Design of Narrow Linewidth Nonpolar m-plane InGaN/GaN Micro-Scale Light Emitting Diode

A thesis submitted
by

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CERTIFICATE

This is to certify that the dissertation report entitled **"Design of Narrow Linewidth Nonpolar m-plane InGaN/GaN Micro-Scale Light Emitting Diode"** has been successfully completed and presented by **Lokesh Sharma** of Second year, IV semester in partial fulfillment of degree of **Master of Technology** in **Electronics and Communication** during the academic year **2018-2019** to the best of my knowledge and belief that this work has not been submitted elsewhere for the award of any other degree.

The work has been found satisfactorily carried out by him under my guidance and supervision in the department and is approved for submission.

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DECLARATION

I, **Lokesh Sharma**, declare that this Dissertation titled as **”Design of Narrow Linewidth Nonpolar m-plane InGaN/GaN Micro-Scale Light Emitting Diode”** and the work presented in it is my own and that, to the best of my knowledge and belief.

I confirm that major portion of the report except the refereed works, contains no material previously published nor present a material which to be substantial extent has been accepted or the award of any other degree by university or other institute of higher learning. Wherever I used data (Theories, results) from other sources, credit has been made to that source by citing them (to the best of my knowledge). Due care has been taken in writing this thesis, errors and omissions are regretted.

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”Dedicated to my family” for their sacrifices, endless support, encouragementand love

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Abstract

We need more and updated infrastructure in order to meet the demand of high speed mobile communication for rapidly increasing population. New technologies in the field of wireless need to be developed which support the existing technologies and updated versions of it. Communication industry plays an important role in the economy of any country and for whole world as well. Now-a-days lots of data is transfered from one point of globe to other and that too within fraction of seconds, we want our communication network to be quick, reliable and secure, to incorporate these features our communication techniques needs regular updation. The ongoing era belongs to wireless communication, Everyday the number of wireless devices are increasing exponentially. The available spectrum and Internet speed is neither sufficient enough nor capable of handling the load. To overcome these issues new updated communication techniques were invented and old technique are either updated or replaced. VLC, Li-Fi, FSO are some of the latest communication techniques in trend. Continuous demand motivated the researchers to keep on exploring the new possibilities. In our research work we focus on visible light communication and LEDs which acts as a source of light emission for visible light communication. VLC has some unique features which make him compatible with advanced wireless technologies, such as energy efficiency and ultra wide bandwidth, along with some shortcoming in transmission range and obstacles in transmission paths.it is a trade off between pros and cons but here the pros are dominating. Light Emitting Diodes (LED) is a potential source of VLC and among all the available LEDs InGaN and GaN are most suitable because of efficient power consumption at nominal extra cost with effective lightning and data communication rate. We discuss the modification attempted so far with InGaN and GaN LED and its impact on communication techniques. Economy of any country depends upon how it utilize the available energy resources. By using energy efficient electronics device one can reduce the energy consumption upto a great extent. we attempted to modify the parameters of LED in order to optimize its linewidth and to enhance its efficiency, reduce it power consumption and increase its speed to transmit the data at higher rate.

List of Important Abbreviations

LED	Light Emitting Diode
LASER	Light Amplification by Stimulated of Radiation
FSO	Free Space Light Optical Communication
MOST	Media Oriented System Transport
OPSD	Optical Power Spectral Density
VLC	Visible Light Communication
IQE	Internal Quantum Efficiency
EQE	External Quantum Efficiency
PSD	Power Spectral Density
POF	Plastic Optical Fiber
LI	Luminous Intensity
Wi-Fi	Wireless Fidelity
Li-Fi	Light Fidelity
RF	Radio Frequency

CB	Conduction Band
SD	Spectral Density
VB	Valence Band
UV	Ultra Violet
Al	Aluminum
GaN	Gallium Nitride
InGaN	Indium Gallium Nitride
nm	Nanometer

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Chapter *1*

Introduction

1.1 Introduction

Terms which are very common in communication industry are Visible light communication (VLC), Light Fidelity (Li-Fi), Free space optical communication (FSO). All these are backbone of the communication industry and these are among the upcoming latest technology. All these communication techniques have some sort of similarity between them. When we talk about VLC, an illumination source(e.g. a light bulb) along with illumination it send information using the same light signal. Any form of information that is sent by using a light signal that is visible to humans could be considred as VLC, but by our defenition the light should be visible to us, but as we cannot see the data, So there seems to be some contradiction but still we can agree on the above mentioned defenition of VLC. And we can at least agree what we meant by VLC. LED bulbs have became a very popular source for high speed data transmission. As they can be switched at a very high speed. Light bulb such as fluorescent and incandescent lamps which are using technology which has advanced in years couldn't perform at high speed. As a result LED is dominating the market and creating multiple options for VLC.
FSO is an optical communication technique based on line of sight technology and it uses lasers to provide optical bandwidth. FSO propagates light in free space (i.e. air) in a similar fashion like a data transmitted wirelessly. The max data rate achieved so far by FSO is 2.5 Gbps and is capable of sending data,voice and video communication through air.It's operational range is between 780 nm-1600 nm. The light used by FSO can be generated by either LED or LASER. It is considered as an alternate to radio relay link line of sight communication.
Li-Fi is an acronym of Light fidelity it falls under Visible light communication systems which operated wirelessly with a ver high speed. With Li-Fi your light bulb is essentially

your router.It uses common household LED light bulb to enable data transfer. Li-Fi is capable of up to 224 Gbps. Both Li-Fi and Wi-Fi transmit data electromagnetically. However, Wi-Fi send data thru radio waves, and Li-Fi uses visible light waves to transmit [23]. Optoelectronics devices are basic building block of communication techniques. These devices acts as a source of light being used. Based on their efficiency and performance the corresponding communication technique perform.To enhance the capability of communication techniques one of the method is to improve the optoelectronic device which is being used.

1.2 A Brief Introduction of Optoelectronics

Optoelectronics is the link between optics and electronics. it include study, designing and hardware implementation of optoelectronics devices which transform electrical energy into light and then further transform this light into energy through semiconductors. Broadly optoelectronic devices are divided into two sub-categories, i.e. systems that emit light or detect light. To generate electromagnetic radiation (i.e. light), devices that emit light use voltage and current. Such light-emitting devices are frequently used for illumination purposes or as indicator lights.

On the other side, light detection systems, such as phototransistors, are intended to transform electromagnetic energy obtained into electrical current or voltage. Devices for light detection and interaction can be used. These include dark-activated switches and remote controls as perfect examples. Generally speaking, devices for light detection job by using photons to release bound electrons into semiconductor materials. In our discussion we will talk about light emitting devices mostly. Semiconductor devices those who emit light are categorized into four categories based on the mode of excitation which trigger the photon that is responsible for the luminescence.

Types of luminescence Based on electronic excitation luminance are of following type.

- Photoluminescence - incident light is the cause for electronic excitation.
- Cathodoluminescence - When an electron beam is passed through, electronic excitation is generated.
- Radioluminescence - ionizing radiation (β-rays) responsible for electronic excitation.
- Electroluminescence - electric field creates electronic excitation.

Examples of optoelctronics devices:

- LEDs
- Solar Cell
- Photo diode
- Incandescent lamp

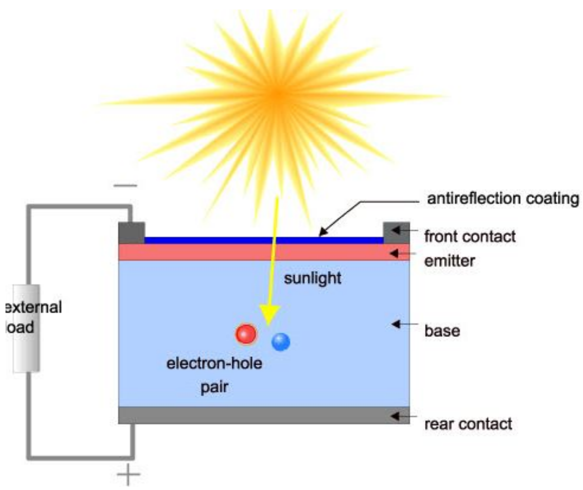

Figure 1.1: Solar Cell [13]

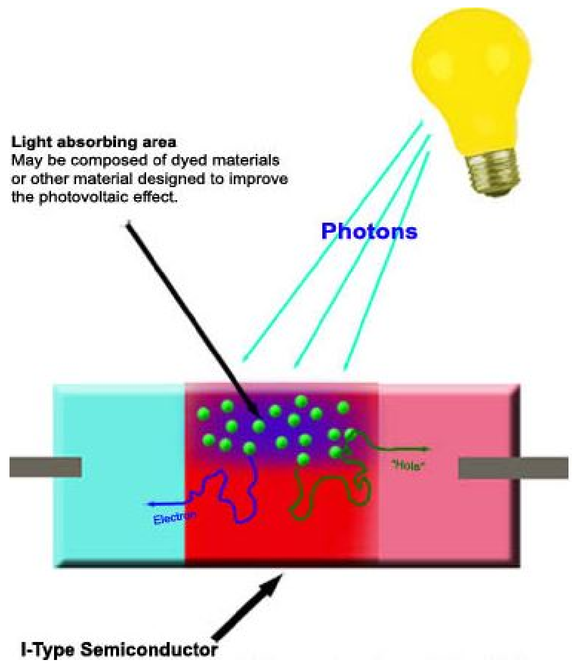

Figure 1.2: Photo Diode [13]

1.3 Light Emitting Diode (LED)

Among the various available semiconductor devices in our research work we will study about LED. LEDs are the devices which convert electrical current to electromagnetic radiation. Electronic devices traditionally access only a small fraction of the electro-magnetic radiation. The electromagnetic radiation available belongs to the visible region of the electromagnetic radiation range, the Infra red region and the Ultra Violet area. LEDs emits light and belong to the general class of luminescent devices. This process is known as Luminescence, the process in which a material absorbs light energy emitted from an external source and re-emits this energy in the form of visible region. When the excited particle returns to the floor, the photon emitted will fall into the Electromagnetic radiation category [17].

1.3.1 Selection of Material For LED

Light-emitting diode(LEDs) are two terminal semiconductor devices comparable to ordinary diode except that they can emit light in visible region, infrared area, or ultraviolet region. Light emission is only possible if we choose the correct semiconductor material. Based on band gap (i.e. the difference between the conductive energy level and the valence band), semiconductor material is divided into two sub-categories (a) Direct band gap,

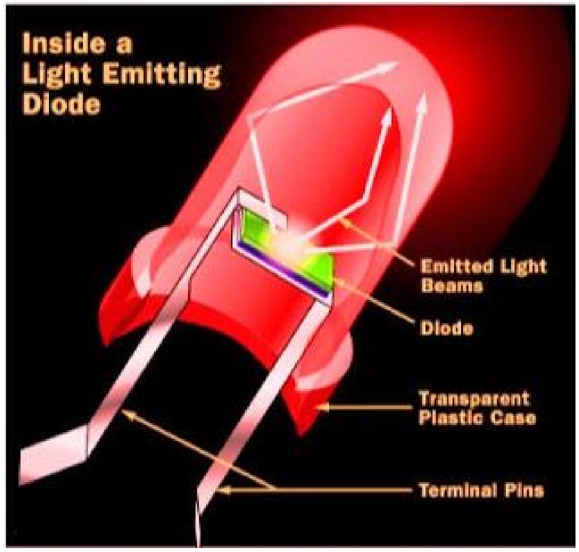

Figure 1.3: Internal Structure of LED [13]

(b)Indirect band gap materials. Figure 1.2 shows the difference between direct and indirect semiconductor materials based on Energy-Momentum curve.

