The Study of the effects of Free Carriers Trap on the Recombination Mechanism through the localized States

By

Tamire Legesse Fole

A Thesis Submitted to

The department of Applied Physics

School of Applied Natural Science

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Declaration

I hereby that this MSc Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis has been duly acknowledged.

Name: Tamire Legesse Fole

Signature……..

This MSc Thesis has been submitted for examination with my approval as thesis advisor.

Name: Dr. Megersa Wodajo Shura

Signature……..

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List of Abbreviation

C_B	Conduction band
C_{na}	Electron Auger recombination coefficient
C_{pa}	Hole Auger recombination coefficient
C_R	Radiative recombination coefficient
E_C	Conduction band energy
E_F	Fermi energy
E_g	Energy band gap
E_i	Intrinsic energy
f_n	Fermi distribution function
E_v	Valence band energy
$GaSb$	Gallium antimonite
G_0	Photon generation rate
m_n^*	Effective mass of electron
m_p^*	Effective mass of hole
N_a^+	The concentration of ionized donor atom
N_a^-	The concentration of ionized acceptor atom
N_C	Effective density of conduction band
N_T	Total density of localized state
N_v	Effective density of Valence band
n_0	Electron concentration
p_0	Hole concentration
n_T	Electron density of localized state
p_T	Hole density of localized state
V_B	Valence band
U	Recombination rate
δn	Concentration of photo generated of electron
δp	Concentration of photo generated of hole
h	Planck constant
τ_A	Auger lifetime
τ_R	Radiative lifetime
τ_{SRH}	Shockley-Read-Hall lifetime

Abstract

In this study, the effects of free carriers trap on the recombination mechanism through the localized states in gallium antimonide (GaSb) is investigated through the simulation of excess carrier traps corresponding to the non-radiative recombination mechanism. Fist, the trapping effects (the ratio of the concentration of trapped carriers to the corresponding concentration of free carriers) is described as a function localized state energy at room and different temperatures inside the sample. Then, the radiative, Auger and Shockley-Read-Hall recombination mechanisms are compute using the relations describing the lifetimes of the excess majority and minority carriers in the band gap of semiconductor (GaSb). Finally, the temperature dependence of the radiative, Auger and Shockley-Read-Hall excess carrier lifetimes in the localized regions are investigated by considering the variation of localized energy positions. Since trap is indirectly related to the temperature, the description of the trapping effect as functions of localized state energies is found to be the important. The analysis of the results also shows that, the under localized regions are divided in to five based on the interaction of localized state energy with the conduction band energy or the valance band energy and decreases with temperature. The trap in shallow levels (donor and acceptor regions) tends to zero and deep levels are dominated at high temperature. The Auger lifetime is dominated than the other (radiative and Shockley-Read-Hall) lifetimes for the sample semiconductor (GaSb). The temperature affects both majority and minority carriers trap and their lifetimes in the three recombination mechanisms as functions of the localized state energies and the Auger lifetime is dominated in the semiconductor gallium antimonide sample.

Chapter 1

Introduction

1.1 Background

There is no doubt that semiconductors changed the world beyond anything that could have been imagined before them. Although people have always needed to communicate and process data, it is thanks to the semiconductors that these two important tasks have become easy and take up infinitely less time than, *e.g.*, at the time of vacuum tubes. The history of semiconductors is long and complicated. Obviously, one cannot expect it to fit one short paper. Given this limitation the authors concentrated on the facts they considered the most important and this choice is never fully impartial.

Semiconductors are a group of materials having electrical conductivities between metals and insulators. The conductivity of these materials can be varied over orders of magnitude by changes in temperature, optical excitation, and impurity content. The column IV semiconductors, silicon and germanium are called elemental semiconductors because they are composed of single species of atoms. Compounds of column III and V atoms, as well as certain combinations from II and VI, and from IV, make up the compound semiconductors. Every solid has its own characteristic energy band structure. This variation in band structure is responsible for the wide range of electrical characteristics observed in various materials. Semiconductor materials at 0 K have basically the same structure as insulators. In metals, the bands either overlap or are only partially filled. Thus in metals, high electrical conductivity is due to the fact that electrons and empty energy states are intermixed within bands so that electrons can move freely under the influence of an electric field [1].

The energy band gap of semiconductor ranges from 0.3 to 3.5 eV. The mobility of free carriers in semiconductor also ranges from $10^4 \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$ to $10^2 \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$. The practical density of room temperature thermal equilibrium majority carrier for semiconductor that was determined using Hall Effect measurement is ranged from $10^{12}\mathrm{cm}^{-3}$ for intrinsic semiconductor to $10^{19}\mathrm{cm}^{-3}$ for highly doped non-degenerate semiconductor, and the density of minority carrier concentration is also ranged from $10^{12}\mathrm{cm}^{-3}$ for intrinsic semiconductor to $10^{5}\mathrm{cm}^{-3}$ for highly doped non-degenerate semiconductor. The room temperature mobility of electrons for most

semiconductors is ranged from $10^3 cm^2V^{-1}s^{-1}$to $10^4 cm^2V^{-1}s^{-1}$ and that of holes is also ranged from $10^2 cm^2V^{-1}s^{-1}$to $10^3 cm^2V^{-1}s^{-1}$ [2, 3].

According to G. Busch [4] the term "semiconducting" was used for the first time by Alessandro Volta in 1782. The first documented observation of a semiconductor effect is that of Michael Faraday (1833), who noticed that the resistance of silver sulfide decreased with temperature, which was different than the dependence observed in metals [5]. An extensive quantitative analysis of the temperature dependence of the electrical conductivity of Ag_2S and Cu_2S was published in 1851 by Johann Hittorf [4].

The beginning of semiconductor research is marked by Faraday's report on negative temperature coefficient of resistance of silver sulfide. This is the first observation of any semiconductor property. As it appears from most of the historical reviews of semiconductor research, semiconductor devices-preceded by the adjectives early and primitive usually, refer to the crystal rectifiers used for wireless applications in the early 1900's. In this sense, early 1900's is regarded as the time when the semiconductor devices first came into application. An investigation into the history of semiconductor research unveils even more primitive and earlier semiconductor devices- they are the semiconductor devices of the 19th century. Pearson and Brattain outlined the developments in semiconductor research before 1900. Semiconductor research and semiconductor device application is an interest-entirely of the 20th century, in a more rigorous sense, of the second half of the century- but the roots of this discipline extend to the 19th century, too. Semiconductor properties- as fascinating as negative dynamic resistance of junctions, were observed. Use of semiconductors for wireless application began in the 1890's. The history of semiconductors in the 19th century lacks proper investigation and integration. How semiconductor properties came to scientists' notice and made debut in the field of application in the pre-1900 era presents us with an untold pre-1900 history of semiconductors [6, 7].

The theory of electron-hole pair recombination through recombination centers was put forth in 50s of the last century in the well-known works by Shockley-Read-Hall (SRH) [8, 9]. Here, we discuss lifetimes, their dependence on semiconductor material and device parameters like energy level, injection level and how lifetimes are measured. Different measurement methods can give widely differing lifetimes for the same material or device. In most cases, the reasons for

these discrepancies are fundamental and are not due to a deficiency of the measurement. The difficulty with defining a lifetime is that we are describing a property of a carrier within the semiconductor rather than the property of the semiconductor itself [3].

Point defects drastically affect the performance of semiconductor devices. In particular, they can act as charge traps and/or recombination centers. In electronic applications, such as in high electron mobility transistors, charge traps deteriorate the performance of the device and can lead to so-called device dispersion. In most cases charge trapping, or capture, occurs non-radiatively, i.e. without the emission of a photon. In optoelectronic applications, such as in light-emitting diodes or photovoltaic cells, defects can act as recombination centers for charge carriers. This so-called Shockley-Read-Hall (SRH) recombination is detrimental, as it decreases the efficiency of the device. SRH recombination can also affect electronic devices that rely on minority carrier transport, e.g., bipolar transistors. SRH recombination is a sequence of two carrier capture processes: one carrier is captured, and then the other carrier recombines with it [3, 10]

Generation and recombination processes through intermediate states in the bandgap of semiconductors (defect states) are of crucial importance for electronic devices. The theory of electron-hole pair recombination through recombination centers (traps) was put forth in 50s of the last century in the well-known works by Shockley-Read-Hall (SRH) [11].They can either be beneficial, when they are exploited for a desired effect, or detrimental, when they tend to decrease device performance. In both cases, it is essential to understand and control the reprocesses. An elegant and powerful description of such processes was developed by Shockley and Read and Hall and their theory has become a foundation for studies of defects in semiconductor devices [12]. In the original theory, the nature of the transitions is assumed to be non-radiative. When an electron falls from the conduction band into the intermediate state, its energy is transferred to the crystal atoms, through multiple emission of phonons. The opposite process, thermal emission, occurs when sufficient energy is transferred from crystal vibration to the electron in the intermediate state for it to rise into the conduction band. However, intermediate states can involve other types of processes, most importantly radiative transitions [13].

The increasing interest for the compound semiconductors, together with the refinement of the characterization methods, such as Deep Level Transient Spectroscopy (D.L.T.S.), has led to a better knowledge of the many different deep levels which one can find in the forbidden band gap of the semiconductors. In the particular case of gallium arsenide numerous traps have been classified by several authors nevertheless, their origin is known only for a few of them which have been voluntarily introduced in the material during the growth and then characterized. The influence of these traps on the optical and electrical properties of the semiconductor depends mainly on three characteristic properties of the level: its activation energy, concentration and capture cross-section for the free carriers. Some traps, such as the level due to the presence of chromium in the material, are very deep; they are then used for compensating the semiconductor in order to get the semi-insulating substrates needed for the realization of some devices. A detailed knowledge of their properties is then of first importance. Another important stimulus for the study of deep levels is the search for recombination centers responsible for the discrepancy between the measured diffusion lengths and those expected in pure GaAs [14, 3].

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. Those electrons captured in traps can be subsequently emitted back to the conduction band by thermal emission. 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 center. If the localized state captures free carriers temporarily and then reemit 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 [15].

