THERMAL AND OPTICAL PROPERTIES OF HIGH POWER INFRARED EMITTER UTILIZING TRANSIENT DUAL INTERFACE METHOD

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By

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“Life is like riding a bicycle. To keep your balance, you must keep moving.” – *Albert Einstein*

“Genius is 1% talent and 99% hard work.” – *Albert Einstein*

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LIST OF ABBREVIATIONS

LEDs	Light emitting diodes
IR	Infrared
IREDs	Infrared emitting diodes
CCTV	Closed circuit television
JEDEC	Joint electron devices engineering council
MCPCB	Metal core printed circuit board
SSL	Solid state lighting
OLEDs	Organic light emitting diodes
WPE	Wall plug efficiency
UV	Ultraviolet
PCB	Printed circuit board
TIM	Thermal interface material
TSP	Temperature sensitive parameter
DUT	Device under test
T3Ster	Thermal transient tester
TeraLED	Thermal and radiometric characterization of LED
R&D	Research and development
SEM	Scanning electron microscope

LIST OF SYMBOLS

K	Temperature sensitive parameter (K-factor)
Rth	Thermal resistance
Rth_R	Real thermal resistance
Rth_E	Electrical thermal resistance
Rth_{JP}	Junction-to-chip thermal resistance
Rth_{JS}	Junction-to-slug thermal resistance
Rth_{JI}	Junction-to-interface thermal resistance
Rth_{JB}	Junction-to-board thermal resistance
Rth_{JC}	Junction-to-case thermal resistance
Rth_{JA}	Junction-to-ambient thermal resistance
T_J	Junction Temperature
T_a	Ambient temperature
T_o	Oven temperature
T_C	Case temperature
T_B	Board temperature
ΔT	Temperature difference between junction and a reference point
P_{el}	Electrical power or input power
P_{op}	Optical power

P_h	Heat power
I_F	Forward current or input current
I_S	Sensor current
I_T	Total current
V_F	Forward voltage
V_{FO}	Forward voltage at the instant forward current was applied
V_{FT}	Forward voltage when sample reached thermal equilibrium
R_{Σ}	Sum of thermal resistance
C_{Σ}	Sum of thermal capacitance

SIFAT-SIFAT HABA DAN OPTIK BAGI PEMANCAR INFRAMERAH BERKUASA TINGGI DENGAN MENGGUNAKAN KAEDAH DWI MUKA FANA

ABSTRAK

Pemancar IR berkuasa tinggi merupakan teknologi baru yang bermuncul dalam pasaran pencahayaan berkeadaan pepejal. Penyelidikan ini bertujuan untuk mengkaji sifat-sifat haba dan optik bagi pemancar IR tersebut dari segi tahap cip dan pakej sedangkan masalah haba telah menjadi kritikal dan dipercayai bertanggungjawab terhadap masalah prestasi terhad and kegagalan pemancar IR. Sejumlah lapan eksperimen telah dijalankan untuk meningkatkan pemahaman mengenai keadaan operasi optimum serta mengenalpastikan faktor-faktor yang mempengaruhi prestasi terma bagi pakej IR. Keputusan menunjukkan bahawa rintangan haba berubah sebagai fungsi arus dan suhu. Selain itu, pengukuran yang dijalankan di atas plat sejuk menawarkan jumlah rintangan haba Rth_{JA} yang lebih rendah, 5.24 K/W berbanding dengan menggunakan oven, 35.5 K/W. Di samping itu, mempertimbangkan kuasa optik dalam penilaian fungsi struktur adalah penting untuk memperolehi rintangan haba sebenar yang tepat bagi pemancar IR sedangkan rintangan haba elektrik dari simpang-ke-lembaga Rth_{JB} yang diperolehi ialah 35.2% lebih rendah daripada nilai sebenar. Dengan menggunakan kaedah dwi muka fana, titik pemisahan sebenar antara pakej IR dan sink haba luaran iaitu MCPCB atau plat sejuk boleh ditentukan dengan tepat. Hasilnya, rintangan haba sebenar dari simpang-ke-selongsong Rth_{JC} serta dari simpang-ke-lembaga Rth_{JB} ialah 4.62 ± 0.05 K/W dan 10.15 ± 0.05 K/W masing-masing. Menggunakan pateri sebagai lampiran dapat menyebarkan haba dari simpang ke arah slug logam dengan berkesan menyebabkan

rintangan haba lebih rendah berbanding dengan penggunaan gam epoksi kerana pateri adalah sebatian konduktif haba. Pemilihan bahan dengan kekonduksian haba yang tinggi dan sesuai serta menjana lapisan dengan nipis amat penting untuk memaksimumkan penyebaran haba dari simpang ke ambien.

THERMAL AND OPTICAL PROPERTIES OF HIGH POWER INFRARED EMITTER UTILIZING TRANSIENT DUAL INTERFACE METHOD

ABSTRACT

High power IR emitters are new emerging technology in solid state lighting market. Since thermal problem is becoming more crucial and is believed to be directly responsible for their limited performance and failures, this master research aims to study thermal behavior as well as optical properties of the high power IR emitters in terms of chip and package levels. A total of eight experiments have been performed to enhance a better understanding on the optimum operating conditions and also to identify factors that would affect the thermal performance of the IR packages. It was found that thermal resistances varied as a function of input current and ambient temperature. Besides, measurement carried out on a cold-plate offered much lower total thermal resistance Rth_{JA}, 5.24 K/W compared to that performed in an oven, 35.5 K/W. In addition, it was essential to consider optical power in the evaluation of structure functions to obtain accurate real thermal resistances of the IR emitters since the electrical junction-to-board thermal resistance Rth_{JB} obtained without optical power consideration was 35.2% lower than its real value. By utilizing transient dual interface method, the exact point of separation between the IR package and external heat sink, i.e., MCPCB or cold-plate could be precisely determined. As a result, real junction-to-case thermal resistance Rth_{JC} and junction-to-board thermal resistance Rth_{JB} were 4.62 ± 0.05 K/W and 10.15 ± 0.05 K/W respectively. It was observed that using solder as die attach could effectively conduct the heat that was spreading from the junction towards the metal slug, resulted in less thermal

