



Faculty of Mechanical Engineering

**INVESTIGATION OF OLED PERFORMANCE IN NON-OPERATED
MODE SUBJECTED TO HIGH THERMAL STRESS AND
HYGROTHERMAL AGING**

Muhammad Azrain bin Mohammad

Master of Science in Mechanical Engineering

2019

**INVESTIGATION OF OLED PERFORMANCE IN NON-OPERATED MODE
SUBJECTED TO HIGH THERMAL STRESS AND HYGROTHERMAL AGING**

MUHAMMAD AZRAIN BIN MOHAMMAD

**A thesis submitted
in fulfillment of requirements for the degree of Master of Science
in Mechanical Engineering**

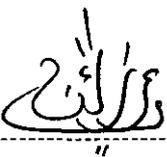
Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled “Investigation of OLED Performance in Non-operated Mode Subjected to High Thermal Stress and Hygrothermal Aging” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :  _____

Name : MUHAMMAD ADRAIN BIN MOHAMMAD

Date : 01/11/2019

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature : 
Supervisor Name : **TS. DR. MUHD RIDZUAN BIN MANSOR**
PENSYARAH KANAN
FAKULTI KEJURUTERAAN MEKANIKAL
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
Date : 01/11/2019

DEDICATION

To ALLAH the Greatest of All,

To my dearest Ibu, Ayah and siblings,

To my supportive Supervisors,

To all my beloved colleagues,

Thank you for walking along with me in this rough and tough journey together,

Every single memory will be craved in my heart.

ABSTRACT

The attention towards organic light emitting diodes (OLEDs) has remarkably increased in recent years due to numerous advantages offered. However, the degradation issues responsible for the short lifetime of the devices, particularly after being exposed to high temperature and humidity has yet to be fully established, even with the invention of encapsulation layers. The root cause of OLED degradations may also be diverse, and hence, involving the outcomes and failure mechanisms. Therefore, a comprehensive knowledge on this particular subject is essentially important as it is the key to unravel the short lifetime issues of OLEDs. Hence, the main purpose of this research is to study the OLED performance subjected to high thermal stress and hygrothermal effect, specifically via non-operated mode. Nonetheless, an optimum discharge time must first be acquired to ensure that the parasitic capacitance (due to thin structure of the OLEDs) can be fully eliminated for the purpose of data validity. In this study, a batch of commercially-available OLEDs has been employed. An on/off cycles approach was employed in which the OLED samples were switched-on (T_{on}) and -off (T_{off}) at a specific time in determining the optimum discharge time. For high thermal test, the OLEDs were subjected to several temperatures in a controlled oven, including temperatures higher than the glass transition temperature (T_g) of the polymer material (~ 126 °C). Whilst in the hygrothermal aging test, the OLEDs were exposed to 85 °C and 85% RH in a humidity chamber at different exposure time. A black box and a chroma-meter were used to monitor the changes in the luminance and voltage-drop values, while an interlayer analysis was performed by using focused ion beam (FIB) and field emission scanning electron microscope (FESEM) equipment. For this particular OLED, the optimum discharge time was found to be at T_{off} 40 s. As for high thermal test, it was observed that the luminance value has dramatically dropped by 90% from the initial value after the OLEDs were stressed at 135 °C, while the voltage-drop greatly escalated from 8.5 V to 30.2 V. The presence of voids between the layers were also evident due to the interfacial thermal stress. The voids have allowed the infiltration of moisture and oxygen into the device and eventually led to the formation of bubble-like defects on top of the cathode's surface. This condition has resulted in deterioration of electrons injection path and permanently changed the morphological structures of the devices. Through calculations, it was verified that the interfacial thermal stress between the layers can be reduced about 50% as the thickness of the polymer layer was increased by two times of its initial dimension. While in hygrothermal aging test, two primary modes of failure were observed. The first process involves the formation of centered-burst defects, and the second mode is the ring-shaped delamination of cathode film. Essentially, both failure modes have destroyed the entire aluminum film and permanently changed the morphological surface of the device which has led to the total failure of the device. As a conclusion, the findings of this study profoundly emphasized on the performance and failure behaviors in OLED under extreme conditions, specifically via non-operated mode.

