Determination of the Photoconductivity in the Bulk of Direct Small Band gap GaSb Semiconductor

By

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Submitted in Partial fulfillment of the requirements for the degree of Master of Science in Physics
In the School of Applied Natural Science at Adama Science and Technology University

Advisor

Dr. Megersa Wodajo

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ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY
FACULTY OF SCIENCE
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Title: **DETERMINATION OF THE PHOTOCONDUCTIVITY IN THE BULK OF DIRECT SMALL BAND-GAP GaSb SEMICONDUCTORS**

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Abstracts

The purpose of this thesis is to determine the photo-response observed from bulk of gallium antimonide(GaSb) semiconductors which is described through the simulation of excess carrier lifetimes corresponding to the radiative, Auger and Shockley read hall recombination mechanisms dependence of excess lifetime as function of excess concentration and absorption coefficient. To conclude some of our results are quite new and requires future studies. First, the photon absorption effect on bulk semiconductor were described, if the penetration depth surface is small: both the absorption coefficient and absorption photon rate per incident photon is large or increased. If the penetration depths surface is large or goes to infinity: both the absorption coefficient and absorption photon rate per incident photon is small or decrease, where the photon absorption rate approximately goes to decrease or zero, because the incident photon directly passes through the material, the material is said to be transparent photon, first electron–hole pair are not produced or absorbed. in this work specifically derive and described the mathematical expression for excess carrier lifetime of Radiative, Auger and SRH under low injection and injection level from bulk semiconductors under thermal and non-thermal Equilibriums were described. Finally the result of SRH lifetime is dominant at low injection in a sample of low doping regions produced heat or phonon. The Auger excess lifetime which is dominate at high doping regions in the entire process released current. As function of excess concentration at high injection level, the SRH lifetime is dominant in a sample of low doping where as the Auger carrier lifetime is the dominant at high doping, if the doping concentration is increased with the decreasing of excess lifetime. In injection level dependence of excess lifetime as function of absorption coefficient, If the penetration depth surface is decreased as increasing of specific absorption coefficient with the decreasing of lowest minimum excess lifetime. The Auger excess lifetime which is dominant and minimum at specific absorption coefficient in a sample of relatively high photon concentration as compared to the minimum radiative and the constant of Shockley read hall lifetime. The three recombination of minimum excess lifetime is inverse proportional to the maximum photon absorption rate of the same point of specific absorption coefficient at different penetration depths surface. The three processes are equal by the principal of the detailed balance.

Contents

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List of Symbol and Abbreviation

e	Charge of electron (1.6×10^{-19} C)
h_c	Planck's constant (1.054×10^{-34}) J.s
α	Photon Absorption coefficient (cm^{-1})
K_b	Boltzmann constant (1.38×10^{-23} $J/_k$)
K	Wave vectors
PC	Photoconductivity
MCB	Minimum of Conduction band
MVB	Maximum of Valance band
E_{photon}	Energy of photon (eV)
E_g	Energy band gap (eV)
N_c, N_v	Electron and hole density of accessible state (cm^{-3})
EHP	Electron-hole pair
SRH	Shockley-Read-Hall
n, p	Non-thermal equilibrium Concentration of Electron and hole (cm^{-3})
n_0, p_0	Thermal equilibrium concentration of electron and hole (cm^{-3})
E_{CB}, E_{VB}	Energy of conduction band and valance band(eV)
E_f	Fermi energy (eV)
E_i	Intrinsic Fermi energy (eV)
C_R	Radiative recombination coefficient(cm^3s^{-1})
$C_{na,}C_{pa}$	Auger coefficient of Electron and hole(cm^6s^{-1})
e_n, e_p	The emission rate of electron and hole
Δx	Thickness of semiconductor (cm)
L	Length of semiconductors (cm)
W	Width of semiconductors (cm)
τ_R, τ_A & τ_{SRH}	Carrier lifetime in Radative , Auger and Shockley read hall (ns)
τ_{A0}	The band–band auger Carrier life rate under thermal equilibrium (ns)
τ_{n0}, τ_{p0}	Thermal equilibrium of minimum lifetime for electron and hole (s)
U_R	The net Radiative recombination rate ($cm^{-3}s^{-1}$)
U_A	The net auger recombination rate ($cm^{-3}s^{-1}$)
R_A	Band–band auger recombination rate under Non thermal equilibrium
τ_{eff}	Carrier lifetime in effective of bulk (ns)
U_{ehh}	The process denote when the excess energy is transferred to make hole, with recombination rate
U_{eeh}	The process denote when the excess energy is transferred to make

	Electron, with recombination rate
U_{cn} ,U_{en}	The probability of capture and emission of the electron by the centre
U_{cp} ,U_{ep}	The probability of capture and emission of the hole by the centre
n_{0T}, p_{0T}	The thermal equilibrium electron and hole occupancy (cm^{-3})
C_{nT}, C_{pT}	Capture coefficient of electron and hole of the state (cm^3s^{-1})
N_T	Density of localized state are a given as a number/unit volume (cm^{-3})
G_0	Absorption photon flux density in Bulk semiconductors ($cm^{-3}s^{-1}$)
Φ_0	Incident Photon flux density ($cm^{-2}s^{-1}$)
Φ_R	Reflectivity of Photon flux density ($cm^{-2}s^{-1}$)
Φ_T	Transmitted of Photon flux density ($cm^{-2}s^{-1}$)
R	Reflectivity (cm)
T	Temperature (K)
$f_F(E)$	Fermi-Dirac probability
$f_t(T)$	The distribution probability for the electron occupation of the trap
	Located at energy E_T in the band gap Fermi-Dirac probability
m_0	Rest mass of the electron (kg)
m_n^*, m_p^*	Electron and hole Effective mass (kg)
x_p	Spin depth or penetration depth (maximum of absorption photon rate(cm))
G_{th}	Thermal equilibrium Generation rate Electron and hole ($cm^{-3}s^{-1}$)
n_T, p_T	When occupied by electron and hole on the trap level (cm^{-3})
E_T	Electron occupation of a trap located at energy in the band gap (eV)
$U_{n,p}$	Net recombination rate of electron and hole ($cm^{-3}s^{-1}$)
δn, δp	Excess charge concentration for electron and hole density (cm^{-3})
$E_g^{(0)}$	Band gap energy at absolute zero on the Kelvin (eV)
$E_g^{(T)}$	Band gap energy at any temperature (eV)
$g_c(E)$	The density of quantum states in CB
$g_V(E)$	The density of quantum states in VB
$n(E)dE$	Density of electrons in CB at energy levels between E and E + dE
$p(E)dE$	Density of electrons in VB at energy levels between E and E + dE

Chapter 1: Introduction

1.1 Back ground

Semiconductors are materials that are very important in modern optoelectronic technologies. The existence of the energy band gap, high charge carrier density and high mobility of a charge in semiconductor makes them very important in this aspect. The energy band gap of semiconductor ranges from 0.3 to 3.5eV. The practical magnitudes of the dimensions of the samples are in micrometers to be compatible with the magnitudes of the parameters of the illuminating radiations [50,63]. The practical density of room temperature thermal equilibrium majority carrier for semiconductor that was determined using Hall Effect measurement is ranged from 10^{10}cm^{-3} for intrinsic semiconductor to 10^{19}cm^{-3} for highly doped non-degenerate semiconductor, and the density of minority carrier concentration is also ranged from 10^{12}cm^{-3} for intrinsic semiconductor to 10^{5}cm^{-3} for highly doped non-degenerate semiconductor [20].

Using the carrier capture coefficients by different energy states representing these recombination mechanisms in different semiconductors were determined by different researchers to be ranged from $10^{-29}\text{cm}^{6}\text{s}^{-1}$ for Auger recombination mechanism to $10^{-11}\text{cm}^{3}\text{s}^{-1}$ for Radiative recombination mechanism to $10^{-7}\text{cm}^{3}\text{s}^{-1}$ for Shockley Read Hall(SRH) recombination mechanism[63,65]. Small direct band semiconductors with energy band gap ranged from 0.3 eV to 1.1 eV, like indium arsenide (InAs), indium antimonide(InSb) and gallium antimonide (GaSb)etc,...,are characterized by the absence or small amount of impurity materials, presence of very high charge carrier concentration and high charge carrier mobility[28,29]. This makes direct small band gap semiconductors to be very important for the use in various domains of optoelectronic devices, 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, infrared thermal imaging, booster cells in solar cell clusters to improve the efficiency of photovoltaic and thermo-photovoltaic (TPV) cells and etc.…[28,30].

Electrical conductivity of the material is the measure whether it would easily accommodate the movement of an electric charge. The SI unit of conductivity is Siemens per meter $[S/m]$.The

conductivity of a given semiconductor is strongly dependent on its band gap[2,3]. Semiconductors are classified into two based on their band gap structures. These are direct and indirect band gap semiconductors. In direct band semiconductor the maximum of valance band and minimum of the conduction band occur for the same value of the wave number k. Because the electron in the higher in the valence band will tend to equilibrate to the lowest energy state available, the top of the valance band will collect holes, as electrons move down into available lower energy states. For the same reason, the bottom of the conduction band will collect electrons. Thus, in a material with a direct band gap, the k values of the points of valance band maxima (VBM) and conduction band minima (CBM)overlap and only photons can be emitted as carriers recombine directly [4,6].On the other hand, in an indirect band gap semiconductor, the points of VBM and CBM occur at different value of the wave number k.Hence, a transition from conduction band to the valance band involves both photons and phonons emission[7,8]. This allows both momentum and energy to be conserved. The energy–momentum relationship is usually obtained by solving the Schrödinger equation[9].

The available charge carriers for conduction in semiconductors are excited electrons to the conduction band and holes in the valence band. When they excited by thermal energy or illuminating photons, electrons can be excited across the band gap to conduction band leaving the holes behind in the valence band [12].When a small voltage is applied across the two ends of the given semiconductor, both of the excited electrons and holes involve in the conduction process, with electrons motion traversed from the point of low potential to the point of high potential and holes traverse from point of high potential to the point of low potential[13]. In general, conductivity depends on the free carrier density of both electrons and holes and their mobility. Since the free carrier concentrations and mobility's' are highly affected by the temperature of the material, conductivity of semiconductors also depends strongly on temperature[14,15].

Semiconductors have 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 without altering the band-gap and other basic parameter of the host material [58]. In general, the semiconductors may be divided into two categories: the pure un-doped semiconductor, which is usually referred to as the intrinsic semiconductor, and the doped semiconductor, which is also called the extrinsic semiconductor.

Another distinct difference between a metal and a semiconductor is that the electrical conduction in a metal is due to electrons, while the electrical conduction of a semiconductor may be attributed to electrons, holes, or both carriers. The electrical conduction of an intrinsic semiconductor is due to both electrons and holes, while for an extrinsic semiconductor it is usually dominated by either electrons or holes, depending on whether the semiconductor is doped with shallow donors or shallow acceptor impurities [58,68].

In the past three decades, we have witnessed remarkable advances in our understanding of semiconductor properties and rapidly expanding uses of semiconductor devices in industrial and consumer products[10,11]. The phenomenal growth of the semiconductor industry has resulted in a gradual increase in material research for better, higher performance, and more reliable semiconductors. For different semiconductor devices, one needs materials with different conductivity which can be affected by the band gap and energies of impurity levels. Physical properties are very different among different semiconductors due to distinct characteristics of energy gaps and impurities. Impurities play a major role in determining the electrical and optical properties of semiconductors[10,67].Semiconductors are the foundation of modern electronic world, enormously applying in daily life products. The advances made in semiconductor technology changed the life style of modern society. Elemental semiconductors include antimony, arsenic, boron, carbon, germanium, selenium, silicon, sulfur, and tellurium. In this, particularly silicon is the most important material. It is second only to oxygen in abundance in the Earth's crust, which makes device grade silicon available at a much lower cost than any other semiconductor material. Common semiconductor compounds include gallium antimonide, indium antimonide, gallium arsenide, indium arsenide and the oxides of most metals. Of these, gallium arsenide (GaAs) is widely used in low-noise, high-gain, and weak-signal amplifying devices[15].

Photoconductivity is also largely determined by the state of electron mobility, temperature, and the available free (photo-generated) carriers' concentration. The densities of the photo-generated carriers' in turn depend on the intensity and the spectral property of the illuminating light and the band gap energy of the semiconductors[12]. Photoconductivity is an optical and electrical phenomenon in which a material becomes more electrically conductive caused by the presence of light or due to the absorption of electromagnetic radiation such as visible light, ultraviolet light, infrared light, or gamma radiation[3]. Photoconductivity of all

kind is more generally a result of energy transition of electrons. When the illuminating photon has energy greater than the band-gap of the semiconductor, photons are absorbed and in turn electron hole pairs are produced. Photons with energies less than the band gap passes directly through the material and hence the material is said to be transparent to these photons[13].

Once the electron-hole pairs are generated, they are again recombined after a while by giving out energy as photon (in radiative recombination mechanism), heat or phonon to the lattice (in Shockley-Read-Hall (SRH) recombination mechanism) and as kinetic energy to other carriers (in Auger recombination mechanism).Hence, the performance of the semiconductor is directly related to the effective lifetime of charge carriers[63,66].Low photo-generated effective lifetime results in less conductivity (or less quality) of the semiconductor. Photoconductivity of materials are characterized primarily on the basis of photo-generated carriers' emission and recombination mechanism(s) (holes with electrons) involved in (1) inter band transitions (band edge or deep in band to band transitions) and (2) intra band transitions including through impurities or defects (band to acceptor level, donor level to valance band, donor to acceptor level, free and bound exciton transition, and deep level transitions). Evaluation of the lifetime also requires of the determination of the density of photo-generated carriers which is directly related to the intensity and the spectral properties of the incident photon[20,21].Due to the small amount of thermal carrier concentration, the minority carriers' lifetime is highly affected by carrier traps in the semiconductor than the majority carrier lifetime. Hence, the techniques mentioned above provide information about the effective lifetime of the minority carriers in the bulk of the semiconductor. In the absence of carriers trap both the majority and the minority carriers have equal effective lifetime[22,24].

In most direct small band gap semiconductors, radiative recombination is dominant. Radiative recombination involves the annihilation of electron-hole pairs by giving out a photon of energy equal to the energy gap between the levels where the two carriers were in before recombination[26,27].One of the verification of the direct small band of semiconductors is gallium antimonide in compound semiconductors. It is the materials for which maximum of valence band and minimum of conduction band lie for the same value of k like Gallium arsenide (GaAs), Indium phosphiride (InP), Candium sulfide (CdS). In direct band gap material, such as Galium arsenide and indium phosphide recombination is radiative considered as very important[25,26].

1.2 Objective

1.2.1 General objective

Hence, the general objective of this thesis is to determination of photo-response of the bulk of direct and small band gap GaSb semiconductor.

1.2.2 Specific Objectives

The specific Objectives of this thesis work is:

- to describe the absorption of photon in the bulk semiconductors,
- to determine the photo-generated carrier's concentrations for both majority and minority carriers,
- to determine the effective photo-generated carrier lifetime by the consideration of the three recombination mechanisms Radiative, Shockley-Read-Hall (SRH) and Auger,
- to determine the photoconductivity of the bulk of direct and small band gap GaSb semiconductor.

1.3 Thesis Outline

The thesis is organized into five chapters: **Chapter 1** deals with Introduction, Background, Objective and Organization of the study. **Chapter 2** provides Literature review of the paper, **Chapter 3** described and determined absorption photon rate in an infinitely thickness and how to the absorption photon rates for some distance bulk semiconductors as function of absorption coefficient and penetration depths surface. Drive and determined the excess carrier lifetime of Radiative, Auger and Shockley Read Hall for bulk semiconductors as function of doped concentration under low injection and injection level dependence of excess carrier lifetime as function of excess concentration and absorption coefficient under thermal equilibrium and non thermal equilibrium. Generally, we use the effective excess carrier lifetime of Radiative, Auger and Shockley Read Hall under thermal equilibrium and non thermal equilibrium is related to doped concentration and excess carrier concentration, absorption coefficient for the bulk of direct small band gap GaSb semiconductors in respectively. **Chapter 4** presents the results and discussions and **Chapter 5** is giving thesis summary.

