The Effects of Electric Field on the thermal Equilibrium properties of p-type Gallium Arsenide (GaAs) semiconductor

By

Tolosa Biri Merga

Adama, Ethiopia

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Tolosa Biri Merga

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Dr. Megersa Wodajo Shura

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As thesis research advisor, I hereby certify that I has read and evaluated this thesis entitled: **"The Effects of Electric Field on the thermal Equilibrium Properties of Gallium Arsenide (GaAs) Semiconductor"** prepared under my guidance by **Tolosa Biri Merga.** I recommend that it can be submitted as fulfilling the thesis requirement.

Dr. Megersa Wodajo Shura	_____	_____
Advisor	Signature	Date

As members of the Board of Examiners of the M.Sc. thesis Open Defense Examination, we certify that we have read and evaluated the thesis work prepared by **Tolosa Biri Merga** and examined the candidate. We recommended that the thesis be accepted as fulfilling the thesis requirement for the Degree of Master of Science in Physics.

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Name of candidate: **Tolosa Biri Merga** Signature: _____

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List of Symbols and Abbreviations

T	Temperature (K)
k_B	Boltzmann's constant (J/K)
E_g	Energy band gap (eV)
$E_g(0)$	Band gap energy at absolute zero on the Kelvin (eV)
$E_g(T)$	Band gap energy at any temperature (eV)
$\boldsymbol{\varepsilon}$	Electric field (NC^{-1})
$\varepsilon(x)$	Electric field at any position (NC^{-1})
Ev	Electro volt
GaAs	Gallium Arsenide
E_C, E_V	Energy of conduction band and valance band (eV)
E_{kn}, E_{kp}	Kinetic energy of electron and hole (eV)
U_n, U_P	Potential energy of electron and hole
α	Absorption coefficient (cm^{-1})
β	Beta (K)
λ	Photon Wavelength (nm)
c	Speed of light $(^{m}/_{s})$
h	Plank's constant (Js)
$\hbar$	Reduced plank's constant (Js)
EHP	Electron hole pairs
K	Kelvin
J	Current density (Acm^{-2})
v	Photon frequency (s^{-1})
k	Wave number
C_R	Carriers radiative capture coefficient $(cm^3 s^{-1})$
E_i	Intrinsic Fermi energy (eV)
E_F	Fermi energy (eV)
E_{BF}	Bulk Fermi energy (eV)
b_1	Width of the layer (nm)
G_{th}	Thermal equilibrium Generation rate Electron and hole $(cm^{-3}s^{-1})$
G_0	Photon absorption rate $(cm^{-3}s^{-1})$
G	Total generation rate $(cm^{-3}s^{-1})$
R	Total recombination rate

U	Net recombination rate
U_R	Radiative recombination rate
τ_n, τ_p	Lifetime for electron and holes (s)
m_n^*, m_p^*	Electron and hole effective mass (kg)
m_0	Rest mass of the electron (kg)
e	Elementary charge (c)
n_i	Intrinsic carrier density (cm^{-3})
n_0, p_0	Thermal equilibrium concentration of electron and hole (cm^{-3})
n, p	Non-thermal equilibrium concentration of electron and hole (cm^{-3})
$\delta n, \delta p$	Excess charge carrier concentration for electron and hole density (cm^{-3})
N_C, N_V	Effective density in the conduction and valence band (cm^{-3})
N_a	Acceptor concentration (cm^{-3})
N_d	Donor concentration (cm^{-3})
x	Final position (nm)
x_0	Initial position (nm)
N_a^-	Concentration ionized acceptor atom (cm^{-3})
N_d^+	Concentration of ionized acceptor atom (cm^{-3})
k_∞	Dielectric constant
ϵ_0	Permittivity of free space (c^2/Jm)
π	Pi
τ_R	Radiative excess carrier lifetime(s)
τ_k	Time constant of the radiative recombination (s)
τ_g	Excess generation carrier lifetime (s)
$\bar{v}_n$	Electron average drift velocity (cms^{-1})
$\bar{v}_p$	Holes average drift velocity (cms^{-1})
μ_n	Electron mobility's $(cm^2v^{-1}s^{-1})$
μ_p	Holes mobility's $(cm^2v^{-1}s^{-1})$
$V(x)$	Electrostatic potential at a point (V)
v_{th}	Thermal velocity of the electrons
α_R	Carrier capture cross section

Abstract

In this study, the effects of electric field on the thermal equilibrium carrier properties on the photoresponse of Gallium Arsenide (GaAs) semiconductor is investgated under different conditions. Hence, the variation of energy, change of energy, thermal carrier concentration and excess carrier lifetime as function of position were determined. The variation in electrical properties and the photoresponses of the bulk of the semiconductor is described by applying constant, linearly varying, cubically varying and quadratically varying electric field with position. The result revealed that, high variations in the electrical properties and the photoresponses occur for the case when the constant field is applied. The variations in the electrical properties and the photoresponses decrease with increasing the variation in the applied electric field. Nevertheless, these variations are unaffected by the doping level of the material, as position was the determinant parameter.

Chapter 1 : Introduction

1.1 Background

Semiconducting materials have been of scientific interest almost for 200 years. The beginning of semiconductor research is marked by Faraday's 1833 report on negative temperature coefficient of resistance of silver sulfide [1] . This is the first observation of any semiconductor property. In his 1833 paper, "Experimental Researches in Electricity" he disclosed this observation. This observation was in distinction from the usual properties of metals and electrolytes in whose case resistance increase with temperature [2].

In 1839, he reported the observation of photo voltage in the silver chloride coated platinum electrodes [3]. In his experiment, an AgCl coated platinum electrode was immersed in an aqueous nitric acid electrolyte solution. This was the first reported about photovoltaic device. Photo voltage was generated at the Ag/AgCl metal semiconductor contact, Ag at the junction was formed by the absorbed silver clusters in the AgCl electronic states [4]. The next important decade in the semiconductor research is the decade of 1870. During this period selenium was discovered as a semiconductor, rectification at metal semiconductor interface came into scientists' notice. In 1873, Willoughby Smith arrived at the discovery of photoconductivity of selenium. He was initially working with submarine cables. He set into experiments with selenium for its high resistance, which appeared suitable for his submarine telegraphy. Various experimenters measured the resistance of selenium bars, but the resistance as measured by them under different conditions did not agree at all [5]. The first observation of photovoltaic effects in a solid system was made in 1876 [6]. Again, W. G. Adams, along with his student R. E. Day was investigating the photoelectric properties of Selenium at Cambridge. They discovered that illuminating a junction between Selenium and Platinum had a photovoltaic effect. Although the most significant observations of the 19th century came during the period 1870-1885, the semiconductors had not received any device application for any practical purpose yet. It was not used until 1890's for any practical application. Wireless communication is the first field to employ these materials for practical application and then in the 1930s a complete theoretical foundation of semiconductors was established [7].

In recent years, considerable progress has been made in the fabrication of optoelectronic devices working at different frequency ranges in the infrared region using small band gap materials. Small band gap materials are used in various domains, such as pollutant detection and infrared thermal imaging, using a variety of device architectures, including near infrared photo-detectors, resonant tunneling structures and other quantum devices [8]. Some of these semiconductors are also used as booster cells in solar cell clusters to improve the efficiency of photovoltaic and thermo-photovoltaic cells. By the beginning of the 20th century the five properties now associated with semiconductors had been discovered but, scarcely characterized such as: negative temperature coefficients, photoconductivity, rectification, photovoltaic effect and electroluminescence (excitation by current).

Semiconductors are a group of materials having electrical conductivities between metals and insulators. The conductivity of these materials can be varied over orders of magnitude by changes in temperature, optical excitation, and impurity content. The column IV semiconductors, silicon and germanium are called elemental semiconductors because they are composed of single species of atoms. Compounds of column III and V atoms, as well as certain combinations from II and VI, and from IV, make up the compound semiconductors.

Every solid has its own characteristic energy band structure. This variation in band structures responsible for the wide range of electrical characteristics observed in various materials. Semiconductor materials at 0 K have basically the same structure as insulators. In metals, the bands either overlap or are only partially filled. Thus in metals, high electrical conductivity is due to the fact that electrons and empty energy states are intermixed within bands so that electrons can move freely under the influence of an electric field [9]. When an electric field is applied to the material by an external voltage source, it causes the electrons and holes to be transported [10]. The net flow of the electrons and holes in a semiconductor will generate currents. The process by which these charged particles move is called transport. The two basic transport mechanisms in a semiconductor crystal, drift- the movement of charge due to electric fields, and diffusion-the flow of charge due to density gradients. An electric field applied to a semiconductor will produce a force on electrons and holes so that they will experience a net acceleration and net movement, provided there are

available energy states in the conduction and valence bands. This net movement of charge due to an electric field is called drift. The net drift of charge gives rise to a drift current [11].

There are two types of direct and indirect energy band gaps. Direct band gap semiconductors are the materials for which maximum of valence band and minimum of conduction band lie for the same value of wave vector (k) [12]. Indirect band gap semiconductors are the materials for which maximum of valence band and minimum of conduction band are not the same value of wave vector (k). Conservation of momentum during an inter-band transition is a major concern in indirect materials. Few of examples; Si, Ge, Gap (including Transition metal Oxide) and etc. Direct-gap semiconductors such as GaAs, GaSb are efficient photon emitters, whereas indirect-gap semiconductors such as Si cannot be efficiently used as light emitters.

The energy band gap of semiconductor ranges from 0.3 to 3.5eV, then GaAs 1.424eV at room temperature to 1.519eV at an absolute zero [13]. The thermal equilibrium charge carrier concentration ranges from 10^{12}cm^{-3}in the intrinsic semiconductor to 10^{19}cm^{-3}in the highly doped non-degenerate semiconductor. The mobility of free carriers in semiconductor also ranges from $10^{2}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}to10^{4}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}$ [14]. The practical density of room temperature thermal equilibrium majority carrier for semiconductor that was determined using Hall Effect measurement is ranged from $10^{12}\text{cm}^{-3}$for intrinsic for intrinsic semiconductor to $10^{5}\text{cm}^{-3}$for highly doped non-degenerate semiconductor. The room temperature mobility of electrons for most semiconductors is ranged from $10^{3}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}$ to $10^{4}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}$and that of holes is also ranged from $10^{2}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}$to $10^{3}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}$ [12, 15]. Generation and recombination processes through intermediate states in the band-gap of semiconductors (defect states) are of crucial importance for electronic devices. The generation of excess carriers in a semiconductor may be accomplished by either electrical or optical means. The inverse process to the generation of excess carriers in a semiconductor is the recombination. The annihilation of excess carriers generated by optical or electrical means in a semiconductor may take place via different recombination mechanisms.