ABSTRAK

Perhatian terhadap diod pemancar cahaya organik (OLEDs) telah meningkat dengan amat memberangsangkan sejak beberapa tahun ini disebabkan oleh banyak kelebihan yang ditawarkan. Namun, isu-isu degradasi yang menyebabkan jangka hayat alat peranti tersebut pendek, terutamanya selepas terdedah kepada suhu dan kelembapan yang tinggi masih belum dapat diselesaikan walaupun terdapat penghasilan lapisan pengkapsulan. Tambahan pula, banyak punca yang boleh menyumbang kepada penyusutan OLED, dan seterusnya, hasil dan mekanisme kegagalan yang terlibat. Oleh itu, maklumat komprehensif berkaitan perkara ini adalah amat penting untuk diperoleh kerana ia merupakan kunci dalam menyelesaikan isu jangka hayat pendek bagi OLEDs. Maka, tujuan utama kajian ini adalah untuk mengkaji prestasi OLED yang dikenakan tekanan termal tinggi dan kesan higrotermal, khusus dalam mod tidak aktif. Selain itu, masa pelepasan optimum mestilah diperoleh terlebih dahulu bagi memastikan kapasitansi parasit (kerana struktur OLEDs yang nipis) dapat disingkirkan sepenuhnya bagi tujuan kesahan data. Dalam kajian ini, satu kelompok OLED komersial telah digunakan. Kaedah kitaran buka/tutup telah digunakan di mana sampel OLED tersebut dibuka (T_{on}) dan ditutup (T_{off}) pada masa tertentu bagi menentukan masa pelepasan optimum. Bagi ujian tekanan termal tinggi, beberapa bacaan suhu telah dikenakan terhadap OLEDs di dalam ketuhar yang terkawal, termasuk suhu yang lebih tinggi daripada suhu peralihan kaca (T_g) bahan polimer (~ 126 °C). Dalam ujian higrotermal pula, OLEDs telah didedahkan kepada 85 °C dan 85% RH di dalam kebuk kelembapan pada masa dedahan yang berbeza. Sebuah kotak hitam dan meter-kroma telah digunakan bagi memantau perubahan nilai luminans dan susut-voltan, manakala analisis antara lapisan telah dijalankan dengan menggunakan peralatan alur ion berfokus (FIB) dan mikroskop pancaran medan elektron (FESEM). Masa pelepasan optimum bagi OLED ini adalah pada T_{off} 40 s. Bagi ujian tekanan termal tinggi pula, nilai luminans didapati telah menurun dengan mendadak sebanyak 90% dari nilai awal selepas OLED didedahkan pada suhu 135 °C, manakala susut-voltan telah meningkat dari 8.5 V hingga 30.2 V. Kehadiran lowong antara lapisan juga tampak jelas disebabkan oleh tekanan haba antara muka. Lowong itu telah membenarkan penyusupan lembapan dan oksigen ke dalam peranti dan akhirnya membawa kepada pembentukan gelembung di atas permukaan katod. Keadaan ini telah menyebabkan kemerosotan laluan elektron dan mengubah struktur morfologi peranti secara kekal. Melalui pengiraan, didapati bahawa tekanan haba antara lapisan boleh dikurangkan kira-kira 50% jika ketebalan polimer dinaikkan dua kali ganda daripada dimensi asal. Dalam ujian higrotermal pula, dua mod kegagalan utama telah direkodkan. Proses pertama adalah pembentukan kecacatan berpusat-pecah, dan mod kedua adalah pelekangan berbentuk cincin pada lapisan katod. Pada dasarnya, kedua-dua mod tersebut telah merosakkan keseluruhan lapisan aluminium dan mengubah morfologi serta telah menyebabkan kegagalan peranti secara keseluruhan. Kesimpulannya, hasil kajian ini menekankan akan kegagalan tingkah laku dalam OLED bawah keadaan melampau, khususnya dalam mod tidak aktif.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my greatest gratitude and praises to Allah S.W.T, the Almighty because without His guidance and blessings, I will not be able to finish this study. To Him be the everlasting glory.

Secondly, I wish to express my gratefulness to my supervisor and co-supervisor, Ts. Dr. Muhd Ridzuan bin Mansor and Dr. Siti Hajar binti Sheikh Md. Fadzullah for their constant supervision and advices. I am thankful for the tireless and endless hours in enlightening arguments and uncertainties throughout this study.

