ELECTROLUMINESCENCE FROM GaN NANOSTRUCTURES

By

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SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN PHYSICS
(CONDENSED MATTER PHYSICS)
AT
JIMMA UNIVERSITY
JIMMA, ETHIOPIA
JUNE 2014

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Department: **Physics**

Degree: **M.Sc.** Convocation: **June** Year: **2014**

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This work is dedicated to:

My Mother Whom I lost When I was 4 Years Old and

My sister, for her constant love and faith on me!!!

"No longer forward nor behind

I look in hope or fear;

But, grateful, take the good I find,

The best of now and here."

John Greenleaf Whittier

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Abstract

When crystals are constructed on a smaller scale (nanometeric scale), the energy gap between the highest occupied molecular orbital and the lowest unoccupied molecular orbital increased. In this thesis, quantum confinement, energy gap, exciton, optical and electrical properties of GaN-ncs were discussed. This work focuses on the study of Electroluminescence (EL) intensity of GaN nanoclusters as a function of different parameters. The dependence of EL intensity of GaN-ncs, on parameters like size of the nanocluster, applied voltage, wavelength, temperature, and time were briefly analyzed. It is shown that as the number of nanoclusters decreases, higher EL intensity is obtained and light emission starts at lower threshold. However selecting the number of samples is based on the applied voltage and wavelength. The high efficient EL is obtained at low operating voltages (about 6V), it is also observed that EL degrades with time. To get our result, we designed computational method and used the idea of quantum confinement model (QCM) and developed model equation that describes the EL intensity as a function of size of the nanoclusters and Fourier transform of the size dependent intensity into energy dependent intensity equations were derived and MATLAB codes were developed to generate data. We computed the data and plotted their graphs in different legends to have a comparative analysis between our results and some experimental results reported in literature. Most of our results agree with experimental results.

Keywords:Nitrides, Quantum Confinement, Excitons, Recombination, Electroluminescence

Acknowledgements

I first wish to thank my Father in Heaven for creating the world that we live in and for blessing me with the curiosity and ability to explore its wonders by giving me strength and success in any aspect of my life. All things were made through Him; Without Him, I am nothing. Next I would like to express my grateful, gratitude and sincere appreciation to my supervisor, Prof. Dr. L.V. Choudary for his guidance, valuable advise and kindness to me throughout the study. I want also to express my deep appreciation to my co-supervisor, Mr. Getnet Melese, for his critical and constructive suggestions, well planned follow up, continuous support and friendly approach during this thesis.

My special and deepest heartfelt appreciation goes to my friend Mr. Mekonnen Tadese, my sisters Sichale Keno and Ture Ararso and my wife Degage Gudina for they have given me their generous offer of useful advice, love and great moral and financial supports during this study, also I would like to extend my sincere thanks to Girum Tibebu, Naol Wagari, Gizesh Gurmessa, Tadese Beyene , Senbeto Kenna and Amsalu Mute from Nekemte College of Teachers' Education and Wollega Univesity for their moral and material support through out the sudy and thesis work.

Last, but not least, I would deeply like to thank those people who were on back of me during the study, to Jimma University, Physics Department for providing this chance and all department staff members who devote their time in following me through out my work and giving me constructive suggestions , Jimma University College of Natural Science for their financial support, Nekemte TTC and Oromiya Education Bureau(BBO) for their Sponsorship.

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June 24, 2014

Chapter 1

Introduction

Nanoscience is a new emerging area of science that involves studying and working with matter on nanoscale, on the order of 10^{-9} m. It is the study of phenomena and manipulation of nanoscale materials at atomic, molecular and macromolecular scales; and how to understand their properties which differ significantly from those at a larger scale [1]. Whereas Nanotechnology is a field of applied science and technology which is creating a plentiful supply of new materials and manufacturing possibilities, which deeply impact our economy, environment, and society. It has shown great impact in different industries that include electronics, optics, biomedical engineering, renewable energy, clean water etc. Low-dimensional semiconductor structures were generally fabricated in two kinds of approach, which are top down and bottom up [2]. Therefore, nanomaterials are the cornerstones of nanoscience and nanotechnology and are anticipated to play an important role in future economy, technology, and human life in general.

In nanoscale materials the surface-to-volume ratio is greatly increased and may bring a better change in the intrinsic properties of the materials. When the device is small enough, the energy levels become discrete, which allows the output energy to be adjusted according to the size of the material, especially for some electronic and photonic devices. The combination of diverse properties of different materials into one material could be achieved at the nanoscale level [3]

In recent years semiconductor nanostructures have become the model systems of choice for investigations of electrical conduction on short length scales. This development was made possible by the availability of semiconducting materials of unprecedented purity and crystalline perfection. Semiconductor nanostructures are unique in offering the possibility of studying quantum transport in an artificial potential landscape. The study of quantum transport in semiconductor nanostructures is motivated by more than scientific interest [4].

In studying properties of semiconductor quantum confinement (QC) is so important, because it leads to new electronic properties that are not present in semiconductors. QC can significantly enhance the exciton binding energy. It contains a single unit of charge and gives off different colors of light depending on size and specific energy levels. These energy levels can be limited by changing the size, shape, charge and potential [5].

In order to investigate these the characteristics of the quantum dots (QDs), the effects of QD, shape and size on the optical and electrical properties are needed. QDs structures have discrete density of electronic states and in this regard they behave more like atoms rather than solids [6].

From semiconductor nanostructures, nitride systems have attracted a lot of attentions due to their wide bandgap, which gives different light sources. The III-nitride semiconductors have wide direct band gap, making them suitable materials for optoelectronic devices as light emission can be realized via recombination of electrons and holes without the need for phonon mediation and for applications in full-color display, traffic signals and automotive lighting [7].

Among the wide band gap semiconducting materials, Gallium nitride (GaN) semiconductors are promising heterostructures for variable wavelength devices due to their high

luminescence efficiency. It can be operated as emitters and detectors in the blue, blue-green, light-emitting diodes (LEDs) or laser diodes (LDs) and ultraviolet region of the optical spectrum and ultraviolet portions of the spectrum as emitters and detectors and as high-power radio frequency electronic devices because of the merits of its direct and wide bandgap (3.4 eV), high carrier mobility, and good thermal and chemical stability [8].

LEDs are the devices that convert electrical energy into optical radiation. As important semiconductor light source, LEDs have found widespread use in myriad areas in our daily life as well as scientific fields like communication and medicine. It belongs to the luminescent device family. Luminescence is the emission of optical radiation resulting from electronic excitation in a material. Depending on the source of the input energy there are different types of luminescence. Such as: photoluminescence (PL) that is excited by optical radiation, cathodoluminescence (CL) that is excited by electron beam or cathode ray, electroluminescence (EL) that is excited by current or electric field, and radioluminescence (RL) that is excited by other fast particles or high-energy radiation [9].

The novel optical and electrical properties of Nanomaterials can be controlled as per their particle size. The absorption and fluorescence spectra of the quantum size semiconductor particles can be greatly improved by modifying the particle surface. These advantages make nanostructured material an ideal candidate for the use in EL applications. Smaller nanoparticles are obtained having increased oscillator strength, which improves the electron-hole radiative recombination and enhance the EL. In the EL process electrons from the valence band are excited to the conduction band on applying the electric field. These excited electrons can be de-excited through non-radiative recombination to some surface or defect state. Different EL studies showed that the light emission started at some threshold voltage and then increases rapidly with increasing applied voltage [10].

1.1 Statement of The Problem

Our work was on EL from GaN semiconductor nanostructures. It focused on EL properties from GaN semiconductor nanostructures on different parameters and tried to answer the following basic questions:

- How properties of semiconductors change when miniaturized into nanometre scale?
- On what parameters would the electroluminescence intensity depends and what is their relation?

1.2 Objective of The Study

1.2.1 General Objective of The Study

⧫ The general objective of the study is to understand electroluminescence properties from GaN nanostructures.

1.2.2 Specific Objectives of The Study

The specific objectives of this study are:

- To determine the dependence of EL intensity on the nanoclusters.
- To study the dependence of EL intensity on parameters (such as wavelength, size, applied voltage, transient time and temprature).

1.3 Significance of The Study

The study is to addressed dependence of EL intensity of GaN on different parameters like applied voltage, wavelength, bandgap, temperature , transient time and size of the nanoculares(ncs). And it would contribute for the input of Nanotechnology, especially for EL intensity of semiconductor (SC) nanoclusters. Also it may provides further opportunity on the knowledge and applications for the researcher and others who would be interested to do more investigation on EL intensity of SC nanostructure.The study addressed dependence of EL intensity on parameters like voltage, wavelength, bandgap, temperature and size of the nanoclusters.

