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TECHNOLOGICAL
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IMPROVING GAN-BASED LIGHT-EMITTING DIODES

Improving GaN-Based Light-Emitting Diodes

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Improving GaN-Based Light-Emitting Diodes

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Abstract

Due to the superior advantages of high energy conversion efficiency, high brightness, high reliability, controllable color properties, long lifetime, and ease of miniature and digitalization, GaN-based light-emitting diodes (LEDs) are regarded as the next generation solid state lighting sources to replace the conventional lighting devices of fluorescent and incandescent lamps. Tremendous effort has been devoted to LED research, development and commercialization, thus drastic advances have been made in the past decades. However, despite these advantages and achievements, GaN-based LEDs still suffer from several technical issues, including insufficient heat dissipation, current crowding effect, low light extraction efficiency, and efficiency droop. All these problems, especially efficiency droop delay LED's further expansion in the general lighting market. Hence, a large amount of research work focusing on improving the efficiency droop has been carried out to achieve better LED performance.

In this dissertation, the InGaN/GaN multiple quantum well (MQW) LEDs have been studied from multiple aspects, including material quality, light extraction efficiency, p-type doping influence, current crowding effect, electron overflow, and carrier transport. The LED epitaxial wafers studied are grown on c-plane patterned sapphire substrate using metal-organic chemical vapor deposition (MOCVD) system. Standard fabrication processes for flip-chip LEDs are developed and electrical and optical characterizations are conducted to evaluate the performance.

Difficulty in p-type doping and low hole injection efficiency lead to non-uniform carrier distribution within MQWs. Consequently, the quantum well (QW) number is crucial to the LED performance considering the recombination volume and carrier distribution. On the other hand, from the perspective of epitaxial growth, the strain will accumulate due to lattice mismatch between III-nitride layers. When the effective thickness of the lattice-mismatched MQW active region is beyond its critical layer thickness, the misfit strain relaxation accompanied with the generation

of defects occurs during the epitaxial growth. As a result, the choice of QW number is critical to LED performance.

In this thesis, the influence of QW number on LED performance is systematically investigated both numerically and experimentally. By investigating the carrier concentration distribution, electron overflow, and current spreading for LEDs with varied QW numbers, the improvement mechanism is uncovered. The deep analysis of the measured external quantum efficiency (EQE) curves in conjunction with carrier lifetime measurement reveals the limitations of increasing QW number from the perspective of strain accumulated and defects generated during epitaxial growth.

Moreover, the study of p-type doping is conducted due to its vital impact on the hole injection for GaN-based LEDs. We propose a depletion-region Mg-doping method to systematically analyze the effectiveness of different Mg-doping profiles ranging from the electron blocking layer to the active region. Numerical computations show that the Mg-doping decreases the valence band barrier for holes and thus enhancing the hole transportation. Meanwhile, the depletion-region Mg-doping approach also increases the barrier height for electrons, which leads to a reduced electron overflow. More importantly, the depletion-region Mg-doping increases the hole concentration in p-GaN layer. Experimentally measured EQE indicates that Mg-doping position is vitally important, i.e., the doping in or adjacent to QW degrades the LED performance resulting from Mg diffusion and the corresponding nonradiative recombination.

One potential approach to improve the power and luminous flux of a micro-LED is to optimize its size and emitting surface area. Nevertheless, the size of GaN-based LEDs is limited by the insufficient current spreading due to the low conductivity of the p-GaN layer. Thus micro-wall geometry with different mesa dimensions for InGaN/GaN LEDs is designed and fabricated to investigate the size effect on the LED performance. Through building a model for current paths, the underlying physics and mechanism of the improvement of the current spreading effect are revealed by numerically calculating the average current density in the vertical direction. In addition, in order to meet the requirement for high output

power and improve the light extraction efficiency, a novel LED architecture with three micro-walls is proposed and the corresponding improvement mechanism is explored as well.

In summary, this dissertation studies the InGaN/GaN MQW LEDs both numerically and experimentally. Several key factors are investigated including the QW number, p-type doping, current spreading, and light extraction efficiency. The underlying physics and mechanism of the influence of these factors are revealed. This work provides insightful knowledge of LED physics and also useful guidelines on the critical QW number, p-type doing, and light extraction architecture when designing the high performance GaN-based LEDs.

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Chapter 1 Introduction

1.1 Background and Motivation

With the significantly rapid development of society and economy over the past few decades, people's living conditions and life quality have achieved tremendous progress. However, this achievement comes at the cost of energy and environment issues, such as air pollution, water contamination and increasing CO₂ emission. The large emissions of CO₂ have brought about the phenomenon, known as the global warming effect that has led to an increased global average surface temperature and climate change. Most of CO₂ emissions originate from the burning of fossil fuels including oil, natural gas and coal, for energy and transportation. Figure 1.1 shows the main sources of CO₂ emissions in the United States which include electricity, transportation, industry, residential & commercial and other combustion [1]. Among these sources, the electricity consumes the most fossil fuel and is responsible for a large part of emissions. According to the US Department of Energy Data from the Energy Information Agency, lighting takes up 30% of the whole electricity consumption for end users in America, as presented in Figure 1. 2 [2].

Figure 1.1 The main sources of CO₂ emissions in the United States [1].

Figure 1.2 The breakdown of electricity consumption in the US [2].

According to Figure 1.1 and Figure 1.2, lighting plays an important part in CO₂ emissions as it takes up a large amount of overall energy consumption. In this regard, considerable effort has been devoted to improving lighting through enhancing energy utilization efficiency by communities, governments, and states all over the world.

Nowadays main source for artificial lighting is dominated by fluorescent lamps and to a lesser extent now, by incandescent lighting. The incandescent lamp glows with visible light when the wire filament inside is heated to a high temperature under an electric bias. The work principle of fluorescent lamp is that an electric current excites the mercury vapor inside the lamp, which produces short wavelength ultraviolet light causing the phosphor coating on the surface of the lamp to glow. However, the luminous efficacy of a typical incandescent bulb and a compact fluorescent bulb is not high, around 16 and 60 lumens per watt (lm/W), respectively [3-5].

A large amount of attention and effort has been devoted to solid state lighting by electroluminescence and remarkable advances have been made in recent decades. Since the phenomenon of electroluminescence in solid state materials was first discovered in 1970 by H.J. Round of Marconi Labs, using a crystal of silicon

carbide and a cat's-whisker detector [6, 7], solid state lighting devices have been continuously reported. Oleg Losev reported the invention of first Light-Emitting Diodes (LEDs) in 1927 [8] and Kurt Lehovec *et al.* explained these first LEDs in 1951 [9]. In August 1962, Biard and Pittman demonstrated a zinc diffused p–n junction LED with an emission of the infrared light under forward bias [10].

The first visible light LED was developed in 1962 by Nick Holonyak and then his graduate student, M. George Craford, successfully invented the first yellow LED and significantly improved the brightness of red and red-orange LEDs by ten times in 1972 [11, 12]. The electroluminescence from GaN film with the peak wavelength of 475 nm was first reported by Pankove *et.al.* from Radio Corporation of America in 1972, even though their brightness remained low [13]. The devices they fabricated later consisted of an indium surface contact, an insulating Zn-doped layer, and an undoped n-type region. Soon afterwards, they began growing Mg-doped GaN films using the technique of hydride vapor phase epitaxy (HVPE), however, the GaN films, even though Mg doped, did not exhibit p-type conductivity.

After the research effort of Pankove and his co-workers ended, work on GaN had almost ceased until Isamu Akasaki and his colleagues demonstrated the first true p-type doping and p-type conductivity in GaN film in 1989 [14]. Subsequent to the achievement of p-type doping, the first GaN p-n homojunction LED was demonstrated by Akasaki in 1992 [15]. Two years later, the first high-brightness blue-emission GaN-based LED was reported by Shuji Nakamura of Nichia corporation [16]. Simultaneously, Hiroshi Amano and Isamu Akasaki in Nagoya were working on the approach to grow the important GaN nucleation layer on sapphire substrates and they also tried to achieve p-type doping in GaN.

Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura were awarded the Nobel Prize in Physics in 2014 for their great contributions to the creation of the blue-emission LED [17]. This great achievement revolutionized LED lighting and made high power blue lighting sources practical, contributing to the remarkable development and application of display technologies. Currently, LEDs are

expanding their share in the lighting market due to their considerable benefits compared to conventional lamps, which are listed as follows:

1. **Energy Efficiency:** LEDs are able to emit more lumens per watt than incandescent and fluorescent lamps. The luminous efficacy of LED lamps can reach 150 lm/W while a typical incandescent bulb is 16 lm/W and a compact fluorescent bulb 60 lm/W [3].
2. **Color:** The color emitted from LEDs covers the whole range of the visible light spectrum and they can emit light close to that of an intended color without using any color filters as traditional lighting methods need.
3. **Miniature and Flexible:** LEDs can be fabricated into various designed shapes according to the application requirement to produce highly efficient illumination and the whole device can be miniaturized in order to be attached to circuit boards.
4. **Stability:** LEDs are built with sturdy components that are highly rugged so that they are extremely durable and can withstand even the extreme conditions. LED illumination is appropriate for extreme requirement operation under both hot and cold outdoor temperature conditions. Compared with conventional lamps, for which low temperature may affect the operation and present a challenge, LEDs operate smoothly even in an extreme cold environment, for instance, outdoors in the winter.
5. **Ecologically Friendly:** LED lights are free of toxic chemicals while most of traditional fluorescent lighting lamps incorporate many harmful chemicals such as mercury which are harmful for the environment.
6. **Lifetime:** Typically, the estimated lifetime of LEDs is in the range from 35,000 to 50,000 hours, while fluorescent bulbs are rated at about 10,000 to 15,000 hours, and incandescent light bulbs are at 1,000 to 2,000 hours [18].
7. **Safety:** A low-voltage power supply is sufficient for LED illumination and this has enabled it to be easily employed in outdoor settings just by utilizing a battery as energy source. One advantage of this is the application in remote or rural areas.

Owing to the superior advantages mentioned above, GaN-based LEDs are treated as the next generation solid state lighting sources to replace the traditional lighting devices of fluorescent and incandescent lamps. Their expanding market share is speeding up in the lighting market. As presented in Figure 1.3, the market revenue of LEDs industry in China reached \$7.1 billion by 2014, up from \$3.4 billion in 2009 with an annual growth rate of 12.8 percent [19] and still showing an increasing trend. Nowadays, the applications of LEDs can be seen all over the world in various fields. Figure 1.4 to 1.7 present some examples of LED applications for bridge lighting, architecture lighting, indoor lightings and outdoor lighting.

Figure 1.3 LEDs market revenue in China from 2009 to 2014 [19].

Figure 1.4 LED lighting with different colors in a bar [20].

Figure 1.5 Bridge and Shanghai Oriental Pearl TV Tower under LED lighting in China [21].

Figure 1.6 LED lighting in the National Aquatics Centre of “Water Cube” in China.

Figure 1.7 Night view of Central Business District in Singapore [22].

Figure 1.8 The beauty of LED lighting in the Garden by the Bay in Singapore [23].

However, despite the superior advantages and the remarkable progress being made in GaN-based LED research, development and commercialization, these LEDs still suffer from several issues, which significantly limit the device performance. The phenomenon of efficiency droop at high current injection is one

of the most challenging problems needing to be solved. Even though, the efficiency droop has been heavily investigated and substantial models are implemented to explain it, there is still not consensus on its root cause. Non-uniform current spreading during device operation also substantially degrades the properties of LED performance. The role of current spreading in GaN-based LEDs has not been clearly understood as yet. Besides, insufficient light extraction efficiency due to total internal reflection (TIR) and thermal heat dissipation of the LED devices presents a challenge to these LEDs. All these limiting factors have to be systematic investigated and resolved before the LEDs can really merge into the general lighting market and take place of the traditional light sources. Thus, the interest of this thesis is to enhance the LED performance through further improving the crystalline quality of the epitaxial film, investigating and optimizing the vital factors and designing novel architectures.

1.2 Objective of the Thesis

The scope of this work includes the introduction of the properties of III-nitride compound semiconductor, recombination mechanisms in the LED, growth and fabrication procedures of InGaN/GaN LEDs, characterization approaches, theoretical and experimental analysis of the proposed LEDs and investigating the influence of server key factors and the underpinning physics. The objectives of this thesis work are summarized below:

- To get insightful and comprehensive knowledge of the properties for III-nitride material and its suitability for LEDs.
- To understand the detailed recombination mechanisms of LED radiation, including radiative and nonradiative recombination.
- To grow epitaxial films with high crystal quality and fabricate high efficiency LED devices.
- To study the underlying physics of LEDs involved in carrier injection and transportation, electron overflow, electron-hole wave function overlap, and bandgap barrier.

- To study the piezoelectric polarization, built-in electric field, and carrier dynamics.
- To investigate the influence of the quantum well (QW) number, p-type doping, and mesa size on the device performance.
- To improve the electrical and optical performance of LED devices by configuration designs.

1.3 Major Contribution of the Thesis

In this dissertation, the epitaxial wafers of InGaN/GaN LEDs with high quality and uniform thickness are successfully grown by a metal-organic chemical vapor (MOCVD) system on a 2 inch patterned sapphire substrate. The LED devices with flip-chip architecture are fabricated using a professional fabrication process. Characterization approaches including electroluminescence, photoluminescence, thickness mapping, and carrier lifetime have been conducted to evaluate the performance of epitaxial wafers and devices. Based upon the technique of epitaxial growth, device fabrication and characterization, the investigation on the effect of quantum well number, p-type doping, mesa dimension, and current spreading are performed.

The quantum well number is crucial to LED performance considering the recombination volume and non-uniform carrier distribution within the active region. By incorporating more quantum wells in InGaN/GaN LEDs, the effective recombination volume is augmented, thus the electron concentration in the active region is reduced and Auger recombination is reduced. Moreover, a reduction on the electron overflow into the p-GaN layer and increase on hole concentration in the quantum well are obtained, hence the efficiency droop is alleviated. We also propose a model for current paths to demonstrate that the current spreads better when more quantum wells are introduced. Nevertheless, the strain accumulated and defects generated in the practical growth degrade the crystal quality, thus leading to the degradation of the LED performance. This imposes limitations on the increase

of the quantum well number, in particular when the QW number is beyond a certain value.

It is common for an electron blocking layer (EBL) to be adopted for InGaN/GaN LEDs to suppress the electron overflow. However, an undoped EBL significantly impedes the hole transport into the active region. Thus, the EBL has to be p-type which can then efficiently reduce electron leakage while reducing the potential barrier height for the holes. Nevertheless, the degradation of LED performance caused by Mg diffusion and diffusion during the p-doping process has also been reported. As a result, a model of depletion-region Mg-doping is proposed to systematically study the influence of p-type doping at different ranges from the EBL to the active region. Based on the analysis of hole movement in the depletion region, it was found that the holes obtaining sufficient energy from built-in electric field and polarization electric field will eventually migrate to p-GaN layer, which contributing to the increased hole concentration. The numerical simulation in conjunction with the experimentally measured results reveals the mechanism for improving LED performance as well as the limitations for p-type doping.

One potential approach to improve the power and luminous flux of a micro-LED is to optimize its size and emitting surface area. Nevertheless, the size of nitride based LEDs is limited by the insufficient current spreading due to the low conductivity of the p-GaN layer. Thus micro-wall geometry with different mesa dimensions for InGaN/GaN LEDs is designed and fabricated to investigate the size effect on the LED performance. According to the calculations and experimental results, the LED devices with smaller size deliver improved optical output power and have a better current-voltage characteristic, which is attributed to the improved current spreading effect. Through building a model for current path, the underlying physics and mechanism of the improvement of current spreading effect are revealed by numerically calculating the average current density in the vertical direction.

Finally, in order to meet the requirement for more output power and avoid the serious current crowding effect in large size device, a novel LED architecture with

three micro-walls is proposed. The benefit of this geometry is that less heat generation, better heat dissipation, and higher light extraction efficiency.