I am also thankful to Prof. Dr. Ghazali bin Omar for providing a positive and productive environment, giving a continuous support and faithful assistance to his students. Besides, I really appreciate all the constructive comments and suggestions given by Advanced Materials and Characterization Lab (AMCHAL) lecturers and members. Importantly, my study would not be possible without the short-term research grant from the Ministry of Higher Education (MOHE), Zamalah Scheme of Universiti Teknikal Malaysia Melaka (UTeM), as well as the grant funding from JABIL Circuit Sdn. Bhd. Penang.

I am deeply indebted to Arpah binti Chah and Mohammad bin Abu Bakar, my beloved parents. Thank you for the unconditional loves and encouragement. I am also grateful to my dearest best friend, Muhamad Muaz bin Nasaruddin, for his endless assistance and moral support through ups and downs all these years. The bitter-sweet moments of ours will never ever be forgotten.

I also wish to express my appreciation to Mr. Lim Lai Ming and Mr. Zambri bin Samsudin from JABIL Circuit Sdn. Bhd. Penang, as well as to Ms. Siti Rahmah binti Esa from MIMOS Semiconductor (M) Sdn. Bhd., and all UTeM's assistant engineers whose assistances have made this work possible. Not forgetting, my humble apology as it is beyond my reach personally mentioned those who are involved directly or indirectly one-to-one in the completion of this study.

TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENTS	iii
TABLE OF CONTENTS	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF ABBREVIATIONS	xiii
LIST OF PUBLICATIONS	xv
CHAPTER	
1. INTRODUCTION	1
1.1 Background study	1
1.2 Problem statement	4
1.3 Objectives of study	5
1.4 Scopes of study	6
1.5 Thesis outlines	7
2. LITERATURE REVIEW	8
2.1 Introduction	8
2.2 Light and artificial lightings	8
2.2.1 Solid-State Lighting (SSL)	13
2.2.2 Differences between OLEDs and LEDs	15
2.3 Brief history of OLED	19
2.4 Developments of OLED	20
2.4.1 OLED displays	20
2.4.2 OLED lightings	22
2.5 Configurations of OLED	25
2.5.1 Single-layer	26
2.5.2 Double-layer	27
2.5.3 Multi-layer	28
2.6 Light emitting mechanism of OLED	29
2.7 Evaluation parameters of OLED	30
2.7.1 Luminance	31
2.7.1.1 CIE color-coordinates	33
2.7.1.2 Discharge time	34
2.7.2 Correlated Color Temperature (CCT)	37
2.7.3 Voltage-drop	38
2.8 Failure mechanisms of OLED	40
2.8.1 Heat-related mechanisms	42
2.8.1.1 Internal heat failures	43
2.8.1.2 External heat failures	59
2.8.1.3 Research gap (for thermal stress effect)	64
2.8.2 Humidity-related mechanisms	66

2.8.2.1	Passivation techniques	78
2.8.2.2	Research gap (for hygrothermal aging effect)	89
2.9	Summary	90
3.	RESEARCH METHODOLOGY	91
3.1	Introduction	91
3.2	OLED material	93
3.3	Experimental set-up	95
3.3.1	Discharge time test	96
3.3.2	High thermal test	97
3.3.3	Hygrothermal aging test	99
3.4	Materials' characterizations	100
3.4.1	Luminance verification using black box	100
3.4.2	Thermal analysis using Differential Scanning Calorimetry (DSC)	103
3.4.3	Interlayer analysis using dual beam equipment	103
3.5	Summary	104
4.	RESULT AND DISCUSSION	105
4.1	Introduction	105
4.2	Determination of optimum discharge time	105
4.3	Effect of high thermal stress	110
4.4	Effect of hygrothermal aging	129
5.	CONCLUSION AND RECOMMENDATIONS	142
5.1	Conclusion	142
5.2	Recommendations for future study	144
	REFERENCES	145