Chapter 2

Theoretical Background of the Study

2.1 Quantum Confinement

Quantum is the smallest physical amount that can exist independently such as a separate quantity of electromagnetic radiation (energy). The effect of having bound electron states (which are not atomic!) when electrons are confined in nanosize systems is called quantum confinement (QC). Quantum size confinement can significantly enhance the exciton binding energy [5].

Quantum confinement is when either or both the electron and hole experience confinement in semiconductors by a potential well in 1D (quantum well), 2D (quantum wire), or 3D (quantum dot). That is quantum confinement occurs when one or more of the dimensions of a nanocrystal is made very small so that it approaches the size of an excitation in bulk crystal called the Bohr excitation radius or corresponding de Broglie wavelength. In turn, the energies of the carrier along that dimension of the material are no longer continuous as in the case where there is no confinement. The appearance of discrete states is one of the fundamental signatures of nanomaterials, so that solving the Schrodinger equation of a carrier to find its eigen values and eigen functions involves using boundary conditions, one can also immediately predict that the actual shape of a quantum well, wire or dot will also play a role indicating the ordering and spacing of states [11, 12].

A quantum well is a structure where the height is about the Bohr excitation radius while the length and breadth can be large, a quantum wire is a structure where the height and breadth is made small while the length can be long and a quantum dot is a structure where all dimension are near the Bohr excitation radius. Nanowires will have a similar but different progression of states than a quantum dot. The same applies to quantum wells as well as more exotic shapes of nanostructures [12, 13].

2.1.1 Quantum dots

Quantum dots are semiconducting nanoparticles that are able to trap electrons in small spaces. QDs are small physical devices that contain a "tiny droplet" of free electrons, small metal or semiconductor boxes that hold a specified number of electrons. QDs confine electrons, holes, or electron-hole pairs to zero dimensions to a region on the order of electrons de Broglie wavelength. They contain a single unit of charge and give off different colors of light depending on size and specific energy levels. These energy levels can be limited by changing the size, shape, and charge potential. Energy spacing's and color are related (i.e., they appear to have a certain color because the energy emitted has an associated wavelength in the visible region of the spectrum). Because of their optical features, different sized quantum dots (with different color/wavelength absorptions) are not visible individually to the naked eye, but the color of their solution can be easily seen since color is related to size. The larger the dot, the more its fluorescence appears toward the red end of the light wavelength spectrum. The smaller the dot, the bluer it appears. Changing the quantum dot size changes energy spacing and in turn affects a solution's visible color. Color change related to changes in particle size is a unique part of the nanoscale world [5, 13]. QDs come in to play for several reasons. Some of them are optical applications because of their high quantum yield; they have absorption and emission spectra which are tenable, size dependent[13].

Modern semiconductor processing techniques permit the artificial creation of quantum confinement in all three spatial dimensions of only few electrons. Such a finite fermions QD system has much in common with the atoms, yet they are man made structures, designed and fabricated in the laboratory. The generalization of Schrodinger equation in three dimensions is:

$$-\frac{\hbar^2}{2m}\nabla^2\psi(r) + V(r)\psi(r) = E\psi(r) \tag{2.1.1}$$

The solution of the differential equation of eqn. (2.1.1) for a particle in 3D infinite trap of volume L^3 with impermeable walls with V(r) =0 is given as:

$$\psi_n(x, y, z) = (\frac{2}{L})^{\frac{3}{2}} \sin(\frac{n_x \pi x}{L}) \sin(\frac{n_y \pi y}{L}) \sin(\frac{n_z \pi z}{L}) \tag{2.1.2}$$

and the corresponding energy Eigen value will be

$$E_n = \frac{\hbar^2\pi^2}{2mL^2}(n_x^2 + n_y^2 + n_z^2) \tag{2.1.3}$$

Eqns. (2.1.2 and 2.1.3) are applicable to electron and hole states in semiconductor "quantum dots". A hole in a full energy band behaves very much like an electron except that it has a positive charge, and tends to float to the top of the band, i.e. the energy of the hole increases oppositely to the energy of an electron. To create an electron hole pairs in semiconductors requires energy at least equal to the energy gap E_g of the semiconductor.

2.1.2 Quantum wires (nanowires)

A quantum wire has dimensions of a few nanometres (10^{-9}m). At this size, quantum mechanical effects are in play, so these wires are also known as nanowires. Nanowires are 1D molecular structure with electrical and/or optical properties. Depending on the application, metallic or multi-layered nanowires made from gold, copper, or manganese (to name a few) has incredible selectivity and specificity. With diameters down to 12

nm, nanowires can be used for optical, magnetic, sensing, solar cell, and/or electronic applications [5].

In order to have enhanced physical properties, the wires must be of small diameter, must have high aspect ratio (i.e. the ratio of length to thickness) and must be uniformly oriented. Nanowires are relatively easy to produce and can have different shapes. They are often thin and short "threads" but can also have other manifestations. The propagation of electromagnetic energy has been demonstrated along a noble metal stripes with band of a few microns, and along nanowires with sub wavelength cross section and propagation length of a few micron [12]

Nanowires have also been used as sensors by monitoring charges in the conductance experienced when different compounds or gases are adsorbed to the wire's surface. In this respect, nanowires may one day be packaged as efficient sensors for minute amounts of toxic gases, chemical weapons, and explosives. The term quantum wire describes a carrier confined in two dimensions say Y and Z to a small dimension d (wire cross-section d) and free to move along the length of the wire X (qualitatively this situation resembles the situation of the carrier moving along a carbon nanotube, or silicon nanowire, although the details of the bound state wave functions are different). The solution of eqn. (2.1.1) in the case of quantum wire of a square cross-section is:

$$\psi_n(x,y,z) = (\frac{2}{d})\sin(\frac{n_y \pi y}{L})\sin(\frac{n_z \pi z}{L})\exp(ik_x.x) \tag{2.1.4}$$

and the corresponding energy is:

$$E_n = \frac{\hbar^2\pi^2}{2mL^2}(n_y^2 + n_z^2) + \frac{\hbar^2 k_x^2}{2m} \tag{2.1.5}$$

2.1.3 Quantum well

A physical situation that often arises in semiconductor devices is a carrier confined in one dimension, say Z to a thickness d and free in two dimensions say X and Y this is called 2D bands or quantum wells. In this case the solution of eqn. (2.1.1) will have form [14, 15].

$$\psi_n(x, y, z) = (\frac{2}{d})^{\frac{1}{2}} \sin(\frac{n_z \pi z}{L}) \exp(ik_x.x) \exp(ik_y.y) \tag{2.1.6}$$

And the energy of the carrier in the nth band is :

$$E_n = \frac{\hbar^2 \pi^2}{2mL^2} n_z^2 + \frac{\hbar^2 k_x^2}{2m} + \frac{\hbar^2 k_y^2}{2m} \tag{2.1.7}$$

2.1.4 Density of states in low dimension structures

For bulk materials, there are three degree-of-freedom directions and zero confined directions. Thus, bulk materials are called three-dimensional systems. Quantum wells are considered to be two-dimensional systems, which means that the charge carriers have two degree-of-freedom directions and one confined direction. In this case, the growth direction is the confined direction. Quantum wires on the other hand, have one degree-of-freedom direction and two confined directions. Thus, quantum wires are considered one dimensional system. When the charge carriers are confined in three directions, the structure is called a zero-dimensional system. We refer to this as a quantum dot system.

Optical absorption spectra in semiconductors are governed by the density of electronic states in the valence and conduction bands. Besides this, at low temperatures the absorption spectra of semiconductors exhibit sharp peaks below the edge of inter-band absorption (i.e. at frequencies $\omega < \frac{E_g}{\hbar}$),where E_g is the band gap energy.
The density of states (DOS) is defined as the number of states per unit energy range per unit volume of real space. On other way the general approach to calculate density of states using series of delta function is:[12, 13, 16].

$$\rho(\varepsilon) = 2\sum_k \delta(\varepsilon - \varepsilon_k) \tag{2.1.8}$$

Where the number 2 refers electron of spin the degeneracy which have been introducing to allow for double occupancy of each state by the different (spin-up and spin down). For "n" dimensions it can be given by:

$$\rho(\varepsilon) = 2 \times (\frac{L}{2\pi})^n \int \delta(\varepsilon - \varepsilon_k) d^n k \tag{2.1.9}$$

2.1.4.1 Quantum wire

The charge carrier confinement in semiconductors can be further decreased by reducing the number of degrees of freedom in the carrier momentum. This can be accomplished through photolithography or even self-assembled epitaxial growth of what is called quantum wires. The quantum wire usually refers to a one-dimensional (1D) system.There is a quantum confinement in two dimensional sites.

$$\rho(\varepsilon) = 2 \times \frac{L}{2\pi} \int \delta(\varepsilon - \varepsilon_k) dk \tag{2.1.10}$$

