DEVELOPMENT OF INLINE RAPID THERMAL TRANSIENT TEST SYSTEM FOR CRACK DETECTION OF AlInGaP ON GERMANIUM CARRIER

LURUTHUDASS ANNANIAH

UNIVERSITI SAINS MALAYSIA

2018

DEVELOPMENT OF INLINE RAPID THERMAL TRANSIENT TEST SYSTEM FOR CRACK DETECTION OF AlInGaP ON GERMANIUM CARRIER

by

LURUTHUDASS ANNANIAH

Thesis submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy

February 2018

ACKNOWLEDGEMENT

First of all, I would like to express my thanks and appreciation to Assoc. Prof. Mutharasu Devarajan for his supervision and guidance throughout my PhD study. His encouragement gave me motivation to move forward and do my research work effectively.

I also would like to express my thanks to School of Physics and University Sains Malaysia for giving me an opportunity to further my studies. Special thanks to Institute of Postgraduate Studies (IPS) of University Sains Malaysia for their assist and support.

In addition, I would like to acknowledge and thanks to my wife, Maria and my two children, Ivy Bungan Dass and Juan Lian Dass, for their patient and understanding of my priority on this PhD study. Their support and sacrifice cannot be substituted by any gift that of I know in this world. I truly indebted to them.

I also would to like to express my profound gratitude to OSRAM Opto Semiconductors management for their generous support and assistant to do my PhD studies. Besides that, I also would like to thank OSRAM Opto Semiconductor R&D staffs for their excellent support for my PhD works.

Lastly I would like to thank Dr. David Lacey for his valuable feedback and sparing my research findings. His inputs and argument on the finding certainly thought provoking and inspiring discussions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A/D	Device Under Test
AlInGaAs	Aluminum Indium gallium Arsenide
AlInGaP	Aluminum Indium Gallium Phosphate
Al_2O_3	Sapphire
CAGR	Compound Annual Growth Rate
CAS	Compact Array Spectrometer
CCT	Colour Control Temperature
CRT	Cathode-ray tube
CTE	Coefficient of Thermal Expansion
DA	Die Attach
DC	Direct Current
DUT	Device Under Test
E_g	Energy gap or Band gap
EQE	External Quantum Efficiency
FBA	Failure Bin Analysis
FCC	Face-Center Cubic
FIB	Focused Ion Beam
GaAs	Gallium Arsenide
GaAsP	Gallium Arsenide Phosphate
GaN	Gallium Nitrate
GaP	Gallium Phosphide
Ge	Germanium
HP	Hewlett-Packard
I_{drive}	High or Drive current
$I_{measure}$	Low or Measurement current
IM	Ion Milled

InGaAlP	Indium Gallium Aluminum Phosphide
InGaN	Indium Gallium Nitrate
IQE	Internal Quantum Efficiency
IR	Infrared
IRT	Inline Rapid Thermal-transient
JEDEC	Joint Electronic Device Engineering Council
LCD	Liquid-crystal display
LED	Light Emitting Diode
lm	lumen
MQE	Multi Quantum Efficiency
PCB	Printed Circuit Board
PTC	Power Temperature Cycle
QFN	Quad Flat No-leads
R&D	Research and Development
R_{th}	Thermal Resistance
SEM	Scanning Electron Microscope
Si	Silicon
SiC	Silicon Carbide
SMT	Surface Mount Technology
SSL	Solid State Lighting
STD	Standard-deviation
ΔT	Temperature Rise
TC	Temperature Cycle
TIM	Thermal Interface Material
TSP	Temperature Sensitive Parameters
UV	Ultraviolet
V_f	Forward Voltage

VPE	Vapour-phase epitaxy
V_R	Reverse Voltage
W	Watt

LIST OF SYMBOLS

A	Area
a	Ejector pin surface contact length
a	Lattice constant
å	Acceleration
Ar	Arsenide
Au	Gold
c	Crack size
^{o}C	Celsius temperature
cd	Candela
C_{th}	Thermal capacitance
Cu	Copper
c_v	Volumetric specific heat capacitance
D_n/D_p	Diffusion coefficient of electron and hole
E	Young Modulus
E_C	Conduction band
E_F	Fermi band
E_g	Band gap energy
E_v	Valence band
eV	Electron volt
F	Force
Ga	Gallium
Ge	Germanium
G_c	Toughness (critical strain energy release rate)
gF	Gram force
h	Planck constant
h	Penetration depth

H	Hardness
I_0	Saturation current of ideal diode characteristic
I_F	Forward current
I_H	Heating current
I_m	Measuring current
In	Indium
I_R	Reverse current
k	Boltzmann's constant
K	Stress intensity
K	K-factor
K_c	Fracture toughness of material
L	Power factor
L_n/L_p	Carrier diffusion length of the free electron and hole
Lm	Lumen
m	Mass
m	Ideality factor
ms	millisecond
n_i	Intrinsic carrier concentration
N_A/N_D	Dopont concentration of free hole and electron
η_i	Internal quantum efficiency
P	Phosphate
P_{el}	Electrical power
P_h	Heating power
P_{opt}	Optical power
Pt	Platinum
R	Ejector pin radius

R_p	Parallel resistance
R_s	Series resistance
R_{th}	Thermal resistance
R_{thJS}	Thermal resistance from junction to solderpoint
s	Second
Sn	Tin (stannum)
Si	Silicon
μs	Micro second
t	Time
T	Absolute temperature
T_J	Junction temperature
T_m	Melting point
t_n	Mean time to recombine non-radiatively
t_r	Mean time to recombine radiatively
T_s	Solderpoint temperature
α/S_{VF}	Temperature coefficient
ΔT	Temperature rise
U	Potential energy stored
ʋ	Velocity
υ	Frequency
V_{c1}	first cold stage voltage
V_{c2}	second cold stage voltage
V_D	Diffusion voltage
V_{Fi}	Initial forward voltage
V_{Ff}	Final forward voltage
$V_{Fp.n}$	Internal junction voltage
V_R	Reverse voltage

V_T	Thermal voltage
V_{th}	Threshold voltage
W	Watt
$\boldsymbol{X}$	Material constant
Y	Displacement at the point of loading
λ	Wave length
θ_c	Thermal conductivity
Õ	Ideal strength
σ	Stress
π	Pi
α	Coefficient of Thermal Expansion

PEMBANGUNAN SYSTEM UJIAN BERTERUSAN TERMAL SEMENTARA BAGI MENCARI KERETAKAN AlInGaP ATAS SUBSTRAT GERMANIUM

ABSTRAK

LED adalah sumbar cahaya yang ulung di technologi pencahayaan dan berkembang pada peratusan dua digit sejak beberapa dekat ini. Walau pun terdapat banyak kelebihan dalam LED ini, ia masih mempunyai banyak cabaran. Salah satu cabaranya ialah keretakan cip LED. Di dalam karya ini, focus utama adalah keretakan cip pada substrate AlInGaP LED di process die-attach (DA). Di sini impak pada sifat elektro-optik dan termal disiasat dan pada masa yang sama suatu kaedah mengesan keretakan cip dicipta. Keretakan pada substrat Ge dilakukan secara sengaja dengan mengunakan mesin DA bergred industri pada daya 40gF ke 210gF. Panjang keretakan cip diukur dengan mengunakan skop pembesaran tinggi. Beberapa cip dianalisa itu mengunakan Mengimbas Mikroskop Electron (SEM) untuk melihat pembentukan keretakannya. Sebahagian cip yang retak dibentuk menjadi LED dan diuji ketahanannya dengan mengunakan ujian Kitaran Suhu dan Kitaran Suhu Kuasa untuk menganalisa impak cip-retak terhadap prestasi elektro-optiknya. Rintangan haba (R_{th}) LED cip-retak diukur dengan mengunakan 3Tster. LED cip-retak telah dicirikan dengan menggunakan oscilloscope untuk menganalisa sifat termal sementaranya. Keputusan penyiasatan menunjukkan bahawa panjang dan keterukan cip-retak menambah dengan menambahnya daya hentakkan pada cip itu. Keputusan elektro-optik selepas ujian ketahanan menunjukkan tiada perubahan ketar pada semua kumpulan LED cip-retak yang diuji itu. Substrat yang dikerat-rentas menunjukkan bahawa cip-retak hanyalah pada permukaan sahaja dan ia tidak sampai pada lapisan aktif, yang mana tidak membawa sebarang impak kepada sifat elektro-optiknya.

