UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

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

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MUHAMMAD AZRAIN BIN MOHAMMAD

A thesis submitted
in fulfillment of requirements for the degree of Master of Science
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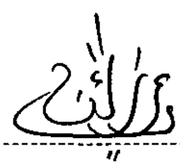
DECLARATION

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 : 

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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.

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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.

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LIST OF ABBREVIATIONS

CCT	-	Correlated Color Temperature
CFL	-	Compact Fluorescent Lamps
CIE	-	Commision 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 21^{st} 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 (CO_2) emission or equivalent to 70% of CO_2 emanated from the world's light vehicles (Azevedo et al., 2009). In fact, almost half of the total CO_2 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.