From dispersion relation we have:

$$\varepsilon_k = \frac{\hbar^2 k^2}{2m^*}$$

$$\Rightarrow d\varepsilon_k = \frac{\hbar^2 k dk}{m^*}$$

$$\Rightarrow dk = \frac{m^* d\varepsilon_k}{\hbar^2 k} \tag{2.1.11}$$

$$\rho(\varepsilon) = 2 \times \frac{L}{2\pi} \int \delta(\varepsilon - \varepsilon_k) \frac{m^*}{\hbar^2} \sqrt{\frac{\hbar^2}{2m^* \varepsilon_k}} d\varepsilon_k \tag{2.1.12}$$

Here we have noticed the properties of delta function,

$$\delta(x) = \delta(-x)$$

$$\int f(x-a)\delta(x)dx = \int f(x-a)f(x)dx = f(a)$$

$$\delta(\alpha x) = \frac{1}{\alpha}\delta(x)$$

$$f(x) = \frac{1}{\sqrt{x}};$$

Similarly

$$f(\varepsilon_k) = \frac{1}{\sqrt{\varepsilon_k}}$$

Therefore using the properties of delta function we have:

$$\rho(\varepsilon) = 2 \times \frac{L}{2\pi} \frac{m^*}{\hbar^2} [\frac{\hbar^2}{2m^*}]^{\frac{1}{2}} \int \delta(\varepsilon - \varepsilon_k) \frac{d\varepsilon_k}{\sqrt{\varepsilon_k}} \tag{2.1.13}$$

$$\rho(\varepsilon) = \frac{L}{2\pi} [\frac{2m^*}{\hbar^2}]^{\frac{1}{2}} \varepsilon^{-\frac{1}{2}} \theta(\varepsilon - \varepsilon_i) \tag{2.1.14}$$

the density of state per unit length becomes:

$$\rho(\varepsilon) = \frac{1}{2\pi} [\frac{2m^*}{\hbar^2}]^{\frac{1}{2}} \varepsilon^{-\frac{1}{2}} \theta(\varepsilon - \varepsilon_i) \tag{2.1.15}$$

where $\theta(\varepsilon - \varepsilon_i)$ Heaviside step function and defined as:

$$\theta(\varepsilon - \varepsilon_i) = 1, for \varepsilon > \varepsilon_i or$$

$$\theta(\varepsilon - \varepsilon_i) = 0, for \varepsilon \leq \varepsilon_i \tag{2.1.16}$$

and ε_i are the sub energy band levels.

Finally,

$$\Rightarrow \rho(\varepsilon) \sim \varepsilon^{-\frac{1}{2}} \tag{2.1.17}$$

This is to mean density of states in quantum wire is inversely proportional to the square root of energy of the state.

2.1.4.2 Quantum wells

The density of states in a quantum well system is restricted to the two dimensions in k-space say k_x, k_y where the electrons or holes are now confined in this plane and their motion is restricted along the growth axis (z direction in the real space, or k_z direction in the momentum space. Thus the density of states in quantum well follows analogously; however there are only two degrees of freedom:

$$\rho(\varepsilon) = 2 \times [\frac{L}{2\pi}]^2 \int \delta(\varepsilon - \varepsilon_k) d^2k$$

Here we assumed Fermic circle like dA = rdrdθ = 2πrdr

$$d^2k = 2\pi k dk \tag{2.1.18}$$

From equn. (2.1.11) we have:

$$kdk = \frac{m}{\hbar^2} d\varepsilon_k \tag{2.1.19}$$

Now density of states becomes

$$\rho(\varepsilon) = 2 \times [\frac{L}{2\pi}]^2 \int \delta(\varepsilon - \varepsilon_k) 2\pi \times \frac{m}{\hbar^2} d\varepsilon_k \tag{2.1.20}$$

$$\therefore \rho(\varepsilon) = 2 \times \frac{A}{(2\pi)^2} \times 2\pi \times \frac{m}{\hbar^2} \int \delta(\varepsilon - \varepsilon_k) d\varepsilon_k \tag{2.1.21}$$

$$\Rightarrow \rho(\varepsilon) = \frac{Am^*}{\pi\hbar^2} \theta(\varepsilon - \varepsilon_i) \tag{2.1.22}$$

The density of states per unit area becomes:

$$\Rightarrow \rho(\varepsilon) = \frac{m^*}{\pi\hbar^2} \theta(\varepsilon - \varepsilon_i) \tag{2.1.23}$$

Notice that the density of state is independent of energy (ε), i.e when energy increases the density of state is constant. If there are many (n) confined states within the quantum well system then the density of states per unit area at any particular energy is the sum over all sub bands below that point, which can be written as:

$$\rho(\varepsilon) = \sum_{i=1}^{n} \frac{m^*}{\pi\hbar^2} \theta(\varepsilon - \varepsilon_i) \tag{2.1.24}$$

2.1.4.3 Bulk(3D)

Following the same procedure, the density of state for bulk is given by:

$$\rho(\varepsilon) = 2 \times [\frac{L}{2\pi}]^3 \int \delta(\varepsilon - \varepsilon_k) d^3k \tag{2.1.25}$$

By spherical coordinate system d^3k is given by:

$$d^3k = k^2 sin\theta d\theta d\phi dk = 4\pi k^2 dk \tag{2.1.26}$$

Here we assumed Fermi sphere filled with electrons for $k \leq k_F$, for $k \geq k_F$ it is empty. From equn.(2.1.11) we have:

$$k^2 = \frac{2m^* \varepsilon_k}{\hbar^2} and$$

$$\Rightarrow dk = \frac{m^*}{\hbar^2 k} d\varepsilon_k = \frac{m^*}{\hbar^2}[\sqrt{\frac{\hbar^2}{2m^* \varepsilon_k}}] d\varepsilon_k \tag{2.1.27}$$

Now density of state becomes

$$\rho(\varepsilon) = 2 \times [\frac{L}{2\pi}]^3 \int \delta(\varepsilon - \varepsilon_k) 4\pi k^2 dk \tag{2.1.28}$$

$$\rho(\varepsilon) = 2 \times \frac{V}{(2\pi)^3} \times 4\pi \times \frac{2m^*}{\hbar^2} \times \frac{m^*}{\hbar^2} \times [\frac{\hbar^2}{2m^*}]^{\frac{1}{2}} \int \delta(\varepsilon - \varepsilon_k) \frac{\varepsilon_k}{\sqrt{\varepsilon_k}} d\varepsilon_k \tag{2.1.29}$$

$$\rho(\varepsilon) = \frac{V}{\pi^2} \times \frac{2m^*}{\hbar^2} \times \frac{m^*}{\hbar^2} \times [\frac{2m^*}{\hbar^2}]^{-\frac{1}{2}} \int \delta(\varepsilon - \varepsilon_k) \frac{\varepsilon_k}{\sqrt{\varepsilon_k}} d\varepsilon_k \tag{2.1.30}$$

Rearranging and simplifying the above question, the density of state per unit volume becomes:

$$\rho(\varepsilon) = \frac{1}{2\pi^2} \times (\frac{2m^*}{\hbar^2})^{\frac{3}{2}} \varepsilon^{\frac{1}{2}} \theta(\varepsilon - \varepsilon_i) \tag{2.1.31}$$

$$\Rightarrow \rho(\varepsilon) \sim \varepsilon^{\frac{1}{2}} \tag{2.1.32}$$

This is to mean density of states in bulk structure is proportional to the square root of energy of the state.

To understand the concept of Fermi energy and the distribution of electrons and holes in a semiconductor, let us first assume that the semiconductor is intrinsic, which means that the number of electrons in the conduction band is equal to the number of holes in

the valence band. The density of states for both the conduction and valence bands can be written as follows:

$$\rho_e(\varepsilon) = \frac{1}{2\pi^2}[\frac{2m^*}{\hbar^2}]^{\frac{3}{2}}(\varepsilon - \varepsilon_c)^{\frac{1}{2}} and$$
$$\rho_h(\varepsilon) = \frac{1}{2\pi^2}[\frac{2m^*}{\hbar^2}]^{\frac{3}{2}}(\varepsilon_v - \varepsilon)^{\frac{1}{2}} \quad (2.1.33)$$

Where the subscript "e" and "h" stands for electrons and holes respectively' and ε_c and ε_v are the bottom and top of the conduction and valence bands respectively.