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	General differences between OLEDs and LEDs	18
2.2	Differences between OLED displays and OLED lightings	23
2.3	Comparison of parameters between electronic lightings (Mertens, 2015a; Mertens, 2015b; Chitnis et al., 2016; Johnson, 2017)	24
2.4	Degradation factors of OLED devices (Xia et al., 2007)	41
2.5	Summary of the encapsulation film effects on the formation of dark spots and OLED performances	83
4.1	Initial and final value of OLED luminance output at different T_{off}	107
4.2	Luminance performance (cd/m^2) of the OLED samples subjected to different temperatures ($^{\circ}C$)	112
4.3	Changes of CIE color-coordinates (x, y) and CCT values of OLED samples	113
4.4	Total (mm^2) and percentage (%) of the defected area of the OLED samples at different temperature ($^{\circ}C$)	119
4.5	Luminance performance (cd/m^2) of OLED at different exposure time (h)	130
4.6	Performance of CIE color-coordinates (x, y) and CCT values of OLED samples	132

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Schematic diagram of the electromagnetic spectrum (Kuehni, 2013)	9
2.2	Historical evolution of artificial lighting technology (Chitnis et al., 2016)	11
2.3	Chip emitter of LEDs which is tinier than a grain of rice (Leadford, 2012)	17
2.4	Wearable OLED displays as health-monitoring devices (a) thin flexible organic chip for muscle contraction sensor (Bansal et al., 2015), and (b) pulse oximeter sensor for measuring pulse rate and arterial blood oxygenation (Lochner et al., 2014)	21
2.5	Promising qualities of OLED lightings (a) transparent, and (b) flexible which allows the panels to be formed into any desired shapes (LG OLED Light, 2014)	23
2.6	Configuration of single-layer structure of an OLED	26
2.7	Configuration of double-layer structure of an OLED	27
2.8	Configuration of multi-layer structure of an OLED	28
2.9	Light emitting mechanism of an OLED	30
2.10	CIE chromaticity diagram which represents different CIE color-coordinates (Kalyani et al., 2017)	33
2.11	CCT scale of color appearances of a luminaire (Elemental LED Inc., 2015)	37

2.12	An increase in the voltage-drop with time of OLEDs (Burrows et al., 1994)	38
2.13	Correlation between voltage-drop and luminance of OLEDs (Pekkola, 2017)	39
2.14	Electrical resistances within an OLED due to different interfaces contact (Tyagi et al., 2016)	43
2.15	IR thermography images of an OLED operating at 10, 20, 30, and 40 mA/cm ² (Tyagi et al., 2014)	44
2.16	Defect formed on HTL of OLEDs (a) An optical microscope image of the defect (b) Surface profilometer illustrating the diameter and height of the defect (Davidson-Hall and Aziz, 2015)	45
2.17	Cross-section of Al grain cluster nuclei: (a) only cavity is formed, (b) only foreign particles are present, and (c) both cavity and foreign particles are observed	47
2.18	Growth mechanism of non-emissive spots: (a) electro-migration process and decomposition of organic layer due to concentrated electric current and heat generation, respectively, (b) cavity is formed and crystalline foreign particles are produced, and (c) Al grain cluster is formed and protrudes from cathode layer	48
2.19	Variability in surface roughness between anode, cathode and organic layer results in instability of electric current	50
2.20	Failure mechanism due to short circuit: (a) normal operation, (b) diversion of current flow into short circuit, (c) large electric current dashed into the short circuit in a circular manner, (d) accumulated al metal atoms will be created at the center of the defect, and (e) al cathode at the circular boundary will become thin enough and not able to inject electrons to cross the boundary limit (Cumpston and Jensen, 1996)	51

2.21	SEM image of star-shaped opening at the top of Al film (Zhou et al., 2000)	54
2.22	Linear relationship between critical temperature (°C) and T _g (°C) (Tokito et al., 1998)	56
2.23	Half-decay lifetime performance HTL materials (Fujikawa et al., 2000)	58
2.24	Effect of external heat on luminance (Parker et al., 1999)	60
2.25	Research gap of this study (high-thermal induced failure)	65
2.26	Shadow effects on OLED's surface due to: (a) organic piece spluttered during organic deposition process and (b) presence of impurities before organic deposition process	68
2.27	Proposed mechanism of dark spot growth: (a) top view and (b) side view of OLED devices	71
2.28	Process of dark spot growth: (a) presence of pinhole allow the penetration of water vapor, (b) bubbles formation due to hydrogen gas evolution, and (c) burst bubbles provide extra entry ports for water vapor penetration	73
2.29	Mechanism of dark spot growth: (a) oxide layer is formed due to oxygen permeation, (b) pinhole is sealed due to increment of molecular volume, and (c) delamination of electrode will block electron injection	76
2.30	Formation of circle gray rings in unbiased condition (Schaer et al., 2001)	77
2.31	Structure of OLED encapsulation: (a) single layer of Al ₂ O ₃ , (b) combination of Al ₂ O ₃ /ZrO ₂ layers, (c) hybrid layer of Al ₂ O ₃ /ZrO ₂ /alucone layers, and (d) three pairs Al ₂ O ₃ /ZrO ₂ /alucone layers	81
2.32	Research gap of this study (hygrothermal induced failure)	90