1.4 Organization of the Thesis

The dissertation begins with the background introduction and motivation of this research work in Chapter 1. Subsequently, a detailed literature review on the unique properties of III-nitride compound semiconductors and the polarization effect is presented in Chapter 2 together with theoretical study on recombination processes through ABC model. In addition, the numerical simulation software of Advanced Physical Models of Semiconductor Devices (APSYS) is introduced, which helps explore the underpinning physics and mechanisms in LEDs. Chapter 3 describes the epitaxial growth and device fabrication of GaN-based LEDs, including the growth technique of metal-organic chemical vapor deposition (MOCVD), characterization methods, LED architectures, and standard fabrication procedures for flip-chip LEDs. Chapter 4 investigates the quantum well number effect on optical output performance of InGaN/GaN LEDs by numerically and experimentally analyzing its carrier transportation, electron overflow and external quantum efficiency (EQE) curve. Chapter 5 explains by a model of depletion region doping how p-type doping influences the carrier transportation and thus optical performance of the LED. Chapter 6 investigates the dimension effect on micro-LED performance by analyzing the current crowding condition for LED devices with varied dimensions. Moreover, a novel LED with three micro-walls geometry is proposed and demonstrated to enhance light extraction efficiency thus improving the LED performance. Chapter 7 summarizes the work presented in this research and finally recommendations for future work are described.

Chapter 2 Literature Review of InGaN/GaN Light-

Emitting Diodes

The group III-nitride compound semiconductors (AlN, InN, GaN) are excellent wide band gap semiconductors, pretty suitable for modern electronic and optoelectronic applications. In this chapter, the properties of III-nitride compound semiconductors and their polarization effect induced are reviewed in detail in the context for semiconducting material adopted in LEDs. Then, the recombination process in LEDs is systematically analyzed through ABC model and the efficiency droop is explained as well. The quantum efficiency of LED including internal and external quantum efficiency is also illustrated. Finally, the numerical simulation of APSYS we performed in this work is introduced as well.

2.1 III-nitride Compound Semiconductor

2.1.1 Properties of III-nitride Compound Semiconductor

The group III-nitride crystals are found to exist in two fundamental structures: wurtzite and zinc blende. For both structures, the nearest neighbors of each atom create the same surroundings. Each N atom is enclosed in tetrahedron of four metal atoms and each metal atom is also surrounded by four N atoms in the tetrahedron. The difference between these two structures comes from the stacking sequence of tetrahedral bounded group III-nitride bilayers. Therefore, the surroundings of atoms are identical, while the overall crystalline symmetry is decided by the stacking periodicity.

Figure 2.1 Comparison of wurtzite and zinc blende structures [24, 25].

As shown in Figure 2.1, due to the variation in packing sequence, the overall crystalline symmetry of wurtzite and zinc blende structures is changed [24, 25]. The wurtzite structure is non-centrosymmetric, which is lack of inversion symmetry, while zinc blende is centrosymmetric crystals. As a consequence, wurtzite crystals always possess some special properties such as pyroelectricity and piezoelectricity, which centrosymmetric crystals lack. The AlGaInN system commonly implemented in LEDs is predominantly wurtzite and the basic material constants in the wurtzite crystal are listed in table 2.1 [26, 27].

Table 2.1 Basic physical parameters of wurtzite lattice GaN, AlN, InN [26, 27].

		Unit	AlN	GaN	InN
Lattice constant (300K)	a_0	10^{-10}m	3.112	3.189	3.545
	c_0	10^{-10}m	4.982	5.185	5.703
Energy bandgap		eV	6.24	3.44	0.78
Refractive index			1.9-2.2	2.43	2.9
Dielectric constant			8.5	8.9-9.5	15-15.3
Thermal conductivity (300K)		W/(cm $\cdot$ K)	5.9	4.1	1.76
Thermal expansion coefficient		10^{-6}K^{-1}	4.15	5.59	3.8
Mobility	Electron	$\text{cm}^2/(\text{V}\cdot\text{s})$	135	~ 1000	1000-1900
	Hole	$\text{cm}^2/(\text{V}\cdot\text{s})$	14	<200	-

There are several unique material properties of III-nitride group compounds that enable them to own the edge over other semiconductor compounds when it comes to application in LEDs. First of all, they are able to withstand high temperature annealing and processing, which means that they are robust and stable materials. III-nitride compounds are direct band gap, and thus there is a large possibility to achieve high intrinsic (band-to-band) light emission efficiency. Moreover, the wide bandgap from 0.78 to 6.24 eV covers the whole wavelength of visible light, and extends to both near infrared and ultraviolet regimes, which makes it suitable for visible lighting. Figure 2.2 depicts the bandgap energy and corresponding emission wavelength versus lattice constant of III-nitride and other group compounds at room temperature.

Figure 2.2 Band gap energy and the corresponding emission wavelength versus lattice constant of III-nitride and other group compounds at room temperature [28].

2.1.2 Polarization Effect

There are several crystal planes existing in the III-nitride group compounds. Figure 2.3 shows the crystal structure and several crystal planes of GaN with wurtzite structure, including the polar c-plane, the semi-polar plane, and the non-polar a- and m-planes. The most common growth of III-nitrides takes the c-plane

as growth orientation, causing the accumulation of polarization charges at the interface. As a result, polarization fields are induced that affect the thin film structure and the optical and electrical properties of the semiconductor. The polarization fields contain two parts: spontaneous polarization (P_{sp}) and piezoelectric polarization (P_{pz}). In absence of external electric field, the overall polarization of the material is the sum of P_{pz} and P_{sp} in the equilibrium lattice.

Figure 2.3 (a) Crystal structure of GaN with wurtzite structure. The hexagonal unit cell is highlighted with bold lines, while the adjacent atoms are included to highlight the overall hexagonal nature of the structure. (b) Different crystal plane of GaN, including the polar c -plane, the semi-polar plane[29], and the non-polar a - and m -planes [30] .

Spontaneous polarization refers to the built-in polarization field, which is due to the lack of inversion symmetry of the GaN crystal and the characteristics of the ionic bonds between Ga and N atoms. Due to the displacement of electron charge clouds towards one of the atoms, a net positive charge is induced on one surface of the crystal while an equal negative charge is presented on the other surface. P_{sp} field is defined as a vector directing from a metal cation toward a nitrogen atom with a fixed orientation along the c -axis. Consequently, the polarization direction relies on the growth face: P_{sp} is parallel with $[0001]$ in case of N-face nitrides while it points to the $[000-1]$ direction in case of Ga-face nitrides. Figure 2.4 depicts how P_{sp} varies across different growth orientations.

Figure 2.4 Spontaneous polarization direction under two different growth faces: Ga face (left) and N face (right).

Piezoelectric polarization is caused by lattice mismatch between different III-nitride materials. As shown in Table 2.1, the lattice constants of AlN, GaN, and InN are different, therefore, strain is induced in the interface of two III-nitride materials with different lattice constants. The direction of the polarization field and internal electric field depend on the strain as well as the growth orientation (Ga face or N face), the illustration is shown in Figure 2.5. The strain in the epitaxial layer can be compressive or tensile according to the lattice constant contrast between the two layers, as displayed in Figure 2.6. In the compressive-strain case, the III-nitride epitaxial layer of interest is laterally compressed. For instance, GaInN is compressively strained when it is deposited on a thick GaN buffer layer due to its lattice constant larger than that of GaN. In the tensile-strain case, the epitaxial layer of interest is expanded along the lateral direction.

Figure 2.5 Surface charge and direction of polarization field and electric field for spontaneous and piezoelectric polarizations in III-nitride films under N and Ga growth faces [31].

Figure 2.6 Schematic diagram of compressive and tensile strains for III-nitride compounds grown on sapphire.

Owing to the influence of polarization induced electric fields, there is band tilting in the quantum well and quantum barrier regions for InGaIn/GaN LEDs, which reduces the overlap between the electron and hole wave functions, hence a redshift is caused, as shown in Figure 2.7. This phenomenon is called Quantum-Confined Stark Effect (QCSE). As displayed in Figure 2.7, an internal electric field leads to band tilting, so that the transition energy between electron and hole is red-shift compared to zero-field condition.

Figure 2.7 Band tilting in active region for InGaN/GaN LEDs with the growth orientation of (0001)

2.2 Recombination in InGaN/GaN Light-Emitting Diodes

The electron in the conduction band is in a metastable state and eventually becomes stabilized to a lower energy level in the valence band by releasing energy. During the stabilization, it must move into an unoccupied energy level in valence band. Hence, when the electron moves down to the valence band, it simultaneously exhausts a hole. This process is called recombination. There are two basic recombination mechanisms in semiconductors, namely radiative recombination and nonradiative recombination, as illustrated in Figure 2.8. During the radiative recombination, the electron recombines with one hole and one photon is emitted with energy equal to the bandgap energy. While in the event of nonradiative recombination, the energy is converted to a phonon instead of transferring to the photon. Eventually, the energy is converted to heat. From the point of energy conversion and lighting, nonradiative recombination events are unwanted and should be minimized in LEDs.

Figure 2.8 (a) In event of radiative recombination, the energy is converted to photon and (b) in nonradiative recombination event, energy is released by a phonon [31].

2. 2. 1 Radiative Recombination

As illustrated in Figure 2.9, in the event of radiative recombination, an electron in the conduction band recombines with a hole in the valence band and the energy is emitted in the form of a photon.

Figure 2.9 Illustration of electron-hole radiative recombination.

III-nitride compounds are direct band material, which facilitates the band-to-band emission. The total radiative recombination rate (denoted as R) of band-to-

band recombination depends on the density of electron and hole involved in the recombination process and is proportional to the product of electron density and hole density. Using a proportionality constant, the net recombination rate per unit time per unit volume can be expressed as:

$$R = B(np - n_i^2) \quad (2.1)$$

where B is the recombination coefficient, n is the electron density, p is the hole density, and n_i is the intrinsic carrier concentration, respectively. The carrier lifetime can be obtained as:

$$\tau_R = \frac{1}{B(n_0 + p_0)} \quad (2.2)$$

where n_0 and p_0 are electron and hole concentration at equilibrium, respectively.

2. 2. 2 Nonradiative Recombination

In the case of nonradiative recombination, the energy of electron-hole pair is emitted in the form of heat in the semiconductor crystal lattice. The nonradiative recombination process mainly contains two components, namely Shockley–Read–Hall (SRH) process and Auger recombination.

Shockley-Read-Hall recombination is also called trap-assisted recombination, where the electron in transition recombines with hole through deep-level traps within the band gap. Most deep-level transitions are nonradiative, while some deep-level transitions are radiative. An example of a radiative deep-level transition in InGaN/GaN LED is shown in Figure 2.10. The luminescence spectrum shows a band-to-band transition at 460 nm and a broad deep-level transition around 550 nm, which occurs near the yellow range of the visible light spectrum. This yellow luminescence line has been reported to be caused by Ga vacancies [32-34], a common point defect in n-type GaN.

Figure 2.10 Room-temperature photoluminescence spectrum of InGaN/GaN LED with a band-to-band optical light emission at 450 nm and a second emission at 550 nm identified as an optically active deep-level transition.

These deep levels can be caused by defects, which include unwanted foreign atoms, native defects (vacancies of group-III and V, group-III interstitials, and group-V interstitials), dislocations, complexes of impurities, and combinations of different types of defects [35-37]. All these defects form one or several energy levels within the forbidden gap that act as effective recombination centers; particularly when the introduced energy level is near the middle of the band gap.

SRH nonradiative recombination is a two-step process. The two steps involved in SRH recombination are:

- An electron (or hole) is captured by the deep level energy state in the forbidden band gap that is incorporated by defects in the crystal lattice.
- A hole (or electron) is captured by the same energy state before the electron is thermally re-emitted into the conduction band, and then recombination occurs.

The rate at which a carrier (electron or hole) is captured by deep energy level in the forbidden region relies on the distance between the introduced deep level to either of the band edges. As a result, if the introduced deep energy level is near the

conduction band edge, the recombination is less likely to occur because there is a high possibility for electron to be re-emitted to the conduction band edge without recombining with a hole that is trapped by the same deep energy level. Accordingly, the deep energy levels close to the middle of the band gap are pretty effective for nonradiative recombination. The recombination of carriers via a deep level is shown schematically in Figure 2.11.

Figure 2.11 Band schematic diagram illustrating nonradiative recombination via deep-level.

The nonradiative recombination rate through a deep level with trap energy $E_{deep-level}$ and concentration N_T is given by [31]:

$$R = \frac{np - n_i^2}{\left(\frac{1}{c_p N_T}\right)(n + n_i) + \left(\frac{1}{c_n N_T}\right)(p + p_i)} = \frac{np - n_i^2}{\tau_p(n + n_i) + \tau_n(p + p_i)} \quad (2.3)$$

where c_p and c_n denote the capture coefficient of recombination process for hole and electron, respectively; N_T denotes the density of recombination levels; n_i and p_i denote the electron and hole concentration at equilibrium state, respectively; τ_p and τ_n are the minor carrier lifetime for hole and electron, respectively.

Another important nonradiative recombination process is the Auger recombination. In the event of Auger recombination, the energy of electron-hole

pair is transferred to a third carrier (electron or hole), which is then excited to a higher energy state. The process is presented schematically in Figure 2.12. Subsequent to the interaction, the third carrier being activated releases its excess energy by thermal lattice vibrations. Because the process involves a three-particle interaction, it is significant only under non-equilibrium conditions especially when the carrier density is pretty high.

Figure 2.12 Schematic illustration of Auger effect process.

The recombination rates due to the two Auger processes are given by

$$R_{Auger} = C_p np^2 \quad (2.4)$$

and

$$R_{Auger} = C_n n^2 p \quad (2.5)$$

In the high-excitation limit, in which the non-equilibrium carriers have a higher concentration than equilibrium carriers, the Auger rate equations reduce to

$$R_{Auger} = (C_n + C_p)n^3 = Cn^3 \quad (2.6)$$

where C is the Auger coefficient. Typical value of the Auger coefficient is from 10^{-28} - 10^{-29} cm⁶/s for III-nitride semiconductors [38-42].

2.3 LED Quantum Efficiency

LED quantum efficiency means the energy conversion efficiency of electricity to light. Ideally, the active region of an LED emits one photon for each injected electron. As a result, the ideal active region of an LED has a quantum efficiency of unity. However, in practical, the quantum efficiency of the LED is not unity due to the carrier loss in nonradiative mechanisms, light trapping induced by total internal refraction, and light absorption in the active region.

Two types of quantum efficiency in LEDs are often considered:

- Internal Quantum Efficiency (IQE) is the ratio of the number of photons emitted by LED to the number of electrons injected into the device.
- External Quantum Efficiency (EQE) is the ratio of the number of photons emitted outside from the LED to the number of charge carriers injected into the LED.

2.3.1 Internal Quantum Efficiency

IQE (η_{IQE}) is the proportion of all electron-hole pairs in the active region that are radiative, producing photons. The IQE can be expressed as:

$$\eta_{IQE} = \frac{\text{number of photons emitted from active region}}{\text{number of electron injected into LED}} = \frac{P / h\nu}{I / e} \quad (2.7)$$

where P is the optical power emitted from the active region, $h\nu$ is the photon energy, I is the injection current and e is the elementary charge. The internal quantum efficiency of LEDs has been frequently described by the ABC model, which is:

$$IQE = Bn^2 / (An + Bn^2 + Cn^3) \quad (2.8)$$

where A is the SRH coefficient, B is the radiative recombination coefficient, C is the Auger coefficient, and n is the carrier concentration, respectively.