resistance compared to epoxy glue as solder was a highly thermal conductive compound. Hence, it was crucial to choose a proper die attach material with high thermal conductivity and generate the die attach layer inside the IR package as thin as possible in order to maximize the heat dissipation from junction to ambient.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter consists of a brief introduction on light emitting diodes (LEDs), describing their rapid development in illumination industry in the recent years, advantages in using LEDs as general light source and also bottlenecks or drawbacks that limit their penetration as general lighting devices. Finally, the detailed scope of this study has been highlighted in accordance with the objectives of this research and followed by the thesis outline which describes the content of each chapter in this thesis.

1.2 Introduction to Light Emitting Diodes

Light emitting diodes (LEDs) are highly efficient electronic-to-photonic devices that emit light via injection electroluminescence [1]. They are capable to emit visible, ultraviolet and infrared radiations under forward bias condition. As other microelectronic devices, the electrical, thermal and optical behaviors are the key characteristics of the LEDs [2-5].

High power LEDs keep attracting researchers' interest and attention due to their significant impacts on illumination industry and increasing market [6]. Performance of LEDs in optical power and efficiency has been increasingly improved due to the extending knowledge in LEDs' characteristics [7,8].

Recently, technology of LEDs has caused revolution in lighting systems, signalization applications and other forms of displays. LEDs have become one of the most promising electronic devices in the recent years by virtue of their small size, high brightness, power saving, long lifespan, low power consumption, environmental friendly, high reliability and efficiency [9,10].

LEDs that emit infrared (IR) are commonly known as IREDs or IR emitters. Development of IR emitters resulted in several key differences between the electrical characteristics of IR and visible LEDs. Those differences are primarily in the forward voltage used to drive the LED, its rated current and the manner in which its output is rated. IR emitters typically have a lower forward voltage and higher rated current than a visible LED due to the material properties of the *p-n* junction. Since IR emitters do not output light in visible spectrum, they are commonly rated in milliwatts (mW). In comparison, the output of visible LED is rated in millicandelas (mcd) where 1000 mcd equals a candela, which represents lumens divided by the beam coverage [11].

1.3 Advantages of Light Emitting Diodes as General Light Source

LEDs are being developed as the next generation lighting source due to their high efficiency and long life time, with a potential to save $30 billion per year in energy cost by 2030. These energy savings would greatly reduce greenhouse gas emissions by 210 million metric tons of carbon. Likewise, the total electricity consumption for lighting would decrease by roughly 46 percent [12].

Unlike most traditional light sources, LEDs do not fail catastrophically. Instead, the light output of LEDs gradually degrades over time while sudden failures which commonly occur in incandescent lamps are very rare [13].

Another advantage of LEDs is that their lamps are amenable to have a compact size and low profile. A single chip LED is typically 1 mm^2 or smaller in size which is typically smaller than their conventional lighting counterparts. Due to their compact size, LEDs are an excellent option where size or weight is a concern. In addition to these major benefits, LED lamps are robust and non-toxic. Besides, LEDs are semiconductor devices and usually do not use any glass and filament, while incandescent and fluorescent lamps do. Also, LEDs do not contain mercury, unlike fluorescent lamps. In addition, directional light emission of LEDs reduces wasted light. LEDs emit light hemi-spherically, while other light sources emit light in all directions.

In spite of many advantages, the high price of LEDs is the main obstacle in using LEDs as general light source. LEDs are currently more expensive, price per lumen, on an initial cost basis than the other light sources. However, considering the total cost which includes energy and maintenance costs, LEDs are competitive enough at present and continue to improve [14].

1.4 Problem Statement

LEDs are conventional solid state light emitting devices that convert the electrical energy into heat and light energy, same goes to the IR emitters. Although IR emitters play an important role in automotive and communication systems nowadays, an average of 60-70% of the input power will be dissipated as heat to the ambience. In other words, only 30-40% of the input power will leave the system as light source.

Since the optical power generated by a single IR emitter is considerably lower, to be competitive, the total light output must be increased with higher forward current and package of multiple IR emitters. However, both of these solutions would increase the junction temperature and the amount of heat that needs to be dissipated [15,16]. The failure rate of an electronic device doubles with every 10°C increase in the junction temperature at the chip [17]. As the operating temperature goes up, the lifetime will be reduced, and the device efficiency and reliability will change [18,19]. As a result, a proper and effective thermal management of IR emitters is needed.

Thermal management of solid state devices is of great concern nowadays especially for high power LEDs and IR emitters that involve large amount of power dissipation [20]. Most challenging issue in thermal management of IR emitters is to prevent the IR emitters from overheating [21] as thermal problem is becoming more crucial with the increasing of input current, ambient temperature, and is believed to be directly responsible for the limited performance and device failures.

In order to efficiently improve the thermal performance of high power IR emitters, it is important to discover the influential factors and clarify the mechanism of the variation of thermal resistance. One of the approaches in this research is to vary the thermal interface materials of the IR package in the forms of thickness and thermal conductivity of the materials used to enhance heat dissipation from the junction towards ambient.

