SYNTHESIS OF Al_2O_3 THIN FILM AS THERMAL INTERFACE MATERIALS (TIMS) USING CHEMICAL VAPOR DEPOSITION (CVD) METHOD FOR SOLID STATE LIGHTING APPLICATIONS

by

LIM WEI QIANG

Thesis submitted in fulfilment of the requirements for the degree of Master of Science

March 2018

ACKNOWLEDGEMENT

I would like to take this opportunity to express my sincere gratitude and deep appreciation to my supervisor, Assoc. Prof. Dr Mutharasu Devarajan for his valuable guidance and advices as well as patience in supporting and motivating me throughout the entire research project. In addition, I would like to give thanks to Dr Subramani Shanmugan for his valuable inputs and sharing his invaluable knowledge in guiding me through the entire project period.

Apart from that, I give my special thanks to all lab technicians from Nano Optoelectronics Research Laboratory (NOR) for the technical support provided on the relevant research equipment. I would like to express my deepest thanks to Mohamed Mustaqim Abu Bakar from X-ray Crystallography Lab for his assistance in XRD data acquisition. Aside that, I would like to thanks my fellow lab colleagues who's helped during tough time and sharing the joy throughout the research journey. I am deeply grateful for the kindness and hospitality showed by them in providing me invaluable ideas and advices besides the experience we have gone through the years of research.

Last but not least, I must grabbed this opportunity to show my warm and utmost appreciation to my family members and friends for the encouragement, support and love they showed me during my post-graduate journey.

Lim Wei Qiang

TABLES OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

LED	Light emitting diode
PCB	Printed circuit board
MCPCB	Metal core printed circuit board
TIM	Thermal interface material
XRD	X-ray diffraction
FESEM	Field emission scanning electron microscope
AFM	Atomic force microscope
DUT	Device under Test
PType	Prototype
CCT	Correlated colour temperature
CRI	Colour rendering index
LUX	Illuminance

LIST OF SYMBOLS

R_{th}	Thermal resistance
T_J	Junction temperature
ΔT_J	Rise in junction temperature
P_{el}	Electrical power
P_H	Power lost as heat
P_{opt}	Optical power
D	Crystallite size
ε	Micro-strain
δ	Dislocation density
V	Voltage
I_{tot}	Total current
I_{in}	Input current
I_{sc}	Sensor current
$P_{thermal}$	Thermal Power
ΔV_F	Difference in temperature sensing voltage
K	Sensitivity value (K-factor)
λ	Dominant wavelength
ΔK	Rise in thermal conductivity
R_{th-tot}	Total thermal resistance
R_{th-PCB}	PCB thermal resistance

SINTESIS Al_2O_3 FILEM NIPIS SEBAGAI BAHAN LAPISAN HABA ANTARA MUKA DENGAN MENGGUNAKAN PEMENDAPAN WAP KIMIA BAGI APLIKASI PENCAHAYAAN KEADAAN PEPEJAL

ABSTRAK

Usaha yang berterusan oleh penyelidik telah menambah baik reka bentuk dan keseluruhan pengeluaran cahaya bagi peranti SSL namun kekuatiran masih ada mengenai keutuhan prestasi peranti dalam keadaan tertentu. Kenaikan aliran arus akan menyebabkan peningkatan pengeluaran cahaya dan suhu persimpangan dalam peranti pada masa yang sama. Peningkatan suhu simpang boleh menyebabkan pelarian haba dan menjejaskan jangka hayat peranti, yang membawa kepada kerosakan peranti. Oleh itu, sistem pengurusan terma yang sangat canggih diperlukan untuk mengimbangi prestasi tinggi peranti SSL. Dalam projek ini, teknik salutan filem nipis telah dicadangkan sebagai salah satu pendekatan yang berkesan dalam meningkatkan sistem pelesapan terma pada tahap sistem. Oleh itu, aluminium oksida (Al_2O_3) dipilih sebagai TIM yang dilapisi pada substrat logam kerana kekonduksian haba yang tinggi dan bahan tahan kimia. Filem nipis aluminium oksida (Al_2O_3) disediakan pada dua gred aluminium (Al) substrat yang berbeza: (i) Al-3003 dan (ii) Al-6061 melalui teknik pemendapan wap kimia (CVD) di bawah keadaan atmosfera yang biasa. Parameter pemendapan telah diubah untuk mengoptimumkan hasil sintesis filem-filem nipis Al_2O_3. Substrat bersalut kemudiannya menjalani proses penyepuhlindapan pada 450 ° C dan 10sccm nitrogen (N_2). Kaedah perincian struktur seperti X-ray difraksi (XRD), mikroskop berkuat kuasa atom (AFM) dan mikroskop elektron scanning emission field (FESEM) digunakan untuk mengkaji pengaruh parameter terhadap kualiti Al_2O_3 yang disintesis berdasarkan struktur kristal dan permukaan morfologi. Pengukuran kekonduksian terma dilakukan bagi menentukan sifat terma substrat bersalut. Parameter pemendapan yang menghasilkan kualiti salutan dan kekonduksian terma yang terbaik dipilih untuk proses fabrikasi prototaip papan litar cetakan logam (MCPCB) menggunakan litar percetakan skrin. LED kuasa tinggi kemudian dipasang pada prototaip MCPCB bagi menjalani penilaian haba

dan optik pada sistem T3Ster dan spektrometer. Peningkatan prestasi filem nipis Al_2O_3 yang disintesis sebagai TIM untuk peranti LED kemudian dibincangkan dalam bentuk bacaan untuk rintangan sementara terma, kecerahan bercahaya, dan nilai suhu warna berhubung kait (CCT). Bagi gred Al-3003, perbezaan ketara sebanyak 22% dan 18% pada $R_{th\text{-}tot}$ dan suhu persimpangan ditunjukkan oleh prototaip berbanding Bare-Al. Manakala gred Al-6061, menunjukkan prestasi yang lebih baik prototaip berbanding substrat Bare-Al di mana perbezaan sebanyak 5.03% pada $R_{th\text{-}tot}$ dapat diperhatikan. Selain itu, suhu persimpangan menunjukkan 6% lebih rendah pada prototaip berbanding Bare-Al. Kajian ini menyimpulkan bahawa salutan filem Al_2O_3 pada gred Al-3003 menghasilkan peningkatan haba dan optik yang lebih baik untuk peranti LED berbanding aluminium gred Al-6061.

