The Effects of Deep Levels Optical Emissions of Free Carriers on the Photo-Responses of p-type Silicon (Si)

By

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As research advisor, I hereby certify that I have read and evaluated this thesis entitled: **"The Effects of Deep Levels Optical Emissions of Free Carriers on the Photo-Responses of Semiconductor**" prepared under my guidance by Alemu Majore**.** I recommend that it can be submitted as fulfilling the thesis requirement.

Dr. Megersa Wodajo	_____	_____
Advisor	Signature	Date

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

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Declaration and Statement of the Candidate

This thesis has been submitted in partial fulfillment of the requirements for M.Sc. degree in Physics at the ASTU. I solemnly declare that this thesis work is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

Name of candidate: Alemu Majore Signature: _____

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List of Symbols and Abbreviations

C_n	Electron capture coefficient
C_p	Hole capture coefficient
E_a	Acceptor energy
E_C	Conduction band energy
E_d	Donor energy
E_F	Fermi energy
E_g	Energy band gap
E_i	Intrinsic Fermi energy
E_T	Trap energy
E_V	Valence band energy of a semiconductor
n_i	Intrinsic carrier density
n_0	Electron density in thermal equilibrium
p_0	Hole density in thermal equilibrium
N_a	The concentration of acceptor atom
m_n^*	Effective mass electrons
m_h^*	Effective mass holes
N_d^+	The concentration of ionized donor atom
N_a^-	The concentration of ionized acceptor atom
N_C	Effective density of states in the conduction band

σ	Capture cross-section
τ_n	Electron lifetime
τ_p	Hole lifetime
τ_{SRH}	Shockley-Read-Hall lifetime
k_B	Boltzmann's constant
U	Recombination rate
T	Temperature
h	Planck's constant
e	Elementary charge
k_∞	Dielectric constant (high frequency)
n_T	Electron density of localized state
p_T	Hole density of localized state
f_n	Fermi distribution function
G_0	Photon generation rate
δn	Concentration of photo generated of electron
δp	Concentration of photo generated of hole
Si	Silicon
v_{th}	The average thermal velocity of the electrons or holes

Abstract

In this study, the effects of deep levels optical emissions of free carriers on the photo-response of silicon (Si) is investigated through the simulation of excess carrier traps corresponding to the non-radiative recombination mechanism. First, the trapping effects (the ratio of the concentration of trapped photo-emitted carriers to the corresponding concentration of free excess carriers in the corresponding bands) is described as a function of localized state energy at room and different temperatures inside the sample. Then, the Shockley-Read-Hall recombination mechanisms are computed using the relations describing the SRH lifetimes and, the lifetimes of the excess majority and minority carriers in the band gap of semiconductor (Si). Finally, the temperature, injection and, localized state density and doping level dependences of the Shockley-Read-Hall lifetimes in the localized regions are investigated by considering the variation of localized energy positions. Since the trapping effect is highly related to the temperature, the description of the trapping effect as functions of localized state energies at various temperatures is found to be the important. The analysis of the results also shows that, the trapping effects are divided into 5 parts based on the interaction of localized state with the conduction band energy and the valance band energy. In general, the trap in shallow levels (donor and acceptor regions) tends to zero and deep levels are dominated. When all the localized states are illuminated at the same rates, the SRH excess carrier lifetimes for excess carriers (for both electrons and holes) increase with increasing the shallowness of the localized states. The deep level SRH lifetimes for minority carriers is highly affected by the trapping effect of the localized states. The shallow level SRH-lifetimes for free holes are not affected by the trapping effects of the localized states.

Chapter 1 : Introduction

1.1 Background

An investigation into the history of semiconductor research shows even more primitive and earlier semiconductor devices. The beginning of semiconductor research is marked by Michael Faraday's 1833 report on negative temperature coefficient of resistance of Silver Sulfide who in 1833 published a description of material with a resistivity which had the opposite temperature dependence to that typically measured for metals. 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 (unaccountable) pre-1900 history of semiconductors [1], [2]. By the beginning of the 20th century the five properties now associated with semiconductors had been discovered but, scarcely characterized such as: negative temperature coefficients, photoconductivity, rectification, photovoltaic effect and electroluminescence (excitation by current).

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) [1], [3]. 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.

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. 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 [4].

There are two types of band gaps called direct and indirect energy band gaps. Direct band gap semiconductors are the materials for which maximum of valence band and minimum of conduction band lie for the same value of wave vector (K) [5]. Indirect band gap semiconductors are the materials for which maximum of valence band and minimum of conduction band are not the same value of wave vector (K). Conservation of momentum during an inter-band transition is a major concern in indirect materials. Few of examples; Si, Ge, GaP (including Transition metal Oxide) and etc. Direct-gap semiconductors such as GaAs are efficient photon emitters, whereas indirect-gap semiconductors such as Si cannot be efficiently used as light emitters. The advantage of using wide band gaps than narrow band gaps are permits higher voltage, frequencies and temperature.

The energy band wide gaps of semiconductor ranges from 2 to 4.0 eV, then Si 1.125 eV at room temperature to 1.17 eV an absolute zero. The thermal equilibrium charge carrier concentration ranges from 10^{12}cm^{-3}in the intrinsic semiconductor to 10^{19}cm^{-3}in the highly doped non-degenerate semiconductor. The mobility of free carriers in semiconductor also ranges from $10^{2}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}to10^{4}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}$. The practical density of room temperature thermal equilibrium majority carrier for semiconductor that was determined using Hall Effect measurement is ranged from $10^{12}\text{cm}^{-3}$for intrinsic semiconductor to $10^{18}\text{cm}^{-3}$for highly doped non-degenerate semiconductor. The room temperature mobility of electrons for most semiconductors is ranged from $10^{3}\text{cm}^{2}\text{V}^{-1}\text{s}^{-1}$

to $10^4 cm^2V^{-1}s^{-1}$and that of holes is also ranged from $10^2 cm^2V^{-1}s^{-1}$to $10^3 cm^2V^{-1}s^{-1}$ [6], [7].

Generation and recombination processes through intermediate states in the band-gap 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) [2]. 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, Read and Hall and their theory has become a foundation for studies of defects in semiconductor devices. 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.

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 [8]. 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. 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 [6], [9].

In Shockley-Read-Hall (SRH) recombination, the recombination of electron-hole pairs 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 (heat) and the localized state is called the recombination center. If the localized state captures free carriers temporarily and then re-emits back to their original band, the Centre is called a free carrier trap. The localized trap states may be created by deep impurities (introducing dopants), dislocations, radiation defects, grain boundaries, point defects and their complexes [10]. The performance of a semiconductor material depends on the lifetime of free charge carriers generated by the interaction of light with the material, referred to as the excess carrier lifetime (τ) [11]. 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 in the bulk.

These are: Radiative recombination, in which the energy of the electron is given as photon during recombination, Shockley-Read-Hall (SRH) recombination in which energy of the electron is transferred to the lattice as heat or phonon during recombination and Auger recombination in which the energy of the electron or hole is transferred to other charge carries during recombination. Of these, the first two recombination mechanisms are two-carrier processes while the third one is a three-carrier process (V. K. Khanna, 2004). For a steady state condition, the excess carrier generation rate (G_o) is equal to their reverse recombination rate (R). The photo-generated carrier concentration (Δn) in the entire sample is proportion to the product of both the recombination or generation rate and the excess carrier lifetime.

The lifetime of charge carriers is one of the important parameters to characterize a material because; it plays a critical role in determining the semiconductor device

parameters. Carrier lifetime is dependent upon a number of quantities and conditions which are characteristic in the nature of semiconductor materials and the recombination process. These quantities and conditions include excess carrier density, the type of light source, sample thickness and temperature. The basic method to measure the lifetime depending on the way that an excess of carriers (electrons and holes) is created in the semiconductor is using the expression for the balance between generation and recombination to calculate the lifetime [6].

1.2 Objectives

The main objective of this study is in general to determine the effects of deep levels optical emissions of free carriers on the photo-responses semiconductor, whereas, the specific objectives of this study includes:

- the study of the free carriers trapping effect at different localized states in the band gap of a semiconductor at different temperature,
- the study of the effects of different localized states on the excess carrier SRH lifetime at different temperatures,
- the effects of the localized state density versus the doping density on the excess carriers SRH lifetime,
- the study of the effect of injection levels on the excess carriers Shockley-Read-Hall (SRH) lifetime.

1.3 Thesis outlines

This thesis organized into five chapters. Chapter two includes review of related literatures. It deals with the theory of energy bands of the semiconductor, thermal equilibrium and non-thermal equilibrium properties of semiconductors and generation-recombination mechanisms of free carriers for photo-response of semiconductors. Chapter three presents the over-all methodology by which important data is collected and analyzed. Chapter four covers the results and discussion of the study. Chapter five gives the conclusions of entire parts of this work and describes the results obtained in chapter 4.