The radiative generation-recombination mechanism is fundamental band-to-band processes which is determined by the electronic band structure of the semiconductor. The role of

radiative mechanism in detection of IR radiation has been recently critically re-examined by Humphreys [16]. Radiative recombination is relatively unimportant in indirect band-gap semiconductors, because the radiative lifetime is extremely high. The radiative lifetime is independent of any impurity density. The radiative can also occur through intermediate energy levels. When electron-hole pairs recombine radiatively through intermediate levels, photons are generally emitted for only one of the transitions. This recombination mechanism is used in light-emitting phosphors that are deliberately doped with impurities of a particular kind to generate light of a particular wavelength [17]. Gallium arsenide (GaAs) and related compounds are direct band-gap semiconductors suitable for fabricating high-frequency electronic devices and optoelectronic devices. The photo response of this material makes it very useful in the design of a variety of device architectures, including photo detectors, resonant tunneling structures and other quantum devices.

The performance of the material in this case depends on the lifetime of free charge carriers generated by the interaction of light with the material, referred to as the excess carrier lifetime (τ) [18]. Using the results from Hall Effect measurements along with the relations describing the lifetimes of the excess minority carriers in the bulk of the semiconductors, the theoretical values of the effective excess carrier lifetime in the materials were also calculated [19]. The excess carrier lifetime is in general determined by the recombination rate of the minority charge carriers in the bulk of the material and at the surface. Recombination is a mechanism by which opposite free charge carriers annihilate each other at the valence band or the impurity level. Depending on the ways in which the energy of an excess carrier is removed during a recombination process, there are three basic recombination mechanisms in the bulk of a given semiconductor, which are responsible for carrier annihilation in a semiconductor. These are: Radiative recombination, in which the energy of the electron is given as photon during recombination, Shockley-Read-Hall (SRH) recombination in which energy of the electron is transferred to the lattice as heat or phonon during recombination and Auger recombination in which the energy of the electron or hole is transferred to other charge carries during recombination. Of these, the first two recombination mechanisms are two-carrier processes while the third one is a three-carrier process (V. K. Khanna, 2004). For a steady state condition, the excess carrier generation rate (G_o) is equal to their reverse

recombination rate (R). The photo-generated carrier concentration (Δn) in the entire sample is proportion to the product of both the recombination or generation rate and the excess carrier lifetime. The lifetime of charge carriers is one of the important parameters to characterize a material because, it plays a critical role in determining the semiconductor device parameters. Carrier lifetime is dependent upon a number of quantities and conditions which are characteristic in the nature of semiconductor materials and the recombination process. Therefore, radiative lifetime is constant at low injection, but then decreases and continues to decrease as the injection level increases. While radiative recombination is typically the dominant recombination process in direct band gap semiconductors under low injection level, it is considered to be small or even negligible compared to other recombination processes in indirect semiconductors. Radiation which is presumably due to the recombination of free electrons and holes has been observed in gallium arsenide (GaAs).

Electric field affects the properties of electronic systems in a number of fundamental ways. The most fundamental properties is the energy band bending, which is affected by electric field. The carrier concentrations are a very strong position dependence. The radiative lifetime is inversely proportional to the total concentration of free carriers under all circumstances. The lifetimes increased then decreased with increasing excess carrier density. This is due to effects of Radiative recombination and the lifetimes were taken at a consistent excess carrier concentration. The lifetime of radiative mechanisms decreases with increase in doping concentration [20, 21, 22]. Carrier lifetime is dependent upon a number of quantities and conditions which are characteristic in the nature of semiconductor materials and the recombination process. These quantities and conditions include excess carrier density, the type of light source, sample thickness and temperature. The basic method to measure the lifetime depending on the way that an excess of carriers (electrons and holes) is created in the semiconductor is using the expression for the balance between generation and recombination to calculate the lifetime [23]. Recombination-generation is nature order restoring mechanism whereby the excess carrier or deficit inside the semiconductor is stabilized (perturbation is maintained) or if perturbation is removed. The rate at which free carriers disappear or recombine was given by the ratio of the free carrier concentration to excess carrier lifetime. In a steady-state situation the generation and recombination rates are

perfectly balanced. Electric fields and optical energy causes electron densities and velocities to be different from the equilibrium values [24]. In this work, we going to be study effects of the variation of electric field on the room temperature photo response of direct band gap of deep bulk of the p-type semiconductors.

1.2 Statement of the problem

Recent researches conducted on the position dependence of electric field were on the p-n junction and the near surface depletion region of group IIIB-VB compound semiconductors, and there is no any publication and researches were conducted on the position dependence of electric field in certain region of the bulk of Gallium Arsenide semiconductor [25]. Since, there is a knowledge gap on position dependence in certain region of the bulk semiconductor. Therefore, this thesis work may focus on the nature of position dependence of electric field in the bounded region in the bulk of Gallium Arsenide.

1.3 Objectives of the study

The general objective of this study is to determine the effects of electric field on the thermal equilibrium properties of the performances of the bulk of Gallium Arsenide semiconductor. The specific objectives of the study are:

- to determine the energy in the bulk of semiconductor,
- to describe the effect of the density of thermal carrier concentrations,
- to investigate the excess carrier lifetime of bulk semiconductor under different conditions of electric field and doping level.

1.4 Thesis outlines

This thesis is organized as follows. Chapter two includes review of related literatures. It deals with the theory of energy bands of the semiconductor, thermal equilibrium properties of semiconductors. Equations governing the recombination lifetimes for the recombination mechanisms depicted are derived in this Sections. Chapter three presents the overall methodology by which important data is collected and analyzed. Chapter four covers the results and discussion of the study. Chapter five gives the conclusions of entire parts of this work and describes the results obtained in chapter 4.

Chapter 2 : Literature Review

2.1 Thermal Equilibrium Properties of Semiconductor

This topic describes the theoretical background of the thermal equilibrium properties and the photo-responses of Semiconductor. First, the theory of energy band gap of Semiconductor is described, then the theory of thermal equilibrium carrier concentration in semiconductors is described. Finally, the theory of the photo-response of the semiconductors, optical generations and recombination of excess carriers is described in terms of the free carrier generation and recombination mechanisms.

2.2 Energy Bandgap

In semiconductors, the electron-hole pairs can be created by either thermal or optical. Electrons diffract from the periodic lattice, this is the physical origin of the band gap – there are some electron energy levels which are forbidden because the electron waves cancel themselves out at these wavelengths i.e. at zone boundary. The equilibrium carrier density for both electrons and holes can also be expressed in terms of the intrinsic carrier density and the electrostatic potential. We have determined the thermal equilibrium concentration of electrons and holes in the conduction and valence bands. In thermal equilibrium, these concentrations are independent of time. However, electrons are continually being thermally excited from the valence band into the conduction band by the random nature of the thermal process. At the same time, electrons moving randomly through the crystal in the conduction band may come in close proximity to holes and fall into the empty states in the valence band. Since the net carrier concentrations are independent of time in thermal equilibrium, the rate at which electrons and holes are generated and the rate at which they recombine must be equal. Semiconductors have a distinctive band structure the

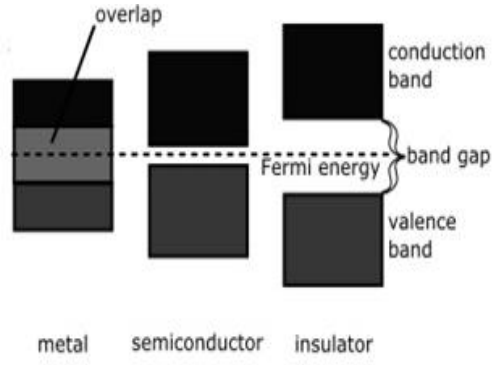

Figure 2.1: This figure shows the difference between the band gap of metal, semiconductor and insulator *[26, 27]*.

Fermi energy lies between the conduction and valence band in the band gap as shown in Figure 2-1 below [26]. The band gap is, also known as forbidden energy band and electrons are absents in the band gap. It is defined as the minimum energy needed for an electron to shift from the valence band to the conduction band. Band gap in semiconductors usually ranges between 1 and 4 eV, less than the band gap in insulators, while more than the band gap in conductors [28]. But, in non-equilibrium condition is established when an external excitation is applied to the semiconductor specimen. As the temperature increases, however, some electrons will be thermally excited into the empty conduction band where there is an abundance of unoccupied states. Therefore, the electrons can act as mobile carriers; they can drift in the crystal lattice under the effect of an applied electric field and there by contribute to the electric current, allowing the remaining electrons in the valence band to exchange places with each other under the influence of an electric field [29]. The material behaves as a semiconductor whose conductivity increases sharply with temperature as an increasing number of mobile carriers are thermally generated. Example, excess electron-hole pairs can be generated in a semiconductor by the absorption of photons with energies greater than the band gap energy [30]. In a solid, the energy difference between the top of valance band (E_V) and the bottom of conduction band (E_C) is defined as the band-gap energy (E_g). The band-gap energy of a semiconductor defines its optical absorption threshold for the photoelectric effect. That is, generation of electric charge-carrier from light absorption only occurs with photons with energies greater or equal to the band gap, E_g (or $h\upsilon \geq E_g$), where E_g is the energy band gap of the given semiconductor, h the Planck's constant and υ, the frequency of the absorbed photon by the semiconductor. When supra-band-gap light is absorbed by a semiconductor, charges move between the valence and conduction bands [31]. When a semiconductor is illuminated by a photon of energy greater than its energy band gap ($h\upsilon > E_g$), electron-hole pairs are generated in the semiconductor. The photo-response of the semiconductor can be described through the current produced due to the electron-hole pairs produced in the process. Hence, the amount of current produced by these charge carriers is also affected by the effective lifetime of the carriers. The band gap can be thermally populated with both electrons and holes as the Fermi energy level is near enough to both bands. There are two types band gap in semiconductors: direct or indirect band gap.

