THERMAL CHARACTERIZATION OF POWER LEDs AND LED ASSEMBLIES

ANITHAMBIGAI PERMAL

UNIVERSITI SAINS MALAYSIA

2012

THERMAL CHARACTERIZATION OF POWER LEDs AND LED ASSEMBLIES

by

ANITHAMBIGAI PERMAL

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

June 2012

ACKNOWLEDGEMENT

I would like to express profound gratitude to my supervisor Dr. Mutharasu Devarajan for his valuable support, encouragement, supervision and useful suggestions throughout this research work. His moral support and continuous guidance enabled me to complete my work successfully. I attribute the level of my Masters degree to his encouragement and effort and without him this thesis too would not have been completed or written. One simply could not wish for a better or friendlier supervisor.

I would like to thank my co supervisor Professor Kamarulazizi Ibrahim for his guidance and all the effort he took to help us out in improvising our lab facilities.

I am responsible to offer my sincerest appreciation to my industrial supervisor Mr. Lim Choon Kim, R & D Manager, Globetronics Sdn. Bhd. who had never ceased in helping me until this thesis was structured. He had supported me throughout my thesis with his patience and knowledge whilst allowing me the room to work in my own way.

I am truly responsible to express sincere appreciation to QAV technologies Sdn. Bhd. staffs for their extended long-term support and especially to Dr. John See for his vast reserve of patience and knowledge. I hereby would show my sincere gratitude to Pentamaster Sdn. Bhd. too for their technical support given extensively without any expectations. It is a pleasure to thank those who made this thesis possible. I would like to make special reference to Mr. Fendi, the technician from Globetronics Sdn. Bhd, Mr. Darren Chin Chia Siang and Mr. Jonathan Tan, the project engineers from QAV technologies, Mr. Dylan Tan, Miss Lina and Mr. Chong Yew Loon from Pentamaster Sdn. Bhd. and Miss Felicia, Mr. Tan Chye Boon from Opulent Technologies. And not forgetting my lab assistants, Ms. Ee Bee Choo, Mr. Sugumaran and Mr. Muthalib. Without their guidance and corporation, I could not have gotten such relevant data.

I owe my deepest gratitude to Miss Shantini for her love and moral support. The times when I was struggling, she was there to guide me through. Only a real friend tells us when our face is dirty. She is more than a friend to me. I salute her with all my heart for all the words of wisdom and encouragement she had given me. My achievement is nothing without her!

My sincere gratitude is hereby extended to all my colleagues especially Mr. Dinash who was ever willing to guide me in experimental work as well as theoretical solutions without any hesitations. Miss Teeba, a sincere childhood friend of mine. No road was long with a good company like her. It is the friends you can call up at 4am that matter. I would like to thank both my colleagues for all the valuable discussions. I could never forget their endless advice, moral support and the sleepless nights of discussions we had together in our lab. The journey of my masters program would have been incomplete without both of them. Not forgetting all my fellow labmates who were enough understanding in sharing the lab.

I would like to thank Miss Nisha for her love, care and encouragement. A sincere roommate who was there to share all my ups and downs. 'Silences make the real conversations between friends.' Not the saying but the never needing to say is what counts. A person who shows so much care and concern in all that I do. A presence of hers simply makes the difference; which is a blessing to me.

I am also highly thankful to Dr. Radhika Thankappan who was my role model, to guide me through and to show me the right footsteps to be followed and Dr. Shanmugan Subramani for his suggestions and guidance throughout this study. Special thanks to dear friends, Miss Kohilavani and Mr. Rubentheren for their support.

I am as ever, especially indebted to my mother for her love and support. This work would never have been completed without her prayers, encouragement and her devotion. All that I am, or ever hope to be, I owe to my angel mother. Not forgetting my father and my two sisters who supported and encouraged me. I owe my lifetime to my sisters who took the burden of the family and let me pursue my studies.

Utmost appreciation to the Almighty, for His blessings.

Anithambigai Permal

TABLES OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF PLATES

LIST OF SYMBOLS

T_J	Junction temperature
R_{th}	Thermal resistance
$R_{thJ\text{-}B}$	Junction to board thermal resistance
$R_{thJ\text{-}C}$	Junction to case thermal resistance
$R_{thJ\text{-}A}$	Junction to ambient thermal resistance
K	Sensitivity value (K factor)
V	Forward voltage
W	Watt
mA	miliampere
Eq	Equation
C_{Σ}	Sum of thermal capacitance
R_{Σ}	Sum of thermal resistance
P_{heat}	Heat power
P_{el}	Electrical power
P_{opt}	Optical power
I_{in}	Input current
I_{sc}	Sensor current
I_{tot}	Total current

LIST OF ABBREVIATIONS

LED	Light emitting diode
RC	Resistance Capacitance
DUT	Device under Test
MCPCB	Metal core printed circuit board
TSP	Temperature sensitive parameter
TDIM	Transient dual interface method
FE	Finite Element

ABSTRAK

PENCIRIAN TERMA DPC BERKUASA DAN HIMPUNAN DPC

Sekaligus dengan kemajuan teknologi diod pemancar cahaya (DPC), haba yang dijana di dalam komponen elektrik kini telah menjadi suatu isu dalam mengekalkan kebolehpercayaan dan kestabilan teknologi ini. Maka, pengurusan haba adalah amat penting diusahakan bagi mengekalkan prestasi teknologi ini. Suhu simpang (S_S) dan rintangan haba (R_H) merupakan dua parameter utama dalam kajian pengurusan haba. Matlamat kajian ini adalah untuk memahami ciri-ciri terma LED berkuasa di bawah pelbagai keadaan yang boleh meningkatkan kefahaman terhadap pengurusan terma. Penggunaan kebuk udara mendedahkan bahawa adalah perlu untuk mengawal persekitaran kawasan penyelidikan untuk memastikan bahawa penyejukan peranti hanya berlaku melalui olakan bebas yang dijana oleh DPC yang diuji. Menggunakan JEDEC JESD51-14, R_H dari simpang ke papan litar bercetak berteras logam (PLBBL) bagi DPC 3W biru telah diperolehi 10.84 K/W pada 700mA berbanding dengan nilai piawai, 17.0 K/W. Aliran air telah mengurangkan jumlah R_H sebanyak 55.6% dengan catatan 11.89 K/W berbanding dengan olakan bebas yang menghasilkan jumlah R_H sebanyak 26.78 K/W. Kajian ini mendedahkan bahawa rintangan haba separa di dalam sesebuah pakej adalah sentiasa parameter yang paling penting menyatakan had prestasi yang terbaik di bawah syarat penyejukan yang terbaik. Perbezaan utama di antara DPC putih sejuk dan panas bercip tunggal adalah disebabkan kepekatan fosfor dalam bahan cip. DPC putih sejuk telah mencapai perbezaan sebanyak 1.62% kurang dalam S_S berbanding dengan DPC putih panas. Perkara ini jelas menunjukkan sebab diberinya lebih tumpuan dalam penghasilan DPC putih sejuk and putih neutral. Kajian juga teah mendedahkan bahawa DPC bercip berbilang mencapai R_H dan S_S yang kurang berbanding DPC bercip tunggal.