Chapter 2 : Literature Review

2.1 Semiconductors property

The electron-hole pairs, in the semiconductors can be created by either thermal or optical. The equilibrium carrier density for both electrons and holes can also be expressed in terms of the intrinsic carrier density and the electrostatic potential. We have determined the thermal equilibrium concentration of electrons and holes in the conduction and valence bands. In thermal equilibrium, these concentrations are independent of time. However, electrons are continually being thermally excited from the valence band into the conduction band by the random nature of the thermal process. At the same time, electrons moving randomly through the crystal in the conduction band may come in close proximity to holes and fall into the empty states in the valence band. Since the net carrier concentrations are independent of time in thermal equilibrium, the rate at which electrons and holes are generated and the rate at which they recombine must be equal. Semiconductors have a distinctive band structure the Fermi energy lies between the conduction and valence band in the band gap [12]. The band gap is, also known as forbidden energy band and electrons are absents in the band gap. It is defined as the minimum energy needed for an electron to shift from the valence band to the conduction band. Band gap in semiconductors usually ranges between, less than the band gap in insulators, while more than the band gap in conductors [13]. But in non-equilibrium condition is established when an external excitation is applied to the semiconductor specimen.

As the temperature increases, however, some electrons will be thermally excited into the empty conduction band where there is an abundance of unoccupied states. Therefore, the electrons can act as mobile carriers; they can drift in the crystal lattice under the effect of an applied electric field and there by contribute to the electric current, allowing the remaining electrons in the valence band to exchange places with each other under the influence of an electric field [14]. The material behaves as a semiconductor whose conductivity increases sharply with temperature as an increasing number of mobile

carriers are thermally generated. Example, excess electron-hole pairs can be generated in a semiconductor by the absorption of photons with energies greater than the band gap energy [15].

2.2 Thermal Equilibrium properties of Semiconductor

In this section, the description of some common properties of semiconductor materials like the energies of the charge carriers, the photo generated carrier, shallow level and the deep level optical emissions of free carriers will be discussed.

2.2.1 Energy band gap of Semiconductor

The band gap can be thermally populated with both electrons and holes as the Fermi energy level is near enough to both bands. There are two types band gap in semiconductors: direct or indirect band gap. A direct band gap is distinguished by having the band edges aligned in k, so that an electron can transit from the valence band to the conduction band. On the other hand, in the indirect band gap, the band edges are not aligned so the electron does not transit directly to the conduction band, both a photon and a phonon are involved.

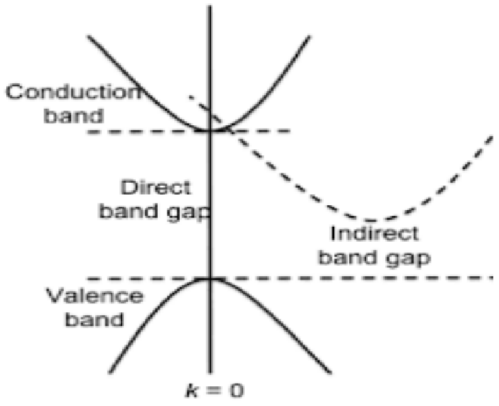

Figure 2-1: Direct and indirect band gap semiconductors [5].

In crystalline solids, the energy band gap between the valence band maximum and conduction band minimum is referred to as energy band gap which is given by [16].

$$E_g = E_C - E_V, \tag{2-1}$$

When band gap light is absorbed by a semiconductor, charges move between the valence band and conduction. A contraction of the crystal lattice with decreasing temperature usually leads to a strengthening of the inter atomic bonds and associated increase in the band gap energy.

The first empirical relation for the band gap shift with temperature was developed by varshni et al. E_g(T) is related by the relation [17], [5]

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

Where α and β are constant and $E_g(0)$ is the limiting value of the band at zero Kelvin, the absorption coefficient α is a property of a material which defines the amount of light it absorbs. Then $E_g(0)$ is 1.170 eV at 0 K, α = 4.73x10^{-4} eV/K, β = 636 K and the energy band gap at room temperature (300K) is equal to 1.125 eV for Si semiconductor.

In such away, the valance band and the conduction band energies determined from eqns. (2-1) and (2-2) are given by:

$$E_V(T) = \frac{\alpha T^2}{2(T + \beta)}, \qquad E_C(T) = E_g(0) - \frac{\alpha T^2}{2(T + \beta)}. \tag{2-3}$$

2.2.2 Thermal equilibrium carrier concentration

The concentration of electrons and holes in semiconductor are determined by many factor including the band gap and band structure of the semiconductor, types and concentrations of the impurities doped in semiconductor, temperature and external disturbances to the semiconductor. Then thermal equilibrium is used to describe the unperturbed state of system, to which no external voltage, illumination, or other perturbing forces are applied [18], [19]. Therefore, thermal equilibrium concentration of electron and hole in conduction and valence band are independent of time. In semiconductors the energy of valance band and the conduction band are used to determine the concentration carriers. In thermal equilibrium electron-hole pairs are constantly being formed and destroyed. For a non-illuminated semiconductor in thermal equilibrium, the concentration of electron in the conduction band is n_0 and holes in valence band is p_0. These concentrations remain constant due to the equilibrium between generation and recombination processes. The thermal equilibrium electron concentration, n_0 in the conduction band and thermal equilibrium holes concentration, p_0 in the valence band for the non-degenerate semiconductor case can be simplified to [20],

$$p_0 = N_V \exp\left(-\frac{E_{F-}E_V}{k_B T}\right) , \qquad n_0 = N_C \exp\left(-\frac{E_C - E_F}{k_B T}\right), \tag{2-4}$$

where, N_V the effective density of valence band states and N_C the effective density of conduction band states is the expression for the equilibrium holes density in valence band and electrons density in conduction band to be as:

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

Where m_p^* and m_n^* are effective mass of electrons in conduction band and holes in valence band, respectively. The density of state function in the conduction and valence of band of semiconductor provided that free electron mass either the electrons density of state effective mass (m_n^*) in the conduction band or holes density of state effective mass (m_p^*) in the valence band. The effective masses for holes and electrons of states of Si are given in [21], [22], as:

$$m_p^* = 1.15 m_0, \qquad m_n^* = 1.08 m_0. \tag{2-6}$$

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

2.2.3 Intrinsic semiconductors

Semiconductors are considered to be as intrinsic semiconductors if it's thermally generated carrier density represented by n_i is much larger than the background doping or residual impurity densities. At zero temperature (T=0), an intrinsic semiconductor behaves like an insulator because the conduction band states are totally empty and the valence band states are completely filled. However, as the temperature increases, some of the electrons in the valence band states are excited into the conduction band states by thermal energy, leaving behind an equal number of holes in the valence band. Suppose that $\mathfrak{N}$ is the concentration of electron hole pairs thermally generated in the respective bands and n_R is the concentration of electron hole annihilated after the generation, the free carrier concentrations in the conduction and valence bands adjust for the intrinsic semiconductor to be:

$$n_0 \approx \mathfrak{N} - n_R = n_i = p_0. \tag{2-7}$$

Since the non-degenerate relations are obviously valid for an intrinsic semiconductor, the intrinsic carrier concentrations are given as follows:

$$n_i = N_C \exp\left(-\frac{E_C - E_i}{k_B T}\right) = N_V \exp\left(-\frac{E_i - E_V}{k_B T}\right), \tag{2-8}$$

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

The intrinsic Fermi energy derived from (2-7) as follows:

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

which indicates that if $m_p^* = m_n^*$ or T = 0 the Fermi level in an intrinsic semiconductor is positioned at mid-gap. In real cases $m_p^* \neq m_n^*$, resulting in small deviation of the Fermi level from mid-gap. The equilibrium density of electrons and holes in a non-degenerate semiconductor is constant at a given temperature. The product of the electrons and holes density, in a non-degenerate semiconductor at equilibrium, is always equal to the square of the intrinsic carrier density [23].

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

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

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

level position and of the individual electrons and holes densities. In other words, the $p_0 n_0$ product is constant at a given temperature regardless of doping.

2.2.4 Extrinsic Semiconductors

Semiconductors doped with foreign atoms to change their intrinsic electron and hole concentrations. By doping, a crystal can be altered so that it has a predominance of either electrons or holes. There are two types of doped semiconductors, n-type (mostly electrons) and p-type (mostly holes). When a crystal is doped such that the equilibrium carrier concentration n_0 is different from the intrinsic carrier concentration n_i the material is said to be extrinsic.

When impurities or lattice defects are introduced into an otherwise perfect crystal, additional levels are created in the energy band structure, usually within the band gap. This level is filled with electrons at 0K and very little thermal energy is required to excite these electrons to the conduction band [24], [25]. In the carrier concentration by doping rather than by thermal electron hole pair generation. Thus, one usually dopes the material such that the extrinsic range extends beyond the highest temperature at which the device is to be used [26]. The most important and unique feature of a semiconductor material lies in the fact that its electrical conductivity can be readily changed by many orders of magnitude by simply doping the semiconductor with shallow-donor or shallow acceptor impurities. The deep level centers can be donor-like (positively charged when empty and neutral when filled with an electron), acceptor-like (neutral when empty and negatively charged when filled with an electron), or may exhibit multiple charge states with associated multiple levels in forbidden gap.

As discussed above, adding donor or acceptor impurity atoms into semiconductor will change the distribution of electrons and holes in the material, and as a result, the position of Fermi energy will change. By equating with each other Eqns. (2-4), (2-5) and (2-10) yields [27]:

$$p_0 = N_V \exp\left(-\frac{E_{F-} E_i}{k_B T}\right), \qquad n_0 = N_C \exp\left(-\frac{E_i - E_F}{k_B T}\right) \tag{2-11}$$

The law of mass action, Eqn. (2-10) allows one to calculate the minority carrier density in an extrinsic semiconductor when the majority carrier density is known [23].