SYNTHESIS OF Al_2O_3 THIN FILM AS THERMAL INTERFACE MATERIALS (TIMS) USING CHEMICAL VAPOR DEPOSITION (CVD) METHOD FOR SOLID STATE LIGHTING APPLICATIONS

ABSTRACT

Continuous efforts by researchers have improved the design and overall light output of the SSL devices yet there are concerns still remain regarding the reliability of devices under certain circumstances. The rise in driving current would lead to an increase in light output and junction temperature within the devices simultaneously. An excessive rise in junction temperature can cause thermal runaway and affect devices lifetime, ultimately leading to devices failure. Thus, a highly sophisticated thermal management system is needed to compensate with the high performance of SSL devices. In this project, thin film coating technique has been suggested as one of the effective approaches in improving the thermal dissipation system at system level. For this purpose, aluminum oxide (Al_2O_3) is selected as the TIM coated on metal substrates due its high thermal conductivity and chemical resistant in nature. Aluminum oxide (Al_2O_3) thin films were prepared on two different grades of aluminum (Al) substrates: (i) Al-3003 and (ii) Al-6061 via chemical vapor deposition (CVD) technique under normal atmospheric condition. Deposition parameters were varied to optimize the synthesis outcome of the Al_2O_3 thin films. The coated substrates were then subjected to an annealing process at 450°C under 10sccm nitrogen (N_2) flow. Structural characterization method namely X-ray diffraction (XRD), atomic force microscope (AFM) and field emission scanning electron microscope (FESEM) were used to study the influence of deposition parameters on the quality of the synthesized Al2O3 based on crystalline structure and surface morphology. The structural analysis showed the increase of crystallite size and reduction in micro-strain and dislocation density due to the increase in deposition temperature. AFM result also indicated that the surface roughness also improved as the deposition temperature is increased. Thermal conductivity measurement were performed to determine the thermal properties of coated substrates. The deposition parameter that yielded the best coating quality and thermal conductivity was filtered and selected for the next process of fabrication as metal core printed circuit board (MCPCB) prototypes by screen printing circuits on them. High power LEDs were then mounted on the MCPCB prototypes to run thermal and optical evaluations on a T3Ster system coupled with spectrometer setup. The improvements of the synthesized Al2O3 thin films as TIMs for LED devices are then discussed in the forms of measurement readings for thermal transient resistance, luminous brightness, and Correlated Color Temperature (CCT). For Al-3003 grade scenario, a significant difference of 22% and 18% in $R_{th\text{-}tot}$ and junction temperature respectively is showed by the prototype compared to bare-Al substrate. In Al-6061 grade case, an improved performance is showed by the prototype compared the bare-Al substrate where 5.03% difference in terms of $R_{th\text{-}tot}$ can be observed. Moreover, the junction temperature result also indicated 6% lower in the prototype compared to bare-Al counterparts. This study concludes that Al_2O_3 thin film coating on Al-3003 grade yields better thermal and optical improvements for LED devices compared to Al-6061 grade aluminium.

CHAPTER 1

INTRODUCTION

1.1 Overview

This chapter is generally focused on the brief introduction of LEDs and current issues faced by the LEDs manufacturer industries. Besides that, contribution and output from the research project also mentioned. In addition, objectives and outline of each chapter in the thesis also included as well in this chapter.

1.2 Introduction

The LEDs technology has been vastly improved since the creation of the first functioning red LED in the sixties based on GaAsP by Nick Holonyak Jr. [1]. Innovation of high power LEDs based on GaN by Nakamura in the early 1990s also further enhanced the luminescent technology [2]. Furthermore, report also showed that the LEDs has achieved the efficacy of 231lm/W at 350mA in 2011 [2]. Owing to the outstanding properties of LEDs such as excellent color saturation, high brightness, environmentally friendly, low power consumption and long operating life-time, LEDs was proved to be feasible alternative to conventional lighting devices [3]–[6]. From the above mentioned advantages of LEDs technology, application of LEDs does not limited to entertainment lighting and display anymore. Usage of LEDs lighting has been expanded to general lighting purpose and these included traffic signals, large screen video displays, LCD backlighting, architecture illumination, street lightings and residential lightings [7]–[9].

With the advancement in the LEDs technology, miniaturization of LEDs package can be realized. However, crucial issues in terms of reliability and performance also have arisen and this brings challenge to thermal management of LEDs technology as highly sophisticated and effective thermal system is needed. Overall, it is reported that average 80-85% of the electrical power of an LED is converted into heat rather than optical power. Accumulation of heat within the package can cause severe damage to the LEDs itself [8]. Thus, thermal management is a key reliability element in enhancing the lifespan and maintaining the performance of LEDs at optimum level.

1.3 Problem Statement

With the increase in demand for higher performance of the LEDs lighting system, LEDs manufacturers putting endless effort in fulfilling the market demand. Generally, the light output of LED packages is affected greatly by the operation conditions. The increase in driving current would have resulted in the increase of light output but at the same time the junction temperature of the device will raise. The excessive rise in junction temperature capable of causing thermal runaway and catastrophic failures which ultimately lead to major drawback in the technology. Device lifetime can be decreased drastically due to large thermal stresses that occur specifically at the interface. It is also predicted that the lifetime of the device decays exponentially as the temperature increases [10]. In addition, it has been reported that a 2°C increment at threshold temperature would cause 10% decrease of fatigue life of package [11]. High heat flux within the die level would have required sophisticated heat spreader in dissipating the concentrated heat loads. In general, approximately 90% of the thermal energy is dissipated from the LED die through conduction and convection at package and system level respectively. Owing to the robustness, the LEDs have built-in potential as energy efficient light sources with limitation to heat generated. As mentioned in the above text, the accumulation of heat within the device is detrimental to its performance and affect the lifetime of device. Thus, it is crucial to gain an understanding on thermal solution of the LEDs.