Figure 2.13 presents the IQE curve as a function of current injection for a common InGaN/GaN LED. It can be seen that the IQE value increases first and then drops gradually after it reaches the maximum with the raising of current injection. It is worth noting that the drop of IQE value become more significant

under high current injection. The phenomenon of the IQE drop under high current injection level is called efficiency droop, as indicated in Figure 2.13. Despite the advantages and their remarkable advance, LEDs is still suffering from the efficiency droop, which has hindered their further expanding the share in the general lighting market. It has been reported by many researchers that the efficiency droop originates from carrier delocalization [43-45], enhanced Auger recombination[46], junction heating[47], insufficient hole injection and transportation [48, 49], and electron leakage [50-52]. Hence, tremendous work has been devoted to suppressing the efficiency droop and thus to improving the LED performance. Thus far, a large number of novel structures including engineered electron-blocking layer [53, 54] and InGaN staircase electron injector [55], graded-thickness quantum barriers [56, 57], AlGaInN alloy quantum barrier [58, 59], p-doped quantum barriers [60], and gradual InGaN quantum well [61-64] etc., have been reported to alleviate the efficiency droop.

Figure 2.13 Illustration of efficiency droop for the InGaN/GaN LEDs.

2. 3. 2 External Quantum Efficiency

In order to maximize the output power, all photons emitted in active region are expected to be emitted into free space. Such an LED has a light extraction efficiency of unity. Nevertheless, practically, not all the photons generated by the active region are able to be emitted into free space. Some photons fail to leave the LED device because of several photon loss mechanisms. For instance, light emitted by the active region can be absorbed by bulk GaN and metallic contact metal. Furthermore, the phenomenon of total internal reflection, also referred to as the trapped light phenomenon, reduces the possibility of the light to escape from the LED devices, as illustrated in Figure 2.14. Thus the light extraction efficiency is defined as

$$\eta_{\text{extraction}} = \frac{\text{number of photons emitted into free space}}{\text{number of photons emitted from active region}} = \frac{P_0}{P} \quad (2.9)$$

where P_0 is the optical power emitted into free space. And the external quantum efficiency is defined as:

$$\eta_{\text{EQE}} = \frac{\text{number of photons emitted into free space}}{\text{number of electrons injected into LED}} = \frac{P_0 / h\nu}{I / e} = \eta_{\text{IQE}} \eta_{\text{extraction}} \quad (2.10)$$

The external quantum efficiency gives the ratio of the number of escaped photons to the number of injected charge carriers.

Figure 2.14 Illustrated diagram of light extraction for LED grown on sapphire.

2.4 APSYS Simulation

APSYS, Advanced Physical Models of Semiconductor Devices, is a general purpose two/three dimensional modeling software program for semiconductor devices, which is based on finite element analysis of electrical, optical, and thermal properties of compound semiconductor devices. It offers a very flexible simulation environment for modern semiconductor devices and includes a lot of advanced physical models such as thermal analysis, heterojunction models and hot carrier transport, which make APSYS attractive for applications in LED devices [65-72].

2.4.1 Models and Capabilities

APSYS self-consistently solves basic equations by boundary conditions, which contain Poisson equations, Schrödinger equations, the current continuity equations, conventional drift-diffusion equations, the heat transfer equations, and the carrier energy transport equations. In addition to the drift-diffusion model, APSYS simulation program also incorporates models of the carrier transport, carrier capture/escape in quantum wells, inter-band optical transitions, thermal effect, and optical ray tracing. The carrier transport model includes Fermi–Dirac statistics distribution, hydrodynamic models for drift and diffusion behaviors, thermionic emission and polarization charge for transport in heterojunctions, and radiative and nonradiative recombination. The Poisson equation and Schrödinger equation are recalculated at the QW for energy state levels. Spontaneous emission in active region is solved by waveguide optical modes for arbitrary complex refractive index distribution.

Data generated by APSYS includes the following:

- 2 dimensional (2D) optical field distributions for LED devices.
- 2D distributions of hot carrier temperatures in the hydrodynamic model.
- 2D distributions of lattice temperature for the heat transfer model.
- 2D electric field, potential, polarization charge and current distributions.

- 2D electron and hole concentration distributions.
- Spontaneous emission spectrum versus injection current density for LED devices.
- Auger recombination emission spectrum as a function of injection current density.
- Current versus voltage (I-V) characteristics.
- Band diagrams under various bias conditions.
- Results of alternating current (AC) small signal analysis for any frequency range.
- Quantum well subband structure with valence mixing model for quantum devices.
- 2D distributions of concentration and occupancy of deep level traps in a semiconductor.
- All of the data above as a function of time and temperatures.

2. 4. 2 Materials and Parameters

By using proper material parameters, such as bandgap, polarization, and recombination rate, reliable simulation results can be obtained.

A. Bandgap Energy of III-nitride Compounds

The energy bandgap of III-nitride compounds at room temperature (RT) can be expressed as following:

$$E_g(In_xGa_{1-x}N) = x \cdot E_g(InN) + (1-x) \cdot E_g(GaN) - 3.0 \cdot x(1-x)(eV) \quad (2.11)$$

$$E_g(Al_xGa_{1-x}N) = x \cdot E_g(AlN) + (1-x) \cdot E_g(GaN) - 1.0 \cdot x(1-x)(eV) \quad (2.12)$$

where $E_g(InN)$, $E_g(GaN)$, and $E_g(AlN)$ are the energy bandgap of InN, GaN, and AlN [73], and the corresponding value for InN, GaN, and AlN at room temperature are 0.711 eV, 3.435 eV, and 6.138 eV, respectively [74-76]. The band-offset ratio, the ratio between the energy band offset in conduction band and valence band, is assumed to be 0.7/0.3 for InGaN and AlGaN ternary alloys [77].

B. Polarization Charge

Due to the lattice mismatch in III-nitride compounds, their alloys with wurtzite structure suffer from polarization effect, which makes significant influences on both electronic and optical properties of LED devices. The polarization induces an electric field leading to a red-shift of the peak emission wavelength. APSYS program employs the $6 \times 6k \cdot p$ model that was developed by Chang *et al.* in order to calculate the strained wurtzite semiconductor [78, 79]. The interface charges induced by spontaneous and piezoelectric polarization effect for nitride material layers is considered in the APSYS software, which is critical since the polarization is vital for c-plane GaN LEDs. Moreover, APSYS also allows for the screening of polarization charges due to strain relaxation in practical situations.

The build-in interface charges in the hetero-interface of III-nitride semiconductor compounds are calculated by the method developed by Fiorentini *et al.*[33]. The spontaneous polarization and piezoelectric polarization of ternary nitride alloys calculated by Vegard are given by [75]:

$$P_{sp}, \text{In}_x\text{Ga}_{1-x}\text{N}(x) = -0.0413 \cdot x - 0.0339 \cdot (1-x) + 0.0378 \cdot x \cdot (1-x) (C/m^2) \quad (2.13)$$

$$P_{sp}, \text{Al}_x\text{Ga}_{1-x}\text{N}(x) = -0.0898 \cdot x - 0.0339 \cdot (1-x) + 0.0191 \cdot x \cdot (1-x) (C/m^2) \quad (2.14)$$

where -0.0413, -0.0339, and -0.0898 are the spontaneous charge value for InN, GaN, and AlN, respectively.

$$P_{pz}, \text{In}_x\text{Ga}_{1-x}\text{N}(x) = x \cdot P_{pz}(\text{InN}) + (1-x) \cdot P_{pz}(\text{GaN}) (C/m^2) \quad (2.15)$$

$$P_{pz}, \text{Al}_x\text{Ga}_{1-x}\text{N}(x) = x \cdot P_{pz}(\text{AlN}) + (1-x) \cdot P_{pz}(\text{GaN}) (C/m^2) \quad (2.16)$$

where

$$P_{pz}(\text{InN}) = -1.373 \cdot \varepsilon + 7.559 \cdot \varepsilon^2 \quad (2.17)$$

$$P_{pz}(\text{GaN}) = -0.918 \cdot \varepsilon + 9.541 \cdot \varepsilon^2 \quad (2.18)$$

$$P_{pz}(\text{AlN}) = -1.808 \cdot \varepsilon + 5.642 \cdot \varepsilon^2 \text{ for } \varepsilon < 0 \quad (2.19)$$

$$P_{pz}(\text{AlN}) = -1.808 \cdot \varepsilon - 7.888 \cdot \varepsilon^2 \text{ for } \varepsilon > 0, \text{ as a function of basal strain } \varepsilon. \quad (2.20)$$

The whole built-in polarization for III-nitride material system is the sum of the spontaneous polarization and piezoelectric polarization. It is worth noting that the

induced interface charges are screened by the injected carriers and defects generated inside the materials so that only 20% to 80% of the theoretical value is used [80-82]. Figure 2.15 illustrates the bandgap diagram under equilibrium state produced by APSYS software, for LEDs with and without polarization effect. It is worth mentioning that the 60% theoretical interface charges due to polarization effect for nitride material layers is used, and 40% of that is relaxed by generating dislocations.

Figure 2.15 Illustration of bandgap diagram under equilibrium for LEDs with and without polarization effect. Inset presents the strain-induced electric field in QW.

C. Other Parameters

Other vital parameters set in the simulation are: nonradiative carrier lifetime (SRH), and Auger coefficient. Commonly, the value SRH lifetime is in the range of 1-50 ns, and the Auger value is in the range of 1×10^{-42} to $1 \times 10^{-40} \text{ m}^6/\text{s}$ [83-89].

Chapter 3 Epitaxial Growth and Device Fabrication of

InGaN/GaN Light-Emitting Diodes

3.1 Introduction to MOCVD Growth Technology

Due to the high melting point of GaN material, the growth by liquid phase epitaxy is difficult to achieve. Instead, it is accomplished by halide vapor phase epitaxy technique using an equilibrium mixture of Ga-containing and nitrogen gas. However, the growth speed of this approach is too high to precisely control the thickness of epitaxial films [90, 91]. To form a high-quality film for GaN-based LEDs, a metal organic chemical vapor deposition (MOCVD) method is adopted. MOCVD is a non-equilibrium growth technology by transport of precursors and the succeeding chemical reaction between group III and V elements in a heated reactor. The MOCVD technique originated from the early research of Manasevit in 1968 who demonstrated trimethylgallium (TMGa) and arsine deposited single crystal GaAs pyrolytically in an open tube cold-wall reactor [92]. The composition and growth rate of the epitaxial film are controlled by precise control of the mass flow rate and diffusion of different components in the gas stream. The organometallic group III sources are either liquids, such as TMGa, trimethylaluminum (TMAI), or solid such as trimethylindium (TMIn). The organometallic sources are stored in bubblers through which a carrier gas flows, as displayed in Figure 3.1. The bubbler temperature is able to precisely control the vapor pressure over source material.

Figure 3.1 Illustration of carrier gas flow into the bubbler.

The carrier gas saturates with vapor from the source and transports the vapor to reaction chamber through a showerhead, as depicted in Figure 3.2. There are a large number of tubes on the showerhead, which allow the source gas to be injected and the density of tubes is 100 tubes/inch² with a tube diameter of 0.6 mm, as depicted in Figure 3.2 (b).

Figure 3.2 (a) Schematic diagram of gas flow in reaction chamber, (b) showerhead with inject holes

The group V sources are most commonly gaseous hydrides. Dopant materials can be metal organic precursors or hydrides. The substrate usually rests on a block of graphite called susceptor that can be heated by a radiofrequency (RF) coil or a resistive heater, as shown in Figure 3.3. An important feature of MOCVD process is that the walls of the chamber are kept substantially colder than the heated interior substrate, which minimizes wall deposits and reduces reactant depletion effects that hot-walls would cause.

Figure 3.3 Exemplary of heater coils used in MOCVD system.

For our case of GaN/InGaN LEDs, TMGa, TMAI, and TMIIn provide gallium, aluminum, indium sources, respectively, while nitrogen is supplied by NH_3 . H_2 and N_2 act as carrier gases, taking sources to the reactor chamber. SiH_4 is used to provide n-type donors while cyclopentadienyl magnesium (Cp_2Mg) is adopted for p-type acceptors. The schematic diagram of MOCVD is shown in Figure 3.4. As indicated in Figure 3.4, reaction chemicals are kept in bubblers with temperature controlled. The connected cylinders are used to provide carrier gas (H_2 and N_2) and

nitride source (NH_3). Valves play a role as controllers of gas flow. Substrate is held on graphite susceptor and the wall is cooled down by running cooling water.

Figure 3.4 Schematic diagram of gas delivery system of MOCVD reactor [93].

The main MOCVD reaction process in GaN growth can be written as follows:

where g and s stand for gas phase and solid phase, respectively. Figure 3.5 exhibits the processes in the reaction chamber for III-nitrides growth. The growth rate is determined by diffusion and pyrolysis of TMGa/TMIn/TMAI sources in the boundary layer. In Figure 3.5, TMGa source and NH_3 source are delivered through the showerhead and transported to the substrate. The pyrolysis of TMGa occurs at the temperature of 500°C while 300°C for TEGa in N_2 and H_2 environment. Therefore, TMGa in the reactor ($\sim 1000^\circ\text{C}$) is totally decomposed to form pyrolysis products. TMGa and the pyrolysis products travel and then get adsorbed to substrate surface, eventually diffuse to the growth sites. Side-products are led out after growth processes are finished.

Figure 3.5 Possible reaction processes in a MOCVD reactor [94].

The composition of AlGa_xN alloys can be accomplished by linearly adjusting the molar flow rate of the TMAI, TMGa, and NH₃ sources. Since the diffusion coefficient of Ga and Al are approximately equal, the solid composition is found proportionally to the flux ratio of Ga and Al. The relative MOCVD reaction of Al_xGa_{1-x}N deposition is expressed as follows:

The detailed growth procedures are shown as below:

- MO sources and hydrides are transported by carrier gas to the heated reactor chamber.
- The injected sources combine with each other inside the reactor and delivered to the deposition area.
- At the deposition area, the high temperature contributes to the decomposition of sources and other gas phase reactions, forming film precursors.
- The precursors are adsorbed on the growth surface and then diffuse to the growth sites.
- In the growth sites, film atoms are incorporated into the growing film through surface reactions.

- The by-products of the surface reactions are desorbed from the growth surface and transported to the main gas flow exhaust.

The MOCVD growth of thin-film materials is monitored and analysed by *in-situ* reflectance monitoring system [95]. The easiest way to explain how the *in-situ* reflectance monitor works is to consider the simple three-phase system with an air/film and film/substrate interface, as illustrated in Figure 3.6. Laser light is reflected at near-normal incidence from this 3-phase system. If the growing layer is partially transparent to the probe wavelength and there is a difference in refractive index of the substrate and growing layer, then an interference pattern results from the two beams reflected from the air/film and film/substrate interfaces.

Figure 3.6 *In-situ* reflectance monitoring through interference between the reflected light beams.

The periodicity in the interference pattern is governed by the laser wavelength and the film refractive index, and is given in the following equation by the delta term:

$$2\pi = \Delta = \frac{2\pi}{\lambda} \cdot \frac{2dn_{GaN}}{\cos \theta}$$

where d is the thickness of the growing layer, λ is the wavelength of incident laser beam, θ is the incident angle and n_{GaN} is the refractive index of the GaN. As the

laser light is near-normal incidence, the incident angle is pretty small ($\cos \theta \approx 1$). The above equation can be further simplified to:

$$d = \frac{\lambda}{2n_{\text{GaN}}}$$

Therefore, the film thickness and growth rate of the epitaxial layer are obtained. Figure 3.7 presents *in-situ* reflectance profile for the entire LED growth, from nucleation layer to p-GaN layer. As mentioned above, the reflectance change of a grown epitaxial layer during the growth process is monitored by the laser interferometer monitors. Figure 3.7 demonstrates a typical interferogram of the whole growth of bulk GaN. The y-axis is the reflectance intensity and the x-axis denotes the growth time. As indicated in Figure 3.7, as the GaN nucleation layer growth begins the reflectance increases until reaches the maximum. During this stage, the TMGa flow is turned off and only ammonia is fed into the reactor to prevent excessive decomposition of the GaN nucleation layer above 900°C. As the GaN nucleation layer evaporates and becomes hexagonal, a lot of nucleation layer islands are generated and a drop in the reflectance is observed. Subsequent to the nucleation layer annealing, TMGa precursor is delivered to the reactor chamber and high temperature GaN growth begins. At the initial stage, growth mode converted from three dimensional to two dimensional. Islands grow vertically and laterally and eventually coalesce with each other. Thus, the GaN surface becomes smooth and the reflectance intensity is fully recovered. Then, the following n-GaN layers are grown on this high temperature GaN bulk with high quality.