Direct Band Gap: The power connected with the bottom of the conductive band(CB) and top of the valance band(VB) has nearly the same crystal momentum values. Thus the possibility of direct recombination of electron with holes increases which give rise to emission of photons. The most popular examples of direct band gap semiconductor material are GaAs, GaSb, InAs etc.

Indirect Band Gap: When compared to the top of the valence band, the energy connected with the bottom of the conductive band(CB) has surplus crystal momentum.To preserve the momentum recombination of the electron-hole involves photon emission and at the same time a rare phenomenon. For example, Si, Ge, GaP are indirect band gap materials.

Among the direct band gap materials, GaAs is the most preferred semiconductor for fabricating LEDs. Its band gap Eg=1.43ev and it can be doped with n type as well as with p type impurities.

1.3.2 Spectrum of Injection Luminescence

The color and wavelength emitted by LED is based on the bandgap of the semiconductor material selected. Figure 1.3 depicts the difference of energy between the bottom of

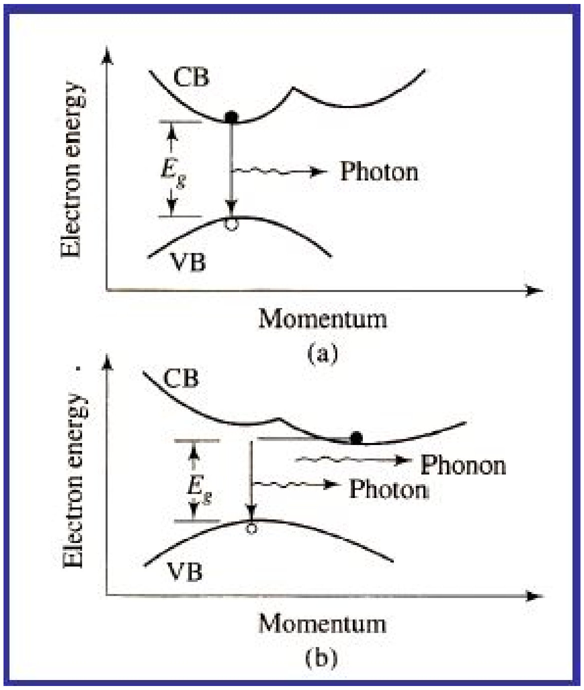

Figure 1.4: Schematic Energy-Momentum diagram (a)Direct band gap (b)Indirect band gap semiconductor [13]

the conduction band and top of valence band.

The Spectral distribution of the emitted radiation is calLED the spectrum of injection Luminescence.

Wavelength associated and energy released with the emitted photon is mathematically expressed as

$$E_{ph} = \frac{hc}{\lambda} = E_C - E_V = E_G \tag{1.1}$$

If the material is chosen correctly then the LED will emit light in the visible region.

Tables 1.1 contain details about the semiconductor material, wavelength of the emitted photon and color associated with that wavelength.

Characteristic of LED

- Relatively Wide Spectrum Produced- LEDs do not generate single wavelength but rather a band of wavelengths and that band is calLED spectral width.

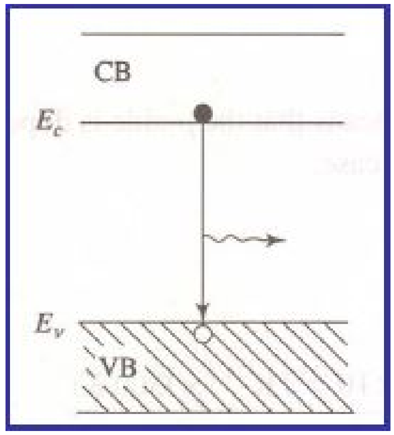

Figure 1.5: Transition of emitted photon from higher state to lower state [13]

S. No.	Wavelength(nm)	Color	Material
1	< 400	UV	AlN, AlGaN, AlGaInN
2	400-450	Violet	InGaN
3	450-500	Blue	InGaN,SiC
4	500-570	Green	Gap, AlGaInP, AlGaP
5	570-590	Yellow	GaAsP, AlGaInP, GaP
6	590-610	Orange/Amber	GaAsP, GaP
7	610-760	Red	AlGaAs,GaAsP,Gap
8	>760	Infrared	GaAs, AlGaAs

Table 1.1: Typical LED Characteristic
[13]

- Incoherent Light- The light produced by LED is neither directional(i.e in a single direction) nor coherent(same phase).

- Digital Modulation- Digital modulation is undemanding. It will turn on the device when forward voltage is applied and the potential developed is greater than the required bandgap energy and comes to an end as voltage drop across it.

- Low Cost- LEDs are cheaper when compared to Lasers.

- Low Power- Maximum generated light output is very less than laser.

1.3.3 LED Operations

The LED is a specific PN junction type that utilizes a junction of a compound. It is a two terminal semiconductor light source. It's a p-n junction diode that only emit lights when it's biased forward. When the voltage applied exceeds the barrier potential, electrons obtain the energy needed to cross the junction and recombine with the hole inside the device, which in turn releases photon-like energy This effect is known as electroluminescence. The color of the light emitted corresponding to the photon's energy depends on the semiconductor's band gap. Junction made up of simple element like Si and Ge do not emit light. Junction made up of Compound semiconductor like GaAs, GaP etc emit light. Most of the light is discovered to be generated from the junction area closer to the P type region. As a result, the diode design is made to keep this area as close to the device's surface as possible to ensure that the structure absorbs the minimum amount of light. Figure 1.6 shows LED operation.

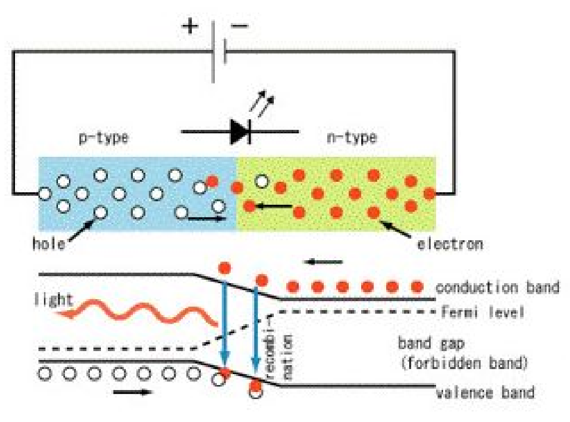

Figure 1.6: LED-Operation [14]

Applications of LED:
Below given figures are the examples of advanced applications of LED in daily life. In Figure 1.5 we can see the use of goggles integrated with LED are being used by surgeons during operations in Figure 1.4.Audi was the first automobile giant who used LED based headlight shown in Figure 1.6. The visibility of these LEDs during day time is better than those previously used traditional headlights which is helpful in preventing accidents and it also enhance the visibility during night.

Figure 1.7: Medical goggles fitted with LED [19]

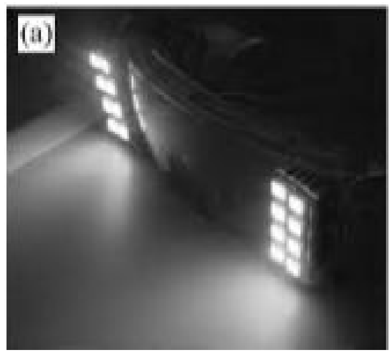

Figure 1.8: First Goggle with Integrated white LED [19]

Figure 1.9: LED-based automotive headlights-first day time running light [19]

1.4 Research Challenges Related to LED

LEDs made up of InGaN/GaN semiconductor material are energy efficient, but improvements are still needed. Their is scope of improvement of modulation speed for optimum performance in communication systems. One of the challenge is polarization related electric field in c-plane device which is reduced remarkably by m-plane but still there are some other effects which are required to eliminate to enhance the capability of communication techniques.

1.5 Problem Definition

Fabrication of optoelectronic devices is a challenging task as one has to deal with very small sizes ranging from millimeter to nanometer.In addition to size, various other factors also exits such as crystal orientation and crystal polarity which play important role in LEDs performance and capabilities, come up with their own characteristics features and challenges. LEDs which are used as a source for Visible light communication are comparatively smaller in size than commercially available LEDs to transmit data at a higher rate. Previously reported LEDs were manufactured in c-plane orientation, suffering from spontaneous and piezoelectric polarizations that cause inner electrical fields in the active region [5]. Distortion of energy band diagram takes places because of this induced electric field and as a result a shorter overlap of electron hole wave function is observed, which in turn increases the carrier lifetime in comparison to the structure which don't suffer internal polarization. Hence the operating speed of LED reduces significantly. To overcome this effect LEDs are fabricated on non-polar crystal orientation which not only successfully eliminate the internal polarization but also enhanced the operational speed of LEDs.

1.5.1 Motivation of Thesis

Radio frequency technology has the potential to support the demand of continuously increasing mobile communication traffic. But in addition to this we need an alternate wireless technology which could support the existing RF infrastructure and updated versions of it [21], [1]. Visible light communication(VLC) fulfills all the mentioned requirements and is a strong contestant [10]. Among the available sources for VLC light emitting diodes are most appealing and out of all the available diode InGaN/GaN diodes are most suitable since they are capable of providing efficient lighting and data communication concurrently at a very minimal extra cost and power consumption [21], [3]. Mostly available LEDs in the market are big in size and that's why they have low modulation bandwidth and unable to transmit data at the rate of Gb/sec which is desired for VLC [17]. At the moment, peculiarly constructed high-speed micro-scale LEDs effectively accomplished big modulation bandwidths varying from 100s of MHz to 1 GHz, resulting in data communication rates of multi-Gb/s [4]- [6].

1.6 Organization of Thesis

This thesis is divided into four sections. In the very first section of this thesis we talked about the latest communication technology in use, the principal of there working, individual capacity and similarity among them. Our prime focus is on VLC which uses LED bulb as a router to transmit data. Hence the next topic of interest was LED, as we are using it a source for VLC. We discussed in brief what is LED, material it is made up of, it's characteristic and most recent and advance application of LED and in the last we studied about the operation of LED.

We have discussed some of the challenges related to LED which motivate us to further investigate the device. In the next section we will see the journey of LED, how it started and what all changes has been done so far to improve its efficiency, linewidth, power consumption,size and other various important parameters. In third section we will see the proposed method and variation of LED parameters to improve the linewidth of LED, in that section we will discuss briefly about the simulation software we used to simulate the device. How that simulator work, its structure [22].

