade faster.

To assess the LED reliability, the manufacturing industry uses the following techniques: Failure Mode Mechanism and Effect Analysis (FMMEA), Fault Tree Analysis (FTA), Lifetime Test and Accelerated Lifetime Test (ALT). Lifetime tests are time consuming and costly as sudden failures do not occur often on LEDs even with long testing time (Nikulin, Limnios, Balakrishnan, Kahle, & Huber-Carol, 2010; Oliveira & Colosimo, 2004). Fan et al. (2011) developed a failure-based prognostic health management approach to understand the reliability of LED thoroughly from chip to system-level using FMMEA. This ‘bottom-up’ method of modelling failures and degradation can determine the potential failure mechanisms. However, it may not properly imitate actual failure processes under different stress levels.

To address these issues, Fan, Yung, and Pecht (2012) suggested the “general degradation path model” to model degradation as a function of time by using degradation data. The model is based on Lu and Meeker (1993). Accelerated degradation test on LED devices are used to accelerate the degradation mode under tougher operating condition. This method allows manufacturers to collect a reasonable amount of test data in shorter time to approximate the degradation rate under standard operating conditions (Tobias & Trindade, 2012). The time to failure, failure probability and failure rate can be determined by the accelerated degradation test methods.

In order to simulate operating conditions in labs and apply the accelerated degradation test on LEDs, there are certain common test conditions used in the industry. Fan, Qian, Fan, Zhang, and Pecht (2017) listed several environmental testing methods, such as the Room Temperature Operating Life Test (RTOL), High-Temperature Operating Life Test (HTOL) and Wet High-Temperature Operating Life Test (WTHOL) to simulate stress thermal, electrical and hygro-mechanical stress. Each manufacturer has their own specification for ambient temperature and forward current used in these operating tests for its product.

2.3 Industry Standards for Degradation Tests

The Illuminating Engineering Society of North America (IES) laid out the industry-wide accepted methodology for LED luminous flux depreciation test and data collection standards in LM-80-08 (Illuminating Engineering Society of North America, 2008). The luminous flux of the samples is measured according to LM-80-08 specification. Meanwhile, TM-21-11 (Illuminating Engineering Society of North America, 2011) described the methodologies to (1) *estimate lumen maintenance life of tested conditions*, (2) *interpolate/predict lumen maintenance life of other operating conditions* and (3) *predict the lumen depreciation trend of other operating conditions*.

1. Estimating lumen maintenance life of tested conditions:

   The methodology to estimate lumen maintenance life of tested conditions is used when the industry wishes to estimate or project the lumen maintenance life using limited test data (e.g., less than 6000 hours of luminous flux measurements). In short, the normalised luminous flux of the test data is fitted to an exponential decay function:

   $$\Phi(t) = B\exp(-\alpha t), \tag{2.1}$$

   where

   t is LED operating time in hours,

   $\Phi(t)$ is the average normalised luminous flux at time t,

   B is the projected initial constant, and

   α is the decay rate constant.

   The parameters α and β are determined by using the exponential least squares method. Then, the lumen maintenance life is estimated using the parameters determined by

$$L_p = \log\big(100 \times \frac{B}{p}\big)/\alpha \tag{2.2}$$

where p is the maintained percentage of initial lumen output. For example, the time taken for the LED to reach 70% of its original luminous flux, or the 70% lumen maintenance life is defined as:

$$L_{70} = \log\big(\frac{B}{0.7}\big)/\alpha \tag{2.3}$$

2. Interpolating/predicting lumen maintenance life of other operating conditions:

   On the other hand, the methodology to interpolate/predict lumen maintenance life of other operating conditions is used to predict the lumen maintenance life of LEDs running at different operating temperatures (specifically, different solder point temperature). The Arrhenius equation, which is used to predict the decay rate constant of the target temperature, is defined as

$$\alpha_i = A \exp\Big(-\frac{E_a}{k_B T_{s,i}}\Big), \tag{2.4}$$

where

α_i is the decay rate constant (from Equation (2.1)),

A is the pre-exponential constant,

E_a is the activation energy of LED in eV,

$T_{s,i}$ is the solder point temperature of the LED package in K corresponding to the decay rate constant, and

k_B is the Boltzmann's constant (8.62×10^{-5}eV/K).