Figure 3.7 Reflectance curve for the GaN growth from nucleation layer to n-GaN layer by MOCVD.

3.2 Epitaxial Growth of InGaN/GaN Light-Emitting Diodes

Wafers

3.2.1 Choice of Substrate

The challenge of high quality GaN film growth originates from the difficulty to obtain a single crystalline GaN substrate or other high quality single crystalline substrates with similar lattice parameters to GaN. Since the high temperature and the high nitrogen partial pressure is required for GaN melting [96], it is extremely difficult to prepare the native GaN film compared to Si and GaAs. To date, the native GaN substrates are available only in small sizes and the quality remains poor. Moreover, the high-cost of the commercial native GaN (\$1,500 and \$6,000 per wafer) makes it unattractive for large scale industry applications [96].

Consequently, the adoption of non-native substrates is an alternative approach. There are several substrates suitable for GaN layer growth including SiC, Si and Sapphire. But there is considerable disparity in the lattice constant and the thermal expansion coefficient between GaN epitaxial layers and substrates as presented in Table 3.1. This discrepancy induces crystalline defects in the epitaxial layers in the form of vacancies and dislocations, thus degradation of optical and electrical performance of III-nitride devices is obtained.

Table 3.1 Material properties of GaN and other semiconductor materials [97-99].

Material	GaN	6H-SiC	Si	Sapphire
Symmetry	Wurtzite	Wurtzite	Diamond	Hexagonal
a (Å)	3.189	3.081	5.431	4.758
c (Å)	5.185	15.117	-	12.99
Lattice Mismatch (%)	0	3.51	-16.96	13.9
Thermal Conductivity at 300K (W/cm ² K)	1.3	4.9	1.3	0.3
Melting Point (°C)	2500	2830	1412	2040

At present, most of the epitaxial growth of LEDs is performed on sapphire substrates, as displayed in Figure 3.8. Sapphire substrate application has come a long way from the original usage in military applications in the 1960's. Sapphire is ideal for use in LED applications due to high strength, high temperature resistance, low dielectric loss, and good electrical insulation. Sapphire substrate in LED lighting also helps hinder stray currents caused by radiation from spreading to adjacent circuit elements. Its crystal structure also allows LED lights to have a wider beam angle.

Figure 3.8 A classic sample of sapphire substrate of 2 inch.

In order to produce more efficient LEDs, researchers have developed ways to create patterns and periodic structures with different geometries and dimensions on the sapphire substrate surface. These sapphire wafers with periodic structures of various shapes such as cone, dome, pyramid, pillar, etc., are called patterned sapphire substrates (PSS). Schematic diagram of the PSS is displayed in Figure 3.9. There are two different manufacturing processes to fabricate PSS currently being practiced in the industry: dry plasma etching and wet chemical etching. Today, the majority of PSS products are produced by dry plasma etching due to its inherently effective control of precision and uniformity.

Figure 3.9 An illustration of PSS structure.

Patterns applied on the LED substrate or wafer can significantly enhance the light output of LEDs in two ways. The technique increases the light emission of active quantum well layers as the result of reduced epitaxial defect density. And patterned sapphire substrate reduces light loss due to total internal reflection (TIR) phenomena by enabling a photon scattering effect, as shown in Figure 3.10.

Figure 3.10 Comparison of light extraction for LEDs with and without PSS structures.

3. 2. 2 Overview of Bulk GaN Growth

An overview of the GaN bulk layer growth is shown in order to understand the correlation between the quality of bulk GaN layer and growth parameters. Standard GaN growth contains five main stages, as shown in Figure 3.11.

- Cleaning of sapphire substrate
- Surface nitridation
- Growth of low temperature nucleation layer
- Nucleation layer annealing
- High temperature GaN layer growth

Figure 3.11 Schematic diagram of growth flow for bulk GaN on sapphire substrate.

Prior to the MOCVD growth of GaN epitaxial layer on sapphire substrate, a high temperature sample handling is adopted. The substrate is exposed to a hydrogen environment at temperatures around 1000 to 1200 °C, so that hydrogen etching occurs, removing contamination of the sapphire substrate. Typically, the annealing time needed is about 10 minutes. Subsequently, the nitridation step starts with the ramping down of the temperature to about 530~560 °C. In this stage, ammonia is first fed into the reaction chamber for a while prior to the coming of the TMGa. The process of nitridation leads to the formation of amorphous AlN_xO_{1-x} with several mono layers [100] and stimulates two dimensional growth of nucleation layer. Furthermore, it removes the nucleation of misoriented GaN islands [101]. The duration of the nitridation is a sensitive and vital factor. Under optimized conditions, a decreased defect density, enhanced electron mobility and a

reduced yellow luminescence can be achieved. Too long nitridation time leads to reduced film qualities. Subsequently, a low temperature GaN or AlN nucleation layer on sapphire is grown which contributes to obtain mirror-like GaN layers. The deposition of nucleation layer of AlN or GaN on sapphire substrate spurs the improvement of GaN quality [102] by relaxing the strain between GaN and sapphire, and promoting lateral growth of GaN. Furthermore, the conversion of the three dimensional growth mode to the two dimensional growth mode occurs, GaN layer with a smooth surface is achieved accordingly.

Since the GaN nucleation layer takes an important role in obtaining a good quality epitaxial film, extensive work has been conducted to optimize it. The critical factors including island dimension, thickness, roughness, density, and orientation determine the quality of the high temperature GaN. Optimization of these factors can be achieved by controlling the nucleation layer growth temperature, the growth rate, the thickness, the V/III ratio, the temperature ramp-up time and the duration of annealing [103-105].

Next step following nucleation layer is the growth of high temperature GaN layer. This layer acts as a template for following growth of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ and $\text{In}_x\text{Ga}_{1-x}\text{N}$. The quality of the high temperature GaN layer is decided by growth pressure, growth temperature, V/III ratio and the thickness. Typically, the range of growth temperature for high temperature GaN layer is 950~1100 °C, in which the growth rate is decided by the diffusion rate of N and Ga atoms. In order to prevent nitrogen vacancies, a high V/III ratio is maintained and ammonia is assumed to be saturated compared to the group III materials. As a result, the GaN growth rate significantly relies on the flow of TMGa. If the temperature exceeds 1030 °C, the growth rate drops slightly due to Ga desorption from the GaN surface. Besides, due to the dislocations generated during the nucleation layer annealing process, the growth temperature also affects the film resistivity [106, 107].

3. 2. 3 Growth Temperature of III-nitride film

Growth temperature is an important parameter for GaN epitaxial growth, which is necessary to control with the aim of achieving high crystalline quality. GaN is

grown at the temperature of 1050°C following the growth of low-temperature nucleation layer on sapphire. Nucleation layer of GaN or AlN is grown at a different growth temperature, at 500°C and 800°C, respectively. The growth of InN or high In composition InGaN is challenging compared to grow GaN, since a lower growth temperature about 500°C for grow InN is required. Under such a low temperature N-H bonds in NH₃ molecular is hard to break, resulting in a low V/III ratio during growth process. Commonly, the deposition of AlN needs rather high temperature of about 1200°C, which affects the quality of AlN layer, however, some researchers reported that the crystalline quality of AlN would be improved by increasing the growth temperature, for example, to 1270°C, or even higher [108-110].

3. 2. 4 Characterization of Light-Emitting Diodes Wafer

In order to characterize the grown GaN layers, photoluminescence (PL), electroluminescence (EL), and carrier lifetime measurement are carried out. Electroluminescence is measured for the grown LED wafers by an integrating sphere attached to an Ocean Optics spectrometer (QE65000). The size of the tested LED devices is 1×1mm² with indium bump used as ohmic contact. The EL characteristics of the LEDs are performed at 9 points across the whole wafer with indium acting as both the p-type and n-type contacts.

Figure 3.12 Electroluminescence spectrum of blue LED wafer with wavelength of 453 nm and full width of half maximum (FWHM) of 22 nm (Insert: LED wafers under current injection).

Photoluminescence spectra mapping were performed using a PL mapper (Nanometric RPM2000) equipped with a 15 mW He-Cd laser (325 nm) as the excitation source. The PL mapping helps to determine a detailed distribution of the peak wavelength distribution, as displayed in Figure 3.13.

Figure 3.13 Photoluminescence spectra mapping for the whole 2 inch LED wafer.

To examine the uniformity of the epitaxial growth, the thickness across the whole epi-wafer is recorded using a mapping system (Nanometrics ® RPM-2000), as shown in Figures 3.14. As can be seen from this figure, the exemplary epi-wafer has an average thickness of 8.18 μm with a standard deviation of 0.11 μm , indicating a good uniformity across the wafer region.

Figure 3.14 Thickness mapping of GaN LED wafers.

The lifetime measurement was conducted by utilizing a pico-second time-resolved photoluminescence (TRPL) system. The system uses a Becker & Hickl GmbH DCS-120 confocal scanning film system, which is a complete confocal laser scanning microscope for fluorescence lifetime imaging and uses a pico-second diode laser with wavelength of 375 nm as the excitation source.

Figure 3.15 Carrier lifetime measurement by time-resolved photoluminescence system (Insert: DCS-120 System)

3.3 Structures of Light-Emitting Diodes

After wafer growth by MOCVD system, fabrication is carried out to make LED devices. From the point of light emission, LED architectures can be divided into two major categories: surface emission and edge emission. Literally, for surface emission structure, light comes out from surface of the LEDs while in the case of edge emission structure, light is emitted into free space from the edge of the LED. A comparison of these two layouts is presented in Figure 3.16.

Figure 3.16 Comparison of surface emitting and edge emitting structures for LEDs.

There are three basic surface emitting LED architectures: Lateral, Flip-up and Vertical structures. An exemplary diagram of LED with lateral structure is depicted in Figure 3.17. In this structure, light emitted from the active region comes out from the top of the surface. In order to mitigate the light extraction from the top surface, the transparency of p-GaN metal electrode has to be high. The indium tin oxide (ITO), as a transparent conductive electrode is the most widely implemented in optoelectronic devices. This is due to its two main properties: its electrical conductivity and optical transparency, as well as the ease to be deposited as a thin film.

Figure 3.17 An exemplary diagram of LED with lateral structure.

FC (Flip-Chip) LED is a new technology by mounting the LED upside down compare to the lateral LED structure. As indicated in Figure 3.18, the light is reflected by reflective layer and emits out from the substrate. For flip chip LEDs, the electrodes are directly contacted with the circuit board and this gives LED chips advantages, such as a larger light-emitting area, better heat dissipation, and easy soldering process by eliminating the wire-bonding step and wire bond shadowing. The reduction in thermal heat leads to remarkable enhancement in the lifetime and performance of the LED devices.

Figure 3.18 Schematic diagram of flip-chip LED architecture.

Figure 3.19 Schematic diagram of vertical LED configuration.

Another alternative structure is the vertical configuration, as displayed in Figure 3.19. There are several benefits of the vertical LED configuration, including improved light extraction efficiency, high heat sinking, and better current spreading. Removing substrate and depositing a high reflective electrode contribute to the reduction of optical loss since some of the light generating in active region penetrates the sapphire substrate. Furthermore, compared with metal substrate, the thermal conductivity of sapphire substrate is poor. A conductive metal substrate, for instance copper, leads high heat sinking. Consequently, higher efficiency and longer lifetime on high power operation can be induced. Moreover, since p-type GaN layer has a high resistance compared to n-type GaN layer, it is contacted to the entire surface by metal substrate in the vertical structure, which contributes to better current spreading and higher light extraction efficiency. Therefore, its radiant flux is higher than conventional lateral LED. A vertical structure LED device under current injection and fabricated vertical LED chips on copper substrate are shown in Figure 3.20.

(a)

(b)

Figure 3.20 (a) A vertical structure LED device under current injection, (b) fabricated vertical LED chips on copper substrate.

3.4 Device Fabrication of InGaN/GaN Light-Emitting Diodes

After wafer growth by MOCVD is completed, the fabrication processes of LEDs are started to fabricate the wafer into devices. Here, the fabrication process of the flip-chip LED is illustration in Figure 3.21.

Figure 3.21 Schematic diagram of fabrication processes for LED wafer.

The fabrication begins with mirror deposition on the bare LED epi-wafer. The mirror deposition of Ni/Ag is performed by e-beam evaporation. After that, wet etching of Ni/Ag is performed using hydrochloric acid (HCl) and nitric acid (HNO₃) to open the window for mesa etching. In this process, a photoresist is used as mask for wet etching. Then a rapid thermal annealing (RTA) is conducted at 300 °C for 5 mins to oxidize the Ni layer into NiO seeds and form low resistive ohmic contact with the p-GaN layer. Subsequently, mesa area is defined by reactive ion etching (RIE) to expose the n-GaN area. Then, a barrier layer is deposited first to protect mirror from being damaged during following passivation etching. SiO₂/SiN deposition with a thickness of 1.4 μm/0.3 μm by chemical vapor deposition (CVD) is carried out to prevent current leakage. Finally, Ni/Ag/TiW layer with a typical film thickness of 0.5/200/500 nm is deposited as contact pads for both the n- and p-electrodes. A fabricated flip-chip LED device on our wafer is depicted in Figure 3.22.

Figure 3.22 Fabricated Flip-chip LED chips.

3.5 Conclusion

In summary, the growth technique of InGaN/GaN MQW LED epitaxial wafer utilizing metal-organic chemical vapor deposition system was illustrated in detail. The choice of substrate, the growth of bulk GaN, the growth temperature as well as

the characterization approaches for LED wafer and devices were discussed. In addition, different surface emission LED structures including lateral, flip-chip and vertical geometries are introduced and the differences among these structures were discussed as well. Furthermore, the standard fabrication procedure for LED with flip-chip architecture was explained. The epitaxial layer growth, device fabrication and characterization methods are adopted as the initiated procedure for the LEDs devices studied in the following chapters.

Chapter 4 Effect of Quantum Well Number in

InGaN/GaN Light-Emitting Diodes

In this chapter, InGaN/GaN LEDs with different QW numbers are systematically investigated both numerically and experimentally. According to the numerical calculations, with the increased QW number, the optical output power is enhanced and the efficiency droop is alleviated when a constant SRH nonradiative recombination lifetime is set for all the LED samples. The improvement of the LED performance is attributed to the expanded recombination volume, reduced Auger recombination due to the reduced electron concentration in the QWs, and suppressed electron leakage into p-GaN layer for LEDs with more QWs. Furthermore, by analyzing the current flow path from p-GaN to n-GaN, we found that the current crowding effect is also alleviated when more QW numbers are adopted. However, there is a discrepancy between the experimental and simulated results. From experimental results, it is observed that, even though the efficiency droop is suppressed, the same as calculated results, the LED optical output power is first improved and then declined with the increasing of QW number. The analysis of the measured EQE curves helps to clarify the disparity. A progressively dominant SRH nonradiative recombination is induced when more epitaxial QWs are adopted, which can be related to the defect generation due to the strain relaxation during the epitaxial growth, especially when the effective thickness of MQWs exceeds its critical thickness. These explanations are further supported by the carrier lifetime measurement using a pico-second time-resolved photoluminescence system, and a revised simulation, which allows for a modified numerical modeling with the varied SRH lifetimes considered.