1.5 Scope of Research Study

Present work is mainly focused on studying the thermal and optical characteristics of the high power IR emitters in terms of chip and package levels by utilizing transient dual interface method. Moreover, influence of input current, ambient temperature, measurement conditions and thickness of die attach layer on thermal parameters of the IR emitters have been investigated to enable us to identify the optimum operating conditions for the particular IR emitters to achieve better performance and longer lifespan.

Besides, optical properties of the IR emitters have also been analyzed and comparison with various types of LED has been made to observe the significant differences in optical characteristics. Consequently, the importance of optical power in the determination of real thermal resistance value for a high power IR emitter has been clarified by considering optical power in the computation of structure functions to obtain accurate values of real thermal resistance.

In this study, boundary conditions have been controlled by varying the thermal interface materials in order to determine the exact point of separation between the IR package and external heat sink, which is metal-core-printed-circuit-board (MCPCB) or cold-plate. Likewise, die-attach layer of the IR emitter has been altered with solder and epoxy glue to examine the effect of die-attach materials on thermal behavior of the IR emitter. By doing this would give a better understanding on the proper materials to be used in order to enhance the thermal dissipation from junction to ambient.

1.6 Research Objectives

- To study the thermal and optical properties of high power IR emitters in terms of chip and package levels.
- To identify the real thermal resistance values of high power IR emitters by utilizing transient dual interface method with optical power consideration.

1.7 Thesis Outline

This thesis contains five main chapters including introduction, literature review, methodology, results and discussion, and finally the conclusion. The first chapter elaborates the development of LEDs in illumination industry in the recent years and the advantages in using LEDs as general light source. This chapter also addresses the drawbacks that limit their penetration as general lighting devices. The chapter ends by highlighting the scope of study, the research objectives and followed by a brief outline on the consecutive chapters in this thesis.

Chapter 2 is an overview of the history and theoretical background of LEDs including the development of IR emitters' technology. Besides, the concept of heat transfer and the importance of an effective thermal management of IR emitters have been presented following by a brief description of thermal and optical parameters.

Chapter 3 describes the methodology that has been carried out to study the thermal and optical properties of the high power IR emitters. Furthermore, the features of the IR emitters, principle of thermal transient measurement, evaluation of structure function, instruments employed in the testing and procedures applied in the thermal characterization have been illustrated in this chapter for better understanding.

Chapter 4 discusses extensively the data and results obtained from all the experiments that have been performed in this master research, inclusive of a brief explanation on the experimental method utilized for each experiment and the valid results found.

Finally, Chapter 5 recaptures the research objectives of this study and presents an overall conclusion for all the remarkable experiments that have been carried out. Limitations of current research and recommendations for future work have also been clarified in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter elaborates the evolution of LEDs starting from the very first invention of the technology up to the recent revolution of the field. It is an overview of the history and theoretical background of LEDs. In addition, this chapter also emphasizes the development of IR emitter's technology and the reasons that cause the scientists and researchers turning their attention and effort on IR emitters. Besides, the concept of heat transfer and the importance of an effective thermal management for IR emitters covering solutions and tools used for efficient heat dissipation have been discussed following by a brief description of thermal and optical parameters.

2.2 History of Light Emitting Diodes

In 1879, Thomas Alva Edison invented the first electric light bulb and with this invention, he entered the public consciousness as 'the inventor' of light bulb [22]. After the tremendous invention of electric light bulb, many innovative light sources have been generated to fulfill the application needs and market demands.

In the early times, traditional light sources such as incandescent light bulb and the standard fluorescent lights played a giant role in lighting market [23,24]. Later on, it was realized that the traditional light systems do show some serious weaknesses such as higher energy consumption, shorter lifetime, lower efficiency and most seriously the emission of harmful gases which would affect human health [25,26].

On top of this, it was found that incandescent lamps with higher power consumption produced only 5-10% of optical power while the rest was emitted as heat and infrared radiation. On the other hand, the compact fluorescent lamps which were claimed to be a better replacement of incandescent lamp also faced some challenges due to its slower switching rate and toxic substance which needed proper waste disposal. The flaws in traditional light systems propelled for the new effective light sources with reduced power consumption and environmental friendliness.

Solid-state lighting (SSL) was discovered in the early twentieth century and LEDs were introduced as practical electronic components in 1962 [27]. SSL is a technology which uses semiconductor materials to convert electricity into light. There are two basic categories in SSL which are LEDs that based on inorganic or non-carbon based materials, and organic light emitting diodes (OLEDs) that based on organic or carbon based materials.

Since 20th century, the luminescence technology has drawn greater attention than the other artificial lighting systems. The phenomenon of electroluminescence in SSL has provoked for promising lighting solutions with better optical performance and thermal stability.

The desire for a highly efficient light source for comfortable lifestyle has prompted for advance development in lighting system. After the fluorescent light source, LEDs were acknowledged as the next advanced optoelectronics technological discovery in the century, which in turn, have been developed as replacement for energy-inefficient incandescent light bulbs. Unlike the incandescent and fluorescent lamps, the higher switching rate of LEDs with lower power consumption and appreciable optical efficiency enhances the longevity of the device effectively [28,29].

Early LEDs emitted low intensity light with limited color and mainly used as signal components in electrical system. These low power LEDs are still widely used as indicators and signs. The applications of modern LEDs became very diverse since they generate all range of visible light and even infrared and ultraviolet lights with very high brightness.

Many assumed that LEDs are unable to compete with the existing light system since the efficiency of LEDs was lower in the earlier times. This explains the reason why LEDs were only used as indicators or decoration lights but not for general illumination purpose as the light emitted was not capable to light up an area due to smaller viewing angle of the light. However, the effort to enhance the efficiency of the LEDs for multiple applications was continued due to its sustainability for longer lifetime with optimized performance [30].