In the last part we have results that we have achieved after simulation and comparison of those results with the existing one. Various important characteristic and variation of LED parameters will be discussed. From next section we will start the literature review of LED [17].

Chapter *2*

Literature survey

2.1 Introduction

As we have already discussed in chapter 1 about the latest technology in communication industry. In this chapter we will see the various phases thru which LED has passed and its role and importance which motivate researchers to keep on exploring the LED for discovering new possibilities. For last many years, technical advancement in the area of LED has been phenomenal and incredible. Modern LEDs are small in size, robust, reliable, bright, and efficient. So far, LEDs have achieved many milestone and accomplished many critical task in order improve communication technique. Contrary to other available light emitting sources, light emitting diode are capable of converting electricity to light nearly to unit efficiency. The discovery of light emitting diode was an accident 1907 and the first research paper on LEDs was published in the same year. After that their were no talks about LEDs. For sometime LED had disappeared but after sometime they again become important device in 1920s and then again in the 1950s. Three groups of scientists worked at General Electric Corporation in the 1960s, the second group of scientists worked at MIT Lincoln Laboratories, and the third group worked at IBM Corporation, pursuing the semiconductor laser demonstration. In that study study, the first operational LED was a product by product.

The demand of LED is continuously increasing because LED is a key component in communication technique like VLC. Now techniques likes VLC are attracting the attention because the existing techniques are not meeting the demand of required spectrum and high energy. By the end of 2014 almost most of the set-up of 4th generation wireless system had finished. And it was already running in full flow with maximum capacity but continuously increasing wireless mobile application are demanding high data rate [10] and large bandwidth and 4G was falling short to fulfill the demands of communication industry. To meet the demand researchers started to explore 5th generation communication techniques, VLC and other latest communication techniques are the potential candidate. Research in this area has been in progress for last two decade and still it is on. People thirst for high speed Internet, instant communication and instant transfer of information is increasing continuously day by day [1]. This demand resulted in huge crisis of spectrum and as result modification in cellular architecture was made. A report published by WWRF(Wireless World Research Forum) forecasted that approximately 7 trillion wireless devices will be in the service of 7 billion people by the end of 2017 i.e. the number of network-connected wireless devices will be 1000 times the population of human beings on earth [2]. One of the main driving force behind the 5th generation cellular architecture is to separate indoor network and outdoor network to mitigate the penetration loss through walls.Also a heterogeneous one should be the 5 G cellular architecture, with macrocells, microcells, small cells and relays. We proposed the portable femtocell idea to accommodate high-mobility users such as car users and high-speed trains, which combines the concepts of mobile relay and femtocell [21]. Figure 2.1 was proposed 5th generation cellular network in which researchers tried to design a network in such a way such that their is a sharp boundary between indoor and outdoor applications.

Li-Fi and VLC Li-Fi and VLC both uses LED as a source of light but there are couple of

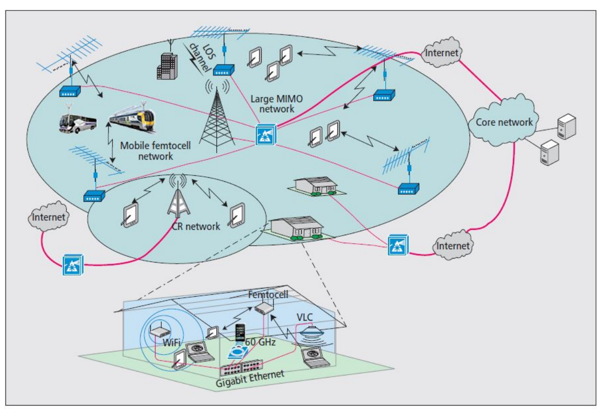

Figure 2.1: Proposed 5th generation cellular Network [5]

differences between them. VLC is considered a point-to-point communication technique, while Li-Fi is a complete wireless networking scheme, i.e. a multipoint-to-point method of communication. Figure 2.2 demonstrate the techniques required to design the optical attocell Li-Fi network. When we talk about the Wi-Fi operating frequency it is 2.4 GHz, 4.9 GHz and 5GHz, on the other hand the Li-Fi operating frequency is ten thousand times the radio frequency spectrum, the difference in operating frequency between Wi-Fi and

Li-Fi is enormous. Whereas the coverage area of VLC is approximately 32 meter Li-Fi coverage area is limited to 10 meter approximately. Wi-Fi works efficiently in a less dense environment while Li-Fi works smoothly in a high dense environment. As far as data privacy is concerned, Wi-Fi rf signals can not be blocked by the walls and therefore need to use techniques to secure data transmission, but the walls are blocked in case of Li-Fi light and thus provide more secure data transmission [10].

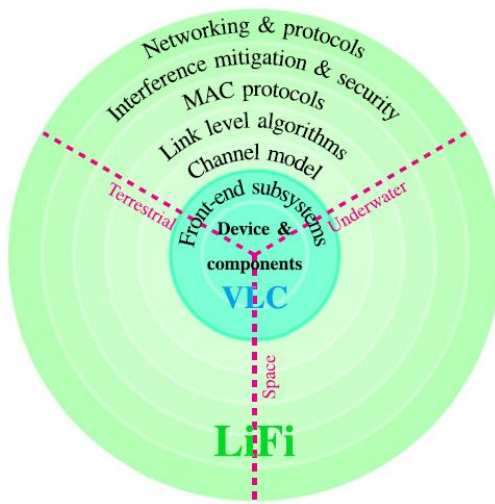

Figure 2.2: Li-Fi and its application and its principal block [23]

VLC and its characteristic In our research work our prime focus is on key component of VLC communication i.e. LED. we will also discuss advantages of VLC over rf and some other important characteristic as well. The reason behind continuous research on LEDs is its criticality. Better the efficiency and output power of LED, better is the communication technique in which is LED is being used as a source. VLC which is the most promising candidate for 5G wireless communications is based on LED.VLC uses visible light for its communication purpose its wavelength spectrum is between 380 nm and 750 nm which corresponds to a frequency spectrum from 430 THz to 790 THz. VLC has several advantage over traditional RF based communication technique, it is energy efficient and posses ultra wide bandwidth and more prone to security threat. As VLC receiver only receive signals if they are located nearby the transmitter, those receivers which are at some distance or separated by physical boundaries could not receive the signal and thus enhances the security. Along with advantages there are some weakness as well (a)Transmission Range (b)obstacles in transmission paths. VLC grab the attention Because existing RF based wireless communication could not meet the demand of wireless communication system. First issue with RF based communication is RF spectra, most of which has been allocated. Second is the improper frequency utilization and it is believed the it will be misused even more in coming days. Third is power consumption. VLC successfully overcome all the problem faced by RF communication systems. VLC have utility in various applications such as vehicle to vehicle communication, underwater communication, robots in hospitals etc. Li-Fi uses VLC to provide high speed internet up to 10GBps [23].

The first resulted that came into being was red in color, created in 1962 and manufactured in 1968 by mass. Followed by yellow, green, infra red and blue LEDs. Now-a-days, you can get LED of any color including white color which is very much in demand. In 2008, scientist built a green color caused multiple quantum wells (MQWs) based on n-type doping and undoped GaN and a current-confined aperture structure with a diameter of 76-μm and reached very elevated optical-to-electrical bandwidth, i.e. in the range of ($\sim$300) and consumption ($\sim$264μw) power, which was quite remarkable at the moment. High Speed red LEDs are one of the most critical component of plastic optical fibers (POFs) [25]. As per the standard of media-oriented systems transport they must transmit data at a rate of 22.5 Mb/s [?]. Because of narrow optical bandwidth and high propagation loss of commercially available red LED which were being used in polymethylmethacrylate (PMMA) POF focus moved on high performance POF systems whose optical bandwidth is higher and propagation loss is lower than PMMA POF. Figure 32 shows the device structure and composition of Green LED based on high speed GaN [24].

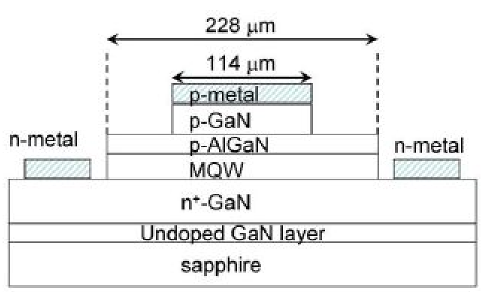

Figure 2.3: Green LED based on high speed GaN [24]

An electro-optical technique for extrapolating the non-radiative and auger recombination coefficients in InGaN / GaN LEDs was also suggested in 2009. The proposed electrical-optical technique has an advantage that, based on the evaluation of quasibulk structures, it allowed the extrapolation of the recombination parameters of packaged instruments which was in essence contrary to current standard methods. The effectiveness of the inner quan-

tity relies strongly on the current density. At elevated current densities the IQE is restricted by the so-calLED effectivenessdroop [18] this impact consists of a reduction in LED efficiency at elevated injection rates and is probably linked with (a) Augerrecombination [7] and/or (b) the presence of elevated polarization areas allowing carrier escape from the quantum well system [7]. whereas At low current densities, the efficiency of the LEDs is limited by non-radiative recombination, which is strongly dependent on the defectiveness of the active layer. The results of the proposed method are better then the existing methods and it accurately calculates the non-radiative recombination coefficient, carrier density in active region and the extrapolation of the Auger recombination coefficient.
Following ongoing research on LED to enhance its efficiency and output power, a method was proposed in which a miniaturized GaN-based cyan LED on a Patterned Sapphire (PS) substrate was designed as a light source for plastic optical fiber (POF) communications operating at 500 nm maximum wavelength. To increase the External Quantum Efficiency (EQE) performance and sustain a reasonable output power, the number of active $In_xGa_{1-x}N/GaN$ layer was reduced and brought down to 4 layer multi quantum well and the device active area was also minimized. As a result, the electrical-to-optical bandwidth achieved was as high as 400Mhz, which was the highest of all reported LEDs under a very small 40ma dc bias current. In Figure 33 and 34 one can see the zoom-in structure and detaiLED device composition structure.