Chapter 2: Review of literature

2.1 Energy band gap in Semiconductors

The band gap is a major factor determining the electrical conductivity of a solid. Energy band gap defined as a region in solids where no electron states can exist, Band gap also called an energy gap or band gap, is an energy range in a solid where no electron states can exist. The band gap generally refers to the energy difference (in electron volts) between the top of the valence band and the bottom of the conduction band in insulators and semiconductors. The closest point between the top of the valance band curve and the bottom of the conduction band is called the materials Energy Gap[28,30]. For insulating materials, this gap can be greater than ten electron volts. However, for semiconductor electronic devices operating a reasonable voltage, the gap has to be a few electron volts. Substances with large band gaps are generally insulators, those with smaller band gaps are semiconductors, while conductors either have very small band gaps or none, because the valence and conduction bands overlap[28,30].There are three types of inter band transitions:

1. Metal or conductors,
2. Insulators,
3. Semiconductor.

2.1.1 Metals

Metal are conductors either have very small band gaps or none, because the valence and conduction bands overlap. Here free carrier absorption is extremely important. Typical plasma energy is $\hbar v_p \cong 10$ eV which occur far out in the ultraviolet. In the case of metals, inter band transitions typically occur at frequencies where free carrier effects are still important. Semimetals, like metals, exhibit only weak temperature dependence with carrier densities almost independent of temperature. Although the carrier densities are low, the high carrier mobility's Nevertheless guarantee a large contribution of the free carriers to the optical conductivity[28,30]. Figure 2-1depicts the energy band structure of metals.

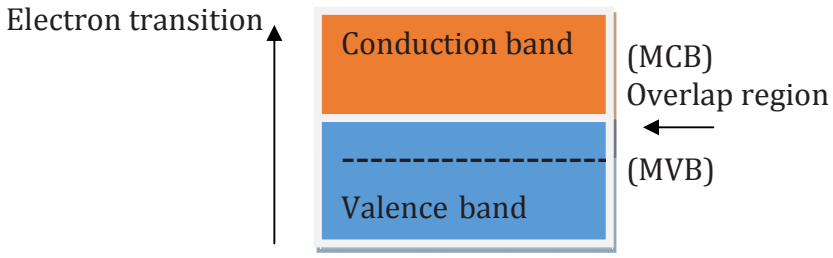

Figure 2-1: Energy band structure of metal.

2.1.2 Insulators

Substances with large band gaps are generally insulators, in insulators; the band gap is sufficiently large so that at room temperature, essentially no carriers are thermally excited across the band gap. This means that there is no free carrier absorption and that inter band transitions only become important at relatively high photon energies (above the visible). Thus, insulators frequently are optically transparent[28,30]. Figure 2-2 shows the energy band structure of Insulators.

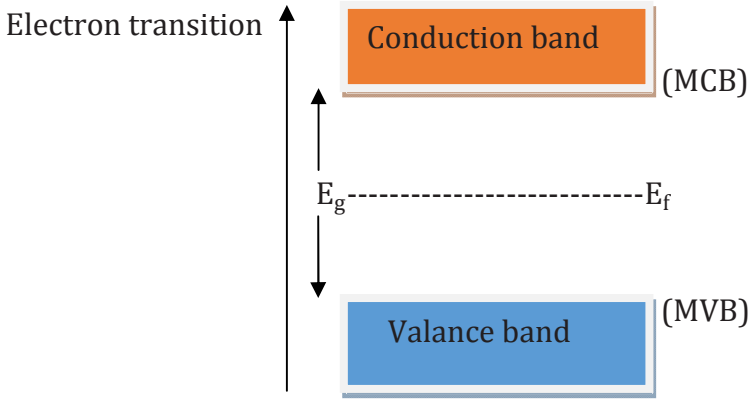

Figure 2-2: Energy band structure of Insulators.

2.1.3 Semiconductors

In a semiconductor, electrons normally have a higher mobility (smaller electron effective mass), thus a smaller transit time, than holes. Semiconductors differ from metals and insulators by the fact that they contain an empty conduction band and a full valence band at absolute zero (0 K). At finite temperature, some of electrons leave the valance band and occupy

the conduction band. The valance band is then left with some unoccupied states [10]. If all the valance band states are occupied, the sum over all wave vector states is zero; here the band gap is small enough so that appreciable thermal excitation of carriers occurs at room temperature. Thus, there is often appreciable free carrier absorption at room Temperature either through thermal excitation or doping. In addition, inter band transitions occur in the infrared and visible ranges. As an example, consider the direct inter band transition in germanium and its relation to the optical absorption. In the curve in Figure 2-3 we see that the optical absorption due to optical excitation across the indirect band gap at 0.7eV is very Small compared with the absorption due to the direct inter band transition[29,30].

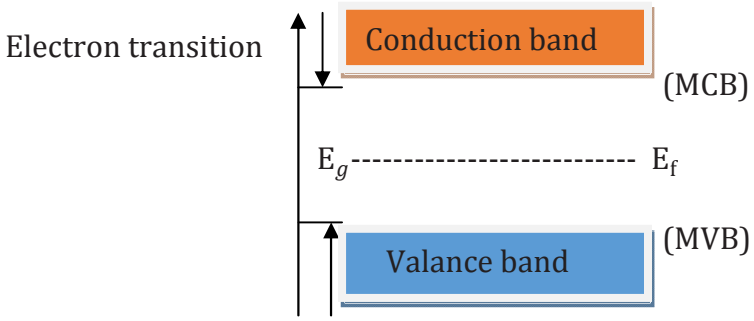

Figure 2-3: Energy band structure of semiconductors.

where $E_g = (E_C - E_V)$ is the energy band gap. If the valence band is completely full and the conduction band is completely empty, then electrons cannot move in the solid. However, if some electrons transfer from the valence to the conduction band, then current can flow[30]. Temperature affects the properties of electronic systems in a number of fundament ways. The most fundamental of properties way is the energy band gap, E_g which is affected by temperature according at (Varshni equation).

If one considers that, the interatomic spacing increases when the amplitude of the atomic vibrations increases due to the increased thermal energy. An increase in inter atomic spacing decreases the average potential seen by the electrons in the material, which consequently reduces the size of the energy band gap. A direct modulation of the inter atomic distance-such as by applying compressive stress-also causes an increase (decrease) of the band gap. The temperature dependence of the energy band gap E_g has been experimentally determined and its dependency can be expressed as of the form (Varshni equation):

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

where $E_g(0)$ is the band gap energy at absolute zero on the Kelvin scale in the given Material, α and β are material-specific constants.

2.1.4 Types of band gap in Semiconductors

Band gap in Semiconductors are classified into two. These are indirect and direct band gap semiconductors [20].

I. Indirect band gap semiconductors

Indirect band gap semiconductor defined as the conduction band is not vertically aligned to the valence band. Interaction of an incident photon with an electron in the valence band will not provide the correct energy and momentum corresponding to that of an empty state in the conduction band. Photon absorption requires the help of another Particle, namely a phonon. Phonon is a particle associated with lattice vibrations, has a relatively low velocity close to the speed of sound in the material, and a small energy and large momentum compared to that of a photon [20, 22]. Conservation of both energy and momentum can therefore be obtained in the absorption process if a phonon is created or an existing phonon participates. The minimum photon energy that can be absorbed is slightly below the band gap energy in the case of phonon absorption and has to be slightly above the band gap energy in the case of phonon emission. Probability of having an interaction take place involving all three particles (photon, phonon, and electron) will be lower than a simple electron-photon interaction. Absorption/Emission process is much stronger in a direct band gap material. Those materials for which maximum of valence band and minimum of conduction band do not occur at same value of, k, called indirect band gap materials [21, 25]. For example Si and Ge

Note Si and Ge that are indirect-gap semiconductors so the smallest band separation (the thermodynamic band gap, which determines the thermal population of electron and hole states) is not vertical in k-space. Silicon is the most prevalent material in the electronics world, not only because of its abundance and low cost, but also because it has a high-quality, stable oxide that provides excellent electronic passivation. However, due to its indirect band gap, the electronic structure of silicon prevents this material from being a strong light emitter. photon

absorption in an indirect band gap semiconductor assisted by Phonon emission. Indirect band gap materials CB minimum and VB maximum occur at the different k in figure 2-4 [21, 25].

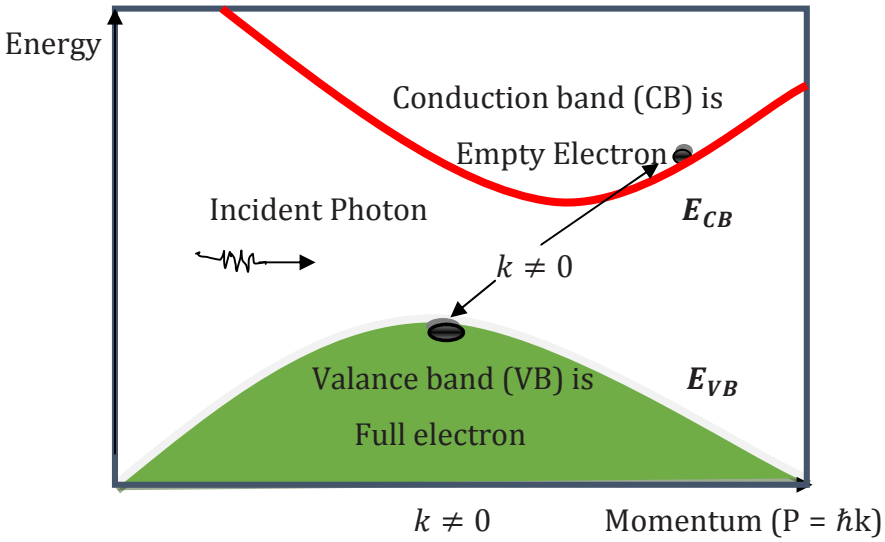

Figure 2-4: Energy vs momentum for a semiconductor with a indirect Band gap.

II. Direct band gap semiconductors

Direct band gap semiconductors defined as the minimum of the conduction band occurs at the same wave vector,k, as the maximum of the valence band. Direct band gap semiconductors have a stronger absorption of light as characterized by a larger absorption coefficient. It is the Energy and momentum conservation required in the Electron-photon interaction. In the direct band gap semiconductor, conduction and Valence bands are vertically aligned. The thermodynamic band gap separating the highest point of the valence band from the lowest point of the conduction band is direct band gap [21, 25]. Absorption of a photon is obtained if an empty state in the conduction band is available for which the energy and momentum equals that of an electron in the valence band plus that of the incident photon [40, 41]. When light with sufficient photon energy strikes a semiconductor, photons can be absorbed. Electrons and holes are generated. Electrons and holes are pulled into regions where they are majority carriers by Φ_0. Photons have little momentum relative of their energy since they travel at the speed of light. Direct band gap materials CB minimum and VB maximum occur at the same k, the electron therefore makes an almost vertical transition on the $E - k$ diagram. In fact Figure 2-5 is a good representation of this region for many direct-band gap III-V (e.g. InSb, GaAs, GaSb, InP, InAs) and II-VI (e.g. CdTe, ZnO, $Cd_{0.2}Te$, $Cd_{0.2}Hg_{0.8}Te$)[4,31],but i worked

the sample of small direct band gap of this thesis in gallium antimonide (GaSb) at $k = 0$ in Figure 2-5.

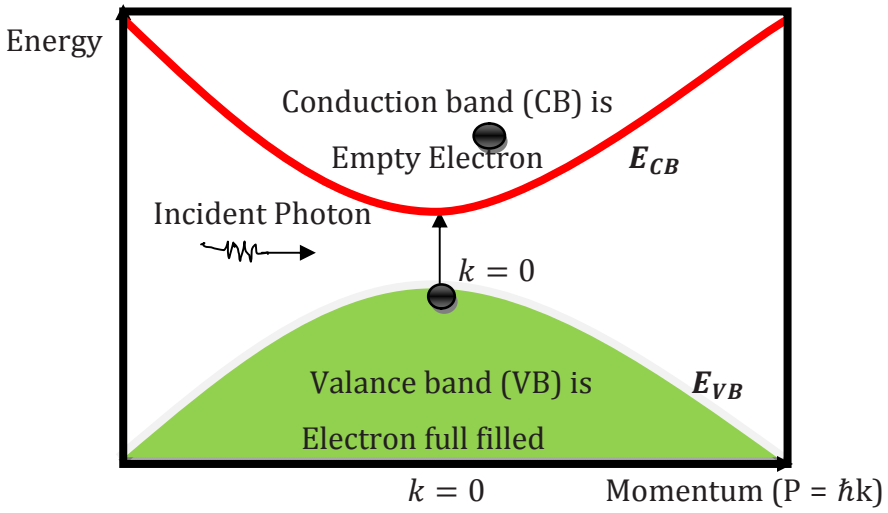

Figure 2-5: Energy vs momentum for a semiconductor with a direct Band gap.

2.2 Thermal Equilibrium Properties of Semiconductors

A system is in thermal equilibrium if detailed balance is obtained every process in the system is exactly balanced by its inverse process so that there is no net effect on the system. This definition implies that in thermal equilibrium no energy (heat, work or particle energy) is exchanged between the parts within the system or between the system and the environment. Thermal equilibrium is obtained by isolating a system from its environment, removing any internal sources of energy, and waiting for a long enough time until the system does not change any more. If two systems are in thermal equilibrium with a third system, they must be in thermal equilibrium with each other. In thermal equilibrium, these concentrations are independent of time. however, electron continually being thermally excited from the valence band into the conduction band by the random nature of the thermal process[42]. 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. This recombination process annihilates both the electron and hole. No external forces such as voltages, electric fields, magnetic fields, or temperature gradients are acting on the semiconductor. All properties of the semiconductor will be independent of time at equilibrium , Equilibrium is our starting point for developing the physics of the semiconductor. We will then be able to

determine the characteristics that result when deviations from equilibrium occur[48]. In Figure 2-6 below in thermal equilibrium Semiconductor balance b/n both electron and hole.

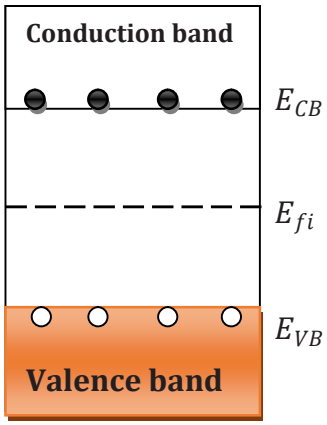

Figure 2-6: Semiconductor under thermal equilibrium balance both electron and hole.

2.2.1 Charge carriers in semiconductor

Current defined as the rate at which charge flow. In a semiconductor, two types of charge carrier, the electron and the hole, can contribute to a current. Since the current in a semiconductor is determined largely by the number of electrons in the conduction band and the number of holes in the valence hand, an important characteristic of the semiconductor is the density of these charge carriers. The density of electrons and holes is related to the density of states function and the Fermi distribution function, both of which we have considered. A qualitative discussion of these relationships will be followed by a more rigorous mathematical derivation of the thermal-equilibrium concentration of electrons and holes[50]. These are two types of charge carriers in semiconductors; namely

1. Conduction-band electrons and
2. Valence-band holes,

An isolated the semiconductor crystal is electrically neutral. The charge-neutrality condition is used to determine the thermal equilibrium electron and hole concentration as a function of impurity doping concentration. Although the term electrons can be used in conjunction with the valence band as in "nearly all the energy states in the valence band are filled with electrons," we should assume that the term usually means conduction-band electrons; the

density of electrons is related to the density of state function and Fermi-Dirac distribution function is given as[50,55].

$$n(E)dE = g_c(E)f_F(E)dE, \tag{2}$$

where $f_F(E)$ is the Fermi-Dirac Probability,$g_c(E)$ is the density of quantum states in conduction band (CB), $n(E)dE$ is density of electrons in CB at energy levels between E and $E + dE$. Holes are the electron voids in the valence band. Electrons and holes carry negative and positive charge ($\mp q$) respectively [52] . $p(E)dE$ is also the density of holes is related to the density of state function and Fermi-Dirac distribution function by the relation:

$$p(E)dE = g_v(E)\big(1 - f_F(E)\big)dE, \tag{3}$$

where $f_F(E)$ is the Fermi-Dirac Probability, $g_v(E)$ is the density of quantum states in Valance band (VB), $p(E)dE$ is density of holes in VB at energy levels between E and $E + dE$.