3.1	Flow chart of research activities	92
3.2	Configuration of OLED samples (a) schematic diagram and (b) FIB cross-sectional view, taken at 100 000× magnification	93
3.3	Captured images of OLED surface structure (a) total of 58×58 individual modules (within the red dotted-line area), (b) zoomed top view image of the OLED modules, taken by Zeiss Axioskop 2 MAT at 50× optical magnification and (c) schematic diagram of electrical circuit of the OLED	95
3.4	Cyclic diagram of the on/off approach at fixed T_{on} and different T_{off}	96
3.5	Schematic diagram of the high thermal test	98
3.6	Schematic diagram for the in-house luminance set-up	101
3.7	Measuring area of the chroma-meter that covers about 30% of the whole sample was fixated at the center of OLED samples throughout the luminance test	102
3.8	Removal of the glass encapsulation layer before the FIB-FESEM interlayer analysis was conducted	104
4.1	Performance of luminance outputs over cycles at different T_{off}	106
4.2	Schematic diagram of the discharge process. The organic layer acted like a closed-loop path to allow the charge-balance process within the OLED to occur (as indicated by the dashed arrows)	109
4.3	T_g value of OLED's polymer layer (~126 °C)	111
4.4	CIE color-coordinates of OLED samples at different temperatures	114

4.5	Changes of light emission (right hand-side) with respect to the top view of FIB images (left hand-side), captured at 80× magnification: (a) 25 °C (as-received samples) by which the performance is similar to the stressed OLEDs at 100 °C and 125 °C, (b) 135 °C, (c) 145 °C (no light emitted), and (d) FIB image of stressed OLED at 200 °C. The red circles show bubble-like structures (on top of the cathode layer)	117
4.6	Effect of high storage temperature on the percentage of defected area (PDA) and total defected area (TDA)	119
4.7	Performance of voltage-drop (V) of the OLED samples in order to maintain a current of 40 mA and their luminance performance with respect to the surrounding temperature (°C)	120
4.8	Schematic diagram of expansion and contraction process (as pointed by the arrows) within the OLED structure due to different CTE rate of materials employed	121
4.9	Formation of voids (in red circle) between the anode layer and the bulge of the separation line at 200 °C, taken at 100 000× magnification and tilted at 52°	126
4.10	Schematic diagram of a separation line between the OLED modules which act as stress raisers. The arrows illustrate the expansion process (forces) between the modules, while the red lines represent the stress distributions	126
4.11	Cross-sectional view of the separation line at (a) non-defected part (as-received sample), and (b) defected part of the OLED after thermally stressed at 200 °C. . Both images are taken at 15 000× magnification and tilted at 52°	127

4.12	Cross-sectional view of bubble-like defect (a) cut area as pointed by the arrow, taken at 1000× magnification, and (b) zoomed image of the cross-sectional area, taken at 80 000× magnification. Both images are tilted at 52°	128
4.13	Effect of hygrothermal aging on the luminance performance (FL) of OLED samples and the percentage of luminance reduction (PLR) at a different time of exposure	130
4.14	CIE color-coordinates of OLED samples at different time of exposure	133
4.15	One unit of OLED sample at 504 h (a) before and (b) after being exposed to 85 °C, 85% RH	135
4.16	Formation of bubble-like defects (a) view of the OLED surface, taken at 25 000× magnification and tilted at 30°, (b) area for EDS mapping analysis, (c) presence of aluminum-based material of cathode layer (blue color), and (c) the presence of carbon-based material of polymer layer (red color)	136
4.17	Mode of failures in failed OLED (a) centered-burst bubble, (b) ring-shaped delamination, (c) destroyed cathode film, and (d) damaged surface of OLED which caused by exploded bubble defects. The black arrows denote the debris of the damaged layers	137
4.18	Formation of bubble defect in OLED (a) cathode film was lifted-up due to outwards pressure that caused by expansion of trapped moisture, and (b) scattered miniature virgin blisters (non-exploded bubbles) on the cathode's surface	138
4.19	Modes of failure in OLED induced by hygrothermal aging (a) hot gas is exploded from the center of the bubble defect, and (b) hot gas burst-out from the boundary region since the stress concentrations are majorly located at the edges of the bubble defect. Both failure modes have utterly destroyed the entire cathode film	140