Recently, metal core printed circuit board (MCPCB) is used as board and substrate in LED application due to its excellent strength and thermal conduction behaviour [12]. Most MCPCBs are attached to the heat sink through thermal interface materials (TIMs) to prevent interfacial resistance. Within the design of MCPCB, the dielectric layer present thermal challenge as the current dielectric layer has low thermal conductivity. Due to such constraint, it is difficult to dissipate the heat loads at system level and this brings negative impact to the reliability and efficiency of the entire system [13]. Furthermore, the low thermal conductivity of commercially available TIM was unable to satisfy the requirement of high power LEDs. To overcome such disadvantage, alternative TIM material with better thermal properties has been suggested as one of the prevailing approach in enhancing the thermal path.

TIMs approach is recommended to be one of the effective approaches in enhancing thermal management system of the SSL devices. There are various types of TIMs available in current commercial market such as thermal greases, thermal adhesive, thermal pads, phase change materials and thin film. An effective TIM need to possess the following characteristics such as high thermal conductivity (0.1 – 7 W/mK) , good adhesive strength (14.20 - 4.34 MPa), high reliability, high heat capacity (1100– 900 J/kg K), low thermal impedance and interface resistance (0.0013 - 0.0006 mK/W) [14-16]. Selection of suitable TIM is crucial as material with high thermal conductivity and optimum thickness is more favourable. [15]. Thin film coating often selected as the suitable TIM in improving thermal dissipation at the system level. Thin film is well known for its capability in filling the air gap between both difference surfaces of medium and conducting the heat effectively.A significant improvement in TIM thermal properties would provide efficient thermal management for the LEDs technology. Among the ceramics implemented as electronic substrates or packages, aluminium oxide, aluminium nitride and boron nitride are widely used as TIM for heat dissipation purpose in the LEDs technology due to its high thermal conductivity nature. In synthesizing the thin film, chemical vapor deposition method has been proposed in this research project. Currently, synthesis of oxide based thin film on the metal substrate required has yet been reported and this is due to CVD synthesis required high temperature (≥ 800°C) and low pressure to be carried out. These constraints limits the application of metal such aluminum or copper as substrate. Therefore, alternative CVD setup has to be established in depositing oxide based thin film on selected metal substrate.

1.4 Objectives

These objectives are needed to be achieved in this study:

- ***To synthesis aluminum oxide (Al_2O_3) thin film on Al substrate by using chemical vapor deposition (CVD) method.***
- ***To investigate and analyse the influence of the thin film on the thermal and optical performance of the LEDs.***
- ***To fabricate a prototype PCB based on the synthesized Al_2O_3 films and verify its performance by performing thermal and optical measurement on it.***

1.5 Research Contribution

A prototype PCB based on the deposited oxide thin film for high power LEDs usage along with thermal and optical data will be delivered for the outcome of this project. Besides that, alternative CVD technique of deposition of thin film on metal substrate is developed as reference for the improvement in PCB manufacture.

1.6 Thesis Outline

Overall, the thesis is comprised of six major topics which includes introduction, literature review, theoretical background, methodology, results and discussion as well as conclusion and recommendations.

i) Chapter 1 : Introduction

The first chapter briefly introduce the LEDs and issues faced by the LED manufacturer industries. Objectives of the research and research output also included in this chapter.

ii) Chapter 2 : Literature Review

The second chapter focused on brief introduction to background of LEDs thermal management followed by development of various design for thermal purpose of LEDs. Asides from that, literatures of previous work on techniques used in synthesis of Al_2O_3 thin films also discussed in this chapter. Summary of various parameters used in CVD deposition of thin film also included.

iii) Chapter 3 : Theoretical Background

In third chapter, the general introduction of aluminum oxide thin films and its properties are discussed here. In addition, the principle of CVD system are explained in detail in this subchapter. A brief description on the thermal resistance and relation in optical power of LED as well as thermal conductivity measurement is also included in this chapter.

iv) Chapter 4 : Methodology

This chapter described in details the methodology used in this project. This involves the synthesis of the thin film, fabrication of prototypes and characterizations done on coated substrates and prototype PCBs.

v) Chapter 5 : Results and Discussion

This chapter presents the results of the data collected from the thin film analysis and LED thermal and optical characterizations. The carried out results are performed in a graphical and Figure formats by using different analysis' equipment.

vi) Chapter 6 : Conclusion and Recommendations

In this last chapter, the results of the work are summarized and conclusion of the project is presented. Future suggestions and recommendations to enhance and further carry out this research are also included in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter generally focused on the concept in thermal management of LEDs and the importance of its in LED application. Other interests involved in this chapter would be the development of various design for thermal system of LED currently and effort in improving the available thermal package design. In addition, this chapter also presented the literatures about deposition techniques used in synthesis of Al_2O_3 thin film. The chapter is divided into 3 sub-chapters:

- ✓ Thermal managements background of LEDs
- ✓ Thermal package design for LEDs
- ✓ Al_2O_3 thin film deposition methods

2.2 Thermal management background of LEDs

For the last few decades, researchers has committed countless development and innovations in the effort of improving the solid state lighting technology especially light emitting diodes (LEDs) since LEDs has become the spotlight in the lighting industry. Advancement in LEDs technology can noticed in terms of its adaptability, lifetime and device efficiency. Compared to the traditional lighting, LEDs also offered design freedom, exceptionally long lifetime, and also considerably more efficient – converting majority energy into light and thus minimizing the heat given off. Figure 2.1 illustrated the improvement of LEDs package size over the years of development.

Despite of the advantages offered by LEDs, thermal management still remain as major challenge for lighting industry as significant amount of heat still produced at the p-n junction and this produced heat can have adverse effect on the LED.