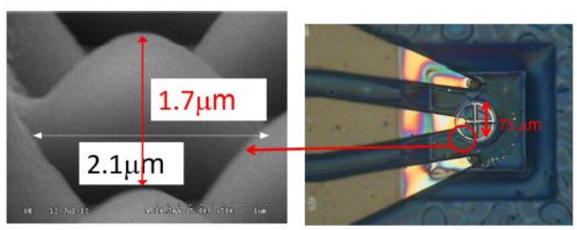

Figure 2.4: A top view of the LED shown and the PS substrate zoom-in SEM image

After red and green LED the next LED in the row was blue. Due to its compatibility with green, blue and ultraviolet light emitters, GaN and its alloys with InN and AlN have attracted attention as well as apps for next-generation lighting and high-power electronic devices [7], [8]. To reduce the power consumption throughout the globe remarkably we need to use efficient light source, studies have shown that by using energy efficient electronics devices we can reduce the consumption upto 50 percent. The reshaping of device design enhanced the carrier injection density in the active region and dispose of lateral current spreading up-to remarkable extent. Figure 2.4 shows the epitaxial view of the designed structure and individual material region. The GaN-based blue LEDs with a diameter of 75-μm showed a 3-dB frequency range of 225.4 MHz and a light output capacity

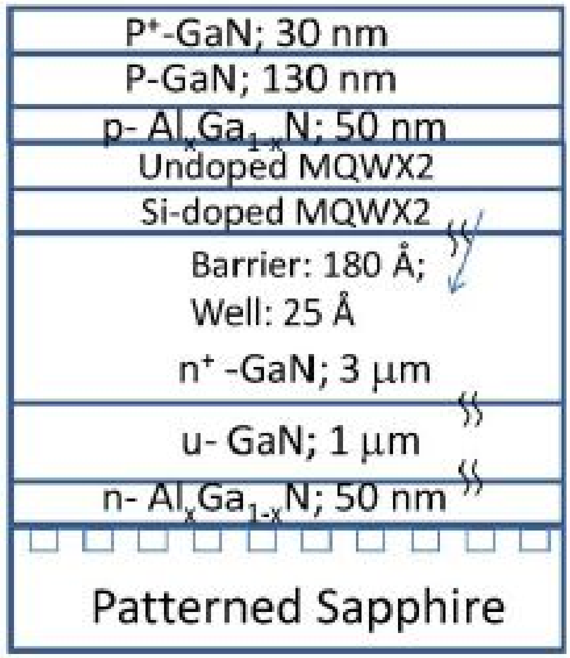

Figure 2.5: The conceptual cross-sectional view of demonstrated device

of 1.6 mW at 35 mA. Such LEDs can be applied to visible light communication in near future [9].

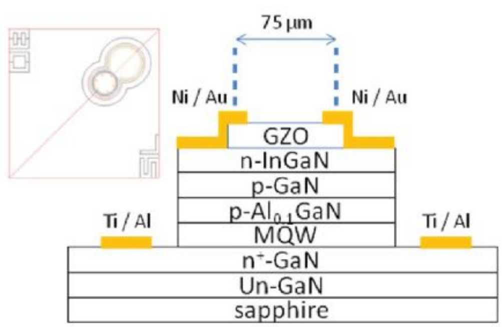

Figure 2.6: Epitaxial structure for blue high-speed LED [12]

Further to achieve higher current density with GaN based LEDs change in shape of electrode were attempted by making them ring shaped so that they can confine the current injection. The ring based electrode have different aperture diameters. By using a suitable design, the carrier injection density in the active region was improved. Experimentally it was shown that the green GaN-based LEDs with a mesa diameter of 75μm show the biggest 3-dB frequency bandwidth of 463 MHz at 5 mA with a powerful light output of 1.6 mW and a small turn-on voltage of 2.8 V. Such LEDs can be introduced in the future to visible light and optical plastic fiber.

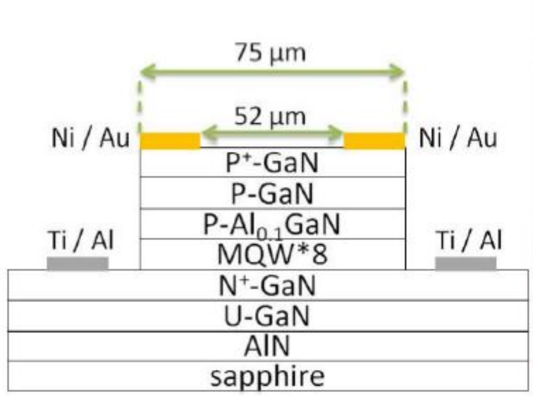

Figure 2.7: The green LED structure with ring-shaped electrode [24]

2.2 Impact of crystal orientation on the modulation bandwidth of InGaN/GaN light-emitting diodes

Recently, INGaN / GaN LEDs have been of excellent concern in visible-light communication in smart lighting systems, plastic optical fiber (POF) communication and wireless optical communication (UWOC) communication. High velocity InGaN / GaN LEDs manufactured on c-plane have greatly enhanced from dozens of MHz to over 800 MHz over the past ten years [20]. By changing the active region layout, thermal management and device architecture, all these advances have been allowed. One challenge that continues to limit the modulation bandwidth in c-plane LEDs is the existence of polarization-related electrical areas that distort the energy band diagram and decrease the overlap of the electron hole wavefunction that improves the carrier lifetime and limits LED velocity. By doping the active region barriers with n-type impurity the carrier lifetime in c-plane LEDs was reduced but that was not sufficient, another way is to fabricate LEDs out of polarization-free nonpolar InGaN/GaN, which not only increase the wave function overlap but also reduce carrier lifetime compared to c-plane GaN which was desirable [16].

First high-speed nonpolar m-plane InGaN / GaN LEDs are shown in Figure 2.6 on free-standing GaN substrates. These LEDs emit light for VLC, POF, and UWOC apps with a main wavelength between 455-465 nm. A high Electrical-to-Optical modulation bandwidth of 524 MHz was obtained at current density of 10 KA/cm2 for a device with a

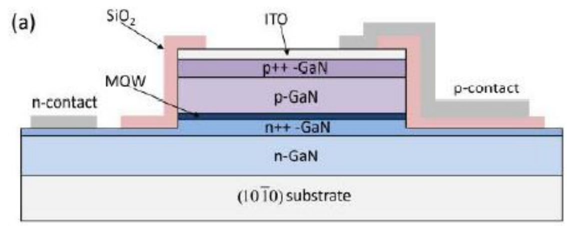

Figure 2.8: Cross-sectional view of high-speed Non-Polar LED device [15]

60-μm diameter aperture [16].

In the next chapter we will see how we have simulated the device, what all modifications are performed to obtain better results, software we used for device simulation and its specifications.

Chapter *3*

Design of Non-Polar m-plane LED

3.1 Introduction

So far we have seen the journey of LED. The advancements which has been done to improve the linewidth. In this chapter we will see method we proposed to optimizt the linewidth further. Most recently proposed modulation bandwidth lies in GHz range. To further optimize the bandwidth The bandwidth we optimized the active region, reduced the operating voltage, and improving the heat sinking. We did all the above mentioned changes by using the software Silvaco-TCAD and redefined the values of LED parameter which in turn produced the better results.

3.2 High Speed LED Device Structure

3.2.1 Heterostructure Device

When a layer of semiconductor material has a particular bandgap power, a double heterojunction is created between layers of other semiconductor components with a greater power bandgap. We call it a double heterojunction because two heterojunctions are present. The double heterojunction created acts as a barrier that regulates the region of recombination of electron-hole to the material below the band gap.This area is known as the Active Region [17].

Heterostructure has a edge over Homostructure.

- It is used to increase the efficiency of carrier confinement.
- It is used to increase efficiency by photon confinement.

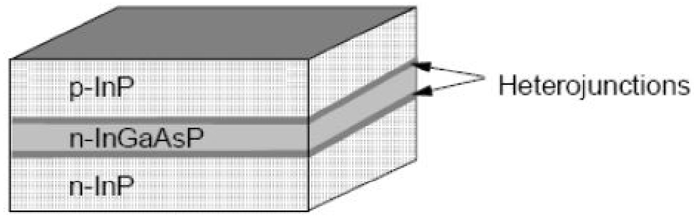

Figure 3.1: Double Heterojunction LED [19]

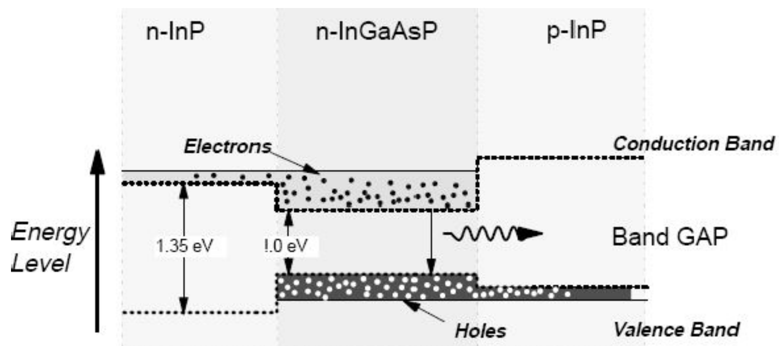

Figure 3.2: Energy Band in Double Heterojunction LED [19]

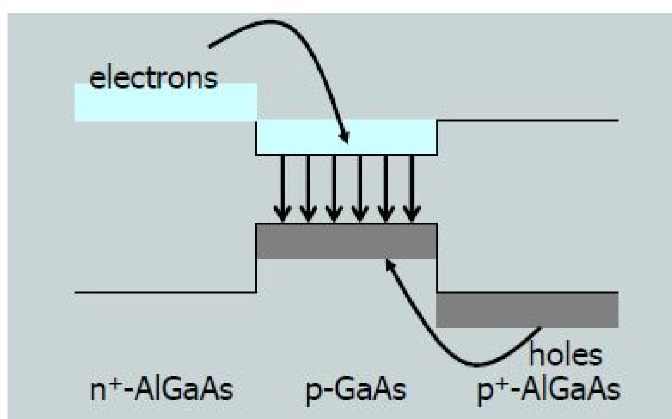

Figure 3.3: Simplified band diagram showing carrier confinement [19]

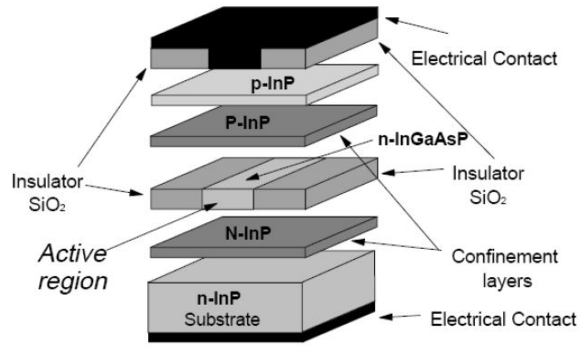

Figure 3.4: Exploded Structure of am idealized double Heterostructure [19]

3.2.2 Layers composition and Dimension

Step Firs was to grow free-standing GaN substrate layer by nearly $\sim 2\mu$m. Metal organic chemical vapor deposition (MOCVD) process. Then $\sim$2 μm of Si doped n-type GaN was deposited on the m-plane GaN substrate layer, come next $\sim$100 nm highly doped n type GaN with doping (electron) concentration of $6\times\ 10^{18}\ cm^{-1}$. Followed by multiple layer of InGaN/GaN layers to constitute active region. Active region is made up of three layers of InGaN quantum well separated by 15-nm wide GaN barriers was then grown on the non-polar n-GaN. doped p-GaN with a doping concentration of $3\times\ 10^{19}\ cm^{-3}$ followed by 15nm of highly doped p++ GaN.

