# 國 立 交 通 大 學

## 電機學院與資訊學院 電子與光電學程
## 碩 士 論 文

高效率光子晶体發光二極体之研究

# A STUDY OF HIGH EFFICIENCY LEDS BY USING PHOTONIC CRYSTAL TECHNOLOGY

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中華民國95年10月

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所 提 論 文 ___高效率光子晶体發光二極体之研究___

**A Study of High Efficiency LEDs by Using Photonic Crystal Technology**

合於碩士論文資格水準、業經本委員會評審認可。

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中華民國 95 年 月 日

# 高效率光子晶体發光二極体之研究

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## 摘　　要

如何加強 LEDs 的發光效率呢?加強內部量子效率是一個根本的方式,但是這須要從磊晶成長計技術著手,要付出相當大的成本.或可以改善級汲光效率為途徑, 例如表面粗糙化,較厚的窗戶層，或者以金屬為反射面.在本研討工作,採取光子晶體反射層為提高發光效率的手段. 光子晶體反射層採用介電質材料. 介電質材料是以電偶極振盪為其光反射機制. 因此僅有及微小的能量耗損.是極佳的反光材料．

本研討將比較光子晶體LED與 ITO LED，金屬反射鏡LED 之效能差異. 藉此來說明光子晶體LED的優越性.

# A STUDY OF HIGH EFFICIENCY LEDS BY USING PHOTONIC CRYSTAL TECHNOLOGY

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## Abstract

How to maximize the efficiency of LEDs? One way is to increase the internal quantum efficiency, this way should put efforts in epitaxy ; the other way is to increase the extraction efficiency .There are many techniques to improve the extraction efficiency, such as rough surface, thick window-layer, wafer bonding with metal reflector…etc. , In this study , we try a new method to increase the light output , that is ,photonic crystal technique . The reflectance ratio of 1dimension photonic crystal reflector is better than metal reflector . It is because the material of PhC layers used for LEDs is dielectrics . The light reflection of dielectrics is dipole-oscillation mechanism , this way, the incident light will not lose energy.

Here we will compare the PhC LED to the ITO LED and Metal reflector LED to convince the advantage of the photonic crystal technology .

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# Chapter 1. Introduction

## 1.1 Motivation

There is a strong demand to improve the luminous efficiency and brightness of light emitting diodes. It is necessary to efficiently transform electrical energy into light and extract it from devices. Up to date, the Wall Plug Efficiency (Optical Power out/Electrical power in (%)) for blue LED is about 7%. In general two methods have been approached to raise the LED efficiency: improving the generation efficiency of the light inside the device, i.e internal quantum efficiency; and improving the extraction efficiency of the light from the device, i.e optical extraction efficiency and external quantum yield.

The internal quantum efficiency can be improved mainly in the epitaxial growth stage, and extensive works have been carried out and remarkable results have been achieved in this field. However, the optical extraction efficiency remains low since the materials used in the LEDs generally have high refractive indices that trap the light inside the device as a result of an internal reflection. This can be explained by using Fig.1.1.

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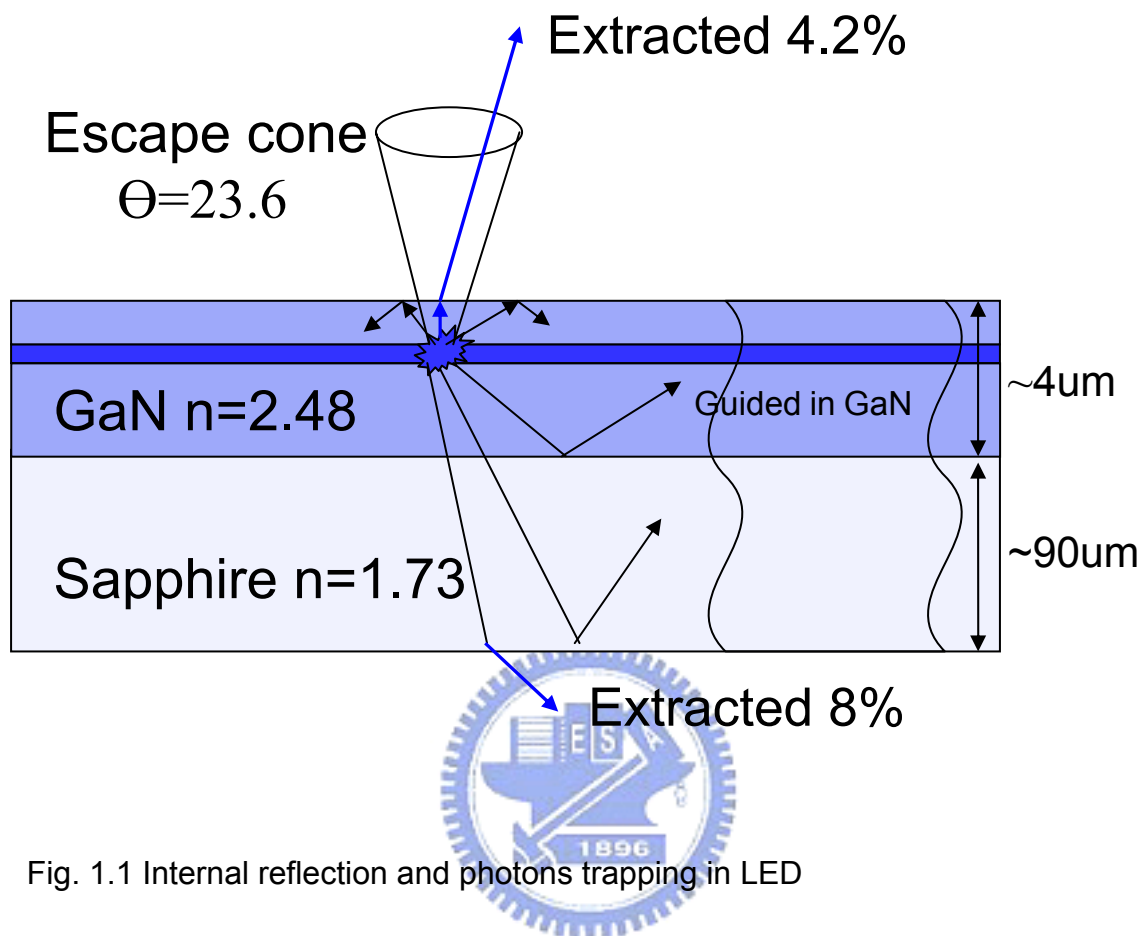
Fig. 1.1 Internal reflection and photons trapping in LED

As seen from the schematic drawings shown in Fig.1.1, the light is trapped due to high refraction index (n=2.48) of GaN and reflects many times between top and bottom of the GaN layer. Only about $1/4n^2$ of the light radiate through top and bottom, the extraction efficiency is less than 10%, more than 66% photons are trapped in LED materials. Therefore, any way of destroying parallelism of the GaN layer – etching, lapping, polishing or texturing – will help to extract this light before it is absorbed in GaN.

Some famous companies such as Lumiled, Cree, Osram and some Taiwan LED manufactures have their own technology strategic to improve the optical extraction efficiency, such as making LED on patterned substrates, using under-cut side wall structure, using surface roughness using and photonic band gap structure to enlarge the photon escape cone. These companies also developed their IPs to protect above mentioned technologies.

In the blue LED structure design both for top emitting and Flip chip structure, it always needs  a perfect reflector to reflect the photons upward to the top surface in order to  extract  them out from the LED. As shown in Fig. 1.2.  ; Fig. 1.3.
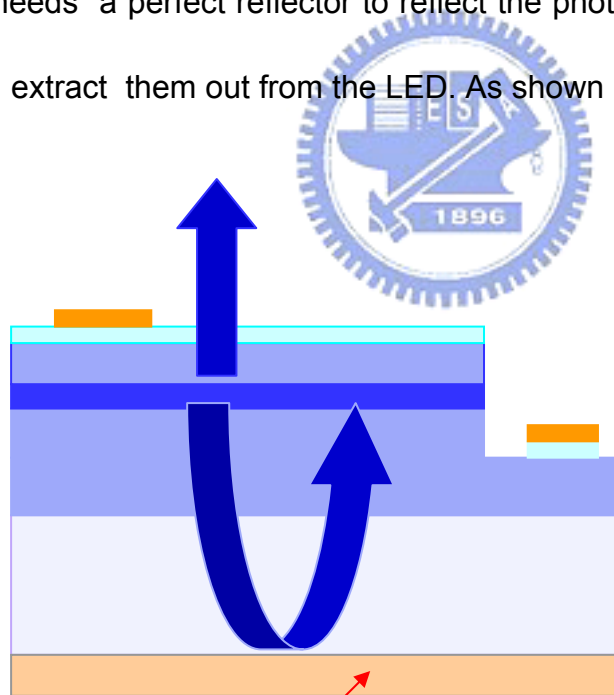


Perfect reflector

Fig.1.2   Structure of Top emitting LED

N-GaN

P-GaN

Submount
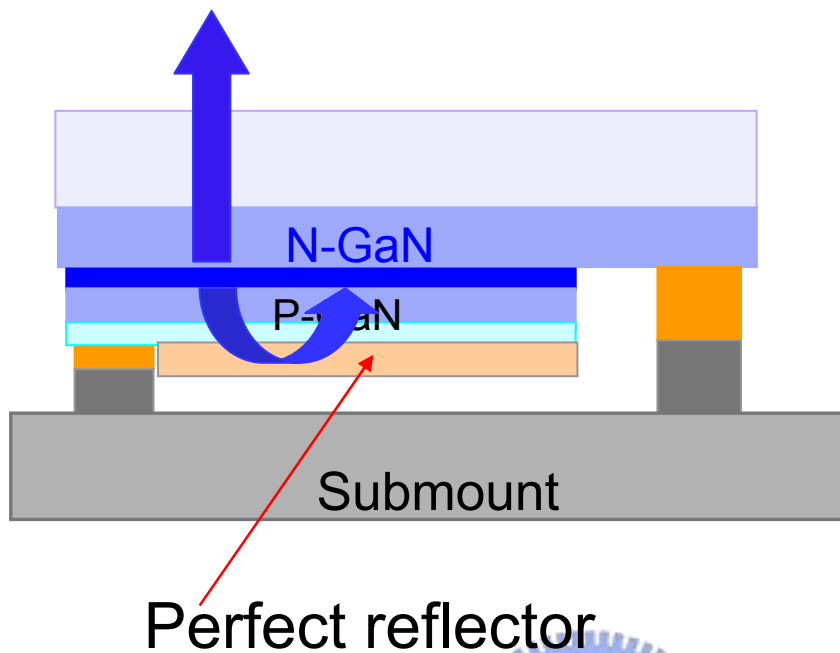
Perfect reflector

Fig.1.3  Structure of Flip Chip LED

The said `perfect reflector ` here means lossless reflector . If the reflector is a metal reflector , then the reflection loss should be higher than dielectric reflector . The reflection mechanism of dielectrics is mostly dipole vibration at same frequency of incident ray. As for the metal reflector, it will loss some energy to the free carriers from the incident light. . Basically, the most important property to LEDs is the light emission ability . The emission ability depends on the internal quantum efficiency and extraction efficiency . The internal quantum efficiency  is attributed to Epitaxy quality ; the extraction efficiency degree come from  device structure design and chip process .

The reflector is a very effective tool to increase the light extraction . According to mentioned previously , we know the dielectric reflector is better than the metal reflector. And the materials of photonic crystal structure used in LEDs is dielectrics , although the essential definition of photonic crystal never limits its material should be dielectrics .Now let us introduce photonic crystal briefly .

Photonic crystals are periodic dielectric or metallo-dielectric (nano) structures that designed to affect the propagation of electromagnetic (EM)waves in the same way as the periodic potential in a semiconductor crystal affects the electron motion by defining allowed and forbidden electronic energy bands. The absence of the propagating EM modes inside the structure , in a range of wavelengths called a photonic band gap, gives rise to distinct optical phenomena such as inhibition of spontaneous emission high-reflecting omnidirectional mirrors and low-loss wave guiding among others.

Since the basic physical phenomenon is based on diffraction , the periodicity of the photonic crystal structure has to the same length-scale as half the wavelength of the EM waves . i.e., ~300 nm fro photonic crystals operating in the visible part of the spectrum.
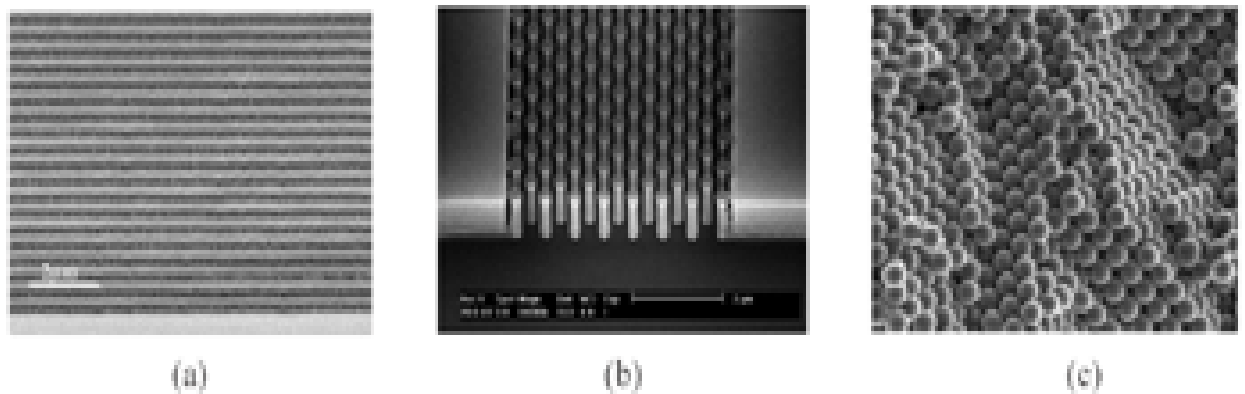
Fig.1-4  The geometric structure of photonic crystal in dielectrics

(a) 1D PhC , (2) 2D PhC  , (c) 3D PhC

Figure 1-4 shows the schematic depiction of photonic crystal periodic in one , two,and three directions , where the periodicity is in the material (typically dielectric) structure of the crystal .

One dimensional photonic crystal (1D PhC) consists of alternating layers of two dielectric media of refractive indices $n_1$ and $n_2$ . Almost all the 1D-PhC structure can form a complete photonic bandgap .

Similar to electronic bandgap, no photon frequencies in the gap region of the photonic crystal correspond to the allowed state for this medium. Hence, the photons in this frequency range cannot propagate through the photonic crystal due to the photons  of these frequencies are multiply scattered by the scattering potential produced by the large refractive index contrast $n_1/n_2$. In other words, of photons of

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frequencies corresponding to the bandgap region are incident on the 1D-PhC structure, they will be reflected from the surface of the 1D-PhC structure and will not enter the crystal. Further more, this kind of reflection is independent on the incident angle and polarization of the incident photons. So 1D-PhC structure can act as a perfect reflect mirror with omnidirectional, high reflection (100%). We can use 1D-PhC as a perfect mirror in high efficient LED structure design.

# Chapter 2.

# Physical , Electrical and Optical Properties of III-Nitrides

## 2.1 Materials properties

The alloy system Al– Ga–In–N, when grown in the typical wurtzite structure, forms a continuous and direct band-gap alloy from6.2 eV (AlN) to 0.8 eV (InN), with GaN itself possessing a large band gap of 3.4 eV. Linked to the enormous differences in the band gap of the binary crystals, also the bond energy between the metal and nitrogen atoms in the crystal lattice show large variations, with EB(Al–N)=2.88 eV, EB(Ga–N)=2.2 eV and EB(In–N)=1.93 eV in the binary nitrides AlN, GaN and InN. Consequently, the group-III nitrides also differ enormously in their thermal stability, with AlN and GaN exhibiting melting points of about $3200^{\circ}C$ and $2500^{\circ}C$, respectively, while InN already sublimates at temperatures above $550^{\circ}C$ (Fig.2.1) . For this reason, (Al, Ga)N films are typically grown at temperatures above $1000^{\circ}C$, whereas the deposition of indium containing alloys is performed at temperatures below $800^{\circ}C$. Furthermore, the lattice mismatch between AlN and GaN is about 3.5%, the lattice mismatch between GaN and InN is as high as 10%. As illustrated in Fig. 2.1[1], the chemical and physical properties of the group-III nitrides are much more diverse than

the properties of the corresponding arsenide (or phosphide ). The profound

differences in the properties not only affect the crystal growth, but also the gas-phase

chemistry in the MOCVD growth chamber[2].
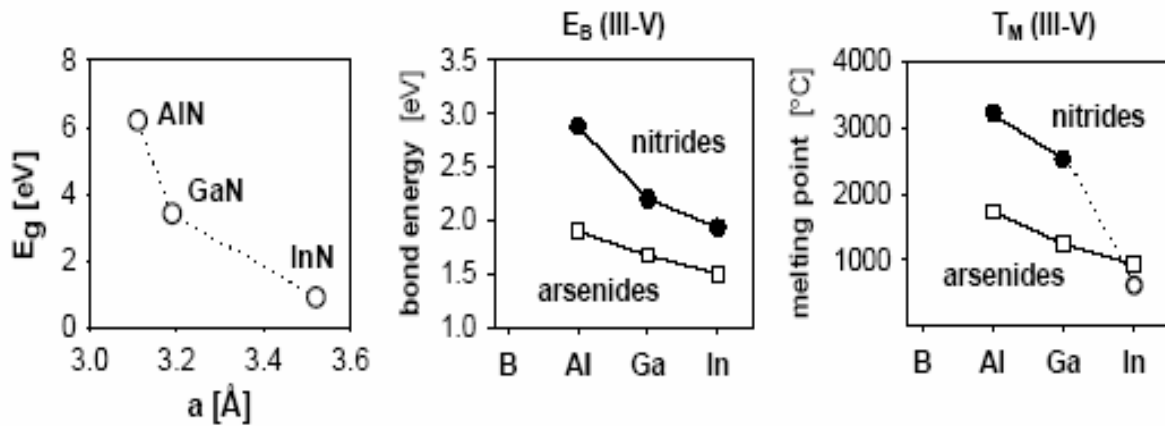


Fig.2.1. Physical and chemical properties of binary nitride semiconductors:

    left: band gap energy Eg as a function of lattice parameter a,

    center : comparison of binary bond energies for group-III nitrides and arsenides,

    right: comparison of the melting points of binary group-III nitrides and arsenides.