An equation that is highlighted with a box, such as Eqn. (2) is particularly important and often cited. Eqns.(2) is the Fermi function, or the Fermi–Dirac distribution function, or the Fermi–Dirac statistics. E_f is called the Fermi energy or the Fermi level. $f_F(E)$ is the probability of a state at energy being occupied by an electron[56]:

$$n_0 = \int_{E_C}^{TOP} n(E)dE = \int_{E_c}^{Top} g_c(E)f_F(E)dE, \tag{4}$$

where

$$f_F(E) = \frac{1}{1 + exp\left(\frac{E-E_F}{k_BT}\right)} \quad \text{and} \quad g_c(E) = \frac{4\pi(2m_n^*)^{3/2}\sqrt{E - E_C}}{h^3}. \tag{5}$$

m_n^* is the density of state effective mass of electrons. For electron in CB, $E > E_c$and $\left(E - E_f\right) \gg k_BT$, then $f_F(E)$ for is symmetrical. That is:

$$f_F(E) = exp\left(-\frac{E - E_F}{k_BT}\right), \qquad (\text{Maxwell} - \text{Boltzmann Distribution}). \tag{6}$$

So, inserting Eqns.(5) and (6)insert in Eqn.(4) To give as yields:

$$n_0 = \int_{E_c}^{Top} \frac{4\pi(2m_n^*)^{3/2}\sqrt{E - E_c}}{h^3} \exp\left(\frac{-(E - E_F)}{k_BT}\right) dE. \tag{7}$$

We define effective number density of accessible states at the conduction band bottom density of states in CB (N_c) is given by:

$$N_c = 2\left[\frac{2\pi m_n^* k_B T}{h^2}\right]^{\frac{3}{2}}. \tag{8}$$

The thermal–equilibrium of electron concentration in CB (n_0) is given by:

$$n_0 = N_c \exp\left(-\frac{(E_c - E_F)}{k_B T}\right). \tag{9}$$

If we assume a quasi-neutrality condition in which the electron concentration is almost equal to the donor impurity concentration, since $n_0 > p_0$, the semiconductor is *n*-type. In an *n*-type semiconductor, electrons are referred to as the majority carrier and holes as the minority carrier[39,40].

The thermal–equilibrium of hole concentration in VB (p_0)is given by [56]:

$$p_0 = \int_{E_c}^{Top} p(E)dE = \int_{E_c}^{Top} g_v(E)[(1 - f_F(E))]\, dE, \tag{10}$$

where

$$g_v(E) = \frac{4\pi\left(2m_p^*\right)^{\frac{3}{2}}\sqrt{E_V - E}}{h^3} \tag{11}$$

For hole in VB,$E < E_V \Rightarrow (E_V - E \gg k_B T)$, so that:

$$1 - f_F(E) = 1 - \frac{1}{1 + \exp\left(\frac{-(E - E_f)}{kT}\right)} = \exp\left(\frac{-\left(E_f - E\right)}{kT}\right).$$

So , Eqn. (10) and insert is simplified as:

$$p_0 = \int_0^{E_V} \frac{4\pi(2m_p^*)^{3/2}}{h^3}\sqrt{E_V - E}\exp\left(\frac{-\left(E_f - E\right)}{kT}\right)dE, \tag{12}$$

where

$$N_V = 2\left[\frac{2\pi m_p^* k_B T}{h^2}\right]^{\frac{3}{2}}. \tag{13}$$

N_V is the effective number density of accessible states at the valence band top of state in VB. The thermal–equilibrium of hole concentration in VB (p_0) gives as:

$$p_0 = N_V \exp\left(-\frac{(E_F - E_V)}{k_B T}\right). \tag{14}$$

Similarly, If we assume a quasi-neutrality condition in which the hole concentration is almost equal to the accepter impurity concentration, $p_0 > n_0$ in a p-type semiconductor, where holes are the majority carrier and electrons are the minority carrier[39,40].

2.2.2 Intrinsic semiconductor

Intrinsic semiconductor which is usually referred to as are the pure un-doped semiconductor, A semiconductor may be considered as an intrinsic semiconductor if its thermally generated carrier density represented by n_i is much larger than the background doping or residual impurity densities. At T = 0K, 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 [58,60]. In intrinsic semiconductor, the concentration of electron in CB is equal to the concentration of hole in VB:

$$n_0 = n_i = N_C \exp\left(-\frac{(E_C - E_i)}{k_B T}\right) = p_0 = N_V \exp\left(-\frac{(E_i - E_V)}{k_B T}\right) \quad (15)$$

For intrinsic carrier concentration is a function of band gap, independent of Fermi level. The intrinsic carrier concentration is nearly increased exponentially with temperature. Are determined by the parameters of effective masses and the effective mass is nearly a constant value (a slight function of temperature) for a semiconductor, which implies the N_c and N_V will increase in values with power of with increasing temperature. Assume m_n^*=m_0, then the value of the density of the effective density of State at 300K is which is lower the density of atoms in semiconductor. The effective mass of the semiconductor is larger or smaller than m_0 (Rest mass of the electron) but still of the same order of magnitude [10, 11].

2.2.3 Extrinsic semiconductor

Extrinsic semiconductor, which is usually referred to as are the doped semiconductor. The electrical conduction of an extrinsic semiconductor it is usually dominated by either electrons or holes, depending on whether the semiconductor is doped with shallow donors or shallow acceptor impurities[46].Their electrical conductivity can be readily changed by many orders of magnitude by simply doping. By cooperating the doping impurities into a semiconductor, the electron or hole density will increase with increasing impurity concentrations. For example,

electron or hole densities can increase from $10^{13}cm^{-3}$ to more than $10^{20}cm^{-3}$ if a shallow-donor or shallow-acceptor impurity are added [37,38].The product n_0p_0 product is one of the fundamental principles of the semiconductor; from charge neutrality of the mass action law is yield to as:

$$n_i^2 = n_0p_0 = N_cN_V\exp\left(-\frac{(E_c - E_V)}{k_BT}\right) \tag{16}$$

Or

$$n_i = \sqrt{N_cN_V}\exp\left(\frac{-E_g}{k_BT}\right). \tag{17}$$

The exponential dependence of n_0p_0 on the temperature is the chief mechanism determining the temperature dependence of the electrical conductivity of semiconductors.

The intrinsic Fermi-level position can be determined considering the $n_0 = p_0$, which can be denoted as, we in Eqn. (15) as:

$$N_c\exp\left(-\frac{(E_c - E_i)}{k_BT}\right) = N_V\exp\left(-\frac{(E_i - E_V)}{k_BT}\right). \tag{18}$$

We obtained intrinsic energy level semiconductor, the thermal concentration of electron in CB (n_0) is equal to the thermal concentration of hole in VB (p_0) which gives:

$$E_i = \frac{E_c + E_v}{2} + \frac{3}{4}k_BT\ln\left(\frac{m_p^*}{m_n^*}\right). \tag{19}$$

The intrinsic Fermi level must shift away from the band with the larger density of states in order to maintain equal numbers of electrons and hole.

$$E_F = E_i - k_BT\ln\left(\frac{p_0}{n_i}\right) = E_i + k_BT\ln\left(\frac{n_0}{n_i}\right). \tag{20}$$

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. Eqns. shows that E_F lies above E_i *for* n-type material *(*$n_i > p_0$*)* and below E_i for p-type material ($n_i < p_0$).

2.3 Photo-Response of Semiconductors

The interaction of light with matter can be viewed macroscopically as consisting of four components: incident, reflected, transmitted and absorbed (or scattered) components. The

photo-response of the material hence can be measured through the change in the photoconductivity due to the absorbed photons and/or by comparing the intensities of the scattered longitudinal optical (L_0) phonon mode and the L_0 phonon-hole Plasmon coupled mode (L^-). In this section, the concepts of photon absorption and the effects it has on the photo-response of the materials will be described in detail [63].

2.3.1 Photon absorption in semiconductors

The band gap is a major factor determining the electrical conductivity of a solid. A photon can excite an electron from an occupied state in the valence band to an unoccupied state in the conduction band. This is called an inter band transition, this process is called photon is absorbed. The term "photo-conductivity" refers to a change in conductivity of a semiconductor when illuminated by photons. The generation of excess electron-hole pairs in a semiconductor is known as the injection of excess carriers[58,59]. At thermal equilibrium, the valence band contains many electrons and the conduction band has many empty states into which electrons may be excited. When photons with energies equal to or greater than the band gap are incident on semiconductor materials, the photons are absorbed by the formation of electron-hole pairs. While the photo-generated carriers exist in their respective bands, they are free to contribute to the conductivity of the material. The electron-hole pairs generated by photon absorption are known as photo-generated carriers. In the case of a pure semiconductor, photons with energy less than the band gap energy will not be enough to excite an electron from the valence band to the conduction band and it will pass through the semiconductor without being absorbed [65,68].

2.3.2 Photon absorption in Bulk semiconductor

The gallium antimonide ($GaSb$) with a model known as length, width and infinitely large thickness denoted by ℓ, w and Δx in respectively. Figure 2-7 illustrate the photon Absorption in infinitely thick semiconductors or bulk semiconductors ($\Delta x \to \infty$) the total photon flux density absorbed in the sample of semiconductors, $\Delta\Phi$ is yield as:

$$\Delta\Phi = \Phi_0(1 - R). \tag{21}$$

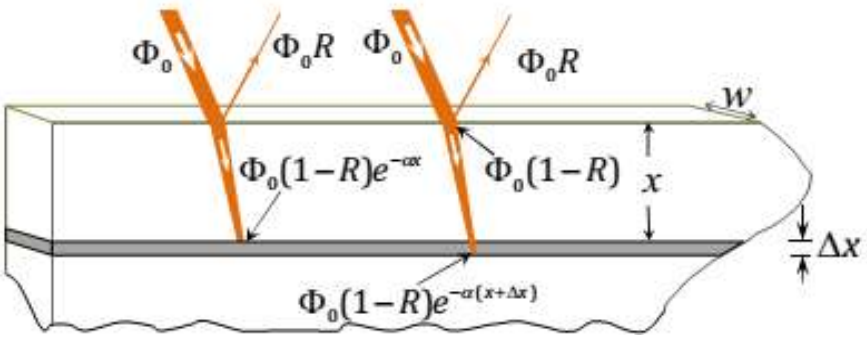

Figure 2-7: Photon Absorption in an infinitely thick semiconductor.

The photon absorption rate (G_0) in the entire volume of the given illuminated area (A) and thickness (Δx) is defined as the total number of absorbed photons per unit volume per unit time:

$$G_0 = \frac{\Delta N_{Ph}}{A\Delta x\Delta t} = \frac{\Delta\Phi}{\Delta x}, \tag{22}$$

where ΔN_{Ph} is the number of absorbed photons, Δt the time and $\Delta\Phi$ the absorbed photon flux density is gives as:

$$\Delta\Phi = \frac{\Delta N_{Ph}}{A\Delta t}, \tag{23}$$

where photon absorption in infinitely thick semiconductors or bulk semiconductors$(\Delta x \to \infty)$ the photon absorption rate (G_0) in bulk semiconductors is defined as the total number of absorbed photons per infinitely thick semiconductors as:

$$G_0 = \frac{\Phi_0(1-R)}{\Delta x}. \tag{24}$$

As the beam passes through the sample, the photon flux density at some distance x from the surface can be calculated by considering the probability of absorption within any infinitesimal thickness dx. The photon absorption rate at depth x for a given wavelength is also proportional to the photon flux density, $\Phi(x)$, remaining at x after being absorbed in a material.

$$G_0 = \frac{d\Phi(x)}{dx} = -\alpha\Phi(x), \tag{25}$$

Taking into account the reflection of a photon flux density $\Phi_0 R$ back to the vacuum or air, the photon flux density entering the illuminated surface is given by the difference between the incident and the reflected photon flux densities obtained:

$$\Phi_s(0) = \Phi_0(1 - R). \quad (26)$$

where α is a constant called the absorption coefficient, which is related to the dielectric properties of the material and the wavelength of the incident photon. The negative (-) sign in Eqns. (25) indicates the decrease of G_0 with increasing x. The value of the absorption coefficient is determined using its dependence on the photon energy, analyzed by (*Bardeen et al*) as.

$$\Phi(x) = \Phi_0(1 - R)e^{-\alpha x}. \quad (27)$$

The solution for Eqn. (27) at a distance x below the illuminated surface, using the boundary condition in Eqn. (27) is known as *Beer's law*. It represents the total photon flux density as a function of distance x below the illuminated surface. For $GaSb$, the refractive index was taken as 3.8. This results in a typical value of $R = 0.34cm$. Eqns. (25) and Eqn. (27) yield the photon absorption rate for different wavelengths as. The general photon absorption rate per incident photon for some distance of bulk semiconductors is yield as:

$$\frac{G_0(\alpha, x_p)}{\Phi_0} = \alpha(1 - R)e^{-\alpha x_p}, \quad (28)$$

Or

$$G_0(\alpha, x_p) = \Phi_0\alpha(1 - R)e^{-\alpha x_p}.$$

The photon absorption rate in Eqn. (28) also depends on the absorption coefficient α. The linear term dominates for lower values of α, while the exponential term dominates for higher values of α. It has a maximum value for intermediate values of α, which can be found by differentiating Eqn. (28) with respect to α and equating it to 0:

$$\frac{dG_0(\alpha, x_p)}{d\alpha} = (1 - \alpha x)\Phi_0(1 - R)e^{-\alpha x_p} = (1 - \alpha x)\Phi(x) = 0.$$

The photon flux density $\Phi(x)$ cannot be zero at all points inside the material, and therefore absorption coefficient is inversely proportional to thickness. So $\alpha = 1/x_p$. this defines a depth x_p below the illuminated surface where the maximum absorption rate occurs for a specific absorption coefficient (i.e. photon wavelength). The depth (x_p) at which $G_0(\alpha, x_p)$, has a maximum value for a given photon energy is called the penetration depth x_p of that photon is given by $x_p = \frac{1}{\alpha}$.

2.4 Optical generation-recombination rate of Free Carriers

Recombination of electrons and holes is a process by which both carriers annihilate each other. To combine again, to refill a hole with an electron, Electrons occupy–through one or multiple steps-the empty state associated with a hole. Both carriers eventually disappear in the process [59]. The energy difference between the initial and final state of the electron is released in the process, this leads to one possible classification of the recombination processes. In the case of radiative recombination, this energy is emitted in the form of a photon. In the case of non-radiative recombination, it is passed on to one or more phonons and in Auger recombination it is given off in the form of kinetic energy to another electron. Recombination of charge carriers is the opposite of generation of charge carriers, representing mechanisms that reduce the excess charge density [49,63, 65].