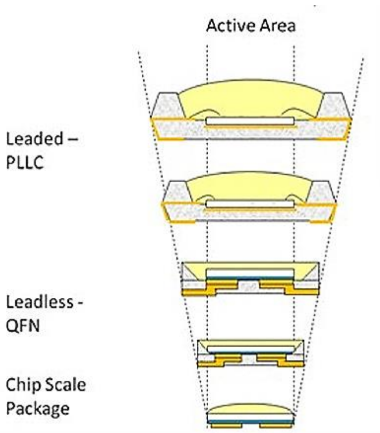
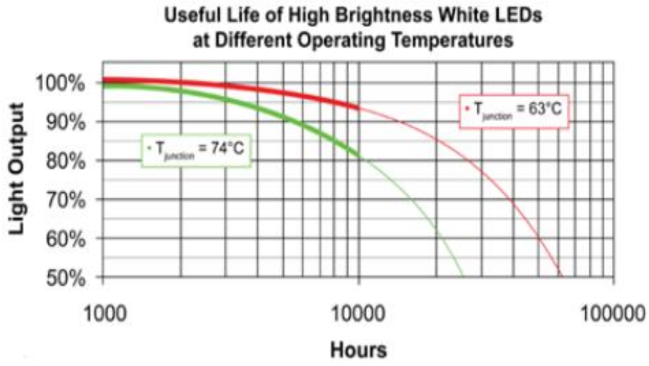
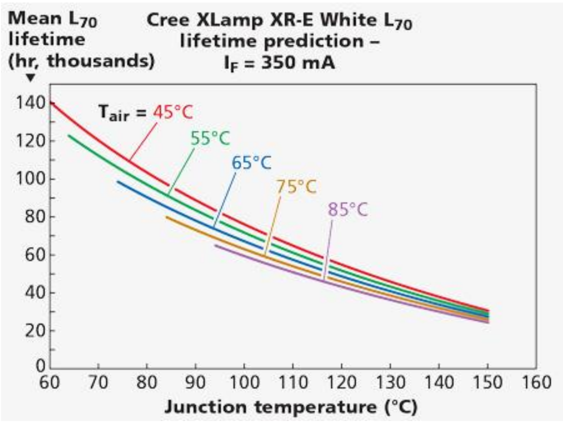


Figure 2.1 Miniaturization of LEDs package as the results of research and developments [15].

Changes in operating condition such as the driving current would have significant impact on the performance and reliability of LEDs. It was explained that when the input power of LEDs increased, this will lead to vast improvement of LED brightness, however the rate of heat generation also increased within the package itself. This phenomenon often explained due to the decrease in internal quantum efficiency at the p-n junction which contributed to the non-radiative recombination within the LEDs. The internal quantum efficiency can be referred to generation of photons as a result of recombination of electrons and holes at p-n junction within the SSL devices. The non-radiative recombination in turn induced the concentration of phonons released and this effect led to the increase in temperature which affect the color and light output of LEDs thereby disrupting the performance of the device [14]. Figures 2.2(a) and (b) showed the decrease of brightness and lifetime of LEDs as a result of increased in temperature.





Figures 2.2 Decrease of (a) brightness and (b) lifetime of LEDs due to increase in junction temperature [15].

In general, approximately 70 – 80% of the input power supplied were converted to the heat and due to reduction in the package size, the heat will be accumulated within the package leading to increase in temperature, thus distorted the overall efficiency of the device [15]. And also due to miniaturization of the package, effective thermal dissipation system highly required in order to maintain its optimum performance. Figure. 2.3 described the heat path of the LEDs under ambient environment. Unlike the design of conventional lighting, LEDs solely relied on the conduction and convection in dissipating the heat to the ambient and this made the task even more challenging [16].

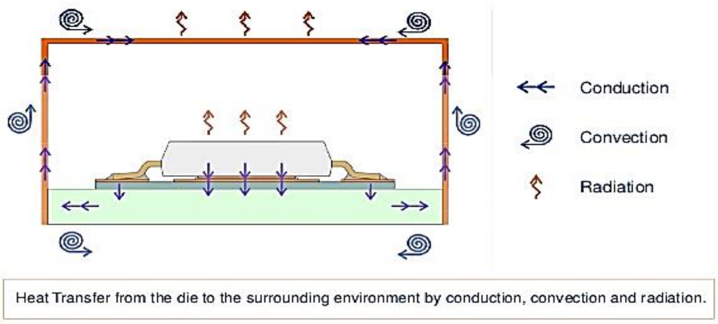


Figure 2.3 Thermal path travelled by heat in LEDs package to the surrounding [17].

An understanding on the thermal dissipation of heat from package to ambient was crucial in the design of suitable system. To describe the thermal dissipation of LEDs package, the system was simplified and illustrated as thermal resistance network shown in Figure. 2.3. From Figure. 2.4, the network was found to be analogous to the electrical circuit. In this case, the LED would be considered as the source of heat whereas the heat flow and thermal resistance, R_{th} were modeled as current source and resistor respectively. The ambient temperature also defined as the voltage source based on the model. Thus, design of thermal system with low thermal resistance and ambient temperature is crucial to reduce the junction temperature of LEDs [17].

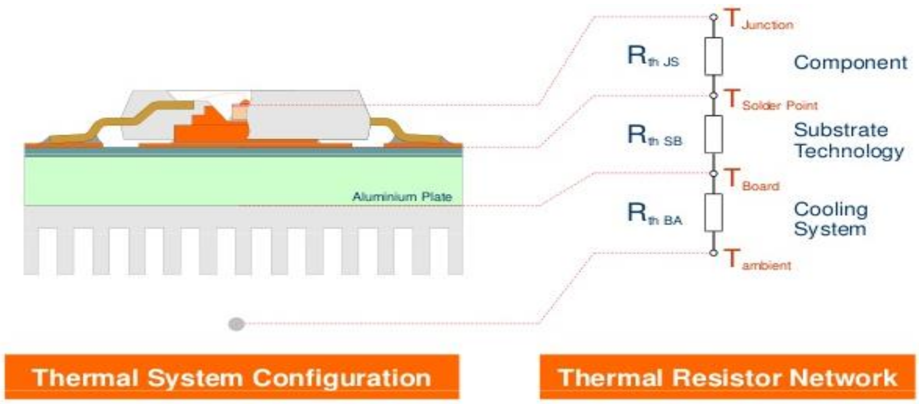


Figure 2.4 Thermal resistor model of the LEDs package.