4.1 Introduction

Owing to the poor p-type doping efficiency and lack of suitable dopants, hole injection and transportation from p-GaN layer to active region, has always been a challenge that limits the LED performance. For a long time, no suitable p-type dopants for GaN were found. In 1960s, Nakamura managed to use magnesium as a p-type dopant to fabricate p-type GaN by low-energy electron-beam irradiation [31]. Even in today, due to the high activation energy, Mg doping is still not ideal and only minor part of the Mg is activated. Furthermore, the low hole mobility of about $10\text{-}20\text{ cm}^2/(\text{Vs})$ and induced high p-GaN resistivity make it hard for holes to penetrate into deeper QWs. These lead to non-uniform carrier distribution within MQWs accordingly. Furthermore, from the perspective of epitaxial growth, the strain will accumulate due to lattice mismatch between III-nitride layers. Consequently, the misfit strain relaxation accompanied with the generation of defects occurs during the epitaxial growth when the effective thickness of the lattice-mismatched MQW active region is beyond its critical layer thickness. As a result, choice of QW number is vitally important to LED performance.

The effect of quantum well number on the GaN-based LED performance has previously been investigated and reported. Unfortunately, the reported findings in their work are full of disparities and controversial in some cases. Tanaka *et al.* indicated that the InGaN/GaN MQW LEDs with more QWs exhibited improved LED performance and they attributed this enhancement to a decreased carrier concentration in QWs and hence a suppressed electron overflow was caused [111]. Chang *et al.* reported that the blue InGaN/GaN LEDs with 5 QWs had worse performance than that with 1-QW at low current injection conditions, while the 5-QW LED devices are superior to the 1-QW ones under high current injection level but commented that more convincing explanations [112] are required to better understand this phenomenon. Kuo *et al.* suggested that for ultraviolet AlInGaN LEDs, the optimized performance may be achieved when the QW number is three [113]. However, according to the numerical results from Huang *et al.*, the optimal QW number was one for a deep-UV AlGaN LED and the performance got worse as more QWs were incorporated [114]. Meanwhile, Xia *et al.* pointed out the

optical output power is boosted with the increasing of quantum well number and the optimal QW number is nine according to the calculated power conversion efficiency [115]. Despite the previous reports on the influence of QW number on the LED performance, no conclusive remarks can be drawn. As a result, a systematical study with complementary both theoretical simulation and experimental investigation is strongly required to address the disparity and reveal the underlying physics and mechanisms. As a consequence, in this work, blue-emitting InGaN/GaN LEDs with different QW numbers are grown and fabricated into devices in order to experimentally explore the underpinning physics in conjunction with theoretical modeling. The influence of QW number on the performance of LED devices is uncovered and understood by systematic analysis.

4.2 Experiments

Four blue-emission InGaN/GaN MQW LED wafers studied in this work were grown on (0001) c-plane patterned sapphire substrates using an AIXTRON close-coupled showerhead MOCVD system. The epitaxial growth was initiated on a 30-nm thick low-temperature GaN nucleation layer followed by a 4- μm unintentionally doped n-type GaN (u-GaN) layer. Subsequently, a Si-doped n-GaN layer was grown on the u-GaN template with the Si doping concentration and thickness of $5 \times 10^{18} \text{ cm}^{-3}$ and 2- μm , respectively. Subsequent to the n-GaN growth, LED wafers with 3, 5, 8 and 11 pairs of InGaN/GaN MQWs were grown separately with 3-nm quantum well and 9-nm quantum barrier. The indium composition of the InGaN quantum well is 12% and the emission peak wavelength of the grown LED samples was centered at $\sim 438 \text{ nm}$. After the growth of MQWs is completed, all LED samples were capped with a 20-nm p-type $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ electron blocking layer to suppress the electron overflow. Subsequently a 200-nm thick Mg-doped GaN with a doping concentration of $3 \times 10^{17} \text{ cm}^{-3}$ was grown as the hole source layer. After epitaxial growth, all the LED wafers were then fabricated into chips with device area of $350 \times 350 \mu\text{m}^2$ by a standard and reliable fabrication process, as shown in Figure 4.1.

Figure 4.1 Fabricated LED devices with device area of $350 \times 350 \mu\text{m}^2$.

In order to reveal the carrier transport dynamics and carrier recombination mechanisms of the LED samples, numerical simulations were carried out by APSYS simulator. APSYS self-consistently solves basic equations by boundary conditions, which contain self-consistent Poisson equations, Schrödinger equations, the current continuity equations, conventional drift-diffusion equations, the heat transfer equations, and the carrier energy transport equations. In the simulations, the carrier screening effect in the active region was also taken into consideration utilizing the self-consistent six-band $k \cdot p$ theory. Due to the crystal relaxation through defect generation during the practical epitaxial growth, a 40% of the theoretical polarization induced sheet charge density was assumed in the heterojunction of quantum well region, the energy band offset ratio $\Delta E_c / \Delta E_v = 70/30$ was taken. The Auger recombination coefficient was set to $1 \times 10^{42} \text{ m}^6/\text{s}$ [116]. The SRH lifetime here was set to a constant 43 ns for the first set of simulations as is commonly done [117, 118] and later reset to be 17, 16, 15, 4.3 ns for the 3, 5, 8, 11-QW LEDs, respectively, in the second set of simulations based on the experimentally measured carrier lifetime. The lifetime measurement was conducted by a time-resolved photoluminescence system (TRPL). This system is a Becker & Hickl GmbH DCS-120 confocal scanning film system, which is a complete confocal laser scanning microscope for fluorescence lifetime imaging and

utilizes a pico-second diode laser with wavelength of 375 nm as the excitation source.

4.3 Comparisons of LED Performance and Discussions

In order to figure out the influence of quantum well number on the optical output power and the efficiency droop, numerical calculations on the aforementioned LED devices is carried out first with the other parameters kept the same including SRH lifetime. Here, the SRH lifetime in the simulation was set to 43 ns for all the LED devices. Figure 4.2 shows the calculated external quantum efficiency and optical output power as a function of current density for the LEDs with varying QW numbers. From Figure 4.2, it can be seen that, as the QW number increases from 3 to 11, both the EQE and the optical output power are enhanced at all current density levels and these enhancements become progressively apparent under higher current injection condition. More importantly, the efficiency droop is declined as the QW number increases, which can be clearly observed in the Figure 4.2. According to the report of Xia *et al.*, the enhanced LED device performance can be attributed to the suppression of electron leakage and the reduction of the Auger recombination with more quantum wells incorporated in the LED devices and their contribution to performance enhancement is remarkable under high current injection condition [115]. This explanation is supported by the variations of electron concentration distribution near p-GaN region with the increasing quantum well number.

Figure 4.2 Calculated EQE and optical output power versus current density for LEDs with varying QW numbers.

The computed electron concentration adjacent to the p-GaN region is depicted in Figure 4.3 (a) for the LED devices with varied QW number at the current density of 50 A/cm², which illustrates that the electron concentration in the last three quantum wells adjacent to the p-GaN layer and in the p-GaN region is decreased as the QW number increases from 3 to 11. The reduction in the electron concentration in the quantum wells results in the suppression of the Auger recombination, and the reduction of the electron concentration in the p-doped region indicates the effective suppression of the electron leakage. These results indicate that with more quantum wells incorporated in the active region, the effective volume of recombination will expand and the electrons is able to spread more homogeneously and be better confined within quantum wells. As a consequence, the optical output power is booted and the efficiency droop is reduced, as displayed in Figure 4.2. It is worth noting that the hole concentration in the quantum wells close to the p-GaN layer is increased with a large of the quantum well number, as indicated in Figure 4.3 (b). This is possibly caused by the reduced electron leakage into p-type region, which

leads to the decrease of the bulk recombination between the electrons and holes in the p-GaN region and allows more holes to be injected into the active region. The increased hole concentration in the active region contributed to an improved recombination and benefit the LED performance as well.

Figure 4.3 (a) Simulated electron concentration in the last three QWs and in the p-GaN region for the LEDs with different QW number under the current density of 50 A/cm², (b) calculated hole concentration distribution in the last three QWs close to the p-GaN under the current density of 50 A/cm².

Moreover, the increased QW number contributes to an alleviated current crowding effect. According to the model shown in Figure 4.4, current crowding effect can be expressed as the ratio of I_1/I_0 and I_2/I_0 , shown as follows:

$$\frac{I_1}{I_0} = \frac{R_{MQW} + R_{n-GaN2}}{R_{MQW} + R_{tc}} = 1 - \frac{R_{tc} - R_{n-GaN2}}{R_{MQW} + R_{tc}} \quad (4.1)$$

$$\frac{I_2}{I_0} = \frac{1}{1 + \frac{R_{tc} + R_{n-GaN1}}{R_{MQW}}} \quad (4.2)$$

where $R_{n-GaN1,2,3}$ is resistance of n-GaN layer, R_{tc} is the total resistance of top contact layer and p-GaN layer, and R_{MQW} is resistance of active regions including QWs and QBs. For a LED device, n-GaN layer has better conductivity than p-GaN due to the conductivity contrast between electron and hole, therefore, we have $R_{n-GaN2} < R_{tc}$. As indicated in equation (4.1) and (4.2), both the ratio of I_1/I_0 and I_2/I_0

increase with R_{MQW} increased resulting from the increasing of QW numbers. That is, the current spreads better in horizontal direct and hence current crowding effect is alleviated.

Figure 4.4 (a) Schematic of current flow path, and (b) resistance model for LED device.

Subsequently, the experimental optical output power of the LED devices with 3, 5, 8 and 11 pairs of QWs was measured, which is displayed in Figure 4.5. It indicates that the optical output power for LEDs with 3, 5, 8, and 11 QWs is 21.6, 25.1, 26.5 and 23.0 W/cm², respectively, under the current injection level of 50 A/cm². The experimental optical output power is improved by 22.7% as the QW number increases from 3 to 8, which is consistent with the numerically calculated results shown in Figure 4.2. However, the optical output power is dropped by 13.2% when the QW number further increases from 8 to 11 at the same current density, which deviates from the trend of the numerical predictions in Figure 4.2.

Figure 4.5 Experimentally measured optical output power under increasing drive current density for the LEDs possessing 3, 5, 8 and 11 QWs.

The electroluminescence (EL) spectra (Figure 4.6 (a), 4.6(b), 4.6 (c) and 4.6 (d)) are collected under 10, 20, 30, 40 and 50 mA/cm² of the injection current density for LEDs with 3, 5, 8, and 11 QWs. All the EL spectra of the LEDs with varied QWs show a little blue shift when the current density increases from 10 to 20 mA/cm², which is due to the carrier screen effect. It is worth noting that the carrier screen effect is only significant in low current density and becomes negligible as the current density increases. From Figure 4.6 (a), 4.6 (b) and 4.7 (c), it can be seen that the LED devices with more QWs have higher EL intensity, which is attributed to the suppression of electron leakage, the reduction of the Auger recombination and alleviated current crowding effect. However, the EL intensity of 11-QW LED is reduced compared to that of 8-QW LED.

Figure 4.6 Experimental EL spectra for (a) 3-QW LED, (b) 5-QW LED, (c) 8-QW LED, and 11-QW LED.

Furthermore, Figure 4.7 presents the experimentally measured EQE as a function of injection current level for the LEDs with varied QW numbers. As can be seen from Figure 4.7, the efficiency droop is considerably enhanced with the increase of QW number. When the current injection increased from 10 to 50 A/cm² the efficiency droop is 19.4%, 17.3%, 15.8% and 12.1% for 3, 5, 8 and 11 QWs LEDs, respectively. The improvement trend of efficiency droop is consistent with the findings in numerical calculations. The suppression of the efficiency droop is due to the reduction in electron leakage [119] and the suppression in Auger recombination as the more QW are incorporated, as consistently supported both by the measured and simulated results. Nevertheless, even though the LED device with 11-QW shows the least efficiency droop among all devices in the experiments, its EQE value measured is not the highest at any current density, which also deviates from the numerical predictions in Figure 4.2.

Figure 4.7 Experimentally measured EQE curves versus injection current density for LEDs with varying QW numbers.

In order to uncover the root cause of the disparities between the simulated and measured results, in particular, for the LED device with 11-QWs, the well-known ABC model [120] is employed here for further discussions. According to the ABC model, three main carrier recombination mechanisms exist in the LEDs, which are Shockley-Read-Hall (SRH) nonradiative recombination rate, expressed as the term An , radiative recombination rate Bn^2 , and Auger nonradiative recombination rate Cn^3 . The IQE can be expressed as follows at low current injection level:

$$IQE = Bn^2 / (An + Bn^2 + Cn^3) = \frac{B}{\frac{A}{n} + B + Cn}. \quad (4.3)$$

The peak efficiency of IQE is achieved when

$$\frac{d(IQE)}{dn} = 0. \quad (4.4)$$

Therefore, the carrier concentration corresponding to the maximum efficiency is obtained at $n_0 = \sqrt{A/C}$. Here, it is worth noting that $n_0 = J_0 / ev$, where J_0 is the

current density at n_0 and e is the elementary electronic charge while v is the carrier drift velocity.

Consequently, according to Figure 4.7, the peak-efficiency current density J_0 (the current density at which EQE reaches the maximum) is 1.4, 1.7, 3.3 and 7.8 A/cm² for the LEDs with 3, 5, 8 and 11 QWs, respectively. It is reasonable that we assume the Auger recombination coefficient in the quantum well region is an invariant for all the grown LED devices. Hence an increased SRH recombination coefficient is obtained for the LED devices with more quantum wells, which is consistent with the finding from Joachim Piprek that the maximum EQE value is remarkably affected by SRH nonradiative recombination[121]. Here, it is worth noting that the self-absorption by QW is insignificant since the QW is thin. As a consequence, the progressively increased SRH recombination accounts for the degradation in the LED performance and this can be induced by the degradation of crystal quality [122] due to the increased thickness. The SRH nonradiative recombination within the active region is represented by the defect-related carrier lifetime. It was set to a constant value of 43 ns for all the LED devices in the numerical calculation displayed in Figure 4.2, which is not appropriate as analyzed from the experimental data here. This may lead to the discrepancy between the experimental and numerical results in Figures 4.2, 4.5, 4.6 and 4.7.

To further experimentally validate this explanation, the carrier lifetime measurement for InGaN/GaN LED devices with different QW numbers was performed by utilizing a pico-second TRPL system [123] and the experimental results are depicted in Figure 4.8. The luminance decay time turns out to be shorter with the increase of QW number. As shown in Figure 4.8, the carrier lifetime for LEDs with 3, 5, 8 and 11 QWs is 6.05, 4.66, 4.56 and 3.22 ns, respectively. The variation among these decay times of LED devices under the low excitation power is mainly due to the different nonradiative recombination rates, which is attributed to the SRH nonradiative recombination rate since Auger recombination rate is minor under the low excitation level [124]. Consequently, the reduction in the carrier lifetime of LED devices with increasing QW number can be a solid support to the claim that during the practical epitaxial growth a more serious defect-related

SRH recombination would be caused in LED devices with more QWs incorporated. Here, it is worth mentioning that the carrier lifetime for the 11-QW LED device is much shorter compared to that for other LED devices with smaller QW number, which is believed to be induced by the strain relaxation in this sample. When the effective thickness of the lattice-mismatched MQW active region is beyond its critical layer thickness [125], the misfit strain relaxation together with the formation of defects occur during the epitaxial growth. The strain relaxation is most likely to occur for the 11-QW LED device according to other reports [126-128]. Hence considerable defects generated during the strain relaxation process resulting in the significant SRH nonradiative recombination. In order to further verify the above conjecture, the numerical calculations were carried out again by resetting a decreased defect-related carrier lifetime for the studied LED devices, that is to say, the defect-related SRH carrier lifetime was set to 17.0, 16.0, 15.0 and 4.3 ns for the 3, 5, 8 and 11-QW LEDs, respectively. The carrier lifetime used for 11-QW LED device is much smaller to account for the effect of the generation of substantial defects in the strain relaxation. The computed results are displayed in Figure 4.9, which exhibits the same trend as the experimental results shown in Figure 4.7. Here, it is worth noting that under a low current density, for instance 10 A/cm^2 , the EQE difference between these LED devices both in experimental and re-produced numerical results is considerable, and this is because the SRH nonradiative recombination is dominant and has significant influence on radiation process under the low current condition. This similarity in turn supports the validity of SRH carrier lifetime in the revised numerical simulations. It is necessary to point out that the analysis in this work is based on the low current density where the SRH recombination is dominated and is responsible for the degradation in the optical output power and EQE. When it comes to higher current density, Auger recombination and electron leakage is the dominant mechanism for efficiency droop and determines the performance[129]. Based on the trend of EQE curve and efficiency droop rate indicated in Figure 4.7, it is possible that the 11-QW LED device will perform best in the even higher current injection condition due to the suppressed electron leakage and Auger recombination.