The generation of excess carriers in a semiconductor may be accomplished by either electrical or optical means. The inverse process to the generation of excess carriers in a semiconductor is the recombination. The annihilation of excess carriers generated by optical or electrical means in a semiconductor may take place via different recombination mechanisms. Depending on the ways in which the energy of an excess carrier is removed during a recombination process, there are three basic recombination mechanisms, which are responsible

for carrier annihilation in a semiconductor. They are: (1) the nonradiative recombination (i.e., the multiphoton process), (2) the band-to-band radiative recombination, and (3) the Auger band-to-band recombination. The first recombination mechanism, known as the nonradiative or multiphoton recombination process, is usually the predominant recombination process for indirect band gap semiconductors such as silicon and germanium. In this process, recombination is accomplished via a deep level recombination center in the forbidden gap, and the energy of the excess carriers is released via phonon emission. With the decrease in feature size in semiconductor manufacturing, molecular contamination problems are increased significantly. The second recombination mechanism is a direct recombination mechanism, in which the electrons in the conduction band decay to the valence band (*i.e.* recombine with holes in the valence band). This is a very efficient process in direct band gap semiconductors. The energy lost by an electron in making the transition is released as a photon. The third recombination mechanism is the inverse of impact ionization, with the energy loss occurring via electron-electron or hole-hole collisions. For small band gap semiconductors such as GaSb, the minority carrier lifetime is usually controlled by band-to-band Auger recombination [3].

Recombination lifetime as well as diffusion length measurements have become universal in the semiconductor industry, because they are a good indicator of wafer contamination. When the defect densities in semiconductors are low, lifetime is one of few parameters that gives significant information about the lower concentration. A. Mitonneau and A. Mircea, et al studied electron and hole capture cross-sections at deep centers in gallium arsenide by using the method, Deep Level Transient Spectroscopy (D.L.T.S.), has led to a better knowledge of the many different deep levels which one can find in the forbidden band gap of the semiconductors [16].

In this thesis, we would have demonstrated the traps and the lifetime properties through the energy band gap (localized state) by using the method, Microsoft excel and Origin. And a thorough discussion on the topic of the study of the effects of free carriers trap on the recombination mechanism through the localized states will be presented. Un doped GaSb is used as the primary sample throughout this study. The competition between different localized states in the recombination mechanism and trapping of free carriers is studied. The effects temperature and the energy level of the localized states on the recombination and trapping of free carriers is also studied. The results of this research will broaden the knowledge of scientific community on

optoelectronics devices by presenting the theoretical description of free carrier trapping effects in the small and direct band-gap semiconductor (GaSb). Moreover, the result obtained from this thesis will be used as an input for other researchers [3].

1.2 Objective of the study

The general objective of this work is to study the effects of free carriers' trap on the recombination mechanism through the localized States. The specific objectives are:

- to study the non-radiative recombination mechanism through different localized states in the band gap of a semiconductor,
- to formulate the statistics of free carriers' trap at different localized states in the band gap of a semiconductor,
- to study the effects of free carriers' trap on the minority carrier lifetime in a semiconductor at various temperature.

1.3 Thesis outlines

The thesis consists of five chapters: Chapter 2 provides Literature review of Semiconductors, Temperature dependence of energy band gap, charge carrier in the semiconductor dopant atoms and energy levels, generation-recombination rates and so on. Chapter 3 deals with the methodology of the study. Chapter 4 presents the results and discussions of the effects of carrier trapping on the radiative, Auger and SRH recombination lifetimes. The end of this thesis will be accomplished by a concise conclusion and recommendation in Chapter 5.

Chapter 2

Literature Review

2.1 Energy Band Theory

The importance of energy band theories for a crystalline solid is due to the fact that many important physical and optical properties of a solid can be readily explained using its energy band structure. A useful way to visualize the difference between conductors, insulators and semiconductors is to plot the available energies for electrons in the materials. Instead of having discrete energies as in the case of free atoms, the available energy states form bands. Crucial to the conduction process is whether or not there are electrons in the conduction band. In insulators the electrons in the valence band are separated by a large gap from the conduction band, in conductors like metals the valence band overlaps the conduction band, and in semiconductors there is a small enough gap between the valence and conduction bands that thermal or other excitations can bridge the gap. With such a small gap, the presence of a small percentage of a doping material can increase conductivity dramatically. An important parameter in the band theory is the Fermi level, the top of the available electron energy levels at low temperatures. The position of the Fermi level with the relation to the conduction band is a crucial factor in determining electrical properties [9, 17, 18].

The band gap of a semiconductor, given by the energetic difference between its valence band maximum and conduction band minimum, has important implications for both the semiconductor's light absorption properties and the maximum photo voltage that can be expected from a corresponding device. In order to absorb a photon, an electron generally must be excited from the valence band of the semiconductor to the conduction band [19]. Thus, a photon must possess energy greater than or equal to that of the semiconductor band gap in order to be absorbed and create an excited electron-hole pair [20].

In a semiconductor, the energy difference between the top of valance band (E_V) and the bottom of conduction (E_C) is defined as the band-gap energy (E_g). The band gap energy $E_g = E_C - E_V$ is perhaps the most important in semiconductor physics. A contraction of the crystal lattice with decreasing temperature usually leads to a strengthening of the interatomic bonds

and an associated increase in the band gap energy. The first empirical relation for the band gap shift with temperature was developed by Varshni *e*t al [21, 3]: [3]

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

where $\alpha = 3.78\ e/K$ and $\beta = 94\ K$ are constants chosen to obtain the best fit to experimental data and $E_g(0) = 0.813\ eV$ is the limiting value of the band at zero Kelvin for GaSb.

2.2 Thermal equilibrium charge carriers in semiconductors

Unlike metals, the electrical conductivity of a semiconductor can be changed by many orders of magnitude by simply adding impurities or by using external excitations (e.g., by photo-excitation). At low temperatures, a pure semiconductor may become a perfect electrical insulator, since its valence band is totally filled with valence electrons and the conduction band is completely empty. However, as the temperature rises, a fraction of the valence electrons is excited into the conduction band by the thermal energy, thus creating free holes in the valence band. As a result, the electrical conductivity will increase rapidly with increasing temperature. Therefore, a semiconductor may become a good electrical conductor at high temperatures. 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 [9, 22].

A unique feature of semiconductor materials is that the physical and transport parameters depend strongly on temperature. For example, the intrinsic carrier concentration of a semiconductor depends exponentially on temperature. Other physical parameters, such as carrier mobility, resistivity, and the Fermi level in a lightly semiconductor, are likewise a strong function of temperature. In addition, both the shallow level and deep-level impurities may also play an important role in controlling the physical and electrical properties of a semiconductor.

For example, the equilibrium carrier concentration of a semiconductor is controlled by the shallow-level impurities, and the minority carrier lifetimes are usually closely related to defects and deep-level impurities in a semiconductor [3, 23].

The density-of-states function is given by:

$$\rho_c(E) \approx \frac{4\pi}{h^3}\sqrt{(2m_n{}^*)^3(E-E_C)} \qquad \text{in the conduction band} \tag{2-2}$$

$$\rho_v(E) \approx \frac{4\pi}{h^3}\sqrt{\left(2m_p{}^*\right)^3(E_V-E)} \qquad \text{in the valance-band.} \tag{2-3}$$

The density-of-states function given in Eqns. (2-2) and (2-3) can be applied to electrons in the conduction band and holes in the valence band of a semiconductor. This can be done by assuming parabolic bands for both the conduction and valence-bands and using the conduction and valence band edge as a reference level. Since the densities of states are the properties of the conduction and the valence-bands, they are not affected by the variation of Fermi-level position in the band gap. The density of state in the non –degenerate case can be written as:

$$n_0 = N_C \exp\left(-\frac{E_C - E_F}{k_B T}\right), \tag{2-4}$$

where

$$N_C = 2\left(\frac{2\pi m_n^*\ k_B T}{h^2}\right)^{3/2} \tag{2-5}$$

is the effective density of state in the conduction band and m_n^* is the electron effective mass in the conduction band, $k_B = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant and $h = 6.63 \times 10^{-34}$ J/s is the plank's constant. Equation (2-4) is valid for low carrier density semiconductors and not valid for carrier densities higher than or degenerate semiconductor. The hole density in the valence band can be derived in the result is given by for the non-degenerate case becomes:

$$p_o = N_V \exp\left(-\frac{E_F - E_V}{k_B T}\right), \tag{2-6}$$

where

$$N_V = 2\left(\frac{2\pi m_p^*\ k_B T}{h^2}\right)^{3/2} \tag{2-7}$$

is the effective density of state in the valence band and m_p^* is the hole effective mass in the valence band [3].

2.3 Intrinsic Semiconductors

Pure semiconductor materials have no impurity atoms. Charge carriers are solely the electrons and holes created in pairs by thermal energy. Electrons in the valence band gain thermal energy and are promoted into the conduction band as temperature increases, leaving behind corresponding holes in the valence band: "electron-hole" pair. The number of electrons in the conduction band equals the number of holes in the valence band. The band gap determines how temperature variation affects conductivity. Intrinsic conduction: process that results from the band structure of a pure element or compound [13, 22].

Intrinsic semiconductors are that do not contain impurities or defects. 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 $T = 0\ K$, 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. Intrinsic Carrier Concentration is the thermal excitation of electrons from the valence band to the conduction band creates free carriers in both bands. The concentration of these carriers in intrinsic materials (semiconductor with no added impurities) are n_i. n_i are the number of electrons in the conduction band or the number of holes in the valence band. In intrinsic semiconductors it depends on the band gap and temperature of the material. A large band gap will make it more difficult for a carrier to be thermally excited, hence n_i is lower in higher band gap materials [24].

For an intrinsic semiconductor where the Fermi level, is equal to the intrinsic level energy, in the semiconductor,

$$n_i = N_C \exp\left(-\frac{E_C - E_i}{k_B T}\right) = N_V \exp\left(-\frac{E_i - \mathrm{E}_V}{k_B T}\right). \tag{2-8}$$

Where intrinsic Fermi energy is given by;

$$E_i = \left(\frac{E_C + E_V}{2}\right) + \frac{3}{4}(k_B T)\ln\left(\frac{m_p^*}{m_n^*}\right). \tag{2-9}$$

When m_p^*, m_n^* and E_g are known at a given temperature and one can easily compute the value n_i and E_i [3].

The product of the electrons and holes density, in a non-degenerate semiconductor at equilibrium, is always equal to the square of the intrinsic carrier density;

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

Eqn.(2-10) is called Mass Action law.

2.4 Extrinsic Semiconductors

Semiconductors doped with foreign atoms to alter their intrinsic electron and hole concentrations. Doped semiconductors: Semiconductors, which contain impurities (foreign atoms) incorporated into the crystal structure of the semiconductor. Sources of impurities: Either (a) Added on purpose to provide free carriers in the semiconductor or (b) Incorporated unintentionally, due to lack of control during the growth of the semiconductor. Free carriers are generated when impurity atoms give off electrons or holes [3, 22].