Although under investigation for several years, the device design

opportunities offered by the alloy systemAl– Ga–In–N have not yet been fully explored.

Similar to the band gap of InN, a variety of properties of the group-III nitrides remain

unclear. These  discrepancies can often be attributed  to th e  insufficient  quality  of

the investigated material.  Advances in the reactor design, the availability of AlN, GaN

or alloy substrates, and possibly the development of alternative precursors will lead to

improvements in the quality of the epitaxial layers. Flow modulation epitaxial

processes and digital alloy approaches may gain importance in particular for the growth of alloys containing both AlN and InN. The influence of kinetic effects on miscibility and ordering needs further investigation as well. Efforts to take advantage of the polarization effects in group-III nitrides, particularly for doping purposes, are just in the early stages of development. Further concerted efforts are necessary to meet these challenges in the materials growth and the understanding of the group-III nitrides.

## 2.2 Electrical Properties

Because gallium nitride (GaN) is an attractive material which has a wide direct band gap, GaN-based optoelectronic devices such as light emitting diodes (LEDs) and laser diodes (LDs) in blue and ultraviolet wavelength regions have been intensively researched and are also commercially available. [3]

In the GaN-based LED fabrication, the p-contact is generally formed by depositing metal layers on p-GaN located at the top of GaN-based LED quantum well structure. Due to the high contact resistance to p-GaN originated from low doping density of p-GaN, many studies have been made to improve the poor electrical

performance. Among these are the use of multilayer materials such as Ni/Au and Ta/Ti and the use of additive metal outline to increase the electron spreading area of p-GaN, etc. [4–7]. In general, Ni/Au ohmic contacts to p-GaN are widely studied in commercial GaN LEDs.

These metal contacts, however, are only partially transparent and most of the light generated in the LED cannot be emitted through the top of the devices even though the GaN-based LEDs are optically transparent. If the ohmic contacts could be formed by transparent conductive oxides instead of partially transparent multiplayer metals, the light emitting area can be increased so that light with a higher intensity could be obtainable, therefore, more efficient LEDs can be fabricated without the loss of contact area. However, up to today, only a few experiments on transparent conductive oxides have been carried out as the materials for ohmic contact to GaN-based LEDs.

ITO is a well known transparent conducting material with resistivity in the range of low $10^{-4}$ $\Omega$cm2 and with transmittance higher than 90% in the blue wavelength region at optimized conditions[7]. Therefore, ITO has been widely applied in various optoelectronic devices. In this study, ITO contact properties were studied by depositing ITO on p-GaN to investigate a possibility of forming transparent ohmic contact on p- GaN. Because the substrate pre-treatment before the contact formation is one of the most important factors in forming a good ohmic contact, the effect of

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substrate pre-treatment on the ITO contact properties was also investigated.

Electrical properties of ITO contact on p-GaN have been investigated as a function of different surface treatments to p-GaN, annealing temperature, and annealing time. The contact resistance initially decreased with the increase of annealing time and showed a minimum contact resistance at a certain annealing time and temperature. Also, the surface treatment before ITO deposition affected the contact resistance.

ITO contact resistivity in the range of low $10^{-1} \Omega cm2$ could be obtained for certain conditions such as the surface treatment B (Acetone+ Alcohol+ HCl+ $3HCl:HNO +(NH_4 )_2 S$) followed by the annealing at $600^oC$ for 90 s and the surface treatment C (Acetone+Alcohol+HCl+3HCl:HNO +KOH+$(NH_4 )_2 S$) followed by the annealing at $700^oC$ for 60 s, etc. The $I-V$ characteristic of the deposited ITO contact was initially Schottky contact, however, at the optimized annealing conditions, the $I-V$ curve showed a near-ohmic behavior possibly due to the formation of a mixed interface layer. Optical transmittance of the 100 nm ITO contact annealed at $600^oC$ for more than 90 s was higher than 90% while that of 50 nm Ni/50 nm Au, typically used for the contact on p-GaN, is lower than 40%. Therefore, it is believed that if the ITO contact to p-GaN is formed after a proper surface treatment followed by adequate annealing, the ITO contact could be applicable as a transparent contact to p-GaN.

## 2.3 Optical Properties

GaN-BASED light-emitting diodes (LEDs) have been the subject of extensive

investigations, and have been developed because of their potential applications in

areas such as full color displays,full-color indicators,and high-efficiency

lamps[10]–[17]. However, the GaN-based LED has a critical weakness in that its

fabrication mainly involves the use of the lateral carrier injection type due to the

absence of an appropriate conducting substrate. In this case, a current crowding

problem is often encountered and impedes the development of the efficient GaN

based LEDs. Several groups have reported on studies relating to this issue, both

theoretically and experimentally [18]–[20]. Based on the assumption that the

transparent electrode represents a perfect current spreader, Eliashevich *et al.*

reported that the conductivity of an n-type GaN layer has a profound effect on uniform

current spreading [18]. It has been shown that the uniform current spreading is

essentially attained above the critical n-type carrier concentration. However, a thin

metal film has a much higher sheet resistance than its corresponding bulk material

due to the reflection of conduction-electrons from defects that are trapped in the film

during the deposition and from internal surfaces [21]. Therefore, the resistivity of the

transparent electrode should not be ignored in the development of a more accurate

model. Based on this consideration, more highly developed theoretical model has recently been proposed and important parameters such as the current density, the resistivities of the transparent electrode and n-type layers, and the effective length for the lateral current path were found to be important factors in uniform current spreading [9], [19].[20]

From the standpoint of both uniform current spreading and high extraction efficiency of a generated light, the determination of the proper thickness of the transparent electrode becomes very important. However, no systematic study on the transparent electrode has yet been reported because of a lack of understanding of the relationships between the transparent electrode and the n-type layer with respect to current spreading. In this study, we report on a method for determining the critical transparent- electrode thickness for the realization of highly efficient LEDs.

Based on the effective length factor, which involves device geometry, significant improvements in LED characteristics have also been demonstrated by local modification of the p-type pad (electrode) geometry [19], [20]. In addition, although it does not mainly concern the current spreading problem, the geometrical design such as the interconnected micro disk LED also showed a 60% increase in optical emission efficiency compared to the conventional broad-area LED [22]. These results indicate the importance of geometrical design on device efficiency. In this regard, in terms of the ideal geometrical design, which gives perfectly uniform current spreading
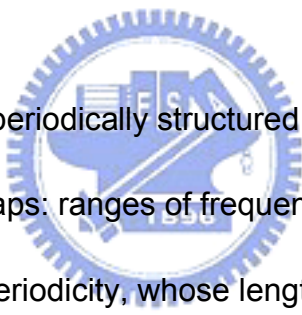
conditions, we report on an attempt to realize highly efficient GaN-based LEDs in the absence of a transparent electrode.

Based on the current spreading phenomenon in the GaN based LEDs, promising fabrication method and design rules were investigated. It was possible to maximize the device performance from the determination of the critical transparent-electrode thickness during the fabrication process. For this work, first, the resistance of the n-type layer should be minimized in order to maximize the carrier injection into the n-type layer. The critical transparent-electrode thickness should then be determined according to the relation of , resulting in the maximization of the carrier injection into the p-type layer through the transparent electrode. This result will be very useful for the fabrication of highly efficient devices in the conventional LED process. In addition, we also investigated the geometrical design rule for the highly efficient LED in terms of a perfect current spreading. Based on this consideration, it was even possible to realize the ideal LED geometry without the need for a transparent electrode, which resulted in improvement in LED performances, compared with a conventional LED. Finally, it is concluded that, although the determination of the critical transparent-electrode thickness has a great influence on the device performance, the design of ideal geometry is a better method to fabricate the highly efficient LED considering the extremely improved device performance as well as the simple fabrication process.

# Chapter 3.
# Theory of Emission Efficiency Improvement

## 3.1 Basic Concepts of Photonic Crystals

Photonic crystals are periodically structured electromagnetic media, generally possessing photonic band gaps: ranges of frequency in which light cannot propagate through the structure. This periodicity, whose length scale is proportional to the wavelength of light in the band gap, is the electromagnetic analogue of a crystalline atomic lattice, where the latter acts on the electron wave function to produce the familiar band gaps, semiconductors, and so on, of solid-state physics.

Photonic crystals represent a class of nanomaterials in which alternating domains of higher and lower refracting indices produce an ordered structure with periodicity on the order of wavelength of light..

In a photonic crystal , for certain range if photons and certain wave vectors ( that is , direction of propagation), light is not allowed to propagate through this

medium. If we generate light inside, it cannot propagate in this direction. If we send

light from outside, it is reflected.

In the case of a large refractive index contrast ( defined by the ratio

n1/n2 )photonic crystal with a proper shape of building blocks ( domains ) and proper

crystal symmetry, a complete bandgap develops. In this case, the bandgap is not

dependent on the direction of wave vector ,which defines the light propagation ; also,

the density of photon states goes to zero in the bandgap region.  These materials with

a complete gap are often called photonic bandgap materials.

Here we would describe the concept of complete and incomplete photonic

bandgap more clearly . A complete photonic band gap is a range of ω in which there

are no propagating (real k) solutions of Maxwell's equations  for any k, surrounded by

propagating states above and below the gap. There are also incomplete gaps, which

only exist over a subset of all possible wave vectors, polarizations, and/or symmetries.

## 3.2  Physics of 1-dim Photonic Crystal

Photonic bandgap crystals are periodic structures in which light is prohibited from

having extended modes by classical electromagnetic theory. In practice, these are

man-made structures, usually made out of two of more materials with different

dielectric constants. The size of the crystal features can be scaled with the wavelength

of electromagnetic radiation used due to the linearity of the Maxwell Equations.

Typically the unit cell of such a crystal has dimensions which are comparable to the

wavelength of radiation it is designed to work with.

The simplest example of a one dimensional photonic crystal is the well known

Bragg mirror. A stack of layers of two materials with different dielectric constants and

optical thicknesses equal to one quarter of a wavelength each will act as a mirror for

light near normal incidence. One way of thinking about this is that there are reflections

from each material interface, and those which reflect back constructively interfere,

while those which reflect an even number of times destructively interfere, resulting in

net reflectivity. In an *infinite* stack of layers, light cannot propagate normal to the

interfaces within a specific frequency range. In a finite stack, light incident upon the

stack at near normal incidence will partially reflect. Within the quarter wave stack, the

intensity will decay exponentially.
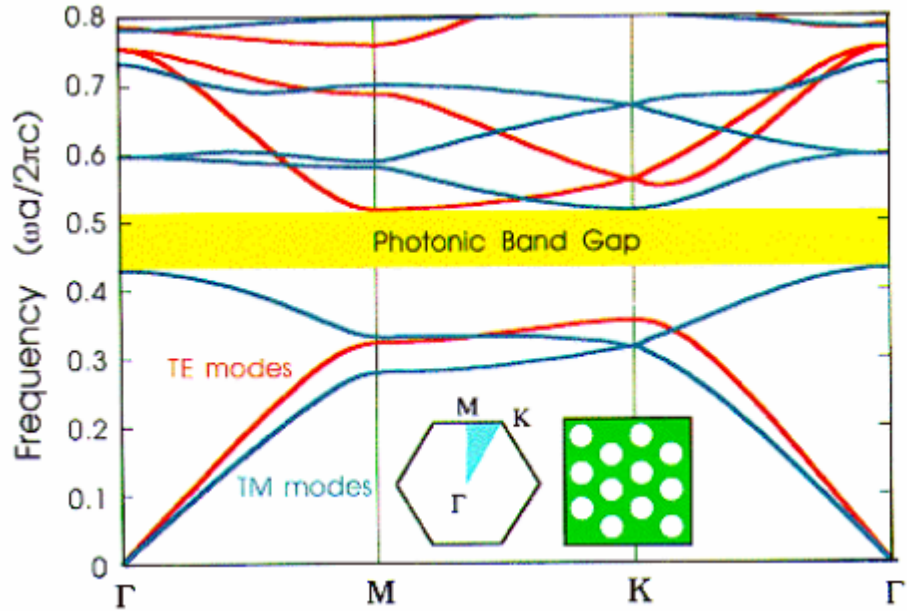


Figure .3.1 : Band Structure of hexagonal lattice of holes

The concept of a Bragg reflector can be extended to two or three dimensions

by considering structures with periodicity in more than one direction. In order for

such a structure to display a useful bandgap, there must be a frequency range in

which electromagnetic radiation cannot propagate in any direction in two or three

dimensions. Calculations have revealed that there are many structures which have

two dimensional photonic bandgaps [23,27], but fewer that possess a full three

dimensional gap [23, 26].

It is sometimes useful to consider a multidimensional photonic crystal as a

superposition of several one dimensional crystals at different angles. In this sense, the

"Bragg planes" of the crystal can be described as the planes normal to which light is

strongly reflected. In this view, it is clear why it becomes harder to create a photonic crystal in higher numbers of dimensions, as it becomes more difficult to find a lattice which provides reflecting Bragg planes in all directions.

In these experiments, we will be concerned with a photonic crystal made by drilling (or etching) a hexagonal array of air holes into a slab of dielectric material. The band structure for this crystal is shown in figure 3.1. It can have a complete two dimensional bandgap for both possible polarizations in the lattice. We will be designing these structures for use with optical and infrared radiation, which results in hole spacings (lattice constants) on the order of hundreds of nanometers in materials with an index of refraction around 3.2.

There is another class of photonic crystals made using combinations of dielectric materials and metals. These also exhibit very large photonic bandgaps in two and three dimensions [28]. At microwave frequencies, these structures are very useful, but most metals are too lossy at optical frequencies to be useful in high Q cavities. Therefore, we will restrict discussion to dielectric photonic crystals.

## 3.3 Photonic crystal---- Advanced approach in enhancing optical extraction

**Features of Photonic Crystals**

Spontaneous emission arises from the intricate interplay between a radiating system and its surrounding environment. A prominent example of this interplay can be seen in a photonic crystal, where spontaneous emission can be enhanced, attenuated or even suppressed by changing the density of electromagnetic states at the transition frequency, or by changing the orbital angular momentum of the emitted photon. The ability to control spontaneous emission could have profound consequences on many optoelectronic devices. One device that could potentially benefit from this control is the LED, which spontaneously emits radiation from a p-n junction. In the past thirty years, various approaches have been proposed to enhance the extraction efficiency of LEDs. Many of these approaches rely on clever geometrical optical designs to either enlarge the escape cone of photons using a hemispherical dome, or to enable multiple entries of photons into the escape cone using photon recycling or surface roughness. These approaches, however, do not alter directly the spontaneous emission properties of the devices.

*Photonic crystals* are ordered nanostructures in which two media with different refractive indices are arranged in periodic form. In the case of a large refractive index

contrast photonic crystal with proper shape of building blocks (domains0 and proper

crystal symmetry, a complete photonic bandgap develops. As shown in Fig.3.2.
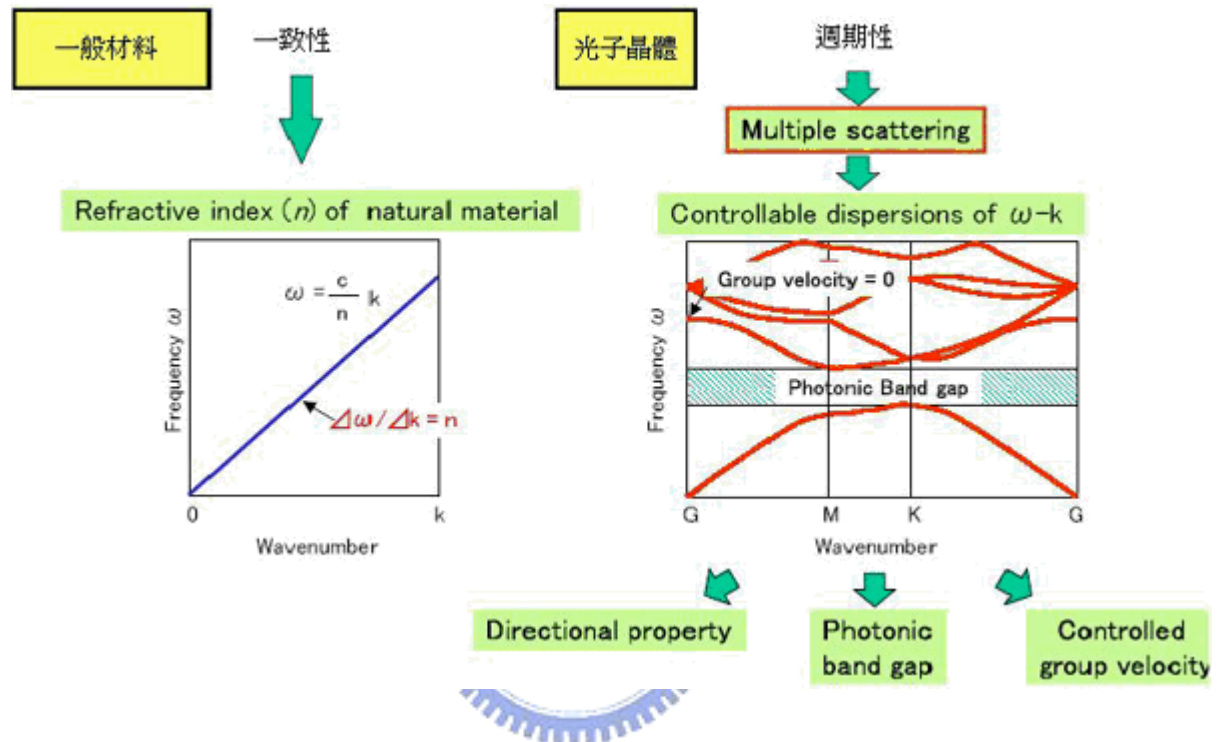


Fig.3.2 Photonic bandgap structure.