Figure 4.8 TRPL carrier lifetime measurement for different LED devices with varied QW numbers.

The well agreement between the numerically calculated and experimentally measured results supports that the increased defect concentration appears with the increased QW number. As a result, even though increasing the QW number is an effective approach to alleviate the efficiency droop, the LED performance improvement is limited simultaneously by the degrading crystal quality as more QW number is incorporated. Our findings in this work also clarify the disparity in the previous reports on the influence of QW number, which can be caused by the different crystal quality of the materials used in their works. Thus in order to release the full potential of an increasing number of QWs in improving the efficiency droop, it is necessary to improve the epitaxial growth process in order to grow less-defective epitaxial films.

Figure 4.9 Re-computed EQE with increasing defect concentration as a function of operation current density.

4.4 Conclusion

In summary, we numerically found that when one increases the quantum well number in the LED devices, the electron leakage induced efficiency droop can be suppressed. Nevertheless, from experimental results, it is found that the improvement of efficiency droop comes at the cost of reduction in quantum efficiency as the QW number is increased beyond a certain value, which is attributed to the worsening crystal quality of the epitaxial films as more quantum wells are incorporated. The QW number dependence of the defect-related carrier lifetime is confirmed by the carrier lifetime measurement and a good agreement has been achieved between the numerical calculation and experimental results when the QW number dependence of the defect-related carrier lifetime is considered in the numerical calculation. As a result, when increasing the quantum well numbers in the LEDs to reduce the electron overflow, maintaining a high crystal quality is crucial to achieve the targeted level of enhanced device quantum efficiency and suppressed efficiency droop simultaneously.

Chapter 5 Depletion Region in InGaN/GaN Light-

Emitting Diodes

In this chapter, due to the limitation of the hole injection, p-type doping is explored for an InGaN/GaN LED with 8 QWs. The choice of QW number for the proposed LEDs is based on the results of investigation on QW number mentioned above. Here, we propose to introduce a depletion-region Mg-doping in the LEDs structure, and we systematically analyze the effectiveness of different Mg-doping profiles ranging from the electron blocking layer to the active region. With this approach, the carrier dynamics and bandgap profiles are examined using APSYS simulator. The numerical computations show that the Mg-doping decreases the valence band barrier for holes and thus enhancing the hole transportation. Furthermore, the depletion-region Mg-doping approach also increases the barrier height for electrons, which leads to a reduced electron overflow. More importantly, the depletion-region Mg-doping increases the hole concentration in p-GaN layer. Experimentally measured EQE indicates that Mg-doping position is vitally important, i.e., the doping in/adjacent to QW degrades the LED performance due to Mg diffusion, which increases the corresponding nonradiative recombination that has been well supported by measuring the carrier lifetime. In addition, the experimental results are well reproduced by modifying the nonradiative recombination lifetimes, which further validates our assumption.

5.1 Introduction

Despite great advantages and the drastic progress in research and commercialization being made in the past decades, the LEDs are still suffering from a serious efficiency droop, especially at high current density injection. Hole transportation is claimed to be one of the most important factors for causing the efficiency droop, such as nonuniform hole distribution in the MQWs and the low

hole injection efficiency [3-5]. Consequently, tremendous effort has been devoted to address these issues to improve the LED performance. As a result, structures such as engineered AlGaIn electron blocking layer (EBL) [5-7], p-type InGaIn hole reservoir layer[8], hole modulator by p-type doped last QB[9], AlGaIn polarization doping [10-12], graded-composition QBs[13], and p-doped QBs [14, 15] etc. have been reported to enhance hole injection to reduce the efficiency droop. However, there is lack of systematic investigations on how the p-type doping at different regions for the LED device influences carrier transportation and hence the carrier recombination.

It is well known that the EBL is commonly adopted for InGaIn/GaIn LED structures to suppress the electron overflow. However, an undoped AlGaIn EBL significantly impedes the hole transport into the active region. Thus the EBL has to be p-type which can then efficiently reduce electron leakage while reducing the potential barrier height for the holes [16]. Kuo *et al.* report that the InGaIn/GaIn MQW LEDs with a partially p-doped last barrier exhibit the enhanced optical performance. They attributed this improvement to the increased hole injection and the larger effective barrier height for electrons [17]. Han *et al.* report that an enhanced performance can be obtained even at the high current for InGaIn/GaIn LEDs for which Mg-doped quantum barriers are implemented, and the better performance is due to the improved hole injection caused by the modification of the energy bands. Moreover, they suggest that the Mg-doped QBs can improve the morphological properties [18]. On the other hand, Kohler *et al.* report damaged active region due to the Mg diffusion and migration, especially when Mg-doped position is near the active region. These in turn increases the nonradiative recombination in the QW active region and reduces the output power [19]. Despite various reports on the effect of Mg-doping on the LED performance, there is still no conclusive consensus that can be drawn. As a result, a systematic study is strongly needed to uncover the underlying physics. Hence, in this work, we propose the depletion-region doping to systematically analyze the Mg-doping effect on active region for blue-emitting InGaIn/GaIn MQW LEDs and investigate the underlying physics in conjunction with theoretical modeling. We found that

Mg-doping at different ranges of the depletion region affects the energy band barriers, carrier injection, and even the optical output power.

5.2 Epitaxial Growth and Fabrication of LED Devices.

Five InGaN/GaN MQW LED wafers studied in this work were grown on (0001) c-plane patterned sapphire substrates using an AIXTRON close-coupled showerhead MOCVD system. The epitaxial growth was started with a 30-nm thick low-temperature GaN nucleation layer followed by a 4- μm unintentionally doped n-type GaN (u-GaN) layer. Then a Si-doped n-GaN layer was grown on the u-GaN template with the Si doping concentration and thickness of $5 \times 10^{18} \text{ cm}^{-3}$ and 2- μm , respectively. Subsequently, 8 pairs of $\text{In}_{0.15}\text{Ga}_{0.85}\text{N}$ /GaN MQWs were grown with 3-nm thick quantum well and 9-nm thick quantum barrier. After the MQWs, all LED samples were capped with a 20-nm $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ EBL and a 150-nm thick p-GaN layer. The difference among these five LED samples comes from variation in the p-type doped position, such that, p-type doping is at EBL solely, EBL+ $\frac{1}{2}$ QB, EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB, as shown in Figure 5.1. For instance, for LED with p-type doping at EBL+QB+QW+QB, when the growth of the 7th QW is finished the Mg precursors is opened until the growth of EBL layer is completed with a flow rate of cyclopentadienyl magnesium (Cp_2Mg) of 0.239 $\mu\text{mol}/\text{min}$ and the estimated effective hole concentration is $5 \times 10^{17} \text{ cm}^{-3}$. After EBL layer growth is completed, the Cp_2Mg flow rate is set to 0.432 $\mu\text{mol}/\text{min}$ with the estimated effective hole concentration of $1 \times 10^{18} \text{ cm}^{-3}$ for the following p-GaN layer growth. Finally, the *in-situ* 720 °C thermal annealing treatment in N_2 ambient was carried out to activate the Mg dopants. After epitaxial growth, all the LED wafers were then fabricated into chips with device area of $1 \times 1 \text{ mm}^2$ by a standard and reliable fabrication process, as shown in Figure 5.2.

Figure 5.1 Schematic diagram of different p-type doped configurations for InGaN/GaN LEDs.

Figure 5.2 Fabricated LED devices with device dimension of $1 \times 1 \text{ mm}^2$.

In order to reveal the mechanism of how Mg-doping in the depletion region influences the LED performance, numerical simulations were conducted by APSYS self-consistently solves basic equations by boundary conditions, which contain self-consistent Poisson equations, Schrödinger equations, the current continuity equations, conventional drift-diffusion equations, the heat transfer equations, and the carrier energy transport equations. The Auger recombination

coefficient was set to $1 \times 10^{-42} \text{ m}^6/\text{s}$, and only 40% of the polarization charges was used such that 60% of the theoretical polarization charges were released because of the crystal strain relaxation by the formation of dislocations [130]. The SRH lifetime was set to 43 ns for the simulation of depletion-region calculation [131] and later SRH was set to 16, 15, 13, 11, and 8 ns for LEDs with p-type doping at EBL, EBL+ $\frac{1}{2}$ QB, EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB, respectively. These lifetime values are based on the experimentally measured carrier lifetime through time-resolved photoluminescence (TRPL) system. The carrier lifetime measurement was conducted by a confocal scanning film system with model of Becker & Hickl GmbH DCS-120, which is a complete confocal laser scanning microscope and uses a pico-second diode laser with wavelength of 375 nm as the excitation source.

5.3 Results and Discussion

When a p-n junction is formed, the carriers will redistribute due to the large carrier concentration contrast until the equilibrium state is reached. There will be a depletion region in which no free carriers exist and a built-in electric field is established. The width of the depletion region can be obtained by[31]:

$$w_d = \sqrt{\frac{2\varepsilon}{e} V_d \left(\frac{1}{N_A} + \frac{1}{N_D} \right)}$$

where ε is the dielectric permittivity, V_d is the diffusion voltage, N_A is the acceptor concentration, and N_D is the donor concentration. It is worth mentioning that the actual depletion region contains two parts: 1) transition region and 2) completely depleted region. In order to probe the exact location of depletion region, we first performed numerical simulations to calculate the bandgap energy diagram and carrier concentration profiles for InGaN/GaN MQW LEDs when the device is under equilibrium state, as presented in Figure 5.3.

Figure 5.3 (a) Schematic energy bandgap diagrams of depletion region for InGaN/GaN MQW LEDs under equilibrium state, (b) computed electron and hole concentration profiles in InGaN/GaN MQW LEDs.

The electron and hole concentration distribution in Figure 5.3 (b) clearly indicates that the depletion region completely depletes the electrons and holes. As displayed in Figure 5.3 (b), the electron concentration drops significantly and

becomes negligible at the depletion region along the growth orientation. Meanwhile, the hole concentration falls down rapidly and becomes negligible at depletion region along the [000-1] direction. The depletion region lies from half of the last QB to the half of EBL and its corresponding width is 15 nm in this case, which is illustrated in Figure 5.3 (a) by grey color. Since the different p-type doping architectures such as p-type doped EBL and QB always affect the depletion region, investigating the link between the p-type doping and the depletion region will help to understand the working mechanisms for LEDs with various p-type doped configurations. For that reason, numerically computed bandgap diagrams and carrier distributions are carried out for LED with Mg-doping at EBL + $\frac{1}{2}$ QB.

Figure 5.4 Comparison of (a) bandgap diagram and (b) carrier distribution for EBL undoped LED and EBL + $\frac{1}{2}$ QB p-doped LED at equilibrium.

Figure 5.4 presents the comparison results of LEDs with and without depletion region Mg-doping layout, respectively. Here, it is worth noting that the EBL is totally doped. As can be seen in Figure 5.4 (a), if the EBL + $\frac{1}{2}$ QB p-type doping is adopted, the barrier height for electron is increased by 175meV, while the barrier height for hole is reduced by 217meV compared to EBL undoped LED, which is consistent with the previous reports of p-EBL LEDs [132, 133]. Moreover, according to the carrier distribution in Figure 5.4 (b), it is observed that the depletion region moves towards the n-GaN and the corresponding width gets larger with a value of 19 nm. More importantly, the hole concentration in the p-GaN at the interface between the p-GaN layer and EBL is increased for EBL + $\frac{1}{2}$ QB p-doped LED. The holes are stored in the p-GaN layer because they are being depleted from p-doped QB by the built-in electric field which is coupled with the polarization induced electric field [131].

Due to the lattice mismatch between InN, GaN, and AlN, polarization is caused at the interfaces of QW and QB, and QB and EBL. Consequently, there are two electric fields existing in the depletion region. As indicated in Figure 5.5 (a), the orientation of the built-in electric field of the depletion region is directed from n-side layer to p-side layer and the orientation of strain-induced electric field in QB and EBL is in the same direction as built-in electric field. However, the polarization induced electric field in the QW region is opposite to the built-in electric field. If the whole depletion region is designed to be p-doped, the holes in this region will move due to the electric field. Figure 5.5 (a) presents the schematic diagram of possible movements of holes if the depletion region is designated to be p-type doping. For instance, the holes in area ④ will move to area ⑤ driven by built-in electric field and strain-induced electric field, as shown in Figure 5.5 (a). The holes then will finally migrate into p-GaN layer, thus contributing to the enhanced hole concentration. For area ③, the holes will gain the energy from both the polarization induced electric field and the built-in field, and they will move from the original site to the interface of GaN last quantum barrier and AlGaIn EBL. If the holes can obtain energy larger than the barrier for the GaN/AlGaIn interface,

they will be able to climb over p-EBL and finally reach the p-GaN layer. On the other hand, the holes will be depleted into the nearest QW and recombine by nonradiative recombination if the obtained energy is not sufficient. As a result, the EBL+ $\frac{1}{2}$ QB LED obtains a higher hole concentration in the p-GaN which contributes to an enhanced overall hole injection efficiency [131]. However, for the p-type doping in areas ① and ②, holes cannot be depleted to p-GaN layer due to the high barrier at QW/QB interface. Moreover, strain-induced electric field in QW does not favor the hole diffusion into the p-GaN layer. Figure 5.5 (b) displays the hole concentration profiles for LEDs with different Mg-doping positions, which support the explanation of hole migration into p-GaN layer.

Figure 5. 5 (a) Schematic bandgap diagram around depletion region with built-in electric field and strain-induced electric field noted, (b) the hole concentration profiles at EBL/p-GaN interface for LEDs with different Mg-doping positions. The hole movement is indicated if the depletion region is p-doped. ①, ②, ③, ④, and ⑤ denote the area of QB, QW, QB, EBL and p-GaN, respectively. Holes obtaining sufficient energy in area ③ and ④ overcome the barrier and transport to p-EBL, and then transport to and store in ⑤ together with holes in p-EBL. Holes with less energy in area ① and ② cannot be depleted to area ⑤, and will finally be eliminated by nonradiative recombination when the equilibrium state is built.

To precisely probe the effectiveness of depletion-region Mg-doping approach, we have measured and demonstrated the optical output power for the five InGaN/GaN MQW LEDs with Mg-doping at EBL, EBL+ $\frac{1}{2}$ QB, EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB, respectively. The experimental optical output power is measured by an Ocean Optics Spectrometer attached to integrating sphere and is depicted in the Figure 5.6. It is worth mentioning that the EBL and 2nd QB are full doped in order to cover the total area of the depletion region. As depicted in Figure 5.6, the depletion-region Mg-doping approach strongly influences the LED performance. The trend of increasing p-type doping range is not consistent with what we would expect that a longer p-type doping region can lead to better performance. The LED with p-type doping at EBL+ $\frac{1}{2}$ QB performs the best, which is attributed to the reduced hole barrier and enhanced hole concentration in p-GaN [131, 134]. Therefore, p-type doping in this region is proved to enhance the hole transportation, hence improving the LED performance. When the p-type doping area in the depletion region increases to the full QB, the performance does not further increase as we would expect, which is attributed to the Mg diffusion from QB into QW; and thus, the degraded crystalline quality induces a higher nonradiative recombination [135]. As a result, increasing the p-type doping range to QW and even to 2nd QB further degrades the LED performance. Note that LED with p-type doping at EBL+QB+QW+QB has better performance than other two LEDs with p-type doping at EBL+QB and EBL+QB+QW. These physical interpretations will be explained in the following analysis.

Figure 5. 6 Optical output power versus injection current for LEDs with varied p-type doping ranges in depletion region.