The availability of charge carriers in the valence and conduction bands is greatly affected by the presence of purposely (or by chance) introduced impurities (i.e. foreign atoms incorporated into the crystal structure of a semiconductor). In semiconductors, some impurities are deliberately introduced to produce materials and devices with desired properties. The process of putting impurities into the lattice is doping. The contribution of free carriers by dopants requires them being ionized (i.e., the dopants have donated or accepted an electron). The ionization of the dopants depends on the thermal energy and the position of the impurity level in the energy gap of a semiconductor. In an extrinsic semiconductor, electrons are majority carriers and holes are minority carriers in n-type semiconductor. In p-type material, electrons are minority carriers and holes are majority carriers. Adding donor or acceptor impurity atoms into semiconductor will change the distribution of electrons and holes in the material, and as a result, the Fermi energy will change. Eliminating N_C and N_V among Eqns. (2-4), (2-6) and (2-8) yields [25]:

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

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

$$\text{Minority carrier density} = \begin{cases} \frac{n_i^2}{p_0} & \text{for p\_type material} \\ \frac{n_i^2}{n_0} & \text{for n\_type material} \end{cases} \quad (2\text{-}12)$$

Intrinsic energy and Fermi energy are equal when Fermi energy lies exactly at middle between the conduction band and valences bands in intrinsic semiconductors. Whereas discussed above, adding donor or acceptor impurity atoms into semiconductor will change the distribution of electrons and holes in the material, and as a result, the Fermi energy will change. $E_i = E_F$ the thermal equilibrium extrinsic Fermi-level position can also be described from Eqn. (2-11) in terms of $\mathrm{E_i}$ and the thermal equilibrium carrier concentrations as [17].

$$\mathrm{E_F} = E_i - k_B T \ln\left(\frac{p_0}{n_i}\right) = E_i + k_B T \ln\left(\frac{n_0}{n_i}\right). \quad (2\text{-}13)$$

As the charge carrier concentrations change, the position of the extrinsic Fermi energy level varies within the band gap until the system reaches thermal equilibrium. Eqn. (2-13) shows that E_F lies above E_i for n-type material ($n_i > p_0$) and below E_i for p-type material (($n_i < p_0$). The equilibrium density of electrons and holes in a non-degenerate semiconductor is constant at a given temperature. At non-thermal equilibrium the excess carrier is created, thermal equilibrium no longer exists and Fermi-energy is strictly no longer defined. We may define ques-fermi energy for electron and holes to relate the concentrations for non-equilibrium semiconductor in the same form of equation as that in thermal equilibrium. In such a way the ques-fermi energy for electron and holes specified for non-thermal equilibrium conditions do not hold constants over the entire material [3, 22, 26].

2.5 Charge neutrality

When free electron-hole pairs annihilate through recombination, the free carrier concentrations in the conduction and valence bands adjust for the intrinsic semiconductor to Eqn. (2-13). For the extrinsic semiconductors this takes the form:

$$n_0 = N_d^+ + \mathfrak{N} - n_R, \qquad p_0 = N_a^- + \mathfrak{N} - n_R, \quad (2\text{-}14)$$

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

contributed by the donor and the acceptor levels to the respective conduction and valence bands. Upon eliminating $\mathfrak{N} - n_R$ in Eqn. (2-14) the well-known neutrality relationship is obtained [27]:

$$n_0 + N_a^- = p_0 + N_d^+. \tag{2-15}$$

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

$$N_d^+ = \frac{N_d}{1 + 2\exp\left(\frac{E_F - E_d}{k_B T}\right)} \quad \text{and} \quad N_a^- = \frac{N_a}{1 + 4\exp\left(\frac{E_a - E_F}{k_B T}\right)}. \tag{2-16}$$

The law of mass action Eqn. (2-10) along with Eqn. (2-16) yields:

$$p_0 = \frac{N_a^- - N_d^+}{2} + \sqrt{n_i^2 + \left(\frac{N_a^- - N_d^+}{2}\right)^2}, \qquad n_0 = \frac{N_d^+ - N_a^-}{2} + \sqrt{n_i^2 + \left(\frac{N_d^+ - N_a^-}{2}\right)^2}. \tag{2-17}$$

2.6 Optical generation and recombination of excess carriers

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. 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. While the photo-generated carriers exist in their respective bands, they are free to contribute to the conductivity of the material [28].

The study of the optical generation and recombination of excess carriers in semiconductor is a crucial issue in study of the performance of the material. Recombination of charge carriers is the opposite of generation of charge carriers, representing mechanisms that reduce the excess charge density. When there is generation of charge carriers, it is always balanced at steady-state by the recombination of charge carriers. Recombination of charge carriers takes place both in the bulk and at the surface of a semiconductor. In deriving our recombination model, it has been assumed that the semiconductor is non-degenerate [15].

Optically generated charge carriers can recombine in two different ways: radiatively or non radiatively. Radiative recombination is the opposite of optical generation of charge carriers. It occurs when the energy of the excited electron is emitted by the formation of a photon during

the annihilation of an EHP. 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 [11, 29].

2.6.1 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. Radiative recombination is a direct recombination mechanism, in which the electrons in the conduction band decay to the valence band (*i.e.* recombine with holes in the valence band). This is a very efficient process in direct band gap semiconductors. The energy lost by an electron in making the transition is released as a photon. The total recombination rate (U_R) is directly proportional to the product of the concentration of electrons n available in the conduction band and the concentration of holes p available in the valence band:

$$U_R = C_R np, \tag{2-18}$$

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}).

$$C_R = \sigma_R v_{th}. \tag{2-19}$$

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 [3]:

$$C_R = \frac{8\pi k_\infty}{c^2} \int_0^\infty \frac{\alpha(\nu)\nu^2 d\nu}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}, \tag{2-20}$$

Where $\alpha(\nu)$ 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. (2-20) for narrow band gap semiconductors as:

$$C_R = e\pi\sqrt{k_\infty}\left(\frac{m_n}{m_n^* + m_p^*}\frac{300}{T}\right)^{\frac{3}{2}}\left(1 + \frac{m_n}{m_n^*} + \frac{m_n}{m_p^*}\right)\left[E_g^2 + 3E_g k_B T + 3.75 k_B^2 T^2\right] \tag{2-21}$$

where E_g and $k_B T$ are in electron volt (eV).

For large band gap materials where $E_g \gg k_B T$ only the E_g^2 term is needed. Since, $E_g \gg k_B T$ the term E_g^2 is dominant in this case as predicted. The net photo-generated carrier recombination rate in the absence of excess carrier traps is given by the difference between the non-thermal equilibrium recombination rates. But, in non-equilibrium electron-hole densities, $np > n_i^2$ and $\delta n = n - n_{o,}\ \delta p = p - p_o$.

In a non-degenerate semiconductor, the rate at which electrons and holes are annihilated via band-to-band Radiative recombination is proportional to the product of electron and hole densities in the conduction and valence bands.

The Radiative recombination rate (U_R), depends on the concentration of free electrons (n) and holes (p) is obtained as follows [3, 27]:

$$U_R = C_R\left(np - n_i^2\right). \tag{2-22}$$

Inserting non-equilibrium concentration $n = n_o + \delta n$ and $p = \delta p + p_o$ into Eqn. (2-22) and for the case of low-level injection, the excess carrier concentration δn and δp with $\delta n = \delta p$, then the following general expression for radiative recombination rate, U_R is given by:

$$U_R = C_R \delta n(\delta n + p_o + n_o). \tag{2-23}$$

The excess electron concentration δn and hole concentration δp are given by:

$$\delta n = \frac{\delta N}{(1 + I_n)}, \qquad \delta p = \frac{\delta N}{\left(1 + I_p\right)}, \tag{2-24}$$

where

I_n and I_p are electron and hole trap respectively.

$$\delta N = G_o \tau_R, \tag{2-25}$$

where G_0 is the optical generation rate of free carriers and τ_g is the steady-state free carrier recombination/generation lifetime given by:

$$\tau_g = \frac{2\tau_{Ro}\tau_K}{\tau_{Ro} + \tau_k}, \tag{2-26}$$

where τ_k is constant of time given by:

$$\tau_k = \frac{\tau_{Ro}}{\sqrt{1 + 4C_R G_o \tau_{Ro}^2}} \tag{2-27}$$

and

$$\tau_{R0} = \frac{1}{C_R(n_o + p_o)}. \quad (2\text{-}28)$$

At steady-state, we have:

$$\delta n \approx \frac{2G_o\tau_{Ro}\tau_k}{\tau_{Ro} + \tau_k}. \quad (2\text{-}29)$$

2.6.2 Auger recombination

Auger recombination is the inverse of impact ionization, with the energy loss occurring via electron-electron or hole-hole collisions. For small band gap semiconductors such as GaSb, the minority carrier lifetime is usually controlled by band-to-band Auger recombination. 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.

The band to-band Auger recombination rate under non-thermal equilibrium conditions is given by:

$$R_A = C_{pa}p^2n + C_{na}n^2p. \quad (2\text{-}30)$$

The thermal equilibrium Auger recombination rate is hence:

$$R_{A0} = (C_{pa}n_o + C_{na}p_o)n_i^2, \quad (2\text{-}31)$$

where C_{pa} and C_{na} are the Auger capture coefficients for holes and electrons, respectively, which can be calculated at thermal equilibrium from their inverse process (i.e. impact ionization). This takes into account the fact that, in thermal equilibrium, the rate at which carriers recombine via Auger recombination equals the generation rate in which EHPs are generated by impact ionization, averaged over the Boltzmann distribution function.

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 [27, 30].

$$C_{na} = \frac{8e^4(2\pi)^{\frac{5}{2}}}{h^3(4\pi\epsilon n_i)^2}\left(\frac{m_n^*|F_1F_2|^2}{(1+2\mu)\sqrt{1+\mu}}\right)\left(\frac{k_BT}{E_g}\right)^{\frac{3}{2}}\exp\left[-\left(\frac{1+2\mu}{1+\mu}\right)\frac{E_g}{k_BT}\right], \quad (2\text{-}32)$$

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 $10^{-(29\pm1)}\text{cm}^6\text{s}^{-1}$. The value used for the analysis of n-type GaSb in the present work is of the same order as these reported values [3].