For the application of photonic crystal technology in LEDs to improve the optical

extraction efficiency, two schemes can be considered for PhC assisted LEDs:

formation of bandgaps to prevent emission into guided modes, or PhC acting as

diffraction gratings to extract guided light.

Let us first consider the various paths accessible to light emitted in a classic

GaN LED (Fig.3.3): 6% of the light is emitted in air towards the top (assuming a

transparent contact), which can be doubled if a mirror is placed under the sapphire

substrate. 22% is trapped by TIR but can propagate in the sapphire – we call this fraction the substrate light. Finally, 66% is trapped in the GaN layer by TIR at the air and sapphire interfaces. We label this light as guided light. Substrate light has negligible interaction with the PhC region, as it propagates for long distances in the thick (~100 um) transparent sapphire wafer, and impinges on the PhC no more than once before exiting the LED region. Therefore, the PhC only aims at extracting guided light.
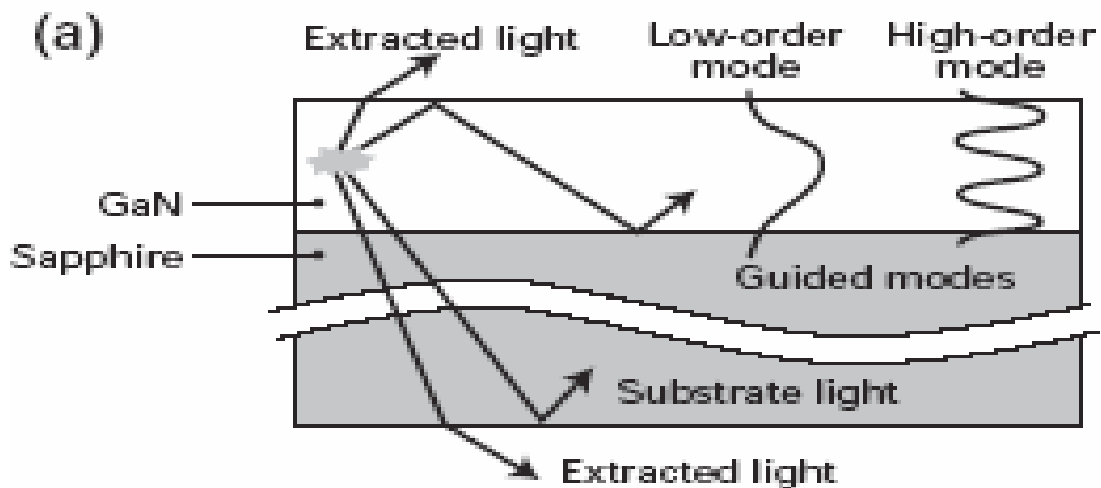


Fig.3.3 Possible paths of emitted light in GaN based LED structure.

The 2D photonic crystal can act as diffraction gratings in extracting light in GaN-based LEDs. Many research works have been carried out to study and characterize a solution based on tailoring the structure of guided modes which

enables nearly all of the guided light to be prone to interaction with the PhC. This can

be illustrated by Fig. 3.4.

Pitch
*a*  Decides diffraction vector *G*  ⇨  Controls diffraction direction

$$G = \frac{2\pi}{a}$$

Height
*h*  Decides the diffraction efficiency

Pitch
*a*
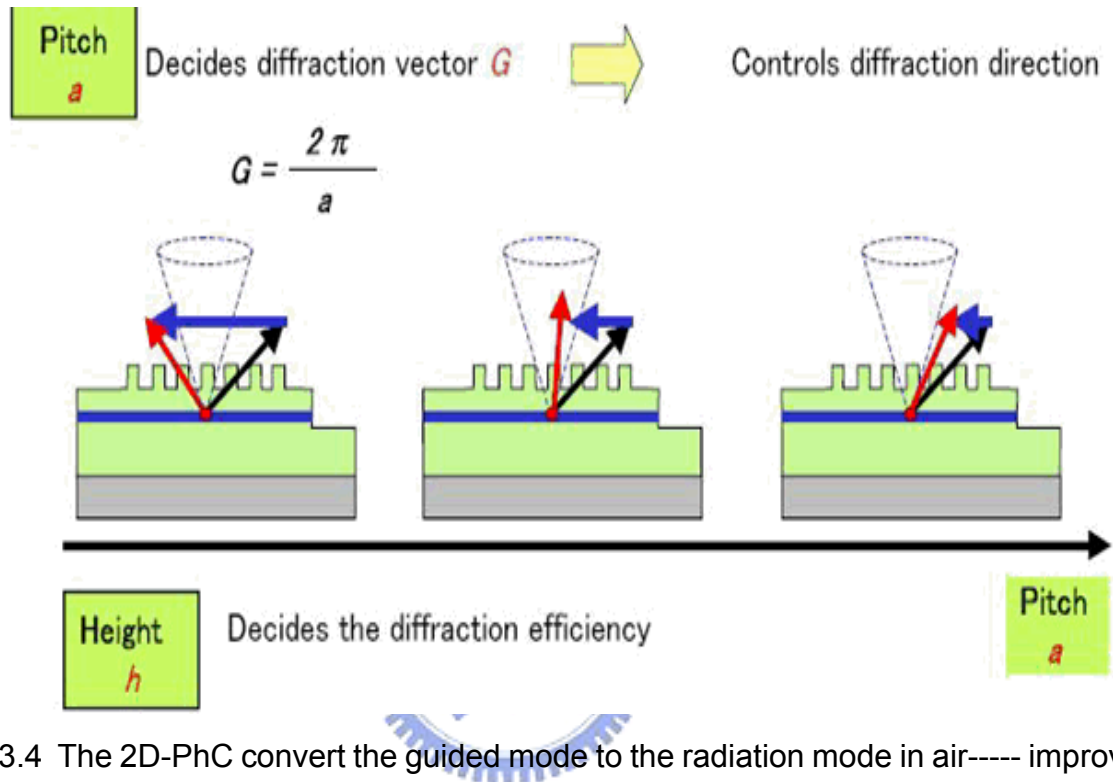
Fig.3.4  The 2D-PhC convert the guided mode to the radiation mode in air----- improve
the light extraction efficiency


**Problems exists in PhC-LED**

However, for the fabricated LEDs using photonic crystal technology, it is still far

from an optimal design, a lot of work need to be done to confirm the validity of the

approach of modes tailoring. This improvement comes at no cost or additional

fabrication steps, and could easily be combined with future optimisation of the intrinsic

PhC properties, bringing us closer to ultra-efficient PhC-assisted LEDs. However,

nonradiative carrier recombination and surface recombination are increased near the etched interfaces. This can pose a problem when the lattice constant of the photonic crystal becomes comparable to the carrier diffusion length in the active region. It is therefore important to avoid penetrating the active region with the photonic crystal. While photonic crystals in general

Result in far-field patterns different from flat-surface  rectangular parallelepiped LEDs, other surface structuring techniques maintain the Lambertian  emission pattern .

**Comparing of 1D-PhC with Al mirror and DBR**

Al mirror is a commonly used reflector in LED structure design. But the reflection of Al mirror is not higher than 85% due the metal absorption in the short wavelength region. For BDR structure, its reflection is higher (90%) but is strongly dependent on the incident angle and the polarization of the incident photons. 1D-PhC structure has better reflection properties as compared with Al mirror and DBR structure.


**technology solution for 1D-PhC LED**

A. For different wavelength, optimize different 1D-PhC structure (*photonic bandgap*) to get maximum reflection.

B. Not only focus on power/brightness enhancement, but also design the far field radiation pattern for different applications.

Our team has proposed several LED structures using 1D-PhC and 1D-PhC to enhance the optical extraction efficiency, as shown in Fig.3.5.,
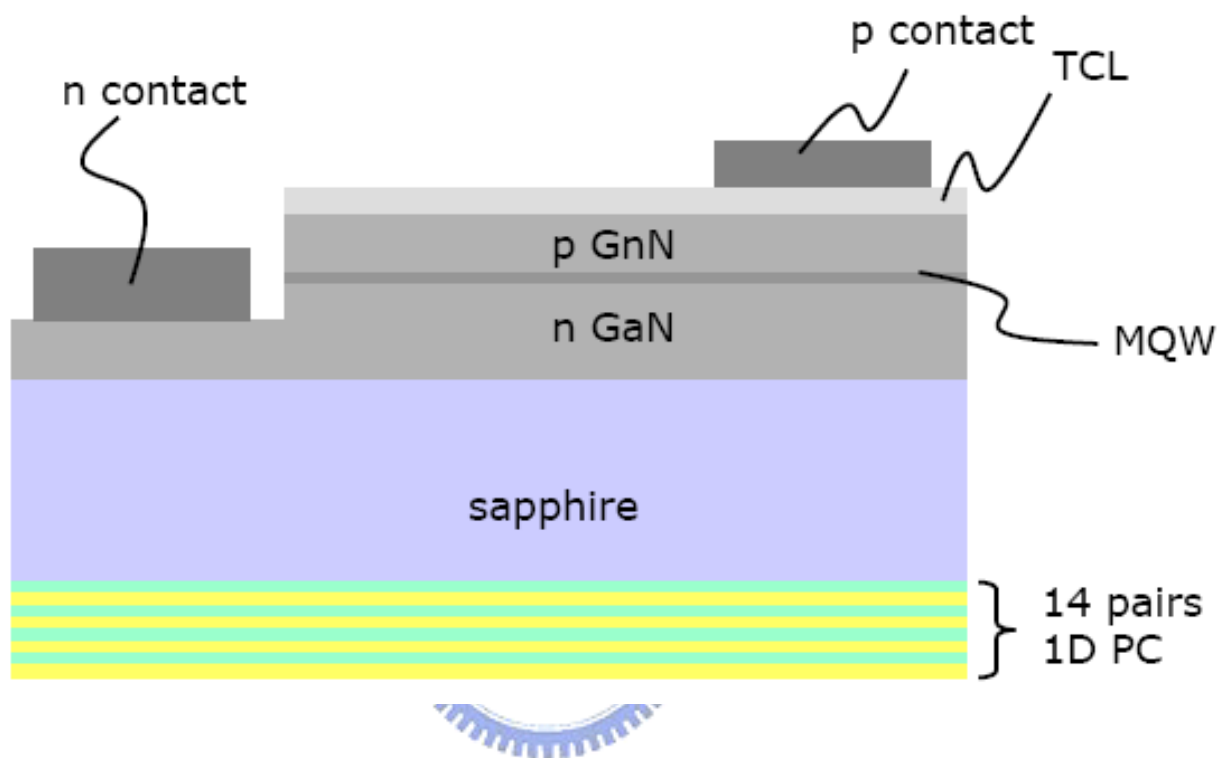


Fig.3.5.Top emitting LED using PhC technology

# Chapter 4.
# Device Fabrication and Processing

## 4.1. Compound Semiconductor Materials

Some of the fundamental principles of semiconductor growth mechanisms and the associated practical methods used in the manufacture of wafers for device fabrication are discussed in this section.

Compound semiconductor materials can be realized by the formation of "solid solutions" of two or more starting materials. These solutions occur when atoms of a different element are able to substitute a given constituent of a material without altering its crystal structure. The ability to do so by the new atom is referred to as its miscibility. In order that atoms can form solid solutions over large ranges of miscibility, they must satisfy the Hume Rothery rules:

- They must belong to the same **group** of the periodic table

- They must have comparable **atomic diameters** allowing substitution without large mechanical distortion

- Their **ionicity** must not be very different so as not to affect the tendency to attract / repel electrons from the site by a large amount

- The **crystal structure** of each constituent must be the same

A two component alloy is known as a *binary* alloy; some common examples include GaAs, AlAs, GaP, InP and InAs all of which have the Zincblende (diamond) crystal structure. Similarly a *ternary* alloy is one with three components and a *quaternary* alloy is one with four.

## 4.2 Epitaxy

Epitaxy refers to the ordered growth of one crystal upon another crystal [97]. Because of the large range of possible semiconductor compounds and their alloys, it is rare in device fabrication to grow bulk crystals of all these materials. Instead, it is more attractive to realize the wider range of materials by epitaxial growth. This is partly due to the difficulties involved in developing easy bulk crystal growth techniques for each new material and also because of historical reasons. Two materials for which thorough research and bulk crystal growth and polishing methods have already been developed are GaAs and InP.

There are three main modes of epitaxial growth: (a) monolayer, (b) nucleated and (c) nucleation followed by monolayer. Monolayer growth occurs when the deposited atoms are more strongly bound to the substrate than they are to each other. The atoms aggregate to form monolayer islands of deposit which enlarge and eventually a complete monolayer coverage has taken place. The process is repeated for subsequent layer growth. In case of nucleated growth, the initial deposit atoms

aggregate as small three-dimensional (3D) islands which increase in size as further

deposition continues until they touch and intergrow to form a continuous film. This

mode is favoured where the forces of attraction between the deposited atoms is

greater than that between them and the substrate. In the final mode, growth starts with

the formation of a single or few monolayers on the substrate followed by subsequent

nucleation of 3D islands on top of these monolayers.

## 4.2.1 Epitaxial Lattice Matching

Epitaxy, although a highly successful approach for growing a wide range of

materials, none the less suffers from an important constraint. Epitaxial growth

requires that the atomic spacing, the lattice constant, of the layer material not differ by

more than a few percent and that they have the same crystal structure. While most

materials of interest have diamond structure, satisfying the latter requirement, the

lattice matching imposes a serious constraint on the range of compositions that can

be grown on a given bulk substrate. Although, traditionally, these were provided by

GaAs and InP, increasing use is being made of InAs and GaSb as the substrate.
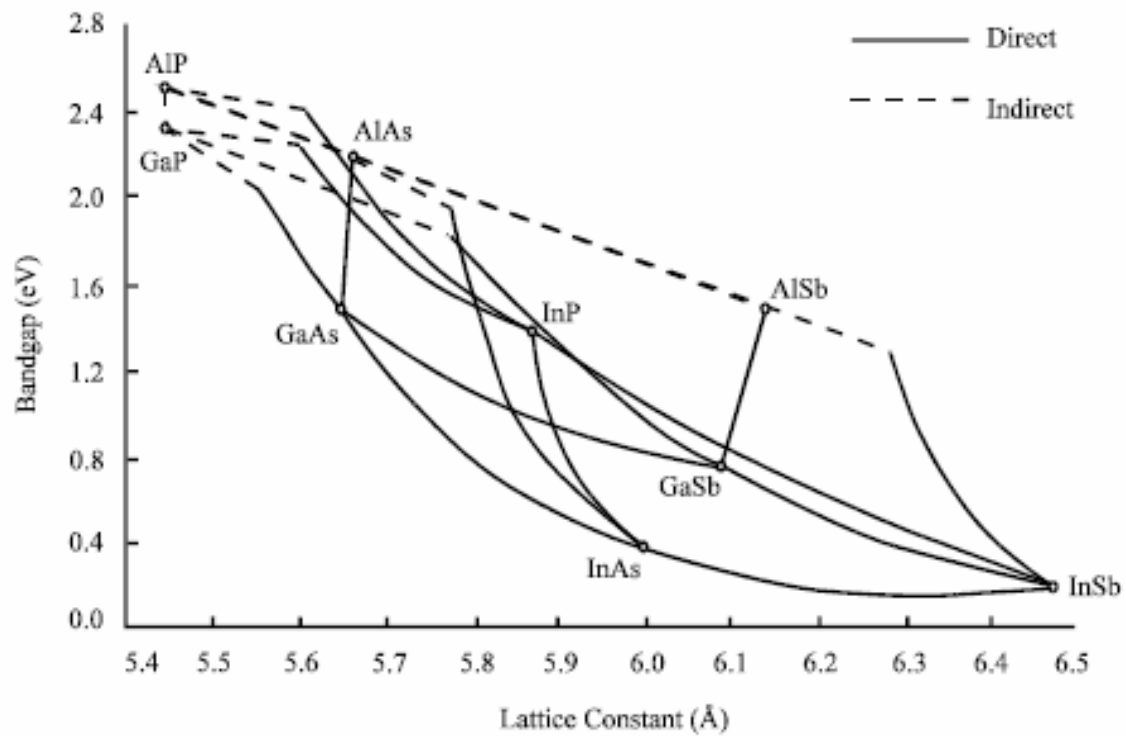
Figure 4.1: Energy bandgap and lattice constant for major III-V compounds

.

This problem is best appreciated by a graph of the energy gap versus lattice

constant for major III-V compounds, as shown in Figure 4.1. This is also known as a

phase diagram. For a possible range of ternary alloy systems, a solid line is generated

between the starting binary materials. In the case of a quaternary compound, the

boundary is laid out by four intersecting lines.