ABSTRACT

THERMAL CHARACTERIZATION OF POWER LEDs AND LED ASSEMBLIES

As the technology of light emitting diode (LED) improves, the amount of heat generated becomes a bottleneck to the technology that affects the reliability, stability and lifetime of the device. Therefore, to sustain the performance of a product, thermal management of power LEDs has become very significant. Both junction temperature (T_J) as well as thermal resistance (R_{th}) are the key evaluation parameters in the study of thermal management. The goal of this research is to understand the thermal characteristics of power LEDs under various conditions which could enhance the understanding towards better thermal management. Utilization of still air chamber revealed that it is necessary to control the environment to ensure the cooling of the devices only takes place through natural convection generated by the package under test. Employing JEDEC JESD51-14, the junction to board thermal resistance of 3W blue LED was 10.84 K/W at 700 mA compared to the datasheet value which was 17.0 K/W. Water flow reduced the total junction to ambient thermal resistance as much as 55.6% where the total R_{th} achieved was 11.89K/W compared to 26.78 K/W achieved in still air chamber. This study revealed that partial R_{th} of a package is always the most important parameter of a device; stating the best performance limit under the best cooling conditions. The primary difference between single chip cool and warm white LEDs were due to the phosphor concentration in the material of the chip. Cool white LEDs achieved a T_J difference of 1.62% less compared to warm white LEDs. This suggest a defined reason for lighting industry to focus more on cool white and neutral white application. It was also found that multi chip achieves less R_{th} and T_J compared to single chip LEDs.

CHAPTER 1

INTRODUCTION

1.1 Overview

The chapter includes a brief introduction on LEDs, the problem statement and the scope of the present work that has been carried out. The scope of the work has been stated clearly in accordance with the research objectives of the present work and followed by the thesis outline which describes the content of each chapter of this thesis.

1.2 Introduction to Light Emitting Diodes

Light emitting diodes (LEDs) have become one of the most promising electronic devices in the past few decades. The development of LED technology has become an integral part of the lighting industry. The market research firm expects a compound annual growth rate (CAGR) of 26% from 2010 to 2015 for street lights, parking lot lights, canopy lights, flood lights and many others [1]. The technology too is being extensively studied by the automobile industry as these LEDs offer a substantial benefit in the automotive lighting applications [2].

Today, one may observe a tremendous change in the worldwide lighting industry as these LEDs are competing the traditional lighting sources with the increasing energy conversion efficiency [3]. However, with the increasing demand for the solid state lighting solutions, comes the need for better thermal management techniques.

1.3 Problem statement

As high power LEDs decrease in package size and the operating parameters keep increasing, the potential for thermal runaway and catastrophic failures increases.

Specifically, as it is widely known, the light output of an LED depends strongly on the operating conditions. Increase in driving current results in more light output which eventually increases the junction temperature. The failure rate of an electronic device doubles with every 10°C increase in the junction temperature at the chip [4]. Unfortunately, the increase in junction temperature is the major drawback of this technology where a continuous rise in the junction temperature drops the light output [5]. In addition to this efficiency loss, the colour of the light also changes by the shift in the peak wavelength [6].

Thus, thermal management of these devices is becoming more and more crucial as poor thermal management would cause an excessive rise in the junction temperature and subsequently would either cause a complete thermal runaway of the device or breakdown of the chip [7]. However, at present, virtually there are no standards for measuring, reporting, testing, or applying LEDs. Fortunately, many organizations and research groups are cooperating in standards development as irrelevant claims about these arising LED products could severely ruin the market acceptance [4]. Organisations such as JEDEC, which has been the global leader in developing open standards for the microelectronics industry is taking a tremendous effort of providing a guideline for effective experimental work both in lab scale as well as in industrial scale.

Thus, understanding the development of the lighting technology and the circumstances of having inadequate standards, it is vital to consider all possible cooling conditions that utilize good thermal management techniques thereby reducing the effect of temperature.

1.4 Scope

Due to inadequacy in the standards for LED thermal characterizations, the product manufacturers all over the world are still facing predicaments in producing a genuine, reliable and ideal datasheet of a particular product. Therefore, the present work has been focussed on studying the thermal performance of LEDs in terms of chip level, package level and board level; which in turn gives the idea on the effect of measurement conditions for the thermal parameters of the LED. The present study enables one to understand the thermal behaviour of LED samples under different conditions and to observe the significant changes in the thermal as well as optical characteristics of the samples.

1.5 Present Work

The measurement environments and the boundary conditions were controlled. The measurements were limited to different types/colours of LEDs housed in packages. Test LED consisting of a heat source was driven with specific driving current and the corresponding one dimensional heat flow through the LED system was analysed using structure function evaluations. Various experiments were carried out to study the effect of the change in measurement environment on the thermal characteristics of the samples as to achieve the following objectives.

1.6 Objectives

- To investigate the effect of natural convection and forced convection on both partial as well as total thermal resistance of an LED package.
- To understand the phosphor concentration effects on the thermal characteristics of cool and warm white LEDs
- To study the effect of thickness and conductive materials of the MCPCB substrates on the effective heat dissipation of the samples.

1.7 Thesis Outline

This thesis consists of 5 major chapters. Chapter 1 is about the introduction to light emitting diodes. Chapter 2 discusses extensively the literature behind the work that has been carried out and the theoretical background of the work. The methodology employed has been explained well in Chapter 3. Chapter 4 presents the results and discussions of the obtained experimental data. Finally Chapter 5 recaptures the main objectives of the work and presents an overall conclusion for the valuable work that had been carried out.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

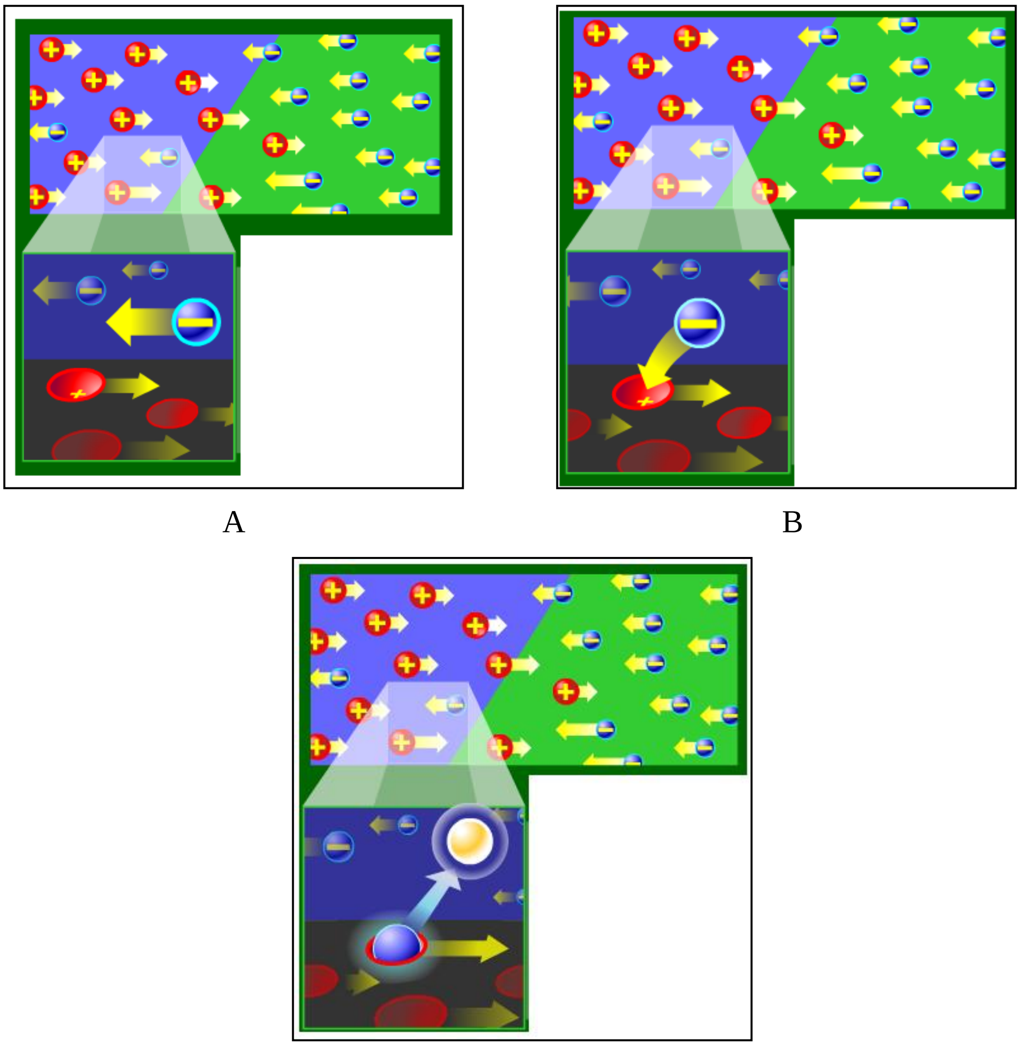
This chapter signifies the background of LEDs from the very first invention of the technology up to the recent evolution of the field. It is an overall view of the theory and the applications of thermal transient measurements. This chapter focuses on the physics behind an LED, the history of LEDs, white light technology, the major drawback in lighting industry, effective thermal management and finally the typical applications of transient measurements and structure function evaluations