In order to support the above explanation that the QW quality is degraded and higher nonradiative recombination is caused during the p-type doping for LEDs, the corresponding experimental external quantum efficiency (EQE) is measured and presented in Figure 5.7. From this figure, we can see that the EBL LED and EBL+ $\frac{1}{2}$ QB LED have higher EQE value; however, EQE value drops fast as the current increases. On the other hand, the rest LEDs with more p-type doping region are observed to obtain an alleviated the efficiency droop even though the EQE values are not high. It is worth noting that the peak-efficiency current (I_{peak} : the current at which EQE reaches the maximum) is 1, 1, 3, 5, and 8 mA for LEDs with p-type doping at EBL, EBL+ $\frac{1}{2}$ QB, EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB, respectively. This value of peak-efficiency current is a signature of the QW quality and the nonradiative recombination in QWs, such that, a large I_{peak} denotes a poor QW quality and a high nonradiative recombination [31, 136]. Therefore, considering the undoped part of the last QB that decreases the Mg

diffusion into QW, LED with p-type doping at EBL+ $\frac{1}{2}$ QB shares almost the same QW quality as that with p-type doping at EBL. However, the QW quality gets worse for those LEDs with Mg-doping at EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB. Consequently, the degradation of QW quality is the major cause for lowering the LED performance. Note, although the worst crystalline quality is expected for the quantum wells in the EBL+QB+QW+QB doped LED, it shows a better EQE than the EBL+QB doped LED and the EBL+QB+QW+QB doped LED, and this might be due to the better electron blocking effect[137].

Figure 5. 7 Experimental EQE versus injection current for LEDs with varying p-type doping ranges in depletion region.

Figure 5.8 shows the EL spectra at different injection current of 100, 200, 300, 400, 500, and 600 mA for the LEDs with p-type doping at EBL, EBL+ $\frac{1}{2}$ QB, EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB. It can be seen from Figure 5.8 that all the EL spectra of the LEDs show a little blue shift when the current increases from 100 to 200 mA, which is due to the carrier screen effect. The EL

intensity of LED with p-type doping at EBL+ $\frac{1}{2}$ QB is highest, which is attributed to the reduced hole barrier and enhanced hole transport. Compared to LED with p-type doping at EBL+ $\frac{1}{2}$ QB, the EL intensity for LED with Mg-doping at EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB is reduced, which is caused by Mg diffusion that increases the nonradiative recombination.

Figure 5.8 Experimental EL spectra for LEDs with Mg-doping at EBL, EBL+ $\frac{1}{2}$ QB, EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB.

To further support this explanation, the carrier lifetime measurement for these InGaN/GaN LED devices with various p-type doping ranges in the depletion region was conducted utilizing a pico-second TRPL measurement system and the experimental results are presented in Figure 5.9. The decay time turns out to be shorter as the p-type doping range in the depletion region increases. As depicted in Figure 5.9, the carrier lifetime of 3.21, 3.17, 2.69, 2.26, and 1.75 ns is observed for LEDs with p-type doping at EBL, EBL+ $\frac{1}{2}$ QB, EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB, respectively. The difference among these luminescence decay times, under the low excitation power, is mainly caused by the different nonradiative recombination rates [124]. Consequently, the reduced carrier lifetime of LED devices with increasing p-type doping range in the depletion region can be a solid support to the claim that a more serious defect-related SRH recombination is induced when p-type doping is close to the active region.

Figure 5. 9 TRPL measurement for different LED devices with varied p-type doping ranges.

To verify the above claim, numerical simulations were performed by setting a decreased defect-related carrier lifetime for the studied devices, that is, the defect-related carrier lifetime was set to 16, 15, 13, 11, and 8 ns for LEDs with p-type doping at EBL, EBL+ $\frac{1}{2}$ QB, EBL+QB, EBL+QB+QW, and EBL+QB+QW+QB, respectively. Here, the SRH lifetimes used in the simulations are estimated by measured luminescence decay time and referring to our previous work as well [136, 138]. The calculated results are displayed in Figure 5.10, which exhibits the same trend as the experimental results given in Figure 5.7. The agreement between the numerical and experimental results supports that the increased nonradiative recombination appears with the increased p-type doping range close to the active region. Therefore, although p-type doping is an effective way to enhance hole injection and transport, the device performance enhancement is limited by the deterioration of crystal quality as the p-type doping is close to the active region. Thus, in order to release the full potential of p-type doping especially in the depletion region, for improving carrier transportation, Mg diffusion and migration have to be well controlled to guarantee the QW quality.

Figure 5. 10 Computed EQE with revised defect concentration as a function of operation current.

5.4 Conclusion

In conclusion, we have explored and investigated the p-type doping effect by using a model of depletion-region Mg-doping to reveal the underlying mechanism of p-type doping improvement. It was numerically found that the depletion region lies in the last QB and EBL for common EBL undoped InGaN/GaN LEDs and it will move forward and become larger when the depletion region is designed to be p-type doping. After p-type doping in the depletion region, the barrier for electrons is increased while it is reduced for holes, which contributes to the improved hole injection and transportation. Furthermore, the holes in the depletion region will move under the force of the built-in electric field and strain-induced electric field. Holes obtaining sufficient energy can overcome the EBL and be stored in p-GaN layer, while other holes will recombine nonradiatively when the equilibrium state is reached. Theoretically, it is better to have more p-type doped layers. However, experimentally we observed that if the p-type doping in depletion region is close to the active region, the quantum efficiency is reduced, which was attributed to the degrading crystal quality and the high nonradiative recombination resulting from Mg migration and diffusion. Therefore, p-type doping ranges near the depletion region will lead to significant increase of nonradiative recombination. This was confirmed by the carrier lifetime measurements and a good agreement has been achieved between the numerical simulation and experimental results when the p-type doping dependence of the defect-related carrier lifetime is considered in the modified numerical simulations. In summary, this work provides a detailed guidance of p-type doping in the LEDs, especially in the depletion region, to enhance carrier transportation and improve device efficiency.

Chapter 6 Micro-LED Dimension Investigation and

Designs in InGaN/GaN Light-Emitting Diodes

In this chapter, micro-wall geometry with different mesa dimensions for InGaN/GaN LEDs is designed and fabricated to investigate the size effect on the LED performance. Both the calculations and experimental results indicate that the LED devices with smaller dimensions deliver higher optical output power and have a better current-voltage characteristic, which are attributed to the improved current spreading effect. The lateral electron current density in p-GaN layer is examined for LEDs with various mesa sizes and the current profiles show an alleviated current crowding effect in p-GaN layer for LEDs with smaller dimensions. Through building a model for current paths, the underlying physics and mechanism of the improvement of current spreading effect are revealed by numerically calculating the average current density in the vertical direction. Furthermore, because of the alleviated current crowding effect, the electron overflow into the p-GaN layer is reduced thus contributing to an improved performance as well.

In order to meet the requirement for more output power and to avoid the serious current crowding effect in large size, a novel LED architecture with three micro-walls is proposed and demonstrated. The proposed three micro-walls LEDs possess enhanced light extraction efficiency thus a better performance is provided, which is attributed to the enlarged escape cone increased from 23.4° to 35.7° due to the fill of SiO_2 within the wall gap. Besides, it was found that the increasing of the wall spacing would lead to an enhanced LED performance resulting from the increased light escaping from device and reduced heat generation.

6.1 Micro-LED Dimension Investigation in InGaN/GaN Light-Emitting Diodes

6.1.1 Introduction

LEDs are important solid state lighting sources and regarded as a promising candidate to replace the conventional lighting devices. Currently, LEDs are extensively applied in various areas, such as automotive, backlight sources, display screens, electronic equipment, and general lighting. In order to fulfil the requirement of these applications, LEDs with various sizes and geometries are developed and fabricated accordingly [139-142]. Micro-LED is an emerging technology in the general lighting and display technology. As the name implies, micro-LED consists of tiny LED chips in micrometer sizes, which is reported to offer higher energy efficiency and lower power consumption [143-145]. Micro-LED display utilizes existing LED technology which is significantly more efficient at producing light compared to OLED, cathode ray tube (CRT) and other display technologies. For this reason, LEDs are fabricated into various structures with the dimension in micro-scale. In order to further improve the output power and luminous flux of a micro-LED, one potential approach is to optimize its size and emitting surface area. At the same time, the size of LEDs is limited by the insufficient current spreading due to the low conductivity of the p-GaN layer. As a result, the dimension effect at the micro-scale on the LED performance is still necessary to explore to further improve the optical output power.

In this work, we develop and comparatively study flip-chip LEDs with varied mesa areas: 45×200 , 90×200 , 135×200 , and $180 \times 200 \mu\text{m}^2$. The distance between the n-electrode and mesa is fixed in order to keep a fair comparison between the different sizes of the LEDs. The experimental results, in conjunction with numerical calculation reveal the influence of mesa dimension on LED performance.

6.1.2 Growth and Fabrication of LED Devices

Four blue InGaN/GaN MQW LEDs studied in this work were grown on c-plane patterned sapphire substrates by MOCVD system. The sapphire substrate used is two-inch PSS that has periodic cone patterns with a diameter of $2.4 \mu\text{m}$, a height of $1.5 \mu\text{m}$ and a pitch of $3 \mu\text{m}$. The growth started with a low temperature (560°C) GaN

buffer layer with a thickness of 30 nm, followed by a 150 nm u-GaN interlayer. Subsequently, a 3- μm thick u-GaN was grown at a high temperature of 1050°C, and then followed by a 2 μm thick Si-doped GaN layer with a doping concentration of $5 \times 10^{18}/\text{cm}^3$, in which SiH_4 was adopted as the dopant source. Then, eight pairs of $\text{In}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$ MQWs with 3-nm thick QW and 12-nm thick QB were grown. In addition, a 20-nm thick p-doped $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$ EBL was grown to suppress the excess electron overflow into the p-GaN region. Subsequently, a 200-nm thick Mg-doped GaN with a doping concentration of $3 \times 10^{17}\text{cm}^{-3}$ was grown as the hole source layer. The p-type conductivity of the EBL and the hole source layer was realized by Mg doping where Cp_2Mg was used as the Mg precursor. Subsequent to the epitaxial growth, the LED wafers were fabricated into flip-chip LED devices using standard fabrication processes. The mesa area was shaped using reactive ion etching (RIE) and the corresponding dimensions for these four LEDs were $45 \times 200 \mu\text{m}^2$, $90 \times 200 \mu\text{m}^2$, $135 \times 200 \mu\text{m}^2$ and $180 \times 200 \mu\text{m}^2$, respectively. Ni/Ag (5nm/5nm) metal layers were deposited as the current spreading layer by using e-beam evaporation, and Ti/Au (30 nm/1000 nm thick) metal layers were deposited as p- and n-electrode. A schematic diagram of the device structure is shown in Figure 6.1. The current-voltage characteristics were determined by a LED tester (M2442S-9A Quatek Group) and the optical output power was measured by an integrating sphere attached to an Ocean Optics spectrometer (QE65000).

Figure 6.1 Schematic diagram of device structure. X is the direction parallel to device surface, while Y is perpendicular to it.

In order to understand the underlying physics, numerical modelling was performed by APSYS to reveal the effect of the mesa dimension on the electrical and optical properties. In the simulations, the carrier screening effect in the InGaIn quantum wells was taken into account using the self-consistent six-band $k \cdot p$ theory. The Auger recombination coefficient was set as $1 \times 10^{42} \text{ m}^6/\text{s}$ and the SRH lifetime was set to 43 ns. Simultaneously, due to the crystal relaxation through dislocation generation during the practical growth, a 40% of the theoretical polarization induced sheet charge density was assumed in the heterojunction of $\text{In}_{0.15}\text{Ga}_{0.85}\text{N}$ quantum well region, the energy band offset ratio $\Delta E_c / \Delta E_v = 70/30$ was taken. The other parameters used in the simulation can be found elsewhere [130, 146-148].

6.1.3 Comparative Results of LED Devices and Discussion

Figure 6.2 presents the electroluminescence spectra for the studied LEDs with different mesa dimensions, where the emission density is the strongest for the 45 μm LED. Meanwhile, the EL intensity for LEDs with larger mesa size is reduced as the increase of the mesa dimension.

Figure 6.2 EL spectra for LEDs with different mesa dimensions at the current density of 100 A/cm^2 .

The experimental and simulated output power as a function of current density for LEDs with different mesa dimensions are illustrated in Figures 6.3 (a) and (b), respectively. As we can see from Figures 6.3 (a) and (b), both the experimental and simulated results of output power show the same trend, that is, with the mesa dimension decreases from 180 to 45 μm , the output power increases consistently. The improved performance obtained from the smaller mesa dimension can also be observed in the curves for current density (J) versus voltage (V) as shown in Figure 6.4. This enhancement is attributed to the improved current crowding effect which is elucidated in the following discussion.

Figure 6.3 (a) Experimental and (b) simulated optical output power for LEDs with different dimensions of mesa.

Figure 6.4 (a) Experimental and (b) simulated J - V curves for LEDs with varied mesa dimensions.

The horizontal profiles of electron current densities at the middle of p-GaN layer from mesa edge to 45 μm off the edge for the LEDs with different mesa

dimensions are plotted in Figure 6.5. It can be clearly seen that most electrons are located at the edge of the p-electrode for all the LEDs with varied mesa sizes, implying the homogeneous distribution of carrier in the X direction. This is caused by current crowding effect, which is always a tough issue for lateral LED geometry. However, the current crowding effect near the edge is alleviated and the electron can distribute more uniform along the X direction for LEDs with smaller dimensions. Since the LEDs are of different mesa dimensions, the mesa size is normalized by dividing the corresponding dimension. Figure 6.6 clearly shows that more uniform electron current distributions are obtained when LEDs have smaller mesa dimensions.

Figure 6.5 The electron current density along X direction at the middle of p-GaN layer from mesa edge to 45 μm off the edge for LEDs with different dimensions.

Figure 6.6 Horizontal profiles of electron current as a function of normalized distance for LEDs with varied mesa dimensions.

Figure 6.7 (a) presents the schematic drawing of the current paths of a common LED. The length and width of the mesa are L and L_0 . In our case, the value of L is 45, 90, 135, and 180 μm , and the L_0 is fixed to a value of 200 μm . The mesa edge is W . To facilitate the analysis, we further simplify the equivalent circuit as shown in Figure 6.7 (b), in which R_l denotes the resistance along the vertical direction from the p-contact layer to the active region and R_0 denotes the resistance of n-GaN layer per unit length. I_i is the current corresponding to each path where $i = 1, 2, \dots, k-1$, and k , in which m is infinity, and x denotes its corresponding length. V is the bias voltage applied to LED.

Figure 6.7 (a) Schematic drawing of current paths, and (b) simplified circuit model for LED.

According to the model shown in Figure 6.7 (b), current crowding effect can be expressed as the average of all I_i , which is denoted as $I_{average}$. If the value of $I_{average}$ is large, that means that crowding effect is alleviated. We use this model to explore the relationship between mesa dimension and current crowding effect.

$$I_i = \frac{V}{R_1 + xR_0 + WR_0} \quad (6.1)$$

$$I_{average} = \frac{1}{L} \int_0^L I_i dx = \frac{1}{L} \int_0^L \frac{V}{R_1 + xR_0 + WR_0} dx \quad (6.2)$$

$$I_{average} = \frac{V}{R_0 L} \left(\ln \frac{1}{R_1 + LR_0 + WR_0} - \ln \frac{1}{R_1 + WR_0} \right) \quad (6.3)$$

As indicated in equation (6.3), $I_{average}$ decreases with the increase of L . That is, for LEDs with smaller dimensions, the current spreads better in horizontal direction and hence current crowding effect is alleviated.

Figure 6.8 Computed electron concentration in the EBL and in the p-GaN region for the LED samples at the current density of 300 A/cm^2 .