2.1.4.4 Quantum dots (QDs)

The situation for quantum dots is quite different. The quantum dot is characterized by having three confinement directions and zero degree-of-freedom directions. The density of state is thus represented by the number of confined states divided by the energy interval. If the energy interval is approaching zero, then the density of states is simply a series of delta (δ) -functions centered on the confined energy levels (ε_1, ε_2, ε_3 . . .). The energy levels are entirely discrete and are given by:

$$\varepsilon_{n_x n_y n_z} = \frac{\pi^2\hbar^2}{2m^*}[\frac{n_x^2}{L_x^2} + \frac{n_y^2}{L_y^2} + \frac{n_z^2}{L_z^2}] \quad (2.1.34)$$

$$\rho(\varepsilon) = 2\theta(\varepsilon - \varepsilon_j) \quad (2.1.35)$$

The factor of 2 accounts for spin degeneracy.

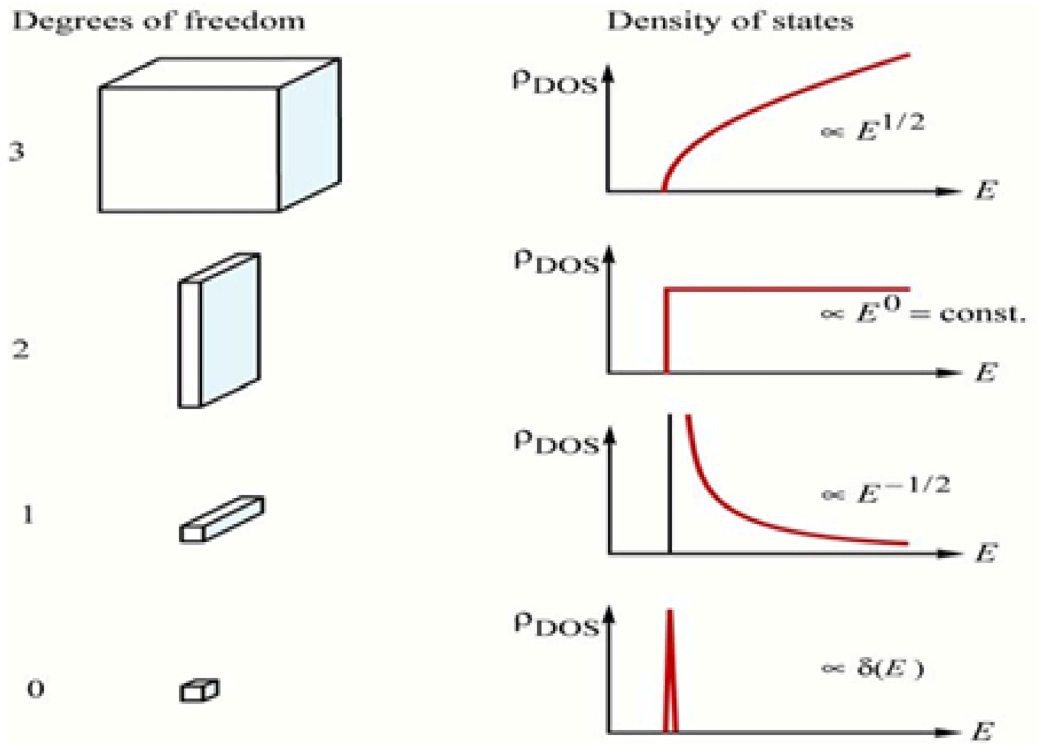

Figure 2.1: Density of state as the number of confining dimension increase

2.2 Band structures of Semiconductor nanostructures

In semiconductors and insulators, the fully occupied valence bands are separated by fully empty conduction bands by an energy gaps E_G, which represents the threshold energy for band-to-band electrons transitions. The difference between highest occupied and the lowest unoccupied level is called band gap. Semiconductors have a band gap in the range between 1eV to 4eV. The band structure of a crystal can be often be explained by the nearly free electron model for which the band electrons are treated as perturbed only weakly by the periodic potential of the ion cores [13]. Semiconductors can be divided into direct band gap and indirect band gap. A direct band gap means that the minimum of the conduction band lies directly above the maximum of the valence band in momentum space. Therefore no momentum transfer is required to launch the electron from the valence band into the conduction band. Indirect band-gap semiconductors do not have the

lowest conduction band energy at the inflection point. Therefore the fast electron has to transfer momentum to an electron in the valence band in order to excite it into the conduction band [17].

To get luminescence spectrum in the visible range highest occupied molecular orbital to lowest unoccupied molecular orbital (HOMO-LUMO) gap has a great influence, which is related to the band gap energy of the bulk structure. In semiconductors the Fermi energy lies in the gap between two bands, i.e. there is an upper most completely filled band called valence band (VB), the unoccupied band is called the conduction band (CB), the two bands are separated by an energy gap (E_g)[13].

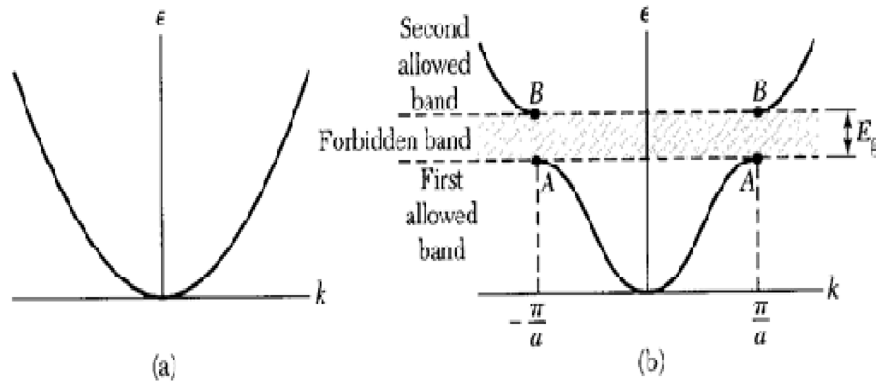

Figure 2.2: Plot of energy versus wavevector
a) plot of energy versus wavevector k for a free electron b) plot of energy versus wavevector for an electron in a mono atomic linear lattice of lattice constant a. The energy gap E_g shown is associated with the first Bragg reflection at k=$\pm\frac{\pi}{a}$ other gaps are found at higher energies at k=$\pm\frac{\pi}{a}$, for integral values of n. [13]

When an electron - hole pair is squeezed into a nanocrystal with one or more dimensions approaching the bulk exciton Bohr radius, the effective bandgap of the semiconductor increases. The smaller the nanocrystal, the larger the effective bandgap, and the greater the energy of optical emission resulting from electron-hole recombination [18].

2.3 Excitons

Reflectance and absorption spectra often shows structure for photon energies just below the energy gap. This structure is caused by the absorption of a photon with creation of a bound electron-hole pair. An exciton is a bound state of an electron hole which are attracted to each other by the electrostatic Coulomb force. An exciton can move through the crystal and transport energy. It does not transport charge because it is electrically neutral quasi-particle that exists insulators, semiconductors and in some liquids [19]. An exciton can form when a photon is absorbed by a semiconductor. This excites an electron from the valence band into the conduction band. In turn, this leaves behind a positively-charged electron (hole).

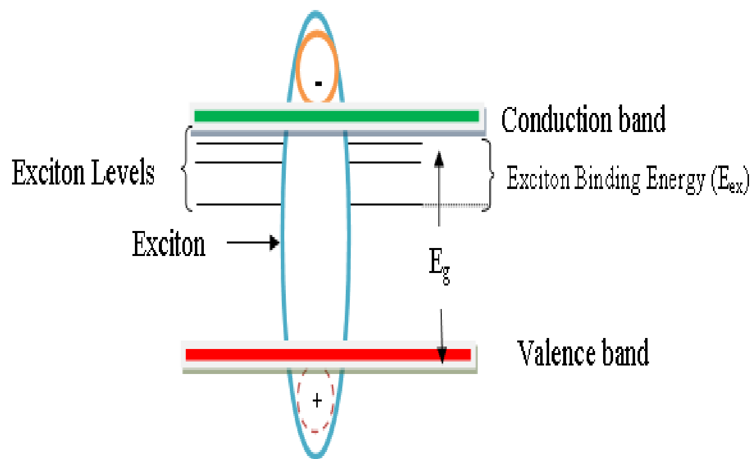

Figure 2.3: Exciton levels for transition from VB to CB [After Ref. 13]

The electron in the conduction band is then effectively attracted to this localized hole by the repulsive Coulomb forces from large numbers of electrons surrounding the hole and excited electron. This attraction provides a stabilizing energy balance. Consequently, the exciton has slightly less energy than the unbound electron and hole. The wavefunction of the bound state is said to be hydrogenic, an exotic atom state similar to that of a hydrogen atom. However, the binding energy is much smaller and the particle's size much larger than a hydrogen atom. This is because of both the screening of the Coulomb force by

other electrons in the semiconductor (i.e., its dielectric constant), and the small effective masses of the excited electron and hole [21]

Excitons can be formed in every insulating crystal. When the band gap is indirect, excitons near the direct gap may be unstable with respect to the decay in to free electron and free hole. All excitons are unstable with respect to the ultimate recombination process in which electron drops in to the hole. A free electron and a free hole are created whenever a photon of energy greater than the energy gap is absorbed in a crystal. The threshold of this process is $\hbar\omega > E_g$ in a direct process. In an indirect process, the threshold is lower by the phonon energy $\hbar\Omega$. But in the formation of excitons the energy is lowered with respect to these thresholds by the binding energy of the exciton [13].