2.2 The Physics behind LEDs – Photon Generation

The process in which an electron, which has been excited from the valence band to the conduction band of a semiconductor, falls back into an empty state in the valence band (hole) is known as the process of recombination. Electrons and holes in semiconductors recombine either radiatively or non-radiatively. Radiative recombination is the one which emits photons.

The physics behind the process of light emission from an LED can be described in two steps as explained clearly by C.J. Nuese [8]. First step is when there occurs a generation of electrons and hole at a higher concentration compared to the permitted concentration at thermal equilibrium. The second step is when a significant fraction of these carriers recombine and eventually produce photons.

The motion of free electrons and holes across the p-n junction is shown in Fig. 2.1(A). When a specific current is driven through a diode, the electrons and the holes move in opposite directions across the p-n junction. Since the holes from the p-type material exist at a lower energy level, when a free electron from a higher energy level falls, it releases energy as depicted in Fig. 2.1(B). The energy is released in the form of photon, the most basic unit of light, shown in Fig. 2.1(C). The colour of the light is determined by the size of the fall of the electrons. A bigger fall generates light with higher frequency.



A B C

Fig. 2.1 Pictorial representation of photon generation (A) motion of free electrons and holes, (B) electron falling from higher to lower energy level and (C) photon emission as energy release

The same mechanism of photon generation or radiative recombination has been utilized in LED technology where the frequencies of the photon emissions are controlled by the manipulation of the specific semiconductor material employed in the chip material of an LED.

2.3 History of Light Emitting Diodes

The phenomenon of electroluminescence evolved in the early of 20th century. This phenomenon was imperative because it occurs even at room temperatures unlike the incandescent which only emits light as a result of heating process at temperatures more than 750˚C. This phenomenon fascinated many scientists in its discovery nearly 70 years ago. In 1907, H.J Round, an electrical engineer came across a practical phenomenon of electroluminescence using Silicon Carbide (SiC) crystal. He connected 2 wires to a battery and created a contact on the SiC crystal and eventually found that the crystal actually gave a yellowish light output [9-12]. He might not have known it at that time; however, he made the very first light emitting diode (LED) to be born.

In 1947, the p-n junction was invented. Only after 1951, the forward bias effect was understood as a result from Kurt Lehovec's effort where it was proposed that SiC might have interesting applications based on the frequency response of light emission [13]. However, due to preparation difficulties with SiC, many doubted the ability of this material. In 1955 and 1956, Haynes and Briggs [14, 15] changed the perception and reported that radiation can be obtained by carrier injection in both Germanium and Silicon. Over the years, various semiconductor compounds were tested for their electroluminescence. In early 1960's, the pioneering material was GaP where Ralph Logan and his co workers developed GaP based red and green LEDs [10]. LED based on GaAsP layers was invented in 1960s by Nick Holonyak Jr. [16].

The first experimental production of light emitting device which was called the 'crystal lamps' began in 1962 [17, 18]. The first LEDs in various colours of green, orange and yellow lights were found in 1970s [19]. Blue light emission [20, 21] was progressed in 1993 [22]. Since the middle of 1990's, solid state lighting has created a vibrant industry by new and expanding markets based on high-brightness light emitting diodes (HBLEDs) [23]. After the development of blue and pure green LEDs by Nichia in 1993, the reproducible area was much wider and fulfilled most of the regions in a colour diagram [24].

2.4 White LEDs

Over the years, LEDs have improved in colour range, lumen output, colour stability, lifespan, and other performance factors, allowing them to dominate, many lighting markets. Nevertheless, creation of white light is the major breakthrough in the evolution of LEDs. The evolution of LED reported by OSRAM is shown in Fig. 2.2. The lighting technology has evolved from incandescent lamps in 1870s to mercury lamps in 1904, followed by fluorescent lamps in 1930s, halogen lamps in 1959, metal halide in 1961 and compact fluorescent lamps (CFL) in 1980s. The technology then proudly presented power LEDs in 1990s.

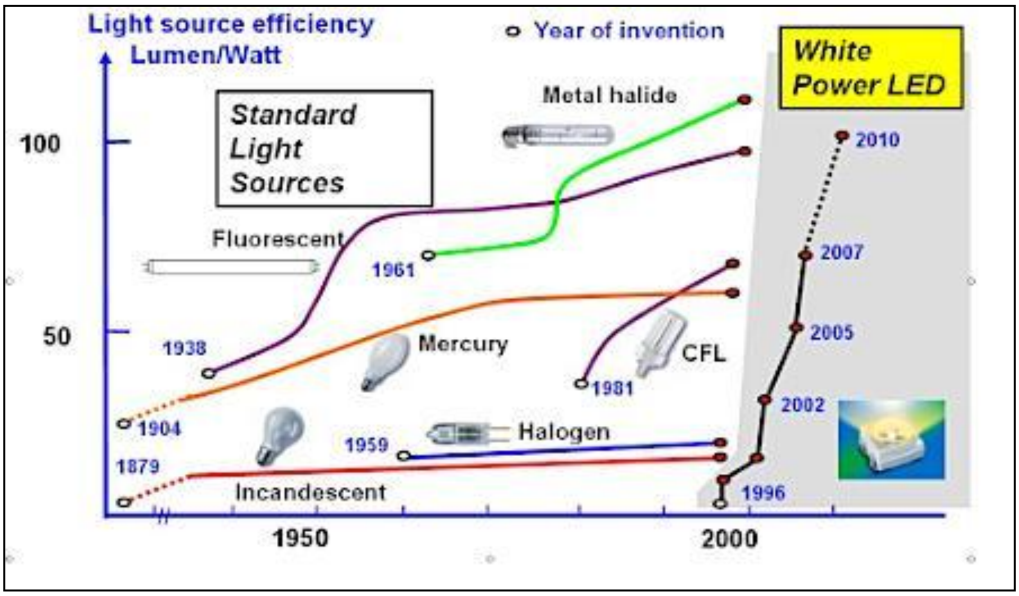


Fig. 2.2 Evolution of LEDs from 1950's to 2000

It is evident from the figure that the gradient of the evolution plot of white LED is much steeper compared to the normal standard light sources. Doubtlessly, the lighting industries are growing outstandingly with latest news of solid-state light source advancements every year.