In short, the solder point temperature and decay rate constant of two operating conditions are needed to estimate A and E_a. Then, the decay rate constant of the target operating solder point temperature can be predicted using the estimated A and E_a. The predicted decay rate constant is used to estimate the lumen maintenance life.

3. Predicting lumen depreciation trend:

   By using the decay rate constant predicted using the Arrhenius equation, the predicted lumen depreciation trend of a target operating solder point temperature is defined by the exponential decay function (2.1) with the predicted decay rate constant.

The complete data collection and analysis procedure for lumen maintenance life estimation, lumen maintenance life prediction and lumen depreciation trend prediction are described in the IES specifications. However, it is by no means perfect or suitable for every LED. The following section will describe some of its weaknesses, and suggestions to overcome it.

2.4 Weaknesses of LM-80-08 and TM-21-11 and Suggestions to Overcome Them

Previous studies (Fan et al., 2012; Fan, Yung, & Pecht, 2015) have shown the lumen maintenance life estimation, lumen maintenance life prediction and lumen depreciation trend prediction carried out using LM-80-08 and TM-21-11 methods are less accurate. In this section, the weaknesses and suggestions to overcome the weaknesses of each step are discussed in the following subsections.

2.4.1 Estimating Lumen Maintenance Life of Tested Conditions

One of the main discussed problems is the inadequacy of the exponential lumen degradation path model to fit the data. Different models have been proposed to improve the accuracy of lumen maintenance life projection. For clarity, the methods proposed are divided into two categories: deterministic methods and stochastic methods. The deterministic methods being summarised chronologically as follows:

1. Degradation-data-driven method (Fan et al., 2012):

   The authors addressed the lack of other reliability information such as confidence interval and reliability function in TM-21-11 standards. Based on the "general degradation path model" developed by Lu and Meeker (1993), the degradation-data-driven approach uses a degradation path model given by

   $$y_{ij} = D(t_{ij}) + \varepsilon_{ij}, \tag{2.5}$$

   where

   y_{ij} is the performance measurement,

   $D(t_{i,j})$ is the actual degradation path and

   ε_{ij} is the measurement errors

   of the ith LED unit at jth measurement time $t_{i,j}$. In this study, actual degradation path $D(t_{i,j})$ is defined as the exponential decay function from TM-21-11 $\big(\Phi(t) = B\exp(-\alpha t)\big)$. This model is used to estimate the failure time distribution and to evaluate the product's reliability (mean time to failure, confidence interval and reliability function). The authors did not compare the lumen maintenance life estimated by their proposed method.

2. Bi-exponential model (Wang & Lu, 2014):

   Following the approach proposed by Fan et al. (2012), a bi-exponential model, or sum of two exponential model is proposed to be used as the actual degradation path model in the degradation-data-drive approach. Again, the authors did not specify any improvement in lumen maintenance life estimation as compared to TM-21-11.

3. Double-exponential model (Bobashev, Baldasaro, Mills, & Davis, 2016):

   Several mechanisms within the LED packages produces a small increase in luminous flux before decreasing. The TM-21-11 approach does not take this behaviour into account, as the exponential decay function (2.1) is a strictly decreasing function. The authors proposed a model given by

   $$\phi(t) = \exp^{\alpha t}\left(B + \lambda(1 - \exp^{-Bt})\right), \tag{2.6}$$

   where

   ϕ is normalised luminous flux,

   t is operating time,

   α, B, λ and B are constants to be determined using non-linear regression.

   This approach gives a better estimation than the TM-21-11 approach. However, this approach is only effective for those LEDs that show small initial increase in luminous flux.