4.20 Cross-sectional view of the OLED sample (a) obliterated cathode film, taken at 1500× magnification, and (b) zoomed image of the obliterated part, taken at 10 000× magnification. Both images are tilted at 30° 140

LIST OF ABBREVIATIONS

CCT	- Correlated Color Temperature
CFL	- Compact Fluorescent Lamps
CIE	- Commission Internationale de l'Éclairage
CO ₂	- Carbon Dioxide
CRTs	- Cathode Ray Tubes
CTE	- Coefficient of Thermal Expansion
DSC	- Differential Scanning Calorimetry
EL	- Emissive Layer
ETL	- Electron Transport Layer
FESEM	- Field Emission Scanning Electron Microscope
FIB	- Focused-Ion Beam
h	- Hour/s
HID	- High-Intensity Discharge
HTL	- Hole Transport Layer
Hz	- Frequency
IEA	- International Energy Agency
K	- Kelvin
kWh	- kilowatt-hours
LCDs	- Liquid Crystal Displays
LEDs	- Light Emitting Diodes
mA	- Milli-Ampere
MPa	- Mega Pascal
mPEG	- Methoxypolyethylene Glycol
OLEDs	- Organic Light Emitting Diodes
PLEDs	- Polymer Light-Emitting Diodes

PPV	- Poly(p-phenylene vinylene)
Pt	- Platinum
R&D	- Research and Development
RH	- Relative Humidity
s	- Second
SSL	- Solid-State Lighting
T_g	- Glass Transition Temperature
T_{off}	- Switch-off Time
T_{on}	- Switch-on Time
TVs	- Televisions
UN	- United Nations
UN-IYL	- International Year of Light and Light-based Technologies
UV	- Ultraviolet
V	- Volt

LIST OF PUBLICATIONS

The research papers produced and published during the course of this research are as follows:

1. Azrain, M.M., Omar, G., Mansor, M.R., Fadzullah, S.H.S.M. and Lim, L.M., 2019. Failure Mechanism of Organic Light Emitting Diodes (OLEDs) Induced by Hygrothermal Effect. *Optical Materials*, pp. 85–92. (Index: ISI | W.O.S Rank: Q2 | Impact Factor: 2.320 | Published).
2. Azrain, M.M., Mansor, M.R., Omar, G., Fadzullah, S.H.S.M., Esa, S. R., Lim, L.M., Sivakumar, D. and Nordin, M.N.A., 2019. Effect of High Thermal Stress on The Organic Light Emitting Diodes (OLEDs) Performances. *Synthetic Metals*, 247, pp. 191–201. (Index: ISI | W.O.S Rank: Q2 | Impact Factor: 2.526 | Published).
3. Azrain, M.M., Mansor, M.R., Omar, G., Fadzullah, S.H.S.M., Sivakumar, D., Lim, L.M. and Nordin, M.N.A., 2018. Analysis of Mechanisms Responsible for The Formation of Dark Spots in Organic Light Emitting Diodes (OLEDs): A Review. *Synthetic Metals*, 235, pp. 160–175. (Index: ISI | W.O.S Rank: Q2 | Impact Factor: 2.526 | Published).
4. Azrain, M.M., Mansor, M.R., Fadzullah, S.H.S.M., Omar, G., Lim, L.M., Zambri, S. and Sivakumar, D., 2018. Determination of Optimum Discharge Time for Organic Light Emitting Diode (OLED). *Journal of Advanced Manufacturing Technology*. (Index: SCOPUS | In-Press).

CHAPTER 1

INTRODUCTION

1.1 Background study

The past decades have witnessed the rapid developments and remarkable achievements in the field of artificial lightings. Currently, the artificial lightings have underpinned the 21st century appliances; from the latest medical apparatuses, to the applications of modern advertising boards, including advanced display devices such as smartphones, televisions and laptops. In upcoming years, the interest in artificial light will constantly grow and lead to additional advancements in the light-based applications (Vandergriff, 2008). Relatively, the artificial lightings have improved the quality standard of living and safety.