There are 2 distinct methods of producing white light. One of the approaches uses an appropriate combination of red, green and blue LEDs to produce white light. The second approach however utilizes a blue or UV LED and a phosphor layer to create white light. This is the most common methods available for producing white light [25] where the colour of white was achieved by combining blue InGaN LED die with the fluorescent powder [24]. There are several configurations of this technology which have been reported. The conventional configuration of a phosphor converted white LED is shown in Fig. 2.3(A).

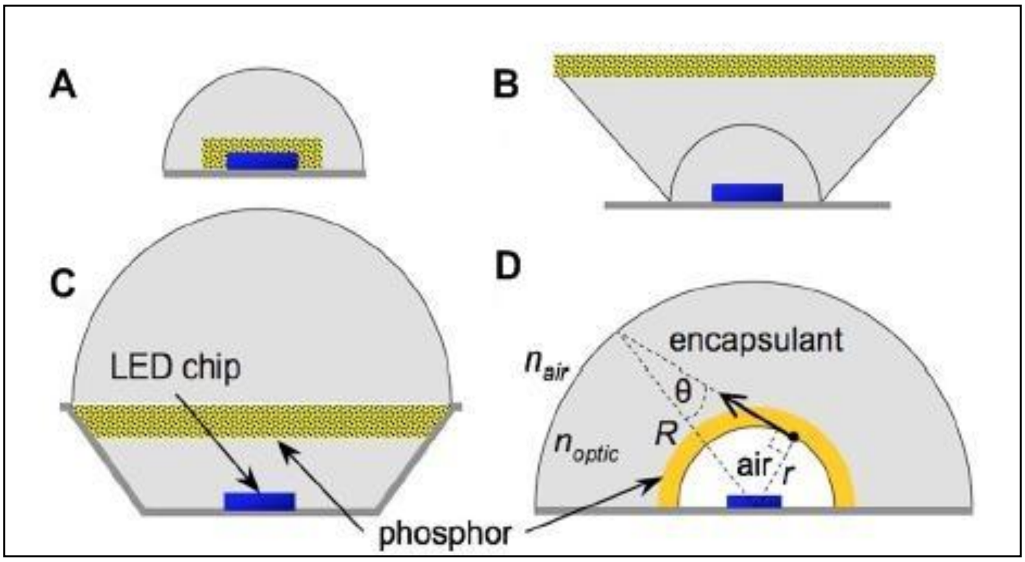


Fig. 2.3 Phosphor converted LED packages (A) Conventional phosphor on chip, (B) scattered photon extraction remote phosphor, (C) remote phosphor with hemispherical dome and (D) ELiXIR - remote hemispherical shell semi-transparent phosphor [26]

This configuration performs the least efficiency as the diffuse phosphor directs 60% of the total white light back to the chip. In year 2004, Scattered Photon

Extraction (SPE) method was introduced where an improved light extraction was obtained by moving the phosphor away from the chip creating a custom optical element between the chip and the phosphor layer. This is shown in Fig. 2.3(B) [27]. Another configuration was reported in 2005 introducing a remote phosphor, diffuse reflector cup and hemispherical optic to minimize trapped light [28]. This method was still a drawback as there were still losses due to trapping of the rays between phosphor layer and the reflector cup shown in Fig. 2.3(C).

Another work was reported in 2007 to a greater degree where a semitransparent phosphor layer was utilized to be separated from the chip by an air gap. This configuration was known as the Enhanced Light Extraction by Internal Reflection (ELiXIR) [29] which has been illustrated in Fig. 2.3(D). Internal reflection at the phosphor/air interface redirects much of the backward phosphor emission away from the die and reflective surfaces without loss. The semi-transparency of the phosphor layer allows light to pass through without deflection and escape the device more easily than diffuse phosphor layers [26] which has been implemented in the other 3 configurations. The reported method has enabled a blue to white conversion with nearly ideal efficiency and the configuration has been expected to exceed the Optoelectronics Industry Development Association (OIDA) efficiency target by 2020.

2.5 The Major Drawback of the Vibrant Industry

Putting aside all the promotion of this technology, in terms of thermal management of these devices, one characteristic is never affirmed; the junction temperature (T_J) of the device. T_J is a side effect which cannot be avoided. A p-n junction generates heat; does not matter if it is one of millions on a chip or the only one within a power LED. It has been reported that an increase in of 10˚C in the T_J causes a 50% of reduction in the reliability of the device [30].

Thus, all these facts appeal towards the need for a thorough grasp of thermal behaviours at the package level, chip level and board level and beyond that to thermal interface materials (TIM) and the heat sinks. The requirements to improve the thermal management of high power LEDs do posses a significant challenge as poor thermal management would cause excessive rise in the T_J as well as the thermal resistance and subsequently would either cause a complete thermal runaway of the device or breakdown of the chip. True understanding comes with physical measurements performed on actual devices.

2.6 Effective Thermal Management

2.6.1 Thermal Resistance

Thermal resistance (R_{th}) of a semiconductor device is generally defined as the ability of the device to transfer heat according to JEDEC standard 51-1 [31] as in Eq. 2.1. Thus, the lower the value the better is the thermal performance.

$$R_{thJX} = \frac{T_J - T_X}{P_{heat}} \tag{2.1}$$

Where R_{thJ-X} is the thermal resistance from device junction to the specific environment, T_J is the device junction temperature under steady state condition, T_X is the reference temperature for a specific environment and P_{heat} is the power dissipated in the device.

As it is widely known, the light output of an LED strongly depends on the operating conditions. The higher the supplied current, the more light is generated by LEDs. However, when the forward current increases or when the LEDs are driven at a constant current, the temperature gradient increases and eventually causes a drop in the light output. The dependence of R_{th} with optical power and temperature of an LED [6] is given in given in Eq. 2.2.

$$R_{th\,JX} = \frac{T_J - T_X}{P_{el} - P_{opt}} \tag{2.2}$$

Where P_{el} is the electrical power, P_{opt} is the optical power. Considering the P_{opt} in the calculation of R_{th} according to Eq. 2.2 yields the real thermal resistance values.

2.6.2 Understanding the Heat Flow through an LED Package

Unlike incandescent bulbs, LEDs do not radiate heat. Instead, generally in an LED, the heat generated in the p-n junction will first be conducted from the chip to the metal core printed circuit board (MCPCB) followed by an external heat sink and finally into the ambient via convection. Fig. 2.4 below describes the one dimensional heat flow path in a typical high power LED mounted on a metal base.