The LED is divided into nineteen regions attached with Al electrode at the top and bottom of the structure. The doping of the device is uniformly distributed from highly doped region to moderately doped region details of the same are given in table 3.1.

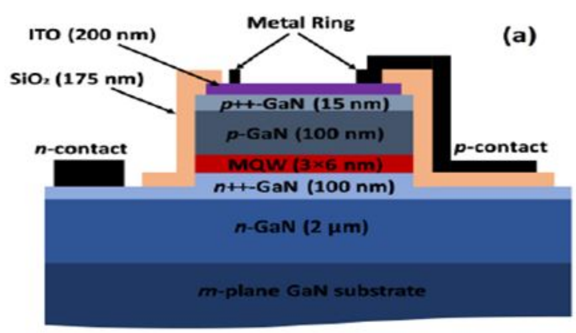

Figure 3.5: High-speed LED device structure cross-sectional view [17]

Region	Width(μm)-X	Width(μm)-Y	Doping level and Type	Semiconductor Material
1	1.5≤x≤3.5	0.0≤y≤0.15	1^{20} and P Type	GaN
2	1.5≤x≤3.5	0.15≤y≤0.115	1^{19} and P Type	GaN
3	1.5≤x≤3.5	0.115≤y≤0.121	LED qwell	InGaN
4	1.5≤x≤3.5	0.121≤y≤0.136	Barrier	GaN
5	1.5≤x≤3.5	0.136≤y≤0.142	LED qwell	InGaN
6	1.5≤x≤3.5	0.142≤y≤0.157	Barrier	GaN
7	1.5≤x≤3.5	0.157≤y≤0.163	LED qwell	InGaN
8	1.5≤x≤3.5	0.163≤y≤0.213	6^{18} and n Type	GaN
9	0.0≤x≤5.0	0.213≤y≤0.263	6^{18} and n Type	GaN
10	0.0≤x≤5.0	0.263≤y≤2.263	1^{15} and n Type	GaN
11	0.0≤x≤5.0	2.263≤y≤5.0	2^{18} and n Type	GaN
12	1.3≤x≤1.5	0.0≤y≤0.413	Insulating layer	$Si\emptyset_2$
13	3.5≤x≤4.5	0.213≤y≤0.413	Insulating layer	$Si\emptyset_2$
14	0.0≤x≤0.4	0.0≤y≤0.413	Blank Space	Air
15	0.9≤x≤1.3	0.0≤y≤0.413	Blank Space	Air
16	3.5≤x≤4.0	0.0≤y≤0.213	Blank Space	Air
17	4.5≤x≤5.0	0.0≤y≤0.413	Blank Space	Air

Table 3.1: LED Device Structure Dimension and composition

In figure 3.5 the pictorial view of cross section of InGaN/GaN LED is presented. This material's LED is a greater band gap LED that includes the spectrum's violet, green and blue region. Due to the lattice mismatch InGaN / GaN LEDs can not be grown on GaAs and is used as a substrate for genre sapphire, SiC or GaN. The substrate cost increases the overall cost of the device.

3.2.3 Optoelectronic Models

We will address the different physical models needed to simulate optoelectronic devices in this chapter. These models are useful in anticipating common basic procedures such as radiative recombination vs. structure of material, temperature, absorption and gain, and optical wavelength.

3.3 Linewidth of LED

When electron return from conduction band to valence band it emit light, the color of emitted light depends upon the difference between conduction band and valence band.

$$E_{ev} = \frac{hc}{\lambda} \tag{3.1}$$

Along with these band transition thermal fluctuation are also involved which alter the energy of the carriers slightly and these transition are responsible for finite width of LED emission. The mathematical equation of radiated energy is given by

$$h\nu = \left(E_c + \frac{h^2k^2}{2m_e^*}\right) - \left(E_v - \frac{h^2k^2}{2m_h^*}\right) \tag{3.2}$$

$$h\nu = \left(E_g + \frac{h^2k^2}{2m_r^*}\right) \tag{3.3}$$

This is known as joint dispersion relation. mr is calLED the reduced effective mass.

$$\frac{1}{m_r^*} = \frac{1}{m_e^*} + \frac{1}{m_h^*} \tag{3.4}$$

we can explicate the joint density of states function by estimation of a particle in 3 dimensional cube. It present the density of possible states in conduction band and it is given as

$$g(E) = \frac{4\pi(2m_r^*)^2}{h^3}\sqrt{E - E_g} \tag{3.5}$$

Electrons and holes those are located at the boundaries of band, far away from the Fermi level and their Fermi function is approximated by the Boltzmann distribution given in equation 3.6 [19].

$$p(E) = \exp\left(\frac{-E}{K_B T}\right) \tag{3.6}$$

The spontaneous emission rate is defined as the product of the density of available states (equation 3.5), with the occupation probability (equation 3.6). is shown in equation 3.7

[19].

$$I(E = h\nu) \propto \sqrt{E - E_g} \exp\left(\frac{-E}{K_B T}\right) \tag{3.7}$$

The peak of the spectrum is located at [19]

$$E = E_g + \frac{K_B T}{2} \tag{3.8}$$

In Photonics, there are many ways to define linewidth (or Bandwidth) the linewidth is the width of the optical spectrum of the output of some light source. Broadening of linewidth is primarily due to thermal effect and is directly proportional to temperature. The mathematical expression of linewidth is given as [19]

$$\Delta\lambda = \frac{1.8 T k_B \lambda^2}{hc} \tag{3.9}$$

3.3.1 Theoretical Emission Spectrum of LED

The theoretical plot of luminescence intensity vs energy is shown in figure(3.2). Full width at half maximum (FWHM) literally means how wide something is when you've defined the edge on either side as being the point where the value has dropped to half of the maximum. FWHM is a convenient measure of the width of a function.

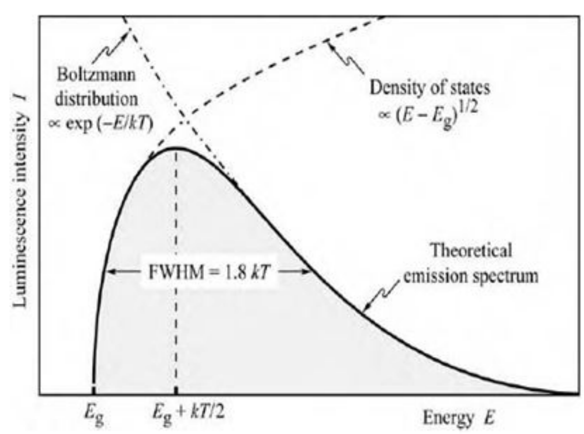

Figure 3.6: Theoretical spectral power distribution as a photon energy [19]

3.3.2 Actual Emission Spectrum of a typical LED

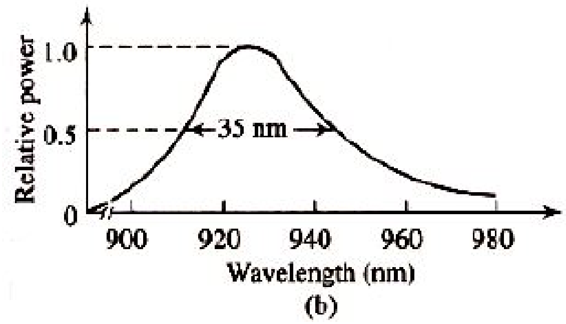

Figure 3.7: Relative Power Vs Wavelength [19]

3.4 ATLAS Simulator

We used the ATLAS simulator to simulate the semiconductor-LED machine. It is a two-and three-dimensional physically based device simulator that anticipates the electrical conduct of specified semiconductor structures and gives insight into the inner physical processes of device operation. Device operation are dependent upon the type of physical model selected.

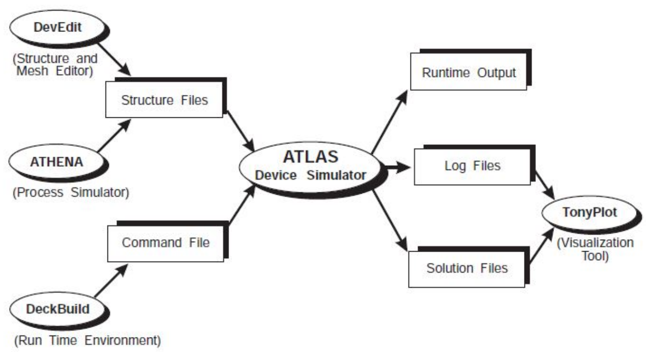

Figure 3.8: Atlas Inputs and Outputs [11]

3.5 ATLAS Overview

Atlas framework contains simulator calLED LED. The LED simulator is capable to simulate light emitting diode devices. It promotes the simulation of the material structures of both zincblende (e.g., AlGaAs / GaAs, InGaAsP / InP) and rotzite (e.g., GaN / AlGaN / InGaN). It helps us to calculate precisely the effects of polarization on both emission spectra and piezoelectric polarization of the effects of strain [11].

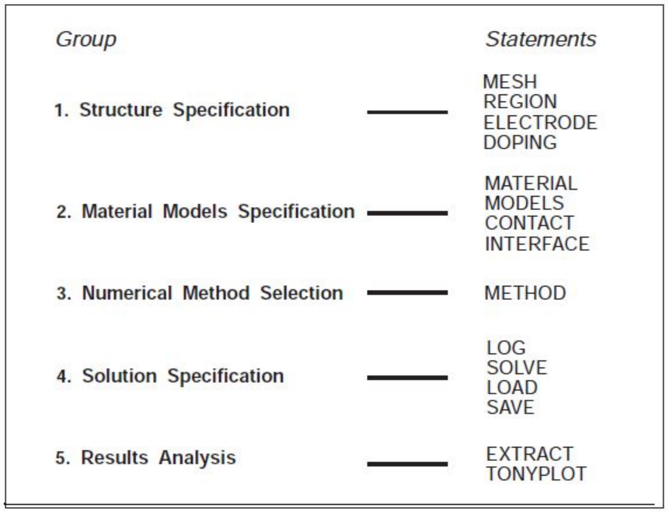

Figure 3.9: Atlas Command Groups with Primary Statements in each Group [11]

3.5.1 Defining Light Emitting Devices

One can define LED device structure in several possible framework such as ATLAS, ATHENA, DevEDIT device builder tool. In our research work we defined LED by using ATLAS framework commands. Defining LED device in atlas framework is the most convenient way as the device structure are somewhat simple. The very first step is to define the mesh structure of LED device and there are two possible ways to define it (a) The general purpose structure definition approach and (b) The auto mesh approach. we have used ”The auto mesh approach” to define our mesh structure as it easier to use, needs less user input and the most important it is most suitable for multi quantum well devices.
MESH AUTO
this command will invoke the auto mesh capability.
Second Step is to specify the device region i.e. the semiconductor material type for specific region, coordinate in X and Y direction, the amount of doping etc.