As reported by several authors, the spin-split off valence band plays a far more important role than the light-hole valence band for n-type direct band gap materials, especially when the band gap energy, E_g approaches the spin-orbit splitting ΔE_{os}. 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 $2.5 \times 10^{-29}\text{cm}^6\text{s}^{-1}$ 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 ΔE_{os} are nearly equal, Auger recombination due to valence band splitting seems to be favored 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 [15, 27]:

$$C_{pa} = \begin{cases} ABx^2e^2\dfrac{2}{\sqrt{\pi}}\left[\Gamma\left(\dfrac{5}{2},\mu x\right)\right] - \dfrac{2\Gamma\left(\dfrac{7}{2},\mu x\right)}{\mu x} + \dfrac{\Gamma\left(\dfrac{9}{2},\mu x\right)}{\mu x}, & \text{for } E_g \geq \Delta E_{os}, \\ AB\left[\dfrac{35}{(2\mu x)^2}\right], & \text{for } E_g = \Delta E_{os}, \\ ABx^2e^2\dfrac{3}{2}\left[1 - \dfrac{5}{\mu x} + \dfrac{35}{(2\mu x)^2}\right], & \text{for } E_g \leq \Delta E_{os}, \end{cases} \tag{2-33}$$

Where

$$\begin{cases} x = \dfrac{E_g - \Delta E_{os}}{k_B T}, \quad \mu = \dfrac{2m_P^* + m_C^*}{2m_P^* + m_C^* - m_{S0}^*}, \qquad \Gamma(a, x_o) = \displaystyle\int_{x_o}^{\infty} e^{-t}\, t^{a-t} dt \\ A = \dfrac{h^3 e^4}{(2m_n k_\infty)^2}\left(\dfrac{m_P^*}{m_V^*}\right)\left(\dfrac{m_{SO}^*}{2m_P^* + m_C^*}\right)^{\frac{3}{2}}, \qquad B = \dfrac{E_p^2\left(1 + \dfrac{m_{SO}^*}{m_n}\right)}{9E_g^2\ \Delta E_{0S}^2\left(E_g + \Delta E_{0S}\right)} \end{cases} . \tag{2-34}$$

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 22.4 eV. The temperature dependence of the valence band split-off energy ΔE_{0S} (eV) is given by Haug as [30]:

$$\Delta E_{SO}(T) = 0.743 + \frac{1.89 \times 10^{-4} T^2}{T + 94}. \tag{2-35}$$

And $E_g(T)$ is given in Eqn. (2-1).

Since C_{pa} is dominant in p-type GaSb, the simplified form of the Auger recombination rate, U_A, for photo-generated carrier is found by the difference between Eqns. (2-30) and (2-31):

$$U_A \approx \frac{\delta n}{\tau_{A0}} + k_A \delta n^2 + C_A \delta n^3. \tag{2-36}$$

and the Auger recombination lifetime for excess carriers is then given by:

$$\tau_A = \frac{\tau_{A0}}{1 + \tau_{A0}(k_A \delta n + C_A \delta n^2)}, \tag{2-37}$$

where

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

$$k_A = C_{pa}(2p_0 + n_0) + C_{na}(2n_0 + p_0).$$

For narrow band gap p-type semiconductors, Auger recombination due to valence band splitting is favored, $C_{pa} \gg C_{na}$, so that, $\tau_{A0} \approx \frac{1}{C_{pa} p_0^2}$, $k_A \approx 2C_{pa} p_0$, and $C_A = C_{pa}$.

Next, 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:

$$G_0 \approx U_A \approx \frac{\delta n}{\tau_{A0}} + k_A \delta n^2 + C_A \delta n^3. \tag{2-38}$$

For high injection levels, the cubic term in the density of the excess carrier on the right side of Eqn. (2-38) dominates and hence, $G_0 = U_A = C_A \delta n^3$, so that [3]:

$$\delta n \approx \sqrt[3]{\frac{G_0}{C_A}} \text{ and } \tau_A = \frac{\delta n}{G_0} \approx \frac{1}{\sqrt[3]{G_0^2 C_A}}. \tag{2-39}$$

For low injection levels, the linear term in the density of the excess carrier on the right side of Eqn. (2-38) dominates, so that $G_0 = U_A = \frac{\delta n}{\tau_{A0}}$ and hence:

$$\delta n \approx G_0 \tau_{A0} \quad \text{and} \quad \tau_A \approx \frac{\delta n}{G_0} = \tau_{A0}. \tag{2-40}$$

2.6.3 Shockley-Read-Hall recombination

In the non-radiative recombination process, the recombination of electron-hole pairs may take place at the localized trap states in the forbidden gap of a semiconductor. This process involves the capture of electrons (or holes) by the trap states, followed by the recombination with holes in the valence band (or electrons in the conduction band). When electron-hole pairs recombine, energy is released via phonon emission. The localized trap states may be created by the deep-level impurities (e.g., transition metals or normal metals such as *Fe, Ni, Co, Au*, etc.), or by radiation- and process-induced defects such as vacancies, interstitials, antisite defects and their complexes, dislocations, and grain boundaries. The nonradiative recombination process in a semiconductor can be best described by the Shockley-Read-Hall (SRH) model, [31, 32].

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. Once the trap is filled it cannot accept another electron. The electron occupying the trap, in a second step, falls into an empty valence band state, thereby completing the recombination process. One can envision this process as a two-step transition of an electron from the conduction band to the valence band or as the annihilation of the electron and hole, which meet each other in the trap. We will refer to this process as Shockley-Read-Hall (SRH) recombination. The rate equations, which describe the SRH model can be derived from the four emission and capture processes shown in figure 1. In deriving the SRH model, it is assumed that the semiconductor is nondegenerate and that the density of trap states is small compared to the majority carrier density [3, 29].

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 center. If the localized state captures free carriers temporarily and then re emits them back to their original band, the center is called a free carrier trap [29].

Figure 1 illustrates the energy band diagram with electrons trap localized state. In this figure, the four transition processes for the capture and emission of electron and holes via the localized state are shown. The probability of capture and emission of the electron by the center are represented by U_{cn} and U_{en} and those of hole capture and emission are described by U_{cp} and U_{ep} , 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 center 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. 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 [3]*:*

$$N_T = n_T + p_T. \tag{2-41}$$

In other words, a center 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 center are all functions of time. The appropriate equations for electrons will be developed in detail, and the equations for holes will merely be stated, since these are analogous

to those of electrons. 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 1. The distribute on probability f_n for the electron occupation of a trap located at energy E_T in the band gap is derived using Fermi-Dirac statistics:

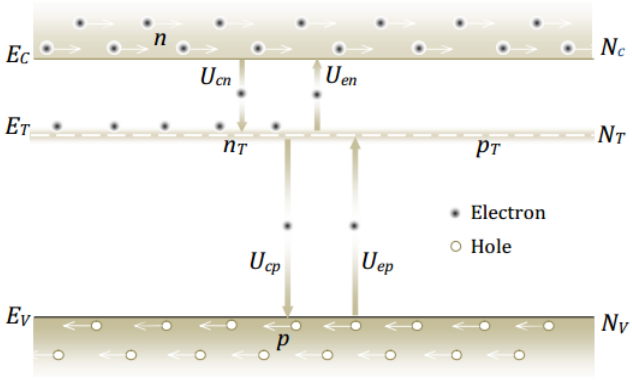

Figure 1: Energy band diagram with a localized trap [15, 33]

$$f_n(T) = \frac{1}{1 + \exp\left(\frac{E_T - E_F}{k_B T}\right)}. \qquad (2\text{-}42)$$

The thermal equilibrium electron occupancy (n_{0T}) and hole occupancy (p_{0T}) of the localized state are given by [15]:

$$n_{0T} = f_n N_T = \frac{N_T}{1 + \exp\left(\frac{E_T - E_F}{k_B T}\right)}, \qquad p_{0T} = N_T - n_{0T}. \qquad (2\text{-}43)$$

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:

$$U_{cn} = C_{nT} n_0 p_{0T}\,, \qquad U_{en} = e_n n_{0T}. \qquad (2\text{-}44)$$

$$U_{cn} = C_{nT} n_0 p_{0T} = C_{nT} n_0 N_T (1 - f_n)\,, \quad U_{en} = e_n n_{0T} = e_n N_T f_n. \qquad (2\text{-}45)$$

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

$$U_{cp} = C_{pT} p_0 n_{0T}\,, \qquad U_{ep} = e_p p_{0T}. \qquad (2\text{-}46)$$

$$U_{cp} = C_{pT} p_o n_{OT} = C_{pT} p_o N_T f_n\,, \qquad U_{ep} = e_p p_{OT} = e_p N_T (1 - f_n). \qquad (2\text{-}47)$$

Where e_p the hole emission rate, the hole capture coefficient (C_{pT}) depends on the proximity of the center to the valance band. According to the principle of detailed balance, the probability of capture and emission for each carrier is equal, so that we have:

$$U_{cn} = U_{en}\,, \qquad U_{cp} = U_{ep}\,. \tag{2-48}$$

Taking in to account Eqns. (2-44) through (2-48) yields:

$$e_n = \frac{C_{nT} n_0 p_{0T}}{n_{0T}}\,, \qquad e_p = \frac{C_{pT} p_0 n_{0T}}{p_{0T}}. \tag{2-49}$$

$$e_n = \frac{C_{nT} n_0 (1 - f_n)}{f_n}, \qquad e_p = \frac{C_{pT} p_0 f_n}{(1 - f_n)} \tag{2-50}$$

From Eqn. (2-50) one obtains:

$$e_n e_p = C_{nT} C_{pT} n_o p_o = C_{nT} C_{pT} {n_i}^2 \tag{2-51}$$

The density of electrons (n_0) and the density of holes (p_0) for the non-degenerate semiconductors are given by:

$$n_0 = N_c \exp\left(-\frac{E_c - E_F}{k_B T}\right), \qquad p_0 = N_v \exp\left(-\frac{E_F - E_v}{k_B T}\right). \tag{2-52}$$

Since the non-degenerate relations are obviously valid for an intrinsic semiconductor where the Fermi level, E_F is equal to the intrinsic level energy, E_i in the semiconductor, one can write from Eqn. (2-52):

$$n_i = N_c \exp\left(-\frac{E_c - E_i}{k_B T}\right) = N_v \exp\left(-\frac{E_i - E_v}{k_B T}\right). \tag{2-53}$$

Eliminating N_c and N_v among Eqns. (2-52) and (2-53) yields:

$$n_0 = n_i \exp\left(-\frac{E_c - E_F}{k_B T}\right), \quad p_0 = n_i \exp\left(-\frac{E_F - E_v}{k_B T}\right). \tag{2-54}$$

From Eqn. (2-42) one can drive for $\frac{(1-f_n)}{f_n}$ *and* $\frac{f_n}{(1-f_n)}$ as:

$$\frac{(1 - f_n)}{f_n} = \exp\left(\frac{E_T - E_F}{k_B T}\right), \quad \frac{f_n}{(1 - f_n)} = \exp\left(\frac{E_F - E_T}{k_B T}\right). \tag{2-55}$$

Now solving Eqns. (2-50) and (2-55) one obtains the electron emission rate and the hole emission rate:

$$e_n = C_{nT} n_1\,, \qquad e_p = C_{pT} p_1, \tag{2-56}$$

where

$$n_1 = n_i \exp\left(\frac{E_T - E_i}{k_B T}\right) \quad \text{and} \quad p_1 = n_i \exp\left(\frac{E_i - E_T}{k_B T}\right), \tag{2-57}$$

are the concentrations of electrons and holes in the conduction and valence bands for the case in which the Fermi-level (E_F) falls at E_i.