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

In extrinsic semiconductor, Fermi level is close to conduction band (n-type) or valence band (p-type). The thermal equilibrium extrinsic Fermi-level, E_F can also be described from Eqn. (2-12) in terms of E_i and the thermal equilibrium carrier concentrations as:

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

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. (2-13) shows that E_F lies above E_i for n-type material ($n_i > p_o$) and below E_i for $p-$ type material ($n_i < p_o$) [28].

2.2.5 Statistics of Donors and Acceptors

The shallow donor-acceptor levels emit their electrons (holes) to the conduction band (valence band) where they travel freely and contribute to the conductivity. The free charge carriers may be trapped by deeper levels, where they are frozen out unless enough thermal energy is provided to excite them back to the bands again. Deeper located levels can interact with both bands easily and the free charge carriers may use these defect states as recombination path. The donor electron can also interact directly with a hole, thus the charge carriers recombine without contributing to conduction or charge carrier compensation takes place [19].

The density of electrons in a shallow-donor state is given by:

$$n_d = \frac{N_d}{1 + \frac{1}{g_d}\exp\left(\frac{E_d - E_F}{k_B T}\right)} \tag{2-14}$$

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

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

When a singly ions-able donor captures an electron it becomes neutral, and when it releases an electron, it becomes positively charged. Using the same analysis, the concentration of ionized acceptors becomes:

$$N_a^- = N_a - p_a = \frac{N_a}{1 + g_a \exp\left(\frac{E_a - E_F}{k_B T}\right)}\ , \tag{2-16}$$

where $p_a$is the density of holes bound to acceptors, N_a the concentration of acceptor atoms, the energy of the acceptor level relative to the valence band, N_a^- the concentration of ionized acceptor atoms and g_a is the acceptor-site degeneracy factor. When a singly ions-able acceptor captures an electron it becomes negatively charged, and neutral when it releases the electron. Most authors set $g_d = 2$ to account for the spin degeneracy at the donor sites (only one parabolic band at the conduction band edge). It is likewise standard practice to argue that the acceptor sites must additionally reflect the two fold (heavy- and light-hole) degeneracy of the valence band. Thus, the acceptor degeneracy factor is $g_a = 2\text{x}2 = 4$.

Hence, the densities of the ionized impurities at both the donor and acceptor centers are given by:

$$N_d^+ = \frac{N_d}{1 + 2 \exp\left(\frac{E_F - E_d}{k_B T}\right)}, \tag{2-17}$$

$$N_a^- = \frac{N_a}{1 + 4 \exp\left(\frac{E_a - E_F}{k_B T}\right)}. \tag{2-18}$$

At sufficiently high temperatures in p-type material, all the acceptors are ionized, so that $N_a^- \approx N_a$ or $p_a \approx 0$. This leads to the conditions $E_a - E_F$ resulting in the Fermi level lying above the acceptor level for p-type materials. In the same way it can be shown that

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

2.2.6 Charge neutrality

Under thermal equilibrium, the electrons are distributed among the various energy states, creating negative and positive charges, but the net charge density is zero. Figure 2-2 shows the energy band diagrams for intrinsic and compensated p-type semiconductors at

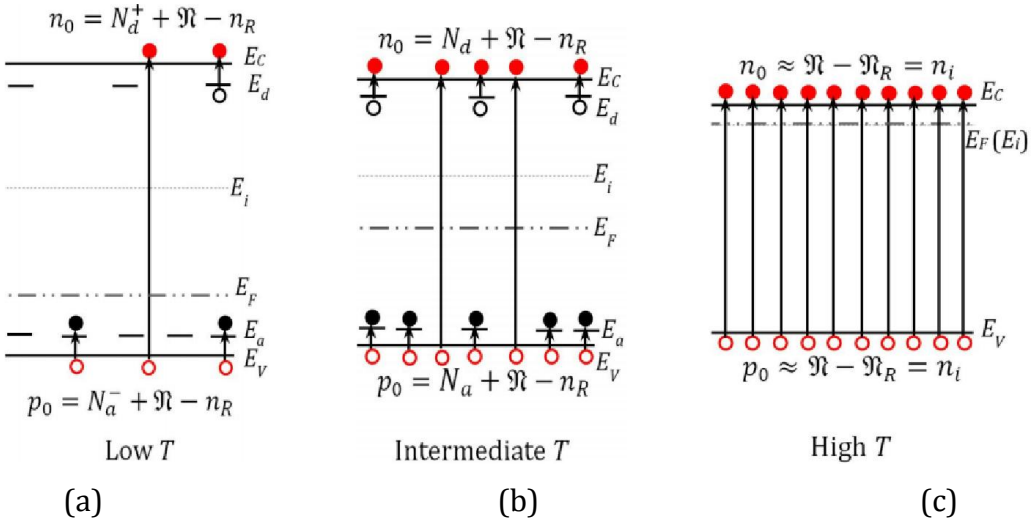

Figure 2-2: Energy band diagrams for intrinsic and compensated p-type semiconductors at (a) low, (b) intermediate and (c) high temperature. Free (conduction) electrons are represented by, ●, free (conduction) holes are represented by, ○, bound electrons (charged acceptor states) are represented by, ●, and bound holes (charged donor states) are represented by, ○.

(a) low (b) intermediate and (c) high temperature. This helps to understand how the addition of donor and acceptor impurities changes the distribution of free electrons and holes. Assuming a system with no free carriers trap center, with the ionization of donors and acceptors, additional electrons and holes are added to the conduction and valence bands. When free electron-hole pairs annihilate through recombination, the free carrier

concentrations in the conduction and valence bands adjust for the intrinsic semiconductor to Eqn. (15). For the extrinsic semiconductors this takes the form:

$$n_0 = N_d^+ + \mathfrak{N} - n_R \qquad \text{and} \qquad p_0 = N_a^- + \mathfrak{N} - n_R, \tag{2-19}$$

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. (19), the well-known neutrality relationship is obtained:

$$\mathrm{n}_0 + N_a^- = p_0 + N_d^+ \tag{2-20}$$

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

$$N_d^+ = \frac{N_d}{1 + 2\exp\left(\frac{E_F - E_d}{k_B T}\right)} \qquad \text{and} \qquad N_a^- = \frac{N_a}{1 + 4\exp\left(\frac{E_a - E_F}{k_B T}\right)}. \tag{2-21}$$

The law of mass action Eqn. (10) along with Eqn. (19) yields:

$$p_0 = \frac{N_a^- - N_d^+}{2}\sqrt{n_i^2 + \left(\frac{N_a^- - N_d^+}{2}\right)^2}, \qquad n_0 = \frac{N_d^+ - N_a^-}{2}\sqrt{n_i^2 + \left(\frac{N_d^+ - N_a^-}{2}\right)^2} \tag{2-22}$$

For very high acceptor impurity concentration $N_a^- \gg N_d^+$ and $N_a^- > n_i$, Equation (22) can be simplified:

$$\frac{p_0}{n_i} \approx \frac{N_a^-}{n_i} + \frac{n_i}{N_a^-} > 1, \quad \Rightarrow p_0 > n_i, \qquad \frac{n_0}{n_i} \approx \frac{n_i}{N_a^-} < 1, \qquad \Rightarrow n_0 < n_i \tag{2-23}$$

It can be seen from Eqn. (23) that the addition of different acceptor and donor impurity concentrations to the semiconductor increases the majority carrier concentration above the intrinsic level and decreases the minority carrier concentration below the intrinsic level. If the acceptor and the donor impurity concentrations are equal (i.e. completely compensated material), Eqn. (22) becomes:

$$p_0 = n_0 \approx n_i. \tag{2-24}$$

For p-type material, the Fermi level lies below mid-gap (closer to the valence band) as discussed $E_F \ll E_d$.

The density of the ionized impurities at acceptors is given by:

$$N_a^- = N_V \exp\left(\frac{E_{V-}E_F}{k_B T}\right) \qquad \text{and} \qquad N_a^- = \frac{N_a}{1 + g_a \exp\left(\frac{E_a - E_F}{k_B T}\right)}. \tag{2-25}$$

Here g_a is the acceptor degeneracy factor. For Si: g_a= 4. The Fermi energy level, E_F or more accurate an acceptor chemical potential ($E_{\mu a}$). In semiconductor physics the term Fermi level is a material property which is often used instead of chemical potential. Where Fermi level is temperature independent while Chemical potential is temperature dependent. Equating the right and the left hand sides of equation (2-25) and solving the Chemical potential is given by:

$$E_{\mu a} = E_a - k_B T \ln\left(\frac{N_V}{2g_a}\left[-1 + \sqrt{1 + 4g_a \frac{N_a}{N_V} \exp\left(\frac{\Delta E_a}{k_B T}\right)}\right]\right) \tag{2-26}$$

and the solved ionized impurities at acceptors are given by:

$$N_a^- = \frac{N_V}{2g_a}\left(-1 + \sqrt{1 + 4g_a \frac{N_a}{N_V}}\right) \exp\left(\frac{\Delta E_a}{k_B T}\right). \tag{2-27}$$

The majority carrier density or the holes, p_0 in an extrinsic semiconductor for very high acceptor impurity concentration $N_a^- \gg N_d^+$ equation (2-22) can be simplified:

$$p_0 = \frac{N_a^-}{2} \sqrt{n_i^2 + \left(\frac{N_a^-}{2}\right)^2}. \tag{2-28}$$