Excitons in semiconductors are stable so long as their binding energy is smaller than the thermal energy (k_BT). The optical absorption and photoluminescence emission of excitons affect the optical properties of the band edge of semiconductors and their heterojunctions. Exciton absorption is profound at low temperatures in most direct bandgap semiconductor materials, and it can even be observed at room temperature in semiconductors, such as GaN, where the binding energy of the exciton is slightly larger than the room temperature thermal energy. Thus, excitons are the main mechanism for light emission in semiconductors at low temperature (when k_BT is less than the exciton binding energy), replacing the free electron-hole recombination at higher temperatures [13].

2.4 Optical and electrical properties of Semiconductor nanostructures

Semiconductor nanoparticles or quantum dots (QDs) have rich optical properties that strongly depend on size, especially when the particle size is less than the exciton Bohr radius of the material. Exciton Bohr radii are typically on the order of a few nanometer(nm). Their optical properties are also very sensitive to the surface characteristics and, to a lesser degree, of shape of the nanoparticles. Another factor affecting the optical properties is the interaction between nanoparticles or between the nanoparticles and their embedding environment [26, 40].

The electronic and optical properties of group III nitride materials are of great interest for light-emitting diodes (LEDs), lasers, and other optoelectronic devices, because of their band structures and the large range of band gap (0.7-6.2 eV) that can be covered by these nitrides and their alloys. GaN-based materials (with a band gap of 3.4 eV) especially have received a great deal of attention for their blue and ultraviolet light emission and because of application in high-temperature; high-power devices [20].

An optical transition in a semiconductor nanostructure is described as the molecule absorbs light; the absorbed photons change the energy of the electronic system. In a simple single-electron approximation, the photon energy is used to promote an electron from one occupied orbital into an unoccupied orbital, for instance HOMO to LUMO transition [22]. The electrical properties are strictly related to the peculiar structure of the active layer, consisting of a very high density of partially interconnected and very small amorphous clusters [23].

The normal size of an exciton in a large (bulk) crystal, expressed as an exciton Bohr radius, provides an approximate dimension for the onset of quantum confinement effects.

When electron-hole pair is squeezed into a nanocrystal, with one or more dimensions approaching the bulk exciton Bohr radius, the effective bandgap of the semiconductor increases. Size of semiconducting nanocrystal and band gap has relations. The smaller, the nanocrystal the larger effective bandgap and the greater energy of optical emission resulting from electron-hole recombination [18].

When semiconductor gets an external perturbation with larger energy than its band gap, an electron in the valence band acquires suitable energy to reach to the conduction band. This excitation of an electron induces formation of a hole in the valence band. This phenomenon is called as generation. The generated electron and the hole tend to return to their ground state by giving up the excess energy through recombination. Before recombination, the generated carriers - electrons and holes - experience various processes such as diffusion, drift, scattering, exciton formation, and so on. If the generated carriers give up their energy in the form of light, the recombination is called as radiative recombination. Otherwise, if the generated carriers lose the excess energy in the form of heat, the process is called as non-radiative recombination [24].

2.5 Emission and absorption of light

The emission and absorption of light in semiconductors is very analogous to the same process that we quite familiar with in atoms, an electron in an excited state of energy E_1 makes a transition downwards to an empty state (E_0) and emits a photon; an electron in a lower state (E_0) absorbs a photon and makes a transition to higher state (E_1).The band gap of insulators is what makes them relatively transparent if the incoming light has a frequency $\omega < \frac{E_g}{\hbar}$, then it cannot be absorbed by the electrons filling the valence band. The very low absorption of wide-gap insulators is generally due to impurities, so light penetrates relatively deeply into them [25].

Photo-excitation of carriers can occur both by absorption or emission of phonon in indirect semiconductors. In direct semiconductors no phonon assistance is needed and the absorption coefficient(α) shows a parabolic dependence with incident photon energy. The net result is that when band-to-band absorption occurs in direct semiconductors, the incident radiation is absorbed in a much shallower depth than in indirect semiconductors the forbidden gap can also mediate an electron-hole pair recombination. In indirect semiconductors, phonon assistance may still be required making gap state mediated radiative recombination potentially less efficient than a direct transition [27].

2.6 Luminescence

Luminescence is emission of light by a substance which is caused by chemical reaction, electrical energy, subatomic motions, or stress on a crystal. Thus luminescence is the emission of optical radiation resulting from electronic excitation in a material. There are three main optical processes for interaction between a photon and an electron in a solid: absorption, spontaneous emission, and stimulated emission. Of these three, spontaneous emission, in which a photon is emitted when the electron in the conduction band spontaneously returns to the empty state in the valence band, is the main process that happens in LEDs. Optoelectronic devices work by exciting electron-hole pairs; when a pair recombines it emits light. Such process is known as luminescence. It results when there is a significant overlap (indirect and reciprocal space) in the electron-hole pair wave functions. Whenever there is such overlap, luminescence is possible; however the strength of the luminescence, that is light emission rate and quantum efficiency depend on the extent of this overlap and the transition probability [27].

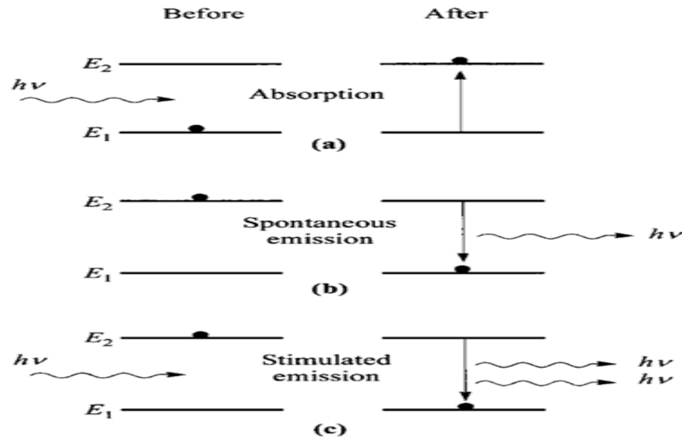

Figure 2.4: The basic optical processes between two energy levels. The black dot indicates the state of the electron. The initial state is at the left; the final state, after the process has occurred, is at the right[27].

There are different types of Luminescence depending on the source of the input energy. Such as: photoluminescence (PL) that is excited by optical excitation (photons), cathodoluminescence (CL) that is excited by electron beam or cathode ray, electroluminescence (EL) that is the emission of light by the injection of current or electric field, and radioluminescence(RL) that is excited by other fast particles or high-energy radiation. Luminescence is further broken down into two categories according to the speed of recombination. Direct electron-hole recombination which is usually relatively fast: the lifetime depends on the number of final states available. The excited electron first makes a transition to such a state, whose energy normally lies in the gap. Then it makes a second transition to finally recombine with the hole in the valence band. Often one of these transitions is non-radiative, by this it meant that the energy given off in the transition appears as heat, not light [27].

2.6.1 Electroluminescence

EL has been reported for porous silicon during anodic oxidation, and also for porous silicon devices employing thin gold, indium tin oxide, silicon carbide, and polymer contacts. EL is a light emission phenomenon caused by the electric current passing through a material. In semiconductors, electrons can also be accelerated by a strong electric field. It is the result of radiative recombination of electrons and holes in a material (usually semiconductors) luminescent device such as light emitting diodes (LEDs), or through excitation by impact of high energy electrons accelerated by strong electric field (as with phosphorus in electroluminescent display). Electrons and holes will be excited and separated by the energetic electrons. When electrons and holes recombine in the material, the energy of the excited electrons will be released in the form of photons [28, 29].

Electroluminescent lighting refers to cool, continuous, low-powered devices that cast a soft light without any glare. Its low-power consumption makes electroluminescent lighting a competitor of other technologies, like neon or fluorescent lighting. EL lighting is commonly used in signs and accent lighting applications, for automotive instrument panel backlighting, aircraft panel lighting, backlights for liquid crystal displays and cell phones, and in battery-operated devices likewristwatches, nightlights, computer monitors, and more. The electroluminescent light in these applications may be any color, but are most commonly green, blue, or red. Green electroluminescent lighting is said to match the peak sensitivity of human vision and produce the greatest light output, while using minimal power input [22].