REGION MATERIAL=GaN X.MIN=2.5 X.MAX=3.5 Y.MIN=4.1 Y.MIN=4.106 x.comp=0.35

The last step is in the structure definition section is to specify the Electrodes.

ELECTRODE NAME=ANODE X.MIN=2.0 X.MAX=2.3 Y.MIN=4.1 Y.MIN=4.4

The above line tells us the name of electrode used i.e. anode and its spacial coordinates defined by X and Y axis. One can use the Keyword TOP or BOTTOM if electrodes are needed at the top and bottom surface respectively.

3.5.2 Light Emitting Diode Models

Once you define the LED the next and critical step is specify the LED models based on effects(Piezoelectric and Polarization) and models(Radiative recombination).

MODELS MATERIAL=InGaN OPTR

The keyword to define model is ”MODEL” followed by the material and then name of the model.

3.5.3 Data Extraction

Last section in the row is to extract the values of various characteristic of led such as luminous intensity, current flowing through led, voltage across it, El intensity etc and variations of all these parameters with other are studied with the help of graphs.
In the next chapter we will see the graphs and figure we obtained after simulation, which gives us visual representation and relation among various parameters of LED with each other.

Chapter *4*

Validation and Simulation Result

4.1 LED Device Structure, L-J-V and Spectrum

In continuation to the chapter 3 in this chapter we will see the simulation results. We have studied various characteristic of LED and attempted to improve them by modifying the related parameters. After re-simulating the Figure 3.7 we have obtained the results which are looking better than most recently reported results.
Figure 4.1 represent the inner layer composition of the simulated LED structure, different colors are used to represent different semiconductor material region. Aluminum metal is used for P and N electrode contact. This active region of LED Structure i.e. multi quantum well is made up multi layer active region. Active region consists of three layers of InGaN which acts as quantum well and two layers of GaN which is acting as a barrier. Figure 4.2 is the expanded view of active region. Quantum well is a potential well which posses only discrete values of energy level. The main function of quantum well is to restrict the particles (electrons and holes) in two dimensions which were freely moving in three dimension by forcing them to occupy a planar region. The effect of confinement of particles is known as quantum confinement, this effect take place when the thickness of quantum well becomes comparable to the de broglie wavelength of electrons or holes. A quantum well is formed when a compound semiconductor is sandwiched between two layers of a material having wider bandgap. There are two methods widely used to grow these structure are (a)molecular beam epitaxy and (b) chemical vapor deposition. The thickness of the layers of quantum well is near to the wavelength of confined electrons, hence change the behavior of electron as they are now restricted to 2 dimensional instead of 3 dimensional. The energies of the electron present in the middle layer shows quantized energy level. When a voltage is applied across its lead current start flowing through it. The value of current will become large when the energy of injected electron matches with

energy of electrons present in the quantum layer present in the middle. Multi quantum wells formed by arranging layer of different semiconductor compound one after other are known as superlattice. These are several important application of quantum well structure such as efficient microscopic lasers, fast computer chips etc.

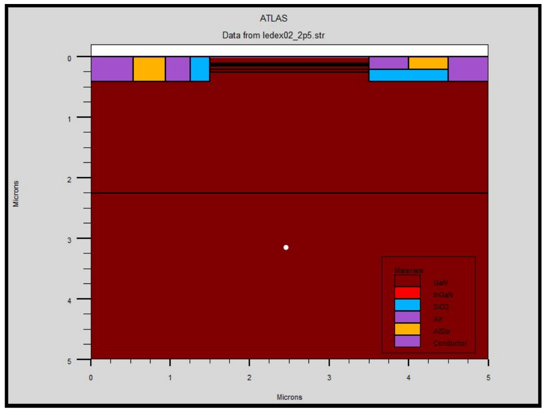

Figure 4.1: LED Inner Layers (Material View)

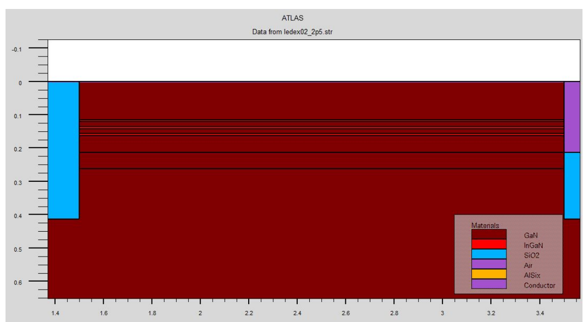

Figure 4.2: Multi Quantum Well Expanded View

Doping is an important step in semiconductor fabrication. As the conductivity of intrinsic semiconductor is limited, to enhance it we dope it with the elements of III and V group of modern periodic table. Amount of doping is small but it increase the conductivity manifold. Thus doping transform an intrinsic semiconductor into an extrinsic semiconductor. The device which we simulated is doped with both type of dopant i.e. III_{rd} group (acceptor impurity) and V_{th} group element (donor impurity).The doping is varying from 10^{12} cm^3 to 1^{20} cm^3. The active region is doped heavily.

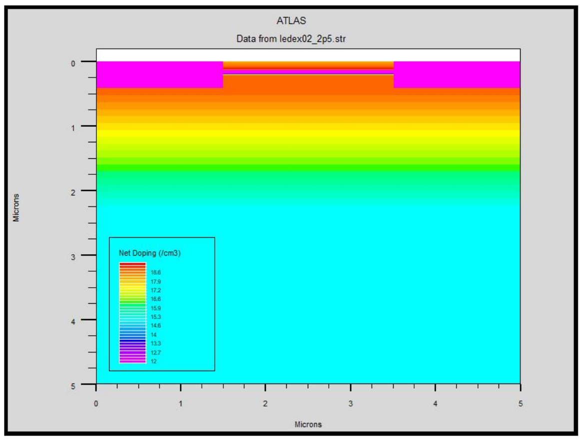

Figure 4.3: Net Doping Level

4.1.1 Comparison

With reference to research paper [1], figure 4.5 shows the relation between El intensity (a.u) and wavelength. El is an abbreviation of electroluminescence it is a electrical and optical phenomenon in which a material emits light when electric current pass through it or when it is placed in a strong electric field. El is the outcome of radiative recombination of electron and holes in a semiconductor material in general. The energy is realeased in the form of photons i.e. packets of light. Electroluminescence is diffrent from incandescence, sonoluminescence, mechanoluminescence. The diffrence lies in the source which is responsible for light emission. electroluminescence intensity is measured in astronomical unit. A.U. is the unit of length, roughly it is the distance between earth and sun which changes continuously as the earth revolve in its orbit. As shown in figure 4.5, Peak wavelength is obtained near 470 nm.

Electrical and Optical Bandwidth To compare our results with existing one we need to calculate optical linewidth. In optical communication modulation bandwidth is defined in

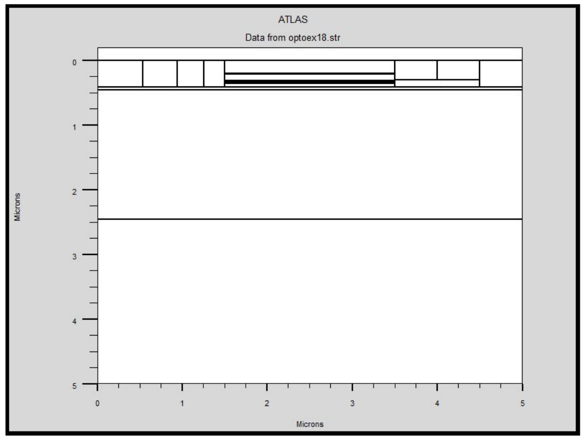

Figure 4.4: LED Inner Layer View

either electrical or optical terms. Optical bandwidth is greater than electrical bandwidth. mathematically optical bandwidth is defined as

$$RO_{db} = 10 \log \frac{OutputPower}{InputPower} = 10 \log \frac{I_{out}}{I_{in}} \tag{4.1}$$

$$RO_{db} \propto \frac{I_{out}}{I_{in}} \tag{4.2}$$

$$\frac{I_{out}}{I_{in}} = \frac{1}{2} \tag{4.3}$$

Similarly the electrical bandwidth is defined as

$$RE_{db} = 10 \log \frac{OutputPower(atdetector)}{InputPower(atsource)} = 10 \log \frac{I_{out}^2}{I_{in}^2} \tag{4.4}$$

$$RE_{db} \propto \frac{I_{out}^2}{I_{in}^2} \tag{4.5}$$

$$\frac{I_{out}}{I_{in}} = \frac{1}{\sqrt{2}} \tag{4.6}$$

By carefully observing the equation 4.3 and 4.6 we can say that optical bandwidth is greater than electrical bandwidth.

Linewidth of LED By calculating the optical bandwidth(i.e.-3db bandwidth) from the graph of el intensity vs wavelength figure 4.5 and comparing it with figure 4.6, figure 4.7 and figure 4.8, the point of attraction is that the linewidth of LED shown in figure 4.6, figure 4.7 and figure 4.8, is narrower then the most recently reported linewidth shown in figure 4.5. Hence the linewidth of high speed non-polar m plane InGaN/GaN LED is optimized successfully. The parameters which need to redefine are the electron and hole lifetime parameters TAUN0 and TAUP0 respectively and the most critical well.gamma0 which specifies the Lorentzian gain broadening factor. We obtain graphs as shown in figure 4.6,4.7 and 4.8. By calculating FWHM (-3db bandwidth) with the help of obtained graph we can comment on optical bandwidth that it lies in nm range. Exact value of Electrical bandwidth can only be calculated practically that's why to compare our results we used optical linewidth in use. As shown in the table we can see the variation in the values of linewidth.