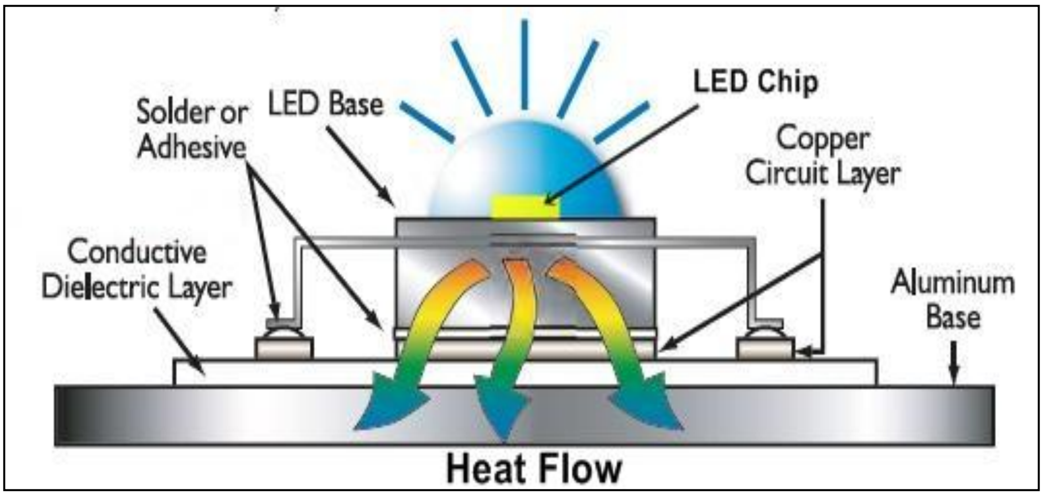


Fig. 2.4 One dimensional heat flow path in a typical high power LED mounted on an aluminium base [32]

The figure describes the heat flow with an assumption that it is a perfect one-dimensional heat flow. It is impossible to assume a perfect one-dimensional heat flow as there is heat loss through surrounding lead frame, epoxy and lens [33]. However, this loss is reported to be insignificant as the material thermal conductivity is very small [34].

A single T_J reading under specific operating conditions is a reasonable predictor of design success. However, measuring the transient that occurs when switching a device on or turning it off produces even more useful information.

2.6.3 Principle of Thermal Transient Measurement

Thermal transient measurement is defined as the recording of heating and cooling curves of a system which is a measure of temperature rise inside a particular network [35-37]. The method itself is virtually the recording of the thermal response function of a structure for a step response excitation. The basic principle of thermal transient measurement is shown in Fig. 2.5 [38-40].

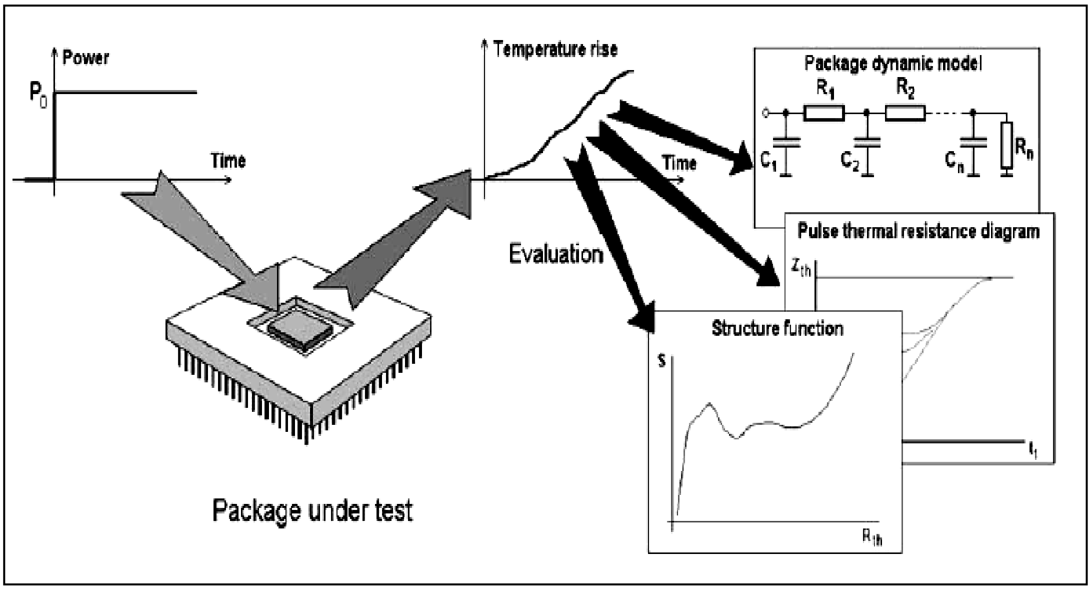


Fig. 2.5 The principle of thermal transient measurement [38-40]

The dynamic thermal properties of an IC package are usually measured in a time domain. The package under device would be given an electrical input in the form of driving current and voltage. Referring to Fig. 2.5, in $t = 0$ time instant, a P_o dissipation step is applied to the package. Beginning with this moment, the temperature rise would be continuously recorded. This function is called the heating curve [41]. As a result of these measurements, a physical equivalent structure of the package will be obtained which is described by the structure functions.

2.6.4 Structure Function Evaluation

The structure functions are defined as the measurement data obtained directly by mathematical transformations from the heating or cooling curves [31]. It is actually the cross sectional area of the heat conducting materials versus thermal resistance (related to the heat source) of the package. Structure functions can be evaluated in two ways known as cumulative structure function and differential structure function.

Cumulative structure function is a direct map of thermal capacitance versus thermal resistance smoothly distributed along the junction-to-ambient heat-flow path for the whole system directly constructed from the Cauer-network equivalent RC model of any thermal system [38, 42]. This gives the sum of the thermal capacitances, C_Σ and thermal resistances, R_Σ of the system.

The derivative of a cumulative structure function is defined as the differential structure function. This function provides a map of the square of the heat current-flow cross-section area as a function of the cumulative resistance [38]. Each peak in a differential structure function corresponds to each layer in a package.

The structure functions are quantitatively valuable corresponding to the physical chip environment and heat source conducting structure. Determination of eventual heat distribution through different regions of the package (chip, board and ambient) is possible with the aid of structure functions.

2.6.5 Advantages of Thermal Transient Measurement and Structure Function Evaluation

The evaluation of thermal transient measurement and structure functions enable one to understand the thermal behaviour of a structure where the heat flow path through each region of a package can be identified accurately by studying the peaks. Thermal transient together with structure function evaluations are usually applied in thermal failure analysis to detect die attach failures. This method plays a role as a detector of the fine structure of the heat flow path in any IC and other semiconductor devices [38, 39, 43-45]. Fig. 2.6 shows a typical cumulative structure function.

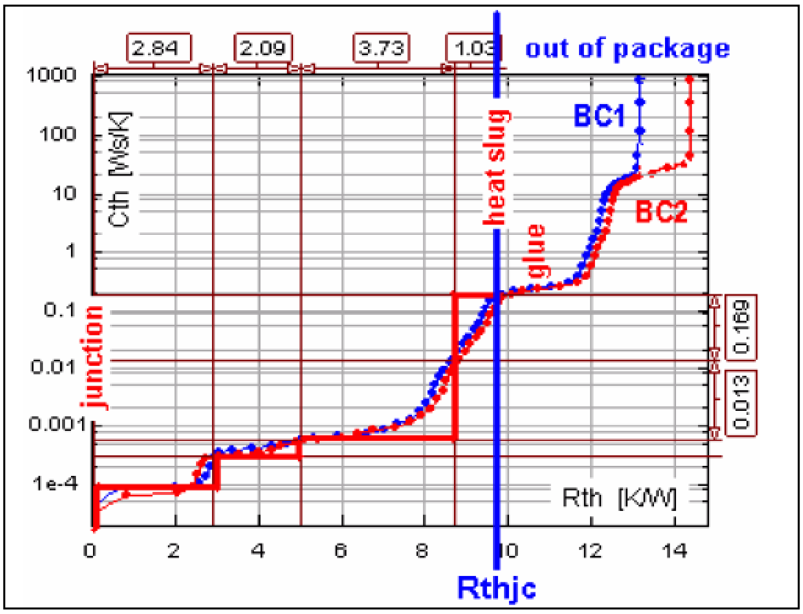


Fig. 2.6 Typical cumulative structure function

In this type of plot as shown in Fig 2.5, the origin of the heat is literally from the junction of the device. Each step upward denotes the heat's progress, going from one resistance, through a capacitance to another resistance. The flat regions or better known as plateaus in the graph refers to the new materials. The width of the plateaus gives the corresponding thermal resistances. The linearly increasing intervals represent the spreading of heat [38].