Types of EL

Basically we have two types of EL; high field EL and injection EL. In injection EL light is emitted up on recombination of minority and majority carriers across the band gaps

and high luminescence efficiency throughout the visible region of the spectrum. Two more phenomena i.e photoelectroluminescence (PEL) and electrophotoluminescence (EPL) used nowadays. PEL is used whenever the excitation mechanism of the electric field is influenced by additional irradiation and EPL is the term employed when the luminescence by irradiation (with UV, X-rays, cathode rays etc) is controlled by electric fields, leading to the enhancement or to a quenching effect of the luminescence emission. The main difference between EPL and EL is that the EPL is an empty of traps by electric field where as the EL is the field of excitation of the luminescence centres [30]. The relative EL intensity of colours depends on the injection current level, which controls the hole concentration distribution among the QWs [31].

2.6.2 Transmission measurement of EL

Semiconductors are transparent to photons whose energies lie below their bandgap and are strongly absorbing for photons whose energies exceed the bandgap energy. Band-to-band absorption involves excitation of an electron from the valence band to the conduction band, resulting in creation of electron-hole pair. When light passes through a material, the light is partially scattered, absorbed, or transmitted. The transmitted beam intensity is exponentially decayed with the specimen thickness and absorption coefficient.The absorption coefficient, α, is a property of a material which defines the amount of light absorbed by it. The inverse of the absorption coefficient, α^{-1}, is the average distance traveled by a photon before it gets absorbed. The light intensity as a function of the effective thickness of the sample z is derived from the probability of light being absorbed or scattered out of the beam in thickness dz and is given as:

$$\frac{-dI_z}{I_z} = \frac{\sigma c A dz}{A} = \sigma c dz \tag{2.6.1}$$

where A is area , dz is thickness, c is concentration of molecule, σ is cross section to which incident beam is related, the product $\sigma c A dz$ is effective area on which the molecules present and dI_z is the change in intensity across dz of the material.

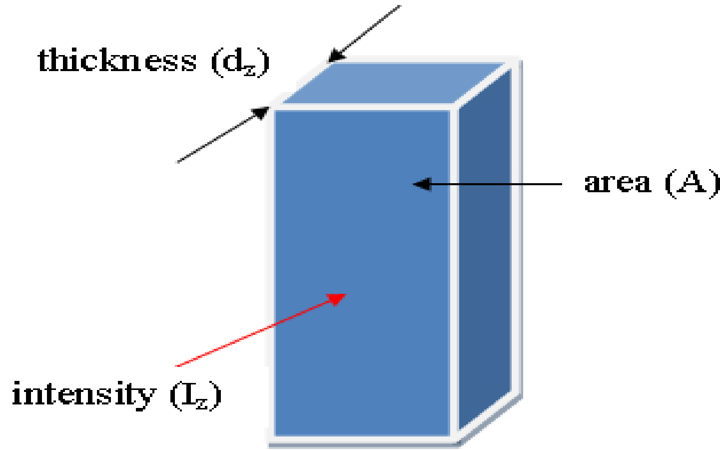

Figure 2.5: Schematically diagram of material absorption and transmission of light [After Ref 24]

Integrating both sides, simplifying and rearranging we get:

$$I(z) = I_o e^{-\alpha z} \tag{2.6.2}$$

Where I_0 and I are the intensities of the incident light before and after it passes the sample and $\alpha = \sigma c$ is linear attenuation coefficient. The attenuation in intensity (I) is not only by the absorption in the material but also by scattering at inner surface of voids in the crystal. The total light absorption is obtained simply by measuring I, I_0 and z i.e $\alpha = \frac{1}{z} ln(\frac{I_o}{I})$ [24].

Electrons in the valence band of a semiconductor can absorb photons whose energy is higher than the band gap energy, E_g , and jump to the conduction band. The absorption coefficient, α(E), for an Photon energy (E) higher than the band gap energy is given by:
i) For a direct semiconductor

$$\alpha(E) = \alpha_0 \sqrt{\frac{E - E_g}{E_g}} \tag{2.6.3}$$

ii) For an indirect semiconductor

$$\alpha(E) = \alpha_0 (\frac{E - E_g}{E_g})^2 \tag{2.6.4}$$

Where E is photon energy, E_g is energy gap and α_o is absorption coefficient fitting parameter. The photon energy E, is given by hν= $\frac{hc}{\lambda}$ where h is Planck's constant and λ is the wavelength of light. Thus the absorption coefficient of a material depends on the wavelength of light incident on it [24].

2.6.3 Dependence of EL intensity on temperature

Temperature dependent EL spectra were measured in the high temperature range. The blue-shift of peak energy induced resulting from the increasing temperature which enables carriers at the localized energy states to populate the higher levels is compensated and overcome by the red-shift of the emission peak wavelength due to the band gap narrowing caused by increasing temperature and with increasing injection currents, the dominant emission peak changed from higher energy to lower energy indicates a radiative recombination of excitons localized in the quantum-dot-like regions. In the high injection current range the heating effect is apparent, leading to the increasing nonradiative recombination of carriers. Injected carriers that are localized in quantum-dot-like regions prevent them from reaching nonradiative recombination sites. The higher energy emission is quenched quickly, and the lower energy emission becomes dominant in the EL emission spectra [32].

EL in three dimension (3D) nanostructures was found almost simultaneously with in the first investigation of the photoluminescence (PL). In contrast, vertical carrier transport in multi layers and 3D nanostructures is very efficient, and a simple device where multi layers are embedded in to a p-n diode or similar structure can easily be fabricated. On increasing applied voltage, it is observed a noticeable EL spectra shift toward greater photon energies, i.e. a "blue shifted". EL intensity as a function of temperature with

intensity at absolute zero temperature (I_0) can be fitted by a standard equation: [18]

$$I_{EL}(T) = \frac{I_o}{1 + C_1 exp(\frac{-E_1}{K_B T}) + C_2 exp(\frac{-E_2}{K_B T})} \quad (2.6.5)$$

Where E_1 and E_2 are the two thermal quenching activation energies, T is the temperature and K_B is the Boltzmann constant, C_1 and C_2 are coupling coefficients. The EL thermal quenching activation energy of GaN is 190meV. Interestingly, in the sample, the device current as a function of temperature depicts nearly exact anti-correlation with the EL intensity and exhibits activation energy of $\sim$ 200 meV [42]. The activation energy E_1 is independent of the intensity, while E_2 depends significantly on the excitation intensity. The optical efficiency of all the LEDs decreases as the temperature raises. This can be attributed to two major factors. First, the injected carriers have a higher thermal energy, and therefore are more likely to escape from the QWs and recombine nonradiatively in the barrier or cladding layers. Second, the nonradiative recombination rate in the multi quantum wells (MQWs) increases rapidly with increasing temperature, leading to a decrease in the radiative to nonradiative ratio [18].

2.6.4 Transient properties of EL

The radiative and non-radiative processes occurring in the active layer containing GaN nanoclusters have been studied by means of time-resolved luminescence measurements. To investigate the carrier injection and relevant carrier recombination mechanisms, time resolved measurements of the EL signals have been extracted by fitting the experimental curves with the equation. By analyzing spectrally resolved EL decays, a stretch exponential dependence was found for each observation wavelength, the equation is described by the function:[33, 34]

$$I(t) = I_o exp[-(t/\tau)^{\beta}] \quad (2.6.6)$$

where $I(t)$ and I_0 are the EL intensity as a function of time and at $t = 0$, respectively, τ is the EL decay time constant, and β is a dispersion factor ≤ 1. In the case of single exponential decay the β is equal to 1. If the decay consists of a combination of several exponentials, reflecting dispersion in lifetimes for the same observation wavelength, then the value of β is less than 1 and the decay is faster in the beginning, i.e. the smaller β is the more 'stretched' the exponential is. EL decay lifetime becomes faster by increasing the current density. This strong dependence of τ on current density suggests the occurrence of non-radiative processes when devices are operating at high current densities. This is because of at high current density the carrier concentration is very high [35].

Chapter 3

Methods and Formulation of models for EL

3.1 Methods

We designed computational method which is based on theoretical study and numerical analysis of EL intensity of GaN-ncs as a function of different parameters. Thus we used both analytical and numerical method for determining the properties of EL intensity of GaN as a function of different parameters, (such as wave length, number of nanoclusters, applied voltage, time and temperature). The theory is supposed to be developed model equation, solving the problem analytically and numerical method for determining the properties of EL intensity as a function of different parameter. i.e We developed theoretical model equation that describes the EL intensity as a function of size of the nanoclusters using quantum confinement model and used Fourier transform of the size dependent intensity into energy dependent intensity equations. After we have derived model equation as a function of energy, we developed suitable MATLAB code for our master equation and theoretically given general equation to generate data and plotted their graphs in different legends. The developed model equation is described as follows.