Walau bagaimanapun, kegagalan-lesu dapat dilihat pada permukaan substrat, yang mana sebahagian besar Ge terpisah dari substrat itu. Dalam satu lagi penyiasatan antara cip bersaiz berbeda menunjukkan cip kecil mempunyai keretakan lebih teruk banding dengan cip besar. Analisa selanjutnya pada LED cip-retak terhadap sifat termalnya menunjukkan R_{th} LED menokok relatif kepada keretakan cip-retak. Cip-cip yang tidak retak tidak menunjukkan perbezaan voltan (ΔV_F) yang menonjol. Isyarat electrik Parameter Sensitive Suhu (TSP) ini, adalah asas bagi mengasingkan LED yang menpunyai cip-retak dan tidak. Dengan mengunakan isyarat TSP ini, ujian termal sementara berterusan (IRT) telah diuji dengan jayanya bagi mengasingkan LED bercip retak dalam skala makmal. Sebagai kesimpulan bidang penyelidikan ini, bolelah dinyatakan dengan jelas bahawa cip-retak pada substrate Ge (111) tidak memberi sebarang kesan kepada prestasi LED pada jangka masa singkat, tetapi ia mungkin memberi impak secara technical pada jangka masa lama. Cip besar terbukti mempunyai ketahanan retak lebih besar dari cip kecil. System ujian IRT, terbukti boleh mengesan cip-retak dan ia boleh digunakan dalam industri LED.

DEVELOPMENT OF INLINE RAPID THERMAL TRANSIENT TEST SYSTEM FOR CRACK DETECTION OF AlInGaP ON GERMANIUM CARRIER

ABSTRACT

LEDs are the ultimate light source in the lighting technology and growing at double digit percentage for the past few decades. Despite of many virtues in LEDs, there are many challenges it have. One of it is die crack. In this work, the focus is on die-crack on die substrate of an AlInGaP LED at die attach (DA) process. Here the impact on electro-optical and thermal properties were investigated and a detection method was invented. The cracks were artificially created at Ge substrate using industrial grade DA equipment at bond force range from 40gF to 210gF. Die-crack length were measured using high magnification scope. A few dice were analysed using Scanning Electron Microscope (SEM) for their crack formation. Some of the cracked dice were packaged and undergone stress test (Temperature Cycle and Power Temperature Cycles) to analyse its impact on electro-optical performance. Thermal resistance (R_{th}) of the cracked LED die were measured using 3Tster. The die-cracked LEDs were further characterized using oscilloscope to check their thermal transient behaviour. The investigation results shows crack length and crack severity increases as the bond force increases. The electro-optical results after stress test shows no significant changes before and after stress test for all the die-crack LED cells. Cross-section of the substrate shows that the crack remains at surface level and did not reach the active layer, hence no impact on electro-optical properties. However, observed fatigue-failure at substrate surface level, in which large chunk of Ge separated from the main body. But, the investigation on different die sizes shows that smaller die has severe crack formation compared to the bigger die. Further analysis

on such die-crack LEDs for thermal behaviours shows that its LED R_{th} increases relatively to the crack severity. Dice without crack does not have significant voltage difference (ΔV_F). These Temperature Sensitive Parameter (TSP) electrical signal, is the basis for segregating the LED with and without die-crack. Using TSP signal, the Inline Rapid Thermal-transient (IRT) test was successfully tested at lab scale to segregate the die-crack LEDs. As a conclusion of this research, it can be clearly mentioned that die-crack on Ge (111) substrate does not affect the LED performance in short-term, but it will have a technical impact long-term. The bigger die has proven to have higher stress fracture toughness compared to a small die. The IRT test system has proven able to detect the die-crack LEDs and can be use in LED industry.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter consists of a brief introduction on light emitting diodes (LEDs), its history and the evolution of LED industry. It touches on the challenges and issues faced by LED industry which form the problem statement of this research project. Finally, the chapter includes a detailed scope of this study that is highlighted in accordance with the objectives of this research and follows by the thesis outline, which briefly describes the contents of the thesis.

1.2 Evolution in Artificial Light

Light is one of the most essential elements for the survival of all living things. The primates in early years learnt to make artificial light. Artificial light has played a crucial role in human civilization. Looking back into history, the highly intelligent primate who dated back to two to six million years ago had mastered the usage of burning wood for many uses, including the use of burning wood as artificial light [1].

Light has fascinated human beings since the dawn of civilization. In the 1980s, archaeologists unearthed an oil lamp made of stone in a cave in Southern France. The occupant of this cave used the lamp for cave drawing [2]. Carbon dating indicated that the lamp might have existed for about seventy thousand years ago [2]. Oil lamps are still in use today in some parts of the world, where electricity is not readily available or affordable in certain communities [3]. Civilization has accelerated ever since the invention of artificial light as their productive hours extended beyond daylight into the night and even indoors [4]. The artificial light that is based on fuel burning technology has evolved from oil to candles, and gas-discharged lamps [3].

In the nineteenth century, there was a breakthrough in artificial light where electric light was invented. Electric light or the incandescent light bulb was further perfected by Thomas Alva Edison [1]. However, this light source was very inefficient as it converted less than 5% of the energy to light and the rest was turned into thermal energy. In the early twentieth century, fluorescent and sodium light took over the standard incandescent light bulb [5]. However, this light source has its own issues such as the content is made of hazardous materials, and it is a short product life span [3]. Hence, this gives the opportunity to the LED to shine as it offers an alternative method of light generation. LED's spontaneous light emission due to radiative recombination of excess electrons and holes is an important selling point that attracts considerable interest besides its energy efficiency.

Even though LED was discovered earlier than compact florescent lights, it did not thrive as there was inadequate development or innovation in the early years of the LED technology. If we examine history, LED was first discovered by Henry Joseph Round in 1907. He found silicon carbide (SiC) which illuminated when it was biased with 10V to 110V. This early form of LED was very dim [6]. In 1928, Oleg Valdimirovich Losev, a brilliant inventor and genius physicist reported a detailed investigation of the luminescence phenomenon observed with SiC metal-semiconductor rectifiers. He found the light could be switched "on" and "off" rapidly, making it suitable for what he called "light relays"[5-7]. His discovery of crystaldyne, which was the first crystal amplifier and oscillator, and the invention of the first semiconductor LED generating visible light was probably the basis of the development of semiconductor electronics [5]. However, this SiC had the efficiency of only 0.03% and was not comparable to the current III-IV material system [6]. In the late 1950s, Welker proposed that compound semiconductors from III and V columns of the periodic table should have comparable semiconductor properties as germanium

(Ge) and silicon (Si). This led to the discovery of infrared (IR) emission from gallium arsenide (GaAs) crystals with very low quantum efficiencies of around 0.01 to 0.1% [6]. This early observation and understanding of band structures of semiconductor materials were soon followed by the quest for visible LED. This was where Nick Holonyak and Bevacqua invented the red LED in 1962 [7-9]. They used vapour-phase epitaxy (VPE) of gallium arsenide phosphate (GaAsP) on GaAs substrate. This technique was applied to produce the first red luminescence diode, triggering an industrial production revolution in LED manufacturing, which benefitted many applications like indicator lights and alpha numeric displays [9]. Monsanto Corporation was the first to start commercializing mass production LED in 1968. It produced low-cost GaAsP LEDs and sold them to numerous customers. Hewlett-Packard (HP) Corporation joined the race to develop LED in the late 1960s, followed by other corporations [6].