Fig. 2.7 shows a typical differential structure function. Each peak in a differential structure function refers to each linearly increasing region in a cumulative structure function which actually denotes each layer in an electronic package.

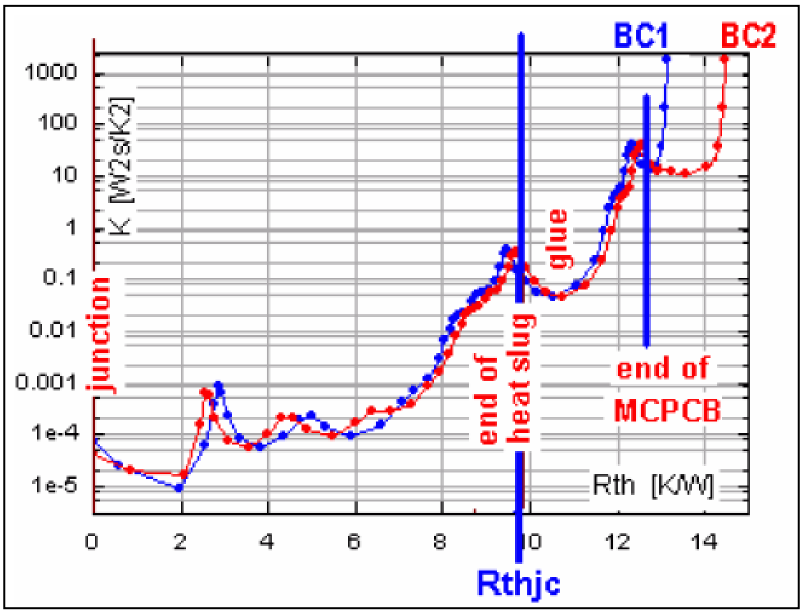


Fig. 2.7 Differential Structure function [46]

With both the cumulative and differential structure functions as a “road map” of the heat path, it is easy to evaluate the performance of individual materials along the way. From Fig. 2.6 and 2.7, the divergence of the structure functions due to different boundary conditions (BCs) enables one to study the significance of employing various BCs. Measurements and data obtained would be fruitful only if the temperature transient measurement is done with sufficient accuracy and resolution and rigorous post-processing of the data. Like wise, so far many investigations have been carried out for heat dissipation solutions for effective thermal management. Primary focus had always been on the package level, board level and system level investigations.

2.6.6 Thermal Investigations of LED – A Package Level Study

In terms of package level analysis, determining the partial thermal resistance between junction and a particular layer in a package is a challenge. Fig 2.8 below describes the basic LED package with the typical positions of temperatures usually referred to. The core layer, which is the base of the LED is known as the 'case' of the package.

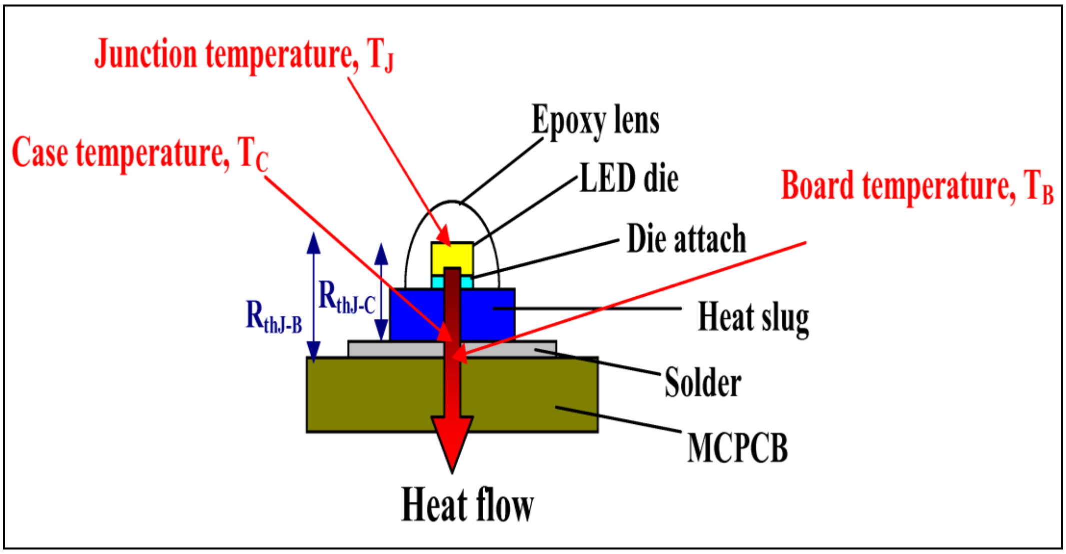


Fig. 2.8 Typical LED package with important positions of temperatures usually referred

Case of a device is the nearest surface (closest) to the chip mounting area of any package. The thermal resistance from chip to this portion which is known as junction to case thermal resistance (R_{thJ-C}) is well appropriate to be described as one of the most important parameter of a semiconductor device; stating the thermal performance limit under best possible cooling conditions. Since power semiconductors are prone to ever increasing power dissipation levels, achieving a low R_{thJ-C} is very significant.

The conventional procedure of measuring R_{thJ-C} is by using the thermocouple measurement. Often this produces inaccurate results since it is difficult to place the thermocouple exactly at the required surface of case of the package. Furthermore, it is important too to employ thermocouples with the correct gauge size. In order to avoid strange temperature reading, the JEDEC Standard No. 51-2A strongly recommends a maximum thermocouple size of 36 gauge and for T type, 40 gauge [47]. Despite these hassles, Szabo et al. presented a method of finding the $R_{thJ\text{-}C}$ by comparing boundary conditions of different interface layers [48].

A comparison of with and without thermal grease was reported in [48] and structure function based evaluation favoured in determining the exact point of separation between package and case. The same dual interface method was reported in 2008 using 3 different boundary conditions; liquid metal (Gallium Indium-Tin Alloy), thermal grease and ceramic plate and thermal grease only as interface materials in each boundary condition [49]. It was reported in 2010 that interface materials like mylar sheet or ceramic are more suitable for smaller chip semiconductor devices [50] which means that the size of the chip is a factor for obtaining optimized $R_{thJ\text{-}C}$ with chosen interface material. If the chip is too large, which covers a large surface area of the module; it may cause a huge additional thermal resistance to the system. However, if the chip is too small, the inserted interface layer might not significantly change the structure function.