As a result, the performance of LEDs was significantly improved in terms of luminous intensity, durability and reliability. This has conveniently increased the efficiency of LEDs compared to conventional lamps. As an example, the luminous flux of a high power white LED has reached 145 lm compared to 92 lm in 2006. At 1000 mA, the luminous flux of the white LED is compatible with the output of a 30W incandescent lamp. Moreover, the wall plug efficiency (WPE) has been increased from 27.7% to 39.5% which is high enough to compete with fluorescent lamp with only 25% in visible region [31-33]. These achievements conveniently established LEDs to be one of the best candidates as commercial light source for numerous applications.

Table 2.1 shows luminous efficacy and efficiency for incandescent, fluorescent and LED light sources. The efficiency of LEDs has already surpassed that of incandescent light sources, and is even comparable to that of fluorescent lamps. The lifetimes of the various light sources are compared in Table 2.2. State of the art LEDs are capable of emitting light at around 115lm/W and have lifetime over 50,000 hours.

Table 2.1: Luminous efficacy and efficiency for various types of light source [34].

Light Source	Type	Luminous Efficacy (lm/W)	Luminous Efficiency (%)
Incandescent	40W tungsten incandescent (120V)	12.6	1.9
	100W tungsten incandescent	17.5	2.6
	Quartz halogen (12-24V)	24	3.5
Fluorescent	9-26W compact fluorescent	57-72	8-11
	T8 tube with magnetic ballast	80-100	12-15
HID	Metal halide	65-115	9.5-16.8
LED	High power white LED	115	16.8

In order to standardize the lifetime of LEDs, the term L_{70} is used, which refers to the time taken for LEDs to reach 70% light output compared to the initial values. Most manufacturers estimate a lifetime of around 35,000-50,000 hours with L_{70}, assuming operation at 350mA constant current and maintaining junction temperature lower than 90°C. Currently LED durability continues to improve, allowing for higher driving currents and higher operating temperature.

Table 2.2: Lifetime for various types of light source [35].

Light Source	Range of Typical Rated Life (hours)
Incandescent	750-2000
Halogen Incandescent	3000-4000
Compact Fluorescent	8000-10000
Metal Halide	7500-20000
Linear Fluorescent	20000-30000
High Power White LED (estimated useful life by L_{70})	35000-50000

One of the main applications of modern LEDs is a general light source using high power white LEDs. These high power LEDs have high efficiency comparable to fluorescent lamps and very long life time exceeding any other traditional light sources. As mentioned earlier, it is expected to save $30 billion per year in energy cost by 2030 by implementing LEDs into a light source. Although the current application is limited due to their high cost, LEDs will gradually replace other general light sources over time, saving significant energy and money.

2.3 Theoretical Background of Light Emitting Diodes

LEDs are different from traditional light sources in the way they produce light. In an incandescent lamp, a tungsten filament is heated by electric current until it glows and emits light. In a fluorescent lamp, mercury atoms are excited and emit ultraviolet (UV) radiation. By striking the phosphor coating inside the glass tubes, the UV radiation is converted and emitted as visible light. In contrast, LEDs are based on a semiconductor diode [36].

Basic technology of LEDs dates back to the 1960s when scientists were working with a chip of semiconductor material doped with impurities to create *p*-*n* junction. Useful feature of a *p*-*n* junction is that current can flow freely from *p* to *n* direction when *p*-region has a positive external voltage bias, whereas virtually no current will flow when *p* is made negative relative to *n*. This asymmetry of current flow makes the *p*-*n* junction diode very useful as a rectifier [37].

LEDs which are commonly known as 'son of diode' are fabricated by using wide band gap semiconductors such as GaN or ZnO to form heterostructure or homostructure devices [38]. Heterojunction LEDs are generated using semiconductor materials with unequal band gaps whereas homojunction LEDs are fabricated using same materials with equal band gaps that are differently doped. The main difference between them is that heterojunction LED is brighter than a homojunction LED [39]. Since heterostructure-based LEDs are expected to exhibit improved electronic and optical confinements compared to homojunction LEDs [40], homojunction structures have been seldom studied [41].

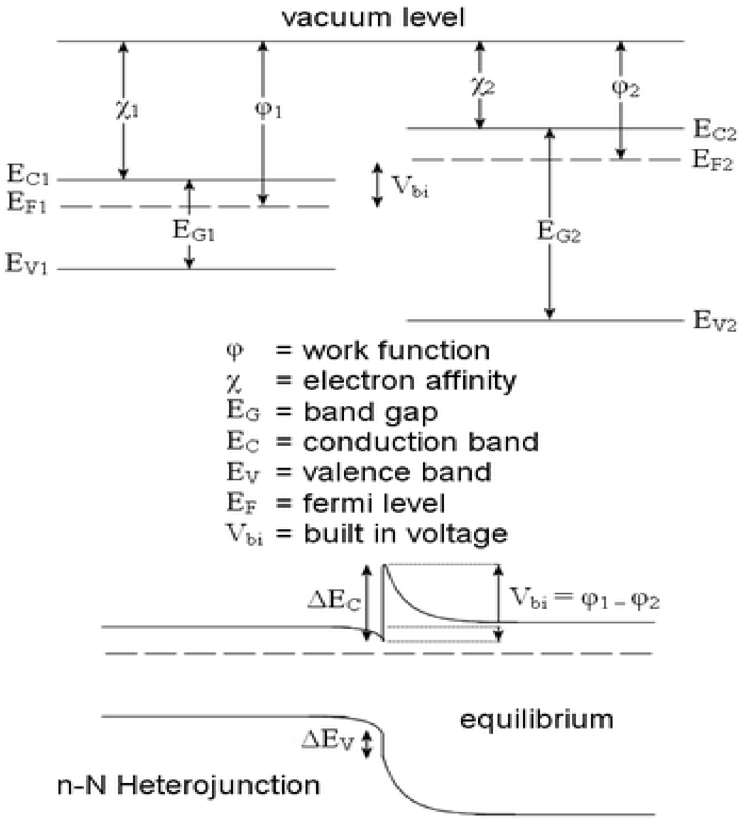

Figure 2.1: Band diagrams for an ideal heterojunction [42].