The development of new semiconductor materials has made it possible to produce LED in a variety of colours as they are even more effective to use. High brightness and efficient blue LED, based on gallium nitrate (GaN) came in the early 1990s. Shuji Nakamura at Nichia made it possible to obtain very efficient blue and green LEDs [10]. He also designed the white LED. This led him to win a Nobel Prize for Physics in the year 2014. The efficiency of the blue LED over the years has improved. The average LED wall-plug efficiency is just 50% to 60%, but GaN on GaN LEDs can outperform traditional LEDs to reach 84% efficiency as claimed by Nakamura recently [11].

1.3 Impact of Light Emitting Diode to the World

The invention of the GaN based blue LED has transformed the lighting industry by storm. Blue LED combines with phosphor has enabled it to convert to white light.

This phosphor conversion material makes it tunable to many other colours. Given this huge potential in LED, more funds have been injected into R&D in many corporations and government funded projects to increase the LED's efficiency and product design for a variety of applications [12].

In the last decade, LED light sources have gone from being an interesting novelty to a new light source option that can be used for energy savings, long lifespan, and high performance in almost any application. For example, a 15W LED lamp can replace a 75W incandescent lamp, delivers a lifetime usage averaging of about 25,000 hours, dimmable, requires no warmup time, and offers superb colour rendering [13, 14].

LED provides vast energy saving because it converts energy in the most efficient way compared to other light sources. Table 1.1 shows the impact of conversion to solid-state lighting on U.S. electrical energy consumption. The power consumption of solid state light (SSL) to produce almost identical light output is just a fraction compared to the 60W incandescent light bulb or compact florescent lamp (CFL). The efficiency of SSL product is almost three times better than the CFL product and nine times better than the incandescent light bulb. The annual SSL product energy cost per lamp if the energy cost is 9.3 cent/kWh, is $1.81 compared to the incandescent light lamp of $16.29 and CFL product at $6.25. These advantages alone capture much attention and ensure a strong future for LED [15]. As a result, this leads to the LED industry's double-digit growth over the last decades [16, 17].

Table 1.1 Potential impact of conversion to solid-state lighting on U.S. electrical energy consumption [13].

General illumination lighting			
Performance estimates	SSL Product	60 W incandescent light bulb	23 W compact fluorescent lamp
Light output (lm)	1000	1000	1200
Power (W)	6.67	60	23
Lumens/W (system)	150	16.7	52
Annual energy consumption (8h/day, 365 days) (kWh)	19.5	175.2	67.2
Factor higher than LED	1	9	3.4
Annual energy cost per lamp (9.3 cents/kWh)	$1.81	$16.29	$6.25
Estimated annual energy savings with LED lighting: 2020 estimated baseline energy consumption for lighting: 7.5 quads			
% U.S. lighting conversion to SSL	Quads saved	$ Saved (Billions)	
1%	0.05	0.33	Assumption: equal replacement of incandescent and fluorescent lighting
10%	0.49	3.23	
25%	1.21	7.99	
50%	2.43	16.04	

Notes: "quad" is one quadrillion BTU; approximately $6.6 billion per quad of electrical energy

In May 2014 issue of LEDs Magazine, it was stated that the world Packaged LED market revenue reported in 2013 was $14.4 billion, and it was projected to grow to USD25.9B in 2018 [15]. The stunning growth as illustrated in figure 1.1, is the proof of LED's potential. This report excludes the IR and UV LED market, which amounts to several billions [15]. As a whole, this clearly shows that the LED industry is expanding. This is basically due to the evolution and revolution growth. Many new inventions are currently seen in LED products and application technology. As funds are injected into R&D, it revolutionized the LED growth in many areas. This has improved the LED performance and cost to a point where it is practically competitive for every light-based signalling and lighting application [16].

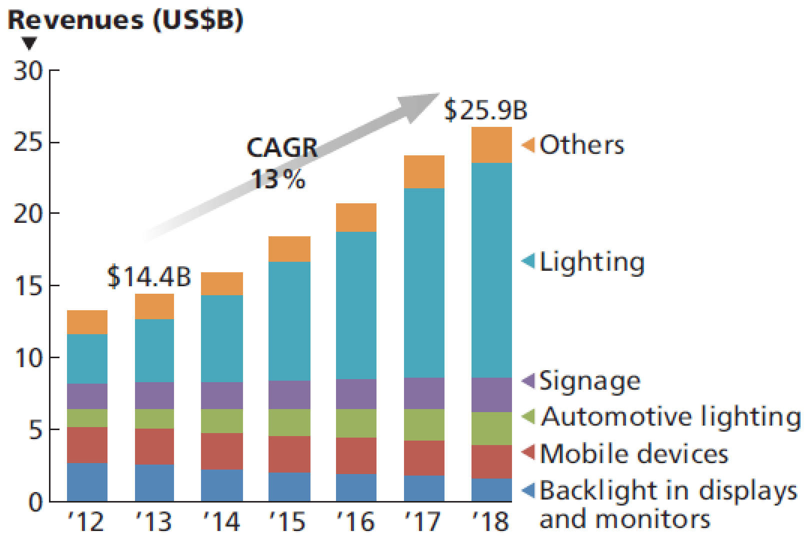


Figure 1.1 - Packaged LED revenue growth segment by application projected through 2018 [15].

As the LED efficiency increases, energy consumed by LED is lesser. This directly reduces the energy consumption and its dependence on fossil fuel. As a result, the environment and the entire living beings in this world would benefit from it. LED lights are the new green technology that bring a bright future to the world [18].

Despite many benefits seen in LEDs, there are many challenges in the LED industry. The industry players are braving these challenges to create many new values to the end user. The challenges and issues faced by the LED industry will be reviewed in the next section.

1.4 The Challenges and Issues in LED Technology

In the last forty years, we have seen the evolution and revolution of the LED industry. As the performance improves and the cost goes down, the consumers benefit

[16]. The next few decades are predicted to be very exciting and full of challenges [18].

One of the challenges is LED efficiency. Roland Haitz predicted that in every eighteen to twenty-four months, the LED brightness will double, which is quite similar to Moore's law in IC industry. His prediction is illustrated in figure 1.2 [16].

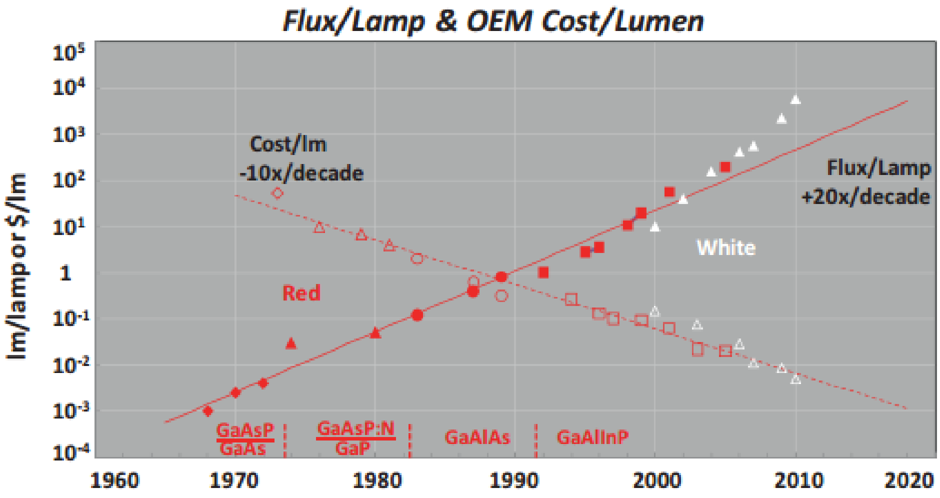


Figure 1.2 LED light output increase/cost decreasing. Source: Ronald Haitz and Lumileds [16, 19].