It was reported again in 2010 by the same author, Dirk Schweitzer that among traditional thermocouple measurement method and finite element simulation method (FE), transient dual interface method is the only method which gives the accuracy of 15% and has been reported to be the only known way to produce more reliable measurement results [33]. Thus, after 5 years of the invention of the method, the transient dual interface method was standardized by JEDEC in November 2010 [51].

2.6.7 Forced Convections for LED Cooling Solutions

There are two types of heat dissipation methods, active and passive cooling. Passive cooling is the heat transfer process to the environment without any external force acting on the system which assists in the cooling process. The most common one in LED applications is the plate fin heat sink method. On the other hand, active cooling is a heat dissipation method which needs an external force to be imposed. Typical examples of active cooling method or simply said as forced convection is forced air, liquid cooling, semiconductor refrigeration and so on. Forced convection methods enable a larger heat flux to be dissipated to the environment [52].

Daliang Zhong et. al. had reported a work on thermoelectric cooler (TEC) and fan applications in LED packaging [53]. 3 models of different cooling methods were investigated as shown in Fig. 2.9.

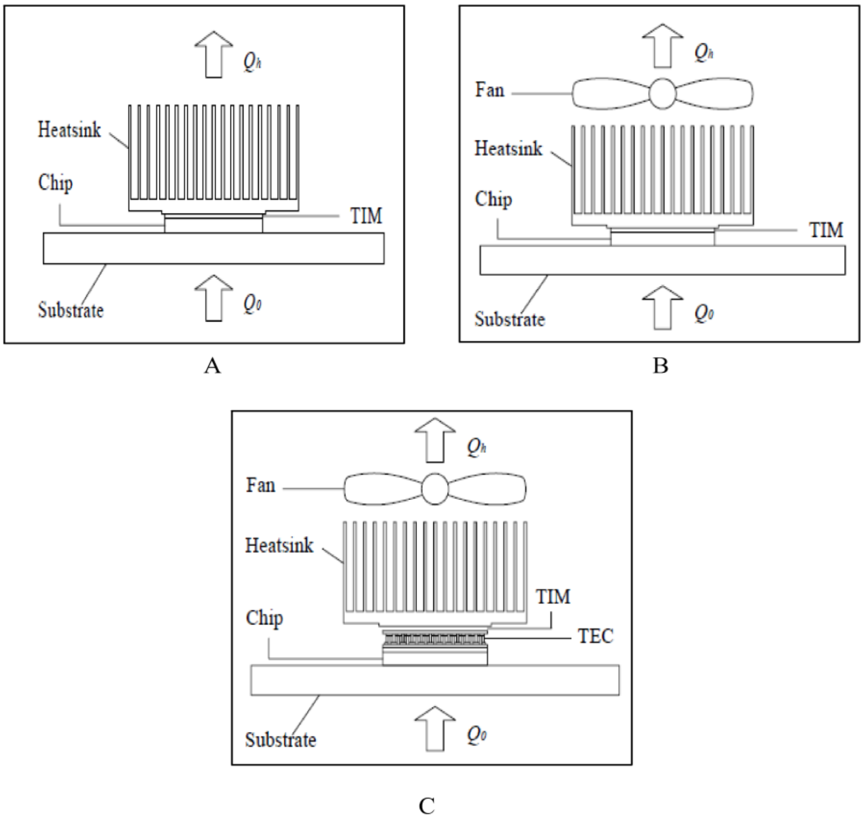


Fig. 2.9 Schematic diagrams of the three experimental models (A) heat sink cooling system, (B) heat sink and fan cooling system and (C) TEC, fan and heat sink cooling system [53]

Evidently, model with TEC + heat sink + fan was better than the heat sink + fan method when the chip power is less then 35W. In contrast to the heat sink with and without fan method, when the input power of LED package is from 10W to 50W, the junction temperature of chip junction drops more than 20˚C. The work actually elucidates the significance of active cooling method for LED's thermal solutions.

Besides, Xiang You Lu et. al. presented a work on improving the thermal characteristics of high power LEDs using heat pipe as heat sink [54]. A new type structure of flat heat pipe (FHP) cooling device was introduced in this work and it was reported that the junction temperature of the LED was about 52˚C for 3W and correspondingly the total thermal resistance of LED system is 8.8 K/W.

Similar work was reported elsewhere where an array of LEDs was tested for its thermal characteristics with and without heat pipe under different boundary conditions [55]. It was demonstrated that applying heat pipe effectively decreases the total thermal resistance of LED array, and was proved to be a good solution for controlling junction temperature of high power LED systems.

2.6.8 Thermal Interface Material - A Major Role as Heat Dissipating Component

Thermal interface materials (TIM) are commonly used to reduce the thermal contact resistance between an electronic device and its cooling solution. In terms of LED application, TIM significantly aids the transfer of heat from the device or the heat source to the heat sink. Fig. 2.10 shows the application of TIM in the heat transfer process of a typical LED package [56].

When an interface material is inserted between the MCPCB and the heat sink as shown in Fig. 2.10, the path of heat removal involves conduction across the interface of the base of the package case through the TIM and then into the external heat sink.

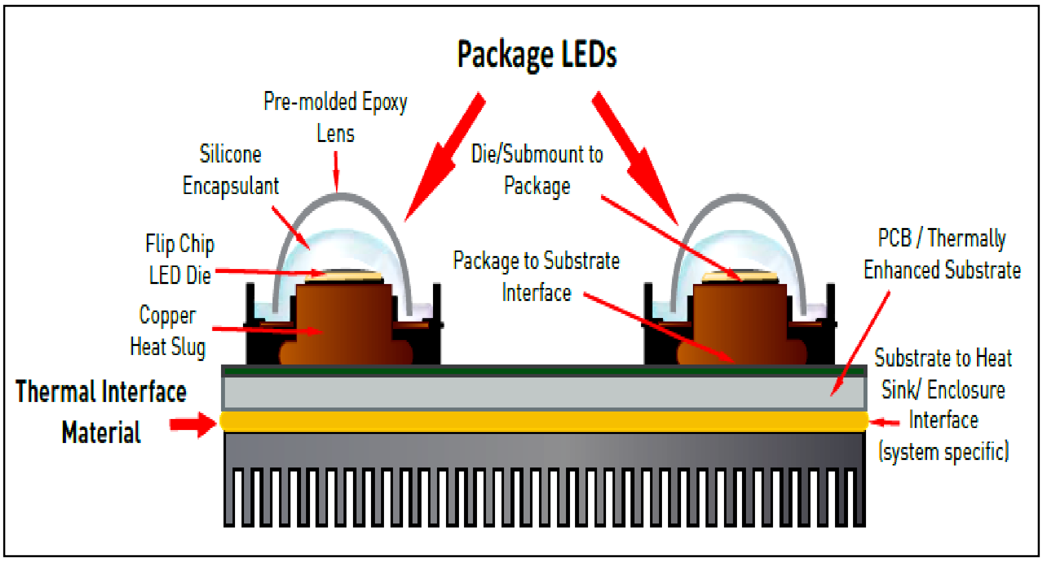


Fig. 2.10 Application of TIM in the heat transfer process of a typical LED package

This interface material plays an integral part of the heat dissipation path where they reduce the thermal interface resistance between two mating surfaces. The transient technique is additionally sensitive to the relative contribution of the TIM in the full junction-to-ambient thermal path [57].