3.2 The Quantum Confinement Model (QCM)

Quantum confinement is a very successful model for understanding the electronic structure of nanometer size semiconductor structures such as quantum wells, nanocrystals, and clusters. It predicts that with decreasing particle sizes the band gap increases due to shifting of the band edges [41]. So that it based on the electronic confinement in dot like structure of the nanocrystals (nc). The development of this model is based on the effective mass approximation theory. In this model, the luminescence process is attributed to an energy shift of carriers (electrons and holes) and is proportional to d^{-2}, where 'd' is diameter of the GaN-nc. We can model nanoclustered QD as a spherical, Quantum wire as a cylinder and Quantum well which is parabolic as a hemispherical all with diameter 'd', and possible to determine their HOMO-LUMO gap by relating their energy gaps of the confined and bulk structures in their geometric domain. A natural choice to find QDs size is to associate the effective size with the diameter of the sphere which has the mass density (ρ) of bulk GaN and contains the same number of GaN nanoclusters as the QD. Then the diameter is: [36]

$$d(N_{GaN}) = (\frac{3}{4\pi\rho})^{\frac{1}{3}} N_{GaN}^{\frac{1}{3}} \simeq 3.3685 N_{GaN}^{\frac{1}{3}} A^o \tag{3.2.1}$$

Assuming that a Gaussian size distribution about the mean diameter 'd_0' for the nanocrystallites;[36]

$$I(d) = \frac{1}{\sqrt{2\pi}\sigma} exp(-\frac{(d-d_o)^2}{2\sigma^2}) \tag{3.2.2}$$

where d is the cluster diameter and σ is the standard deviation.

The number of carriers (N_c) in a column diameter 'd' participating in the EL process will increase as the cluster size increases; for large clusters more carriers are available to take part in optical transitions. The number of carriers available in a cluster scales with cluster diameter d is proportional to 'd^2'. Therefore it is given as:

$$N_c \simeq d^2 \Rightarrow N_c = ad^2 \tag{3.2.3}$$

where "a" is suitable normalization constant.

For a GaN sample consisting of varying column diameters the probability distribution of electrons participating in the EL process is;

$$I_{cd} = \frac{1}{\sqrt{2\pi}\sigma} N_c(d) exp(-\frac{(d-d_o)^2}{2\sigma^2}) \tag{3.2.4}$$

$$I_{cd} = \frac{1}{\sqrt{2\pi}\sigma} ad^2 exp(-\frac{(d-d_o)^2}{2\sigma^2}) \tag{3.2.5}$$

The luminescence intensity can be determined by the Fourier transform of equn.(3.2.5) to the energy axis as:

$$I(\Delta E) = \int_0^\infty I(d)\delta(\Delta E - \frac{c_1}{d^2}) d(d) \tag{3.2.6}$$

Note that d(d) is to means derivative of "d"

$$I(\Delta E) = \int_0^\infty \frac{1}{\sqrt{2\pi}\sigma} ad^2 \delta(\Delta E - \frac{c_1}{d^2}) exp(-\frac{(d-d_o)^2}{2\sigma^2} d(d) \tag{3.2.7}$$

$$I(\Delta E) = \frac{1}{\sqrt{2\pi}\sigma} a \int_0^\infty \delta(\Delta E - \frac{c_1}{d^2}) d^2 exp(-\frac{(d-d_o)^2}{2\sigma^2} d(d) \tag{3.2.8}$$

The Dirac delta function facilitates a straight forward integration.

Now letting $y = \frac{c_1}{d^2}$ where c1 is arbitrary constant, and simplifying for d(d) and substituting it in equn(3.2.8), simplifying and applying the properties of Dirac delta function, the above integral will be transformed in to the form:

$$I(\Delta E) = \frac{1}{2} \frac{ac_1^{\frac{3}{2}}}{\sqrt{2\pi}\sigma} \int_0^\infty \delta(\Delta E - y) y^{\frac{-5}{2}} exp\{\frac{-d_o^2}{2\sigma^2}[(\frac{c_1}{d_o^2 y})^{\frac{1}{2}} - 1]^2\} dy \tag{3.2.9}$$

Now if we let $y = \Delta E$, $\frac{c_1}{d_o^2} = \Delta E_o$ and apply the properties of Dirac delta function the above integral gives the intensity as a function of ΔE

$$I(\Delta E) = \frac{ac_1^{\frac{3}{2}}}{\sqrt{8\pi}\sigma} \Delta E^{\frac{-5}{2}} exp\{\frac{-d_o^2}{2\sigma^2}[(\frac{\Delta E_o}{\Delta E})^{\frac{1}{2}} - 1]^2\} \tag{3.2.10}$$

where ΔE is the energy shift due to the confinement given by;

$$\Delta E = h\nu - (E_g - E_b) \tag{3.2.11}$$

where h is Planck's constant, E_g is the bulk band gap of GaN in this sample and E_b is the exciton binding energy, d_0 being the nanocrystal mean diameter and σ standard deviations. Depending on temperature the values of E_g ranges from 3.39 eV to 3.52 eV ; however, we took 3.4 eV which is actually reported in most standard experiments at room temperature, while the value of E_b varies with nanocrystal radius of the sample. For GaN-ncs it is reported as in the range 20.4meV to 28meV [18, 25, 37, 38].

The EL spectrum is caused by injection of strong electric field **E** or current, the energy associated to this field is:

$$\varepsilon = NZeEd = NZVe \tag{3.2.12}$$

where N is the number of nanocrystallite GaN taken in the sample, Z is the number of electrons in each crystal, e is the charge of electron, E is the magnitude of external applied electric field which is responsible for EL and in the direction of diameter, 'd' is the diameter of the single nanocrystal and V is the voltage applied to the nanocrystal sample; since EL and light emitted due to photon energy (photoluminescence (PL)) occurs at the same energy, using the analogy of the PL spectrum model we can write the energy shift as:

$$\Delta E = NZVe - (E_g - E_b) \tag{3.2.13}$$

According to the QC model, the emission wavelength and intensity depends on nanocrystal diameter, size distribution and concentration. This model can explain the general tendency of most experimental results such as the blue shift of the luminescence spectrum with decrease of the GaN-nc size [10, 30].

Chapter 4

Results and discussion

In this chapter we will study the properties of EL intensities form GaN nanostructures, whose data was computed and piloted in graphs as a function of different parameters in different legends and a comparative analysis between our result and the experimental results reported in literature.

4.1 EL intensity as a fuction of wavelength

Fig 4.1 shows our result of the EL intensity as a function of wavelength for GaN nanostructures. When we compare our result and the experimental result in ref [39] nearly they

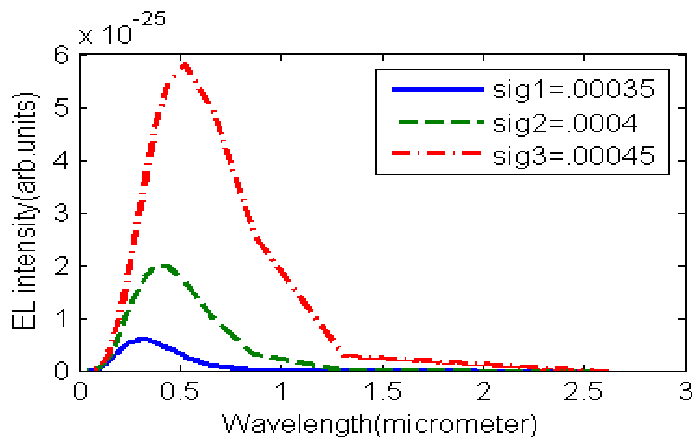

Figure 4.1: EL intensity versus wavelength for GaN nanoclusters

have the same nature Gaussian shaped peak curve. In both cases the EL intensity has

more sharp peak when near the center of the gaussian curve. As shown in the figure in both cases as wavelength increase the the intensity spectra shifts to lower energy (red-shifted).

4.2 EL intensity as a function of number of sample GaN nanoclusters

Fig 4.2 shows EL intensity as a function of number of sample GaN nanoclusters for different fixed values of applied voltage. Changing the number of nanoclusters means changing the size of the nanoclusters, which in turn changes the EL intensity. i.e. decreasing the number of nanoclusters in the sample results in decreasing the diameter of the nanoclusters, this results a change in the luminescence intensity since it is related by the equation of our model. When the size of nanoclusters decreases, the surface-to-volume ratio increases leading to quantum confinement effect that enhance radiative recombination rate of excitons for emission of light. This is due to the result of an increases in band gap energy and the excited electronic state become discrete with high oscillator strength.