Moreover, due to the improved current spreading, the electron overflow into p-GaN will be suppressed. The simulated electron concentration near the p-GaN is depicted in Figure 6.8 for the LED devices under the current injection level of 300 A/cm^2 , which demonstrates that the electron concentration in EBL and the p-GaN region is reduced when the mesa dimension decreases from 180 to 45 μm . The reduction of the electron concentration in the p-doped region indicates the effective suppression of the electron leakage. These results suggest that with a smaller mesa dimension, the current crowding effect is alleviated and the electrons will spread more homogeneously. As a result, the optical power is increased, as shown in Figure 6.3. Meanwhile, the increased ratio of side surface to the whole mesa area for the LEDs with smaller mesa sizes leads to improved heat dissipation, which contributes to improvement of the LED performance as well.

6.1.4 Conclusion

The InGaN/GaN LEDs with different mesa dimensions are investigated to explore the size effect on the LED performance. The experimental and calculated optical output power and J - V curves indicate that the LED with smaller mesa dimension performs better than that with large mesa size. The mechanism of this enhancement is revealed by using a model of current paths, which suggests that the current crowding effect is alleviated for LED with smaller mesa dimension. In addition, the lateral electron current distributions in the p-GaN layer are also a solid support to the explanation. Due to the alleviated current crowding effect, the electron overflow into p-GaN region is reduced as well.

6.2 Micro-LED Designs in InGaN/GaN Light-Emitting Diodes

6.2.1 Introduction

Owing to the advantages of small mesa dimensions in alleviating current crowding effect for LEDs, micro-LEDs have attracted a large amount of attention and substantially applied in display and lighting technologies [149, 150]. However, the total power and flux of solely one LED with small size is not able to reach the requirement for more specialized applications. On the other hand, even though LEDs with large size can meet the demand of optical power, the energy conversion efficiency is lower than the small-size LEDs under the same current density injection. Moreover, the large-size LEDs suffer from insufficient heat dissipation due to the small side-wall surface ratio. Therefore, we propose a new LED architecture by incorporating several micro-LEDs into a device. The advantages of this structure are the alleviated current crowding effect, higher light extraction efficiency, less thermal heat generation, and improved heat dissipation from the side wall surface.

In this study, a wall-like LED structure consisting of three micro InGaN/GaN LEDs with different wall spacing is demonstrated and investigated. The optical output power of the proposed LED and single micro-wall LED is comparatively

studied. The light extraction and thermal heat generation is comparatively discussed.

6.2.2 Device Fabrication

After MOCVD growth was completed, the wafers were fabricated into LED devices with proposed the 3 micro-walls and the 1 micro-wall structures. The fabrication process started with mirror deposition on the bare LED epi-wafer. The mirror deposition of Ni/Ag was performed by e-beam evaporation. After that, wet etching of Ni/Ag was conducted using hydrochloric acid (HCl) and Nitric acid (HNO₃) to open the window for mesa etching. Then a rapid thermal annealing process was conducted at 550 °C for 5 min, to oxidize the Ni layer into NiO seeds, and form low resistive ohmic contact with the p-GaN layer. Subsequently, mesa area was defined by reactive ion etching (RIE) to expose the n-GaN area. In this process, different mask patterns were adopted to shape the different mesa structures. Subsequent to that, LED structures of three and one micro-walls were defined with the wall dimensions of $45 \times 200 \mu\text{m}^2$. For the LEDs with three micro-walls geometry, the wall spacing was designed to be varied as 11, 22, and 33 μm . In order to reduce the current leakage and increase the light extraction efficiency, the wall gap was filled with SiO₂ by chemical vapor deposition (CVD) and the corresponding thickness was 1.4 μm . Finally, Ni/Ag/TiW layer with a typical film thickness of 0.5/200/500 nm was deposited as contact pads for both the n- and p-electrodes. The schematic diagrams of the different LED structures are shown in Figure 6.9 and the fabricated devices are presented in Figure 6.10.

Figure 6. 9 Schematic diagram of two LED architectures: one micro-wall LED (top) and three micro-walls LED (bottom).

Figure 6. 10 Fabricated LED devices (a) single wall LED, (b) three-wall LED with wall spacing of 11 μm , (c) three-wall LED with wall spacing of 22 μm , and (d) three-wall LED with wall spacing of 33 μm .

6.2.3 Comparison Results of LEDs and Discussion

Figure 6. 11 Optical output power for single micro-wall LED and proposed three micro-walls LEDs.

Figure 6.11 displays the optical output power for single micro-wall LED and proposed three micro-walls LEDs. As can be seen from Figure 6.11, the proposed three micro-walls LEDs has a higher output power than that with single micro-wall, which is attributed to the improved light extraction efficiency. Figure 6.12 displays the light escape cone for the LED with SiO₂ deposited. According to Snell's law [151], the relationship between the angles of incidence and refraction is expressed as:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (6.4)$$

where n_1 and θ_1 are the refractive index and incidence angle for material 1, and n_2 , θ_2 are the refractive index and incidence angle for material 2. Under the total internal refraction, we calculate the critical angel (θ_c), as:

$$\theta_c = \arcsin \frac{n_2}{n_1} \quad (6.5)$$

For GaN-based LED, the refractive index for GaN, SiO₂, and air are 2.52, 1.47, and 1, respectively. Therefore, we calculate the escape cone for GaN/air and GaN/ SiO₂ to be 23.4 ° and 35.7 °, respectively. As indicated in Figure 6.12, the adoption of SiO₂ leads to an increased escape cone, thus higher light extraction efficiency is obtained for the proposed geometry.

Figure 6. 12 The increase of light escape cone due to the adoption of SiO₂ for GaN-based LED.

Furthermore, the increase of wall spacing contributes to a better performance, because with large wall spacing, more light escapes from the side wall gap rather than reentering the nearby GaN wall and being absorbed. In addition, there is less thermal heat generation for the LED with wider wall spacing due to the reduced series resistance when current horizontally passes the n-GaN layer. Figures 6.13 (a) and (b) depict the current paths for the LEDs with three micro-walls geometries and a simplified current paths model. As indicated in the Figure 6.13 (b), the voltage and the thermal heat generation in the LED can be expressed as:

$$V = I(R_1 + R_0) \quad (6.6)$$

$$J_{heat} = I^2(R_1 + R_0) \quad (6.7)$$

$$R_0 = \rho \frac{l}{S} \quad (6.8)$$

where R_1 is the total resistance of top contact layer, p-GaN layer, and active region; R_0 denotes the resistance of n-GaN; V is the applied voltage; I is the current; ρ , l ,

and S denote the resistivity of the n-GaN, the lateral distance from n-electrode to mesa edge, and the surface area of n-GaN in horizontal direction, respectively. According to equation (6.8), if the spacing of the micro-walls increases the resistance of R_0 increases due to the enlarged area S . Hence, the total heat generation in the LED device is reduced, which contributes to a better LED performance. It is worth noting that the enhancement of the proposed LEDs is more significant under lower current injection than that in the high current injection case. This can be explained by the fact that reduced thermal heat generation and light extraction improvement for the side wall surface is constrained by current injection.

Figure 6. 13(a) Illustration of current path for LEDs with three micro-walls architecture, (b) simplified current path model.

6.2.4 Conclusion

InGaN/GaN LEDs with micro-wall architectures are demonstrated and the comparative study is performed. The proposed structure has the advantage of alleviating current crowding effect, enhancing the light extraction efficiency due to the adoption of SiO_2 , and generating less thermal heat. Therefore, a better performance is observed in the proposed LEDs.

6.3 Conclusions

In summary, InGaN/GaN LEDs of micro-wall geometry with different mesa dimensions are designed and fabricated to investigate the size effect on the LED performance. Both the calculated and experimental results indicate that the LED devices with smaller dimension deliver higher optical output power and have a better current-voltage characteristic under the same current density, which are attributed to the improved current spreading. The lateral electron current density in p-GaN layer is examined for LEDs with various mesa sizes and the current profiles show an alleviated current crowding effect in the p-GaN layer for LEDs with smaller dimensions. Through building the model for current paths, the averaged current density is calculated, which indicates that the current spreading is enhanced when the mesa size is decreased. In addition, owing to the alleviated current crowding effect, the electron overflow into p-GaN region is also suppressed.

A novel LED architecture with three micro-walls is also proposed and demonstrated. The proposed three micro-walls LEDs have a better optical performance due to the enhanced light extraction efficiency. In this structure, SiO₂ is used to fill in the wall gap, which leads to an enlarged escape cone increased from 23.4° to 35.7°. Furthermore, the increase of wall spacing contributes to a higher optical output power, and this is because with large a wall spacing, more light will escape from the side wall gap rather than re-entering the nearby GaN wall and being absorbed. In addition, there is less heat generation for the LEDs with wider wall spacing due to the reduced series resistance when current horizontally passes the n-GaN layer.

Chapter 7 Conclusions and Recommendations

7.1 Conclusions

In this dissertation, the InGaN/GaN multiple quantum well LED epitaxial wafers with high quality and uniformity were grown on c-plane patterned sapphire substrate through MOCVD method. In order to fabricate the LED wafer into chips, a stable and reliable standard fabrication procedure was developed for flip-chip LEDs. Based on the epitaxial growth and fabrication, several key factors including quantum well number, p-type doping, mesa size, and light extraction were systematically investigated both experimentally and numerically.

Since the QW number determines the active volume for recombination and influences the carrier distribution owing to the difficulty of hole transport into the active region, the choice of QW number is crucial to LED performance. Consequently, in this thesis a comparative study of InGaN/GaN LEDs with varied QW number was conducted. According to the numerical results, with the increase of the QW number, the optical output power and efficiency droop are improved due to the reduction of electron concentration in the QWs and thus reduced Auger recombination. The increase of hole concentration in the QW caused by the suppression of electron overflow into the p-GaN region also benefits the LED performance. Moreover, through building a model for current paths, it was found that the current crowding effect is alleviated for LEDs with more QWs. On the other hand, the experimental results indicate that even though the efficiency droop is improved, the optical power increases first then declines as more QWs are introduced, which exhibits a discrepancy between the numerical and experimental results. Analyzing the experimentally measured external quantum efficiency with ABC model reveals that even though increasing the QW number is an effective way to suppress the efficiency droop, the device performance enhancement is limited simultaneously by the lowering crystal quality when the QW number increases. The carrier lifetime measurement of the LEDs wafers with different QW number and the revised simulation with varied SRH lifetimes also support the

observation that more serious nonradiative recombination is caused when more QWs are implemented, which may be attributed to increased defects generation during epitaxial growth.

Due to the limitation of the hole injection, p-type doping was explored for InGaN/GaN LED with 8 QWs. Here, we propose a depletion-region Mg-doping method, and we systematically analyzed the effectiveness of different Mg-doping profiles ranging from the electron blocking layer to the active region. With this approach, the carrier dynamics and bandgap profiles were examined using the APSYS simulator. The numerical computations show that the Mg-doping decreases the valence band barrier for holes, and thus enhancing the hole transportation. Furthermore, the depletion-region Mg-doping approach increases the barrier height for electrons, which leads to a reduced electron overflow into the p-GaN region. More importantly, the holes in the depletion region is depleted to the p-GaN layer under the force of the built-in electric field and strain-induced electric field, which increases the hole concentration in p-GaN layer.

Experimentally measured EQE indicates that Mg-doping position is vitally important, i.e., the doping in/adjacent to QW degrades the LED performance due to Mg diffusion, which increases the corresponding nonradiative recombination that has been well supported by measuring the carrier lifetime. In addition, the experimental results were well reproduced by modifying the nonradiative recombination lifetimes, which further validates our assumption.

In order to further improve the output power and luminous flux of a micro-LED, one potential approach is to optimize its size and emitting surface area. At the same time, the size of LEDs is limited by the insufficient current spreading due to the low conductivity of the p-GaN layer. Thus InGaN/GaN LEDs of micro-wall geometry with different mesa dimensions were designed and fabricated to investigate the size effect on the LED performance. Both the calculated and experimental results indicated that the LED devices with smaller dimension deliver higher optical output power and have a better current-voltage characteristic under the same current density, which are attributed to the improved current spreading.

The lateral electron current density in p-GaN layer was examined for LEDs with various mesa sizes and the current profiles apparently show an alleviated current crowding effect in the p-GaN layer for LEDs with smaller dimensions. Through building the model for the current paths, the averaged current density was calculated, which indicates that the current spreading is enhanced when the mesa size is decreased. In addition, owing to the alleviated current crowding effect, the electron overflow into p-GaN region is also suppressed.

Finally, in order to meet the requirement for more output power and to avoid the serious current crowding effect in large size, a novel LED architecture with three micro-walls is proposed and demonstrated. The proposed three micro-walls LEDs possess enhanced light extraction efficiency thus a better performance is observed. The improvement is caused by the adoption of SiO₂ in the wall gap, which leads to an enlarged escape cone increased from 23.4 ° to 35.7 °. Furthermore, the increase of wall spacing contributes to a higher optical output power, because with a large wall spacing, more light escapes from the side wall gap rather than re-entering the nearby GaN wall and being absorbed. In addition, there is less heat generation for the LEDs with wider wall spacing due to the reduced series resistance when current horizontally passes the n-GaN layer.

In summary, this dissertation covers the knowledge of the material properties of III-nitride compounds, mechanisms of recombination radiation, epitaxial layer growth, fabrication procedures for flip-chip LEDs and characterization approaches. Several critical factors including QW number, p-type doping, mesa size and light extraction for InGaN/GaN MQW LEDs were investigated both numerically and experimentally. The underlying physics and mechanism of how these factors influence the LED performance are explored. This work provides a comprehensive knowledge of GaN-based LEDs and useful guidelines on designing and developing a high performance InGaN/GaN LEDs.

7.2 Recommendations for Future Work

In this thesis we have explored the influence of p-type doping on LED performance and examined the carrier distribution within the MQWs. Even though p-type doping is able to lower the barrier height for hole thus enhance the hole transportation, p-type doing in or adjacent to the QWs degrades the quality of QWs. However, from the experimentally measured EQE curves in chapter 5, we found that the efficiency droop for LEDs with degraded QW quality, seem to be improved compared to other LEDs under relatively high current injection condition. This means even though p-type doing in the active region may degrade the performance under low current levels, the hole transport improvement due to p-type doping turns to be more significant under high current density, which may compensate the performance degradation caused by lowering crystal quality. Therefore, we can design the LED structures that have p-type doping in the QBs close to n-GaN layer with a purpose of improving hole transport. The schematic structure of the proposed LED with p-type doing at several QBs close to n-GaN layer is shown in Figure 7.1. By adopting the p-type doping in these QBs or even QWs, the performance of this proposed LEDs will not be substantially affected in the event of low injection level while a better performance may be observed in high current injection condition.

Due to the difficulty of hole transport, under low current injection most of holes cannot penetrate into deeper active region thus only a few QWs close to p-GaN account for the recombination. So that even though the Mg-migration and diffusion may affect the nearby QW quality, their contribution to the recombination is minor due to their low hole concentration under low current levels. Furthermore, in case of high current injection condition, the hole transporting into deeper QWs due to Mg-doping effect contributes to a better performance.

Figure 7. 1 Schematic diagram of the proposed LEDs with Mg doping at several QBs close to n-GaN layer.

In addition, from the perspective of LED application to solid state lighting, the major objective is the white light. Thus, the light emitted from the InGaN/GaN LEDs is investigated to generate white light by adopting yellow (green or red) phosphors, for instance cerium (III)-doped yttrium aluminum garnet (Ce:YAG) [152, 153]. However, the phosphors, employed to convert blue light to green, yellow and even red light, have longer tail emission in the green/yellow region which leads to a low color quality. Moreover, the conversion efficiency of blue light into red is not sufficient compared with that of the green and yellow color. Meanwhile, colloidal quantum dots provide alternative promising approach to convert the blue light into white light. The advantage of quantum dots in color purity, high external quantum efficiency, coverage of whole visible light spectrum, flexibility, and low production cost make it very attractive in color conversion applications [154-157]. Based on the micro-wall architecture, the quantum dot

color converters can be employed into the InGaN/GaN LEDs, as shown in Figure 7.2, to generate white light.

Figure 7. 2 White-light generation structure for micro-wall LED with quantum dots filling in the wall gap.

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