2.4.1 Generation of electron-hole pairs

When photons with energies equal to or greater than the band gap energy are absorbed in a semiconductor, electron-hole pairs are generated. The excess charge carriers generated by absorption of photons are known as photo-generated carriers. The photo-generated carriers can dominate the conduction processes in the semiconductor material. Because of the existence of two types of charge carriers in semiconductors, excess carriers can be created in the bulk without introducing any significant space charge [49,52]. A large concentration of excess carriers can hence be maintained in a semiconductor under non-thermal equilibrium conditions, and this alters the conduction properties of the specimen. If each electron-hole pair (EHP) is generates by the incident photon, the relation between the rate of absorption of photons and the rate of generation of EHPs in the material [45,51]. In addition, there are generation mechanisms, which do not have an associated recombination mechanism: generation of carriers by light absorption or a high-energy electron or particle beam. These processes are referred to as ionization processes. Impact ionization, which is the generation mechanism, associated with Auger recombination also belongs to this category [59,60]. The generation mechanisms are illustrated with Figure 2-8.

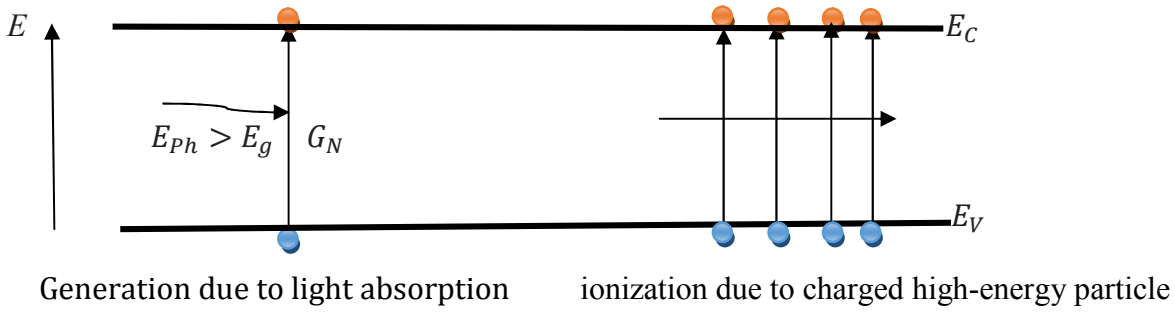

Figure 2-8: Carrier generation due to light absorption and ionization due to high-energy particle beams.

Carrier generation due to light absorption occurs if the photon energy is large enough to lift an electron from the valence band into an empty conduction band state, generating one electron-hole pair. The photon energy needs to be larger than the band gap energy to satisfy this condition [59]. Carrier generation or ionization due to a high-energy beam consisting of charged particles is similar except that the available energy can be much larger than the band gap energy so that multiple electron-hole pairs can be formed. The high energy particle gradually loses its energy and eventually stops. This generation mechanism is used in semiconductor-based nuclear particle counters [57,59].

2.4.2 Recombination mechanisms in the bulk semiconductors

Bulk semiconductors are material that is solid in bulk that can be used to make semiconductors. The energy of photon(E_{photon}) less than the energy of band gap (E_g), the incident photon directly passes through the material, the material is said to be transparent photon. Once electron–hole pair are not produced and also electron–hole pair are not generated or absorbed. Photon absorption rate also depends on the absorption coefficient α and thickness [22].

PC can be used to determine energy levels, concentration. When a semiconductor absorbs a photon of energy greater than the band gap, and an electron is excited from the valence band into the conduction band leaving behind a hole of impurities, defects and fundamental properties of semiconductors [10,11]. Photoconductivity materials are characterized primarily on the basis of the Mechanism involved in (1) inter band transitions, (2) transition including Impurities or defects and (3) hot carrier intra band transitions. The first category is further broken down into near band edge band-to-band transition, and hot carrier Band-to-band

transition. Second category consists of conduction band to acceptor Level, donor level to valance band, donor to acceptor level transition, free and bound exciton transition, and deep level transition. All these transitions could result in the Emission of photon [57,58]. These different processes are further illustrated with Figure 2-9. Whether this is likely or not depends on both the transition mechanism and the material[21,22]. The generated charge carriers can recombine in two categories.

1. Radiatively recombination,
2. Non-radiatively recombination.

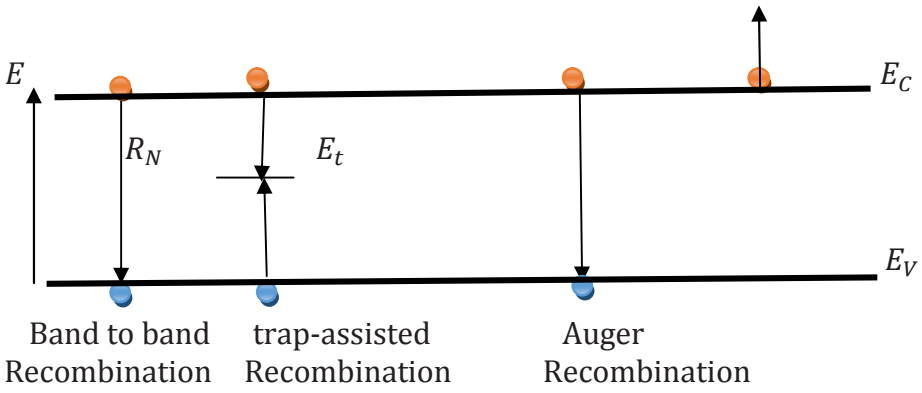

Figure 2-9: Carrier recombination mechanism in semiconductors.

Radiative recombination is the opposite of optical generation of charge carriers. When the electron returns to its original state, it may do so through radiative (release of a photon). It occurs when the energy of the excited electron is emitted by the formation of a photon during the annihilation of an EHP [14,16]. Non-radiative recombination occurs when excess energy is released as phonons or transferred as excess kinetic energy to another charge carrier,(*i.e.* the excess energy is dissipated as heat during the recombination process), When the electron and hole recombine through radiative recombination a photon is emitted and the energy of the emitted photon is dependent on the change in energy state of electron-crystal system[16,18].There are three main mechanisms recombination of electron–hole pair in the bulk of a semiconductors, namely 1.Radiative (relating to τ_R) recombination mechanisms and 2.Auger (relating to τ_A) 3.Shockley Read Hall recombination mechanisms or thermal recombination (SRH relating to τ_{SRH}) recombination mechanisms.

A) Radiative Recombination

Radiative recombination refers energy lost to photon or Band-to-band recombination occurs when an electron falls from its conduction band state into the empty valence band state associated with the hole, this band-to-band transition is typically also a radiative transition in direct band gap semiconductors [44,45]. If an Electron and hole recombine across the band gap, then a photon is released. A photon with energy near a semiconductor band gap has almost zero momentum. This important process is called radiative recombination, where an electron in the conduction band annihilates a hole in the valence band, releasing the excess energy as a photon. Radiative recombination involves the annihilation of electron-hole pairs by giving out a photon of energy equal to the energy gap between the levels where the two carriers were in before recombination[25,26,63]. If the electron has a k-vector near the conduction band minima (the hole will share the same k-vector), but not possible in an indirect band gap semiconductor, as photons cannot carry crystal momentum, and thus conservation of crystal momentum would be violated. Both carrier types need to be available in the recombination process. Therefore, the rate is expected to be proportional to the product of n and p. Also, in thermal equilibrium, the recombination rate must equal the generation rate since there is no net recombination [46,47].

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 (v_{th})[2,23]: 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:

$$C_R = \sigma_R v_{th} = \frac{8\pi k_\infty}{c^2} \int_0^\infty \frac{\alpha(v) v^2 dv}{\exp(\frac{hv}{k_B T}) - 1}, \tag{29}$$

where $\alpha(v)$ is the absorption coefficient, h is Planck's constant and c is the speed of light. Values of C_R can be obtained by numerical integration of Eqn.(29) for narrow band gap semiconductors as [2, 26]:

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

where $E_g$and k_BT are in electron volt (eV) and radiative recombination coefficient between $10^{-5}cm^3s^{-1}$ and $10^{-11}cm^3s^{-1}$.

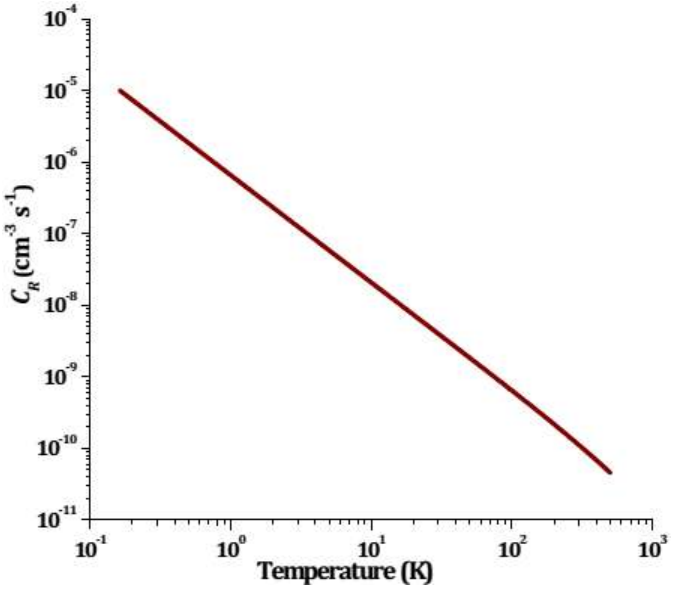

Figure 2-10: Radiative recombination coefficient as function of temperature for GaSb.

for large band gap materials where $E_g \gg k_BT$ only the E_g^2 term is needed. Figure 2-10 shows the radiative recombination coefficient as function of temperature. As we observed from the figure the radiative coefficient decreases with temperature increases and increases as the temperature decreases, Since $E_g \gg k_BT$ the term E_g^2 is dominant in this case as predicted.

In thermal equilibrium the electron-hole product is equal to intrinsic carrier concentration squares $(n_0p_0 = n_i^2)$(the law of mass action)[11]. But, in non- thermal equilibrium electron-hole densities,$(np > n_i^2)$and the net excess carrier charge concentration is difference b/n non-thermal equilibrium and thermal equilibrium is given by:

$$\delta n = n - n_0, \quad \delta p = p - p_0. \tag{31}$$

The Radiative recombination rate(U_R), depends on the concentration of free electrons (n) and holes (p) is obtained as follows. The net excess carrier recombination rate (U_R) is defined as the difference between the total recombination rate and the thermal equilibrium generation rate is result as [24].

$$U_R = C_R(np - n_i^2), \tag{32}$$

Inserting non-Thermal equilibrium concentration $n = n_0 + \delta n$ and $p = \delta p + p_0$ into Eqn. (31) and (Assume the charge neutrality, (i.e $\delta n = \delta p$)), following general expression for radiative recombination rate, U_R, is given by:

$$U_R = C_R \delta n(\delta n + p_0 + n_0). \tag{33}$$

Radiative carrier lifetime defined as the excess carrier charge of electron concentration (δn) divided by the net excess radiative recombination rate (U_R).It obtained, the general form of carrier lifetime for the radiative recombination with injection level is result as:

$$\tau_R = \frac{\delta n}{U_R} = \frac{1}{C_R(n_0 + p_0 + \delta n)}, \tag{34}$$

Under low injection condition, $\delta n \ll n_0$ and $\delta p \ll p_0$,where the excess carrier lifetime under low injection or doped for the radiative recombination under thermal equilibrium is yields:

$$\tau_{R0} = \frac{1}{C_R(n_0 + p_0)}. \tag{35}$$

The injection level dependence of radiative excess carrier lifetime, τ_R,takes the form:

$$\tau_R = \frac{\delta n}{U_R} = \frac{\tau_{R0}}{1 + C_R \tau_{R0} \delta n}. \tag{36}$$

B) Auger recombination

Auger recombination to refers energy lost to other carrier–other electron or hole ,but not both for one event or a process in which an electron and a hole recombine in a band-to-band transition, but now the resulting energy is given off to another electron or hole. The involvement of a third particle affects the recombination rate so that we need to treat Auger recombination differently from band-to-band recombination [57,55]. Auger recombination processes in semiconductors are band-to-band processes where the excess energy–set free during the recombination of an electron and a hole is transferred to a third charge (current) carrier. There are two types of Auger recombination mechanism depending on their carrier concentration coefficient.

I. Electron Auger capture coefficient

The dominant Auger process in n-type material is band-to-band Auger recombination, called the Auger 1 (CHCC) process, in which a conduction band electron recombines with a heavy hole (C-H) and a conduction electron is excited to a higher energy level (C-C). This

mechanism is developed by Beattie and Landsberg for InSb like band structures. The Auger 1 electron capture coefficient is given by [60, 63]:

$$C_{na} = \frac{8e^4(2\pi)^{\frac{5}{2}}}{h^3(4\pi\epsilon n_i)^2}\left(\frac{m_n^*|F_1F_2|^2}{(1+2\mu)\sqrt{1+\mu}}\right)\left(\frac{k_BT}{E_g}\right)^{\frac{3}{2}}\exp\left[-\left(\frac{1+2\mu}{1+\mu}\right)\frac{E_g}{k_BT}\right],$$

where μ is the ratio of conduction to heavy-hole valence band effective mass, ϵ is the permittivity of the material F_1,and F_2 are the overlap integrals of the periodic part of the electron wave functions, with constant practical value of $|F_1F_2|$ between 0.1 and 0.3. Several authors reported the value of C_{na} in n-type GaSb to be of the order of$10^{-(29\pm1)}\text{cm}^6\text{s}^{-1}$.

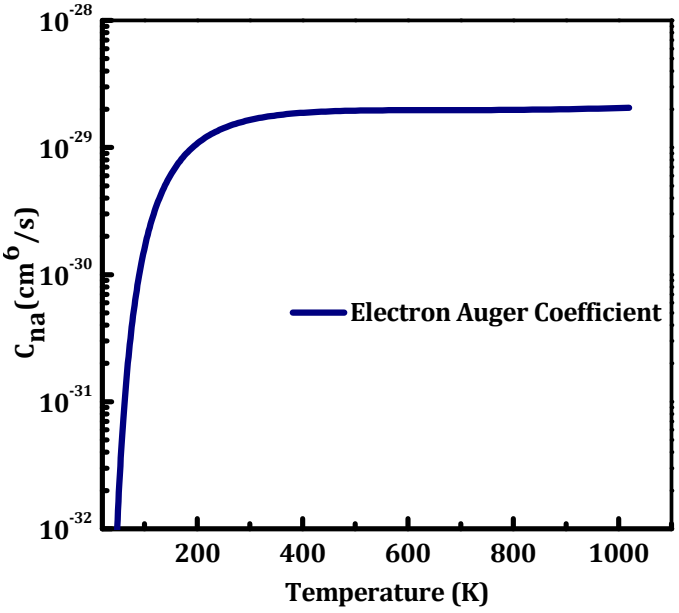

Figure 2-11: Temperature dependence of the Electron Auger recombination coefficient.

Figure 2-11 shows the temperature dependence of the Auger recombination coefficient for the conduction band electron recombines with a heavy hole (C-H) and a conduction electron is excited to a higher energy level (C-C) is described. A maximum Auger recombination coefficient exists, with a strong decrease at low temperatures and remains constant at higher temperatures, as shown in this figure. Since it is constant from 500K to 900K.Since C_{na} is dominant in p-type GaSb[40].