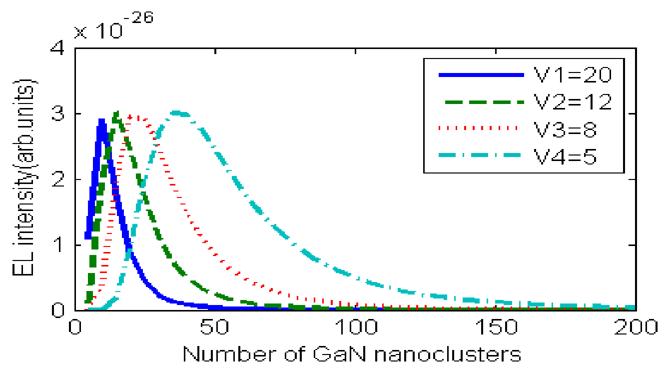

Figure 4.2: EL intensity versus number of sample GaN nanoclusters

It is shown that in case of smaller particles, higher EL intensity is obtained and light

emission starts at lower threshold. However in selecting the number of samples it should be based on the applied voltage and wavelength. As shown in the figure for a fixed value of voltage we have different number of sample clusters related to the peak of the curve in order to get EL spectrum in the visible range. If we choose too large or too small sample for a fixed voltage, the EL spectrum will lie in the ultraviolet or infrared region respectively, which has no physical utility for applications since both are out of visible light ranges.

4.3 EL intensity as a function of voltage

Figure (4.3) shows EL intensity as a function of voltage for different fixed number of nanoclusters of GaN. As shown in the figure the EL intensity increases as the value of applied voltage for each nanoclusters increase and then reaching certain maximum peak it decrease infinitely with increasing value of the applied voltage. This phenomenon is known as efficiency drop effect. The causes for this effect may be carrier linkage at high

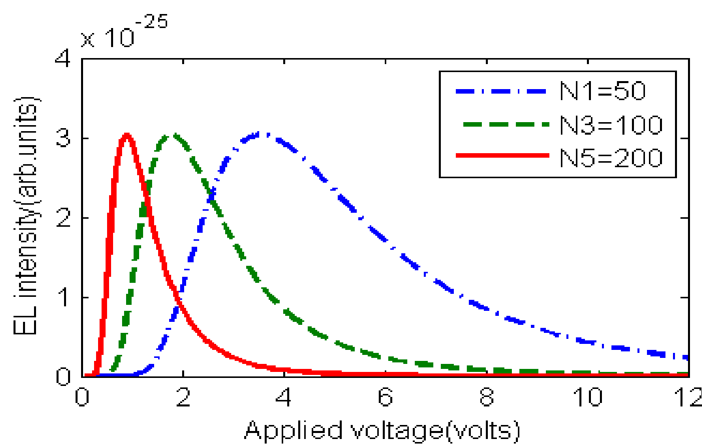

Figure 4.3: EL intensity versus applied voltage for GaN nanoclusters

forward currents, Auger recombination, or junction heating carrier delocalization. Yet to have a spectrum in the visible range for a given size of nanoclusters we need to select

the appropriate range of values of voltage. This shows that the power efficiency is very sensible to the applied voltage and that low voltage is necessary to obtain high efficiency. In our sample case we get maximum average intensity when the applied voltage is about 6v.

4.4 EL intensity as a function of temperature

Fig(4.4)shows that the dependence of EL intensity on the temperature of the nanoclusters, which relates with Ref[33]. The temperature dependance of EL intensity for nanoclusters is given by equn(2.6.5) with specified values of E_1 and E_2.

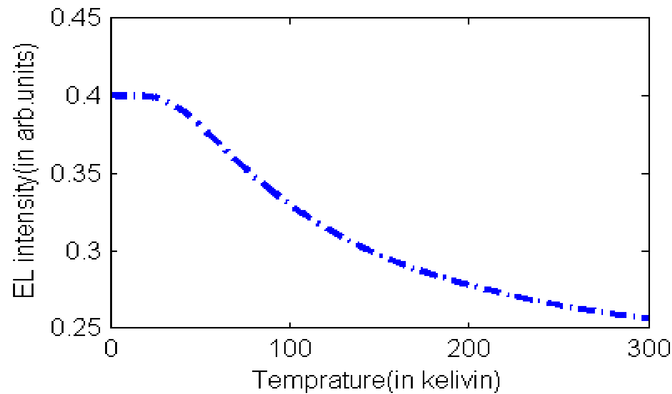

Figure 4.4: EL intensity versus temperature

As shown in the figure as the temperature increases the EL spectrum shifted decreasing the intensity of EL. This is due to high absorption and the shrinkage of band gap with increasing temperature. The EL quenching at increased temperature is a combination of a reduced confinement and thermally activated non-radiative recombination processes within "active" crystallites.

4.5 EL intensity as a function of time

Fig (4.5) shows the time dependence of EL intensity of our result which is much with experimental value in Ref [34], both have similar pattern. A shorter decay time constant allows a higher modulation frequency, but reduces the efficiency, This is due to the decrease in oscillation period and resulting non radiative recombination of the particles in the nanocrystal.

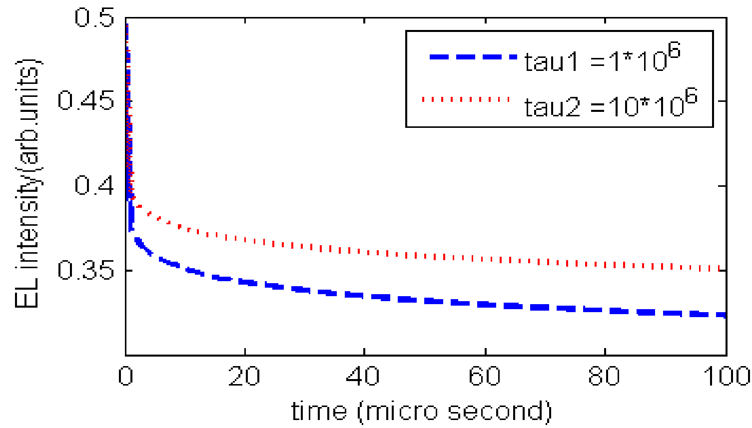

Figure 4.5: EL intensity versus time

Chapter 5

Summary, Conclusion and Future outlook

5.1 Summary and Conclusion

This work was inspired by the recently discovered phenomenon that GaN nanostructures in the nanometer size range are able to emit visible light. The aim was to investigate the EL properties from GaN nanostructures. QC effect is more prominent in nanostructures as an efficient luminescence source because it enhances radiative recombination rate of excitons and carrier localization effect with decreasing the cluster size by increasing the surface-to-volume ratio, which gives new electronic properties that are not present in host semiconductors. Band gap increases with decreasing size which allow light to emit and useful to observe the intensity of emitted light. EL spectrum occurs by electrical excitations (current and high injection field), has Gaussian sub peaks and more red shifted. A blue shift of EL is observed with decreasing nanocrystals size and applied voltage. The light generated by electron-hole recombination in GaN nanostrcutures is quantified by quantum efficiency.

Generally the energy of emitted photon spectrum determined by the HOMO-LUMO gap. The intensity of the spectrum depends on the size of the nanocluster and the energy

shifted due to confinement, and the EL intensity depends on applied voltage, temperature, transient time and size and nature of the nanocluster sample taken. EL shows either reversible or permanent degradation with time. It decreases with increase in temperature due to high absorption.

The low luminescence can be due to either the nature of the semiconductor or a high density of internal and/or surface trap states that quench the luminescence. Luminescence usually increases at lower temperature due to inhibition of electron-phonon interactions and thereby increases the excited electronic state lifetime. Controlling the surface by removing surface trap states can lead to significant enhancement of luminescence as well as of the ratio of band edge over trap state emission.
Generally,

- EL spectrum is red shifted as temperature of the nanocluster increase.
- EL intensity efficiency exhibit a rapid degradation in high temperature and high driving current range.
- The range of the spectrum depends on the HOMO-LUMO gap.
- For smaller particles, higher EL intensity is obtained and light emission starts at lower threshold.
- Further treatment improves the stability of the EL intensity. The voltage needed to obtain a given EL intensity increases with storage time.

5.2 Future outlook

The improvement and understanding of the luminescence properties of GaN nanostructures has largely advanced. However, it requires better EL efficiency and further studies of the current transport and luminescence mechanism in order to improve the quantum efficiency and electroluminescence intensity. For example, the efficiency of the light-emission from the device may be improved by choosing better material as the electrical contact for GaN.

In our work detailed explanation and study of EL from GaN nanoclusters has not been done sofar. Thus detailed theoretical and experimental work need to be done in the future to optimize the devices EL intensity in different parameter aspects. So that enhancing the stability, reliability and repeatability of EL intensity; increasing the quantum efficiency, minimizing the EL degradation, controlling Auger recombination, enhancing radiative recombination, brief and justified reason for non-radiative recombination will be the future work for researchers on EL spectrum from GaN nanostructures.

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