When semiconductors of different band gaps and electron affinities are brought together to form a junction called heterojunction, discontinuities in the energy bands occur as the Fermi levels line up at equilibrium. Discontinuities in the conduction band ΔE_c and the valence band ΔE_v accommodate the difference in band gap ΔE_g between two semiconductors. The built-in contact potential is divided between the two semiconductors as required to align the Fermi levels at equilibrium. The resulting depletion region on each side of the heterojunction and the amount of built-in potential are found by solving Poisson’s equation with the boundary condition of continuous electric flux density at the junction. The barrier that electrons must overcome in moving from the *n* side to the *p* side may be quite different from the barrier for holes moving from *p* to *n*. When an electron crosses the barrier and meets a hole, recombination occurs that will result in spontaneous emission of photons (light) which is a carrier of electromagnetic radiation of all wavelengths [43,44].

The actual wavelength and color of light emitted by the LEDs are dependent on the band gap energy of the materials used to make the *p-n* heterojunction LEDs. For examples, red and infrared LEDs are based on aluminum gallium arsenide (AlGaAs). Blue LEDs are made from indium gallium nitride (InGaN) and green from aluminum gallium phosphide (AlGaP). White light is created by coating a blue LED with yellow phosphor, by combining the light from red, green, and blue LEDs or through the fabrication of heterostructure LED by exploiting the ZnO nanotubes [45,46].

2.4 Technology of High Power Infrared Emitters

The actual invention of the first practical LED is attributed to Nick Holonyak in 1962 [47]. He contributed to the development of integrated circuit and was responsible for the development of *p-n-p-n* switch which is now widely used as a dimmer switch to control lighting. In 2004, Mr. Holonyak was officially recognized as the inventor of LED at a ceremony that was held in Washington [48-50].

Although Nick Holonyak is recognized as the inventor of LED, during 20th century, several companies either inadvertently or by design were able to generate electroluminescence from different materials by the application of electric fields. By the later portion of 1960s, *p-n* heterojunction devices were fabricated that resulted in the development of blue LEDs [51]. Although the first generation of blue LEDs were extremely inefficient, subsequent efforts to improve the efficiency of blue SiC LEDs only marginally improved due to an indirect band gap in the *p-n* heterojunction [52,53]. Thus, the low efficiency of SiC LEDs caused scientists turning their attention to other semiconductor materials both to enhance efficiency as well as to generate light from other frequency spectrums. One of the approaches was the discovery of infrared LEDs or commonly known as IREDs or IR emitters based on the use of GaAs.

During the 1960s, IR emitters were developed based on the use of GaAs that was grown as a crystal then sliced and polished to form substrate for the epitaxial growth of *p-n* hetero`junction diode structures, either by vapor-phase epitaxy or liquid-phase epitaxy. The use of GaAs resulted in the development of IR emitters whose application capability was limited owing to the absence of visible light [54-56].

In 1961, Bob Biard and Gary Pittman were working together on a project for Texas Instruments to develop gallium arsenide (GaAs) diodes. Using an infrared microscope, they found that these diodes emitted significant light in the infrared region. Based on their findings, they received the patent for the IRED, and Texas Instruments marketed the first commercial LED product [57]. The work of Pittman and Biard followed intense interest in the properties of semiconductor alloys at numerous American industrial research labs in the 1950s. For example, Rubin Braunstein, a physicist at RCA Laboratories in Princeton, NJ (now the David Sarnoff Research Center), was the first to report on experiments in which he observed light emission from GaAs and other semiconductor alloys in 1955 [58].

Until 1968, visible and infrared LEDs were extremely costly in the order of US$200 per unit and so had little practical use. Early in the 20th century, remote control with the use of IR emitters was one of the most remarkable inventions for operator convenience as IR region represented a more effective method to control remotely performed operations [11].

Nowadays, modern IR emitters usually operate in the near IR range in which light emitted at wavelength from 700-950nm. Today, high power IR emitters are extensively used in fiber optical communication systems, CCTV, cameras, touch screen technologies, as well as in the automotive industry such as automatic number plate recognition, night vision, driver assistance systems, pre-crash sensing systems, machine vision systems and also as remote control for consumer products [59].

Figure 2.2: Examples of high power IR emitter.

2.5 Concept of Heat Transfer

Heat generation of a solid state lighting device is concentrated in a small region of the semiconductor die from which it diffuses outward towards the package where it becomes progressively less concentrated. In other words, the heat flux density is greatest in the heat generating region of the device. As the energy moves further and further, heat flux densities are lower and the temperature elevations are smaller. At the component level, differences in package design, material selection and quality of manufacture can have enormous impacts on junction operating temperatures and lifetime of the device. The increase of heat flux densities and the necessity to control junction temperatures create the need for device characterization.

Thermal characterization of a solid state lighting device is the determination of temperature response of the device junction due to internal self heating, which is a byproduct of electrical current flow in the device during operation. The heat generated which elevates the temperature in the semiconductor junctions, conducts from the junction area through the die towards the package, and eventually dissipates into the ambient. This flow of heat is governed by the laws of thermodynamics and the principles of heat transfer. The temperature elevation of the junctions drives the need for thermal characterization of semiconductor packages since higher junction temperatures are associated with reduced operating life [60].