II. Hole Auger capture coefficient

The dominant recombination mechanism in p-type GaSb and other small band gap materials at relatively higher injection level is the band-to-band Auger S (CHHS) process, in which a heavy hole recombines with a conduction band electron (C-H) and a heavy hole is

excited to the spin-orbit split off the valence band (H-S). Benz and Conradt determined a very high CHHS hole capture coefficient of $10^{-(25\pm1)}\text{cm}^6\text{s}^{-1}$ by measuring the excitation and doping dependence of the luminescence produced by the recombination of Auger excited holes. The result, however, relied on an estimation of the internal quantum efficiency of the recombination luminescence. Titkov et al. also derived a significantly smaller Auger coefficient of $2.5\text{x}10^{-29}\text{cm}^6\text{s}^{-1}$ for degenerate p-type GaSb using an optical orientation method. The Auger coefficient due to Auger S (CHHS) used in this work is calculated using Haug's formula. Haug reported that, because the values of E_g and the valence band splitting $\Delta E_{os}$are nearly equal, Auger recombination due to valence band splitting seems to be favoured in GaSb. The Auger process, which involves the spin-split-off valence band (CHHS), is very efficient, since energy and wave vector conservation allow 'vertical' transitions in k-space. The corresponding Auger capture coefficient for holes in the case of non-degenerate carrier densities (Boltzmann statistics) is given by [4, 63]:

$$C_{pa} = \begin{cases} ABx^2e^2\dfrac{2}{\sqrt{\pi}}\left[\Gamma\left(\dfrac{5}{2},\mu x\right)\right] - \dfrac{2\Gamma\left(\frac{7}{2},\mu x\right)}{\mu x} + \dfrac{\Gamma\left(\frac{9}{2},\mu x\right)}{\mu x}, & \text{for } E_g \geq \Delta E_{os}, \\ AB\left[\dfrac{35}{(2\mu x)^2}\right], & \text{for } E_g = \Delta E_{os} \\ ABx^2e^2\dfrac{3}{2}\left[1 - \dfrac{5}{\mu x} + \dfrac{35}{(2\mu x)^2}\right], & \text{for } E_g \leq \Delta E_{os}, \end{cases}$$

where

$$\begin{cases} x = \dfrac{E_g - \Delta E_{os}}{k_B T}, \quad \mu = \dfrac{2m_P^* + m_C^*}{2m_P^* + m_C^* - m_{S0}^*}, \quad \Gamma(a, x_o) = \displaystyle\int_{x_o}^{\infty} e^{-t}\, t^{a-t} dt \\ A = \dfrac{h^3 e^4}{(2m_n k_\infty)^2}\left(\dfrac{m_P^*}{m_V^*}\right)\left(\dfrac{m_{SO}^*}{2m_P^* + m_C^*}\right)^{\frac{3}{2}}, \quad B = \dfrac{E_p^2\left(1 + \frac{m_{SO}^*}{m_n}\right)}{9E_g^2\Delta E_{0S}^2\left(E_g + \Delta E_{0S}\right)}. \end{cases}$$

The parameter $\Gamma(a, x_o)$is the incomplete gamma function, $m_{c,p,s}^*$ the effective masses of the corresponding bands, m_V the density-of-states mass of the valence band and $E_p$is the square of the momentum matrix element, multiplied by $2/m_n$and its value is 22.4eV.

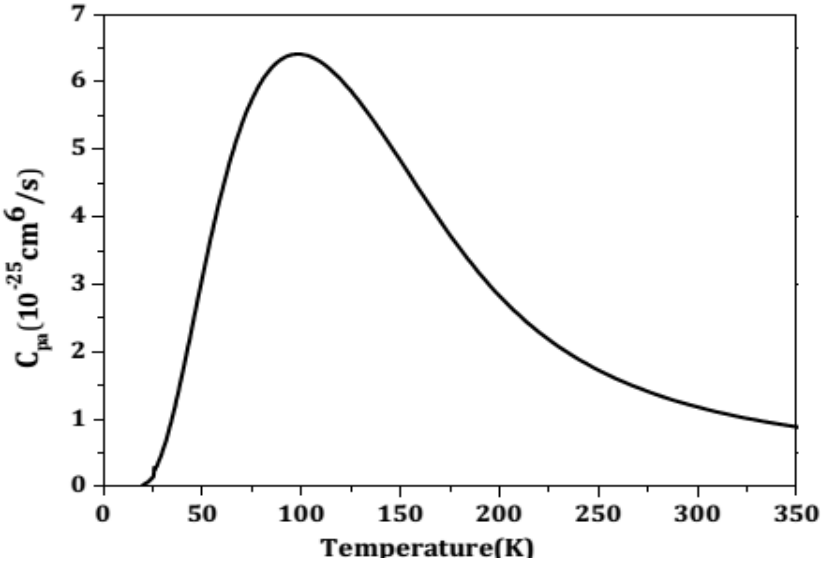

Figure 2-12: Temperature dependence of the Auger recombination coefficient.

Figure 2-12 depicts the temperature dependence of the Auger recombination coefficient for the spin split-off valence band described. According to Haug, a maximum Auger Recombination Coefficient (C_{pa}) exist, decreases strongly for lower temperatures whereas the decrease is weaker for higher temperatures, as shown in this figure. The maximum value of a temperature is approximately at T = 95K to T = 100K. The auger coefficient of electron and hole through experimentation this value has been determined to be between $10^{-26}cm^6s^{-1}$ and $10^{-32}cm^6s^{-1}$ [11]. Auger recombination is viewed as a three particle interaction where a conduction band electron and a valence band hole recombine, with the excess energy being transferred to a third free electron or hole. The charge carriers involved are assumed to be non-interacting quasi-free particles. The eeh process denotes when the excess energy is transferred to another electron, with the recombination rate given by ($U_{eeh} = C_{na}n^2p$).Similarly, the ehh process denotes when the excess energy is transferred to another hole, with recombination rate given by($U_{ehh} = C_{pa}p^2n$)[23].This is a three-particle process, which involves either an electron-electron collision in the conduction band, followed by recombination with a hole in the valence band; or a hole-hole collision in the valence band, followed by recombination with an electron in the conduction band [47]. The total recombination mechanism rate and its carrier lifetimes are taken by the following equations, the total Auger recombination rate under non thermal equilibrium condition, (R_A), is given by:

$$R_A = U_{eeh} + U_{ehh} = C_{na}n^2p + C_{pa}p^2n, \quad (36)$$

where p and n are the hole and electron concentrations in respectively, C_{na} are Auger recombination coefficients of electron, C_{pa} is the Auger recombination coefficient of holes [49].The rate of Auger recombination under thermal equilibrium generation rate condition can be written as:

$$R_{th} = G_{th} = C_{na}n_0^2p_0 + C_{pa}p_0^2n_0, \tag{37}$$

Therefore, the net Auger Recombination rate defined as the difference b/n band to band Auger recombination rate under non-thermal and thermal equilibrium condition is result as under steady-state condition can be obtained Eqns. (36) and (37) which gives:

$$U_A = R_A - G_{th} = C_{pa}(p^2n - p_0^2n_0) + C_{na}(n^2p - n_0^2p_0), \tag{38}$$

Where inserting Eqns. $n = n_0 + \delta n$ and $p = p_0 + \delta p$ into Eqn. (38), we obtained as:

$$\begin{aligned} U_A = {} & C_{pa}((p_0^2+2p_0\delta p + \delta p^2)(n_0 + \delta n) - p_0^2n_0) + \\ & C_{na}((n_0^2+2n_0\delta n + \delta n^2)(p_0 + \delta p) - n_0^2p_0), \end{aligned} \tag{39}$$

Since, the charge neutrality assume (i.e $\delta n = \delta p$) and from the Law of action mass($n_0p_0 = n_i^2$) to obtain the general form auger recombination rate (U_A) is yield as:

$$\begin{aligned} U_A = {} & \delta n(C_{pa}(p_0^2 + 2p_0\delta n+\delta n^2) + 2n_i^2(C_{pa} + C_{na}) + C_{pa}n_0\delta n \\ & +C_{na}(n_0^2 + 2n_0\delta n + \delta n^2) + C_{na}p_0\delta n). \end{aligned} \tag{40}$$

Auger carrier lifetime defined as the excess carrier charge of electron concentration (δn) divided by the net excess auger recombination rate (U_A). It obtained, the general form of carrier lifetime for the Auger recombination carrier lifetime with injection level is result as:

$$\tau_A = \frac{\delta n}{U_A},$$

$$\tau_A = \frac{1}{(C_{pa}(p_0^2 + 2n_i^2) + C_{na}(n_0^2 + 2n_i^2) + (C_{pa}(2p_0 + n_0)+C_{na}(2n_0 + p_0))\,\delta n + (C_A)\delta n^2)}, \tag{41}$$

where $C_A = C_{pa} + C_{na}$ and $k_A = C_{pa}(2p_0 + n_0) + C_{na}(2n_0 + p_0)$.under low injection level , $\delta n \ll n_0$ *and* p_0, where the band-to-band Auger carrier lifetime under thermal equilibrium is yield as:

$$\tau_{A0} = \frac{1}{C_{pa}(p_0^2 + 2n_i^2) + C_{na}(n_0^2 + 2n_i^2)}. \tag{42}$$

Next, depend on injection level, we wish to evaluate the steady-state description of δn and τ_A for the optically generated excess carriers. If the Auger recombination rate is dominant in the material at steady state the net recombination rate is equal to the optical generation rate of excess carriers. So that in excess carrier charge concentration electron in terms of Auger recombination carrier lifetime with absorption photon rate for bulk semiconductors is given by ($\delta n = G_0\tau_A$).

$$G_0 \approx U_A \approx \frac{\delta n}{\tau_{A0}} + k_A\delta n^2 + C_A\delta n^3, \delta n = \frac{-k_A}{3C_A} + \sqrt[3]{\frac{B}{2} + \sqrt{\frac{B^2}{4} + \frac{A^3}{27}}} - \sqrt[3]{\frac{-B}{2} + \sqrt{\frac{B^2}{4} + \frac{A^3}{27}}},$$

where $A = \frac{1}{C_A\tau_{A0}} - \frac{{k_A}^2}{3{C_A}^2}$, $B = \frac{G_0}{C_A} + \frac{k_A}{3C_A}[A + \frac{{k_A}^3}{9{C_A}^2}]$.

The injection level dependence of Auger excess carrier lifetime, τ_A,takes the form:

$$\tau_A = \frac{\tau_{A0}}{1 + \tau_{A0}(k_A\delta n + C_A\delta n^2)}. \quad (43)$$

C) Shockley Read Hall (SRH) Recombination

Shockley read hall refers energy lost lattice in the form of phonon or Trap-assisted recombination occurs when an electron falls into a "trap", an energy level within the band gap caused by the presence of a foreign atom or a structural defect. SRH recombination refers to recombination of carriers that are a direct result of Defect trap sites. A trap is located in the forbidden region of the energy band between the valence band and conduction band. Once an electron falls into a trap, it is unavailable to carry charge it will remain in the trap until it loses energy and falls back to the valence band and recombines, there is also the option that it may gain energy and be promoted back to the conduction band (particularly if the trap is located at an energy level just below the conduction band). Since only one carrier can reside in a trap in a given period this type of recombination is usually dominant at lower carrier densities, when the ratio between number of traps and carriers is closer [63,67]. In Shockley-Read-Hall (SRH) recombination, the recombination of EHPs may take place at localized traps with states in the band gap of the material. This process involves the capture of electrons from the conduction band (or holes from the valence band) by the trap, followed by the recombination with holes in the valence band (or electrons in the conduction band). When EHPs recombine, energy is

released through phonon emission and the localized state is called the recombination centre. If the localized state captures free carriers temporarily and then reemits them back to their original band, the centre is called a free carrier trap. The localized trap states may be created by deep impurities, dislocations, radiation defects, grain boundaries, point defects and their complexes [55].there are four transition processes for the capture and emission of electron and holes via versa the localized state are shown in 2-13. The probability of Capture and emission of the electron by the centre are represented by U_{cn} and U_{en} , and the probability of hole capture and emission are described by U_{cp} and U_{ep}, in respectively. When occupied by an electron, the trap level is in the n_T state, and when occupied by a hole it is in the p_T state. After the electron has been emitted, the centre finds itself in the p_T state and subsequently emits a hole, returning to the n_T state, and then the cycle repeats. Just like a donor level, if the n_T state is neutral, then p_T is positively charged, and vice versa. The localized states are spatially distributed throughout the volume of the semiconductor, so that n_T, p_T and the total density of the localized state N_T are given as a number per unit volume [53,54]. The total density of the trap levels occupied by electrons, n_T, and holes, p_T ,must equal the total density of traps N_T Under non-thermal equilibrium is yield as:

$$N_T = n_T + p_T. \tag{44}$$

In other words, a centre is either in a neutral or negatively charged state, or in a neutral or positively charged state. When electrons and holes recombine (or are generated), the electron density *n* in the conduction band, the hole density *p* in the valence band, and the charge state of the trap centre are all functions of time. The rate equations of free and trapped charge carriers, which describe the SRH model, can be derived from the four emissions and capture processes illustrated in Figure 2-13:The distribution probability (f_n) for the electron occupation of a trap located at energy E_T in the band gap is derived using Fermi-Dirac statistic[68]:

$$f_t(T) = \frac{1}{1 + exp\left(\frac{E_T - E_f}{K_b T}\right)}. \tag{45}$$

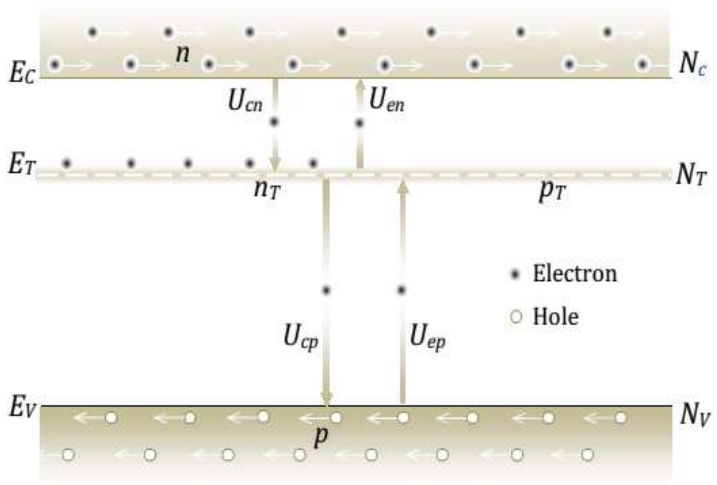

Figure 2-13: Energy band diagram with a localized trap.

The thermal equilibrium electron occupancy (n_{0T}) and hole occupancy (p_{0T}) of the localized state under thermal equilibrium are given by:

$$n_{0T} = f_t N_T = \frac{N_T}{1 + exp\ (\frac{E_T - E_f}{K_b T})}, \qquad p_{0T} = N_T - n_{0T}\,. \tag{46}$$

The probability of electron capture by a localized state (U_{cn}) at thermal equilibrium is a function of the density of electrons in the conduction band (n_0), the electron capture coefficient of the state (C_{nT}) and the density of empty traps (p_{0T}). However, the probability of emission of an electron (U_{en}) depends only upon the electron emission rate (e_n) and the density of traps occupied by electrons (n_{0T}). Thus one can write $U_{cn}$and U_{en} as:

$$U_{cn} = C_{nT} n_0 p_{0T} = C_{nT} n_0 N_T (1 - f_t),\ U_{en} = e_n n_{0T} = e_n f_t N_T. \tag{47}$$

The electron capture coefficient (C_{nT}) depends on the proximity of the centre to the conduction band. Similarly, the probability of hole capture (U_{cp}), and rate of probability of hole emission (U_{ep}) is given by:

$$U_{cp} = C_{pT} p_0 n_{0T} = C_{pT} p_0 N_T f_t\ ,\ U_{ep} = e_p p_{0T} = e_p N_T (1 - f_t). \tag{48}$$

The probability of recombination rate due to electron is the difference b/n the probability of electron capture by localized state (U_{cn}) and the emission of electron (U_{en}). Similarly to the probability of recombination rate due to hole is the difference b/n the probability of hole capture by localized state (U_{cp}) and the emission of hole (U_{ep}). In symbol as:

$$U_n = U_{cn} - U_{en}, \quad U_p = U_{cp} - U_{ep}, \tag{49}$$

where e_p is the hole emission rate, the hole capture coefficient (C_{pT}) depends the proximity of the centre to the valance band. According to the principle of detailed balance, the rate of capture and emission for each carrier at trap level are equal in thermal equilibrium. Thus one can write as:

$$U_{cn} = U_{en}, \quad U_{cp} = U_{ep}. \tag{50}$$

Eqns. (47) are equal insert in to Eqn. (50) to solving electron emission rate (e_n):

$$e_n = \frac{C_{nT} n_0 (1 - f_t)}{f_t} = C_{nT} n_1, \tag{51}$$

where $n_1 = \frac{n_0(1-f_t)}{f_t}$.