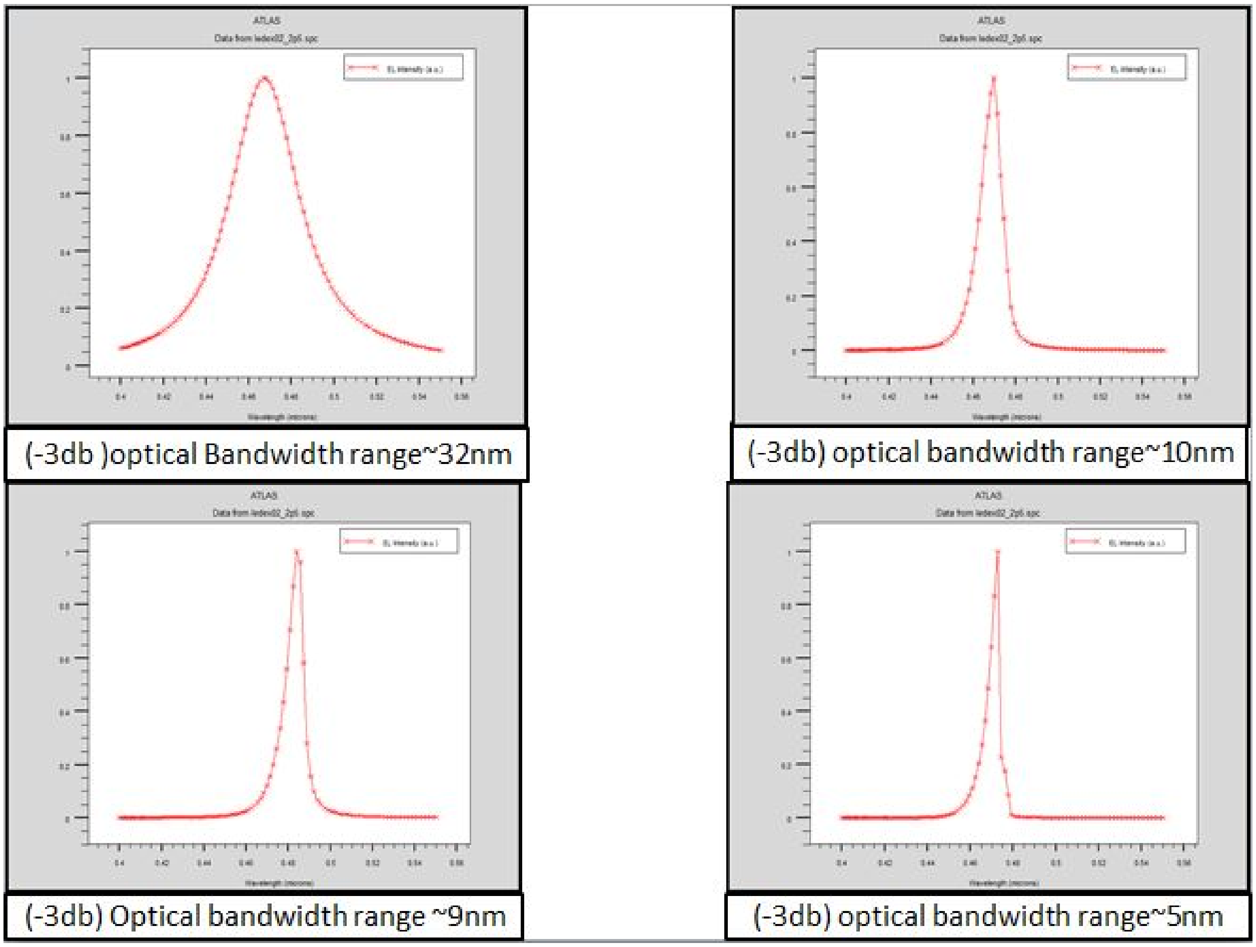

Figure 4.5: Optimized linewidth

I-V chracterstic LEDs are the current dependent devices to emit light currents needs to flow through it. Their output intensity is directly dependent upon the forward current flowing through them. For proper functioning of LED in forward bias a resistor in series needs to be connected which limit the current generated when LED is connected across a power supply. Direct connection of LED across a power supply without any resistor can damage it instantly because of flow of too much current. Generally LEDs are operated from a low voltage DC power supply connected with a series resistance. I-V curve shown in figure 4.9 is one of the most important characteristic of LED. The knee voltage is recorded at 3.1 volt. The maximum value of current reaches to 1×10^{-5} amp at 6.5 volt.

LED Luminous Intensity Luminous intensity (LI) is a measure of brightness and it is measured in candelas unlike lumens which is for light output. Manufactures rate their devices in terms of candelas. LI is a function of the angle from which an LED is seen, so it is a important feature need to be taken care of when characterizing the light output of a particular LED. If beams angles are different then two LEDs with same luminous

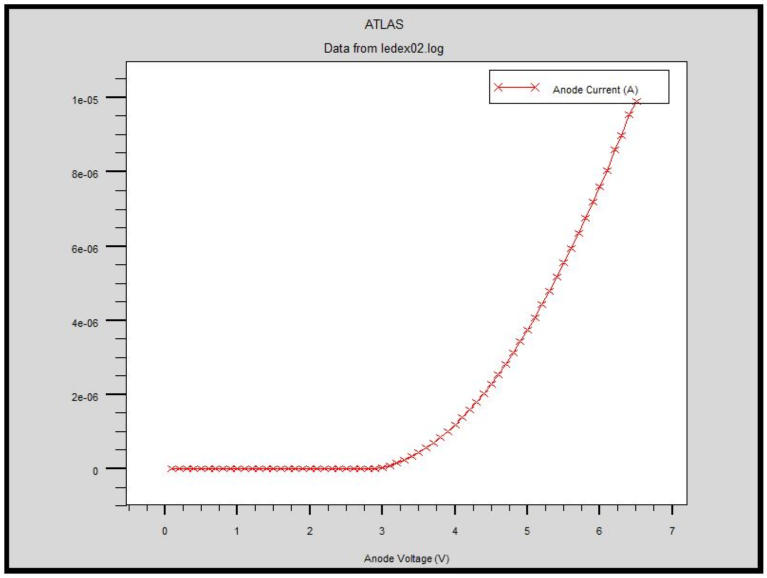

Figure 4.6: Current vs Voltage

output flux will have different peak luminous intensity. A narrow beam angle refers to a higher maximum luminous intensity for the same light output. **Power Spectral densities** When we talk about optics PSD(power spectral density) interchangeably known as power densities occur basically in 2 types (a) Optical power spectral densities which is defined as optical power per optical frequency and measured in either mW per THz or mw per nm. (b) noise power densities. in our discussion we will talk on optical power spectral density(OPSD) only. Spectral distribution of optical power of any light emitting source is measured with the help of spectrograph we get the answer in power spectral density or power. OPSD are also helpful in visualizing for example pulse shape with the help of spectrograms. In such times, SD is calculated for set time periods by using some window function to apply Fourier transforms to information segments as extracted.

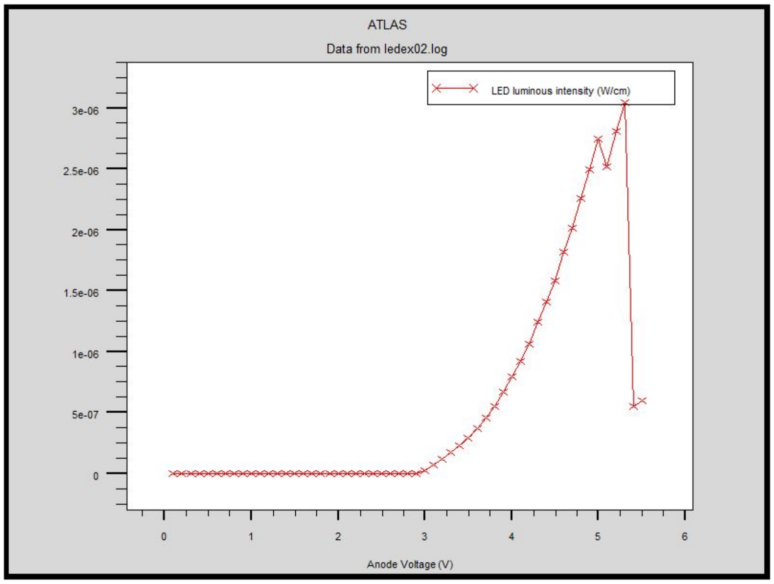

Figure 4.7: LED Luminous Intensity vs Wavelength

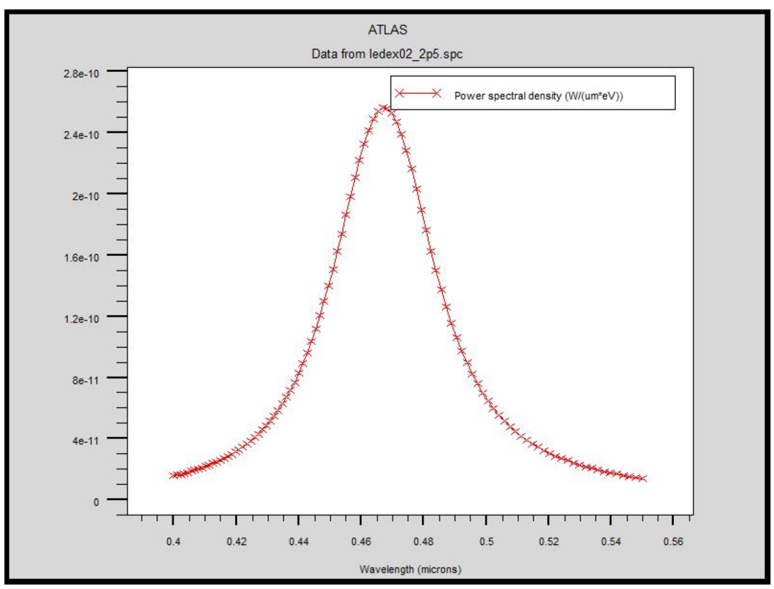

Figure 4.8: Power Spectral Density vs Wavelength

4.2 Modification in structural design and composition

Along with parameters related to LED linewidth we also attempted some modification in design and composition of LED quantum well and compared the changes with each other. First change we did is related to active region, we Increase the active InGaN layer from 3 to 4 without changing the width of active region. we observed slight variation in peak wavelength though not much but shifting is their. Second change we attempted is by increasing the width of InGaN layer (quantum well) and simultaneously reduce the width of barrier i.e. GaN layer. This time the peak wavelength is observed far away in comparison to previous two modification. Lastly we change the composition of InGaN from .2 to .35 and we observed that shift in the peak wavelength is maximum and unlike previous result the peak is obtained at maximum value of anode voltage. Figure 4.12 shows the graphical variation of El intensity vs wavelength and all the modification we attempted.

Figure 4.10 shows the expanded view of active region received after device simulation. Here without altering the width of active region we did some modification with quantum well later and barrier layer between them. It may be derived from the results that to achieve maximum intensity at a particular wavelength alternation in active region could help.