The ability to tailor the bandgap of III-V alloys to a desired wavelength makes

them particularly attractive for optoelectronic applications. The dark currents are

significantly reduced in compound detectors from their Ge and Si predecessors. In

addition, heterojunction structures can be easily used to enhance their high speed

operations. One such system that is of great interest is the InP/InGaAs

heterostructure which is sensitive to 1.55um wavelength. In this case the composition

of $In_{0.53}Ga_{0.47}As$ ternary compound, with the desired bandgap of 0.75 eV, is dictated

by the lattice matching constraint to the InP substrate.

Lattice mismatch, on the other hand, manifests itself in the form of dislocation

-induced  junction leakage and low quantum efficiency in optoelectronic devices.


## 4.3 GaN LED Process

1.  **wafer cleaning**

2. **Mg activation**

3. **photolithography for P –type mesa patterning**

4. **metal mask-Ti/Al/Ni Deposition**

5. **ICP Etching**

6. **n-type Electrode Formation( Ti/Al/Ni/Au)**

7.**Anneal**

8.**Transparant Conductive Layer Deposition**

9.**P-type Electrode Formation**

10.**Anneal**

## 4.4 Fabrication process of 1D-PC LED

The complete 1D PC LED process is ITO LED process and 1D PC structure coating process . Here we show the ITO LED process in detail , and the 1D PC structure coating process that include the preparation work and the optoelectronic characteristics measurement .

**Step A : ITO-LED process**
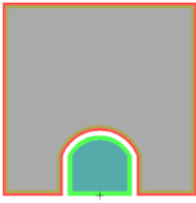
| Mask NO. | | Layout |
|---|---|---|
| Mask-1 | MESA |  |
| Mask-2 | ITO |  |
| Mask-3 | ITO |  |
| Mask-4 | ELECTRODES |  |
| Mask-5 | PASSIVATION |  |

Table 4.1 Masks

350um

320um

340um

50um

340 um

100um

90um

110um

80um

70um

105um

100um

33
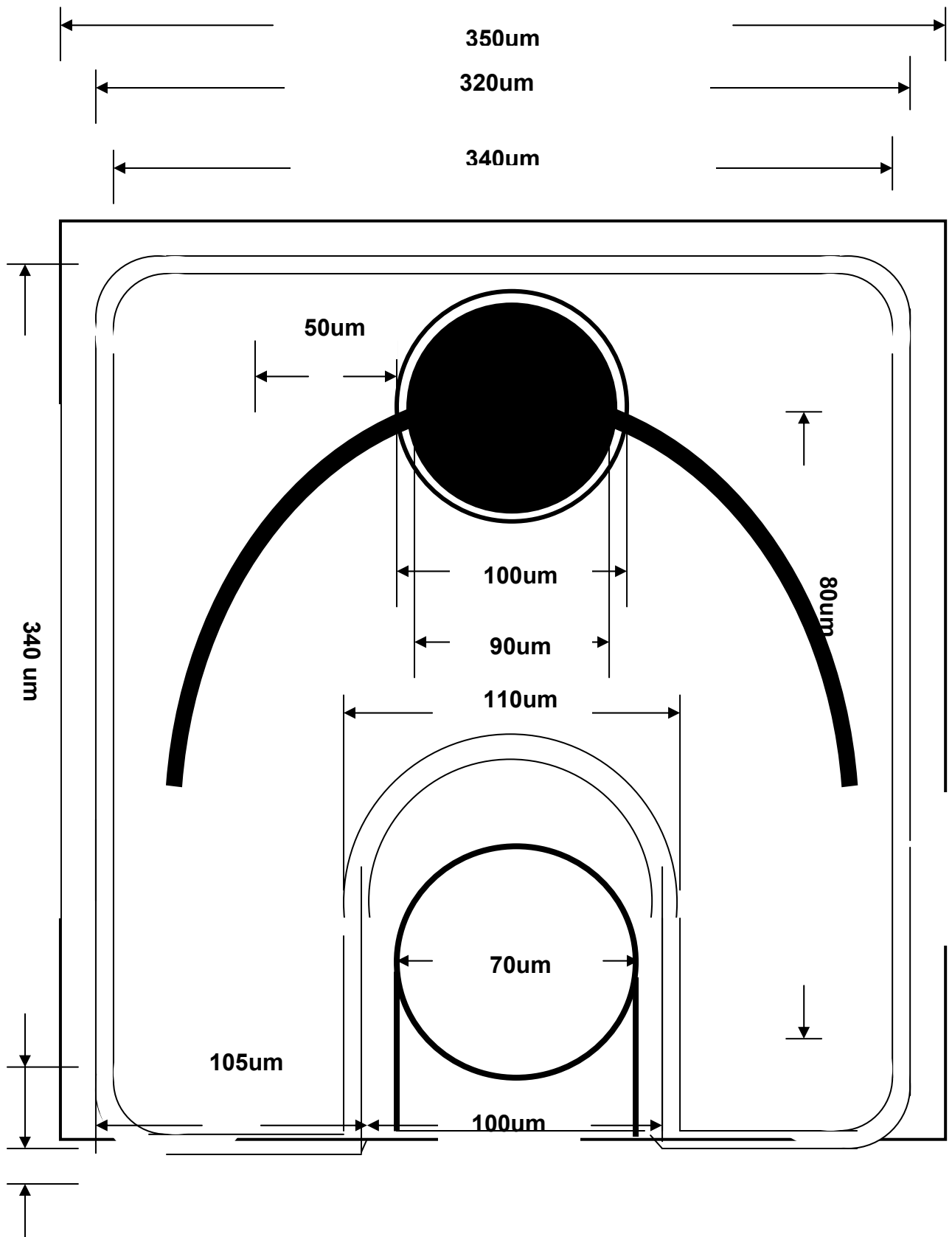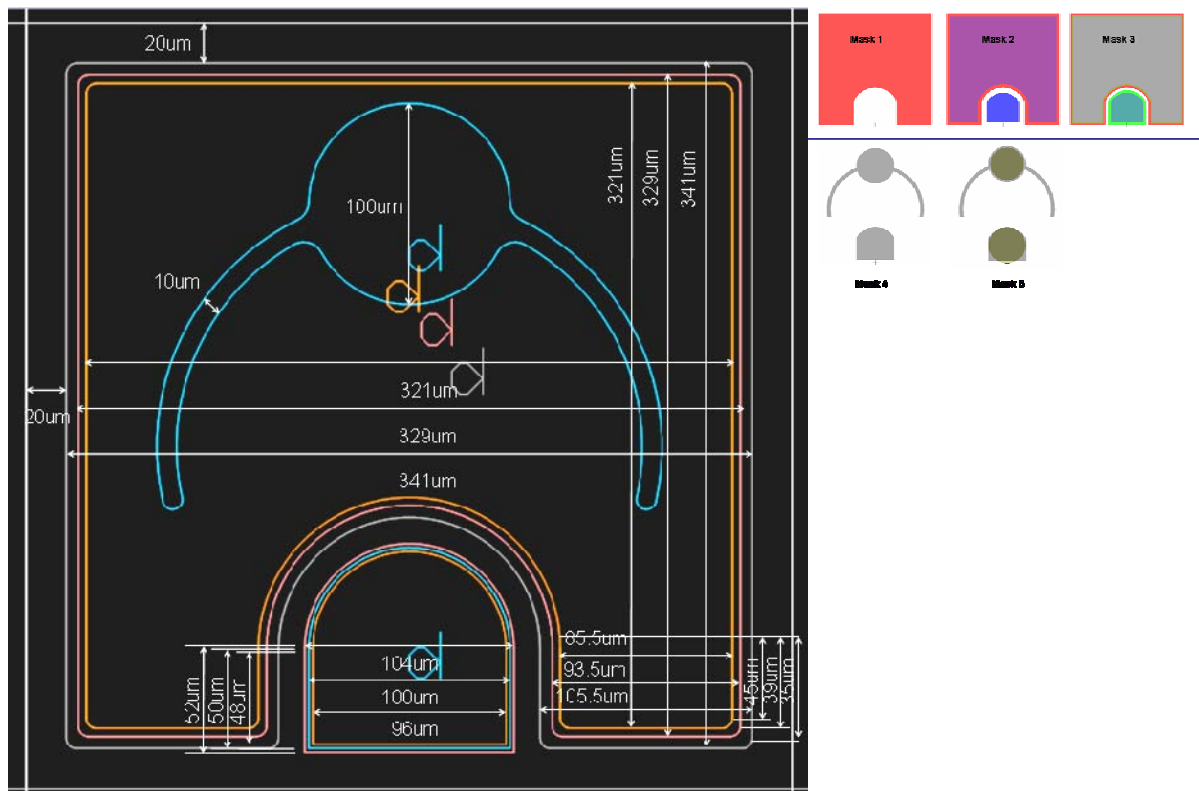
Figure4.2   Detailed mask design

**Procedures：The Processed wafers used for mesure the improvement after ID**

**PhC structure coating：**

Step01: Sapphire substrate lapping to 90±10 um

Step02: Sapphire surface polishing to mirror like surface

Step03: Wax cleaning using acetone, IPA and DI water

Step04: Electrical and optical test (chips on wafer) by wafer mapping probe before

1D-PhC structure coating

Step05: 1D-PhC structure coating by optical thin film coating machine

(OPTORUN Model 320)

Step6: Electrical and optical test (chips on wafer form) by wafer mapping probe after

1D-PhC structure coating

Step07: Wafer dicing and package in Lamp and TO CAN

Step08: Electrical and optical test of LED in package form

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## Table 4.2 1D PC LED Chip-process

| Step | Sub-process | Mask | Condition |
|---|---|---|---|
| Clean | 0.1 Surface Clean | | HCl, H2O, H2SO4 = 1: 1: 3 Acid solution 30min |
| | 0.2 Clean | | DI water, 4 cycles |
| Mesa | 1.1 Clean | | Acetone; IPA; DI water, 4 cycles |
| | 1.2 Baking | | 120C, 30min |
| | 1.3 SiO2 growth | | PECVD, 700nm |
| | 1.4 Clean | | DI water 4 cycle |
| | 1.5 Baking | | 120C, 30min |
| | 1.6 HMDS | | HMDS, 15min |
| | 1.7 PR coating | | PR 204, 4K/30sec 110C, 1min baking |
| | 1.8 Photolithography | Mask-1 | 8.3 sec |
| | 1.9 Development | | FHD-5, 1 min |
| | 2.0 Baking | | 120C, 30min |
| | 2.1 Discum | | 70C, 0.7 min |
| | 2.2 SiO2 Wet etching | | BOE, 4 min |
| | 2.3 PR strip | | Acetone, IPA, DI water 4 cycles |
| | 2.4 Baking | | 120C, 30min |
| | 2.5 Dry Etching | | ICP, 1 min |
| | 2.6 SiO2 strip | | BOE, > 10min |
| | TEST | | |
| ITO | 3.1 Clean | | Acetone; IPA; DI water, 4 cycles |
| | 3.2 Pre-treatment | | H2SO4: H2O = 1:3 <br> HCL: H2O = 1:1 <br> (10min, 5min) |
| | 3.3 ITO Deposition | | AST, Fuline Tech |
| | 3.4 TEST | | |

| | | | |
|---|---|---|---|
| **P-sprd** | **4.1 Clean** | | **Acetone, IPA, DI water 4 cycles** |
| | **4.2 Baking** | | **120C, 30min** |
| | **4.3 PR coating** | | **PR204, 4K/30sec 110C, 1min baking** |
| | **4.4 Photolithography** | **Mask-2** | **8.3 sec** |
| | **4.5 Development** | | **FHD-5, 1min** |
| | **4.6 Baking** | | **120C, 30min** |
| | **4.7 Discum** | | **70C, 0.7min** |
| | **4.8 Wet Etching** | | **HCL: HNO3 = 1:3 ;ITO (150nm/min)** |
| | **TEST** | | |
| | **4.9 Clean** | | **Acetone, IPA, DI water 4 cycles** |
| | **4.10 Baking** | | **120C, 30min** |
| | **4.11 PR coating** | | **PR204, 4K/30sec ,110C, 1min baking** |
| | **4.12 Photolithography** | **Mask-3** | **8.3 sec** |
| | **4.13 Development** | | **FHD-5, 1min** |
| | **4.14 Baking** | | **120C, 30min** |
| | **4.15 Discum** | | **70C, 0.7min** |
| | **4.16 Wet Etching** | | **HCL: HNO3 = 1:3  ITO  (150nm/min)** |
| | **I-V TEST** | | |
| **Pad** | **5.1 Clean** | | **Acetone, IPA, DI water 4 cycles** |
| | **5.2 Baking** | | **120C, 30min** |
| | **5.3 PR coating** | | **PR5214, 4K/30sec**<br>**90C, 1.5min baking**<br>**110C, 3min post baking** |
| | **5.4 Photolithography** | **Mask-4** | **2 sec, 11sec (FL)** |
| | **5.5 Development** | | **FHD-5, 1min** |
| | **5.6 Discum** | | **70C, 0.7min** |
| | **5.7 E-beam Evaporation** | | **Ni(250nm)/Au(250nm) 3A/sec: 3A/sec** |
| | **5.8 Lift Off** | | **Acetone, IPA, DI water 4 cycles** |
| | **I-V TEST** | | |

| | | | |
|---|---|---|---|
| **Passivation** | 6.1 Clean | | Acetone; IPA; DI water, 4 cycles |
| | 6.2 Baking | | 120C, 30min |
| | 6.3 SiO2 growth | | PECVD, 700nm |
| | 6.4 Clean | | DI water 4 cycle |
| | 6.5 Baking | | 120C, 30min |
| | 6.6 HMDS | | HMDS, 15min |
| | 6.7 PR coating | | PR204, 4K/30sec |
| | 6.8 Photolithography | Mask-5 | 8.3 sec |
| | 6.9 Development | | FHD-5, 1min |
| | 6.10 Baking | | 120C, 30min |
| | 6.11 Discum | | 70C, 0.7min |
| | 6.12 Wet etching | | BOE, 4min |
| | 6.13 Clean | | DI water 4 cycles |
| **PhC Structure** | 7.1 Clean | | Acetone; IPA; DI water, 4 cycles |
| | 7.2 Pre-treatment | | H2SO4: H2O = 1:3 HCL: H2O = 1:1 (10min, 5min) |
| | 7.3 ITO Deposition | | AST, Fuline Tech |
| | 7.4 TEST | | |

# 4.5 Simulation of PhC Structure

***Optimization of the 1D-PhC structure for Blue LED by theoretical modeling***

Software: *Essential Macleod*

**PhC ODR Structure-α**

| Layer No | Material | Thickness (nm) |
|:---:|:---:|:---:|
| 1 | $TiO_2$ (n=2.5) | 53.33 |
| 2 | $SiO_2$(n=1.42) | 211.89 |
| 3 | $TiO_2$ | 56.16 |
| 4 | $SiO_2$ | 104.22 |
| 5 | $TiO_2$ | 44.47 |
| 6 | $SiO_2$ | 100.31 |
| 7 | $TiO_2$ | 52.1 |
| 8 | $SiO_2$ | 99.53 |
| 9 | $TiO_2$ | 49.18 |
| 10 | $SiO_2$ | 115.55 |
| 11 | $TiO_2$ | 61.31 |
| 12 | $SiO_2$ | 54.9 |
| 13 | $TiO_2$ | 0 |
| 14 | $SiO_2$ | 109.62 |
| 15 | $TiO_2$ | 33.95 |