Based on the Figure. 2.4 above, it can be seen that the junction temperature, T_j and thermal resistance, R_{th} were both critical parameters which affect both the reliability and performance of LEDs. An increase in the driving current usually led to the occurrence of self-heating effect. The self-heating effect increased the temperature of the LEDs package through several mechanism [18]:

a) Heat generation within the p-n junction due to non-radiative recombination process
b) Joule heating at the series electrical resistance of the diode and interconnects as well
c) Light absorption in the material and interface

The self-heating effect also caused the degradation of LED materials and such degradation always had adverse effect on the efficiency and reliability of the LEDs. With the increase in the temperature within the package, the heat dissipation system had been distorted due to deterioration in the material quality. Thermal path within the package had been lengthen which further increased the difficulty of heat to transfer to the ambient environment, thus led to the increase in thermal resistance. Due to the failure of heat dissipation, accumulation of heat occurred which ultimately led to device failure. Therefore, it was crucial in designing effective thermal management to minimize the rise of temperature within the package.

2.3 Thermal Package Design for LEDs

Thermal design of LED system has become essential as LEDs technology continue to develop. Due to the reasons mentioned in section 2.2, it is important to maintain the temperature of LEDs. Major challenge in designing the thermal package for the LEDs would be the removing of heat completely from LED particularly high power LED to ambient. Numerous technologies which includes printed circuit board (PCB), heat sink/pipe and thermal interface materials (TIMs) have been invented in designing the optimum thermal management system for LEDs application. Among the technologies, PCB technique is greatly implemented in the design of the thermal system as it is one of the effective method where it directly dissipated the heat from the chip level to ambient. It is stated that thermal features of the board such as types of board material, presence of thermal vias, and surface metallization design affect the thermal path significantly and these features were typically decided by the product design team. All these factors played their role in managing the temperature of the LED chip.

Previously, FR (Flame Retardant) - 4 PCB was widely used for the LED and other electrical device applications due to its electrical insulating characteristics and cost of manufacture. Lots of LED industries mainly incorporated the FR4 design for low power LEDs application, however due to lack of high thermal conductivity, FR4 PCB was found to be unfit for high power LEDs application [19]. Since conventional PCB materials were unable to meet the demand of thermal requirement of high power dissipation PCB, metal-core printed circuit board (MCPCB) approach was employed in addressing the issue. Design of MCPCB usually composed of thick metal core substrate, dielectric and conductor layer whereas the FR4 consisted of FR4 layer embedded on top and bottom of thick copper substrate. Layouts of MCPCB was illustrated in Figure. 2.5. Over the years, multiple layout of MCPCB were designed but single layer design MCPCB still preferred by the industries due to its simplicity [20].

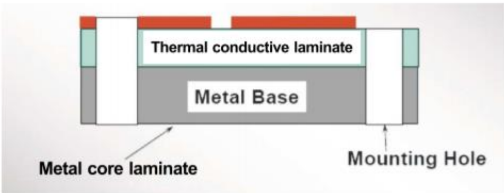


Figure 2.5 Layout of MCPCB [20].

In the effort of designing effective thermal system, numerous research were conducted by researchers around the globe. K.C. Yung *et. al.* performed thermal modelling analysis on the LEDs array which mounted on FR4 and MCPCB in comparing their performance. Figure. 2.6 illustrated the temperature of LED mounted on (a) FR4 and (b) MCPCB while Figure. 2.7 displayed the simulated thermal profile of LEDs array on FR4 and MCPCB respectively. From the simulation result, the average temperature of the FR4 circuit was found to be 76°C whereas the MCPCB exhibited temperature at 55°C and Figure. 2.7 also showed that there was an overlapping of thermal profiles for the FR4 case and MCPCB case did not displayed such behavior. Based on these results, it can speculated that the MCPCB offered significantly higher thermal conductivity than the FR4, thus the MCPCB was able to conduct the heat away from the chip in all directions thereby dissipated the heat effectively [21].

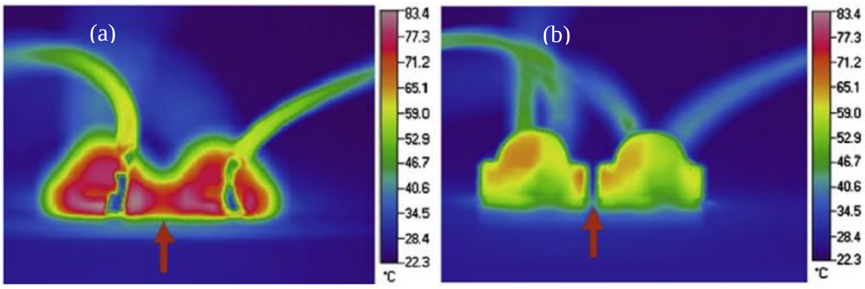


Figure 2.6 Temperature of (a) LEDs on FR4 and (b) LEDs on MCPCB [21].

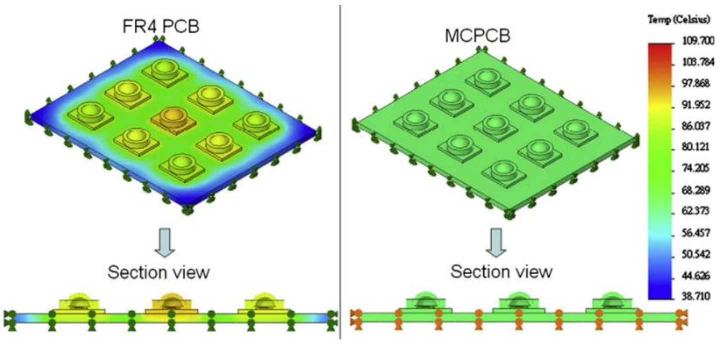


Figure 2.7 Simulated thermal profile for a 3 × 3 LED array on FR4 and metal core PCB [21].