Second Law of Thermodynamics states that heat will flow from a higher temperature region to a lower temperature region. Once a heat source is attached to one surface of a component and the opposite surface is kept at a lower ambient temperature, heat will flow in the direction as indicated in Figure 2.3. The heat will flow continuously as long as there is a temperature difference [61].

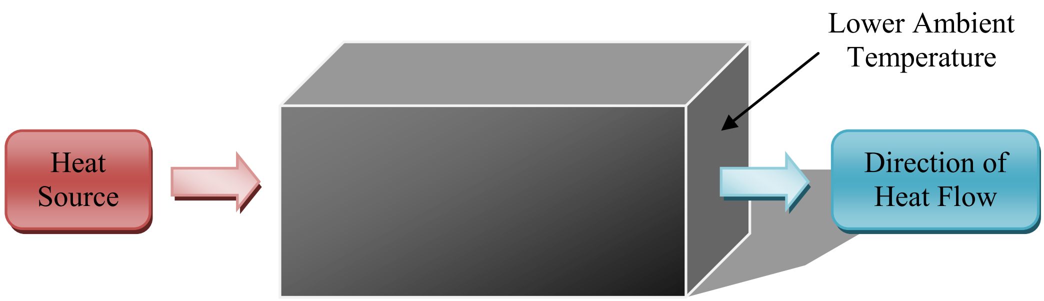

Figure 2.3: Heat flow in a component with temperature difference.

For solid state devices, heat will be generated at the *p-n* junction once an active device is in operation. Operating temperature of a device is a result of the balance between heat generation and heat dissipation. Heat itself does not become a problem until there is enough heat to cause rise in temperature above critical point. Basically, heat is flowing from a high temperature region to a region with lower temperature by one of the three modes, which are conduction, convection or radiation.

Conduction is the most effective way to transfer heat among the three, in which the hot body is in direct contact with the cooler one and heat moves from hot to cold materials in an attempt to reach equilibrium. The rate of transferring heat from one to another depends on the temperature gradient, thermal conductivity of the materials and thickness of the materials.

$$\frac{dQ}{dt} = -kA\frac{dT}{dx} \quad (1)$$

This equation is known as the law of heat conduction. *dQ/dt* is the rate at which heat flows across the area *A*, in Joules per second or Watts. *dT/dx* is the temperature gradient in degrees Kelvin or Celsius per meter. The thermal conductivity *k* is a property of the material [62].

In conjunction with this, convection is a method of transferring heat from a hot body to a cooler fluid through molecular motion, in which it happens naturally based on the resulting density gradients caused by temperature variation. In convection, heat could be carried away faster by forcing the cooling fluid to flow through the warm body. Conversely, convection heat transfer can be significantly impeded by device enclosures that restrict air flow, resulting in higher device temperatures.

Radiation is a removal of heat from a body by the emission of energy in the form of electromagnetic radiation. It might be in the infrared or even visible parts of the spectrum depending on the body temperature.

2.6 Importance of Thermal Management

High power IR emitters are penetrating fast into lighting applications due to their improved performance in optical power, efficiency and reliability. However, the ability to prevent the IR emitters from overheating is the most challenging task for thermal designers. Hence, an effective thermal management method plays an important role in the success of solid state lighting devices especially for the high power IR emitters [63].

Generally, when input current is applied to an IR emitter, only a small portion of the input power will be emitted as optical power and the rest will be dissipated as heat from junction to the ambient. As the heat escalates and causes excessive rise in junction temperature, several key characteristics may become apparent which might influence and reduce the reliability performance and lifespan. If the thermal management continues to race out of control, the junction may break down causing a state of complete thermal runaway. Therefore, thermal management of solid state lighting devices is becoming more crucial now in order to achieve optimum performance and longer lifespan especially for high power IR emitters that involve large amount of power dissipation.

Reliability of an IR emitter is a complex function of the heat generated by the operation of the IR emitter, the tools used to dissipate heat and the environment in which the IR emitter is required to operate. Since the demands and applications of the IR emitters are increasing, diverse thermal management tools have evolved to help mitigate the issues regarding device reliability. These tools include active cooling systems, heat sinks, heat pipes and gap fillers.

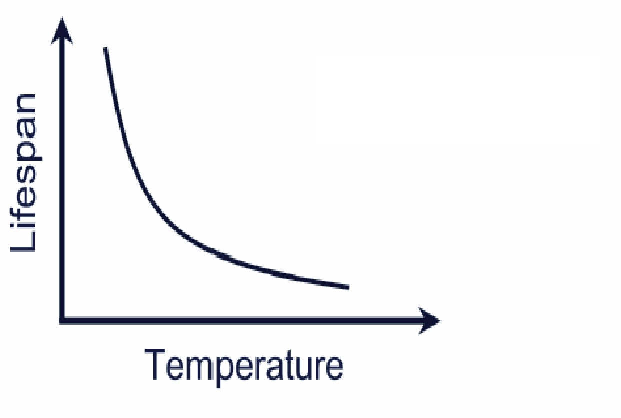

Figure 2.4: Arrhenius equation [63].

Since failure rates, which are described as an Arrhenius equation, increase exponentially with temperature, a 10°C increase in temperature can double the failure rate as shown by Figure 2.4. For an operating device where reliability is critical to success, even 1°C can matter. Thus, the key to improve reliability is to reduce device temperature by increasing the rate at which heat is dissipated from the device to the ambient [64].