Also expressions for n_1 and p_1 are given respectively by:

$$n_1 = n_0 \exp\left(\frac{E_T - E_F}{k_B T}\right), \quad p_1 = p_0 \exp\left(\frac{E_F - E_T}{k_B T}\right). \tag{2-58}$$

Solving Eqn. (2-58) yields:

$$n_1 p_1 = n_0 p_0 = {n_i}^2. \tag{2-59}$$

If the equilibrium is now disturbed by illumination, the photo-generated electrons and holes are involved in the recombination processes. The concentrations of photo generated electrons the conduction band (δn) and holes in the valance band (δp) are given by:

$$\delta n = n - n_0, \quad \delta p = p - p_0. \tag{2-60}$$

The respective changes the concentrations of n_T and p_T states of a center due to illumination, δn_T and δp_T, is given by the difference between the electron and hole occupancies during and without illumination:

$$\delta n_T = n_T - n_{0T}, \quad \delta p_T = p_T - p_{0T}. \tag{2-61}$$

Since the defect concentration does not vary with illumination, Eqn. (2-41) holds true for both thermal and the non-thermal equilibrium conditions. That is:

$$N_T = n_{0T} + p_{0T} = n_T + p_T. \tag{2-62}$$

When we rearranging Eqn. (2-62) and uses the relation in Eqn. (2-61) yields:

$$n_{0T} + p_{0T} = \delta n_T + n_{0T} + \delta p_T + p_{0T}, \tag{2-63}$$

$$(n_{0T} + p_{0T}) - (n_{0T} + p_{0T}) = \delta n_T + \delta p_T, \tag{2-64}$$

$$\delta n_T + \delta p_T = 0, \tag{2-65}$$

$$\delta n_T = -\delta p_T. \tag{2-66}$$

Equation (2-66) shows that the trapping of electrons by the localized state removes the same amount of states. Trapping of electrons by the trap center will reduce the concentration of excess electrons in the conduction band, so that the probability of holes' recombination with conduction band electrons is also reduced. This enhances the concentration of excess holes in the valence band.

Suppose that δN density of electron hole pairs is generated due to illumination in a semiconductor with electrons trap center; the total concentrations of excess electrons (δn) and holes (δp) in the respective conduction and valence bands are then given by:

$$\delta n = \delta N - \delta n_R - \delta n_T, \quad \delta p = \delta N - \delta n_R. \tag{2-67}$$

Rearranging Eqn. (2-67) yields:

$$\delta N = \delta n + \delta n_R + \delta n_T, \quad \delta N = \delta p + \delta n_R. \tag{2-68}$$

Where δn_R the concentration of electron hole pairs involved in the recombination process at the center. Elimination of $\delta n_R - \delta n_T$ in between the relations in Eqn. (2-67) gives the photo-generated charge carrier neutrality equation for the system with an electron trap center to be:

$$\delta n = \delta N - \delta n_R - \delta n_T, \quad \delta n = \delta p - \delta n_T. \tag{2-69}$$

$$\delta n + \delta n_T = \delta p. \tag{2-70}$$

Similarly, the equation for a system with a hole trap center is:

$$\delta n = \delta p + \delta p_T. \tag{2-71}$$

In a system with dominant recombination through the impurity level, the rate of electron accumulation (dn/dt) in the conduction band is given in terms of the total generation rate (G), the rate of electron emission (U_{en}), and the rate of electron capture (U_{cn}), by the localized state:

$$\frac{dn}{dt} = G - (U_{cn} - U_{en}). \tag{2-72}$$

The rate of hole accumulation (dp/dt) in the valence band is also given in similar way as:

$$\frac{dp}{dt} = G - \left(U_{cp} - U_{ep}\right). \tag{2-73}$$

Equations (2-72) and (2-73) involve the accumulation of the total free charge carriers (thermal equilibrium and photo-generated). The terms in the bracket at the right sides of both Eqns. (2-72) and (2-73) represent the rates of flow of free carriers from the respective conduction and valence bands to the localized Centre. For an electron trap center, $(U_{cn} - U_{en})$ involves both the accumulation and recombination rates of electrons at the localized center, and $\left(U_{cp} - U_{ep}\right)$ involves only the recombination of holes at the center. When Eqns. (2-72) and (2-73) are simplified by eliminating the contribution of the thermal equilibrium conditions (applying the principle of Detailed Balance) using Eqns. (2-60) to (2-71). The rates of accumulation of photo generated charge carriers in the conduction and the valence bands were therefore found to be:

$$\frac{d\delta n}{dt} = G_0 - (U_{c\delta n} - U_{e\delta n}), \quad \frac{d\delta p}{dt} = G_0 - \left(U_{c\delta p} - U_{e\delta p}\right), \tag{2-74}$$

where G_0 the optical generation rate. The term $(U_{c\delta n} - U_{en})$ in Eqn. (2-74) involves the sum of the SRH recombination rate with trapping effect (U'_{SRH}) and the rate of accumulation photo-generated electrons ($d\delta n_T/dt$) at the localized center given by:

$$(U_{c\delta n} - U_{en}) = C_{nT}[p_{0T}\delta n - (n_0 + \delta n + n_1)\delta n_T] = U'_{SRH} + \frac{d\delta n_T}{dt}. \tag{2-75}$$

and the term $\left(U_{c\delta p} - U_{e\delta p}\right)$ in Eqn. (2-74) involves only the SRH recombination rate (U'_{SRH}) of the photo generated holes at the center:

$$\left(U_{c\delta p} - U_{ep}\right) = C_{nT}[n_{0T}\delta p - (p_0 + \delta n + p_1)\delta n_T] = U'_{SRH}. \tag{2-76}$$

The accumulation of free carriers in the respective conduction and valence bands are then given using Eqns. (2-74) to (2-76) as:

$$\frac{d\delta n}{dt} = G_0 - C_{nT}[p_{0T}\delta n - (n_0 + \delta n + n_1)\delta n_T] = G_0 - U'_{SRH} + \frac{d\delta n_T}{dt}. \tag{2-77}$$

$$\frac{d\delta p}{dt} = G_0 - (C_{nT}[n_{0T}\delta p - (p_0 + \delta n + p_1)\delta n_T]) = G_0 - U'_{SRH}. \tag{2-78}$$

The rate of accumulation of photo-generated electrons at the localized center can be derived using Eqns. (2-75) and as:

$$\frac{d\delta n_T}{dt} = C_{nT}[p_{0T}\delta n - (n_0 + \delta n + n_1)\delta n_T] - [n_{0T}\delta p - (p_0 + \delta n + p_1)\delta n_T]. \tag{2-79}$$

Under the steady-state condition, the net rate of electron capture per unit volume may be found by solving Eqns. (2-3) through (2-51) and (2-59) which yields:

$$U_n = U_{cn} - U_{en} = C_{nT}N_T[n(1 - f_n) - n_1 f_n]. \tag{2-80}$$

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

$$U_p = U_{cp} - U_{ep} = C_{pT}N_T[pf_n - n_1(1 - f_n)]. \tag{2-81}$$

The excess carrier lifetimes under steady-state conditions are defined by the ratio of the excess carrier density and the net capture rate for electrons and holes, and are given respectively by:

$$\tau_n = \frac{\delta n}{Un}, \qquad \tau_p = \frac{\delta p}{U_p}. \tag{2-82}$$

For the small injection case (i.e. δn $\ll n_0$ and δp $\ll p_0$), the charge-neutrality condition requires that:

$$\delta n = \delta p. \tag{2-83}$$

Under steady-state conditions, if one assumes that the net rates of electron and hole capture via a recombination center are equal, then one can write:

$$U = U_n = U_p. \tag{2-84}$$

Substituting Eqns. (2-83) and (2-84) into Eqn. (2-82) one finds that the electron and hole lifetimes are equal (i.e. $\tau_n = \tau_p$) for the small injection case. The electron distribution function, f_n at the trap level can be expressed in terms of the electron and hole capture coefficients as well as the electron and hole densities. Now solving Eqns. (2-80), (2-81) and (2-83), one obtains:

$$f_n = \frac{C_{nT} n + C_{pT} p_1}{C_{nT}(n + n_1) + C_{pT}(p + p_1)}. \tag{2-85}$$

A general expression for the net recombination rate can be obtained by substituting Eqn. (2-85) into Eqn. (2-80) or (2-81) and the result yields:

$$U = U_n = U_p = \frac{(np - {n_i}^2)}{\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)}, \tag{2-86}$$

where τ_{p0} and τ_{n0} are given respectively by:

$$\tau_{p0} = \frac{1}{C_{pT} N_T}, \qquad \tau_{n0} = \frac{1}{C_{nT} N_T}, \tag{2-87}$$

where $C_{pT} = \sigma_p v_{th,p}$ and $C_{nT} = \sigma_n v_{th,n}$ denote the hole and electron capture coefficients.

The capture cross section of hole and electron are given respectively by:

$$\sigma_p = \sigma_{p\infty} \exp\left(-\frac{E_T - E_V}{k_B T}\right), \qquad \sigma_n = \sigma_{n\infty} \exp\left(-\frac{E_c - E_T}{k_B T}\right), \tag{2-88}$$

where the constant $\sigma_{p\infty} = 10^{16} cm^2$ and $\sigma_{n\infty} = 10^{15} cm^2$.

And the average thermal velocity of electrons or holes given by [14]:

$$\mathrm{v_{th,n/p}} = \left(3k_B T / m^*\right)^{\frac{1}{2}}. \tag{2-89}$$

τ_{p0} is the minority hole lifetime for an n-type semiconductor, and τ_{n0} is the minority electron lifetime for a p-type semiconductor [14].