Various approaches were implemented in order to improve the thermal performance of MCPCB such as materials selection for dielectric layer and introduction of thermal vias. Thermally conductive ceramic particles such as alumina has been used as alternative material for the dielectric layer. It was also revealed that the thickness of dielectric layer and quality of interface have significant effect on thermal performance of MCPCB [22]. Eveliina

Juntunen *et. al.* introduced thermal vias to copper core MCPCB to analyze the effect of thermal vias on thermal performance of MCPCB. Thermal transient analysis were conducted on the blue LEDs which mounted on alumina module and copper core MCPCB with vias. Figure 2.8 (a) and (b) showed the different module of board material and cumulative structure function of blue LEDs on different modules respectively. From the Figure 2.8, it can been that the introduction of vias did significantly improved the thermal resistance of the MCPCB particularly the module with 9 vias and this was due to the relative high in number and density of the vias [22]. Despite of the advantage presented by the vias in MCPCB, it was difficult as the lamination process was inaccurate to realize the vias on the dielectric layer.

(a)

(b)

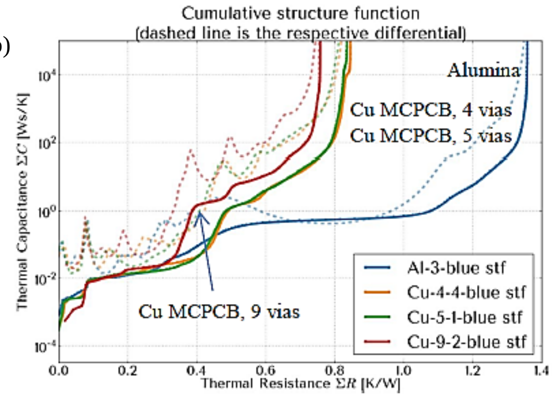


Figure 2.8 (a) Cu MCPCB module (left) and alumina module (right) and (b) Structure function of blue chip array on alumina module (blue) and on Cu MCPCB module with 9 vias (red), 5 vias (green) and 4 vias (orange) per chip [22].

The board and heat sink were categorized as the active cooling system whereas the thermal interface material, phase change materials, adhesives and thermal grease were belong to the passive cooling system [23]. The passive cooling system offered simplicity, low cost manufacturing and flexibility in terms of application. In the area of materials, products range from thermally conductive encapsulation resins, offering both heat dissipation and environmental protection, to thermal interface materials used to improve the efficiency of heat conduction away from the LED junction. In designing effective thermal management system, thermal interface materials (TIMs) played a major role in providing the thermal path between two dissimilar interface (LED array and heat sink/MCPCB) and eliminating air gaps.

In effort of improving thermal performance of the system and minimizing the heat losses, one of the prevailing approaches was to improve the thermal conductivity of TIMs. There were several literatures which reported the use of thin film and nanoparticles as TIMs in LED application where significant improvement in thermal performance was observed. AlN thin films were synthesized by Shanmugan *et. al.* as TIM on Al substrate and the thermal transient analysis were performed on LED attached with bare Al and coated substrate at three different driving currents. The cumulative structure functions of the test were presented in Figure 2.9 and the AlN coated Al substrate displayed low value of thermal resistance compared to bare Al substrate [24]. In addition, BN thin films was deposited on Cu substrate and a green LED was mounted on the deposited substrates as reported by Shanmugan *et. al.* The coated substrate was then compared with bare Cu substrate as well as Cu substrate with thermal paste. The thermal transient result showed that BN substrate exhibited lower T_j and total thermal resistance compared to other tested samples as showed in table 2.1 [25]. There was also literature that reported the deposition of Al_2O_3 thin film on Al substrate using RF sputtering. Thermal transient result revealed that LEDs on Al_2O_3 coated substrate exhibited lower value of thermal resistance and junction temperature compared to bare Al substrate as shown in Figure 2.10 and table 2.1 [26]. Other work conducted by I. Chowdhury *et al.* on designing a superlattice-based thin film thermoelectric cooler for a test chip reported the cooling as much as 15 °C at the targeted region of Si test chip [27].

Table 2.1 Properties of 3W green LED tested for three boundary conditions LED/Cu [25].

Table 1 Properties of 3W green LED tested for three boundary conditions

	LED/Cu			LED/TP/Cu			LED/BN/Cu		
	100	350	700	100	350	700	100	350	700
T_J	14.23	54.62	115.43	14.09	53.38	115.07	14.48	52.94	111.64
$R_{th-b-hs}$	38.35	37.72	35.32	38.06	36.87	35.89	38.25	35.00	33.00

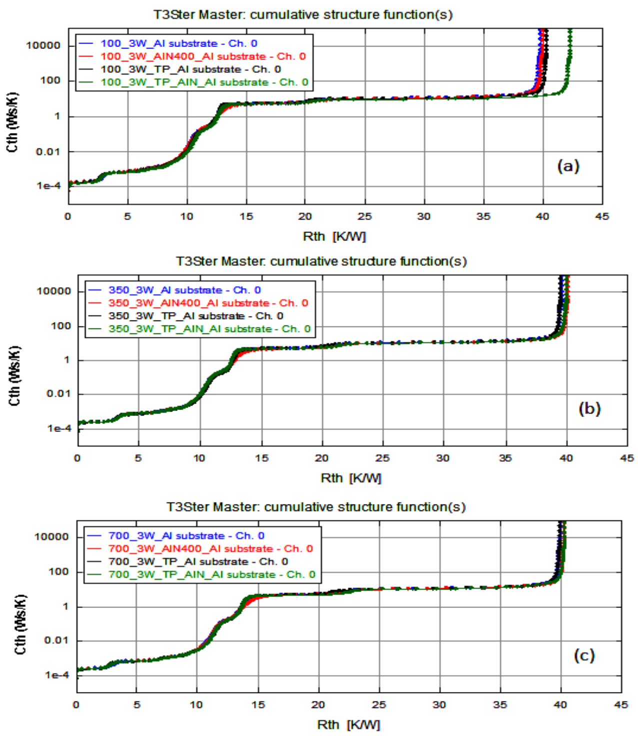


Figure 2.9 Cumulative structure function curve of 3W green LED fixed on bare Al and AlN thin film coated Al substrates with and without thermal paste measured at (a) 100 mA, (b) 350 mA and (c) 700 mA [26].