A direct band gap is distinguished by having the band edges aligned in k, so that an electron can transit from the valence band to the conduction band. On the other hand, in the indirect band gap, the band edges are not aligned so the electron does not transit directly to the conduction band, both a photon and a phonon are involved. In crystalline solids, the energy band gap between the valence band maximum and conduction band minimum is referred to as energy band gap $E_g = E_C - E_V$ [32]. When band gap light is absorbed by a semiconductor, charges move between the valence band and conduction. A contraction of the crystal lattice with decreasing temperature usually leads to a strengthening of the interatomic bonds and associated increase in the band gap energy. The first empirical relation for the band gap shift with temperature was developed by varshni *et al*. the temperature dependence of the energy band-gap, $E_g(T)$ is related by the relation [34].

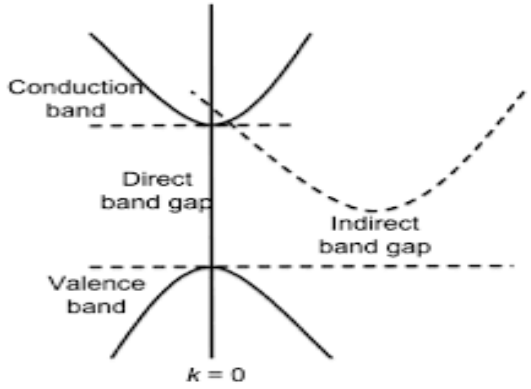

Figure 2-2: Direct and indirect band gap semiconductors *[33].*

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta}, \tag{2-1}$$

Where, α and β are constant and $E_g(0)$ is the limiting value of the band at zero kelvin, the absorption coefficient α, is a property of a material which defines the amount of light it absorbs. Then, $E_g(0)$ is 1.519 eV at 0 K, $\alpha = 5.41 \times 10^{-4}$ eV/K $\beta = 204$ K and the energy band gap at room temperature (300 K) is equal to 1.424 eV for GaAs semiconductor [35]. In such away, the valance band and the conduction band energies determined are given by [36]:

$$E_V(T) = \frac{\alpha T^2}{2(T + \beta)}, \qquad E_C(T) = E_g(0) - \frac{\alpha T^2}{2(T + \beta)} \tag{2-2}$$

2.3 Thermal equilibrium carrier concentration

In this section, the general properties of an isolated semiconductor under different conditions will be discussed. These properties, unlike metals, the electrical conductivity of a semiconductor can be changed by many orders of magnitude by simply adding impurities or by using external excitations (e.g., by photo- excitation). At low temperatures, a pure semiconductor may become a perfect electrical insulator, since its valence band is totally filled with valence electrons and the conduction band is completely empty. However, as the temperature rises, a fraction of the valence electrons is excited into the conduction band by the thermal energy, thus creating free holes in the valence band. As a result, the electrical conductivity will increase rapidly with increasing temperature. The concentration of electrons and holes in semiconductor are determined by many factor including the band gap and band structure of the semiconductor, types and concentrations of the impurities doped in semiconductor, temperature and external disturbances to the semiconductor. Then thermal equilibrium is used to describe the unperturbed state of system, to which no external voltage, illumination, or other perturbing forces are applied [37, 38]. Therefore, thermal equilibrium concentration of electron and hole in conduction and valence band are independent of time. In thermal equilibrium electron-hole pairs are constantly being formed and destroyed. For a non-illuminated semiconductor in thermal equilibrium, the concentration of electron in the conduction band is $n = n_0$ and holes in valence band $p = p_0$. These concentrations remain constant due to the equilibrium between generation and recombination processes. The thermal equilibrium electron concentration, n_0 in the conduction band and thermal equilibrium holes concentration, p_0 in the valence band for the non-degenerate semiconductor case can be simplified to [39].

$$n_0 = N_C \exp\left(-\frac{E_C - E_F}{k_B T}\right), \quad \text{and} \quad p_0 = N_V \exp\left(-\frac{E_F - E_V}{k_B T}\right). \tag{2-3}$$

Where, N_C and N_V are the effective density of conduction band states and the effective density of valence band states is the expression for the equilibrium holes density in valence band and electrons density in conduction band to be as [40]:

$$N_V = 2\left(\frac{2\pi m_p^* k_B T}{h^2}\right)^{3/2} \quad \text{and} \quad N_C = 2\left(\frac{2\pi m_n^* k_B T}{h^2}\right)^{3/2}, \tag{2-4}$$

Where m_n^* and m_p^* are effective mass of electrons in conduction band and holes in valence band, respectively. An electron in crystal may behave as if it had a mass different from the free electron mass m_0. There are crystals in which the effective mass of the carriers is much larger or much smaller than m_0. The effective mass may be anisotropic, and it may even be negative. The important point is that the electron in a periodic potential is accelerated relative to the lattice in an applied electric or magnetic field as if its mass is equal to an effective. The density of state function in the conduction and valence of band of semiconductor provided that free electron mass either the electrons density of state effective mass (m_n^*) in the conduction band or holes density of state effective mass (m_p^*) in the valence band. The effective masses for holes and electrons of states of GaAs are given in [41, 42].

$$m_p^* = 0.48m_0, \qquad m_n^* = 0.067m_0 \tag{2-5}$$

Where, m_0 is the rest mass of electron which is equal to 9.11×10^{-31}kg.

2.3.1 Intrinsic Semiconductors

Pure semiconductor materials have no impurity atoms. Charge carriers are solely the electrons and holes created in pairs by thermal energy. Electrons in the valence band gain thermal energy and are promoted into the conduction band as temperature increases, leaving behind corresponding holes in the valence band: "electron-hole" pair. The number of electrons in the conduction band equals the number of holes in the valence band. The band gap determines how temperature variation affects conductivity. Intrinsic conduction: process that results from the band structure of a pure element or compound [43, 44]. Semiconductors are considered to be as intrinsic semiconductors if it's thermally generated

Carrier density represented by n_i is much larger than the background doping or residual impurity densities. At zero temperature (T=0), an intrinsic semiconductor behaves like an insulator because the conduction band states are totally empty and the valence band states are completely filled. However, as the temperature increases, some of the electrons in the valence band states are excited into the conduction band states by thermal energy, leaving behind an equal number of holes in the valence band. Suppose that $\mathfrak{N}$ is the concentration of electron hole pairs thermally generated in the respective bands and n_R is the concentration

of electron hole annihilated after the generation, the free carrier concentrations in the conduction and valence bands adjust for the intrinsic semiconductor to be: (M. W. Shura, 2013):

$$n_0 \approx \mathfrak{N} - n_R = n_i = p_0 \tag{2-6}$$

Where n_0 and p_0 denote the equilibrium electron and hole densities, respectively. Since the non-degenerate relations are obviously valid for an intrinsic semiconductor where the Fermi level (E_F) is equal to the intrinsic energy level (E_i) in the semiconductor. When an external field is applied, the electrons that are excited into the conduction band by thermal means accelerate using the vacant states available in the conduction band. At the same time the holes in the valence band move but in a direction opposite that of the electrons. Since the non-degenerate relations are obviously valid for an intrinsic semiconductor where the Fermi level, E_F is equal to the intrinsic level energy, E_i in the semiconductor, one can write Eqns. (2.3) gives:

$$n_i = N_C \exp\left(-\frac{E_{C-} E_i}{k_B T}\right) = N_V \exp\left(-\frac{E_{i-} E_V}{k_B T}\right) \tag{2-7}$$

Where, E_i is intrinsic energy level and K_B is Boltzmann constant which is equal to 1.38 ×10^{-23}J/K.

The intrinsic Fermi energy can be derived from Eqns. (2-4)along with Eqns.(2-7):

$$E_i = \frac{E_C + E_V}{2} + \frac{3}{4} k_B T \ln\left(\frac{m_p^*}{m_n^*}\right) \tag{2-8}$$

Where m_p^* , m_n^* and E_g are known at a given temperature and which indicates that if m_p^*= m_n^* or T = 0 the Fermi level in an intrinsic semiconductor is positioned at mid-gap. In real cases $m_p^* \neq m_n^*$, resulting in small deviation of the Fermi level from mid-gap. Figure 2-3 illustrates the carrier density and energy band structure for intrinsic *p*-type semiconductor ($m_p^* > m_n^*$) at (a) zero *T*, (b) intermediate *T* and (c) high *T*. The intrinsic carrier density increases with increasing temperature.

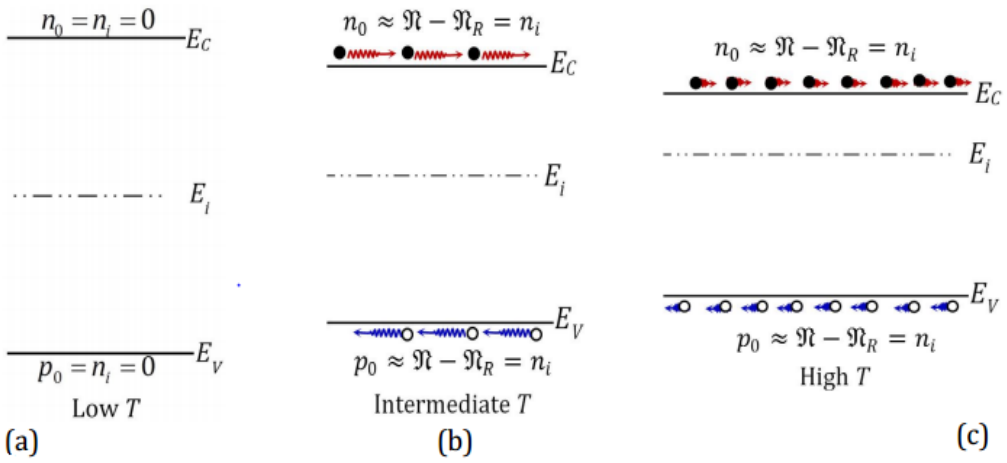

Figure 2-3: Carriers density and energy band structure for intrinsic semiconductor at (a) low T, (b) intermediate T and (c) high T.