The lifetime τ_{n0} is often called the minimum lifetime for electrons when all the localized states are empty, and τ_{p0} is the minimum lifetime for holes when all localized states are occupied by electrons. Since the trapping of free carriers in the bulk of the semiconductor can have significant

effects on the total recombination of charge carriers, the statistics of free carriers trapped in the bulk of a given semiconductor needs to be evaluated under different conditions. Hence, the density of the excess electrons trapped at the localized center can be simplified as [34, 27]:

$$\delta n_T = \frac{(\tau_{p0} p_{0T} - \tau_{n0} n_{0T})\delta p}{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + p_{0T} + \delta p)}. \quad (2\text{-}90)$$

The total concentration of excess holes in the valence band is then given by using Eqns. (2-70) and (2-90) as:

$$\delta p \approx \frac{[\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + p_{0T} + \delta p)]\delta n}{\tau_{n0}(p_0 + p_1 + n_{0T} + \delta p) + \tau_{p0}(n_0 + n_1 + \delta p)}. \quad (2\text{-}91)$$

The fraction of photo-generated electrons trapped at the localized Centre to the excess electrons in the conduction band is given by:

$$I_n = \frac{\delta n_T}{\delta n} = \frac{(\tau_{p0} p_{0T} - \tau_{n0} n_{0T})}{\tau_{n0}(p_0 + p_1 + n_{0T} + \delta N) + \tau_{p0}(n_0 + n_1 + \delta N)}. \quad (2\text{-}92)$$

Taking into account Eqn. (2-66), (2-91) and (2-92) gives the fraction of trapped photo generated holes at the localized trap state to the excess holes in the valence band energy to be:

$$I_p = \frac{\delta p_T}{\delta p} = \frac{(\tau_{n0} n_{0T} - \tau_{p0} p_{0T})}{\tau_{n0}(p_0 + p_1 + \delta P) + \tau_{p0}(n_0 + n_1 + p_{0T} + \delta P)}. \quad (2\text{-}93)$$

The subscripts n and p in Eqns. (2-92) and (2-93) represent the electrons and holes concentration. For low injection levels of carriers $N_T, p_0, p_1, n_1 \gg \delta n$, Eqns. (2-92) and (2-93) gives:

$$I_n = \frac{(\tau_{p0} p_{0T} - \tau_{n0} n_{0T})}{\tau_{n0}(p_0 + p_1 + n_{0T}) + \tau_{p0}(n_0 + n_1)}, \quad (2\text{-}94)$$

and

$$I_p = \frac{(\tau_{n0} n_{0T} - \tau_{p0} p_{0T})}{\tau_{n0}(p_0 + p_1) + \tau_{p0}(n_0 + n_1 + p_{0T})}. \quad (2\text{-}95)$$

The fraction of photo-generated hole in the valence band energy is then given by using:

$$I_P = \frac{\delta p}{\delta P} = \frac{\tau_{n0}(p_0 + p_1 + \delta P) + \tau_{p0}(n_0 + n_1 + p_{0T} + \delta P)}{\tau_{n0}(p_0 + p_1 + n_{0T} + \delta P) + \tau_{p0}(n_0 + n_1 + \delta P)}. \quad (2\text{-}96)$$

The fraction of photo-generated electrons in the conduction band is then given by using:

$$I_N = \frac{\delta n}{\delta N} = \frac{\tau_{n0}(p_0 + p_1 + n_{0T} + \delta N) + \tau_{p0}(n_0 + n_1 + \delta N)}{\tau_{n0}(p_0 + p_1 + n_{0T} + \delta P) + \tau_{p0}(n_0 + n_1 + \delta P)}. \quad (2\text{-}97)$$

Applying the steady-state condition to Eqns. (2-75) and (2-76) and eliminating δn_T in between the two relations gives the SRH recombination rate in terms of δn and δp as:

$$U'_{SRH} = \frac{(n_0 + \delta n)\delta p + p_0 \delta n}{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + \delta n)}. \quad (2\text{-}98)$$

or applying Eqns. (2-70) and (2-92) to Eqn. (2-98) recombination rate can be described in terms of only as:

$$U'_{SRH} = \frac{(n_0 + \delta p(1 + I_n)^{-1})\delta p + p_0 \delta p(1 + I_n)^{-1}}{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + \delta p(1 + I_n)^{-1})}. \quad (2\text{-}99)$$

The excess electron SRH lifetimes with the trapping effect, τ'_{SRH} is derived using Eqn. (2-98) or Eqn. (2-99) as:

$$\tau'_{nSRH} = \frac{\delta n}{U'_{SRH}} = \frac{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + \delta n)}{(p_0 + (n_0 + \delta n)\delta p/\delta n}. \quad (2\text{-}100)$$

Or

$$\tau'_{nSRH} = \frac{\tau_{n0}(p_0 + p_1 + \delta p)(1 + I_n) + \tau_{p0}(n_0 + n_1)(1 + I_n) + \delta p)}{(p_0 + n_0(1 + I_n) + \delta p)(1 + I_n)}. \quad (2\text{-}101)$$

The excess hole SRH lifetime with the trapping effect, τ'_{pSRH} is hence takes the form:

$$\tau'_{pSRH} = \frac{\delta p}{U'_{SRH}} = \frac{\delta p \delta n}{\delta n U'_{SRH}} = (1 + I_n)\tau'_{nSRH} \quad . \quad (2\text{-}102)$$

Using Eqns. (2-98) and (2-99) along with Eqn. (2-102), one can easily show that:

$$\tau'_{pSRH} = \frac{\delta p}{U'_{SRH}} = \frac{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + \delta n)}{n_0 + (p_0 + \delta n)\delta n/\delta p} \quad (2\text{-}103)$$

or

$$\tau'_{pSRH} = \frac{\tau_{n0}(p_0 + p_1 + \delta p)(1 + I_n) + \tau_{p0}(n_0 + n_1)(1 + I_n) + \delta p)}{p_0 + n_0(1 + I_n) + \delta p}. \quad (2\text{-}104)$$

Once the excess minority carrier (electron) lifetime is determined for any process in steady state, the corresponding excess majority carrier (hole) lifetime can be calculated by multiplying the excess electron lifetime with$(1 + I_n)$. This discussion will therefore continue for the excess electron lifetime in *p*-type materials [27, 29].

Chapter 3

Methodology

For the analysis of the effects of free carriers trap on the recombination mechanism through the localized states in the materials for this work, Gallium antimonide (GaSb) was found to be suitable for its small and direct band gap, very high carrier densities, mobility and its very high purity. The statistics for the rate of accumulation of free carriers at different energy levels including the conduction band, valance band other localized states in the band gap is formulated. 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 minority carrier concentration, n_0 is determined from p_0 and the intrinsic carrier concentration using the law of mass action for a particular semiconductor.

The typical carrier capture coefficients used in the analysis were 3.02×10^{-11} $cm^{-3}s^{-1}$ for radiative recombination, 2.44×10^{-26} $cm^{6}s^{-1}$ for Auger holes' capture, 1.538×10^{-28} $cm^{6}s^{-1}$ for Auger electron capture and 1×10^{-21} to 1×10^{-9} for SRH electron capture and 1×10^{-23} to 1×10^{-10} for SRH hole capture.

Based on which carriers trap is dominating the entire process, the statistics for SRH recombination mechanism for excess holes and electrons would be formulated through different localized states. By combining the statistics for the accumulation of free holes and electrons in the respective valence band and conduction band, the statistics for the free carriers trapping at different levels were obtained in terms of the free carriers in the valence and the conduction band.

The effects of trapping on the SRH excess carrier lifetime was studied by substituting the density of the trapped carriers in the relations describing the recombination mechanisms. The effect of the temperature on the density of the carriers trapped at different localized states also studied. The radiative lifetime (τ_R), Auger lifetime (τ_A) and SRH lifetime (τ_{SRH}) for excess carriers in p-type GaSb material are determined as functions of localized state at different temperatures. We calculated and plotted all graphs by Microsoft excel and origin using the standard formulas.

Chapter 4

Results and discussion

In this chapter deals with the analysis, discussion and the results of this thesis. First, the trapping effects at room and at various temperatures in different regions of semiconductor (GaSb) were analyzed (invented). Next, the computation of radiative, Auger and SRH recombination mechanisms through their recombination lifetimes described. Finally, the radiative lifetime (τ_R), Auger lifetime (τ_A) and SRH lifetime (τ_{SRH}) for excess carriers in p-type GaSb material were analyzed as functions of localized state energy.

4.1 The temperature dependence of trapping effects

Figure 2 (a) and (b) illustrates the trap effects I_n and I_p as functions of energy position of the trap level for un-doped p-type gallium antimonide (GaSb), (a) at 300 K and (b) at different temperatures. The graphs are drawn using Eqns. (2-94) and (2-95), for a continuous distribution of impurity states with uniform trap level concentrations equal to the carrier concentration throughout the bulk. This helps to understand the interplay between different localized states and the free carrier concentrations at different temperatures. Figure 2 (a) shows both the effects of the majority and minority carrier traps at a relatively room temperature (300 K). These result analyzed by fixing the total density of localized state value at $N_T = 10^{17} cm^{-3}$, doping level at $N_a = 10^{18} cm^{-3}$ value and injection level $G_0 = 0$.

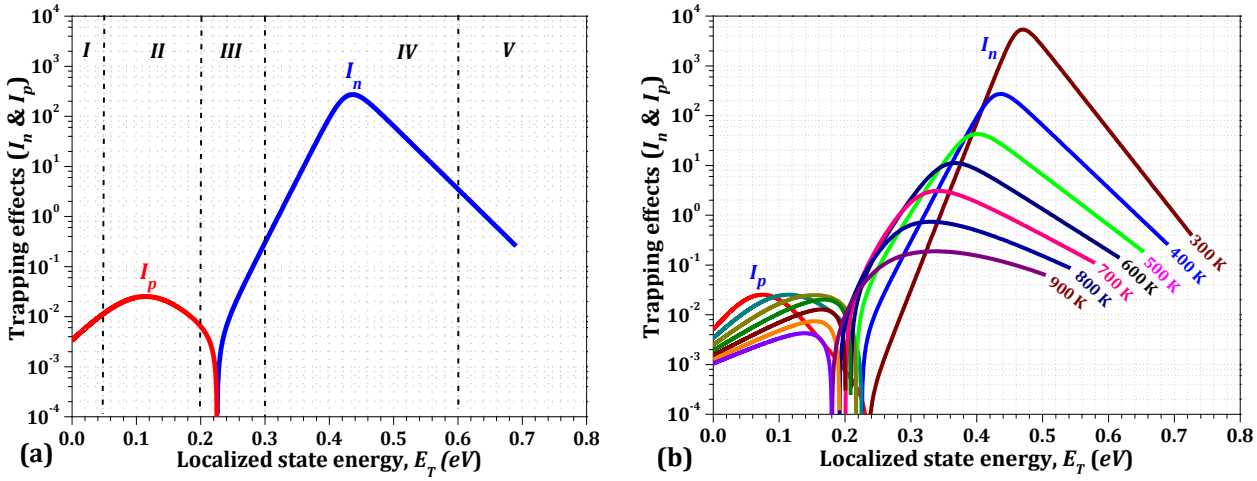

Figure 2: The free carriers trapping effect as a function of energy of the trap level for (a) room and (b) different temperatures.