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

$$n_0 = \frac{n_i^2}{p_0}. \tag{2-29}$$

At sufficiently low temperatures, $p_0, n_{0,}$ and N_a^- all vary with temperature, and as a result the intrinsic concentration n_i also increases with temperature. This region in which N_a^- varies with temperature is called the partial ionization region. When the temperature is increased beyond the partial ionization region, there is the chance of ionized acceptor

carriers' equality with the holes impurities carriers. After a while the concentrations of holes and electrons increase by the same amount due to the increment in intrinsic concentration but the ionized acceptor continued remains constancy. Upon a further increase in temperature (beyond the extrinsic region), the intrinsic concentration n_i begins to dominate. Both the majority and minority carrier concentrations approach the intrinsic concentration and the semiconductor enters a quasi-intrinsic region. Figure 2-3 shows (a) two regions in which a simulation of the ionized acceptor partial ionization and continued remains constancy with acceptor concentration, (b) four regions in which a simulation of variations in majority carrier concentration varies as a function of temperature for the p-type semiconductor of acceptor density 10^{16} cm^{-3} being analyzed. Region I is a range in which N_a^- varies with temperature (partial ionization region). Region II in Figure 2-3 in both (a) and (b) is the temperature range of extrinsic region in which the acceptor level is completely ionized (complete ionization region). Region III in (b) is the transition region between the completely ionization and intrinsic regions. The boundaries of this region are not clearly defined [11]. Region IV in (b) is the region in which both the majority and minority carrier concentrations become equal and approach the intrinsic concentration (quasi-intrinsic region).

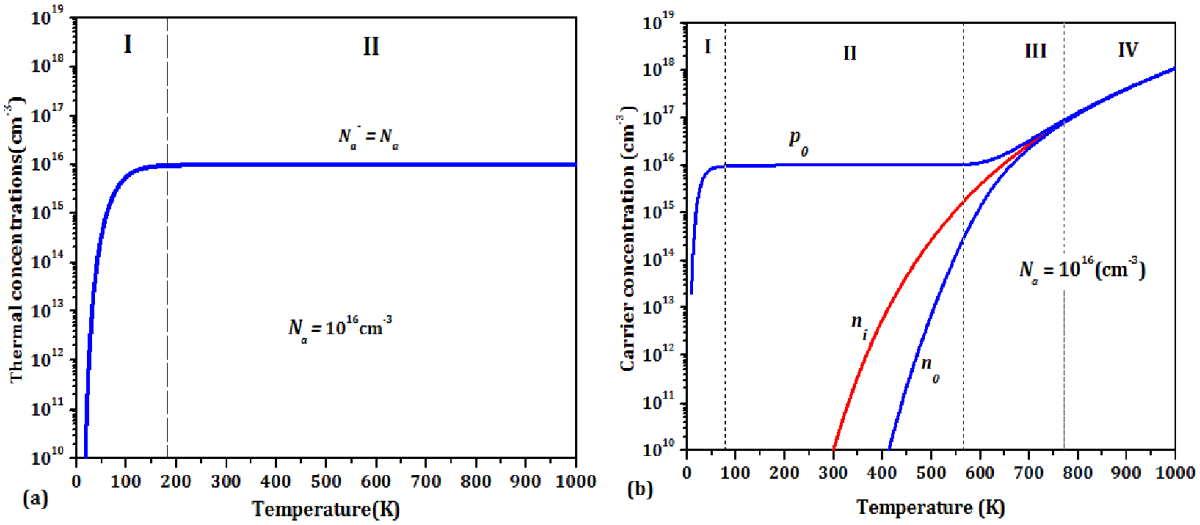

Figure 2-3: (a) two regions in which a simulation of the ionized acceptor partial ionization and continued remains constancy with acceptor concentration (b) four regions in which a simulation of variations in majority carrier concentration varies as a function of temperature for p-type semiconductor of acceptor density 10^{16} cm^{-3} being analyzed using eqns.(2-10),(2-17),(2-18) and (2-19).

2.2.6 Shallow and Deep levels

Shallow levels in semiconductors are commonly defined as those levels in the forbidden gap which lie $<$ 0.1eV from the valance or the conduction band-edges. Thus, these levels are ionized at room temperature. These levels behave as hydrogen-like levels and can be adequately described by the effective mass theory, in which the effective mass of the carriers is much larger or much smaller than m_0.

Since these levels have very low activation energies so they provide free charge carriers making the semiconductor n- or p-type. Commonly shallow levels are obtained by adding an impurity atom has, in its outermost shell, one electron in excess or one electron less than in the host atoms in the host atoms electronic configuration.

If the energy levels introduced in the forbidden gap of a semiconductor lie greater than 0.1eV from the valance or the conduction band-edges, the level is referred to as a deep level. One major difference between a shallow and a deep level is that a deep level cannot be described by the effective mass theory because of its higher ionization energies; they do not contribute so much to the conduction mechanism like the shallow levels [29], [30]. Deep levels, on the other hand, can be very important in controlling certain properties of the semiconductor. They are can be formed by either introduction of impurities or be the result of inherent crystal defects. They may behave as carrier traps or as generation recombination centers if they are near to mid-band-gap. As traps they capture free carriers supplied by the doping atoms, thus compensating the shallow levels and reducing the effective doping density. This increases the resistivity of the material and could, therefore, have a detrimental effect. However, for very high levels of compensation the material takes on intrinsic-like properties. They behaving as recombination centers may also be either beneficial or detrimental.

Deep levels can be characterized by three major parameters: the activation energy (E_A) which is related to the position of the level in the band-gap; its concentration (N_T) and its capture cross-section (σ) for carriers which provide a measure of the ability of the deep level to trap carriers.

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 can be measured through the change in the photoconductivity due to the photo-generated free carriers. In this section, the effect the recombination of free carriers' causes on the performance of semiconductor is described by the energy and doping effects dependence on the photo-response.

2.4 Generation-Recombination Mechanisms of Free Carriers

In this thesis study also, when photons with energies greater than or equal to 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 [31].

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 [27], [32]

2.4.1 Generation-recombination of excess carriers' rate equation

The mechanism by which electron-hole pairs annihilated is called recombination mechanism [33], [34]. The rate at which free carriers disappear or recombine was given by the ratio of the free carrier concentration to excess carrier life time. In a steady-state situation the generation and recombination rates are perfectly balanced. Electric fields and optical energy causes electron densities and velocities to be different from the equilibrium values. The time interval through which excess carrier can stay in conduction is called excess carrier lifetime. The excess carrier lifetime is an important parameter as it characterizes the quality of the semiconductor material and hence affects the performance of the electron devices fabricated from it. Therefore, for many applications, it is necessary. Then, the carrier lifetime is the most important electronic property of semiconductor materials as fast method to characterize the material quality. The conductivity of the semiconductor material under doping and illumination in this study used for determine the excess carrier lifetime changes through localized states of the energy and trap via recombination center on the bulk semiconductor. Excess carrier lifetime is dependent upon a number of quantity and condition which are characteristic in nature of semiconductor material and recombination process. These quantities and condition include excess carrier density, the activation energy (E_A) which is related to the position of the level in the band-gap; its concentration (N_T), trap capture, degenerate factor (g_0) and temperature. The basic method to measure the lifetime depending on the way that an excess of carriers (electrons and holes) is created in semiconductor is using the expression for the balance between generation and recombination to calculate the lifetime [35]. The rates of change of electrons in the conduction band and holes in the valence band are equal and always given by the difference between the generation and the recombination rates, i.e.:

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R \,, \tag{2-30}$$

where n and p represent the non-thermal equilibrium electron and hole concentrations in the conduction and valence bands respectively, and G and R are the total generation and

recombination rates of charge carriers, respectively. The total generation rate involves both the thermal (G_{th}) and photon (G_0) generation rates:

$$G = G_{th} - G_0. \tag{2-31}$$

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

$$G = G_{th} - G_0. \tag{2-32}$$

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

$$U = \frac{\delta n}{\tau_n} = \frac{\delta p}{\tau_p} \tag{2-33}$$

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

The lifetime for the respective excess electrons and holes τ_n and $\tau_p$in terms of the recombination rate of excess carriers, U are given by [36]:

$$\tau_n = \frac{\delta n}{U} \text{ and } \tau_p = \frac{\delta p}{U}, \tag{2-34}$$

If one photon ejects one electron-hole pair during illumination, the photon absorption, G_0 can be considered as equal to free carriers generation rate, so that the steady state $U = G_0$. Hence the steady state excess carrier lifetime Eqn. (2-34) can be written as:

$$\tau_n = \frac{\delta n}{G_0} \text{ and } \tau_p = \frac{\delta p}{G_0} \tag{2-35}$$

Using the principle of detailed balance along with Eqns. (2-30) to Eqns. (2-33), the rates of change of the excess carriers are:

$$\frac{d\delta n}{dt} = G_0 - U = \frac{d\delta p}{dt}. \tag{2-36}$$

2.4.2 Recombination mechanism in semiconductors

Generation in semiconductors refers to the process by which electron-hole pairs are created. The electron-hole pair is the fundamental unit of generation and recombination, corresponding to an electron transition between the valence band and the conduction band. Recombination refers to the inverse processes by which the electron -hole pairs are lost due to the spontaneous transition of an excited electron from conduction band to a hole in valence band. The annihilation of excess carriers generated by electrical in a semi conductor may take place via different recombination mechanisms [37]. Depending on the ways in which the energy of an excess carrier is removed during a recombination process, optically generated charge carriers can recombine in two different common 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. Know from different recombination mechanisms, in the next section we are going to investigate only the non-radiative, it refers here to the recombination process through energy levels in the band gap, and it can be described by the Shockley-Read-Hall (SRH) statistics recombination mechanisms [Shoc1952] [Hall1952]; and the lifetime associated with it for a indirect band gap (Si) of a p-type semiconductor [38], [39].