Figure 2-4 also shows the temperature dependence of the intrinsic Fermi-level, E_i, conduction band edge, E_C and valence band edge, E_V. One can easily see from Figure 2-4 that, if the electron and hole effective masses are equal, $m_p^* = m_n^*$ the intrinsic Fermi level, E_i is exactly in the Centre of the band gap. The intrinsic Fermi level, E_i moves toward the conduction band edge if $m_p^* > m_n^*$ and toward the valence band edge if $m_p^* < m_n^*$. One can also see that, the energy band gap also decreases with increasing temperature. The equilibrium density of electrons and holes in a non-degenerate semiconductor is constant at a given temperature. The product of the electrons and holes density, in a non-degenerate semiconductor at equilibrium, is always equal to the square of the intrinsic carrier density [46] .

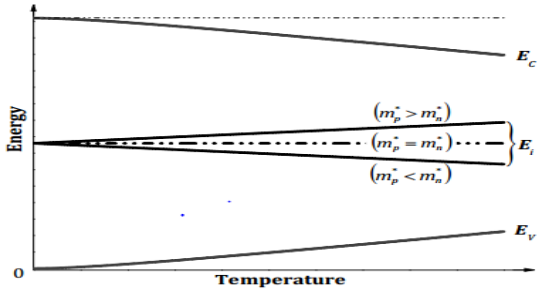

Figure 2-4: Temperature dependence of intrinsic Fermi level, E_i, in the band gap energy of a semiconductor for $m_p^* = m_n^*$, $m_p^* > m_n^*$ and $m_p^* < m_n^*$ *[45]*.

$$n_i^2 = p_0 n_0 \tag{2-9}$$

The intrinsic carrier density (which is specific to a given semiconductor) is related to the effective density of conduction and valence band, i.e.

$$n_i = \sqrt{p_0 n_0} = \sqrt{N_V N_C} \exp\left(\frac{-E_g}{k_B T}\right) \tag{2-10}$$

This relationship, referred to as the law of mass action, which allows (at thermal equilibrium) to determine the electron density if the hole density is known or vice versa. It should be noted that this equation signifies that, the electron-hole pairs may be continuously generated and recombined; the product of the concentration (averaged in time) stays constant. This equation also indicates that, for a non-degenerate material in equilibrium, the $p_0 n_0$ product depends on the effective conduction and valence band densities of states, the energy band gap of a semiconductor, and the temperature. It is independent of the Fermi level position and of the individual electrons and holes densities. In other words, the $p_0 n_0$ product is constant at a given temperature regardless of doping.

2.3.2 Extrinsic Semiconductors

In addition to the intrinsic carriers generated thermally, it is possible to create carriers in semiconductors by purposely introducing impurities into the crystal. The process of deliberate addition of controlled quantities of impurities to a pure semiconductor is called doping.

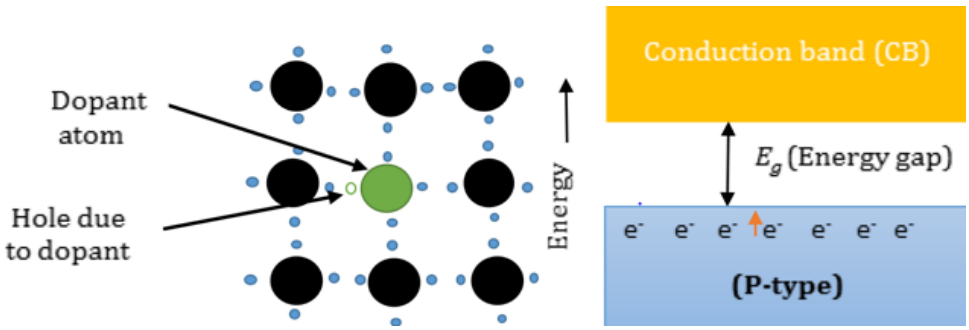

Figure 2-5: p–type doped semiconductor with an acceptor *[47].*

If the doping process results into a p-type semiconductor then the impurity atoms are called acceptors and the energy levels of these holes are called the acceptor energy levels (E_a). By doping, a crystal can be altered so that it has a predominance of either electrons or holes. Thus, there are two types of doped semiconductors, n-type (mostly electrons) and p -type (mostly holes). When a crystal is doped such that the equilibrium carrier concentration n_0 is different from the intrinsic carrier concentration n_i the material is said to be extrinsic.

When impurities or lattice defects are introduced into an otherwise perfect crystal, additional levels are created in the energy band structure, usually within the band gap. This level is filled with electrons at 0K, and very little thermal energy is required to excite these electrons to the conduction band [48, 49]. In the carrier concentration by doping rather than by thermal electron hole pair generation. Thus, one usually dopes the material such that the extrinsic range extends beyond the highest temperature at which the device is to be used [47]. The most important and unique feature of a semiconductor material lies in the fact that its electrical conductivity can be readily changed by many orders of magnitude by simply doping the semiconductor with shallow-donor or shallow-acceptor impurities. The deep level centers can be donor-like (positively charged when empty and neutral when filled with an electron), acceptor-like (neutral when empty and negatively charged when filled with an electron), or may exhibit multiple charge states with associated multiple levels in forbidden gap. As discussed above, adding donor or acceptor impurity atoms into semiconductor will change the distribution of electrons and holes in the material, and as a result, the position of Fermi energy will change. Eliminating N_C and N_V among Eqns. (2-3) and (2-10) yields [50].

$$n_0 = n_i \exp\left(-\frac{E_i - E_F}{k_B T}\right) \quad \text{and} \quad p_0 = n_i \exp\left(-\frac{E_F - E_i}{k_B T}\right). \tag{2-11}$$

The law of mass action allows one to calculate the minority carrier density in an extrinsic semiconductor when the majority carrier density is known.

$$\text{Minority carrier density} = \begin{cases} \frac{n_i^2}{p_0}, & \text{for p} - \text{type material,} \\ \frac{n_i^2}{n_0}, & \text{for n} - \text{type material.} \end{cases} \tag{2-12}$$

The intrinsic concentration, n_i for free carriers the corresponding bands can be computed from Eqns. (2-3) and (2-4) above as:

$$n_i = \sqrt{p_0 n_0} = \sqrt{N_V N_C} \exp\left(\frac{E_g}{k_B T}\right). \tag{2-13}$$

Eqn. (2-13) is called the *law of mass action* [51].

The thermal equilibrium extrinsic Fermi-level, E_F can also be described from Eqn. (2-11). In terms of E_i and the thermal equilibrium carrier concentrations as:

$$E_F = E_i - k_B T \ln\left(\frac{p_0}{n_i}\right) = E_i + k_B T \ln\left(\frac{n_0}{n_i}\right). \quad (2\text{-}14)$$

As the charge carrier concentrations change, the position of the extrinsic Fermi energy level varies within the band gap until the system reaches thermal equilibrium. Eqn. (2-14) shows that, E_F lies above E_i for n-type material ($n_i > p_0$) and below the E_i for p-type material ($n_i < p_0$) [52].

2.3.3 Statistics of Donors and Acceptors

The shallow donor-acceptor levels emit their electrons (holes) to the conduction band (valence band) where they travel freely and contribute to the conductivity. The free charge carriers may be trapped by deeper levels, where they are frozen out unless enough thermal energy is provided to excite them back to the bands again. Deeper located levels can interact with both bands easily and the free charge carriers may use these defect states as recombination path. The donor electron can also interact directly with a hole, thus the charge carriers recombine without contributing to conduction or charge carrier compensation takes place [53]. The density of electrons in a shallow-donor state is given by:

$$n_d = \frac{N_d}{1 + \frac{1}{g_d}\exp\left(\frac{E_d - E_F}{k_B T}\right)} \quad (2\text{-}15)$$

where, n_d is the density of electrons occupying the donor level is, N_d is the concentration of donor atoms, E_d is the energy of the donor level and g_d is the donor-site degeneracy factor. The concentration of ionized donors N_d^+ is then:

$$N_d^+ = N_d - n_d = \frac{N_d}{1 + g_d \exp\left(\frac{E_F - E_d}{k_B T}\right)} \quad (2\text{-}16)$$

When a singly ionsable donor captures an electron it becomes neutral, and when it releases an electron, it becomes positively charged. Using the same analysis, the concentration of ionized acceptors N_a^- we have:

$$N_a^- = N_a - p_a = \frac{N_a}{1 + g_a \exp\left(\frac{E_a - E_F}{k_B T}\right)} \quad (2\text{-}17)$$

Where, p_a is the density of holes bound to acceptors, N_a the concentration of acceptor atoms, E_a the energy of the acceptor level relative to the valence band, N_a^- the concentration of

ionized acceptor atoms and g_d is the acceptor-site degeneracy factor. When a singly ionsable acceptor captures an electron it becomes negatively charged, and neutral when it releases the electron. Most authors set g_d = 2 to account for the spin degeneracy at the donor sites (only one parabolic band at the conduction band edge). It is likewise standard practice to argue that the acceptor sites must additionally reflect the two fold (heavy- and light-hole) degeneracy of the valence band. Thus, the acceptor degeneracy factor is g_a = 2 × 2 = 4. Hence, the densities of the ionized impurities at both the donor and acceptor centers are given by: At sufficiently high temperatures in p-type material, all the acceptors are ionized, so that

$$N_d^+ = \frac{N_d}{1 + 2\exp\left(\frac{E_F - E_d}{k_B T}\right)}, \quad \text{and} \tag{2-18}$$

$$N_a^- = \frac{N_a}{1 + 4\exp\left(\frac{E_a - E_F}{k_B T}\right)} \tag{2-19}$$

The case for $N_a^- \approx N_a$ or $p_a \approx 0$ leads to the conditions $E_a - E_F$ resulting in the Fermi level lying above the acceptor level for p-type materials. In the same way it can be shown that complete ionization of donors for n-type materials satisfies the conditions, $N_d^+ = N_d$ or $n_d \approx 0$ and thus, $E_d \gg E_F$. For complete freeze-out at very low temperatures in p-type material assuming zero or negligible compensation, all the acceptors are neutralized; i.e., $p_a \approx N_a$ or $N_a^- \approx 0$. This again leads to the conditions $E_a - E_F > 0$ or,$E_a > E_F$ with the Fermi level below the acceptor level. Similarly, for n-type materials at very low temperature, it can be shown that $N_d \approx n_d$ or $n_d \approx 0$ and the Fermi level lies above the donor level ($E_d < E_F$).