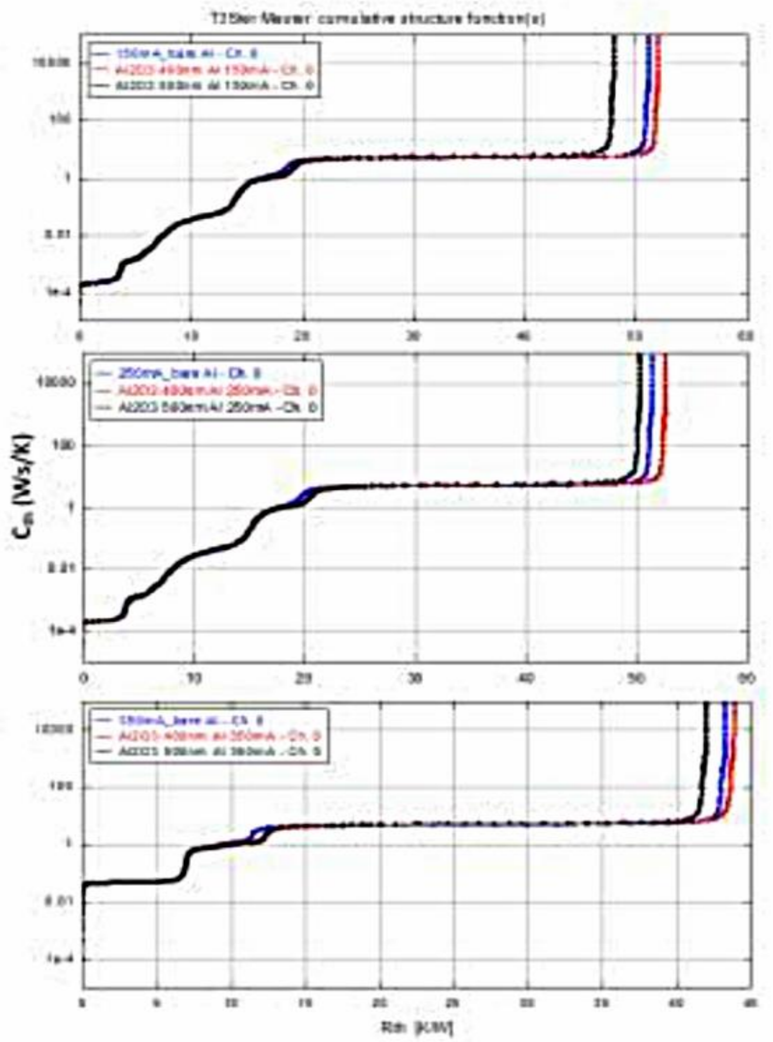


Figure 2.10 Cumulative structure function of LED fixed on bare and Al_2O_3 thin film coated Al substrates [26].

Table 2.2 Thermal parameters of LED on bare Al and Al_2O_3 coated Al substrates at three different driving current [26].

PERFORMANCE OF HIGH POWER LED FOR VARIOUS BOUNDARY CONDITIONS TESTED AT THREE DIFFERENT DRIVING CURRENTS.

	Non annealed			Annealed	
Driving current (mA)	LED/Al	LED/ 400AO*/Al	LED/500AO* /Al	LED/ 400AO*/Al	LED/500AO* /Al
Total thermal resistance (K/W)					
150	50.3	51.3	47.2	65.2	64.6
250	51.5	52.6	49.5	70.4	68.6
350	43.3	43.9	41.8	60.7	58.0
Rise in Junction Temperature (°C)					
150	23.0	23.5	21.8	30.0	29.8
250	40.3	40.5	38.9	55.2	54.0
350	48.2	48.7	46.3	67.8	64.8
Thermal resistance between MCPCB and film coated substrates (K/W)					
150	31.1	32.0	27.4	37.6	38.9
250	30.3	30.6	28.1	41.8	40.4
350	30.5	29.9	28.2	42.3	40.1

Table 2.3 Types of TIMs used in thermal management application.

TIM Material	Thickness	Coating technique	Remarks	Ref.
AlN thin film	30um (average)	Aerosol Deposition	- Required low pressure deposition (0.9 – 1.0 Torr) - Selection of AlN powders with average particle size of 12um - Required high flow rate of carrier gas, He (5000 – 7000 sccm) - Difficulty in achieving the thickness needed.	[28]
BN thin film	200nm	Sputtering	- Required long period of time (2hrs) to achieve 200nm	[29]
B-AlN thin film	100 – 300 nm	Sputtering	- Difficult in achieving the desired thickness. - The film thickness is found to be decreased as the deposition temperature increased.	[30]
GaN thin film	0.31-1.27um	MOCVD	-Required high temperature deposition (1100 °C) which limit the choices of suitable material as substrate for SSL application	[31]
ZnO thin film	1um	Screen printing	- High thickness of Zno thin film is unfit for SSL thermal management application.	[32]
Ca doped ZnO thin	12.0 – 17.9um	Screen printing	- The porous nature of doped ZnO thick film reduced the conduction of heat. - The distribution of voids within the thick	[33]

film			film also caused the increase of thermal resistance.	
Al_2O_3 filler	-	Chemical synthesis	- Observed a rise in junction temperature due to lower thermal conductivity compared to Al and AlN fillers.	[34]
Al_2O_3 thin film	50nm	ALD	- The thermal conductivity of the film reduced with decreasing film thickness	[35]