In general, free carrier traps are relatively inactive at high temperatures compared to low temperatures. Only deep levels can trap free carriers at higher temperatures as shown in Figure 2 (a). The minority carrier traps farther away above the intrinsic level become more effective with decreasing temperature as shown in Figure 2 (b). Depending on the interactions of localized states with the conduction or valence bands, the energy level dependence plot of the trap in Figure 2 (a) can be divided into five regions labelled I through V.

Region I: This region including all the energy levels very close to the valence band edge (from valance band energy to 0.05 eV). The energy value of this region is approximately equal or less than to thermal energy k_BT. Most of the impurities are in the n_T state (When we compare the density of states n_{0T} with p_{0T}, the n_{0T} state is much greater than p_{0T}) and the hole emission rate is very high. Hence the effects of the traps of a localized center in both Eqns. (2-94) and (2-95), become negligibly small in this region. The localized centers hence act as acceptor levels. Therefore, the region is in n_{0T} state and we can call this region acceptor region.

Region II: This region includes all the energy levels far above the valence band edge and far below the intrinsic Fermi level (from the localized energy level 0.05 eV to 0.2 eV). The energy value of this region is much greater than thermal energy k_BT or ($E_T \gg k_BT$). In this region the capture cross section of holes much greater than capture cross section of electrons ($\sigma_p \gg \sigma_n$). When we compare the density of states (n_{0T} with p_{0T}), n_{0T} is greater than p_{0T} ($n_{0T} > p_{0T}$). Since the capture cross section represents the probability of traps can be capturing the free carries, the probability of hole capture is greater than the probability of electron capture and emission rate of holes are decreased in this region. In this region specially from the energy level 0.08 eV to 0.15 eV, hole trapping has maximum values and thus the hole trapping effect becomes dominant as shown in Figure 2a. Therefore, we can call this region holes trapping region.

Region III: This region consists all the energy trap level very closer to the intrinsic Fermi level in both sides, where the localized levels are partially ionized. According to this sample the range of the region includes trap center from the energy level 0.2 eV to 0.3 eV. In this region almost the capture cross section of holes and capture cross section of electrons are equal ($\sigma_p = \sigma_n$). So that the effects of free charge carrier traps are negligibly small as shown in Figure 2 above and the probability of hole capture is equal to the probability of electron capture. The SRH recombination

becomes dominant in this region *i.e.* recombination takes place. Therefore, we have called this region recombination region.

Region IV: This region including all the energy levels that are very close to the intrinsic Fermi level and most of the regions far below the conduction band energy (from the energy level 0.3 eV to 0.6 eV). In this region specially at the energy level equal to 0.42 eV, the electron trapping has maximum values. Most localized states are in the p_T state and the electron capture rate is very high and in this region the capture cross section of electrons much greater than capture cross section of holes ($\sigma_n \gg \sigma_p$). When we compare the density of states (p_{0T} with n_{0T}), n_{0T} is greater than p_{0T} ($n_{0T} > p_{0T}$). So, the probability of capture electron is greater than the probability of hole capture or emission rate of electron are high in this region. The electron trap effect becomes the most dominant as shown in Figure 2a. The levels of the effective electron traps at room temperature is in complete agreement with the results reported by Habegger et al in p-type GaSb samples. Therefore, we have called this region electron trap region.

Region V: This region including all the localized energy levels (from 0.6 eV to conduction band energy) which is closer to the conduction band edge. The energy value of this region is approximately equal or less than to thermal energy $k_B T$. Most of the impurities are in the p_T state (When we compare the density of states n_{0T} with p_{0T}, the p_{0T} state is much greater than n_{0T}) and the electron emission rate is very high. Hence the effects of the traps of a localized center in both Eqns. (2-94) and (2-95), become negligibly small in this region. The localized centers hence act as donor levels. Therefore, the region is in p_{0T} state and we can call this region donor region.

Generally, we can analyze that the localized energy found between the value from valance band edge to 0.05 eV has no carriers trap, the localized energy levels found between 0.05 eV to 0.2 eV, has high hole traps and 0.3 eV to 0.6 eV has high electron trap and the value from conduction band edge to 0.6 eV has no carriers traps for semiconductor material (GaSb) samples. And as the temperature is increases, the trap effect is decreasing.

4.2 The computation between the radiative, Auger and SRH recombination lifetimes

Figure 3 illustrates the radiative, Auger and SRH recombination mechanisms through their recombination lifetimes at room temperature as a function of localized state energy in gallium antimonide samples (a) excess electrons lifetime and (b) excess hole lifetime. These result

analyzed by fixing the total density of localized state value at $N_T = 10^{17} cm^{-3}$, doping level at $N_a = 10^{18} cm^{-3}$ value and injection level $G_0 \approx 0$ (low injection level).

From Figure 3 (a) the minority carrier SRH lifetime (blue line) is the largest one and it depends on the energy of localized states i.e. there is no recombination and trapping of carriers for localized levels near to the valence and conduction band edges (acceptor and donor region). Also, this tells us the SRH excess recombination rate U_{SRH} is much smaller than excess recombination rate of radiative (U_R) and Auger (U_A), since the carrier lifetimes calculated by the ratio of carrier concentration (δn) to recombination rate (U_{SRH}) as predict earlier in Eqn. (2-100) or (2-101). Again, from Figure 3 (a) shows the minority carrier (electron) radiative lifetime (black line) is the larger one and the Auger lifetime (red line) the smallest and both are independent of the energy of localized states.

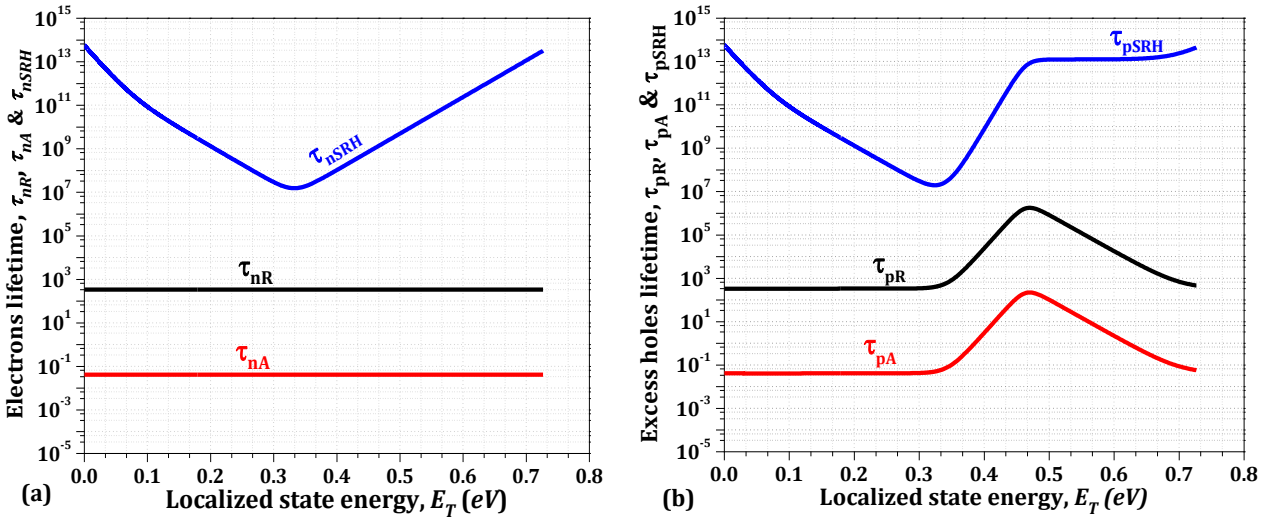

Figure 3: The computation between radiative, Auger and SRH recombination mechanisms as function of localized state energy for (a) the excess electron (b) the excess hole lifetimes.

The minority carrier radiative lifetime is larger and it is constant over the whole region which is independent of the localized state energy. This tells us radiative excess minority carrier lifetime under the localized region or forbidden gap is remain constant for all localized energy level as shown in Figure 3 (a). The minority carrier Auger lifetime is small and other explanation is similar to radiative lifetime (see Figure 3 (a)). Both radiative and Auger excess carrier lifetime in the localized region (valance to conduction band) in the semiconductor material (GaSb) remain constant at different localized energy levels. The Auger excess minority carrier lifetime

in the semiconductor material (GaSb) dominate at different localized energy levels as shown Figure 3a.

From Figure 3 (b) majority carrier SRH lifetime is the largest, radiative lifetime larger, Auger lifetime small and all are the functions of the localized state energies. This shows us again the Auger excess majority carrier lifetime in the semiconductor material (GaSb) dominate at different localized energy levels as shown in Figure 3 (b). Therefore, the Auger excess carriers' lifetime dominated compared to the radiative and SRH excess carriers' lifetimes.

4.3 The temperature dependence of Radiative and Auger lifetimes

Figure 4: illustrates the radiative and Auger lifetimes at different temperatures as a function of localized state energy for (a) radiative excess electrons, (b) radiative excess holes, (c) Auger excess electrons and (d) Auger excess holes. The graphs are drawn by using the ratio of Eqn. (2-23) to Eqn. (2-24) for radiative and (2-37) for Auger. As describe above Figure 3, the carrier lifetime can be calculated as the carrier concentration divided by recombination of carriers. Therefore, based on this calculation the radiative electrons lifetime remains constant over the whole regions as function of localized state energies and increases with temperatures below 800 K but no changes above (for 900 K & 1000 K). The radiative hole lifetime varies entire the whole regions and reaches a maximum value in electron trap region for low temperature (300 K) for this sample and increases with temperatures in the acceptor, donor and hole trap regions. But decreases with temperatures in electron trap region. The Auger excess electrons lifetimes is constant over the whole regions and increases for room temperature to 600 K then decreases above. The Auger excess electrons lifetimes shows similar distribution to the radiative hole lifetime varies entire the whole regions.