2.4.3 Shockley-Read-Hall recombination

An energetically deep defect level may affect τ by providing an alternative recombination path (usually non-radiative), or may distort the measurement of by acting as a trapping center. The distinction between a trap and a recombination center depends on the relative probability of a trapped carrier being thermally re-emitted to its appropriate band or recombining with a free carrier from the opposite band. 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 Au, Ni, Co etc.), or by radiation-and process-induced defects such as vacancies, interstitials, antisite defects and their complexes, dislocations, and grain boundaries. The non-radiative recombination process in a semiconductor can be best described by the Shockley-Read-Hall (SRH) model [40], [41]. 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(from deep level-conduction-an empty state) 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 emissions and capture processes shown in figure 2-4. In deriving the SRH model, it is assumed that the semiconductor is non-degenerate and that the density of trap states is small compared to the majority carrier density [8], [42].

In Shockley-Read-Hall (SRH) recombination, the recombination of EHPs may take place 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 [37]

Figure 2-4 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 trapsN_T:

$$N_T = p_T + n_T. \tag{2-37}$$

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 of equations of free and trapped charge carriers, which describe the SRH model,

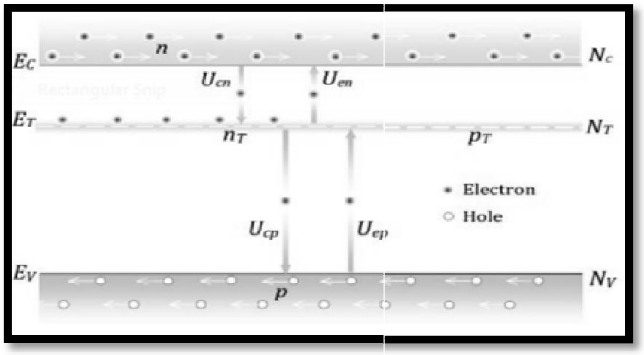

Figure 2-4: Energy band diagram with a localized trap [10], [43]

can be derived from the four emissions and capture processes illustrated in Figure 2-4. 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:

$$f_n(T) = \frac{1}{1 + \exp\left(\frac{E_T - E_F}{k_B T}\right)} \tag{2-38}$$

The thermal equilibrium electron occupancy (n_{0T}) and hole occupancy (p_{0T}) of the localized states are given by [44]:

$$n_{0T} = N_T f_n(T) = \frac{N_T}{1 + \exp\left(\frac{E_T - E_F}{k_B T}\right)}, \qquad p_{0T} = N_T - n_{0T}. \tag{2-39}$$

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}) [45], [46]. 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:

$$U_{cn} = C_{nT} n_0 p_{0T}, \quad U_{en} = e_n n_{0T},$$

$$U_{cn} = C_{nT} n_0 p_{0T} = C_{nT} n_0 N_T (1 - f_n), \quad U_{en} = e_n N_T f_n. \tag{2-40}$$

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:

$$U_{cp} = C_{PT} p_0 n_{0T}, \quad U_{ep} = e_p p_{0T,}$$

$$U_{cp} = C_{PT} p_0 N_T f_n, U_{ep} = e_p N_T (1 - f_n), \tag{2-41}$$

Where e_p is the hole emission rate. The hole capture coefficient (C_{PT}) depends on the proximity of the centre 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:

$$U_{cn} = U_{en}, U_{cp} = U_{ep} \tag{2-42}$$

Taking in to account Eqns. (2-40) and (2-41) through (2-42) yields:

$$e_n = \frac{C_{nT} n_0 p_{0T}}{n_{0T}}, \qquad e_p = \frac{C_{pT} p_0 n_{0T}}{p_{0T}}$$

$$e_n = \frac{C_{nT} n_0 (1 - f_n)}{f_n}, \qquad e_p = \frac{C_{pT} p_0 f_n}{(1 - f_n)}. \tag{2-43}$$

From Eqn. (2-43) one obtains:

$$e_n e_p = C_{nT} C_{pT} n_0 p_0 = C_{nT} C_{pT} n_i^2 \tag{2-44}$$

From eqn. (2-11) the density of electrons (n_0) and the density of holes (p_0) for the non-degenerate semiconductors are given by:

$$n_0 = N_C \exp\left(-\frac{E_C - E_F}{k_B T}\right), \qquad p_0 = N_V \exp\left(-\frac{E_F - E_V}{k_B T}\right) \tag{2-45}$$

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. (2-45):

$$n_i = N_C \exp\left(-\frac{E_C - E_i}{k_B T}\right), \qquad p_0 = N_V \exp\left(-\frac{E_i - E_V}{k_B T}\right) \tag{2-46}$$

Eliminating N_C and N_V among Eqns. (2-45) and (2-46) yields:

$$n_0 = n_i \exp\left(-\frac{E_C - E_F}{k_B T}\right), \qquad p_0 = n_i \exp\left(-\frac{E_F - E_V}{k_B T}\right) \tag{2-47}$$

From Eqn. (2-38) one can drive for $\frac{(1-f_n)}{f_n}$ and $\frac{f_n}{(1-f_n)}$ as:

$$\frac{(1 - f_n)}{f_n} = \exp\left(\frac{E_T - E_F}{k_B T}\right), \qquad \frac{f_n}{(1 - f_n)} = \exp\left(\frac{E_F - E_T}{k_B T}\right) \tag{2-48}$$

Now solving Eqns. (2-43) and (2-45) one obtains the electron emission rate and the hole emission rate:

$$e_n = C_{nT} n_1, \quad e_p = C_{pT} p_1 \tag{2-49}$$

Where

$$n_1 = n_i \exp\left(\frac{E_T - E_i}{k_B T}\right), \qquad p_1 = n_i \exp\left(\frac{E_i - E_T}{k_B T}\right) \tag{2-50}$$

are the non-thermal concentrations of electrons and holes in the conduction and valence bands for the case in which the Fermi-level (E_T) falls at E_i. Also expressions for $n_1$and $p_1$are given respectively by:

$$n_1 = n_0 \exp\left(\frac{E_T - E_F}{k_B T}\right), \qquad p_1 = n_0 \exp\left(\frac{E_F - E_T}{k_B T}\right). \tag{2-51}$$

Solving Eqn. (2-51) yields:

$$n_1 p_1 = n_0 p_0 = n_i^2 \tag{2-52}$$

From Eqns. (2-50) the thermal equilibrium electron occupancy (n_{0T}) and hole occupancy (p_{0T}) of the localized states in Eqn. (2-39) are also given by:

$$n_{0T} = \frac{n_0 N_T}{n_0 + n_1}, \qquad p_{0T} = \frac{n_1 N_T}{n_0 + n_1} \tag{2-53}$$

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 (δn) and holes in the conduction band (δp) are given by:

$$\delta n = n - n_0, \qquad \delta p = p - p_0 \tag{2-54}$$

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

$$\delta n_T = n_T - n_{0T}, \qquad \delta p_T = p_T - p_{0T} \tag{2-55}$$

Since the defect concentration does not vary with illumination, Eqn. (2-37) holds true for both thermal and the non-thermal equilibrium conditions.

That is:

$$N_T = p_{0T} + n_{0T} = p_T + n_T \tag{2-56}$$

When we rearranging Eqn. (2-56) and uses the relation in Eqn. (2-55) yields:

$$p_{0T} + n_{0T} = \delta n_T + n_{0T} + \delta p_T + p_{0T} \tag{2-57}$$

$$(p_{0T} + n_{0T}) - (p_{0T} + n_{0T}) = \delta n_T + \delta p_T \tag{2-58}$$

$$\delta n_T + \delta p_T = 0 \tag{2-59}$$

$$\delta n_T = -\delta p_T. \tag{2-60}$$

Equation (2-60) 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 $\delta\mathfrak{N}$ 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:

$$\delta n = \delta\mathfrak{N} - \delta n_R - \delta n_T, \qquad \delta p = \delta\mathfrak{N} - \delta n_R \tag{2-61}$$

Rearranging Eqn. (2-61) yields:

$$\delta\mathfrak{N} = \delta n + \delta n_R + \delta n_T, \qquad \delta\mathfrak{N} = \delta p + \delta n_R \tag{2-62}$$

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. (2-61) gives the photo-generated charge carrier neutrality equation for the system with an electron trap center to be:

$$\delta n = \delta\mathfrak{N} - \delta n_R - \delta n_T, \qquad \delta n = \delta p - \delta n_T \tag{2-63}$$

$$\delta p = \delta n + \delta n_T \tag{2-64}$$

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

$$\delta n = \delta p + \delta p_T \tag{2-65}$$

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:

$$\frac{dn}{dt} = G - (U_{cn} - U_{en}) \tag{2-66}$$

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

$$\frac{dp}{dt} = G - \left(U_{cp} - U_{ep}\right) \tag{2-67}$$

Equations (2-66) and (2-67) 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. (2-66) and (2-67) 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. (2-66) and (2-67) are simplified by eliminating the contribution of the thermal equilibrium conditions (applying the principle of Detailed Balance) using Eqns. (2-52) to (2-65). The rates of accumulation of photo-generated charge carriers in the conduction and the valence bands were therefore found to be:

$$\frac{d\delta n}{dt} = G_0 - (U_{c\delta n} - U_{e\delta n}), \quad \frac{d\delta p}{dt} = G_0 - (U_{c\delta p} - U_{e\delta p}). \tag{2-68}$$