This prediction still holds ground up to this day. However, the challenge to this prediction is the law of physics. The GaN and AlInGaP based material systems are hitting the efficiency limit. It is getting very expensive to improve every percent of efficiency further, as the epitaxy built on sapphire is almost threshold with very low dislocation or cracks as reported by Ansgar *et al.* of OSRAM Opto Semiconductors [20]. He further mentioned in his report that high internal quantum efficiency (IQE) in InGaN based LED is attainable by optimizing the multi-quantum well (MQW) combined with an advanced chip design optimized for high current density operation and high light-extraction efficiency. In another study by Krames of Soraa, the efficiency can be further improved by growing epitaxy on GaN, where the dislocation and cracks in the epitaxy layer are very low [21]. This GaN on GaN technology also helps to reduce Auger non-radiative recombination loss [22]. In fact, the focus of Krames and Ansgar is almost similar except that they are in a different substrate. They claim of achieving more than 80% efficiency [20, 22]. In another study by Krames, he claims that saving the photon emitted by the die is cheaper than improving the efficiency of the LED die further [23]. This notion still holds ground. It is a fact that some of the lights emitted by the die went astray or absorbed by the package and chip substrate [24]. This means that the packaging technology has to be further improved. It is vital to have a package that maximises the external quantum efficiency (EQE). It needs to have good reflectivity, as well as good thermal and electrical conductivity (lower ohmic losses).

In order to have good thermal and electrical conductivity, a thinner die substrate is needed. On the other hand, thinner substrate has always been associated with weaker mechanical strength. This makes the substrate cracks easily.

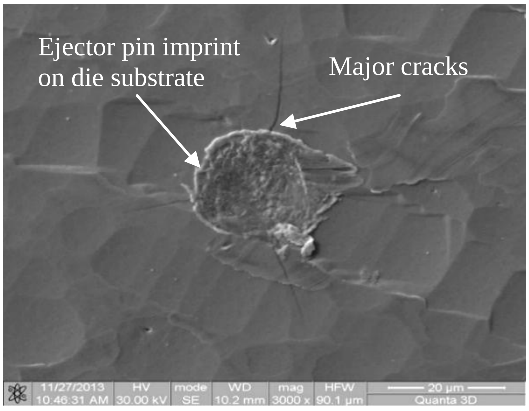
Another big challenge is the cost down pressure. Figure 1.2 illustrates LED cost reducing against the efficiency improvement in LED. Due to the cost pressure to compete with the existing fluorescent lamp and other LED industrial players, many innovations have been introduced. For example, Quad Flat No-leads (QFN) packages it with thinner package substrates. Thinner package substrate improves thermal dissipation and reduces efficiency droops. Hence, the die can be driven by higher current without losing too much of its efficiency [25]. Thinner substrates in the packages mean lower material usage and the cost is reduced. A thinner package also requires less encapsulation material. Less encapsulation material means less cost. In terms of the die, LED manufacturers opt for cheaper substrate materials, for example, Silicon (Si) or thinner existing substrate like Ge or GaAs. All these improvements have their own setback. One of the drawbacks is that mechanical strength of the package or substrate of the die will be compromised. This can cause cracks in the die or package during the manufacturing process or even in the reliability test that will directly affects the LED electro-optical performance. In the next section, this problem will be further discussed.

1.5 Problem Statement

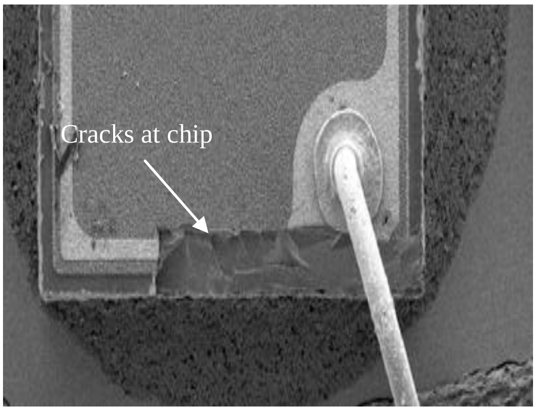
As mentioned in the earlier section, the set back in the LED facing is due to the pressure to lower the cost and to push the LED performance to its limit. This compromises the mechanical strengths and leads to die-crack. Die-crack is very often observed during the die attach (DA) process. In view of this situation, this research project focuses on the die-crack formation in DA process. Also, this research investigates the impact of die-crack LED after the stress test to its electro-optical performance. Having seen the risk of a die-crack, a viable detection method is required for a mass manufacturing environment. This, in particular, uses Temperature Sensitive Parameters (TSP) where it is known to have detection capabilities to detect defects in semiconductor devices [26, 27]. By understanding the die-crack phenomena, and using the Inline Rapid Thermal-transient (IRT) system, the die crack can be better controlled in the LED industry. On the other hand, the scientific findings can be utilized by scientists and engineers for their future work on LED.

In the DA process, a crack occurs at the bottom of the die (substrate) during the die pick and place from mylar. This type of crack is difficult to detect because it is hidden at the back of the die that is attached to a substrate with glue. If the crack does not reach the active region, then it will not show any electrical abnormalities during outgoing electro-optical testing. However, it may fail during operation [28]. In order to actually experience and study this die-crack phenomena, this research is mostly conducted in the LED industry facilities, where the equipment and dice are readily available. In fact, this is also in the interest of the industry as well. In the extension to the die-crack research, developing the IRT test system is also in line with LED industry.

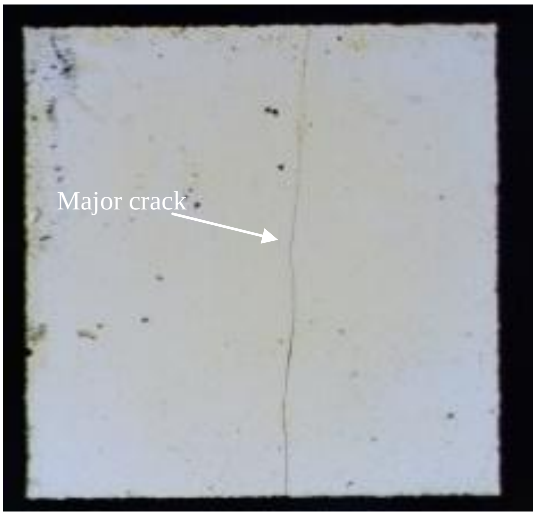
Many types of die-cracks are observed by the LED industry. Some of the cracks are demonstrated in figure 1.3. These cracks occur at different processes in the LED packaging industry.



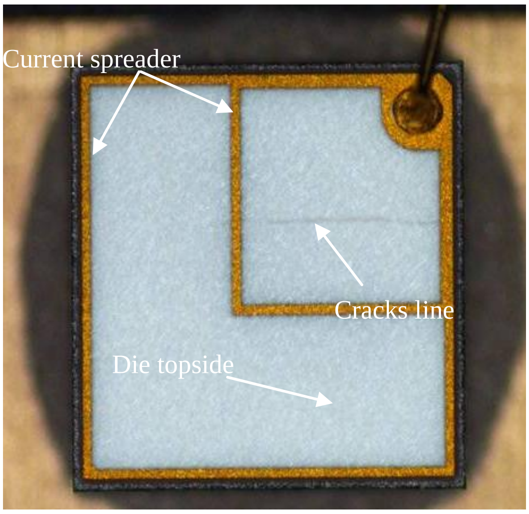
a. Crack at die substrate (Ge) due to high bond force from ejector pin



b. Crack at die top breaking metallization layer due to high wire bonding bond force on AlInGaP on GaAs substrate.



c. Straight hairline crack at die substrate [29].



d. Crack at the top of die pass through active layer [30].