Table 2.3 summarized the types of TIMs used in thermal management application. It is found that most literatures reported that high deposition temperature is required to synthesize the thin films [31]. In SSL thermal management application, the industries is focused on the Al metal as the MCPCB substrate. This is because Al is cheaper compared to Cu and thermal conductivity of Al also still comparable with Cu [21]. The high deposition temperature is one of the drawbacks for the application of Al as the substrate in thermal management. In AlN thin film scenario, the low pressure deposition required sophisticated equipment and this caused additional resources in customization and maintenance based on the experiment requirement [28]. Apart from that, most literatures reported that the thickness of thin film obtained is approximately 1um above which is unfit for SSL application [31-33]. The desired thickness of TIM in SSL application is around 400 – 600nm as higher thickness present additional thermal path which disrupt heat transfer mechanism within the SSL devices. In addition, the synthesized ZnO thin film also showed the presence of voids which caused additional thermal resistance as reported by the literature [33]. In Al_2O_3 thin film scenario, it is found that the thermal conductivity of film reduced as film thickness is decreased as reported in the literature [34]. It is

deduced that with the increase in film thickness, the thermal conductivity of the film can be enhanced.

Most of the industries are implementing the use of Al metal as the main substrate for thermal management application in SSL. As mentioned, the cost of Al substrate is cheaper comparing to Cu in mass production scale and Al is abundant and ease to obtain. Besides this, the thermal conductivity of Al (205 W/mK) substrate is still comparable to Cu (385 W/mK) [21]. Although nitride based thin films do possess excellent thermal conductivity, synthesis proces often involved the use ammonia (NH_3) gas. This is because NH_3 is the common nitrogen source in synthesizing it and the gas is toxic and required sophisticated exhaust system to filter the by-products. Disadvantage of fabricating nitride based thin films also include difficult and complex processes involved high temperature (typically ≥ 1000 °C) and raw materials cost [28]. The high temperature synthesis process heavily limit the choices of substrate material available for this project. From the literatures above, Al_2O3 was proposed as alternative TIM due to its excellent electrical and thermal insulator in nature as well as mechanical properties. Apart from that, it is deduced that Al_2O_3 thin films possessed a thermal conductivity of 1 W/mK for thickness of 140nm, it will create a better thermal path for high power LED to dissipate heat to the ambient [36]. Also, Al_2O_3 is extremely resistant to wear and corrosion [37]–[39].

2.4 Al_2O_3 Thin Film Deposition Method

Over the decades, numerous deposition techniques have been developed for the fabrication of aluminum oxide thin films and the techniques include DC/RF magnetron sputtering, spin coating, atomic layer deposition (ALD), chemical vapor deposition (CVD), molecular beam epitaxy (MBE) [40]–[42].

Molecular beam epitaxy (MBE) often used in the semiconductor fabrication due to its superior deposition rate (less than 3000nm per hrs) which allow the films to grow epitaxially. Besides that, the absence of carrier gas as well as the ultra-high vacuum environment also assisted in achieving high purity of the grown films. Yet, the setup of MBE is costly and required high and frequent maintenance [43].

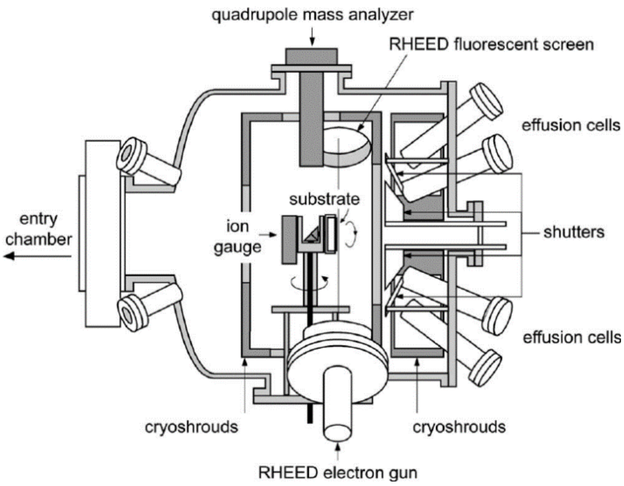


Figure 2.11: Schematic diagram of Molecular Beam Epitaxy (MBE).

DC/RF magnetron sputtering was also described as one of the physical vapor deposition (PVD) techniques. Figure 2.12 illustrates the schematic diagram of magnetron sputtering. The magnetron sputtering usually known for its advantages such as capability in producing thin compound films of controllable stoichiometry and composition as well as the elemental target can be easily purified, hence high purity films can be obtained [30], [31]. Magnetron sputtering also incorporated in the deposition of large area uniform films with high relative growth area even at low deposition temperature. However, it was difficult in achieving high thickness of film which required in thermal management application through sputtering [32], [33].

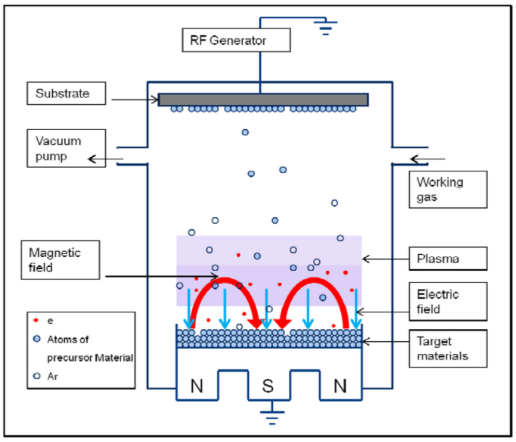


Figure 2.12: Schematic diagram of magnetron sputtering.

The chemical vapor deposition (CVD) is well known for its possibility in synthesizing almost any metallic or non-metallic type elements or compounds. The materials deposited by the CVD process also reported to have high purity and the material formation is well below the designated melting point. One of the key advantage of the CVD technique lies in the fact that the reactants are in gaseous form, thereby taking the unique characteristics of gas and unlike the PVD and MBE, the setup of complete CVD system are comparatively economical. Moreover, the CVD reactor chamber can be modified based upon the design of experiment thereby verified its versatility of applications [48]. Besides this, chemical processes are involved in the nucleation, growth and microstructure of the films deposited by a CVD process and thus it can be said that the properties of CVD-grown