2.3.4 Charge neutrality

When free electron-hole pairs annihilate through recombination, the free carrier concentrations in the conduction and valence bands adjust for the intrinsic semiconductor to Eqn. (15). For the extrinsic semiconductors this takes the form:

$$n_0 = N_d^+ + \mathfrak{N} - n_R \qquad \text{and} \qquad p_0 = N_a^- + \mathfrak{N} - n_R, \tag{2-20}$$

Where n_R is the concentration of the total electron-hole pairs being annihilated each other after the donors and the acceptors are being ionized, $\mathfrak{N}$ is the concentration of electron-hole pairs thermally generated from band to band, N_d^+ and N_a^- are the densities of free electrons

and holes contributed by the donor and the acceptor levels to the respective conduction and valence bands. Upon eliminating $\mathfrak{N} - n_R$ in Eqn. (2-20), the well-known neutrality relationship is obtained:

$$\mathrm{n}_0 + N_a^- = p_0 + N_d^+ \tag{2-21}$$

The density of the ionized impurities at both the donor and acceptors are given by:

$$N_d^+ = \frac{N_d}{1 + 2\exp\left(\frac{E_F - E_d}{k_B T}\right)}, \quad \text{and} \tag{2-22}$$

$$N_a^- = \frac{N_a}{1 + 4\exp\left(\frac{E_a - E_F}{k_B T}\right)} \tag{2-23}$$

The law of mass action Eqn. (2-10) along with Eqn. (2-20) yields:

$$p_0 = \frac{N_a^- - N_d^+}{2}\sqrt{n_i^2 + \left(\frac{N_a^- - N_d^+}{2}\right)^2}, \qquad n_0 = \frac{N_d^+ - N_a^-}{2}\sqrt{n_i^2 + \left(\frac{N_d^+ - N_a^-}{2}\right)^2} \tag{2-24}$$

For very high acceptor impurity concentration $N_a^- \gg N_d^+$ and $N_a^- > n_i$, Equation (2-24) can be simplified:

$$\frac{p_0}{n_i} \approx \frac{N_a^-}{n_i} + \frac{n_i}{N_a^-} > 1, \quad \Rightarrow p_0 > n_i, \qquad \frac{n_0}{n_i} \approx \frac{n_i}{N_a^-} < 1, \qquad \Rightarrow n_0 < n_i \tag{2-25}$$

It can be seen from Eqn. (2-25) that the addition of different acceptor and donor impurity concentrations to the semiconductor increases the majority carrier concentration above the intrinsic level and decreases the minority carrier concentration below the intrinsic level. If the acceptor and the donor impurity concentrations are equal (i.e. completely compensated material), Eqn. (2-24) becomes:

$$p_0 = n_0 \approx n_i. \tag{2-26}$$

For p-type material, the Fermi level lies below mid-gap (closer to the valence band) as discussed $E_F \ll E_d$. the density of the ionized impurities at acceptors is given by:

$$N_a^- = N_V \exp\left(\frac{E_V - E_F}{k_B T}\right) \quad \text{and} \quad N_a^- = \frac{N_a}{1 + g_a \exp\left(\frac{E_a - E_F}{k_B T}\right)}. \tag{2-27}$$

Here g_a is the acceptor degeneracy factor. For GaAs: g_a= 4. The Fermi energy level, E_F or more accurate an acceptor chemical potential ($E_{\mu a}$). In semiconductor physics the term Fermi level is a material property which is often used instead of chemical potential. Where Fermi level is temperature independent while Chemical potential is temperature dependent. Equating the right and the left hand sides of equation. (2-27) and solving the Chemical potential is given by:

$$E_{\mu a} = E_a - k_B T \ln\left(\frac{N_V}{2g_a}\left[-1 + \sqrt{1 + 4g_a \frac{N_a}{N_V}\exp\left(\frac{\Delta E_a}{k_B T}\right)}\right]\right) \tag{2-28}$$

And the solved ionized impurities at acceptors are given by:

$$N_a^- = \frac{N_V}{2g_a}\left(-1 + \sqrt{1 + 4g_a \frac{N_a}{N_V}}\right)\exp\left(\frac{\Delta E_a}{k_B T}\right). \tag{2-29}$$

The majority carrier density or the holes, p_0 in an extrinsic semiconductor for very high acceptor impurity concentration $N_a^- \gg N_d^+$ Equation (2-24) can be simplified:

$$p_0 = \frac{N_a^-}{2}\sqrt{n_i^2 + \left(\frac{N_a^-}{2}\right)^2} \tag{2-30}$$

The law of mass action, Eqn. (2-10) allows one to calculate the minority carrier density in an extrinsic semiconductor when the majority carrier density is known:

$$n_0 = \frac{n_i^2}{p_0} \tag{2-31}$$

At sufficiently low temperatures, $p_0, n_{0,}$ and N_a^- all vary with temperature, and as a result the intrinsic concentration n_i also increases with temperature. This region in which N_a^- varies with temperature is called the partial ionization region. When the temperature is increased beyond the partial ionization region, there is the chance of ionized acceptor carriers' equality with the holes impurities carriers. After a while the concentrations of holes and electrons increase by the same amount due to the increment in intrinsic concentration but the ionized acceptor continued remains constancy. Upon a further increase in temperature (beyond the extrinsic region), the intrinsic concentration n_i begins to

dominate. Both the majority and minority carrier concentrations approach the intrinsic concentration and the semiconductor enters a quasi-intrinsic region.

2.4 Energy of free carriers

Electron's energies increase upward in the energy band diagram, while hole's energies increase downward in the energy band diagram. The kinetic energy (E_k) of a carrier is equal to the energy difference between the carrier's level in a band and the band edge. For electrons and for holes respectively:

$$E_{kn} = E - E_C \tag{2-32}$$

$$E_{kp} = E_V - E \tag{2-33}$$

The kinetic energy and the potential energies of an electron in the conduction band; and the upward increase of electron energy and the downward increase of the hole energy. The energy supplied to excite an at-rest valence band electron from E_V to E_C is totally used up in the excitation process. Then, $E = E_C$ electron and $E = E_V$ hole thereby created are therefore at rest. Electron or hole carrier energies are thus logically associated with the energy of motion (kinetic energy). Since the electron kinetic enery(E_k) plus its potential energy (U_n) is equal to the total energy (E):

$$E = E_{kn} + U_n \tag{2-34}$$

The electron potential energy is equal to the energy difference between the conduction band edge (E_C) and the reference energy (E_0):

$$U_n = E_C - E_0 \tag{2-35}$$

The electron potential energy (and hence the total energy) is of course arbitrary to within a constant, and the position-independent refrence energy, E_0 may be chosen to be any convenient value.

2.5 Band bendings

When an electric field ($\boldsymbol{\mathcal{E}}$) is applied to the material, the band energies become a function of position. The variation of (E_C) and (E_V) with position is referred to as *band bending*. From Eqn. (2-35), it is possible to deduce, by inspection, the general form of the electrostatic variables inside the material. Since from elementary physics that the potential energy of a $-e$ charged particle is related to the electrostatic potential V at a given point in the material by:

$$U_n(x) = -eV(x). \tag{2-36}$$

Thus, taking into account Eqn. (2-35) along with Eqn. (2-36), yields:

$$V(x) = -\frac{1}{e}(E_C - E_0). \tag{2-37}$$

Moreover, by definition:

$$\mathcal{E} = -\nabla V. \tag{2-38}$$

Or, in one dimension along the x direction:

$$\mathcal{E} = -\frac{dV}{dx}. \tag{2-39}$$

Upon substituting Eqn. (2-37) into Eqn.(2-39) , we get:

$$\mathcal{E} = \frac{1}{e}\frac{dE_C}{dx}, \qquad E_0 = \text{Constant} \tag{2-40}$$

And

$$\mathcal{E} = \frac{1}{e}\frac{dE_V}{dx}, \qquad E_g = \text{Constant}. \tag{2-41}$$

The volume charge density in the material is also given from Poisson's rule as:

$$\rho(x) = \epsilon\frac{d\mathcal{E}}{dx}, = -\epsilon\frac{d^2V(x)}{d^2x} \tag{2-42}$$

If the field is applied in the region of width x_0 and x in the material directing from left to right, the position dependence of the energy band edge and the corresponding potential in the field region of the material are given as:

$$E(x) = E_0 + e\int_{x_0}^{x} \mathcal{E}(x)dx, \tag{2-43}$$

$$V(x) = V_0 - \int_{x_0}^{x} \mathcal{E}(x)dx, \tag{2-44}$$

Where, E_0 and V_0 are the conduction band edge and the corresponding potential at$x = x_0$. If a constant field, $\mathcal{E}$ is applied in the region of width, x_0 and then, no charge is accumulated in the material,$\rho(x) = 0$ the energy band edge and the corresponding potential are varying with position in the field region of the material as:

$$E(x) = E_0 + e\mathcal{E}(x - x_0), \tag{2-45}$$

$$V(x) = V_0 - \mathcal{E}(x - x_0), \tag{2-46}$$

From Eqn. (2-39), it is noted that the energy band edge and potential are linearly varying with position. At the point where $x = x_0 - b_1$, Eqn.(2-45) and Eqn. (2-46) can be simplified to:

$$E = E_0 - e\mathcal{E}b_1, \quad \text{and} \tag{2-47}$$

$$V = V_0 + \mathcal{E}b_1. \tag{2-48}$$

Where, b_1 is the width difference between x_0 and$x$. The most practical case for the semiconductor is when the field is varying linearly with position in the form of:

$$\mathcal{E}(x) = k(x - x_0), \tag{2-49}$$

Where k is a constant which is a function of doping. The volume charge density in this case remains constant throughout the field region and zero outside the field region.

$$\rho(x) = \epsilon\frac{d\mathcal{E}}{dx} = \begin{cases} \epsilon k, & \text{between 0 and } x_0, \\ 0, & \text{otherwise.} \end{cases} \tag{2-50}$$