The effect of different types of TIM was investigated by Jun Wu et. al. and it was reported that thermal conductivity, performance of filled materials of TIMs and the mount pre-compact force were the influencing factors of reducing thermal contact resistance [58]. Reduced thermal contact resistance is vital for best mating surfaces between the sandwiched regions; ie between MCPCB and external heat sink for LED applications. However, the contact surfaces between the bottom of MCPCB and the top of heat sink or in fact in the case of any 2 mating surfaces are usually never perfectly flat due to the manufacturing process which induces warpage in heat sink and electronic packages [59]. Fig. 2.11 shows the waviness and the roughness between any two surfaces.

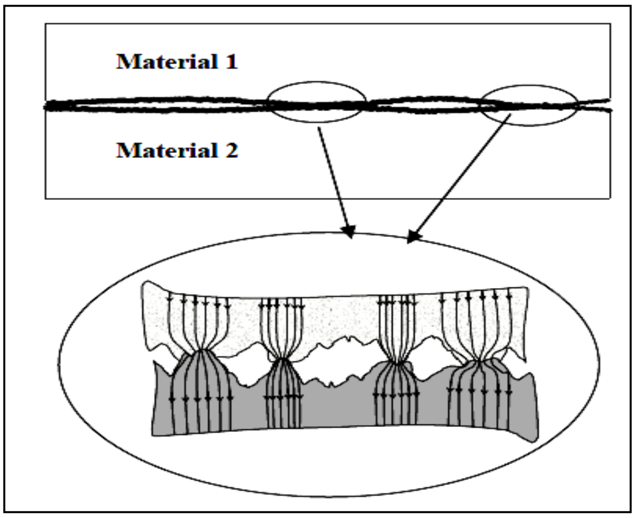


Fig. 2.11 Waviness and the roughness between any two surfaces [60]

Theoretically, the contacting surfaces will only contact one another at discrete points. The air gaps act as a thermal barrier due to its very poor thermal conductivity, preventing efficient heat transfer across the interface [61]. Fig. 2.12 shows the TIM being inserted between two surfaces, forming an almost ideal contact with minimized contact resistance.

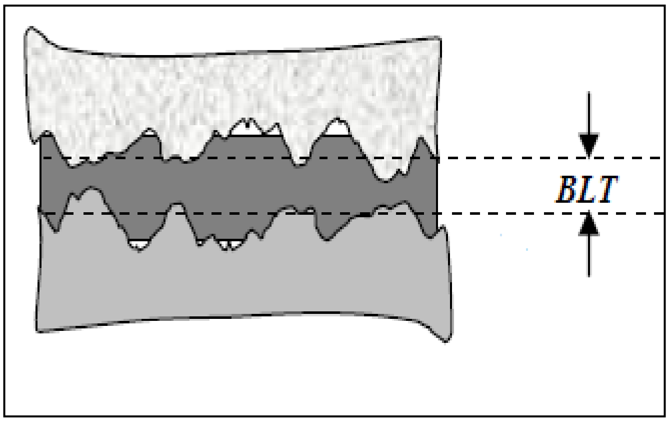


Fig. 2.12 TIM being inserted between two surfaces [60]

A perfect contact would ease the flow of heat in an LED package thus the rise in T_J can be maintained at required benchmark.

2.6.9 MCPCB as a Cooling Solution for Effective Heat Dissipation

In conjunction with the vibrant progress of this LED industry, the board technology is being studied extensively too in order to compensate the need for thermal management. Conventional PCB materials such as FR4 share the lowest thermal conductivity and are not capable of meeting the continuously increasing demand of the thermal requirement of the high power dissipation PCBs.

One of the current approaches to address this thermal dissipation problem is the issue of Metal Core Printed Circuit Board (MCPCB) [62]. An MCPCB with a 1W LED can remain near an ambient of 25˚C, while the same 1W LED on a FR4 board reaches 12˚C over ambient [63]. Thus a detailed study on the striking behaviour of the printed circuit board is a must to enable an efficient thermal management [64, 65].

The main difference between an FR4 board and MCPCB is the thermally conductive dielectric material in the MCPCB which acts as a thermal bridge between the IC components and metal substrate. Fig. 2.13 shows the comparison of a conventional FR4 and an MCPCB published by Thermagon Inc. [66].

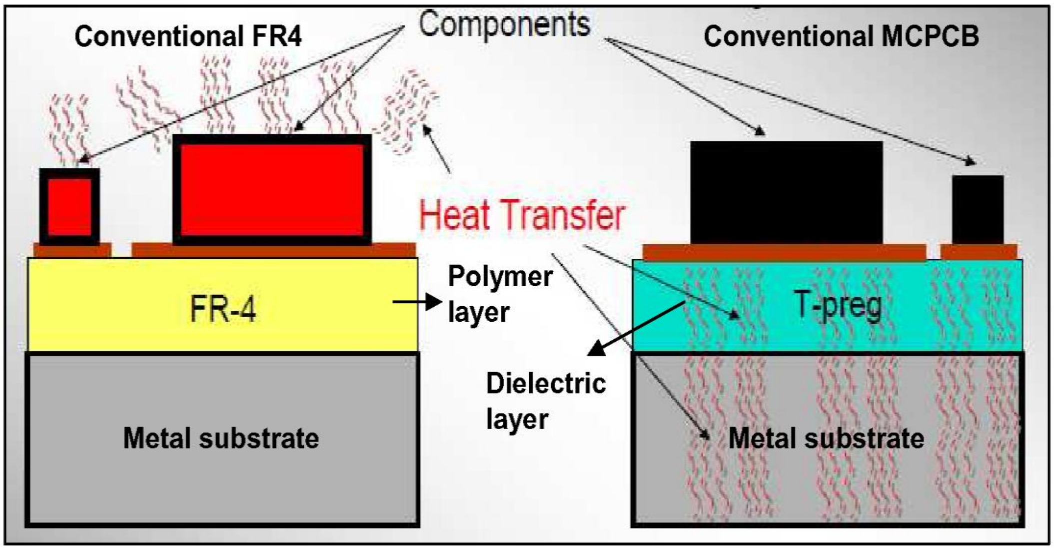


Fig. 2.13 Comparison of conventional FR4 and MCPCB [66]

Fig. 2.13 shows that the heat from the component radiated more in FR4 compared to in MCPCB which conducts the heat more downwards which absolutely favours in better heat dissipation. These MCPCBs are normally composed of a thick metallic substrate, with a thin circuit layer composed of dielectric material laminated on top, a copper layer and a solder layer on the copper for tinning and component attachments. The key property which determines the effectiveness of an MCPCB is the determination of the dielectric material.

In conventional MCPCBs, composite epoxy powders and inorganic powders have been used in dielectric layer to increase the heat dissipation performance. In many cases, alumina powders are used for the inorganic filler of the MCPCB dielectric layer. It was reported in [67] that dense alumina thin films, deposited by an aerosol deposition process, showed low leakage current and good dielectric breakdown for high power applications. Using high thermally conductive fillers like boron nitride and aluminium nitride in epoxy is another technology which has been reported elsewhere [68, 69].

2.7 Typical Applications of Transient Measurements and Structure Function Evaluations

The effect of different types of assemblies of FR4 and MCPCB having primary concerns on the substrate material and the material of the TIM for efficient heat dissipation in an LED system was investigated [70]. A typical application of thermal transient measurement and structure function evaluation on the above assemblies is shown in Fig. 2.14. The description of the structure function and the assemblies employed in the study has been given in bullets.