Eqns. (48) are equal insert in to Eqn. (50) to solving hole emission rate (e_p):

$$e_p = \frac{C_{pT} p_0 f_t}{(1 - f_t)} = C_{pT} p_1, \tag{52}$$

where $p_1 = \frac{p_0 f_t}{(1-f_t)}$.

Eqns. (51) and Eqns. (52) multiplying each other to give:

$$e_n e_p = \frac{C_{nT} n_0 (1 - f_t)}{f_t} \cdot \frac{C_{pT} p_0 f_t}{(1 - f_t)} = C_{nT} C_{pT} n_0 p_0. \tag{53}$$

$$C_{nT} = (1E+27)\sqrt{k_\infty}\left(\frac{m_n}{m_n^* + m_p^*}\frac{300}{T}\right)^{\frac{3}{2}}\left(1 + \frac{m_n}{m_n^*}\right)[(E_T - E_V)^2 + 3(E_T - E_V)k_B T + 3.75k_B^2 T^2]$$

$$C_{pT} = (1E+27)\sqrt{k_\infty}\left(\frac{m_n}{m_n^* + m_p^*}\frac{300}{T}\right)^{\frac{3}{2}}\left(1 + \frac{m_n}{m_n^*}\right)[(E_C - E_T)^2 + 3(E_C - E_T)k_B T + 3.75k_B^2 T^2]$$

where C_{nT} and C_{pT} are Capture coefficient at room temperature of electron and hole of the state through experimentation this value has been determined to be between $2.99\text{x}10^{-12} cm^3 s^{-1}$ and $1.85\text{x}10^{-9} cm^3 s^{-1}$ in respectively. From mass action law, we have ($n_0 p_0 = n_i^2$) and $e_n e_p = C_{nT} C_{pT} n_i^2$, From Eqns. (53) one can write as the reciprocal of distribution probability

(f_t) for the electron occupation of a trap located at energy E_T in the band gap is derived using Fermi-Dirac statistics:

$$\frac{1-f_t}{f_t} = \exp\left(\frac{E_T - E_i}{K_b T}\right), \tag{54}$$

Put Eqns. (54) insert in Eqn. (51) to get electron emission rate (e_n) in terms n_1 are given by:

$$e_n = C_{nT} n_i exp\left(\frac{E_T - E_i}{K_b T}\right) = C_{nT} n_1 \text{ , where } n_1 = n_i exp\left(\frac{E_T - E_i}{K_b T}\right). \tag{55}$$

are the concentrations of electrons in the conduction band for the case in which the Fermi-level E_f falls at E_T, to find hole emission rate in VB. Put Eqns. (54) insert in Eqn. (52) we get the rate of hole emission rate (e_p) in terms p_1 are given by:

$$e_p = C_{pT} n_i exp\left(\frac{E_i - E_T}{K_b T}\right) = C_{pT} p_1, \text{ where } p_1 = n_i exp\left(\frac{E_i - E_T}{K_b T}\right). \tag{56}$$

Are the concentrations of holes in the valence bands for the case in which the Fermi-level E_f falls at E_T .The product of Eqns. (55) and (56) to gives as:

$$n_1 p_1 = n_i exp\left(\frac{E_T - E_i}{K_b T}\right) . n_i exp\left(\frac{E_i - E_T}{K_b T}\right) = n_0 p_0 = n_i^2. \tag{57}$$

From mass action law($n_1 p_1 = n_0 p_0 = n_i^2$), under the steady–state condition, the net rate of electron capture per unit volume may be found by solving Eqns. (49) which yields:

$$U_n = U_{cn} - U_{en} = C_{nT} N_T [n_0(1 - f_t) - n_1 f_t], \tag{58}$$

Similarity, the net rate of hole capture per unit volume may be written as:

$$U_p = U_{cp} - U_{ep} = C_{pT} N_T [p_0 f_t - p_1(1 - f_t)], \tag{59}$$

under low injection condition ($i.e \Delta n \ll n_0$ and $\Delta p \ll p_0$), the charge neutrality condition required($\Delta n = \Delta p$).Under steady–state condition ,if one assumes that the net rate of electron and hole capture via a recombination center are equal ,then can written as:

$$U = U_p = U_n \Rightarrow U_{cn} - U_{en} = U_{cp} - U_{ep}, \tag{60}$$

$$C_{nT} n_0 + C_{pT} p_1 = f_t [C_{pT} p_0 + C_{pT} p_1 + C_{nT} n_0 + C_{nT} n_1],$$

To obtain the distribution probability (f_t) for the electron occupation of a trap located at energy E_T in the band gap is derived using Fermi-Dirac statistics:

$$f_t = \frac{C_{nT}n_0 + C_{pT}p_1}{[C_{pT}p_0 + C_{pT}p_1 + C_{nT}n_0 + C_{nT}n_1]} = \frac{C_{nT}n_0 + C_{pT}p_1}{C_{pT}(p_0 + p_1) + C_{nT}(n_0 + n_1)}, \quad (61)$$

A general expression for the net recombination rate for electron and hole are can be obtained by substituting Eqns. (61) into Eqn. (58) and Eqn. (59) the result as:

$$U_n = C_{nT}N_t\,[n_0(1 - \frac{C_{nT}n_0 + C_{pT}p_1}{C_{pT}(p_0 + p_1) + C_{nT}(n_0 + n_1)}) - \frac{n_1(C_{nT}n_0 + C_{pT}p_1)}{C_{pT}(p_1 + p_0) + C_{nT}(n_0 + n_1)}], \quad (62)$$

Due to low injection $n = n_0 + \delta n$ or $(n = n_0)$ and $p = p_0 + \delta p$ *or* $(p = p_0)$ so replaced each other. The excess carrier lifetime of Shockley-Read-Hall with trap or impurity in to simplified:

$$U_n = C_{nT}N_t\,[\frac{C_{pT}np - n_1p_1C_{pT}}{C_{pT}(p + p_1) + C_{nT}(n + n_1)}] = [\frac{C_{nT}N_tC_{pT}(np - n_1p_1)}{C_{pT}(p + p_1) + C_{nT}(n + n_1)}], \quad (63)$$

where both sides dividing by $C_{nT}N_tC_{pT}$ are yield as the carrier lifetime of hole and electron due to thermal equilibrium is given by:

$$\tau_{p0} = \frac{1}{C_{pT}N_t} \text{ and } \tau_{n0} = \frac{1}{C_{nT}N_t}. \quad (64)$$

General expression net recombination rates in (SRH) due to electron are can be obtained as:

$$U_n = \frac{[np - n_i^2]}{\tau_{n0}(p + p_1) + \tau_{p0}(n + n_1)}. \quad (65)$$

Now solving the excess carrier lifetime of Shockley-Read-Hall, this is given by:

$$\tau_{SRH} = \frac{\delta n}{U_n}, \quad (66)$$

Substitution Eqns. (65) in to Eqn. (66) in thermal equilibrium the electron-hole product is equal to intrinsic carrier concentration squares($n_0p_0 = n_i^2$)(the law of mass action).But, in non-thermal equilibrium electron-hole densities,($np > n_i^2$).Shockley Read Hall carrier lifetime(τ_{SRH}) defined as the excess carrier charge of electron concentration (δn) divided by the net excess Shockley-Read-Hall recombination rate (U_n) under electron, The general excess carrier lifetime of Shockley-Read-Hall without trap or impurity under injection is result as:

$$\tau_{SRH} = \frac{\tau_{n0}(\delta p + p_1 + p_0) + \tau_{p0}(\delta n + n_1 + n_0)}{n_0 + p_0 + \delta n}. \quad (67)$$

Under low injection case ($i.e\ \Delta n \ll n_0$ and $\Delta p \ll p_0, n_1$ and p_1), it obtained the excess carrier lifetime by Eqns. (67) is reduced to the general excess carrier lifetime on Shockley-Read-Hall with low injection under thermal equilibrium it become:

$$\tau_{SRH0} = \frac{\tau_{n0}(p_1 + p_0) + \tau_{p0}(n_1 + n_0)}{n_0 + p_0}. \tag{68}$$

Special cases for the excess electron SRH lifetime for different localized states exist. For a p-type material under low injection level the excess electron SRH lifetime, depend on injection level, he slope of the curve representing δn starts to decrease and finally becomes zero $\frac{d\delta n}{dt} = 0$ when the recombination rate equals the generation rate,(*i.e.* when a steady-state is achieved), so that in excess carrier charge concentration electron in terms of Shockley read hall recombination carrier lifetime with absorption photon rate for bulk semiconductors is given by ($\delta n = G_0\tau_{SRH}$). The injection level dependence of Shockley read hall excess carrier lifetime, τ_{SRH}, takes the form:

$$\tau_{SRH} = \frac{(\tau_{SRH0}(n_0 + p_0)) + (\tau_{n0} + \tau_{p0})\delta n}{n_0 + p_0 + \delta n}. \tag{69}$$

2.4.3 Effective excess carrier lifetime

The concept of lifetime is introduced here to estimate the time span of life of the carrier before its death by recombination. The lifetime referred to here is the recombination lifetime (τ_{eff}). It is a measure of the period of recovery of carriers from the perturbed state to the equilibrium one [63]. Effective carrier excess lifetime in bulk semiconductors is the sum of three carrier lifetime in Radiative, Auger and Shockley–Read Hall (SRH) with low injection (doped) and injection level dependence of excess lifetime under thermal and non thermal equilibrium condition, described by:

$$\frac{1}{\tau_{\text{eff}}} = \left(\frac{1}{\tau_R}\right) + \left(\frac{1}{\tau_A}\right) + \left(\frac{1}{\tau_{SRH}}\right) \text{ or } \tau_{\text{eff}} = \left[\left(\frac{1}{\tau_R}\right) + \left(\frac{1}{\tau_A}\right) + \left(\frac{1}{\tau_{SRH}}\right)\right].^{-1} \tag{70}$$

Chapter 3: Methodology

The model was designed of a GaSb semiconductor sample known length, width and infinitely thickness denoted by l , w and Δx in respectively. It described the total photon flux density sample GaSb in the bulk of semiconductors. They have found some distance of photon absorption in bulk semiconductors sample of GaSb in Eqns. (28). The analysis for this data was performed using semi-log & origin soft ware for both the photon absorption rate as function of absorption coefficient and penetration depth surface. The values of photon absorption rate process in this case is varied from $10^0 cm^{-3} s^{-1}$ to $10^6\ cm^{-3}\ s^{-1}$. The majority carrier concentration, p_0 used in the analysis for different doping levels GaSb samples was taken from the simulation of the existing temperature dependence Hall measurements data measured at Nelson Mandela Metropolitan University, South Africa.

The effective excess carrier lifetime was determined using the three recombination mechanisms radiative, Shockley read hall and Auger that are usually dominant in small band gap materials. The radiative lifetime (τ_R), Shockley read hall lifetime (τ_{SRH}) and Auger lifetime (τ_A) for excess carriers in p-type GaSb material are determined as functions of doping concentration, injection level dependence of excess carrier lifetime as function of excess carrier concentration and absorption coefficient. The theoretical results were analyzed using the thermal equilibrium majority carrier concentration results from Hall Effect measurements along with the relations describing the effective excess carrier lifetimes in the bulk of direct band gap semiconductor. The results of the analyses were described using semi-log & origin soft ware graphs for all the excess carrier lifetimes.

The results of the doping dependence of the excess carrier lifetimes were performed by carrier lifetime Eqn. (35), (42) and Eqns. (68) in Radiative, Auger and Shockley Read Hall (SRH) by varying the doping level ranged from 10^{10}cm^{-3} for intrinsic semiconductor to 10^{19}cm^{-3} for highly doped on the performance of the semiconductors under low injection for three samples with different energy trap at room temperature depend up on SRH. That is, a) $E_T \rightarrow E_C$ at 0.01eV, b)$E_T \approx E_f$ at 0.36eV and c) $E_T \rightarrow E_V$ at 0.72eV. The analysis for this data were performed using semi-log & origin soft ware for both the effective excess carrier lifetime & the doping level axes. The values of the excess carrier lifetimes in this case is varied from 10^{-6} ns to 10^{12}ns.

The description of the results of the injection level dependence of the excess carrier lifetimes were also performed by carrier lifetime Eqns.(34), (41)and Eqns.(67) in Radiative, Auger and Shockley Read Hall (SRH) on the performance of the semiconductors under injection levels by varying the excess concentration ranges from 10^{10} cm^{-3} to 10^{20} cm^{-3} for two samples with different doping levels. That is, a)$p_0 = 1.5x10^{12}cm^{-3}$ with different energy trap. That is, $(E_T \rightarrow E_C)$ at 0.01eV, $(E_T \rightarrow E_f)$ at 0.36eV and $(E_T \rightarrow E_v)$ at 0.72eV. b)$p_0 = 1.5x10^{16}cm^{-3}$ with different energy trap. That is, $(E_T \rightarrow E_C)$ at 0.01eV, $(E_T \rightarrow E_f)$ at 0.36eV and $(E_T \rightarrow E_v)$ at 0.72eV. In the analysis of this result, the vertical axis for the effective excess carrier lifetime was taken as semi-log and the horizontal axis of the excess concentration was kept linear. The results obtained for the excess carrier lifetimes for all the excess concentration were varied from 10^{-6}ns to 10^{12}ns.

For the description of the injection level dependence of excess lifetime were also performed by carrier lifetime Eqn.(36), (43)and Eqns.(69) in Radiative, Auger and Shockley Read Hall (SRH) on the performance of the semiconductors under injection levels by varying the absorption coefficient ranges from 10^{-2} cm^{-1} to 10^{10} cm^{-1} for four samples with different penetration depth surface. That is, $x_p = 10^{-3}cm$, $x_p = 10^{-4}cm$, $x_p = 10^{-5}$cm and $x_p = 10^{-7}cm$. In the analysis of this result, the vertical axis for the effective excess carrier lifetime was taken as semi-log and the horizontal axis of the absorption coefficient was kept up warred parabola. The results obtained for the excess carrier lifetimes for the entire absorption coefficient were varied from 10^{-2} ns to 10^{8}ns. the effective excess carrier lifetime using the Eqns. (70) recombination mechanisms.

Chapter 4: Data Analysis and Discussion

In this section we discussed and determined the result of this work in detail. In this work, in the first sections of this chapter the results of the photon absorption in infinitely thick semiconductor photo-response of direct band gap determined by the three recombination mechanisms under low injection(doping) and injection level dependence of excess lifetime as function of excess concentration and absorption coefficient were presented; the graph of photon Absorption effect on bulk semiconductor versus absorption coefficient and penetration depth surface were presented; the graph of excess lifetime(ns) vs doping concentration under thermal equilibrium and also as function of excess concentration and absorption coefficient under injection level of small direct band gap semiconductor were presented. In generally, the effective excess carriers' lifetime (τ_{eff}) is determined from the analysis of Eqn. (70) using Eqn.(34),(41) and Eqns.(67) for the Radiative, Auger and (SRH) excess carrier life times with low injection and injection level τ_R, τ_A and τ_{SRH} in respectively.

4.1 Photon absorption effect on semiconductors

To perform the process of plotting the graph in figure 4-1,the photon absorption effect on semiconductors dependence of absorption coefficient and depth was described using Eqn. (28), it shows that the optical absorption rate per incident photon as function of absorption coefficient in figure 4-1(a) and as function of penetration depth below surface in figure 4-1(b).