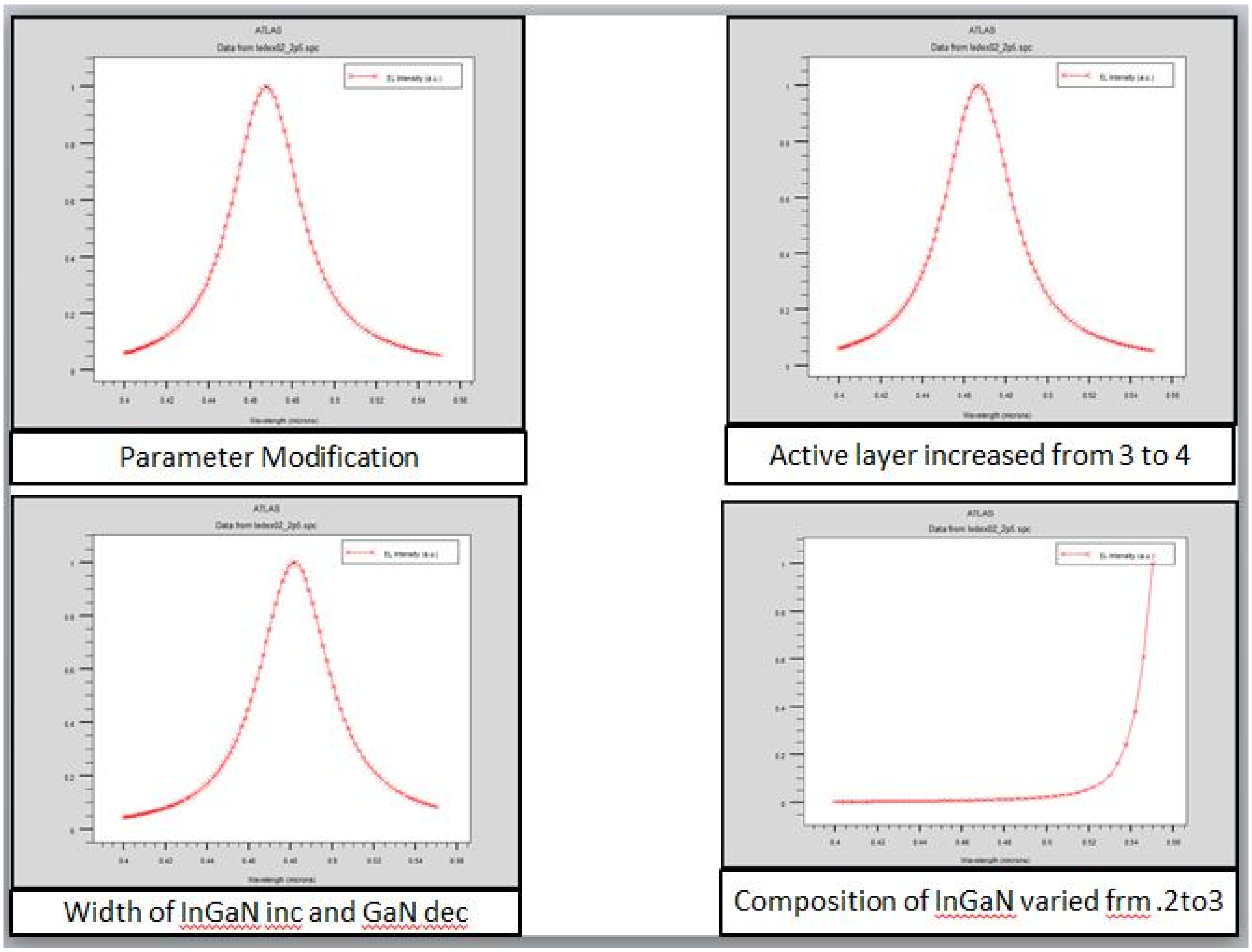

Figure 4.9: Variation of EL intensity vs Wavelength

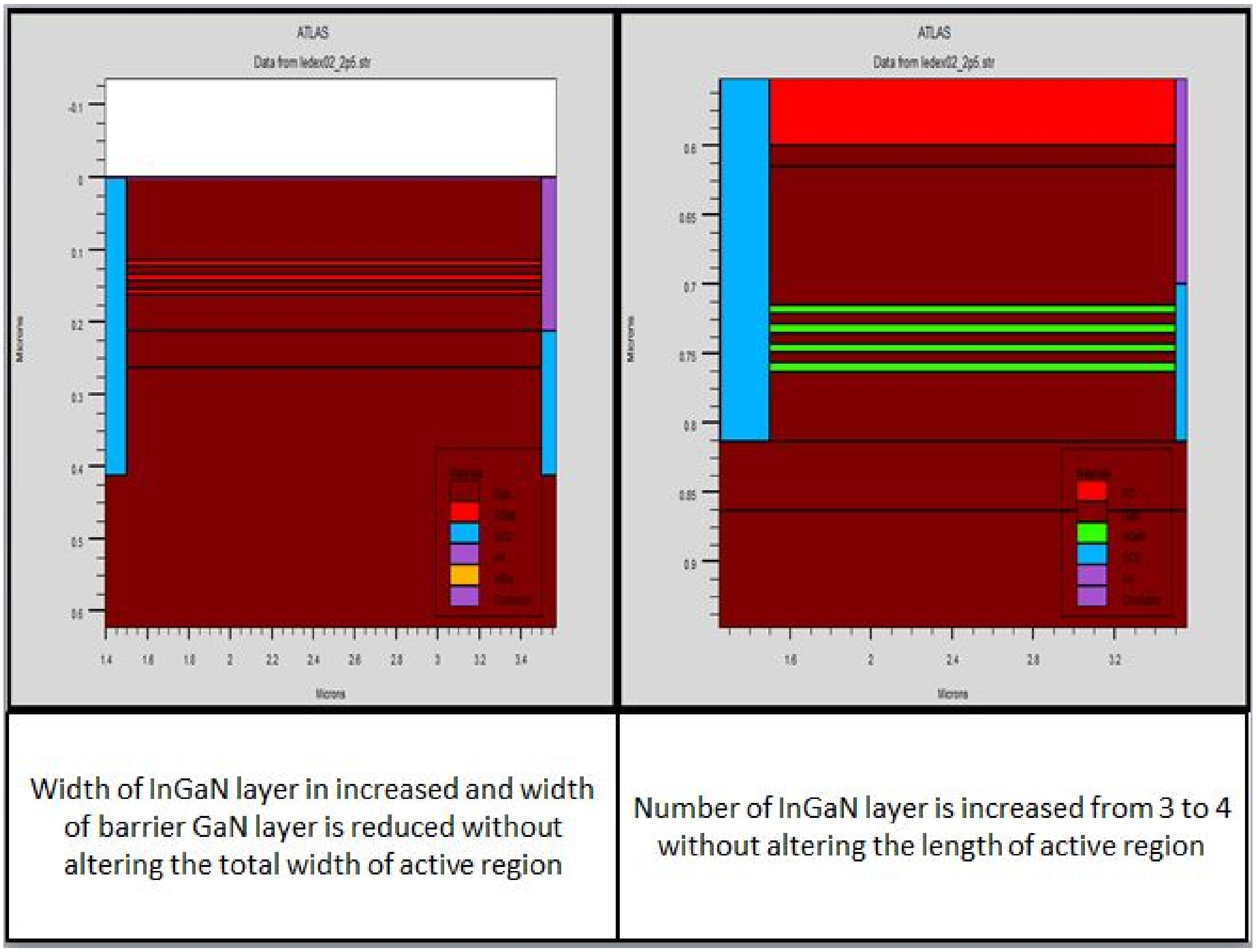

Figure 4.10: Expanded view of active region of modification 2 and 3

Chapter 5

Conclusions

Lastly we would like to conclude this thesis after carefully studying most of the aspects of GaN/InGaN LED. We have reverified the existing relation among various LED characteristics and attempted to modify parameter related to linewidth of LED and fortunately the results we achieved are better and motivating.

5.1 Spectral LineWidth of LED

. Compared to the range of the entire visible spectrum, the line width of an LED emitting in the visible range is relatively narrow.
. The LED spectrum is even smaller than a single color's spectral width as viewed by the human eye.
. For example, the range of red colors in the wavelength from 625 to 730 nm is much wider than the typical LED emission spectrum. Thus, the human eye perceives LED emission as monochromatic.

5.1.1 Variation of Radiative Recombination and Luminescent

Constant Parameter	Variable Parameter	Radiative Recombination
Wavelength (800nm)	Voltage	Max value of radiative recombination Increases as voltage increases
At higher Wavelength(1310nm)	Voltage	Max value of Luminescent power increases as voltage increases
Voltage(2 volt)	Wavelength	Max value decreases as λ increases
At higher voltage(5 volt)	Wavelength	Remain constant

Table 5.1: Variation of Radiative Recombination

Constant Parameter	Variable Parameter	Luminescent power
Wavelength (800nm)	Voltage	Max value of Luminescent power increases as voltage increases
At higher Wavelength(1310nm)	Voltage	Max value of radiative recombination Increases as voltage increases
Voltage(2 volt)	Wavelength	As λ increase max value of luminescent power decrease
At higher voltage(5 volt)	Wavelength	Decreases

Table 5.2: Variation of Luminescent power

5.2 Scope of further work

While the state-of-art LEDs are energy efficient, robust, can operate at high speed and reliable in near future it is possible to develop smart LED in all the segment where LED is being used in continuation to smart phone, smart television and other smart gadgets. With the help of sensors we can think to design a LED which can adjust its color and brightness. In addition to above thought efforts needed to reduce the initial price of high watt LEDs. LEDs do not approximate a point source of light, its light distribution is lambertian. Some design modification could make LED capable of distributing light spherically as well. Hence with many advantages there is always a scope of something better.

Appendix *A*

Atlas Statements

A.1 Convention Followed

- The ATLAS coordinate convention for the Y axis is that positive Y is directed down into the device.
- In the default version, 2-D ATLAS simulations have a maximum node limit of 20,000.
- An electrode in contact with semiconductor material is assumed by default to be ohmic. If a work function is defined, the electrode is treated as a Schottky contact.
- In all simulations, the device starts with zero bias on all electrodes.
- A number may contain the symbols + (positive), - (negative), and/or E (decimal notation).

[11]

A.2 Input Language

In Atlas statements and parameters are not case sensitive, either uppercase or lowercase can be used for device definition. There are four types of parameters allowed inn atlas. In Table A.1 description of all the parameters with allowed values and examples are shown. Any statement can be defined as STATEMENT PARAMETER=VALUE here STATEMENT is the name of the statement that one want to define and parameter keyword define the characteristic whose value we are defining [11].

S.No.	Parameter	Description
1	NY	Y mesh lines contained in the region
2	SY	Specify the spacing in microns between Y mesh line in the regions
3	TAUP	Specifies the lifetime of holes in trap level
4	TAUN	Specifies the lifetime of holes in trap level

Table A.1: Parameters Description

[11]

Appendix *B*

Semiconductor Material

B.1 Bandgap and type of semiconductor compound

Compound semiconductor are formed when different elements combined together, these elements could be from III or V group. IIIrd group elements are known as p-type elements and Vth group elements are known as n-type. These are classified as P or n type based upon the type of majority carrier present. Table B.2 Shows some common semiconductor material and their composition, value of bandgap(ev) and type of bandgap.

Group	Element	Material	Formula	Bandgap(ev)	Bandgap type
III-V	2	Aluminum Phosphide	AlP	2.45	Indirect
III-V	2	Aluminum Aesenide	AlAs	2.16	Indirect
IV	2	Silicon carbide,6H-SiC	SiC	3.0	Indirect
I-V	2	Gallium nitride	GaN	3.44	Direct
III-V	2	Gallium Phosphide	GaP	2.26	Indirect
III-V	2	Gallium Arsenide	AlP	1.43	Direct
IV	1	Germanium	Ge	.67	Indirect
IV	1	Silicon	Si	1.12	Indirect
III-V	2	Aluminium Nitride	AlN	6.28	Direct

Table B.1: Semiconductor material and their properties

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