Figure 1.3. Many varieties of crack found in the LED packaging processes (Courtesy of OSRAM Opto Semiconductors).

Out of ten billion LED produced by OSRAM Opto Semiconductors, roughly six billion LEDs are using Ge substrate. Occasionally, when the process is out of control, die-crack occurs in this substrate. Some of the cracks occur, the LED fails to perform as the intended purpose of the end users. As a consequence, OSRAM has to pay huge penalties. There are several works on Ge substrate that have been published. However, this is purely on mechanical properties of Ge substrate. No research work has been published on the impact of Ge substrate crack impact on the electro-optical properties and reliability. Hence, work on this substrate is important for the LED industry and scientific communities.

As the scope of the die crack is very wide, this research project mainly focuses on Ge substrate that is used in the AlInGaP die and the die attach (DA) process, where a majority of the crack occurrence reported in this process is due to the high stress induced on the die during the pick and place process as exemplified in figure 1.4. Even though cracked die is common in the LED industry, it is the least understood among the Ge substrate as the literature on LED with Ge substrate is insufficiently published. One question which is still unanswered is that how big of a crack at the die Ge (111) substrate is bad for LED.

All LED substrates will have indentation mark at the back of the die due to the DA process as illustrated in figure 1.4. The die is pushed from the mylar tape upward. The pickup tool comes down and picks up the die. These push and pick processes assert high stress on the die. Hence, it is very likely to have an indentation, and in certain cases, cracks occur during this process. This is inevitable due to the nature of the current DA equipment design. In fact, almost all of the DA equipment in the world is using this concept. The question is how big of a Ge die substrate crack is bad for the LED performance and its reliability.

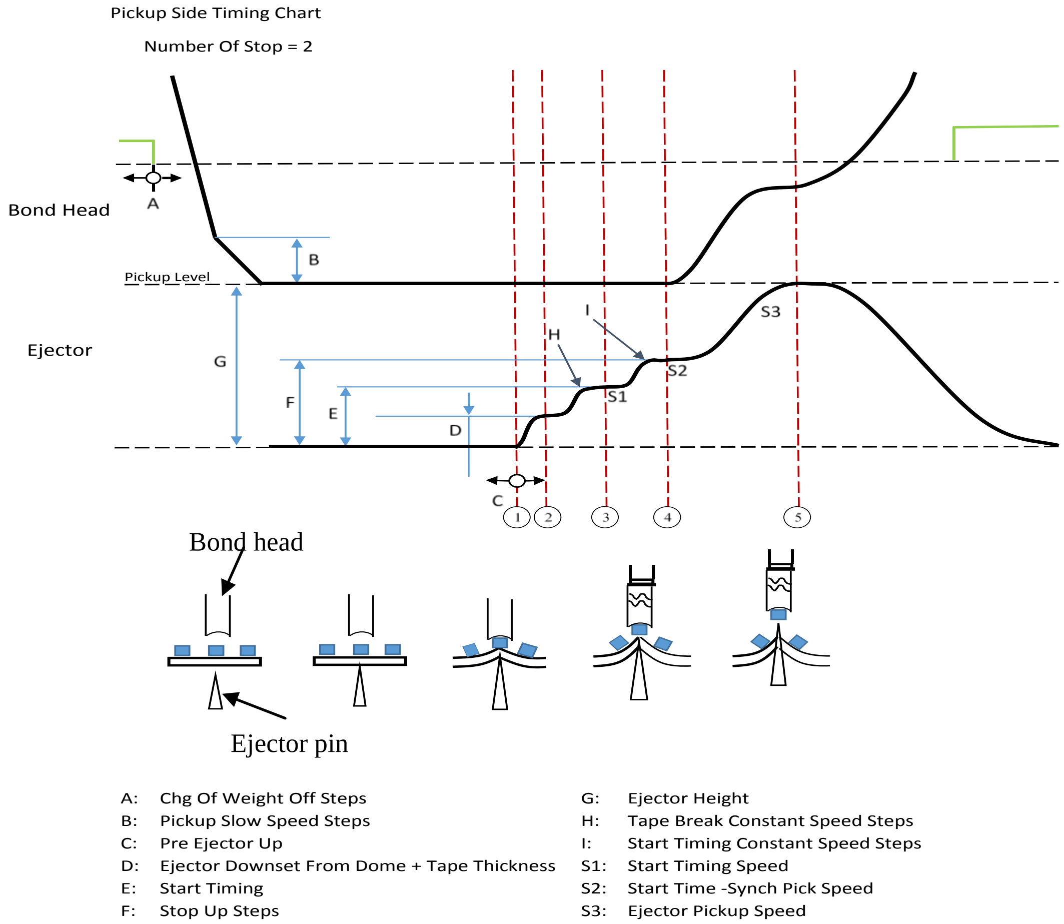


Figure 1.4 Die Attach Process Sequence [31].

The scope of this research study is mainly focused on the crack phenomenon of the germanium (Ge) substrate of Aluminium Indium Gallium Phosphate (AlInGaP) die during the DA process where most of the cracks occur. The objectives of this research are elaborated in the next section.

1.6 Research Objectives

The objectives of this project are as follows:

a. To understand the crack formation on Ge substrate against bond force and to compare the crack formation on two different die sizes.

b. To understand the impact of these cracks against the LED reliability performance and LED thermal resistance.

c. To develop IRT test system to detect die-crack LED.

1.7 Scope of the Study

This work focuses on the AlInGaP LED on Ge substrate. The LED die that is used is with the size of 150µm by 150µm, 300µm by 300µm and 1000µm by 1000µm. Die thickness are 120µm, 190µm and 190µm, respectively. The die with the size of 150µm by 150µm and 300µm by 300µm are with Ge (111) cleavage plane, and the die with the size of 1000µm by 1000µm is with Ge (001) cleavage plane. The characterization work is conducted at OSRAM R&D facilities.

1.8 Originality of Thesis

Since there is lack of information on the crack formation on the Ge substrate of AlInGaP die and its impact to electro-optical properties and thermal resistance, therefore in this work, an attempt is made to investigate the crack formations on Ge (111) substrate of AlInGaP die and impact to its electro-optical properties and thermal resistance. Stress tests are conducted on these dice to check their reliability performance. Besides that, crack formation on two different die sizes is investigated. In addition, IRT test system is developed to detect die-crack LED and isolate them. This will prevent any potential failures in the LED application.

1.9 Thesis Outline

This thesis contains five main chapters that include an introduction, literature review, experimental procedure, result and discussion, and the conclusion. The first chapter elaborates the history of the light source to the invention of LED as an alternative light source. This chapter explains the evolution of light source in human civilization and the revolutions that are created by LED light. The introduction chapter also gives some LED business numbers and a rough picture of its impact on world energy consumption. This chapter also addresses the drawbacks in the LED industry and narrows down to the key issue, that is, the cracked die in LED where the research scope is focused on and also the objectives of this research.

Chapter 2 is the chapter that will cover the project background and literature review. It begins with a brief overview of the LED fundamental and substrate material technology. The chapter discusses the material properties of Ge that is used in this LED as a substrate and followed by the review of past research to support the current study. This chapter also provides an overview of the DA process that is related to stress that may cause a crack of the die substrate. Then it is followed by an overview of the influence of the cracked die on the LED thermal resistance and the impact of die-crack on the electro-optical properties of LED. Lastly, this chapter touches the current electro-optical testing technology.