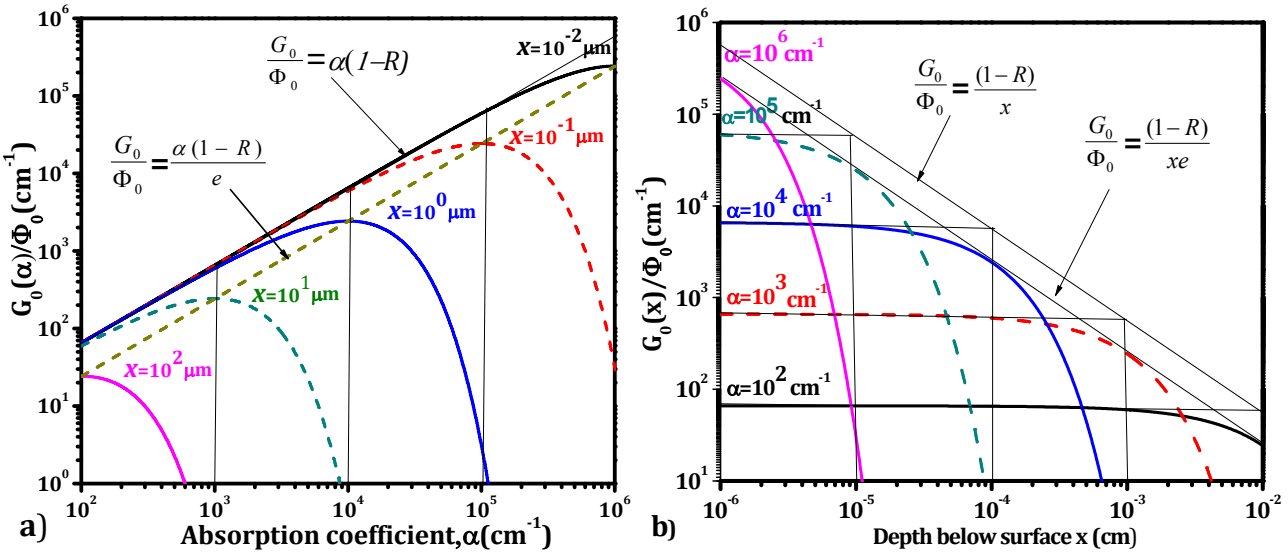

Figure 4-1: Optical absorption rate in semiconductors (a) as function of absorption coefficient at different depths in the material and (b) as function of depth for photons at different absorption coefficients.

Figure 4-1 (a) illustrates the normalized absorption rate of photons as function of α at different depths in a given sample. The value of the absorption rate goes to zero for very large penetration depth and very small α. It can be seen that each photon has maximum absorption rate, where the photon absorption rates are largely absorbed on surface or takes the form of $0.37\alpha(1-\mathrm{R})$. On the line $\alpha x_{\mathrm{p}} = 1$, the value of α where each curve intersects the line $\alpha x_{\mathrm{p}} = 1$ is equal to the reciprocal of the penetration depth, x_{p}, of the corresponding photon.

Figure 4-1(b) also shows the normalized absorption rate of different photons as function of depth x in the sample. The absorption rate in this case has value: The absorption rate falls to 37% of the maximum value at the surface or takes the form of $0.37\alpha(1-\mathrm{R})$ at the absorption depth (x_{p}), and goes to zero when the values of x is much exceeding the values of the absorption depth (x_{p}) of the absorbed photons (or $\Delta x \to \infty$). Because the incident photon directly passes through the sample, the sample of material is said to be transparent photon, Once electron–hole pair is not generated or absorbed. As one can see from this figure, photons with higher absorption coefficients α (i.e short wavelength photons) are highly absorbed near the illuminated surface, while photons with lower α (*i.e* long wavelength photons) pass through the sample without being absorbed.

4.2 Doping level dependence of excess carrier lifetime

Figure 4-2 illustrates the room temperature doping concentration dependence of excess carrier lifetime for p-type semiconductor under low injection level as predicted by Eqn. (70) from intrinsic level to high doping level. The determination of the doping level dependence of effective excess carriers' lifetime, τ_{eff} in this case is performed from the analysis of Eqn. (70) at low injection level.

To perform the process of plotting the graph in figure 4-2, first the doping level dependence of τ_{eff} was described using Eqn. (70) at low injection level ($\delta n \ll p_0$). As can be seen from the relations in Eqns.(35),(42) and Eqns.(68) the excess carrier lifetime has inverse proportion with the doping concentration for all the radiative, Auger and the Shockley read hall case. The three samples with different energy trap at room temperature depend up on SRH. That is, a) $\mathrm{E_T} \to \mathrm{E_C}$ at 0.01eV, b)$\mathrm{E_T} \approx \mathrm{E_f}$ at 0.36eV and c) $\mathrm{E_T} \to \mathrm{E_V}$ at 0.72eV. The Shockley

read hall excess carrier lifetime varies approximately from 0.01mili seconds at intrinsic level to 0.1microseconds for doped samples; the result we obtained is almost the same as that of Ascazubi et al [61] and the Auger excess carrier lifetime varies approximately from 0.1microsecond at doped level to 0.1 picoseconds for highly doped samples. This was in good agreement with the result reported by Titkov et al[62]. Figure 4-2 depicts the doping dependence of excess carrier lifetimes. The radiative excess carrier lifetimes are represented by magenta lines, the Auger excess carrier lifetimes are represented by red lines ,the (SRH) excess carrier lifetimes are represented by blue lines and the effective excess carrier lifetimes are represented by green lines, as can be seen from Figure.

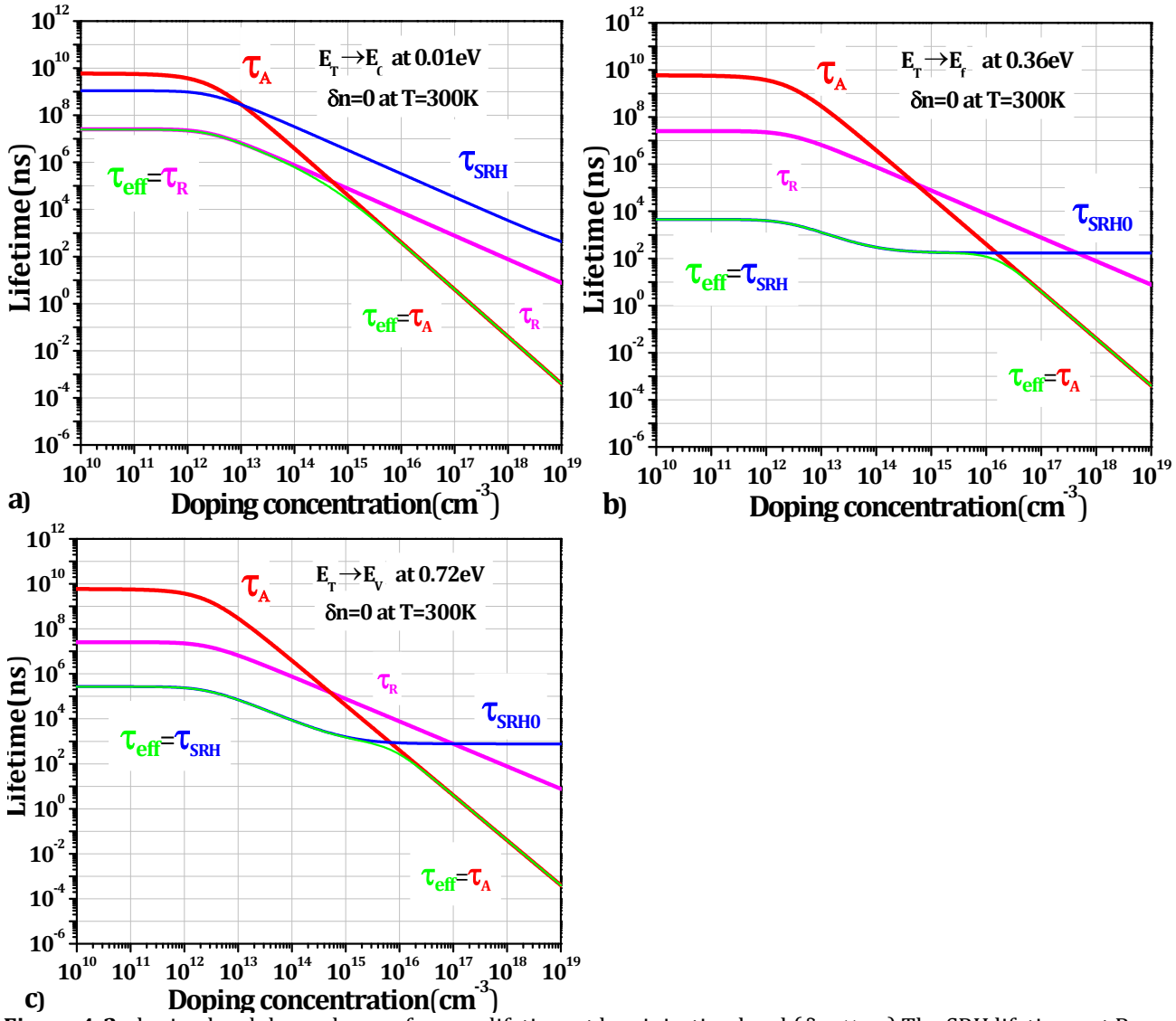

Figure 4-2: doping level dependence of excess lifetime at low injection level ($\delta n \ll p_0$).The SRH lifetimes at Room temperature for different localized energy trap states as function low injection level in un-doped p-type a)$E_T \rightarrow E_C$ *at* $0.01eV$ b))$E_T \rightarrow E_f$ *at* $0.36eV$ c) $E_T \rightarrow E_V$ *at* $0.72eV$.

Figure 4-2(a) illustrates the room temperature of excess lifetime for bulk semiconductor as a function of doped concentration is result as: The radiative Recombination mechanism is hence the dominant mode of recombination at low doping levels, approximately below the doping level of $1.0x10^{14}cm^{-3}$ in figures 4-2(a). Now, the radiative recombination which is lightly affected by doping level as compared to the SRH and Auger recombination is dominant at very low doping regime. The region varies approximately below$1.0x10^{14}cm^{-3}$ of Samples with energy trap concentration equal to $E_T \rightarrow E_C \; at \; 0.01eV$ is low lifetime and constant in intrinsic region released photon, and where Auger recombination is hence dominate above $1.0x10^{15}cm^{-3}$ at faster rate decreasing in the high doping regime (figure4-2(a)).

In two figures 4-2(b) and (c) shows, the SRH recombination which is the most lightly affected by doping level as compared to the radiative and Auger recombination is dominant at very low doping regime. The samples with energy trap concentration closer to $E_T \rightarrow E_f \; at \; 0.36eV$ and $E_T \rightarrow E_v \; at \; 0.72eV$, the region varies approximately below $1.00x10^{15}cm^{-3}$ is low lifetime and constant in intrinsic region, and where Auger recombination is hence dominate above $1.00x10^{16}cm^{-3}$ at faster rate decreasing in the high doping regime.

It is known that, the SRH recombination mechanism is dominant at low injection level in a sample of very low acceptor or donor concentration as compared to Auger and the radiative lifetime. The effective excess carrier lifetime hence, decreases slightly at a slower rate in the low doping region and a faster rate in the high doping region as shown in all Figures 4-2, Because of the styles of the variation of the three involved mechanisms with the doping concentration. In the intrinsic region, the radiative, Shockley read hall and the Auger excess carrier lifetimes slope is constant or zero with increasing doping concentration, in extrinsic region is increasing doping concentration as decreased as excess lifetime. Nevertheless, the Auger recombination which is dominant lightly affected by doping level as compared to the radiative and SRH recombination is faster decreasing at very high doping regime.

Therefore, one can conclude from these relations, the optical generation of excess carriers of photon and the excess energy is released as phonons (*i.e.* the excess energy is dissipated as heat during the recombination process) dominates at low doping regime and the two holes and one electron are imparted to the third transferred charge carrier is released current dominates at higher doping regime.

4.3 Injection level dependence of excess lifetime as function of excess Carrier concentration

Figure 4-3 depicts the injection level dependence of excess carrier lifetimes for intrinsic samples of varying doping with equal to (a) $p_0 = 1.5x10^{12}\text{cm}^{-3}$ with different energy trap that is $E_T \rightarrow E_C$ at 0.01eV, $E_T \rightarrow E_f$ at 0.36eV and $E_T \rightarrow E_v$ at 0.72eV and (b) $p_0 = 1.5x10^{16}\text{cm}^{-3}$ with different energy trap is $E_T \rightarrow E_C$ at 0.01eV, $E_T \rightarrow E_f$ at 0.36eV and $E_T \rightarrow E_v$ at 0.72eV. In general, photo-generated carriers can be recombined both with opposite photo-generated carriers and thermally-generated carriers in the material. Each of the recombination rates for photo-generated carriers discussed above is hence the sum of the recombination rate of a photo-generated carrier with opposite photo-generated carriers and thermally-generated carriers. The net recombination rate of photo-generated carriers with other photo-generated carriers is dominant in high injection level material ($\delta n \gg p_0$) and only a function of thermally-generated carrier concentrations in low injection level system($\delta n \ll p_0$). As a result, the excess carrier lifetime given in Eqn. (34), (41) and Eqns. (67) remain only a function of Photo-generated carrier concentrations in high injection level system and only a function of thermally-generated carrier concentrations in low injection level material. Generally, the determination of the excess concentration dependence of effective excess carriers' lifetime, τ_{eff} in this case is performed from the analysis of Eqn. (70) at high injection level($\delta n \gg p_0$). Figure 4-3 depicts the injection level dependence of excess carrier lifetimes. The radiative excess carrier lifetimes are represented by magenta lines, the Auger excess carrier lifetimes are represented by red lines, the (SRH) excess carrier lifetimes are represented by blue lines and the effective excess carrier lifetimes are represented by green lines, as can be seen from Figure.