If the field region is limited to interval between 0 and x_0, then the field has minimum value $-kx_0$ at $x = 0$ and increases until it reaches its maximum value 0 at x_0. By using Eqns. (2-43) and (2-44) along with Eqn. (2-49), the position dependence of the energy band edge and the corresponding potential are bending in parabolic form. The band bending and the potential barrier formed in the material between is then given by:

$$E(x) = E_0 + \frac{ek}{2}(x - x_0)^2, \text{ and} \tag{2-51}$$

$$V(x) = V_0 - \frac{k}{2}(x - x_0)^2. \tag{2-52}$$

The energy band and potential becomes E_0 and V_0 at $x = x_0$ respectively, and at $x = x_0 - b_1$, Eqn.(2-51) and (2-52) can be simplified to:

$$E = E_0 + \frac{ek}{2}b_1^2, \quad \text{and} \tag{2-53}$$

$$V = V_0 - \frac{k}{2}b_1^2. \tag{2-54}$$

Since, the most practical case for the semiconductor is when the field is varying linearly with Position, then one can extend from Eqn. (2-49) that, when the field varying in quadratic with position in the form of:

$$\mathcal{E}(x) = \lambda(x - x_0)^2 \tag{2-55}$$

Where, λ is a constant which is a function of doping. The volume charge density in this case remains constant throughout the field region and zero outside the field region.

$$\rho(x) = \epsilon\frac{d\mathcal{E}}{dx} = \begin{cases} \epsilon\lambda, & \text{between 0 and } x_0, \\ 0, & \text{otherwise.} \end{cases} \tag{2-56}$$

If the field region is limited to interval between 0 and x_0, then the field has minimum value $-\lambda x_0^2$ at $x = 0$ and increases until it reaches its maximum value 0 at x_0. Again also using Eqn. (2-43) along with Eqn.(2-55), the position dependence of the energy band edge is bending in cubic form. The band bending energy formed in the material between is then given by:

$$E(x) = E_0 + \frac{e\lambda}{3}(x - x_0)^3. \tag{2-57}$$

Again from Eqn. (2-57), it is noted that the energy band edge is varying in cubic form with position. The energy band edge becomes E_0 at $x = x_0$, and at $x = x_0 - b_1$ Eqn. (2-57) can be simplified to:

$$E = E_0 - \frac{e\lambda}{3} b_1^3. \tag{2-58}$$

In similar fashion it is possible to proceed the variation of electric field with position, then one can extend from Eqn.(2-49) that, when the field is varying in cubic form with postion in the form of:

$$\mathcal{E}(x) = \beta(x - x_0)^3 \tag{2-59}$$

where, β is a constant which is a function of doping. The volume charge density in this circumstances remais contant throughout the field region and zero outside the field region.

$$\rho(x) = \epsilon \frac{d\mathcal{E}}{dx} = \begin{cases} \epsilon\beta, & \text{between 0 and } x_0, \\ 0, & \text{otherwise.} \end{cases} \tag{2-60}$$

For the condition the field region is restricted to interval between 0 and x_0, then the field has minimum value $-\beta x_0^2$ at $x = 0$ and increases until it reaches its maximum value 0 atx_0. Again also using Eqn. (2-43) along with Eqn. (2-59) the position dependence of the energy band edge bending is in exponential (exponent of four) form. The band bending energy formed in the material between is then given by:

$$E(x) = E_0 + \frac{e\beta}{4}(x - x_0)^4 \tag{2-61}$$

Once more from Eqn. (2-61) it is well-known that the energy band edge is varying in exponential form with position. The energy becomes E_0 at $x = x_0$, and at $x = x_0 - b_1$ Eqn. (2-61) can be simplified to:

$$E = E_0 + \frac{e\beta}{4} b_1^4. \tag{2-62}$$

The electron and hole change of energy for each cases are equal to the energy difference between the reference energy (E_0), conduction band edge, (E_C) and valence band edge in the form of:

$$\Delta E = E_0 - E_{C0}, \qquad \text{and} \qquad \Delta E = E_0 - E_{V0}. \tag{2-63}$$

The thermal equilibrium electron concentration, n_0 in the conduction band and thermal equilibrium holes concentration, p_0 in the valence band for the non-degenerate semiconductor case can be simplified to:

$$n_0 = N_C \exp\left(-\frac{E_{C0} - E_F}{k_B T}\right) \tag{2-64}$$

$$p_0 = N_V \exp\left(-\frac{E_F - E_{V0}}{k_B T}\right) \tag{2-65}$$

The band bending in different layers accounts for the variation of the majority carrier concentrations in the layers. The description of the band bending, $E(x)$ at any location x in the depletion region also enables us to evaluate the thermal equilibrium free carriers' densities at any point x in the depletion region under each cases. The majority carrier density, (E) at any energy, E in the depletion layer of a p-type semiconductor can be expressed as [54].

$$p(x) = p_0 \exp\left(-\frac{\Delta E(x)}{k_B T}\right) \tag{2-66}$$

The majority carrier concentration in Eqn. (2-66) is in general decreases with increasing the band bending. The minority carrier concentration at any point in the depletion layer for every cases can be described using the law of mass action and along with Eqn. (2-64) as:

$$n(x) = n_0 \exp\left(\frac{\Delta E(x)}{k_B T}\right) \tag{2-67}$$

Hence, the position dependence of the energy bending in the entire depletion layer between the surface and the edge of the quasi-neutral region can be approximated in general as [55]:

$$E(x) = -\frac{e^2 N_a^-}{2\epsilon}(b_1 - x)^2. \quad (2\text{-}68)$$

Where $E\ (x)$ is the band bending at depth x, N_a^- is doping concentration, k_∞ is dielectric constant (1.32×10^1) and ϵ_0 is permittivity of free space ($8.85 \times 10^{-12}\, c^2/Jm$) and b_1 is width interval of p-type material.

2.6 Free carriers Generation-Recombination Mechanisms

The rates of change of electrons in the conduction band and holes in the valence band are equal and always given by the difference between the generation and the recombination rates [56], *i.e.*

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R. \quad (2\text{-}69)$$

Where, n and p represent the non-thermal equilibrium electron and hole concentrations in the conduction and valence bands respectively, and G and R are the total generation and recombination rates of charge carriers, respectively. The total generation rate involves both the thermal (G_{th}) and optical (G_0) generation rates:

$$G = G_{th} = G_0. \quad (2\text{-}70)$$

The net excess carrier recombination rate U is defined as the difference between the total recombination rate and the thermal equilibrium generation rate:

$$U = R - G_{th}. \quad (2\text{-}71)$$

The net recombination rates for photo -generated electrons and holes are given by [57]:

$$U = \frac{\delta n}{\tau_n} = \frac{\delta p}{\tau_p}. \quad (2\text{-}72)$$

Where, δn and δp are the concentrations of photo -generated carriers. The parameters τ_n and τ_p are called the electron and hole recombination lifetimes, respectively. Using the

principle of detailed balance along with Eqns. (2-69) to Eqns. (2-72), the rates of change of the excess carriers are:

$$\frac{d\delta n}{dt} = G_0 - U = \frac{d\delta p}{dt}. \tag{2-73}$$

Electron-hole pairs are continuously generated under illumination, and the excess charge carrier concentrations will increase. Recombination, on the other hand, tries to reduce the excess carrier concentrations to zero.

2.6.1 Radiative Recombination

Radiative recombination is the opposite of the optical generation of charge carriers. It occurs when the energy of the excited electron is emitted by the formation of photon during the annihilation of an electron–hole pairs. The Radiative recombination rate depends on the concentration of free electrons (n) and holes (p) is obtained as follows.

$$U_R = C_R(np - n_i^2) \tag{2-74}$$

Inserting non-equilibrium concentration $n = n_o + \delta n$ and $p = \delta p + p_o$ into equation (2-74) and for the case of low-level injection, the excess carrier concentration δn and δp with $\delta n = \delta p$, then the following general expression for radiative recombination rate, U_R is given by:

$$U_R = C_R\delta n(\delta n + p_o + n_o), \tag{2-75}$$

So, the radiative excess carrier lifetime, τ_R takes the form:

$$\tau_R = \frac{\delta n}{U_R} = \frac{1}{C_R(n_o + p_o + \delta n)} = \frac{\tau_{R0}}{1 + C_R\tau_{R0}\delta n} \tag{2-76}$$

Where, C_R is a constant known as the coefficient of holes in the valence band for the capture of electrons, and is related to the electron capture cross-section (σ_R) and the thermal velocity of the electrons ϑ_{th}.

$$C_R = \sigma_R \vartheta_{th}\,. \tag{2-77}$$

The band-to-band capture coefficient for bands with spherical symmetry was shown by van Roosbroeck and Shockley to depend on the absorption coefficient through the relation as [58, 59]:

$$C_R = e\pi\sqrt{k_\infty}\left(\frac{m_n}{m_n^* + m_p^*}\frac{300}{T}\right)^{\frac{3}{2}}\left(1+\frac{m_n}{m_n^*}+\frac{m_n}{m_p^*}\right)\left[E_g^2 + 3E_g k_B T + 3.75\, k_B^2\, T^2\right], \quad (2\text{-}78)$$

Where, E_g and $k_B T$ are in (eV). For large band gap materials $E_g \gg k_B T$, only the E_g^2 term is needed. So, the general form of carrier lifetime for the radiative recombination with injection level is result as [60]:

$$\tau_R = \frac{\delta n}{U_R} = \frac{1}{C_R(n_0 + p_0 + \delta n)} = \frac{\tau_{R0}}{1 + C_R \tau_{R0}\delta n} \quad (2\text{-}79)$$

For a material under low injection level ($\delta n \ll p_0 + n_0$), so that:

$$\tau_R = \tau_{R0} = \frac{1}{C_R(n_0 + p_0)}, \quad (2\text{-}80)$$

Chapter 3 : Methodology

For the analysis of the effects of electric field of free carriers on the photo-responses of p-semiconductor in the materials for this work, Gallium Arsenide (GaAs) was found to be suitable for its direct band gap, very high carrier densities and melting point. Then, the important theoretical data concerned with the optical and electrical properties of these direct band semiconductors were gathered and described. The position dependence constant, linear, quadratic and cubic electric field, $\boldsymbol{\mathcal{E}}(x)$ the energy, $E(x)$ and the change of energy, $\Delta E(x)$ the position independent reference energy, E_0 can be determined using the samples parameters and the width interval between initial and final position from the relation in Eqns. (2-39), (2-49), (2-55), (2-59), resulting energy by Eqns. (2-47), (2-53), (2-58), (2-62) and(2-63) respectively. The description of the all horizontal axis results were performed by varying the position ranging from 0 to 400nm. The majority carrier concentration, p_0 used in the analysis was determined from the relation in the Eqn. (2-30), which is equal to the ionized acceptor concentration, N_a^-. The minority carrier concentration, n_0 is determined from majority carrier concentration p_0 and the intrinsic carrier concentration using the law of mass action for a particular semiconductor, relation given by Eqn. (2-13). The carrier capture coefficient used in the analysis was taken $1.65 \times 10^{-10} cm^{-3} s^{-1}$ at room temperature for the radiative recombination coefficient. The radiative recombination coefficient can be determined using the relation in Eqn. (2-78). The results of the analyses were described using linear for both horizontal and vertical values. The results of the position dependence of the room temperature thermal majority carrier concentration, $p_0(x)$ minority carrier concentration, $n_0(x)$ and intrinsic carrier concentration, n_i can be determined using the free carrier energy from the relation given by Eqns. (2-66) and (2-67) by varying the doping level from low to highly doped samples. However, intrinsic carrier concentration is independent of the position throughout the material. The analysis of this data was performed using semi log for both majority and minority carrier concentration and linear for horizontal axes. The values of the thermal equilibrium carrier concentration in this case is varied from $10^{-8} cm^{-3}$ to $10^{20} cm^{-3}$. The description of the results of the position dependence of the excess carrier lifetimes were also performed at room temperature for samples with two types of doping levels. That is,

$10^{16} cm^{-3}$ and$10^{19} cm^{-3}$. In the analysis of this result, the vertical axis for excess carrier lifetime was taken as semi-log and horizontal axis of the position was kept linear. The results obtained for the excess carrier lifetimes for both doping levels were varied from $10^{2} ns$ to$10^{14} ns$.