$TiO_2$ (n=2.5) , $SiO_2$(n=1.42) @

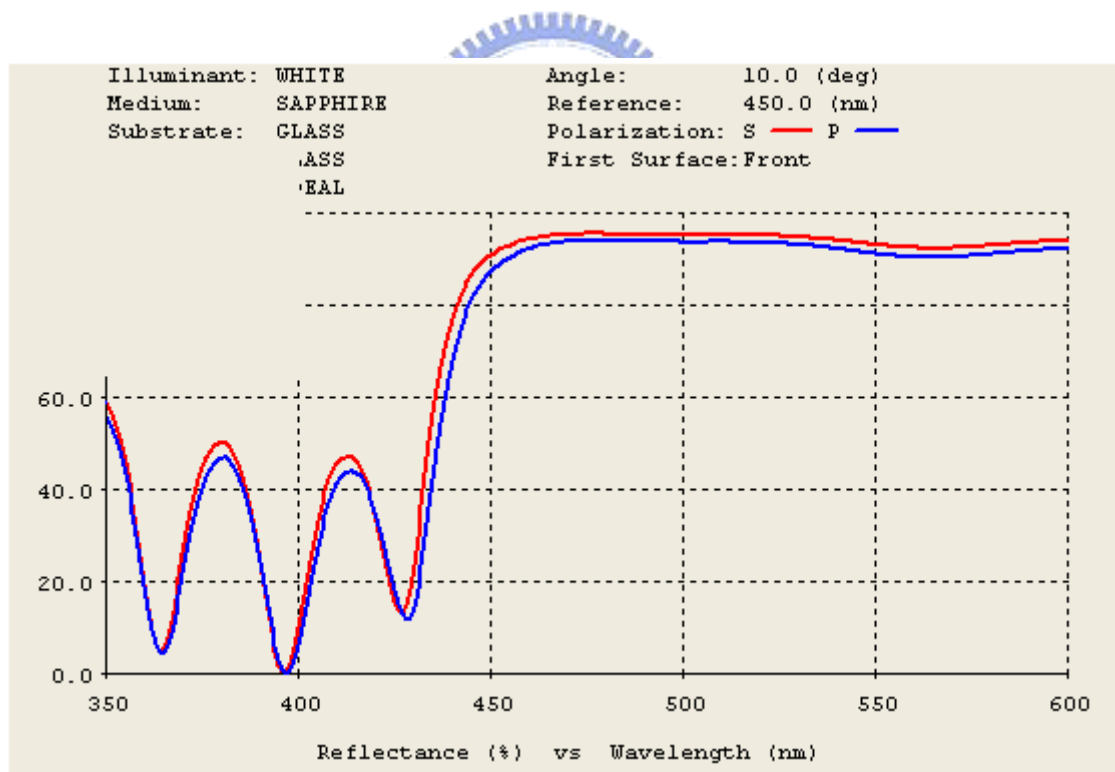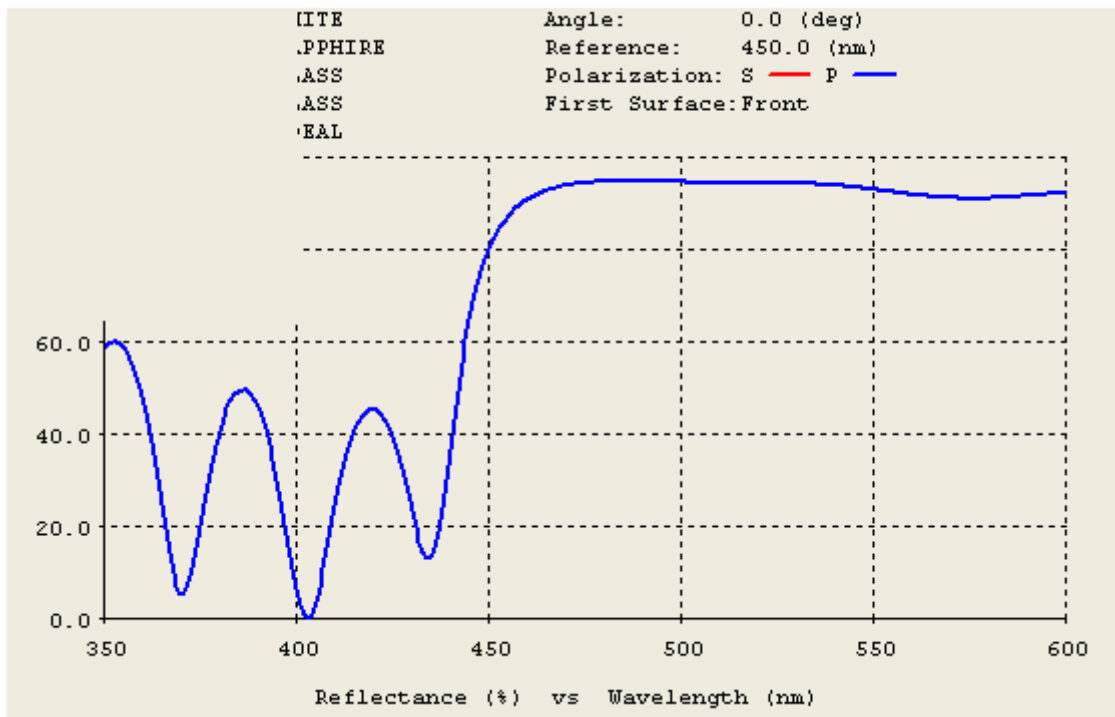Table 4.3 Simulation: 1D-PhC structure of blue LED:

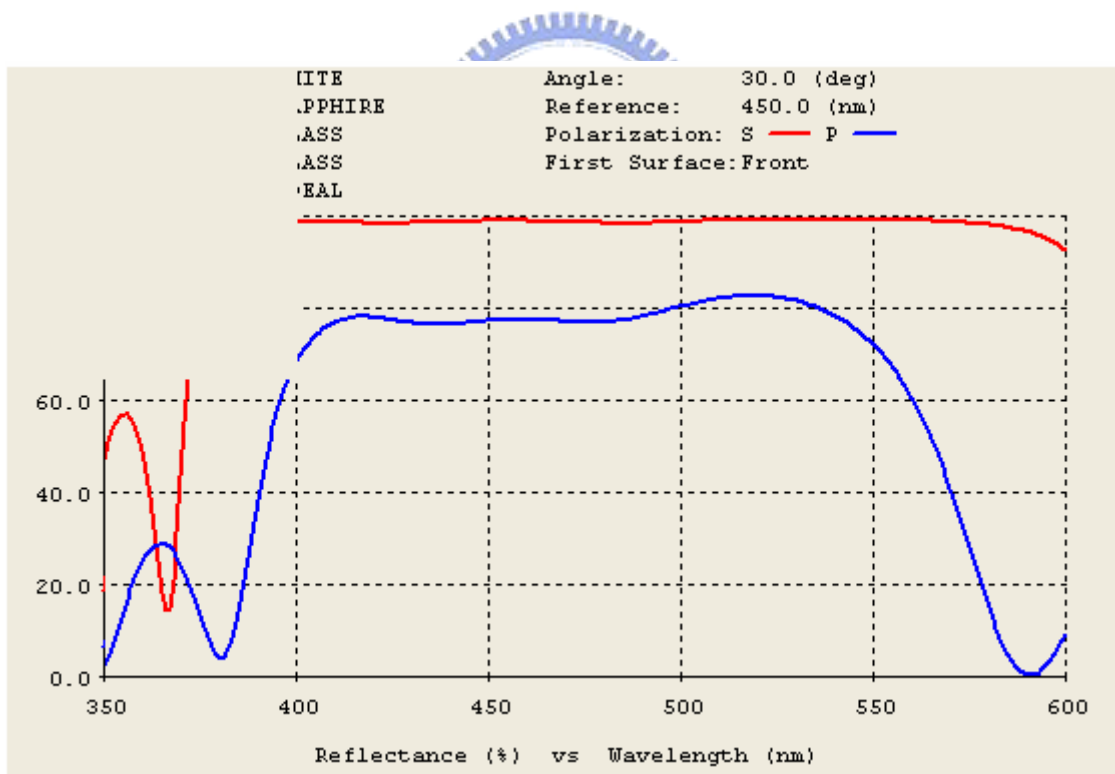## _Optimization of the 1D-PhC structure for Blue LED by theoretical modeling_

Software: _Essential Macleod_

## PhC ODR Structure-β

| Layer No | Material | Thickness (nm) |
|----------|----------|----------------|
| 1 | $Ta_2O_5$ (n=2.1~2.23) | 67.43 |
| 2 | $SiO_2$ (n=1.42) | 169.92 |
| 3 | $Ta_2O_5$ | 75.69 |
| 4 | $SiO_2$ | 90.09 |
| 5 | $Ta_2O_5$ | 64.59 |
| 6 | $SiO_2$ | 83.65 |
| 7 | $Ta_2O_5$ | 67.81 |
| 8 | $SiO_2$ | 83.56 |
| 9 | $Ta_2O_5$ | 65.96 |
| 10 | $SiO_2$ | 86.03 |
| 11 | $Ta_2O_5$ | 66.47 |
| 12 | $SiO_2$ | 84.56 |
| 13 | $Ta_2O_5$ | 26.89 |
| 14 | $SiO_2$ | 121.52 |
| 15 | $Ta_2O_5$ | 60.48 |

Table 4.4.Simulation: 1D-PhC structure of LED

40

Illuminant: WHITE          Angle:          35.0 (deg)
Medium:     SAPPHIRE       Reference:      450.0 (nm)
Substrate:  GLASS          Polarization: S —— P ——
Exit:       GLASS          First Surface:Front
Detector:   IDEAL

Reflectance (%)  vs  Wavelength (nm)



Illuminant: WHITE          Angle:          40.0 (deg)
Medium:     SAPPHIRE       Reference:      450.0 (nm)
Substrate:  GLASS          Polarization: S —— P ——
            .ASS           First Surface:Front
            ·EAL

Reflectance (%)  vs  Wavelength (nm)

Illuminant: WHITE  Angle: 45.0 (deg)
Medium: SAPPHIRE  Reference: 450.0 (nm)
Substrate: GLASS  Polarization: S — P —
ASS  First Surface: Front
EAL

Reflectance (%)  vs  Wavelength (nm)



ITE  Angle: 50.0 (deg)
PPHIRE  Reference: 450.0 (nm)
ASS  Polarization: S — P —
ASS  First Surface: Front
EAL

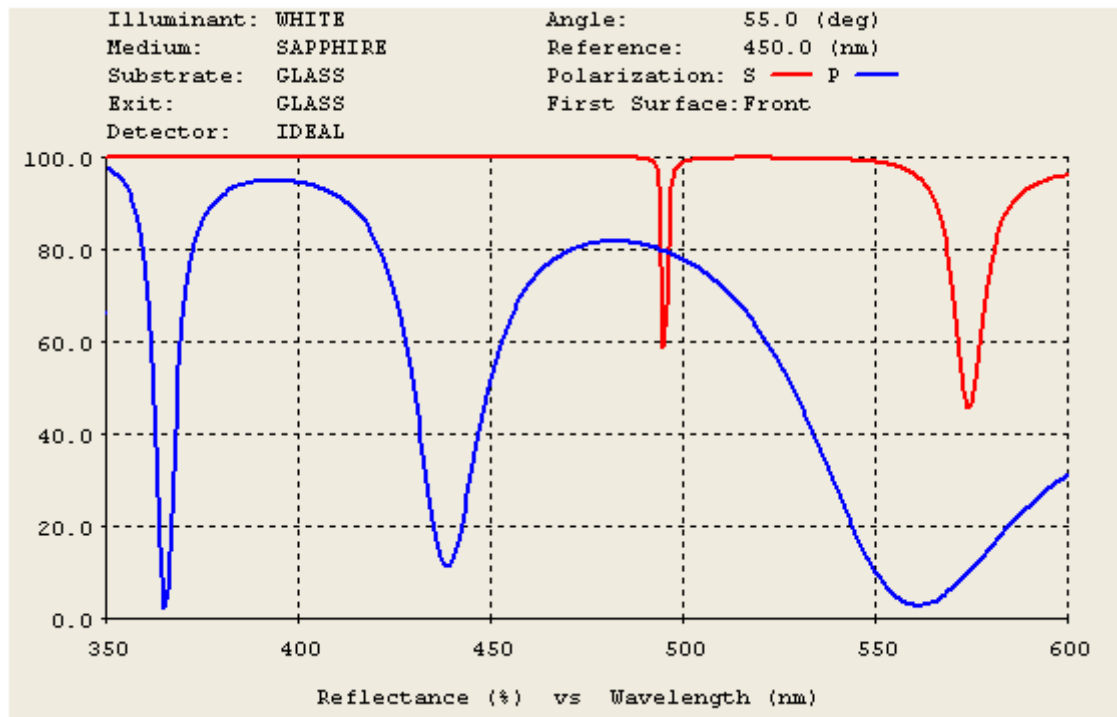Reflectance (%)  vs  Wavelength (nm)

43

Figure.4.3 .Simulation: reflection spectrum for blue LED

# Chapter 5.
# Experimental Results and Discussion

In this chapter , we show the experimental results ( measurement data ) of

1. Light emission mapping result before and after dielectric layers of photonic crystal

   structure coating on the sapphire-face ( backside) : Then we see the big

   improvement in light output that almost doubles the LOP of the processed half-cut

   wafer before PC-ODR layers coating .

2. Axial emission measurement in lamp-form : Here we choose the lamp-package of

   narrower view angle , then we can see the strong emission enhancement at axial

   direction clearly if the LED chips have PC-ODR films.

3. Measurement of NiAu ,ITO and PC LEDs in lamp-form : Comparing the light output

   of ITO LED to NiAu LED , we can see the bigger light extraction of ITO LED due to

   the higher ITO transparency . Comparing PC LED to ITO LED in lamp form ( lamp

   package has the silver paste and the die-cup to be the reflector) , PC LED has the

   higher photometric intensity ( lm , lm/watt) due to the red-shift ,even though their

   radiometric intensity is very closed .

4. Radiation pattern measurement of NiAu , ITO and PC LEDs packaged in TO can :

   We put the bare LED chip on TO-can without any material coating on this chip in

   order to obtain the information of the emission intension distribution in all emitting

angle.  We find the very big jump in light extraction ability between NiAu and ITO

LED ; between ITO and PC LED ,respectively .

## 5.1. Light Emission Mapping Result of Half-cut wafer

The purpose of  this light emission mapping is to find the increasing percentage

after  LED chips added Photonic Crystal reflector , and show the results of different

photonic crystal structure of  two kinds of material composition , PhC-structure-$\alpha$ :

$TiO_2$/ $SiO_2$ and PhC-structure-$\beta$：$Ta_2O_5$/ $SiO_2$   .   Both of the two PhC structures are

7 pairs + 1 layer .( 15 layers ) .

❖ 01 - Samples :    #01-301C, #02-301A,#03-301D,#4-2822A .

(InGaN-based LED before and after  photonic crystal ODR layers coating)

❖ 02 - Test equipment :   LED mapper *MP - WeiMin ,model  LED 628*

❖ 03 - Test result :

| Sample | #01 - 301C | #02 - 301A | #03 - 301D | #04 – 2822A |
|---|---|---|---|---|
| PhC-structure | PhC-structure-$\alpha$ | PhC-structure-$\beta$ | | |
| Emission Improvement | 104% | 95% | 110% | 96.5% |
| Sample Amount | 3219 | 2415 | 3829 | 3164 |

Measurement condition : $I_F$ = 20mA

PhC-structure-α and PhC-structure-β are the designed structures mentioned in section 4-5 .

**Table 5-1 Light emission mapping result of half-cut sample wafers before and after PC-ODR layers coating**

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◆ Axial Power Improvement calculation using mapped data .,

$$110\% = \frac{[\Sigma_{j=1to3829}(L_{ODR-j} \times \#_{ODR-j})] - [\Sigma_{k=1to3829}(L_{No\ ODR-k} \times \#_{No\ ODR-k})]}{[\Sigma_{k=1to3829}(L_{No\ ODR-k} \times \#_{No\ ODR-k})]}$$

❖ Concluding remarks :

■ 1./. Using the two PhC ODR- structures, **α**, **β**, the LOP is doubled compared to the

sample before PC layers coated .

■ 2. /. The causes of the spreading of LOP ( before & after PC-film Coating) are :

2.a./. The LOP increasing factor should be constant , η , at a fixed angle .

The sample before PC-layers coated , the LOP spreading is $\Delta$ LOP $_{bf.PhC-ODR}$ .

Then after coating PC- layers , the LOP range should be spreading to a

bigger range η x $\Delta$ LOP $_{bf.PhC-ODR}$ .( where η > 1) .

2.b./. A little bit non-uniformity of the PC-layers also resulted in spreading of LOP.

( See the measurement data below)

❖ **04 -Light Output Maps and Statistics of 4 samples with and without PC-layers:**
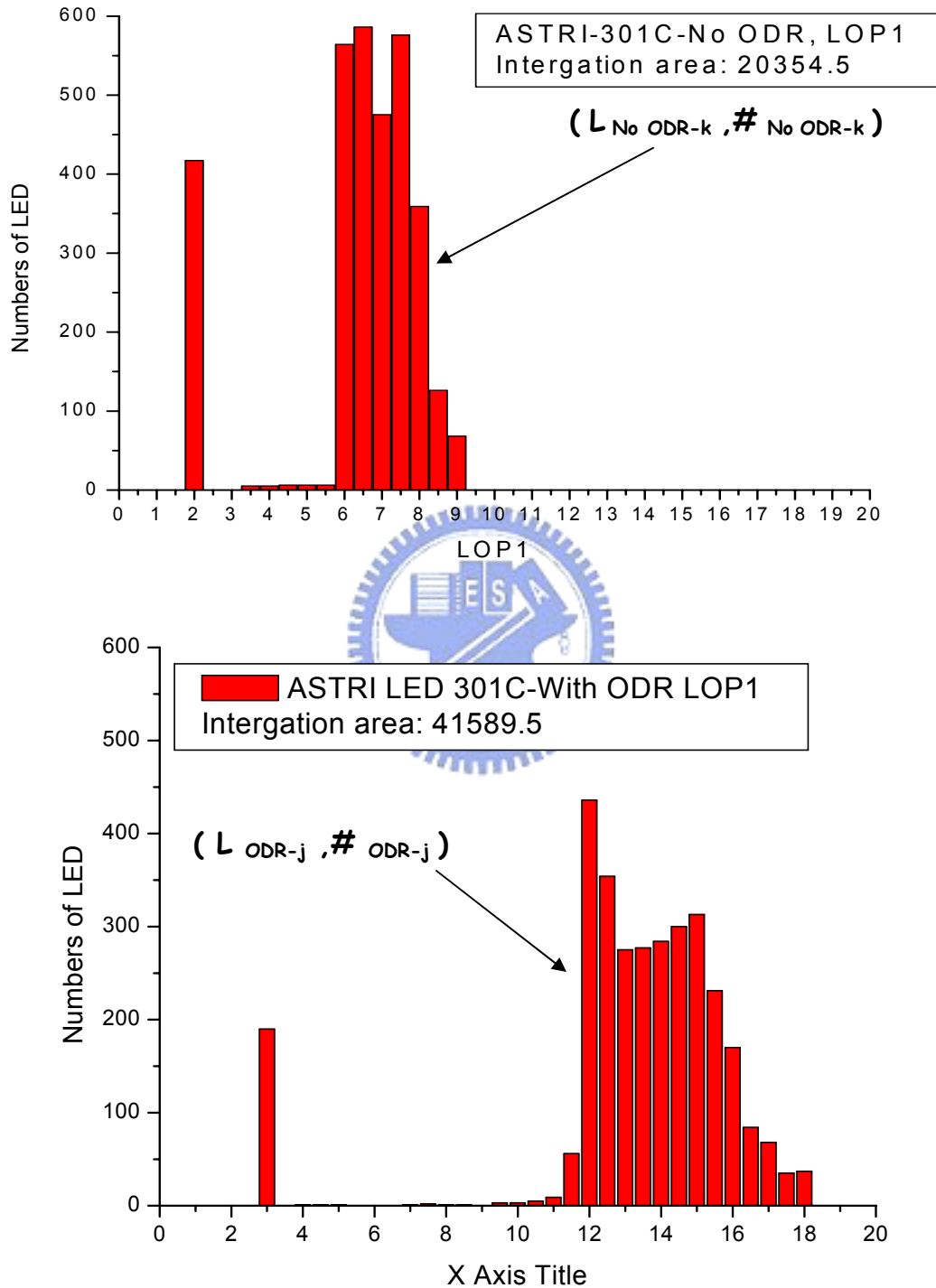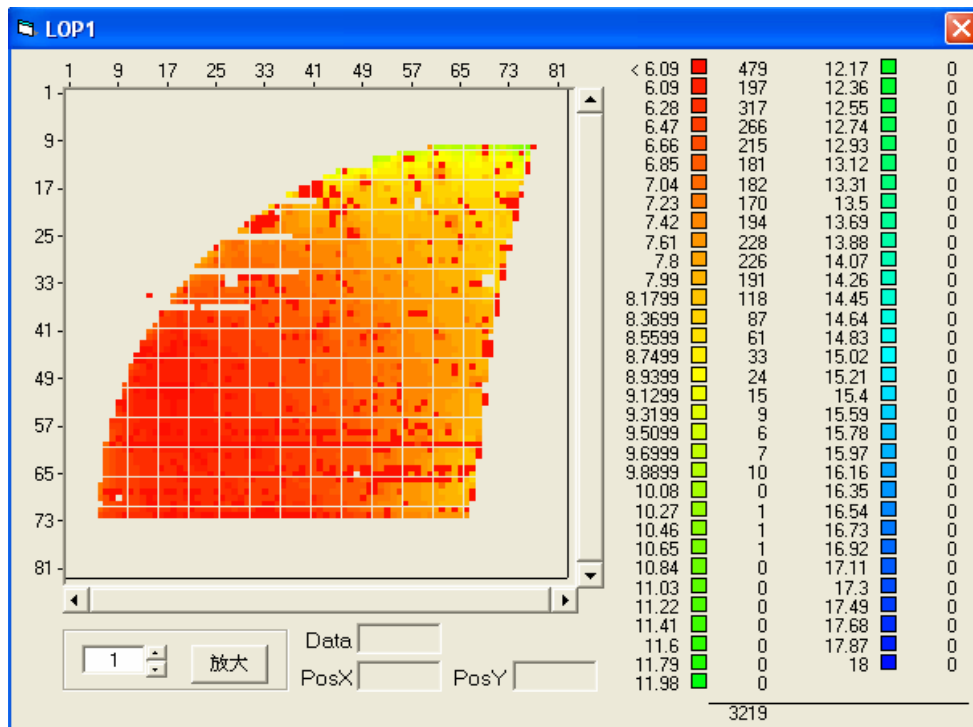
**#01 - 301C / PhC-structure –α**