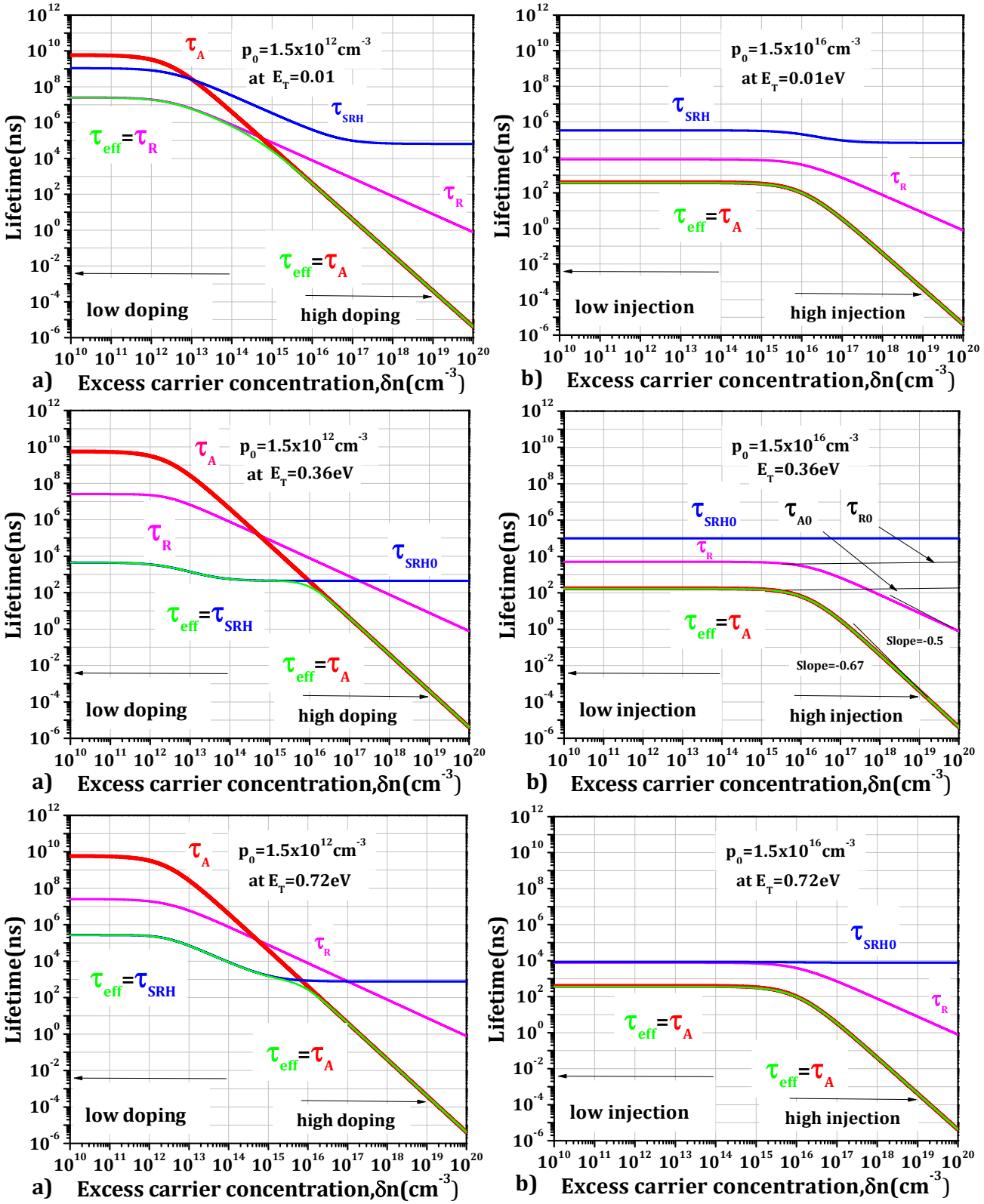

Figure 4-3: Injection level dependence of excess lifetime in Radiative, Auger and SRH lifetime as function of excess carrier concentration $(a)\ p_0 = 1.5x10^{12}cm^{-3}$ with different energy trap is $E_T \rightarrow E_C$ at 0.01eV, $E_T \rightarrow E_f$ at 0.36eV and $E_T \rightarrow E_v$ at 0.72eV of low doping and (b) $p_0 = 1.5x10^{16}cm^{-3}$ with different energy trap is $E_T \rightarrow E_C$ at 0.01eV, $E_T \rightarrow E_f$ at 0.36eV and $E_T \rightarrow E_v$ at 0.72eV of high doping.

Figure 4-3 illustrates the injection level dependence of excess lifetime as a function of excess concentration is result as: The same as low injection, only in figure 4-3(a) illustrate the radiative recombination mechanism is the dominant mode of recombination at low doping levels, approximately below the excess concentration of $1.00x10^{14}cm^{-3}$ depend on high injection of energy trap closer to energy conduction band. otherwise, in the Shockley read hall recombination which is lightly affected by excess concentration as compared to the Auger and Radiative recombination is dominant at very low doping regime, approximately below the excess concentration of $1.00x10^{15}cm^{-3}$ depend on high injection of energy trap closer to energy Fermi and energy valance band. The effective excess carrier lifetime is hence decrease slightly at a slower rate in the low doping region as shown in all Figures 4-3(a).

The Auger lifetime is the dominant mode of recombination at high doping levels, approximately above the excess concentration of $1.00x10^{16}cm^{-3}$ under high injection level. The Auger excess carrier lifetime is dominant at high injection level in a sample of relatively high acceptor or donor concentration as compared to radiative and the Shockley-read-hall lifetime at high doping level. The effective excess carrier lifetime hence decreases at faster rate in the higher doping regime as shown in all Figure 4-3(b).The slope of the injection level dependence of the excess carrier Auger lifetime in the low injection region is zero or high lifetime and in the high injection region the slope become -0.67or low life time. The slopes of the injection level dependence of the excess carrier lifetimes in radative(recombination and generation) in the low injection region is zero or high lifetime and in the high injection region the slope of τ_{R0} become -0.5 or low lifetime. The slope of the injection level dependence of the excess carrier SRH lifetime in the low and high injection region is zero.

As result, dominant at injection level in all the samples in the high injection level samples irrespective of the acceptor or donor concentrations as shown in all figure 4-3. This is because of most of the photo-generated carriers will be involved in the process of Auger recombination processes in semiconductors are band-to-band processes where the excess energy-set free during the recombination of an electron and a hole is transferred to a third charge produced current carrier. If the doped concentration is increasing as the decreased of the excess lifetime, so the performance of the semiconductor is directly related to the effective lifetime of charge carriers, High photo-generated effective lifetime results in great conductivity (or greater quality) of the semiconductor in Auger.

4.4 Injection level dependence of excess carrier lifetime as function of Absorption coefficient

Figure 4-4 depicts the injection level dependence of excess carrier lifetimes as function of absorption coefficient at different penetration depths. The Photo-generated carriers can be recombined both with opposite photo-generated carriers and thermally-generated carriers in the material. Each of the recombination rates for photo-generated carriers discussed above is hence the sum of the recombination rate of a photo-generated carrier with opposite photo-generated carriers and thermally-generated carriers. The net recombination rate of photo-generated carriers with other photo-generated carriers is dominant in high injection level material ($\delta n \gg p_0$) and only a function of thermally-generated carrier concentrations in low injection level system($\delta n \ll p_0$). The photon absorption rate at depth x for a given wavelength is also proportional to the photon flux density,$\Phi(x)$, remaining at x after being absorbed in a material. The photon absorption rate also depends on the absorption coefficient α. The maximum absorption rate occurs for a specific absorption coefficient (i.e. photon wavelength) is inverse proportional to the three minimum lifetimes at the same point. The depth (x) at which $\tau_{eff}(\alpha, x)$, has a minimum value for a given photon energy is called the penetration depth x_p of that photon is given by $x_p = \frac{1}{\alpha}$. As a result, the excess carrier lifetime given in Eqn. (36), (43) and Eqns. (69) remain only a function of Photo-generated concentrations in high injection level system and only a function of thermally-generated carrier concentrations in low injection level material. Generally, the determination of the absorption coefficient dependence of effective excess carriers' lifetime, τ_{eff} in this case is performed from the analysis of Eqn. (70) at high injection level($\delta n \gg p_0$). Figure 4-4 depicts the injection level dependence of absorption coefficient. The radiative excess carrier lifetimes are represented by magenta lines, the Auger excess carrier lifetimes are represented by red lines ,the (SRH) excess carrier lifetimes are represented by blue lines and the effective excess carrier lifetimes are represented by green lines, as can be seen from Figure.

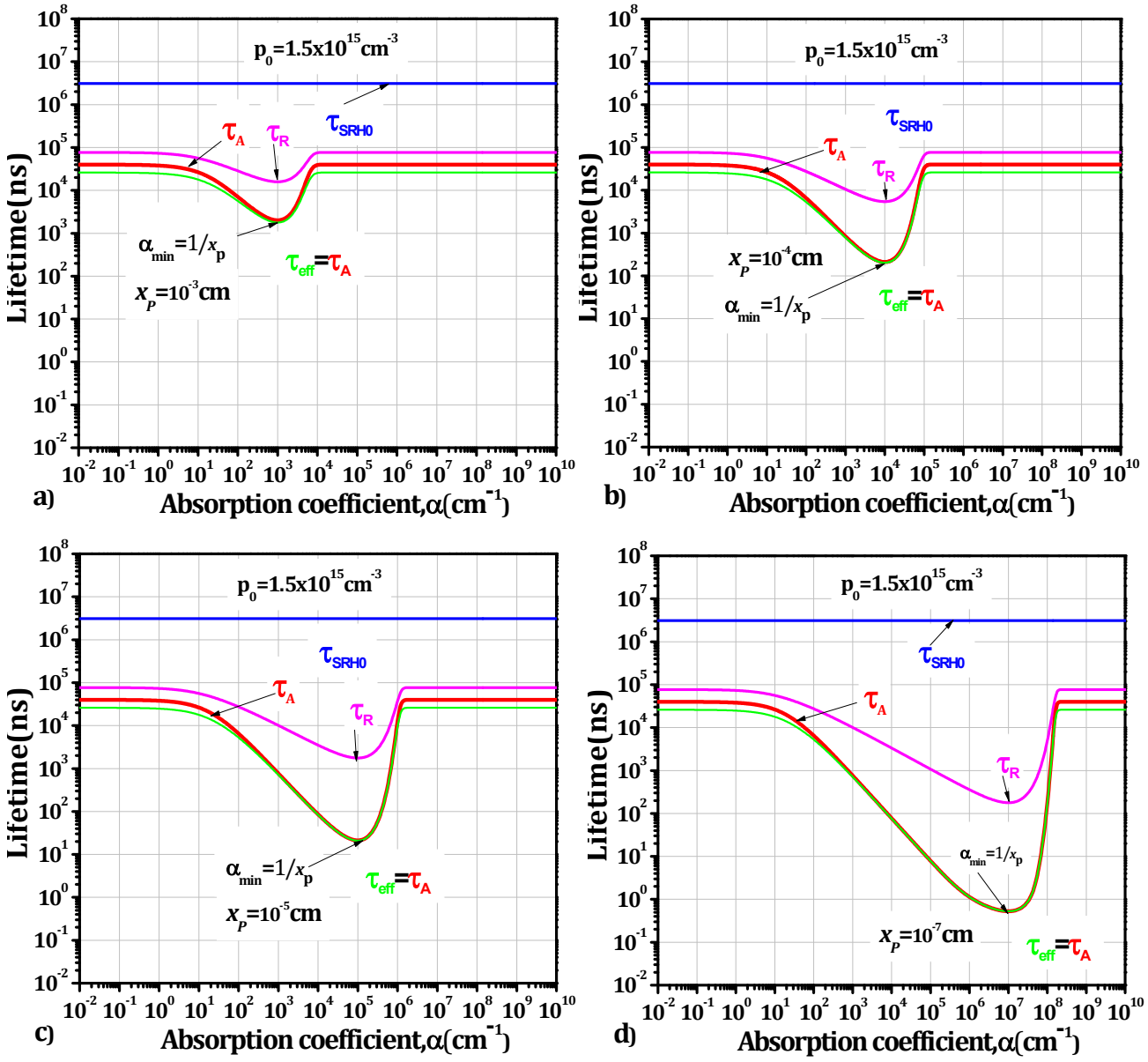

Figure 4-4: Injection level dependence of effective excess lifetime in Radiative, Auger and SRH lifetime as function of absorption coefficient for photon at different penetrations depths surface in the material, a) $x_p = 10^{-3}\ cm$ b) $x_p = 10^{-4}$cm c) $x_p = 10^{-5} cm$ d) $x_p = 10^{-7} cm$.

Figure 4-4 depicts the injection level dependence of excess lifetimes as function of absorption coefficient is result as: the Auger recombination mechanism is the dominant mode of all figure recombination decreased for a specific absorption coefficient under injection level that specific absorption coefficient is the minimum of recombination lifetime, but the SRH lifetime is constant lifetime under injection level. If the sample of penetration depth surface is decreased as increasing of specific absorption coefficient with the decreased of the two minimum lifetime, The Auger lifetime which is dominant at absorption coefficient in a sample

of relatively high acceptor or donor concentration as compared to radiative and the SRH lifetime. The photons with higher absorption coefficients α (i.e short wavelength photons) are highly absorbed near the illuminated surface with lowest of minimum lifetime, while photons with lower α (*i.e* long wavelength photons) pass through the sample without being absorbed with highest of lifetime. It has a minimum lifetime recombination value for intermediate values of α, so $\alpha_{min} = \frac{1}{x_p}$.

The result that, first regions where the excess carrier lifetimes remain constant with increasing the injection level in all the samples are the region where the thermal equilibrium majority carriers dominate the entire recombination mechanism ($p_0 \gg \delta n$), this condition is called low injection level. The regions where the excess carrier lifetimes decrease with increasing the injection level are where the injection levels dominate the entire recombination mechanism ($\delta n \gg p_0$), and this condition is called high injection level.

As can be seen from figures 4-2 and 4-3 above, the effective excess carrier lifetime decreases slightly at a slower rate in the low doping region where SRH recombination is dominating the entire process and at a faster rate in the higher doping regime where Auger recombination is dominating the entire process. As can be seen from figures 4-4 the effective excess carrier lifetime decreases slightly at a below specific absorption coefficient slower rate is equal to in the given penetration depths surface where Auger recombination is dominating the entire process.

Chapter 5: Conclusion

In this study, the determination of the photoconductivity of gallium antimonide (GaSb) bulk semiconductors is studied by describing the photon absorption rate per incident photon as function of absorption coefficient and penetration depth were described. The doping level dependence of excess carrier lifetime and the injection level dependence of excess carrier lifetime as function of excess carrier concentration and absorption coefficient were described. The effective excess carrier lifetimes for minority carriers in the entire bulk of a given sample was calculated from the combined effects of the radiative, Shockley read hall and Auger recombination mechanisms. Photons absorption on effect of Bulk semiconductors for some distance is, concluding that: If the penetration depths is small: both the absorption coefficient and photon absorption rate per incident photon is large or increased, where the photon absorption rate is largely absorbed on surface. Therefore, once electron–hole pair is produced and electron–hole pair is generated. If the penetration depths is large: both the absorption coefficient and photon absorption rate per incident photon is small or decreased, where the photon absorption in infinitely thick semiconductors or bulk semiconductors the thickness is goes to infinity($\Delta x \to \infty$) to conclude that; Therefore, the incident photon directly passes through the material, the material is said to be transparent photon. Once electron–hole pair is not produced and electron–hole pair are not generated or absorbed. The room temperature doping level dependence results of the excess carrier lifetime revealed that, the main contribution of the photo-response comes from the Shockley read hall recombination mechanism at very low doping level in all energy traps sample slower decreasing except energy trap closer to energy conduction and from Auger recombination mechanism at very high doping level dominate entire process. As a result, the room temperature values of the low injection level minority carrier lifetimes in GaSb varies approximately from 0.1picoseconds for highly doped samples to 10 second for intrinsic samples. The Shockley read hall recombination mechanism also dominates in the region for the un-doped and slightly doped samples. The entire intrinsic region is dominated by the Shockley read hall recombination mechanism because of the highly increasing of the intrinsic carrier concentration above the dopant concentration and Auger recombination mechanism dominates the entire injection level in highly doped samples faster decreasing. The Auger carrier lifetime is dominant at low injection

level in a sample of relatively high acceptor or donor concentration and produced charge (current) carrier. In injections level also the same as low injection level; the Shockley-read-hall lifetime is the dominant of recombination at low doping levels produced heat as compared to the Auger and Radiative. The Auger lifetime is dominant at high doping levels in a sample of relatively high acceptor or donor concentration and produced charge (current). The slope of the injection level dependence of the excess carrier Auger lifetime in the low injection region is zero or constant and in the high injection region the slope become -0.67. The slopes of the injection level dependence of the excess carrier radative lifetimes in the low injection region is zero or constant and in the high injection region the slopes become -0.5. The slopes of the injection level dependence of the excess carrier SRH lifetimes in the low and high injection region is zero or constant. Injection levels dependence of excess carrier lifetime as function of absorption coefficient conclude that: the Auger carrier lifetime is the dominant mode of recombination for specific in absorption coefficient is equal to the minimum lifetimes at intersection of penetration depth surface. If the penetration depth surface is decreasing as increasing of specific absorption coefficient and high energy of photon with the lowest of two minimum excess lifetimes. The three recombination of minimum lifetime is inverse proportional to maximum photon absorption rate.

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