Where G_0 the optical generation rate. The term $(U_{c\delta n} - U_{e\delta n})$ in Eqn. (2-68) involves the sum of the SRH recombination rate with trapping effect (U_{SRH}) and the rate of accumulation photo-generated electrons ($d\delta n/dt$) at the localized center given by:

$$(U_{c\delta n} - U_{e\delta n}) = C_{nT}[p_{0T}\delta n - (n_0 + \delta n + n_1)\delta n_T] = U_{SRH} + \frac{d\delta n_T}{dt} \tag{2-69}$$

and the term $(U_{c\delta p} - U_{e\delta p})$ in Eqn. (2-69) involves only the SRH recombination rate (U_{SRH}) of the photo generated holes at the center:

$$(U_{c\delta p} - U_{e\delta p}) = C_{nT}[n_{0T}\delta p - (p_0 + \delta n + p_1)\delta n_T] = U_{SRH}. \quad (2\text{-}70)$$

The accumulation of free carriers in the respective conduction and valence bands are then given using Eqns. (2-68) to (2-70) as:

$$\frac{d\delta n}{dt} = G_0 - C_{nT}[p_{0T}\delta n - (n_0 + \delta n + n_1)\delta n_T] = G_0 - \left(U_{SRH} + \frac{d\delta n_T}{dt}\right) \quad (2\text{-}71)$$

$$\frac{d\delta p}{dt} = G_0 - C_{pT}[n_{0T}\delta p + (p_0 + \delta p + p_1)\delta n_T] = G_0 - U_{SRH} \quad (2\text{-}72)$$

The rate of accumulation of photo-generated electrons at the localized center can be derived using Eqns. (2-69) and as:

$$\frac{d\delta n_T}{dt} = C_{nT}[p_{0T}\delta n - (n_0 + \delta n + n_1)\delta n_T] - C_{pT}[n_{0T}\delta p + (p_0 + \delta p + p_1)\delta n_T] \quad (2\text{-}73)$$

Under the steady-state condition, the net rate of electron capture per unit volume may be found by solving Eq (2-42) through (2-44) and (2-52) which yields:

$$U_n = U_{cn} - U_{en} = C_{nT}N_T[n(1 - f_n) - n_1 f_n] \quad (2\text{-}74)$$

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

$$U_p = U_{cp} - U_{ep} = C_{pT}N_T[pf_n - n_1(1 - f_n)] \quad (2\text{-}75)$$

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:

$$\tau_n = \frac{\delta n}{U_n}, \quad \tau_p = \frac{\delta p}{U_p}. \quad (2\text{-}76)$$

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

$$\delta n = \delta p \quad (2\text{-}77)$$

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:

$$U = U_n = U_p \tag{2-78}$$

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. (2-75), (2-76) and (2-77), one obtains:

$$f_n = \frac{C_{nT} n + C_{pT} p_1}{C_{nT}(n + n_1) + C_{pT}(p + p_1)}. \tag{2-79}$$

A general expression for the net recombination rate can be obtained by substituting Eqn. (2-79) into Eqn. (2-74) or (2-75) and the result yields:

$$U = U_n = U_p = \frac{(np - n_i^2)}{\tau_{n0}(p + p_1) + \tau_{p0}(n + n_1)} \tag{2-80}$$

Where τ_{p0} and $\tau_{n0}$are given respectively by:

$$\tau_{n0} = \frac{1}{C_{nT} N_T}, \qquad \tau_{p0} = \frac{1}{C_{pT} N_T} \tag{2-81}$$

Where $C_{nT} = \sigma_n v_{th}, n$ and $C_{pT} = \sigma_p v_{th,P}$ denote the hole and electron capture coefficients. The capture cross section of hole and electron are given respectively by:

$$\sigma_n = \sigma_{n\infty} \exp\left(-\frac{E_C - E_T}{k_B T}\right), \qquad \sigma_p = \sigma_{p\infty} \exp\left(-\frac{E_T - E_V}{k_B T}\right) \tag{2-82}$$

Where the constant $\sigma_{n\infty} = 10^{-16} cm^2$ and $\sigma_{p\infty} = 10^{-15} cm^2$ and the average thermal velocity of electrons or holes given by [9], [41]:

$$\mathrm{v_{th,n/p}} = \sqrt{\frac{8 k_B T}{\pi m^*}}. \tag{2-83}$$

where τ_{n0} the minority is hole lifetime for an n-type semiconductor, and τ_{p0} is the minority electron lifetime for a p-type semiconductor [9], [47].

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 [44], [22]. 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 [48], [37]:

$$\delta n_T = \frac{(\tau_{p0} p_{0T} - \tau_{n0} n_{0T})\delta p}{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + p_{0T} + \delta p)}. \tag{2-84}$$

The total concentration of excess holes in the valence band can be obtained by substituting Eqn. (2-84) into Eqn. (2-72) and the result yields:

$$\delta p = \frac{2Q_P}{P + \sqrt{P^2 + 4Q_P}}, \tag{2-85}$$

where

$$P = \left(\frac{n_0(n_0 + n_1 + p_{0T}) + n_1(p_0 + p_1)}{n_0 + n_1} - G_0(\tau_{p0} + \tau_{n0}) \right), \tag{2-86}$$

$$Q_P = G_0 \left(\tau_{n0}(p_0 + p_1 +) + \tau_{p0}(n_0 + n_1 + p_{0T}) \right). \tag{2-87}$$

Similarly, the total concentration of excess electrons in the conduction band obtained is given by:

$$\delta n = \frac{2Q_N}{N + \sqrt{N^2 + 4Q_N}}, \tag{2-88}$$

where

$$N = \left(\frac{p_0(p_0 + p_1 + n_{0T}) + p_1(n_0 + n_1)}{n_0 + n_1} - G_0(\tau_{n0} + \tau_{p0}) \right), \tag{2-89}$$

$$Q_N = G_0 \left(\tau_{p0}(n_0 + n_1) + \tau_{p0}(p_0 + p_1 + n_{0T}) \right). \tag{2-90}$$

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

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

Taking into account Eqn. (2-60), (2-85) and (2-91) gives the fraction of trapped photo generated holes at the localized trap state to the excess holes in the valence band to be:

$$I_p = \frac{\delta p_T}{\delta p} = \frac{(\tau_{n0} n_{0T} - \tau_{p0} p_{0T})}{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + p_{0T} + \delta p)}. \quad (2\text{-}92)$$

The subscripts n and p in Eqns. (2-91) and (2-92) represent the electrons and holes concentration. For low injection levels of carriers $N_T,\ p_0,\ p_1,\ n_1 \gg \delta n,\ \delta p$. In this case eqns. (2-91) and (2-92) gives:

$$I_n = \frac{\delta n_T}{\delta n} = \frac{(\tau_{p0} p_{0T} - \tau_{n0} n_{0T})}{\tau_{n0}(p_0 + p_1 + n_{0T}) + \tau_{p0}(n_0 + n_1)} \text{ and,} \quad (2\text{-}93)$$

$$I_p = \frac{\delta p_T}{\delta p} = \frac{(\tau_{n0} n_{0T} - \tau_{p0} p_{0T})}{\tau_{n0}(p_0 + p_1) + \tau_{p0}(n_0 + n_1 + p_{0T})}. \quad (2\text{-}94)$$

From eqns. (2-91) the trapped photo-generated electrons at the localized trap state is given by:

$$\delta n_T = I_n \delta n. \quad (2\text{-}95)$$

Similarly, the trapped photo-generated holes at the localized trap state are given by:

$$\delta p_T = I_n \delta p. \quad (2\text{-}96)$$

Applying the steady-state condition to Eqns. (2-69) and (2-70) and eliminating δn_T in between the two relations gives the SRH recombination rate in terms of δn and δp as:

$$U_{SRH} = \frac{(n_0 + \delta n)\delta p + p_0 \delta n}{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + \delta p)} \quad (2\text{-}97)$$

Or applying Eqns. (2-66) and (2-93) to Eqn. (2-97) recombination rate can be described in terms of only as:

$$U_{SRH} = \frac{(n_0+\delta p(1+I_n)^{-1})\delta p+p_0\delta p(1+I_n)^{-1}}{\tau_{n0}(p_0+p_1+\delta p)+\tau_{p0}(n_0+n_1+\delta p(1+I_n)^{-1})}. \quad (2\text{-}98)$$

The excess electron SRH lifetimes with the trapping effect, τ_{SRH} is derived using Eqn. (2-97) or Eqn. (2-98) as:

$$\tau_{nSRH} = \frac{\delta n}{G_0} = \frac{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + \delta n)}{p_0 + (n_0 + \delta n)\delta p/\delta n}, \qquad U_{SRH} \approx G_0. \quad (2\text{-}99)$$

or

$$\tau_{nSRH} = \frac{\tau_{n0}(p_0 + p_1 + \delta p)(1 + I_n) + \tau_{p0}\big((n_0 + n_1)(1 + I_n) + \delta p\big)}{(p_0 + n_0(1 + I_n) + \delta p)(1 + I_n)}. \quad (2\text{-}100)$$

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

$$\tau_{pSRH} = \frac{\delta p}{G_0} = (1 + I_n)\tau_{nSRH} \quad (2\text{-}101)$$

Using Eqns. (2-97) and (2-98) along with Eqn. (2-99), one can easily show that:

$$\tau_{pSRH} = \frac{\delta p}{G_0} = \frac{\tau_{n0}(p_0 + p_1 + \delta p) + \tau_{p0}(n_0 + n_1 + \delta n)}{n_0 + (p_0 + \delta p)\delta n/\delta p} \quad (2\text{-}102)$$

or

$$\tau_{pSRH} = \frac{\tau_{n0}(p_0 + p_1 + \delta p)(1 + I_n) + \tau_{p0}((n_0 + n_1)(1 + I_n) + \delta p)}{(p_0 + n_0(1 + I_n) + \delta p)}. \quad (2\text{-}103)$$

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 [49], [50].