However, the uncontrollable usage of the artificial lightings has caused light pollution, especially in crowded populated areas (Hölker et al., 2010a; Falchi et al., 2016). The light pollution can be defined as the inefficient, unnecessary, misused or excessive consumption of artificial light that exhibits numerous adverse effects on health and ecosystem (Hollan, 2008; Hölker et al., 2010b). Hence, this undesirable event signifies that the electricity (energy) used for lightings is ineffective or merely wasted.

Powell et al. (2008) have reported that over 2,650 billion kilowatt-hours (kWh) has been consumed by more than 30 billion lamps across the globe. The electricity associated with this occasion is approximately 19% of the worldwide electricity production. Correspondingly, more than 1.5 billion tons of greenhouse gas per annum has been released into the atmosphere. According to the International Energy Agency (IEA), this includes

about 1,900 metric tons of carbon dioxide (CO₂) emission or equivalent to 70% of CO₂ emanated from the world's light vehicles (Azevedo et al., 2009). In fact, almost half of the total CO₂ emissions is caused by the production of global electricity, specifically for lighting purposes (Bessho and Shimizu, 2012). This particular event is forecasted to be much worse in the approaching years since the usage of the electricity for artificial lightings is expected to increase by ~20% each year (Hölker et al., 2010b).

Henceforth, the United Nations (UN) has declared the year 2015 as the International Year of Light and Light-based Technologies (UN-IYL) to apprise the public on the importance of light; from its technological and manufacturing impacts, to applications in healthcare, as well as from poor lighting to light pollution (Kyba et al., 2014). The UN-IYL 2015 is seemed to be a significant opportunity to enlighten the issues of sustainability and development towards the energy-saving products since a small change in lightings would have a major impact on the carbon footprint, energy consumption and world's ecological condition.

Through this program, the solid-state lighting (SSL) technology has been introduced and proved to be the next promising alternative for display and general lighting applications (Kim et al., 2012; Sandahl et al., 2014; Tsao et al., 2014; Pust et al., 2015). Primarily, the organic light emitting diodes (OLEDs) have captured a worldwide attention as compared to other electronic lamps, including the existing LEDs. This is due to countless potentials offered such as higher energy efficiency, recyclable and toxic free (Azevedo et al., 2009; De Almeida et al., 2014; Kim et al., 2015). Moreover, Chitnis et al. (2016) also reported that the OLEDs have the lowest power consumption while operating; as low as 0.01 W which is almost 800 times lesser than the power consumed by normal LEDs (consume about 8 W). This condition implies that the energy utilized by the OLEDs is highly effective and efficient.

This main advantage of OLEDs, however, is accompanied by a major hidden cost – where they only have an average service lifetime of merely 10,000 hours (about 1.1 years). This circumstance is evidently inadequate for the common household uses and extremely incompetent for the industrial applications since the conservative lifetime figure for a luminaire is normally around 15 years (Tyan, 2011). The short lifetime of OLEDs is predominantly due to poor environmental stability, especially when they are subjected to high temperatures or exposed to humidity, oxygen and water vapor. Although a number of measures have been performed to improve the performance of OLEDs, their lifetime interval is still considered as one of the major hinderances towards the long-term commercialization success (Aziz and Popovic, 2004; Geffroy et al., 2006; Gardonio et al., 2007; Nenna et al., 2009; Tyagi et al., 2014; Tyagi et al., 2016).

Concerning the deficient lifespan of OLEDs, systematic studies are essentially needed to provide better understandings and allow the new emerging technology to achieve an expanded stability and become more viable in the upcoming years. Thus, a definite understanding of failure mechanisms in OLEDs is essentially important to be comprehended as it is the key to solve the short lifetime and stability issues of OLEDs.

Therefore, the failure mechanisms, as well as the modes of failure were investigated after the OLEDs being subjected to high thermal stresses and hygrothermal effects. Following these, the interlayer characterizations were performed to elucidate the OLEDs' performances at a nanoscale level. The knowledge gained from this study is significant to fundamentally comprehend the scientific explanations behind the induced-failure for further improvements of OLEDs applications.