Chapter 4 : Results and discussion

This chapter deals with the analysis and discussion of the entire results of this thesis. First, the effects of the variation of the electric field with position, $\boldsymbol{\mathcal{E}}(x)$ in different cases i.e. constant electric field, linear electric field applied and quadratic form of field applied, cubic field, energy with position, $E(x)$ change of energy, $\Delta E(x)$ the density of free electron carriers, $n_0(x)$ in the conduction band, the density of the hole carriers, $p_0(x)$ in the valence band, intrinsic carrier concentration,n_i, in a semiconductor were determined. Finally, the photo-response (excess carrier lifetimes), in all cases of field applied for p-type semiconductor relations with positions under each step were analyzed. The values of, τ_{RO} described under different condition in this work are all determined using Eqn. (2-80) for the corresponding field applied to the sample.

The constant, linear, quadratic and cubic electric field in the bulk of semiconductor is obtained as a function of position between the width intervals of the material using Eqn. (2-39), (2-49), (2-55) and (2-59). Figure 4-1 illustrates the effects of those electric field in the entire region sample material as a function of position: (a) constantly, linearly, quadratically and cubically applied electric field, and the resulting energy, and the change of energy. As can be seen from Figure 4-1 (b) and (c) displays the energy bending as function of position. As one can see from Figure 4-1 (a) the constant electric field runs in steady state throughout the material between the width intervals of the sample. A constant force acting on the electron means constant acceleration, increasing electron velocity, and increasing current through the sample with a longer electric field applied. Therefore, the electric field distribution throughout the semiconductor is constant. This means, the electric field exerted in this mechanism has greater value and should be controlled than any other cases. No matter how much the field is varying in different form, energy and change of energy bending has greater deviation than any other circumstances. The conduction band and valence band energy are equal to the sum of reference energy, E_0 and the field applied to the region. Since, the maximum attainable energy at the top of the valence band, $E_V(x)$ and $E_C(x)$ are equal to constant energy (independent of position), E_0 at the region x_0 and x have the same value. As can be seen from the relation in equation (2-48) and (2-49), the electrical field intensity for

one dimension has direct proportion to the band energy gradient as a function of the position [61].

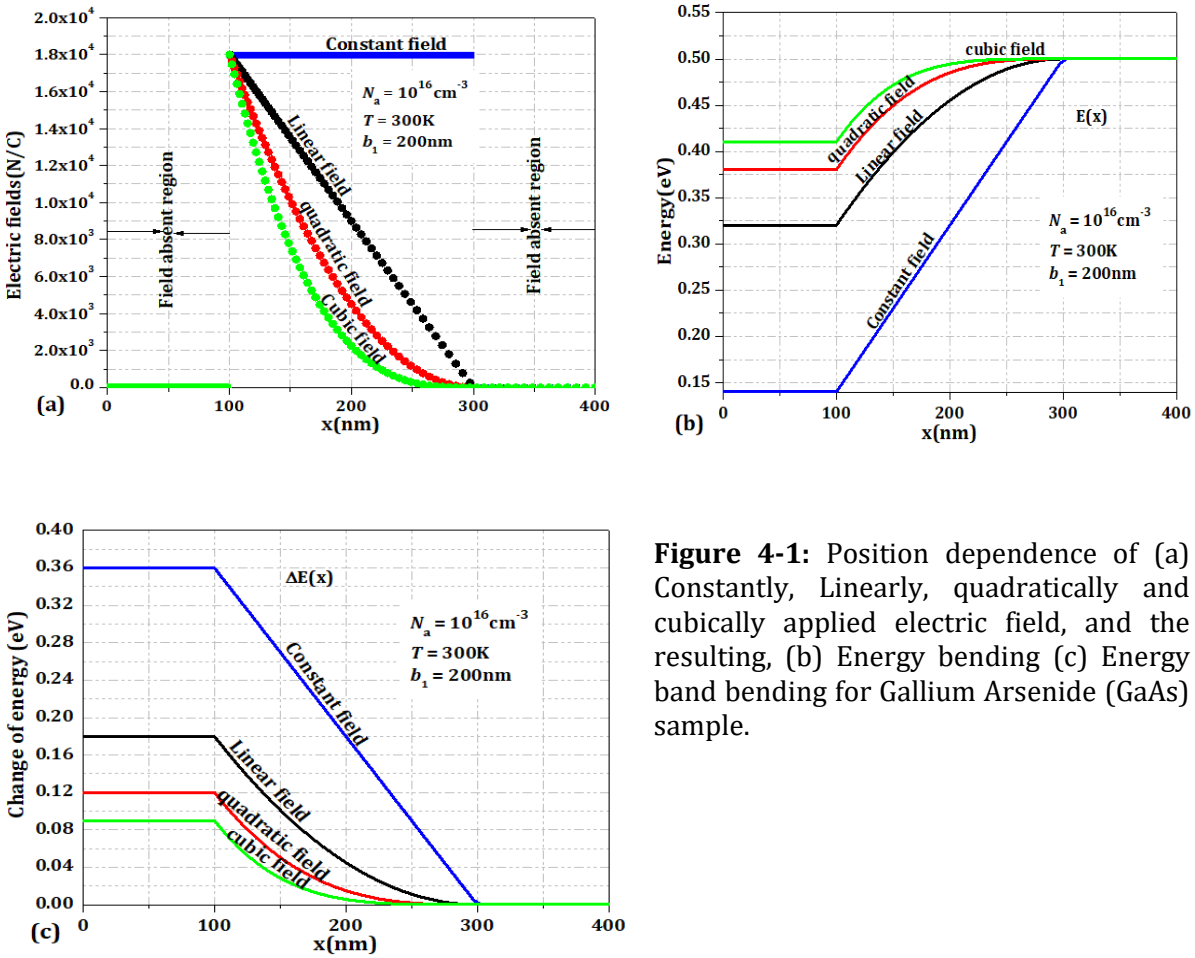

Figure 4-1: Position dependence of (a) Constantly, Linearly, quadratically and cubically applied electric field, and the resulting, (b) Energy bending (c) Energy band bending for Gallium Arsenide (GaAs) sample.

The field applied to the sample varies approximately from 0 to $1.8x10^4NC^{-1}$ for the acceptor density equal to, $N_a = 10^{16}cm^{-3}$ at room temprature as shown in Figure 4-1 (a). The applied voltage produces an electric field, $\mathcal{E}(x)$. Since an electron at the Fermi energy can be considered free because of unlimited empty energy states above it, the only force acting on the electron is that due to the applied electric field. This Figure shows electric field applied to bulk semiconductor as function of position between the width interval of b_1 under different conditions. Figure 4-1 (a) display the blue line with constant electric field, the black with linear, the red line as quadratic and the green the cubic electric field variation with position.

The linear electric field applied to the material sample decreases from its maximum value $1.8\,x10^4NC^{-1}$ with increasing position. Among all approaches this mechanism were the

most practical case for the semiconductor in which the field is varying linearly with position given by Eqn. (2-49). Since the electric field gradient depends on the position, the field gradient goes to zero for width below initial and above final position. This form of field applied to the material sample produces quadratic form of energy bending whereas, constant form of electric field results in linear variation of energy bending. In general, the electric field applied to the material sample would further extended with position to thermally generated carrier in the material. The red and green line in Figure 4-1(a) also illustrates that the dependence of the quadratic and cubic electric field on position as previously discussed for constant and linear cases. The quadratic and cubic electric field applied results in the energy bending and change of energy band bending as indicated with its corresponding graphs colour in a Figure 4-1 (b) and (c) respectively. The deviation of energy and change of energy formed was increasing for energy and decreasing for change of energy with increasing position for the same sample intervals as indicated by red and green colour in Figure 4-1 (b) and (c) respectively.

The bottom of the conduction band corresponds to the electric potential of the electron. Since we are interested in the gradient of the energy and not the energy itself, we can use any energy level of the band diagram, see Figure 4-1 (c). The energy bending varies approximately from 0.14eV to 0.5eV and all forms of energy becomes equal at maximum position. Since, this point is maximum reference energy which was independent of position and common for all forms of energy under consideration. In the reverse direction, the gradient of change of energy band bending which was given by Eqn.(2-63), and formed from its corresponding field, falls from maximum value 0.36eV to around 0.09eV with increasng position. The maximum and minimum value of energy and change of energy deviation was obtained from constant and cubic form of electric field applied to Gallium Arsenide (GaAs) sample for the same width interval increasing with position. Therefore, one can conclude from this relations that, constant electric field produces the largest energy and its corresponding change of energy bending whereas, the smallest energy and change of energy deviation was resulted from cubic form of electric field applied to the sample.