For a system under high injection ($\delta p = \delta n \gg p_0$), the excess electron SRH lifetime in Eqn. (2-100) simplifies to:

$$\tau_{nSRH} = \tau_{pSRH} = \tau_{n0} + \tau_{p0}. \quad (2\text{-}104)$$

Chapter 3 : Methodology

For the analysis of the effects of deep levels optical emissions of free carriers on the photo-responses of p-semiconductor in the materials for this work, Silicon (Si) was found to be suitable for its indirect band gap, very high carrier densities and very high melting point. Then, the important theoretical data concerned with the optical and electrical properties of these indirect band semiconductors were gathered and described. The temperature dependence of energy band-gap $E_g(T)$, the valance band energy (E_V) and the conduction band energy (E_C), the intrinsic Fermi energy, E_i and the Fermi energy, E_F can be determined using the samples parameters and the free carrier concentrations from the relation in Eqns. (1, 2, 9) and Eqn. (2-14) respectively. The first and new one equation for the ionization of acceptors carriers concentrations, N_a^- used in the analysis for different state of energy level can be determined from Eqn. (2-24) and the majority carrier concentration, p_0 is determined from , N_a^-. 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 C_{nT} and C_{pT} can be determined using Eqn. (2-82) and (2-83) for SRH electron capture and 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 were studied by substituting the density of the trapped carriers in the relations describing the recombination mechanisms. The effects of the temperature, changing the total density of trap and the doping level, and injection, G_0 on the density of the carriers trapped at different localized states also studied. The SRH lifetime for excess carriers in p-type Si material are determined as functions of localized state at different temperatures, and at low and at high injection levels. We calculated and plotted all graphs by Microsoft excel and origin using the standard formulas.

Chapter 4 : Results and discussion

This chapter deals with the analysis, discussion and the results of the thesis. First, the trapping effects at different temperatures and at different illuminations in different regions of p-type semiconductor (Si) were analyzed. Next, the SRH excess carrier lifetimes for holes and electrons through the localized states are described under different conditions.

4.1 The temperature dependence of trapping effects

Figure 4.1 illustrates the trap effects for electrons, I_n and and for holes, I_p at the localized centers as functions of energy of the trap level for p-type silicon (Si), (a) at 300 K and (b) at different temperatures. The graphs are drawn using Eqns. (2-91) and (2-92), as function of localized state energy levels by keeping the localized state density uniform throughout the bulk. This helps to understand the interplay between different localized states and the valence and conduction bands. Figure 4.1 (a) shows both the effects of the majority and minority carrier traps at relatively room temperature (300K). These result analyzed by fixing the total density of localized state at N_T = 10^{16}cm^{-3}, doping level at N_a = 10^{18}cm^{-3} value and injection level G_0 = 0.

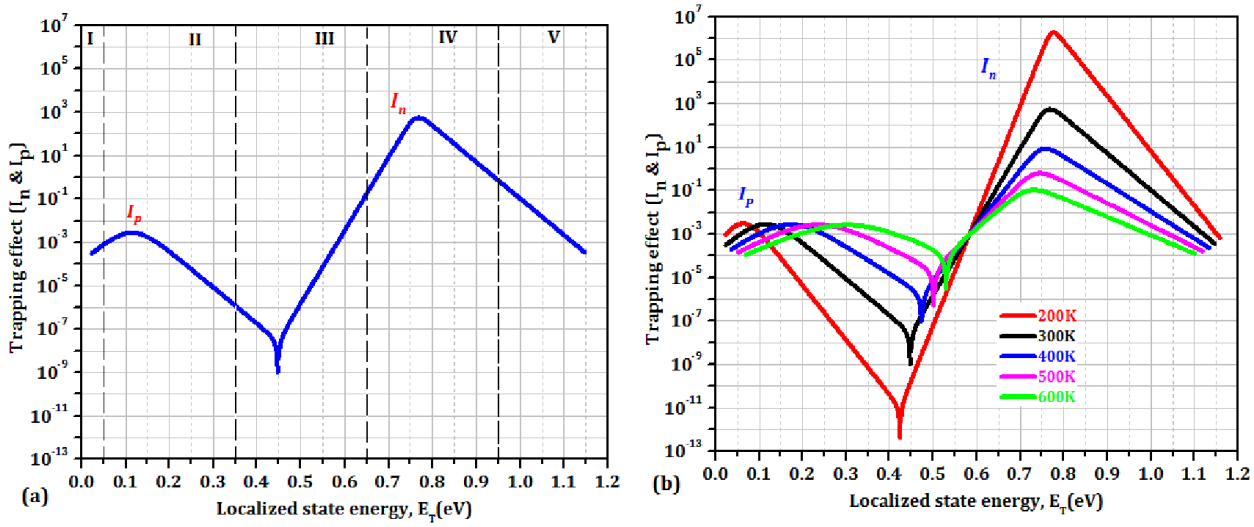

Figure 4-1: The free carriers trapping effect as a function of energy of the trap level for (a) room and (b) different temperatures.

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 4.1 (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 4.1 (a) can be divided into five regions labeled I through V.

Region I (Acceptor region): 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 the thermal energy $k_B T$. Most of the impurities are in the n_T state (When we compare the density of n_{0T} states with p_{0T}, the state $n_{0T} >> p_{0T}$) and the hole emission rate is very high. Hence the effects of the traps of a localized center in both Eqns. (2-91) and (2-92), 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 (Holes trap region): 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 0.35 eV). The energy value of this region is much greater than thermal energy $k_B T$ or ($E_T \gg k_B T$). In this region the capture cross section of holes are 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 4.1a. Therefore, we can call this region holes trapping region.

Region III (Recombination region): This region also encompasses all the energy trap level very closer to the intrinsic Fermi level in both sides, where the localized levels are partially ionized ($n_{0T} \approx p_{0T} \approx N_T/2$). According to this sample the range of the region

includes trap center from the energy level 0.35 eV to 0.65 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 4.1 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 called this region recombination region.

Region IV (Electron trap region): This region comprises 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 0.65 eV to 0.95 eV). In this region particularly at the energy level equal to 0.77 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 is much greater than the capture cross section of holes ($\sigma_n \gg \sigma_p$). When we compare the density of states (p_{0T} with n_{0T}), p_{0T} is greater than ($p_{0T} > n_{0T}$). So, the probability of capture of electron is greater than the probability of hole capture. The electron trap effect becomes the most dominant as shown in Figure 4.1(a). Therefore, we call this region electron trap region.

Region V (Donor region): This region includs all the localized energy levels closer to the conduction band minima (from 0.95eV to conduction band minima). The energy value of this region is approximately equal or less than the thermal energy $k_B T$. Most of the impurities are in the p_T state (When we compare the density of states p_{0T} with n_{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. (2-91) and (2-92), 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 as donor region.

Generally, we can say that, by comparing the two graphs as the temperature increases, the trap effect decreases for all the localized states or vice versa.

4.2 The temperature dependence Shockley-Read-Hall lifetime

Figure 4.2 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. (2-99) for Figure 4.2 (a) and Eqn. (2-103) for Figure 4.2 (b). As predicted earlier in Figure 4.1, since the recombination and the trapping of carriers are negligible for localized levels near the valence and conduction band edges, 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 4.2. The SRH lifetime for excess electrons has a minimum value at the recombination center states, as shown in Figure 4.2 (a), and this point of minimum SRH lifetime shifts toward the conduction band edge with increasing temperature.