2.6.1 Metal Core Printed Circuit Board

In conjunction with the rapid progress of solid state lighting industry, board technology has been extensively examined in order to compensate the need for thermal management of IR emitters. Printed circuit board (PCB) which consists of multi-layer structures, plays dual role as electrical circuit connector for developing electric circuit or arrays of IR emitters and also as heat sink. It was found that 86% of the heat generated at the p-n junction was dissipated to PCB through conduction whereas only 14% was dissipated via convection and radiation [65].

Typical FR4 board could not be used because of its low thermal conductivity, high thermal resistance and it is not capable to meet the continuously increasing demand on requirement of thermal dissipation for high power IR emitter packages.

For more effective thermal management, Metal Core Printed Circuit Board (MCPCB) should be used [66,67].

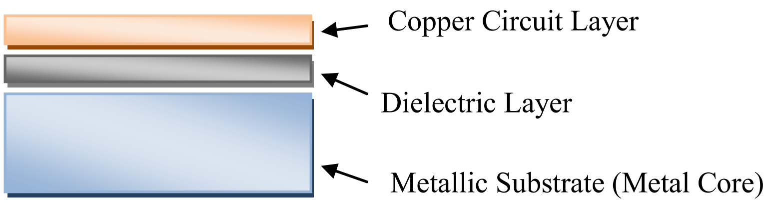

Figure 2.5: Internal structure of MCPCB.

MCPCB is composed of a metallic substrate, thin circuit layer with dielectric material laminated on top, copper layer and a solder layer on top for tinning and component attachment. The thickness of dielectric layer is usually 100μm as it has poor thermal conductivity. The metal substrate can be either copper or aluminum. In most applications, the substrate is attached to a heat sink by using thermal interface material to provide cooling [68,69].

Compared to conventional FR4 board, the MCPCB provides a better heat dissipation. MCPCB with a 1W IR emitter can persist at ambient temperature of around 25^{o}C while the same IR emitter on FR4 board would achieve 12^{o}C more than the ambient temperature. Besides, it is one of the simplest ways to provide efficient cooling to surface mount type electronics. The technology of MCPCB resides in the dielectric layer, excellent electrical isolation properties and low thermal impedance [70,71].

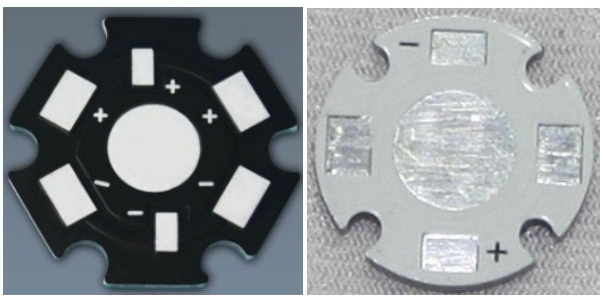

Figure 2.6: Examples of MCPCB.

The main difference between MCPCB and FR4 board is the thermally conductive dielectric material in the MCPCB that acts as a thermal bridge between the components and metal substrate. It was reported that IR emitter soldered on FR4 board tended to radiate more compared to that using MCPCB which conducted heat in downwards direction for better heat dissipation [72].

2.6.2 Thermal Interface Material

Thermal interface material (TIM) is widely used to fill the gaps between the IR package and MCPCB or external heat sink which could retard the heat transfer from the junction to ambient. Without the existence of TIM, these gaps are normally filled with air which is a very poor conductor (k=0.026 W/mK). TIM could be either electrically conductive or insulating and materials used for gap filling cover a wide variety of choices such as solder, thermal paste, thermal grease, thermal tape, phase change material and others. Typical thickness of a TIM depends on the types of material used and usually ranges from 50 μm to 1 mm [73].

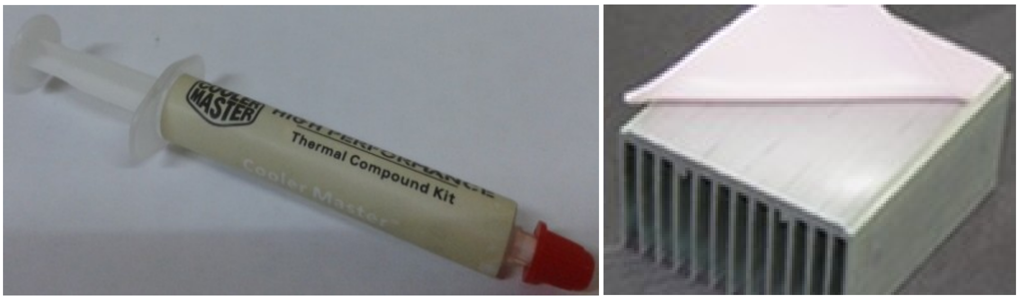

Figure 2.7: Different types of TIM.

Primary advantage of using TIM is that it could minimize the air gaps between two surfaces, decrease the thermal contact resistance and hence reduce the impedance to heat flow at the interfaces. Reducing of thermal contact resistance is necessary for best surface contact between two sandwiched regions, i.e. between IR package and MCPCB or between MCPCB and external heat sink [74].

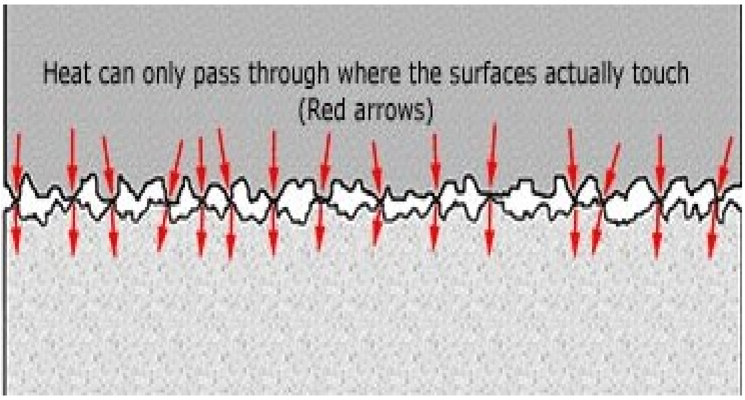

Figure 2.8: Poor surface contact without TIM.