Chapter 3 describes the methodology that has been carried out to study the crack formation against bond force. This includes the DA machine setting up process to do the die indentation. Besides that, this chapter also explains the analysis and reliability of the test methodology, where a brief description of the stress test is put forward. An overview of thermal resistance measurement is explained. Lastly, a crack detection method is described in detail.

Chapter 4 extensively discusses the data and results which are obtained from all the experiments that have been performed in this research work, including a brief explanation on the experimental method utilized for each experiment and the valid results found. The data obtained from this work is thoroughly discussed and elaborated in view of the scientific significance.

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

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Introduction

This chapter presents the fundamentals of LED and describes the LED substrate material technology. The crack mechanism of a substrate is explained, and the practical aspects of a crack occurrence are also explored in this chapter, where it touches on how cracks occur in the LED packaging processes, specifically in DA process. Lastly, this chapter discusses the impact of a crack die to LED electro-optical and thermal properties, and briefly describes the current LED testing technology performed.

2.2 Fundamental of LED Technology

Most of the LEDs in the world today are constructed using semiconductor material alloys that are based on group III-V of the Periodic Table [3, 6].

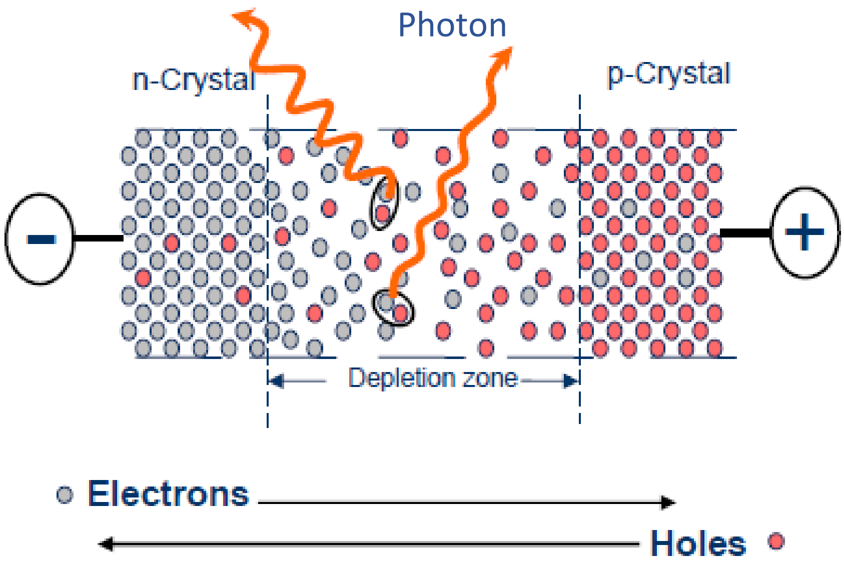
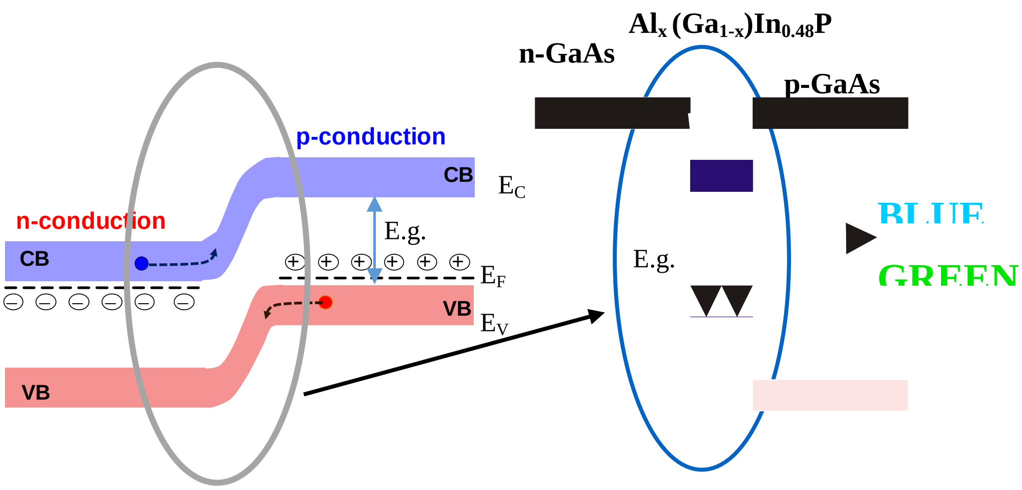


Figure 2.1. LED p-n junction in forward bias [6]. Recombination occurs in the depletion region that produces photon (light).

Most commonly used materials are GaAs, indium gallium aluminium phosphate (InGaAlP), aluminium indium gallium arsenide (AlInGaAs), GaAsP, and gallium phosphide (GaP) or GaN [6, 32]. Each of this material system emits different wavelengths that are directly related to their bandgap energy. Light is produced when an LED is biased at a certain voltage and current. Here, an electron crosses the junction from n- to p-type material, where the electron-hole recombines [9, 16]. This recombination process produces photons (light) in IR or visible wavelength in a process called electroluminescence as illustrated in figure 2.1 [33, 34].

In a more elaborated explanation, an LED works as per the illustration in figure 2.2a which shows the p-n junction situation at forward biasing conditions of a simple LED. Figure 2.2b shows the band diagram of the heterostructure of an $Al_x(Ga_{1-x})In$



$_{0.48}GaP$ LED with quantum wells inside the p-n-junction.

a. Simple LED with p-n-junction

b. AlInGaP LED with quantum wells inside the p-n-junction.

Figure 2.2 p-n junction under the forward bias conditions, minority carriers diffuse into the neutral regions where they recombine. [6, 34].

When a forward voltage is applied to the structure (positive to p-side layer and negative to n-side layer), the electrons are injected from the n-side layer into the p-side layer and holes from the p-side layer into the n-side layer as shown in figure 2.2a. These injected carriers are called minority carriers, a relatively small number of electrons surrounded by a large number of holes on the p-side and vice versa on the n-side. These electrons and holes can be in the same physical space, but they are separated in the energy gap or band gap, E_g as shown in figure 2.2b [6, 35].

In a very simple analogy, a positively charged hole is nothing else but a missing electron in the crystal lattice. Both electrons and holes can move freely through the crystal lattice. By applying a positive voltage or forward voltage (V_F) to the p-side electrode, electrons will diffuse from the n-side to the p-side of the conduction band. Similarly, holes will diffuse from the n-side of the valence band.

A positively charged hole can attract a negatively charged electron and the electron can recombine with the hole and release photons (light). However, this process has to obey two fundamental laws of physics that are energy and momentum conservation [3, 36].

The law of energy conservation can be equated with quantum energy law that is $E_g = h\upsilon$. This process results in the conversion of an injected electron or hole into photons as long as the energy gap is in the range of 1.9eV (red) to 3.0eV (violet) for visible light and 1.4eV to 1.8ev for IR light [22]. Direct bandgap materials, such as GaAs, GaAlAs, GaInN and GaAlIP, have injected electrons that recombine readily with holes by emitting infrared or visible light with a wavelength depending on the band gap energy $E_{g.}$ The band gap energy of the above material system is illustrated in figure 2.3 [22]. GaN base material system has a bandgap energy of approximately 3.47eV. GaP has a bandgap energy of 2.5eV and GaAs, on the other hand, has a bandgap energy of 1.52eV [3, 22]. However, electrons also have a chance to recombine without emitting light. In order to recombine radiatively, the electron (or hole) must find a hole (or electron) with the exact opposite momentum to meet the law of momentum conservation.