**Fig.5-1 LOP Distribution of #01-301C with and without PC ODR Structure**

３０１Ｃ － Ｎ ｏ  Ｐ ｈ Ｃ - ｓ ｔ ｒ ｕ ｃ ｔ ｕ ｒ ｅ



３０１Ｃ － Ｐ ｈ Ｃ - ｓ ｔ ｒ ｕ ｃ ｔ ｕ ｒ ｅ

**Fig.5-2  Raw data of LOP Distribution of #01-301C with and without PC ODR structure**
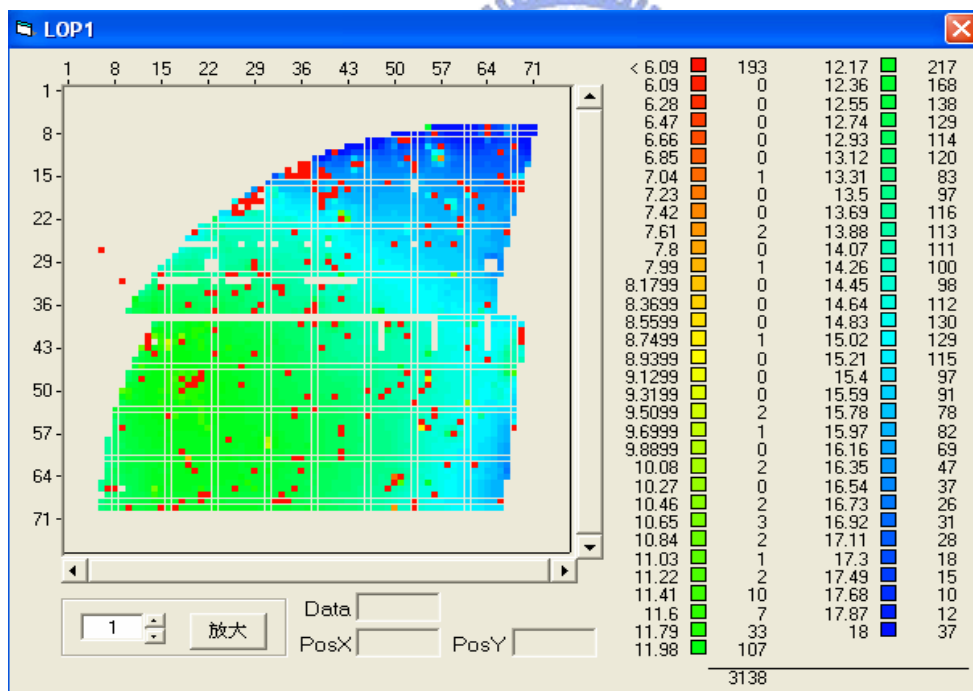
**Fig.5-3  LOP Distribution of #02-301A with and without PC ODR structure**

50

301A – No PhC-structure



 301A –PhC –structure

**Fig.5-4 Raw data of LOP Distribution of #02-301A with and without PC ODR structure**

#03 - 301D / PhC-structure -β

**Fig.5-5  LOP Distribution of #03-301D with and without PC ODR layers**

301D – No PhC-structure
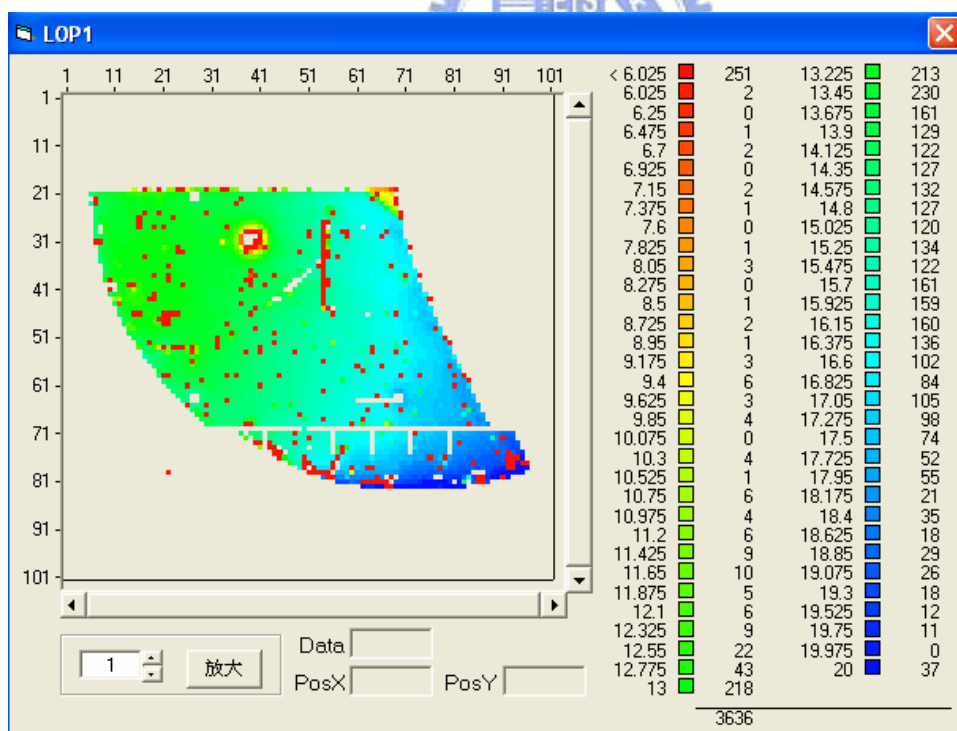


3 0 1 D – P h C - s t r u c t u r e

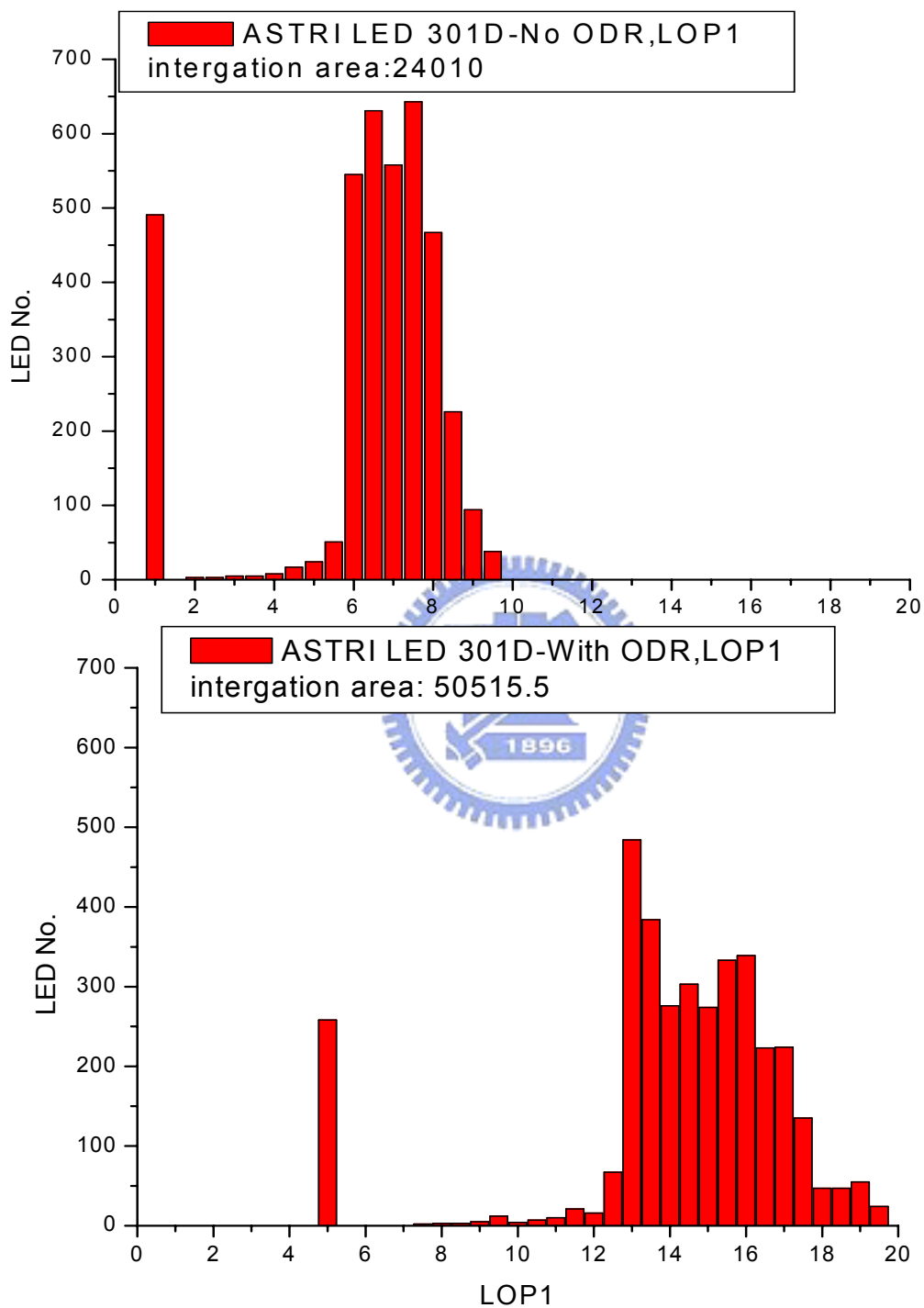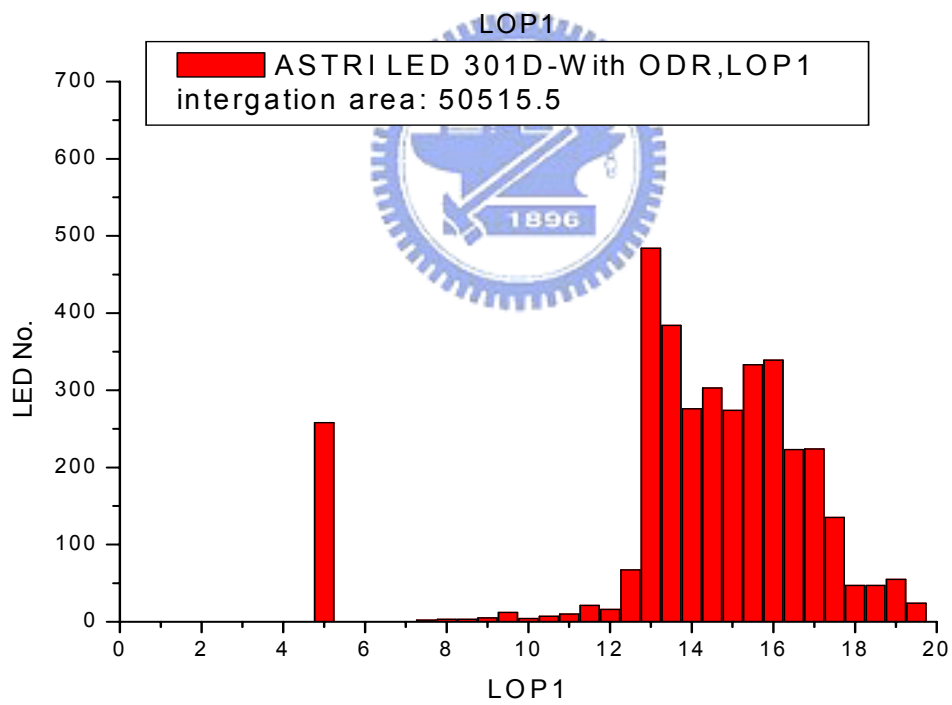**Fig.5-6  Raw data of LOP Distribution of #03-301D with and without PC ODR structure**

## #04 - 2882A / PhC-structure -β



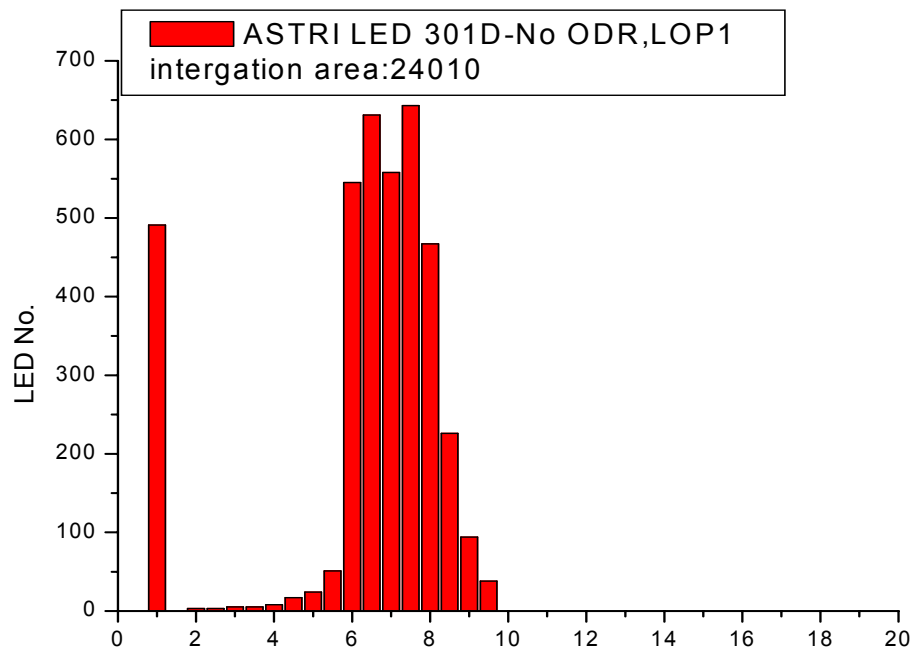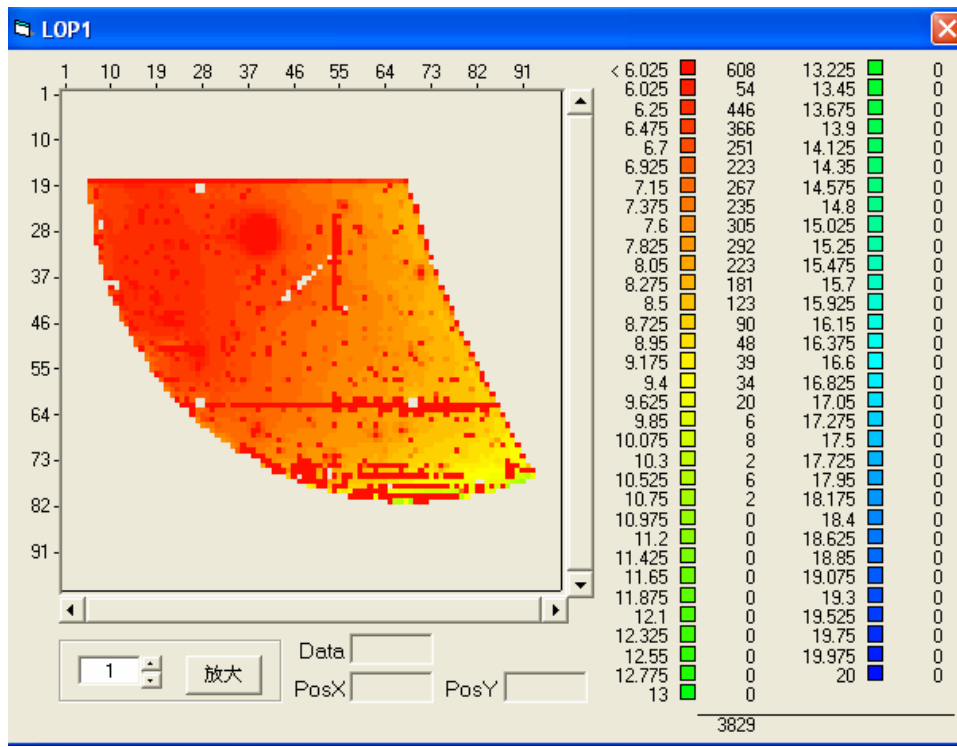**Fig.5-7  LOP Distribution of #04-2882A with and without PC ODR structure**