Generally, the radiative and Auger lifetimes in general increase then decrease with temperature as shown in Figure 4. Both radiative and Auger excess minority carrier lifetime in the localized region (valance to conduction band) in the semiconductor material (GaSb) remain constant and varies for excess majority carrier lifetime at different localized energy levels.

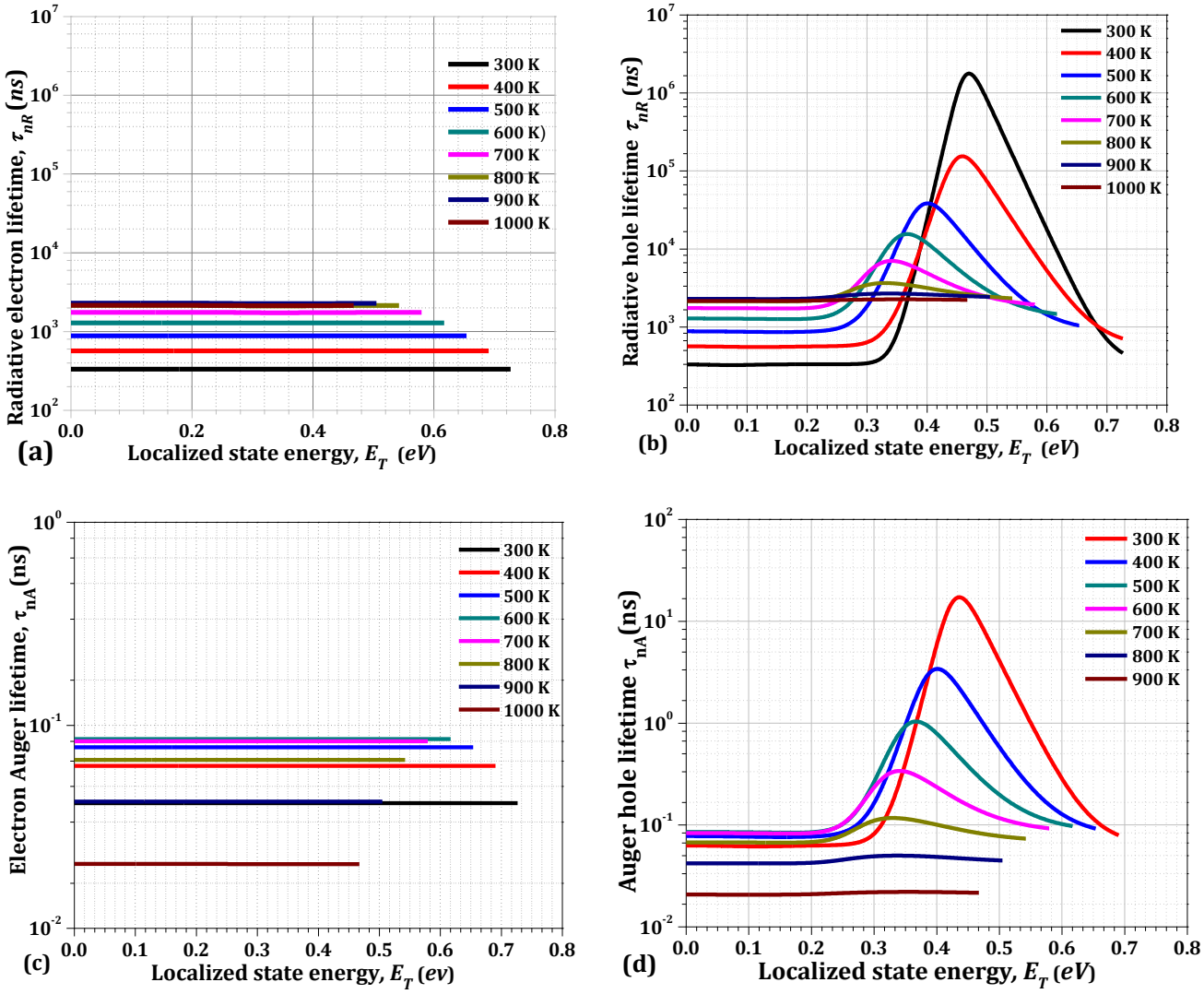

Figure 4: The lifetimes at different temperatures as a function of localized state energy, (a) the excess electrons & (b) the excess holes' radiative lifetimes and (c) the excess electrons & (d) the excess holes Auger lifetimes

4.4 The temperature dependence Shockley-Read-Hall lifetime

Figure 5 illustrates the SRH lifetimes at different temperatures as a function of localized state energy for (a) excess electrons and (b) excess holes. The graphs are drawn using Eqns.(2-101) for Figure 5 (a) and (2-102) Figure 5 (b). As predicted earlier in Figure 2 and Figure 3, since the recombination and the trapping of carriers are negligible for localized levels near the valence and conduction band edges (acceptor and donor regions), the magnitude of both SRH lifetimes reaches a maximum value in these regions. The SRH lifetime in general decreases with increasing temperature, due to the dominance of trapping over emission at lower temperatures. This increases the SRH recombination rates and reduces the SRH carrier lifetimes at these centers, as

shown in Figure 5. The SRH lifetime for excess electrons has a minimum value at the sensitization states, as shown in Figure 5 (a), and this point of minimum SRH lifetime shifts toward the conduction band edge with decreasing temperature.

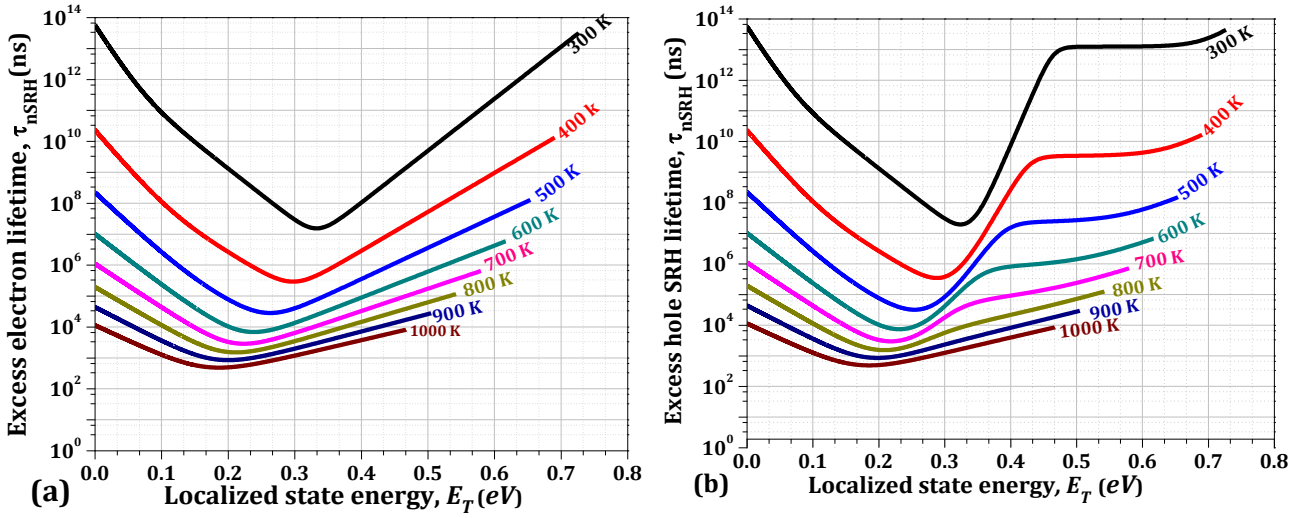

Figure 5: The SRH lifetime at different temperatures as a function of localized state energy (a) the excess electrons and (b) the excess holes.

The sensitization effect increases the SRH lifetime of excess holes in the region where the electron trap is influential (powerful). At very low temperatures, the SRH lifetime curves for holes become smooth in electron trap region and at high temperature slightly changes to the fashion of electron lifetime form smooth crescents at the bottom and symmetrically about the mid-gap. As temperature increases, the SRH lifetime for holes and electron decreases in the entire regions and localized state sensitization tends to increase the excess electron lifetime. The effect of minority carrier traps in the bulk of a semiconductor can be neglected at high temperatures. The Shockley-Read-Hall lifetimes in general decreases with increasing temperature. The SRH carrier lifetimes small at recombination center, as shown in Figure 5. Therefore, the SRH carrier recombination lifetimes depends on the deep level density carrier concentrations.

Chapter 5

Conclusions

In this study, the effect of free carrier trap on the recombination mechanism at different localized state are calculated inside the sample of gallium antimonide (GaSb). Then, the effect of temperature on the trap effect and radiative, Auger and SRH excess carrier lifetimes investigated.

The results obtained from the description of the effect of free carrier trap, the localized regions have different traps for their different localized energy levels. Depending on the interactions of localized states with the conduction or valence bands, the energy level dependence plot of the trap can be divided into five regions (*i.e.* acceptor, hole trap, recombination center, electron trap and donor regions). Most of the impurities are in the n_T state for acceptor and in p_T state for donor regions. In these regions (acceptor and donor) the effects of the traps of a localized center negligibly small. The energy value of these region is approximately equal or less than to thermal energy $k_B T$.

In hole trap region, the probability of emission of hole much greater than the probability of capture of electron i.e. $\sigma_p \gg \sigma_n$) and the process reverse for electron tap region but in the recombination center approximately the capture cross section $\sigma_n = \sigma_p$ which represents the probability of taps capturing carriers. From the energy level 0.08 eV to 0.15 eV, hole trapping has maximum values and thus the hole trapping effect becomes dominant and for the energy level equal to 0.42 eV, the electron trapping has maximum values in this sample.

In general, we conclude that, the free carrier traps are relatively inactive at high temperatures compared to low temperatures. Only deep levels can trap free carriers at higher temperatures and trap is decreases with increasing temperature as function of localized state energies. All the radiative, Auger and SRH lifetimes are function of temperature and the Auger lifetime is dominated in the semiconductor gallium antimonide sample.

Outlook

In these work the study of the effects of free carriers trap on the recombination mechanism through the localized states is studied by used Micro soft excel and origin. The developed methods can be applied for other types of small and direct band gap semiconductors. In the future, this research will be extended into three directions. One is further studying of the remaining parameters of gallium antimonide under different temperature and excess carrier concentrations. The second is the effects of the temperature and the energy level of the localized states on the trap effect for gallium antimonide samples needs to be subjected to different laboratory. Therefore, further experimental studies are required to be done in order to see the effects of free carrier trap of small and direct band gap semiconductors. The third is focusing on the application of gallium antimonide.

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