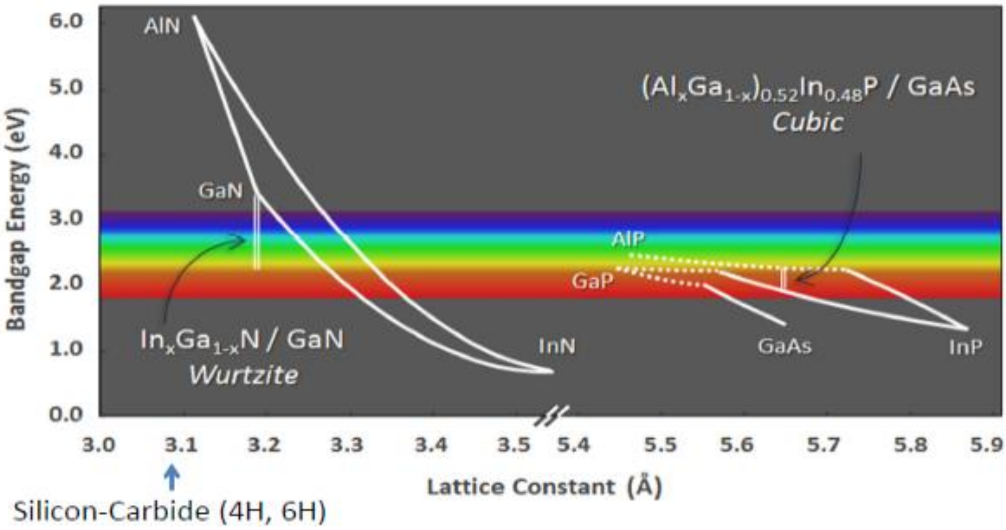


Figure 2.3. The bandgap energy versus the lattice constant in the III-V material system [22]

Radiative recombination requires momentum conservation, and recombination probability of an electron is proportion to the number of holes available at the equal momentum. The recombination probability decreases with the increasing temperature. The recombination process will take some time. During this time delay, the electron (or hole) has a finite probability to drop into an electron (or hole) trap such as a crystal defect or crack [16]. While being trapped, the electron (or hole) will eventually recombine with a hole (or electron). Instead of generating a photon, the recombination process will apply the energy conservation law by emitting multiple phonons or lattice vibration (heat) as shown in figure 2.4. This is not desirable in the LED industry.

Considering these two recombination paths, radiative and non-radiative, the efficiency of the recombination process can be described by a simple equation as shown below [36]:

$$\eta_i = t_n / (t_n + t_r) \qquad (1)$$

where η_i is the internal quantum efficiency, t_n is the mean time to recombine non-radiatively, t_r is the mean time to recombine radiatively. The best case is a very small $t_r < t_n$, then $\eta_i \sim 1$. This means the efficiency of the electrons that recombined radiatively at quantum is close to 100% [36]. However, the actual condition of the LED efficiency is still relatively lower than this [36, 37].

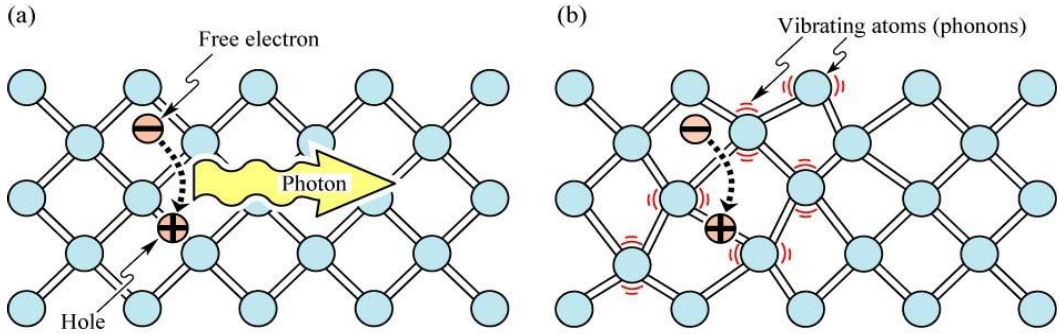


Figure 2.4. (a). Radiative recombination of an electron-hole pair accompanied by the emission of a photon with energy hv = E_g. (b). In non-radiative recombination events, the energy released during the electron-hole recombination is converted to phonons (adopted from Shockley, 1950) [6, 34].

The non-radiative combination occurs due to several physical mechanisms. These include the defects in the epi-layer, for example cracks, dislocations, foreign atoms and any complexes of the defects [22]. All defects have energy level structures that are different from the substitutional semiconductor atoms. It is quite common for such defects to form one or several energy levels within the bandgap of the semiconductor [36]. There are many factors causing these defects. Minimising these defects such as crack and dislocation is the key to gain superior LED performance [36, 37].

2.3 LED Structure and LED Die Substrate

All LEDs have the same basic common structure, that is, epitaxial layers (p and n) and substrate as illustrated in figure 2.5. The epitaxial layer is grown on a suitable substrate layer where the lattice constant matches with the epitaxial material system

[38, 39]. For example, the AlInGaP lattice constant has almost the same lattice constant value as the GaAs substrate. By having a similar lattice constant value, dislocation and crack occurrences in the epitaxial layer can be minimised [11, 40, 41].

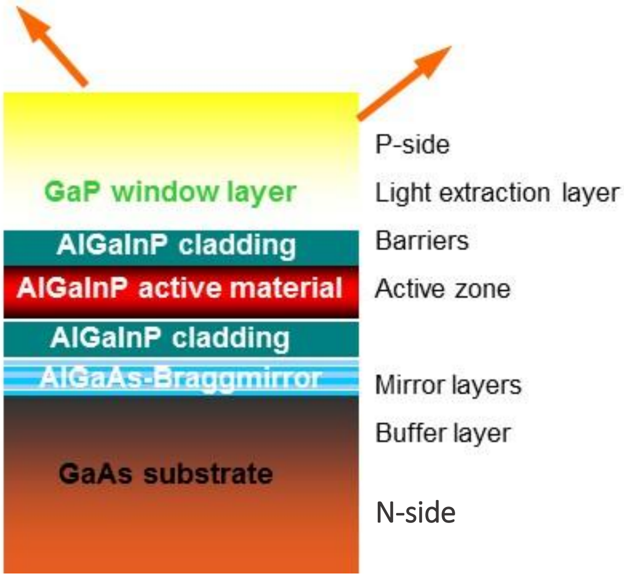
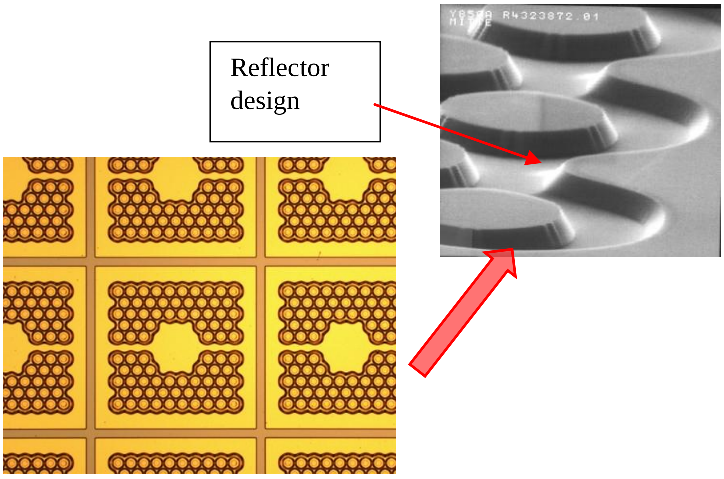


Figure 2.5. Basic LED structure showing the substrate and the active layer.