2882A – No PhC structure



2882A –PhC structure

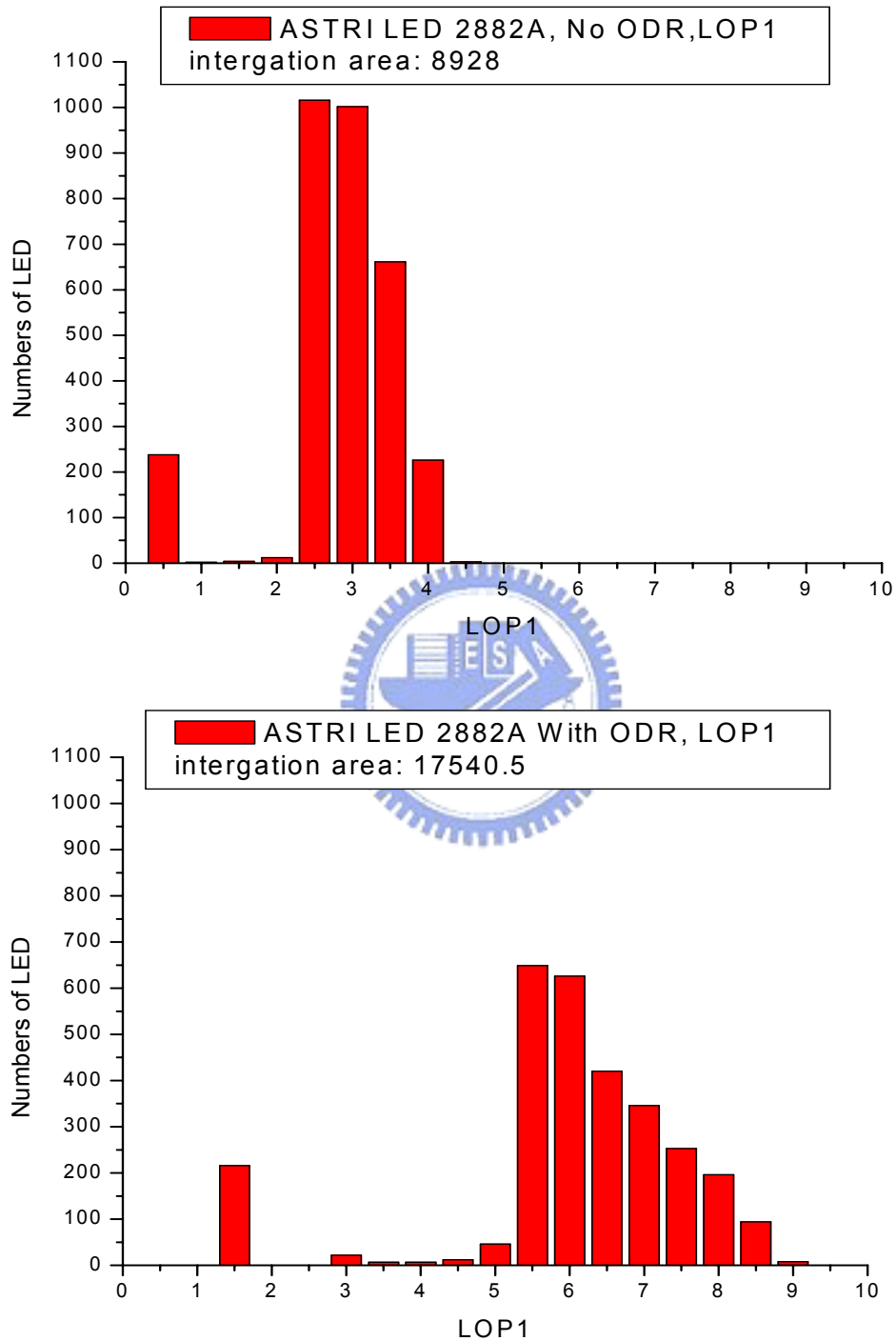**Fig.5-8  Raw dataLOP Distribution of #04-2882A with and without PC ODR structure**

## 5.2. Axial Emission Measurement in Lamp-form

Comparing the axial emission intensity of PC LED to the ITO LED, under 1. / same lamp-package , 2./ these 10 x2 LED chips are produced from the same epitaxial wafer, the average of PC LED axial Iv increases by 92.1%.

Why are we interested in the emission enhancement at axial direction ? The reasons are : The reflection loss of dielectric material ( PC layers) should be lower than metal reflector . It is because the reflection mechanism of dielectric material is the dipole vibration, it will not loss energy ; on the other hand, the incident light has to share some part of energy to the mobile charge near to the surface when the light reflection happens at the metal reflector . Besides., the ID PC reflector can also be applied to the AlInGaP LEDs by Thin –film LED technology . The epitaxial layer thickness of AlInGaP LED is around 10 um , and the ID PC reflector is located between the epitaxial layers and substrate of Thin-Film LED .That is, 1D PC reflector is positioned at the depth of around 10 um . It is very shallow reflector . The axial light emission enhancement is very strong and is very useful to the narrow view angle LED device .

|  |  | AVG | #01 | #02 | #03 | #04 | #05 | #06 | #07 | #08 | #09 | #10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PC LED Lamp | Iv(mcd) | 390.66 | 463.8 | 451.3 | 363.2 | 445.2 | 335.1 | 382.8 | 442.9 | 354 | 314.5 | 353.5 |
|  | VF(volt) | 3.136 | 3.1 | 3.12 | 3.14 | 3.16 | 3.14 | 3.1 | 3.09 | 3.15 | 3.22 | 3.14 |
| ITO LED Lamp | Iv(mcd) | 203.39 | 238.2 | 174.1 | 161.7 | 231 | 234.9 | 206.4 | 158.5 | 230 | 168.7 | 230.4 |
|  | VF(volt) | 3.189 | 3.16 | 3.19 | 3.19 | 3.18 | 3.17 | 3.22 | 3.18 | 3.23 | 3.19 | 3.18 |

| Axial Iv Increase % | 92.1% | LED Lamp $\theta_{1/2}$=15$^o$ , @ $I_F$ = 20 mA |
|---|---|---|

Test equipment: 遠方LED620

1.) LED chips of these PC LED and ITO LED lamps come from the same epitaxial wafer

2.) The PC LED is ITO LED with 1D Photonic Crystal reflector at sapphire face( backside) .

**Table 5-2  Axial emission intensity measurement of PC LED Lamps and ITO LED Lamps .**
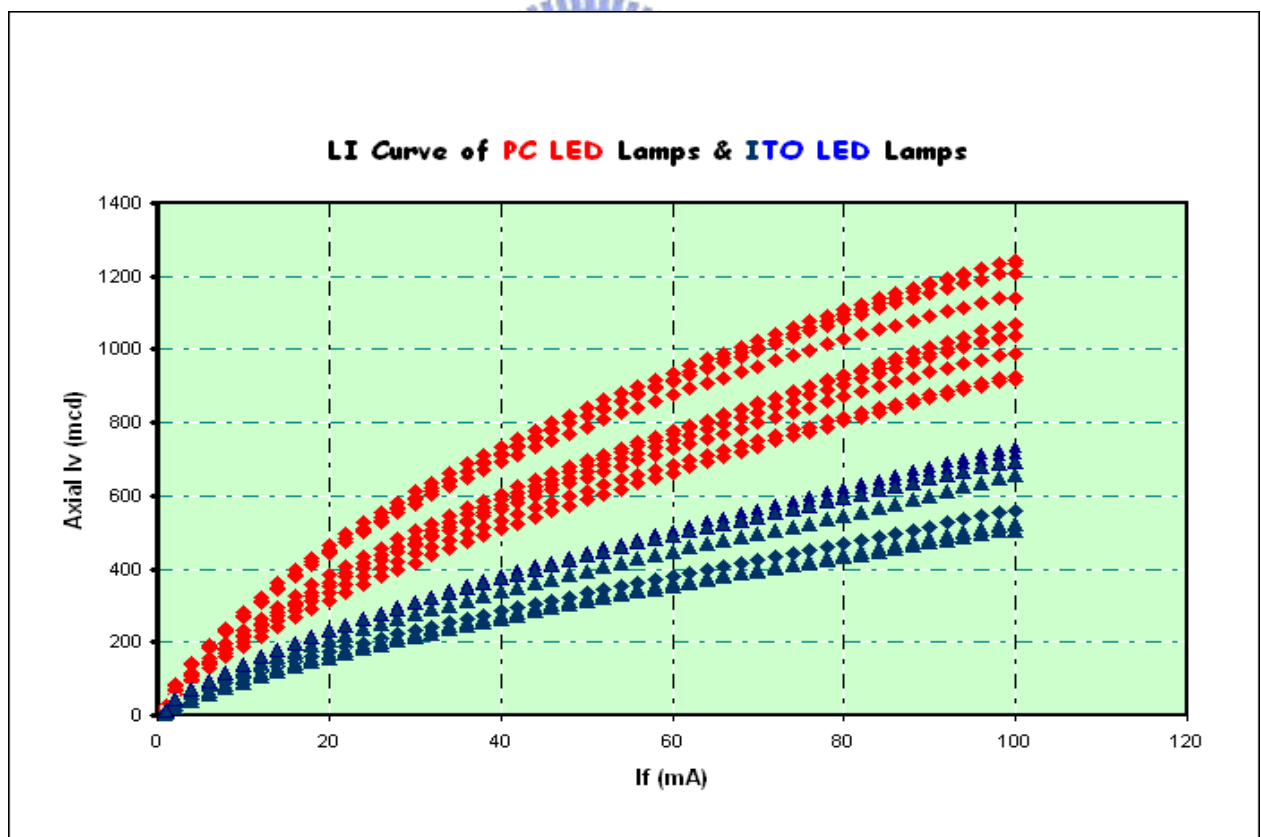


**Fig.5-9  LI Curve of PC LED Lamps and ITO LED Lamps**

According to the results above, the processed wafer after PC-films coating will have around 90 % axial Iv improvement . We know the major cost of LED chips is the epitaxial wafer . So, we can process  the epitaxial wafers of regular grade with axial emission layer of photonic crystal structure,  And obtain the higher light output especially from the lamp of narrower view angle ,

## 5.3. Radiometric and photometric Measurement of NiAu ,ITO and PC LED in Lamp-form

LED chips of  these NiAu LED lamps,ITO LED lamps and PC LED lamps , 3 x3ea, are produced from the same epitaxial wafer.    According the optoelectronic characteristics measurement results shown below,  we find :

a.) Radiation power ( radiometric ,mW,  and photometric ,lm)of   ITO LED and PC LED  are  much  higher  than  NiAu  LED .  The  TCL(  Transparent  Conductive Layer) of NIAu LED is NiAu layer ; The TCL of ITO LED and PC LED is ITO layer. The transparency of ITO layer (~90%) is higher than NiAu layer( ~60%). So the result of NiAu LED`s lower radiation extraction is reasonable .

b.)  The radiometric power of ITO LED and PC LED are very close, 11.8 mW and 11.63 mW, respectively . However, the photometric power of PC LED , 526.3 mlm, is higher than ITO LED, 468.7mlm.   According to this measurement

table , we find the possible explanation ,that is , after PC-films Coating, due to the red-shift effect ( ~3nm) , the emission flux ( photometric ) will improve 12.3% ,

**HighLink sample wafer (HL 146566)**  $\text{lamp}\theta_{1/2}=7.5^{\circ}$

| @20mA | | Vf | mW | mlm | $\lambda_P$(nm) | $\lambda_D$(nm) | WH(nm) | lm/W |
|---|---|---|---|---|---|---|---|---|
| **Ni/Au LED** | 1 | 3.21 | 6.9 | 237 | 448 | 455 | 21 | 3.69 |
| | 2 | 3.19 | 6.2 | 226 | 449 | 455 | 21 | 3.54 |
| | 3 | 3.20 | 7.0 | 252 | 449 | 455 | 20 | 3.94 |
| | | **3.20** | **6.73** | **238.3** | **448.5** | **455.0** | **20.6** | **3.723** |
| | | | | | | | | |
| **ITO LED** | **1** | 3.19 | 11.6 | 474 | 452 | 458 | 22 | 7.43 |
| | **2** | 3.21 | 12.2 | 461 | 451 | 456 | 22 | 7.18 |
| | **3** | 3.20 | 11.6 | 471 | 452 | 458 | 22 | 7.36 |
| | | **3.20** | **11.80** | **468.7** | **451.5** | **457.3** | **22.0** | **7.323** |
| | | | | | | | | |
| **PC (+ITO) LED** | 1 | 3.18 | 12.3 | 480 | 451 | 457 | 20 | 7.55 |
| | 2 | 3.15 | 11.0 | 571 | 458 | 463 | 23 | 9.06 |
| | 3 | 3.16 | 11.6 | 528 | 455 | 460 | 22 | 8.35 |
| | | **3.16** | **11.63** | **526.3** | **454.7** | **460.1** | **21.6** | **8.320** |

**Table 5-3  Radiometric and photometric measurement of NiAu LED lamps, ITO LED lamps and PC LED lamps.**

## 5.4. Radiation Pattern of NiAu ,ITO and PC LEDs packaged in TO Can

In order to have the real emission pattern of LED dice , TO-can is a very useful tool . We put the bare LED die on TO-can without any material coating on this die. In this way , the measured radiation pattern will not be disturbed . Then we can obtain the information of the emission intension distribution in all emitting angle. We find the very big jump in light extraction ability between NiAu and ITO LED ; between ITO and PC LED ,respectively .
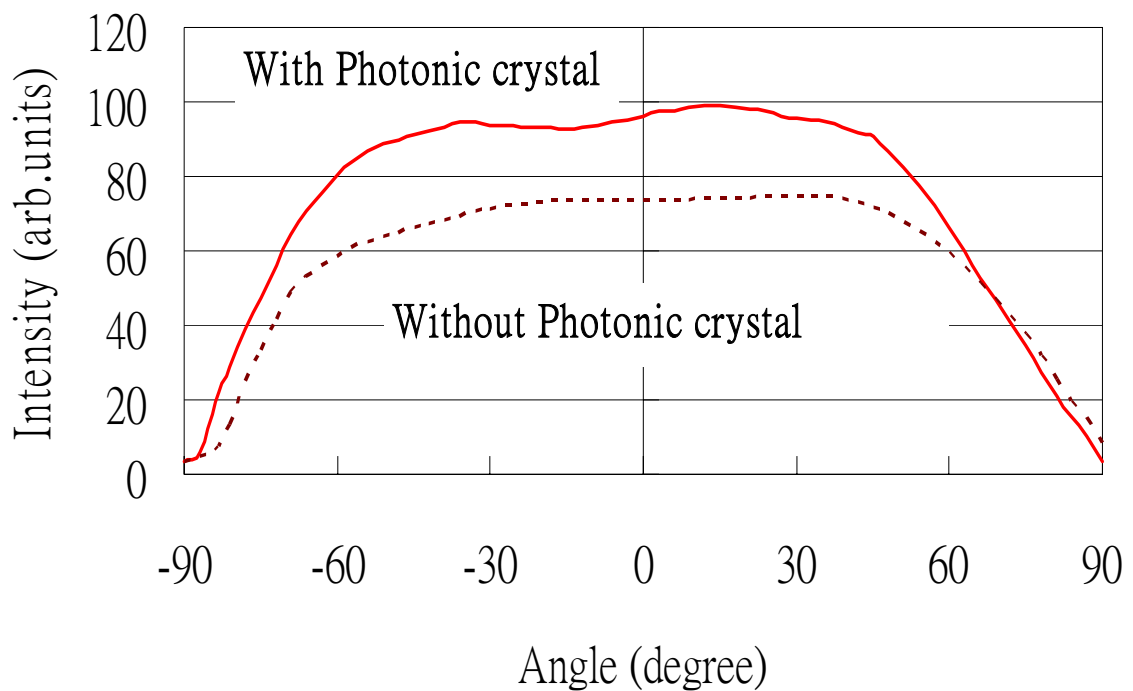