The contact surfaces are usually not perfectly smooth and flat due to the manufacturing process and hence, two surfaces will only contact with each other at discrete points as shown in Figure 2.8. Therefore, poor surface contact will cause the existence of air gaps that act as thermal barrier due to its very poor thermal conductivity, preventing efficient heat transfer across the interfaces. When TIM is being inserted between two surfaces, an almost ideal contact will be formed with minimized contact resistance as illustrated in Figure 2.9. A perfect contact would ease the flow of heat in IR package and thus, the junction temperature rise can be maintained [75].

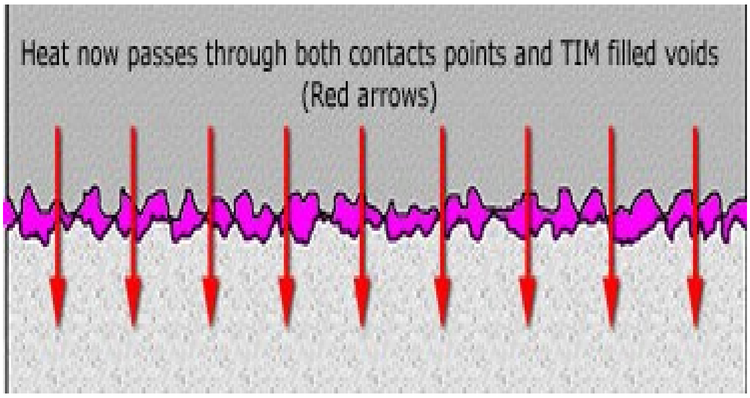

Figure 2.9: Perfect contact formed between 2 surfaces with TIM.

2.6.3 Heat Sink

The miniaturization of high power IR emitters causes the need for higher heat power density which requires a better heat dissipation system than the MCPCB alone. For this reason, an external heat sink is attached to the end of MCPCB with TIM to increase the rate of heat transfer of an IR package. By doing so, large amount of heat flux could be easily removed from the junction to the ambient due to larger heat conducting basement of the heat sink. The fins of heat sink are responsible to dissipate the heat to ambient via thermal buoyant effect. Since heat sink is one of the most important factors in reducing the thermal resistance of an IR emitter package, the number of fins, its arrangement and orientation play a significant role to enhance the heat dissipation steadily [76].

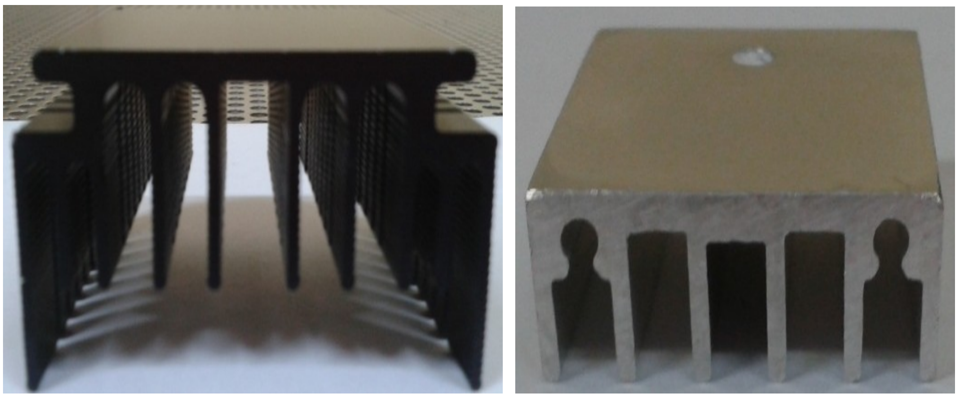

Figure 2.10: Various types of heat sink.

2.7 Thermal and Optical Parameters

Application of an effective and appropriate thermal management is essential in order to achieve the expected reliability, optimal performance and longest lifetime for today's standard IR emitters. For high power IR emitters that involve large amount of power dissipation, an effective thermal management is vital.

Basically, operation of IR emitters is limited by various factors depending on the material and technology used. In thermal study, one of the most important parameters with practical interest is the temperature of an active layer for semiconductor devices or commonly known as junction temperature since it significantly influences the reliability and durability of IR emitters. Hence, it is recommended that the maximum junction temperature should not be exceeded during operation to prevent damage to the IR emitters [77].

Moreover, the main goal in the development of thermal management is to keep the junction temperature as low as possible. Since thermal resistance is required to describe the thermal characteristics of the IR emitters independent of the environment conditions and also it allows the junction temperature to be determined with sufficient precision, thermal resistance value of the IR emitters is another important parameter to be studied.

2.7.1 Junction Temperature

Junction temperature is not only a performance indicator but it is one of the key parameters for solid state lighting devices especially high power IR emitters as thermal, optical and electrical characteristics of the IR emitters are strongly dependent on the absolute junction temperature [78].

Junction temperature refers to the temperature of silicon die within the IR package when the IR emitter is operated or applied with input power. It can also be referred to as the operating temperature. Junction temperature which is a critical parameter of the IR emitters affects significantly the internal efficiency, maximum output power, reliability and other parameters [79]. Thus, low junction temperature operation is favorable since operating under high temperature will strongly reduce the overall performance and cause degradation [80].

However, direct junction temperature measurement is not possible due to the encapsulation and alternative methods must be developed to accurately determine the