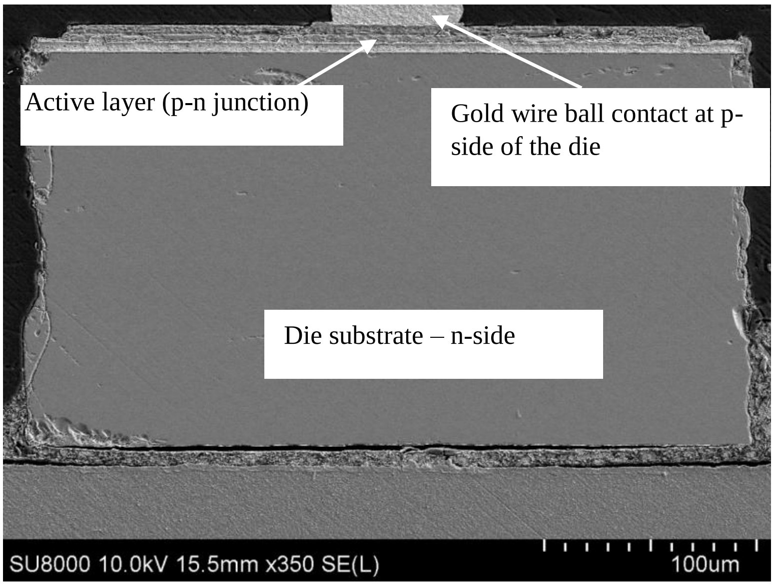
Figure 2.6a and b show the actual die structure that is depicted from OSRAM Opto Semiconductors Thinfilm LED technology. The active layer of this Thinfilm die is always at the top of the die with large substrate that has good mechanical, electrical and thermal properties. p layer of epitaxy will be highly p dopant and on the other hand n layer will be highly doped by n dopant. LED die substrate can be conductive, as it is highly doped like GaAs, Ge or Si. There are also non-conductive substrates like Sapphire [21, 41].

The epitaxial layers are the active region. It has grown on a substrate that usually has a lattice constant almost similar to the epitaxial layer to avoid dislocation or cracks, which directly affects the LED performance. Currently, the substrates that are commonly used are silicon carbide (SiC), GaAs, GaN and Sapphire (Al_2O_3) [11, 28, 42]. LEDs in green and blue wavelengths are usually grown on Sapphire, SiC or

GaN where the GaN epitaxy has quite similar lattice constant [3, 6, 28]. However, due to the recent push by the LED industry to drive the cost down , many research work has been carried out on GaN-on-Si [41, 43, 44] .



a. LED die structure in top view. Courtesy of OSRAM Opto Semiconductors.



b. Cross-sectioned view of an actual LED Thinfilm die.

Figure 2.6 Detailed structure of Thinfilm Technology LED die. Courtesy of OSRAM Opto Semiconductors.

In spite of many attempts by researchers to optimize the yield and performance of GaN base LED on Si, the yield is still low due to the dislocated and cracked die [45, 46]. Further research is needed to overcome the stress induced by the lattice mismatch for GaN-on-Si [47-49]. The LED in the Infrared to the yellow wavelength on the other hand, mostly use GaAs substrate to grow the epitaxy layer as their lattice constant match GaAs lattice [28, 50].

As mentioned earlier, in order to avoid dislocations and cracks, it is vital that substrate selection must match the epitaxial lattice constant. The LED substrate primarily acts as a carrier that provides mechanical stability, where it protects the epitaxy from damages during the packaging processes [6, 28]. GaN and Sapphire are transparent substrates that absorb considerably less photon. Hence, more light can be easily out-coupled from the LED. However, GaAs also absorb photon [36, 50]. To avoid this, a Bragg reflector (mirror) as shown in figure 2.6a, is grown below the epitaxy to reflect the lights from the active region of the LED [51]. This method is commonly used in Thinfilm technology LEDs [51].

Substrates play a very important role for the stability of an LED thermal and electro-optical properties, as well as its reliability performance. Many LED failures related to the substrate are reported by many researchers [36, 42, 52]. Hence, it is crucial to understand substrate material technology related to LED performance. This will be further discussed in the next section. In this research paper, the main focus will be on the Ge substrate which is commonly used in surface emission Thinfilm LEDs, especially by OSRAM Opto Semiconductors [51, 53].

2.4 Substrate Material Technology

The LED die substrate used for Thinfilm LED must have good thermal and electrical conductivity and mechanical strength in order to enhance the LED performance [54]. Heat generated from the active region of the LED must be dissipated efficiently to avoid it from being overheated in the LED die. Hence, a good thermal conductivity property of the substrate is important. On the other hand, the mechanical strength of the substrate helps to prevent die cracks on the substrate during the LED packaging processes [55]. Table 2.1 summarizes the properties of commonly used LED die substrates for Thinfilm Technology LEDs.

Table 2.1 Material properties of Si, Ge and GaAs Substrate [56]

Material property	**Si**	**Ge**	**GaAs**
Crystal Structure	Diamond	Diamond	Zinc Blende
Cleavage Plane	<111>	<111>	<100>
Density (gcm^{-3})	2.32	5.32	5.32
Band gap (eV)	1.12	0.66	1.43
Melting point T_m (°C)	1412	937	1240
Thermal conductivity (Wcm^{-1} $°C^{-1}$)	1.3	0.58	0.55
Linear thermal expansion, linear ($°C^{-1}$)	$2.6 X 10^{-6}$	$5.9 X 10^{-6}$	$5.73 X 10^{-6}$
Tensile strength (MPa)	700-7000	40-95	-
Knoop surface hardness ($kgmm^{-2}$)	1150	780	750
Moh's hardness	7	6	4 to 5
Young's modulus (GPa)	130-190	103	86
Bulk modulus (GPa)	98	75	75
Shear modulus (GPa)	52	41	33

The Young's modulus is a measure of the resistance of a solid to deformation when mechanical forces are exerted to it. The Young's modulus of Ge is substantially lower than the one of Si but higher than GaAs. Given that fact, the sensitivity for wafer breakage increases accordingly to the sequence Si<Ge<GaAs. GaAs is more prone to crack due its crystal structure [52, 56].

The coefficient of the linear thermal expansion (CTE) is another property affecting the LED quality. Considering CTE in LED construction is very important, CTE mismatch can cause serious dislocation and crack issues in the LED die during the epitaxial growth process. Based on Table 2.1, the CTE of Si is lower compared to Ge [56]. Hence, the Si wafers will be more prone to bowing/warping when used as a substrate to grow GaN epitaxy as their mismatch constitute roughly 54%. This was observed by Keith Strickland in his work [44]. Bowing wafer induces high stress to the epitaxial layer that causes cracks [44].

Besides the bowing effect that causes die-cracks, there are other plausible reasons for die cracks at the substrate in the LED manufacturing process. One of the examples includes DA process which was explained in the earlier section. It is important to understand the crack mechanism at the die substrate before exploring the DA process. In the next section, the crack mechanism at the die substrate due to the DA process is explored.

2.5 Crack Mechanisms at Die Substrate

Die-cracked is one of the major concerns in the LED manufacturing industry [52]. It can depreciate the LED performance and sometimes kill the LED [28, 57]. This was reported by Shailesh *et al.* in their studies on LEDs. When the LED undergone thermal shock stress, they found that LED failed to function due to die-crack. [57]

A crack is formed due to a large amount of dislocation generation in a specimen as a result of a large amount of energy absorbed by the bond that in the end overcomes the atomic bonding energy [58]. In a simple term, when energy absorbed by the bond is greater than the equilibrium inter-atomic bond energy, a new surface area is created (crack) [59]. The minimum stress where the rapture of the equilibrium inter-atomic bonding takes place is termed as the Ideal Strength Õ, where the material has reached the maximum level of strength. This ideal strength can be described as per equation 2 [60].

$$Õ = E/15 \qquad (2)$$

where E is the Young’s modulus of the material.