Figure 4-2 illustrates the position dependence thermal equilibrium carrier densities for p-type semiconductor under low injection level for two different cases. The determination of

the position dependence thermal equilibrium carrier densities in this case is performed from the analysis of Eqns. (2-66) and (2-67) at low injection level. Since, the change in intrinsic carrier concentration does not affect the majority carrier concentration, p_0 is remains constant. The thermal equilibrium majority carrier density, p_0 is equal to the the ionized acceptor concentrations, N_a^- i.e. the value was constant from relation in Eqn.(2-30).

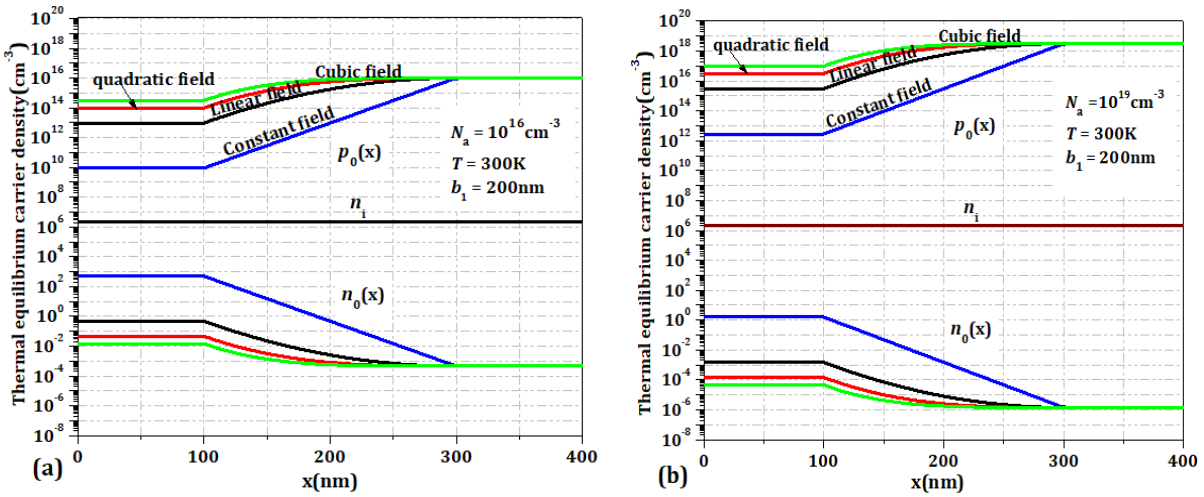

Figure 4-2: Position dependence carrier densities with doping levels of (a) $10^{16}cm^{-3}$ (b) $10^{19}cm^{-3}$ for the system under influence of the electric field in figure 4-1(a).

The position dependence majority carrier density, $p_0(x)$ and minority, $n_0(x)$ carrier concentration are represented by blue line, black line, red and green line with their corresponding fields respectively. The Fermi energy for p-type non-degenerate semiconductor was calculated from the Eqn. (2-14). As can be seen from Figure 4-2 (a) and (b), for the intrinsic semiconductor the intrinsic density, n_i refers to either intrinsic electron or hole concentration. After the condition of intrinsic semiconductors, the electron concentration, $n_0(x)$ decreases whereas, hole concentration, $p_0(x)$ increases as the position increases, since the intrinsic density, n_i are the densities of electrons in the conduction band or the densities of holes in the valence band in the intrinsic semiconductors are independent of the position of the material. As the Fermi energy, E_F moves closer to the conduction band the electron concentration increases and the energy band edge is decreases, since small energy band edge makes the less carriers to be accumulated. As can be seen from the above Figure 4-2 shows the room temperature (300K) for all the samples with low and high doping level of the variation of the thermal equilibrium carrier concentration with position under the influence of different electric field applied. In dealing with general band bending, in the

downward band bending holes are depleted (majority carrier concentration decreases) whereas, minority carrier concentration is increasing. The situation where the band bends down the minority carrier concentration (electrons) increases exponentially, we call this accumulation. Therefore, in the case of upward band bending holes accumulate and electrons are decreasing as indicated in Figure 4-2(a) and (b) respectively. For low doping level majority and minority carrier concentration become close to the intrinsic carriers and at high doping level position dependence carriers are far away from intrinsic density as shown in Figure 4-2 (a) and (b). In general, as doping level increases majority carrier increases whereas, minority carrier decreases within the same width.

Figure 4-3 depicts the position dependence of excess carrier lifetime for sample with acceptor densities equal to (a) $10^{16}\,cm^{-3}$ (b) $10^{19}\,cm^{-3}$. The radiative excess carrier lifetimes are represented by blue lines for contant field, black lines for linear field, red lines for quadratic field, green lines for cubic field and position independent radiative excess carrier lifetimes are represented by wine lines. As can be seen from Figure 4-3 the style of the variation of the excess carrier lifetime with position also depends on the doping levels. The functional dependence of excess carrier lifetime on position shown in Figure 4-3 (a) and (b) is predicted by Eqn. (2-80), when considered along with position independent radiative capture coefficient, Eqn. (2-78), and the position dependence of thermal equilibrium carrier concentration, Eqn. (2-66) and Eqn.(2-31); for sample with the different doping level.

At very minimum position in the field free region (below 100nm) the radiative excess carrier lifetime are remain constant with decreasing position, because of absence of electric field in the respective bands and hence the decrease in the recombination process. In field exerted region the radiative excess carrier lifetimes decreases slightly up to maximum position, because of limited field region of majority carrier concentration and decrease in radiative capture coefficient. Field exerted region is getting narrower and far away from intrinsic radiative excess carrier lifetime with increasing position, because of variation of excess carrier concentration in the region as function of doping see Figure 4-3 (b). This is not observed in photoresponse of a sample without acceptor or donor concentration. The regions varies approximately from 100nm to 225nm for cubic field,100nm to 250nm for

quadratic field, 100nm to 275nm for linear field and 100nm to 300nm for constant field in both samples with acceptor concentrations equals to $10^{16}cm^{-3}$and $10^{19}cm^{-3}$ (Figure 4-3).

In the electric field applied region all radiative excess carrier lifetime decreases slightly

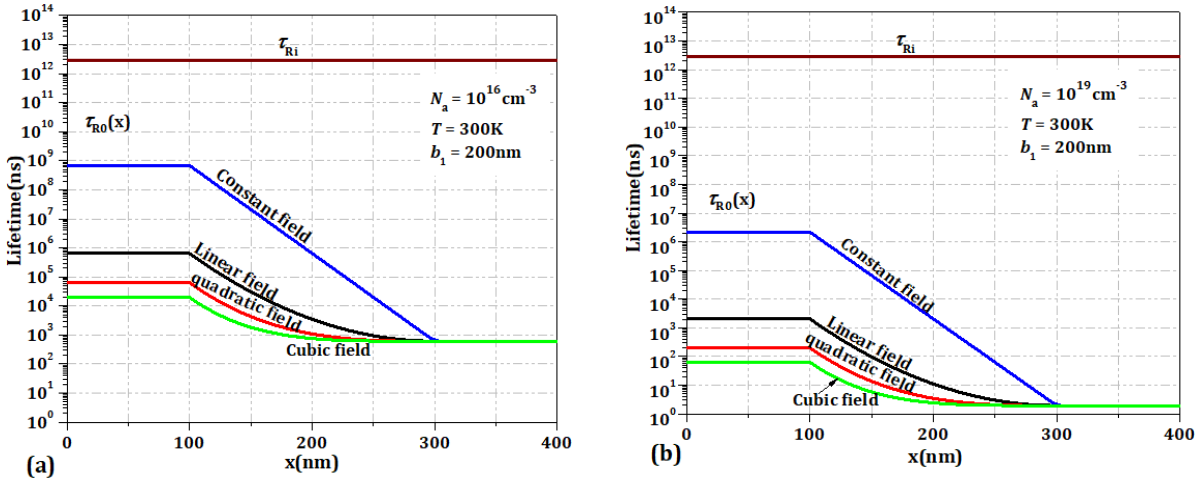

Figure 4-3: Position dependence radiative excess carrier lifetime with doping levels of (a) $10^{16}cm^{-3}$ (b) $10^{19}cm^{-3}$ for the system under influence of the electric field in figure 4-1(a).

with increasing position irrespective of doping effect. Then, radiative excess carrier lifetime formed due to constant field becomes dominant in this region. This is because of constant electric field is independent of position which can produces linearly varying radiative lifetime with position that has larger gradient than others. As one can see from Figure 4-3, hence, thermal generation rate closes to intrinsic radiative lifetime in the low doping samples and become far away in highly doped samples for the same field exerted region in both samples.

As a result, the value of the bulk excess carrier lifetime in this case rising up, with decreasing position and slightly decreasing in the high doping samples with increasing position for same region of field effects [62].

Chapter 5 : Conclusion

In this study, the effects of electric fields on the thermal equilibrium properties of semiconductor under diffferent conditions are calculated inside the sample for Gallium Arsenide (GaAs) sample. Then, the effects of position dependence electric field on energy, change of energy, thermal equilibrium carrier concentration and radiative excess carrier lifetime with doping levels are investigated. The results obtained from the description of the effects of electric field, the energy and change of energy has different bending deviation for different electric field applied. Depending on the form of electric field applied, energy and change of energy for conduction band or valence band in the entire bulk of a given sample was calculated from effects of its corresponding electric field. Hence, the position dependence electric field results in greatest energy bending revealed that, the conribution of enegy band bending comes from the constant electric field than any other forms(cases). As aresult the energy bending value varies for GaAs approximately in the range of 0 to 0.036eV. The result indicates that, high variations in the electrical properties and the photoresponses occur for the case when the constant field is applied. As doping levels of the sample increases the additional electron-hole pairs are thermally generated by thermal ionization of of donors or acceptors, so that; carriers generated by thermal ionization of donors or acceptors starts to dominate the entire conduction process in a given region at higher doping levels. The results obtained from the description of position dependence thermal equilibrium carrier densities, shows that; majority carrier densities increases at high doping samples and decreases in the low doping sample whereas, minority carrier concentration are high at low doping samples and decreases for high doping samples at a given position. so that; in downward band bending holes are depleted (decreases) whereas, in the case of upward bendings minority carrier concentration are increasing. The room temperature doping level dependence of of the excess carrier lifetimes also shows that, radiative excess lifetime obtained from constant field dominates at both low and highly doped sample. Finally, The variations in the electrical properties and the photoresponses decrease with increasing the variation in the applied electric field. However, these variations are unaffected by the doping level of the material.

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