**Fig.5-10.Radiation pattern of Blue LED with and without photonic crystal layers ( packaged in TO46)**
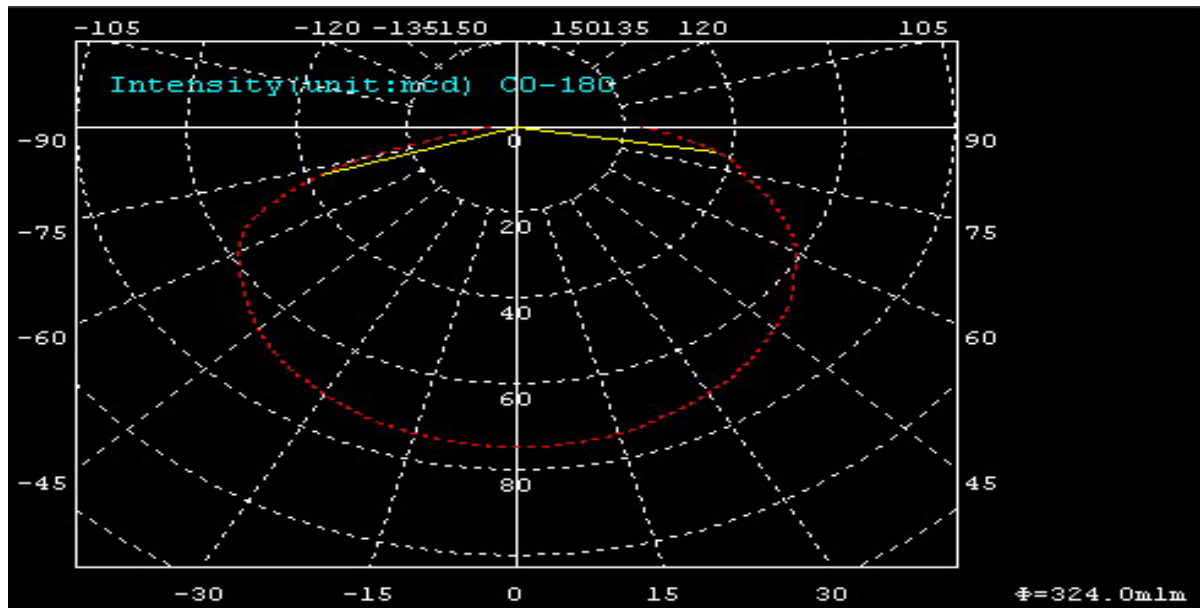
**Fig.5-11. Raw data of radiation pattern of blue LED without photonic crystal**
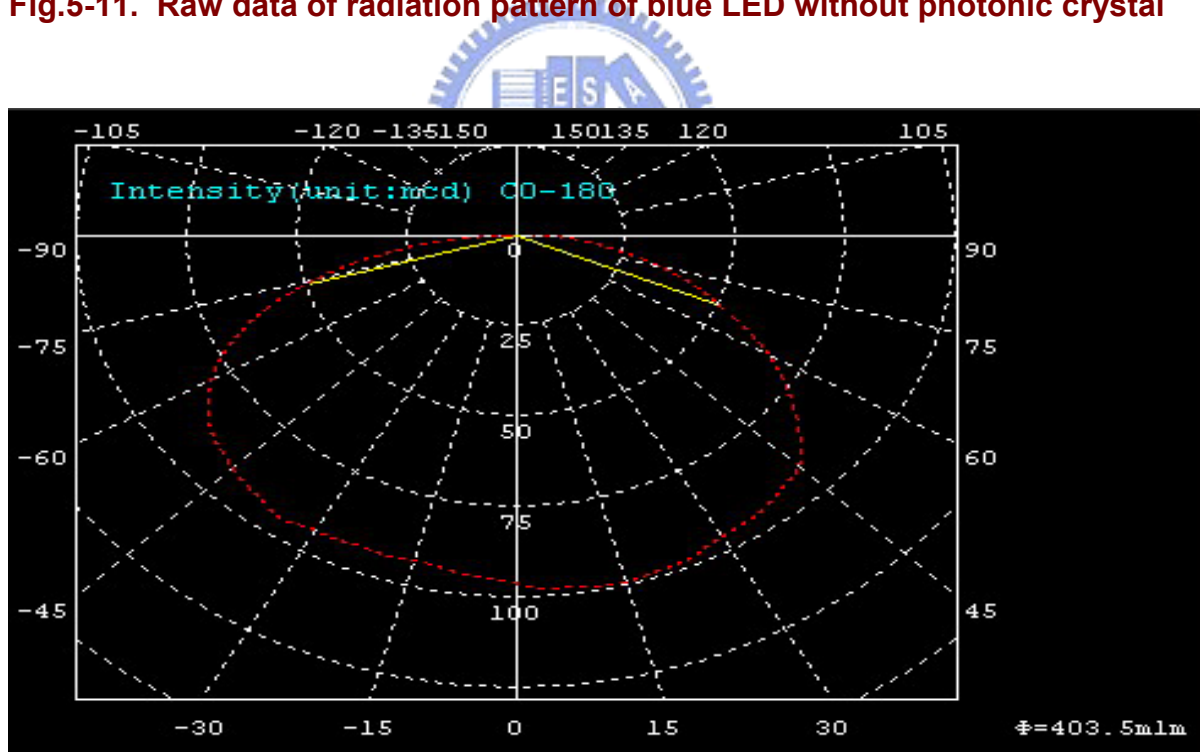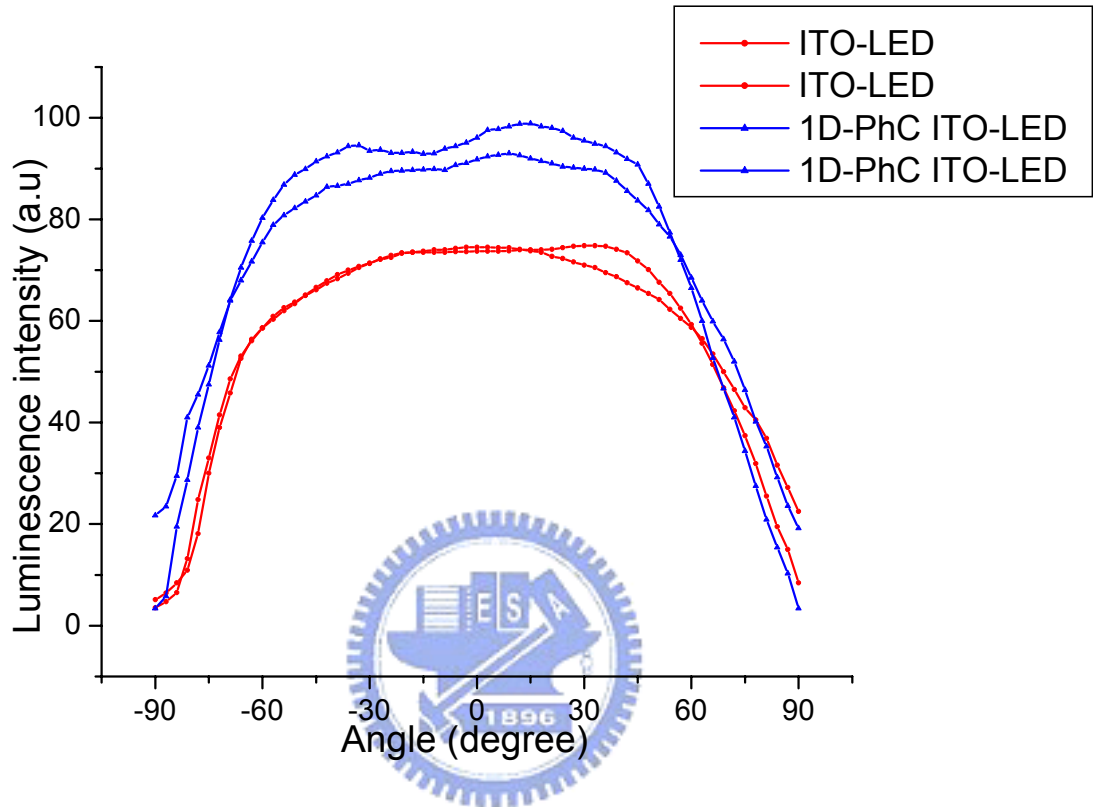


**Fig.5-12. Raw data of  radiation pattern of blue LED with photonic crystal**

In order to make sure the result of Fig.5-10 , we measured other 2 x 2 LED dice

packaged in TO46-can . All these dice are processed from the same epitaxial wafer .

And the result below shows the repeatability of the strong light extraction enhancement of PC LED.



**Fig.5-13. Radiation pattern of LED with and without photonic crystal**
**( PC LED and ITO LED packaged in TO46 -can )**

According to the measurement results shown above , we find the big luminous intensity at almost all emission angle can be achieved from PC LED than that of ITO LED. The PC LED has photonic crystal reflector to enhance the light extraction efficiency is the very reasonable explanation .

Following the content of the ``section 5.3. Radiometric and Photometric Measurement of NiAu ,ITO and PC LEDs in Lamp-form`` , we are interested in the radiation pattern difference between ITO LED and NiAu LED .
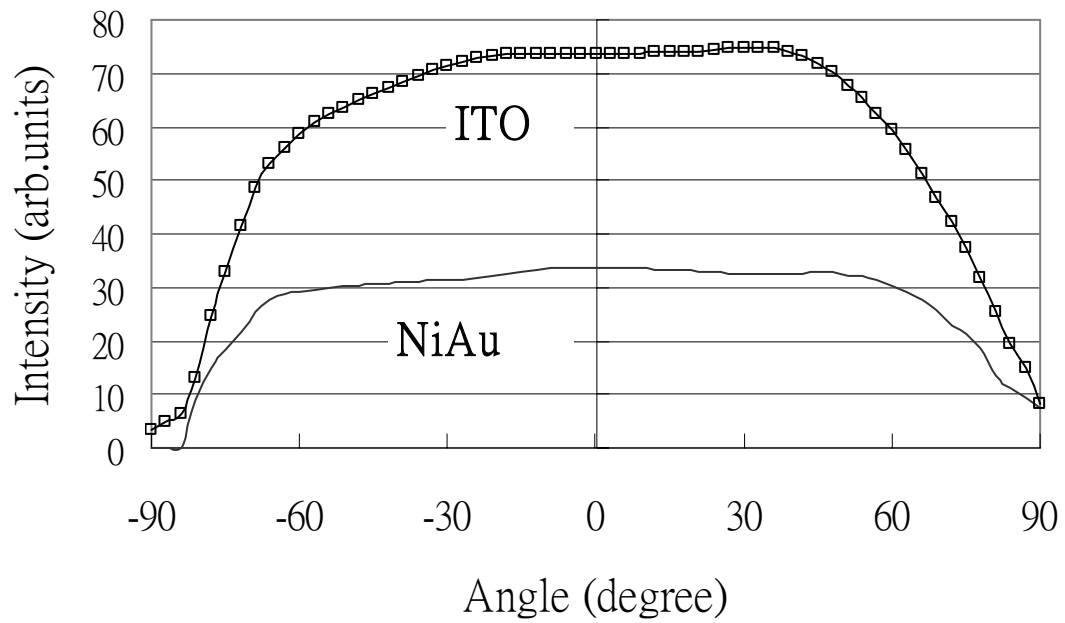
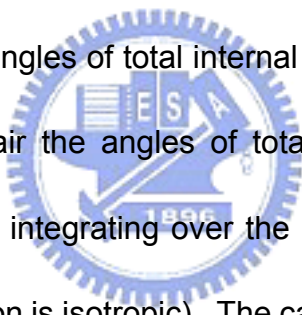**Fig.5-14. Radiation pattern of ITO LED and NiAu LED.**

By this figure 5-14 , we also find the larger luminous intensity can be achieved

from ITO LED than that of NiAu LED at different emission angle.

# Chapter 6. Conclusions

6.1 Conclusions

In light emitting diodes, the spontaneous emission (SE) of photons in directions which are not extracted is highly detrimental to the efficiency of the LED. For general lighting applications the conversion efficiency from electrical energy to useful light energy is an important factor determining whether LEDs may be used to replace conventional lighting technologies.

A straightforward estimate of the amount of light which can be extracted can be obtained by calculating the angles of total internal reflection for light going from GaN (refractive index ~2.48) to air the angles of total internal reflection in going from sapphire (n~1.73) to air and integrating over the respective solid angles (assuming that the spontaneous emission is isotropic). The calculations are detailed in appendix 1 and tabulated in table 6-1.

| Direction of light emission | % of total emission |
|---|---|
| Top | 4.2 % |
| Bottom (through the substrate) | 4.2 % |
| confined in sapphire substrate (n=1.73) | 20 % |
| confined in Guided Layer (n=2.48) | 71.6 % |

Table 6-1 Estimate of light output from top and bottom of LED and percentage confined by total internal reflection in the GaN and the sapphire layers

Thus, in a conventional GaN LED without any coatings or other efficiency enhancing schemes, only about 4.2% of the light is emitted in air towards the top and over 90% of the light is confined by total internal reflection to the GaN and sapphire layers.

In this thesis , we use one dimensional photonic crystal structure to improve the extraction efficiency of GaN LED . The metal reflector is popularly used to increase the light output by reflecting the downward radiation from active layer . The drawback of metal reflector is the a little bit higher reflection loss than the reflector of dielectric materials . This drawback of metal reflector results from the different light reflection mechanism . The photonic crystal structure is a better reflector to enhance the light extraction. We see the axial light output is doubled compared to the sample before the PhC –ODR layers coated  (section 5-1) . And the wall plug efficiency increases by around 12%  when the LED adds photonic crystal reflector (section 5-3) .  When the photonic crystal reflector LED is applied to the smaller viewing angle lamp packaging, we can see the strong enhancement of axial optical emission (section 5-2).  We know the major cost of LEDs is the cost of the epitaxial wafer . If we only have the lower-rank epitaxial wafers , we can use the photonic crystal reflector technology to improve the light extraction efficiency . The radiation quality of this kind LED ( PC LED) should be as good as the conventional LED made from the higher-rank epitaxial wafers.

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## Appendix 1 -  Estimate of the fraction of light extracted from GaN LED
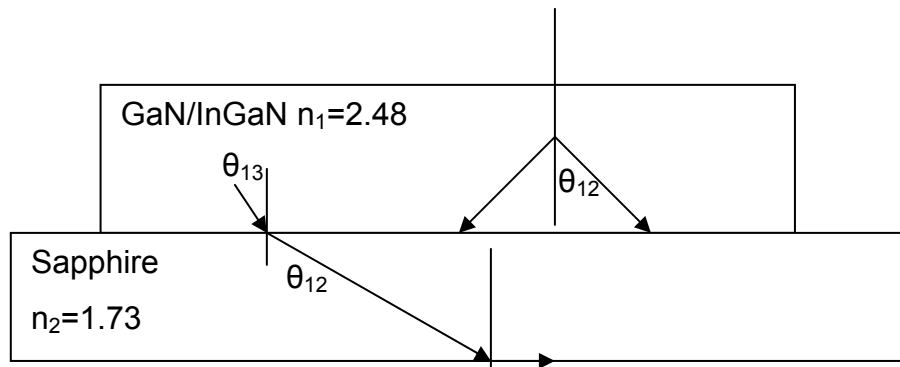
**Fraction escaping top interface**
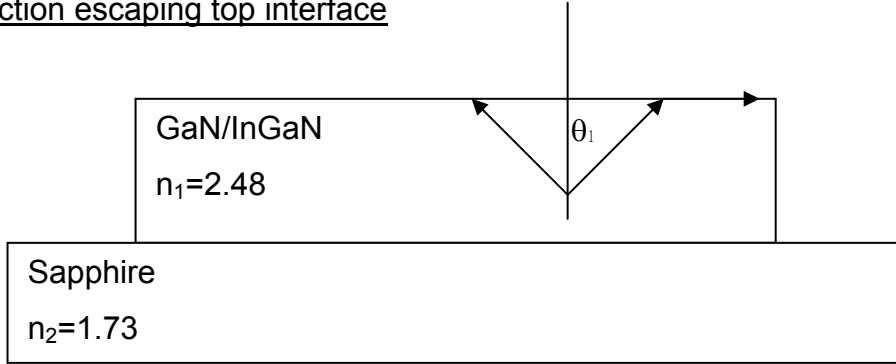


$\theta_1 = \sin^{-1}(1/2.48) = 0.403$ rad

Only fraction of light which falls within the cone of the critical angle can escape. Integrating over the unit sphere:

Fraction of light escaping top surface $= \dfrac{\int_0^{\theta_1} 2\pi \sin\theta \, d\theta}{\int_0^{\pi} 2\pi \sin\theta \, d\theta} = \dfrac{[-\cos\theta]_0^{\theta_1}}{[-\cos\theta]_0^{\pi}} = \dfrac{0.0849}{2} = 0.042$

**Fraction escaping sapphire and fraction confined in the GaN layer**

Critical angle at the GaN/Sapphire interface is $\theta_{12} = \sin^{-1}(1.73/2.48) = 0.442$ rad

Critical angle at the Sapphire/air interface is $\theta_{23} = \sin^{-1}(1/1.73) = 0.616$ rad

Angle of incidence in GaN for critical angle in sapphire

$= \sin^{-1}(1.73/2.48 \times \sin 0.616) = 0.4032$

Hence fraction escaping sapphire lower surface = 0.042

Fraction (excluding TIR from top surface) escaping GaN/sapphire interface =

$$\frac{\int_0^{\theta_{12}} 2\pi \sin\theta \, d\theta}{\int_0^{\pi} 2\pi \sin\theta \, d\theta} = \frac{[-\cos\theta]_0^{\theta_{12}}}{[-\cos\theta]_0^{\pi}} = \frac{0.2835}{2} = 0.1417$$

Hence fraction confined in the GaN waveguide = 1-0.1417 – 0.1417 = 0.7165

Fraction entering sapphire = 0.1417 + TIR from top

$= 0.1417 + (0.1417\text{-}0.042) = 0.2414$

Fraction confined in sapphire = 0.2414-0.042 = 0.2