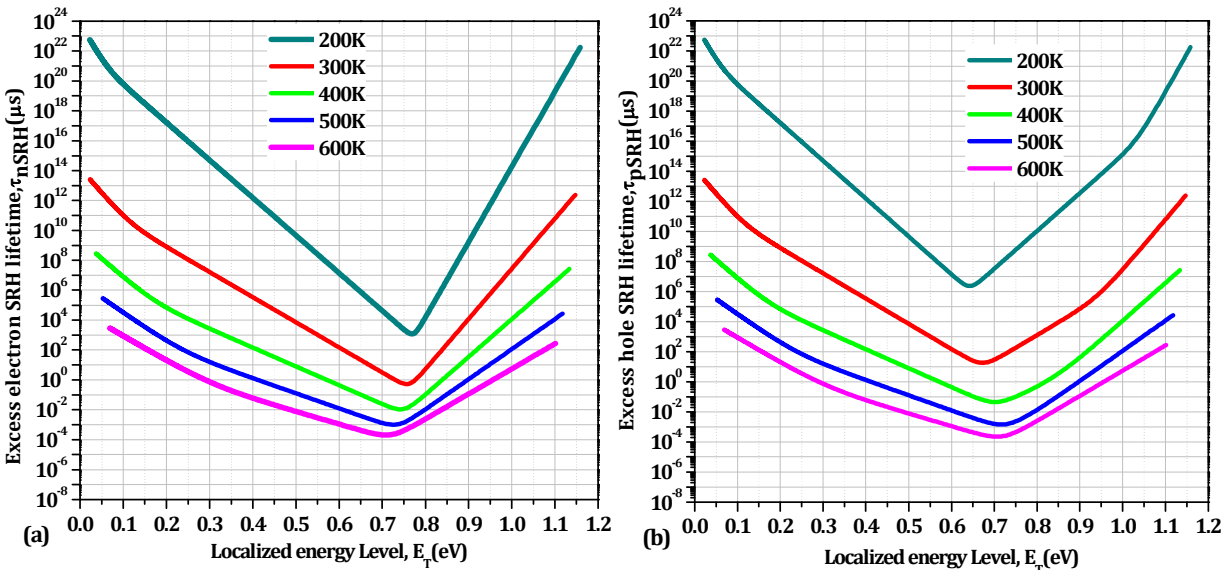

Figure 4-2: The SRH lifetime at different temperatures as a function of localized state energy (a) the excess electrons and (b) the excess holes.

The sensitization effect increases the SRH lifetime of excess holes in the region where the electron trap is influential. At very low temperatures, the SRH lifetime curves for holes become rapidly increases vertically above the mid-gap. As temperature increases, the SRH lifetime for holes decreases below the mid-gap in the region where the hole traps become

influential, 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 4-2. Therefore, the SRH carrier recombination lifetimes depends on the deep level density carrier concentrations.

4.3 Injection level dependence of trapping effects

Figure 4.3 (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 silicon (Si), (a) at injection level $G_0 = 0$ and (b) at different injection levels. The graphs are drawn using Eqns. (2-91) and (2-92), 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 injection levels. Figure 4.3 (a) shows both the effects of the majority and minority carrier traps at a relatively zero injection level. These result analyzed by fixing the total density of localized state value at $N_T = 10^{18}cm^{-3}$, doping level at $N_a = 10^{18}cm^{-3}$ value and at room temperature (300K). As discussed in Figure 4.1 (a), Depending on the interactions of localized states with the conduction or valence bands, the energy level dependence plot of the trap in Figure 4.3 (a) can be divided into five regions labeled I through V.

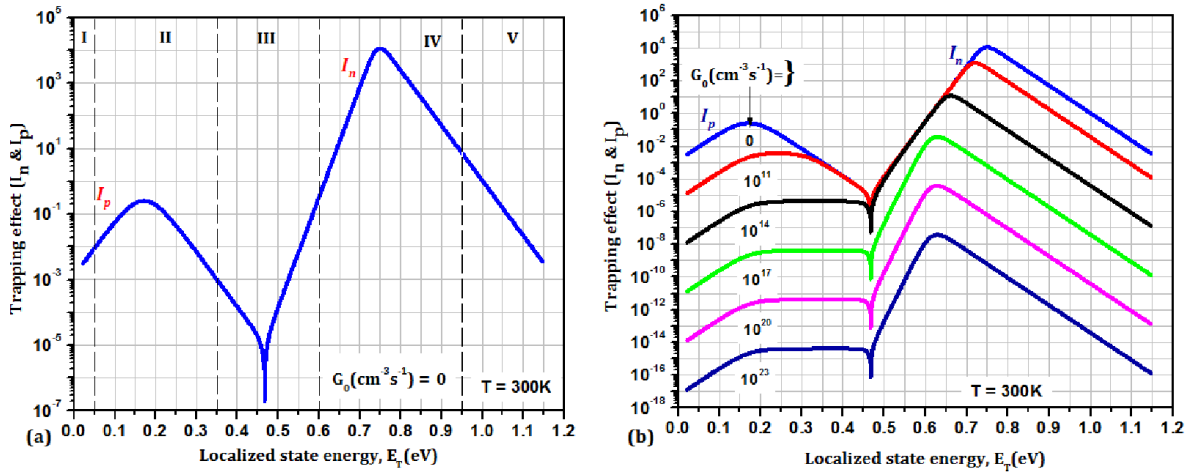

Figure 4-3: The free carriers trapping effect as a function of energy of the trap level for (a) low injection level and (b) different injection levels.

Here, free carrier traps are relatively inactive at high injection compared to low injection. Only the electron trapping shows maximum values after the recombination center at higher injection as shown in Figure 4.3 (b). The minority carrier traps farther away below the intrinsic level become less effective with increasing injection levels while more effective above as shown in Figure 4-3 (b). In general, as injection levels increases the trapping effects decreases.

4.4 Injection level dependence of Shockley-Read-Hall lifetime

A SRH recombination center is basically characterized by three parameters, which are its energy position in the gap, usually expressed as the energy distance to the nearest band edge, and the capture coefficients for electrons and for holes C_{nT} and C_{pT}, respectively. For a center concentration of N_T, the capture coefficients C_{nT} and C_{pT} govern the lifetime of excess electrons or holes, under the condition that the center is occupied by a hole or an electron in Eq. (2-81). Instead of N_T, C_{nT}, and C_{pT}, only the two lifetimes τ_{n0} and τ_{p0} defined by Eq.(2-81) are given. Note, however that these are not always real excess carrier lifetimes. The real lifetime still depends on the occupancy state of the center has two charge states, one if occupied by an electron and one if not, or one if not occupied by a hole and one if occupied, which is the same and holds for energy bands. In addition, injection level system is one of the parameter determinations of SRH lifetime. In a case, the excess carrier lifetimes given in Eqns. (2-104) remain only a function of photo-generated carrier concentrations in high injection level system at τ_{SRH} increases with increasing δn and ($\delta n = \delta p$) yields $\tau_{SRH} = \tau_{n0} + \tau_{p0}$, a function of thermally-generated carrier concentrations in low injection level materials ($\delta n \ll p_0$) in Eqn. (2-99). As a result, the excess carrier lifetimes given in Figure 4.4 illustrates the SRH lifetimes at the $G_0 = 0$, $G_0 > 0$ and $G_0 \rightarrow \infty$ as a function of localized state energy for silicon samples (a) excess electron SRH lifetime and (b) excess hole SRH lifetime. As one can see from Figure 4.4 (a) & (b) the room temperature, low level injection trapping effect for excess electrons and holes is very low at lower and higher localized energy levels and reach maximum value at a localized state closer to 0.76eV and 0.66eV, respectively. In figure 4.4 (a) between localized energy levels

0.6eV and 0.85eV, this makes the center more recombination-active to incoming electrons and holes.

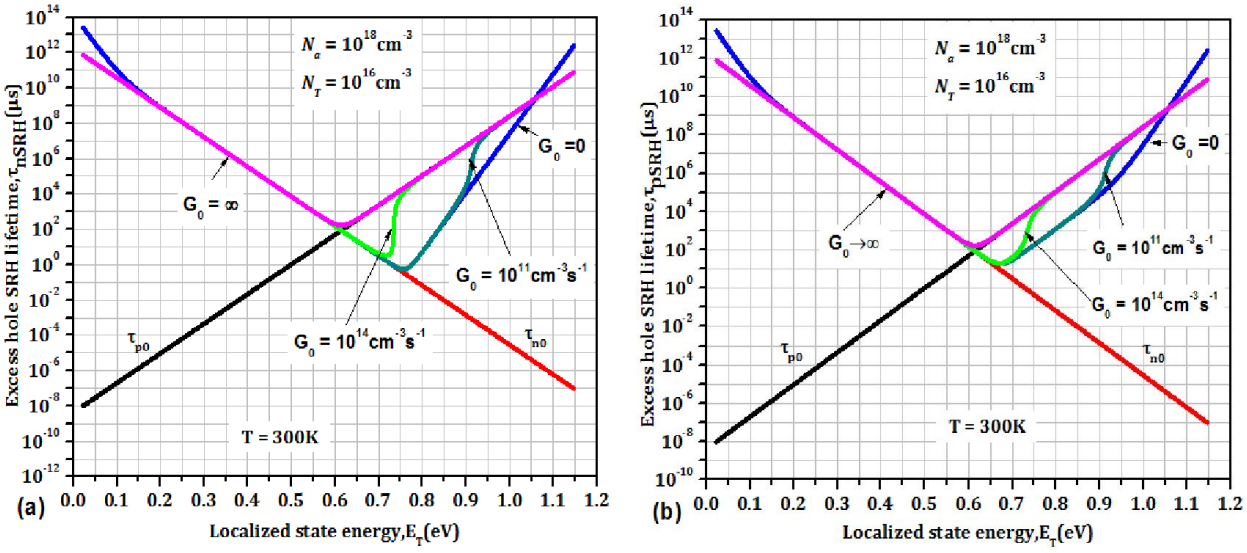

Figure 4-4: Injection level dependence SRH lifetime as function of localized state energy (a) the excess electrons SRH lifetime (b) the excess holes SRH lifetime

In figure 4.4 (b) between localized energy levels 0.6eV and 0.75eV, this makes the center more recombination-active to incoming electrons and holes. SRH lifetime in both cases is high at the lower and higher localized energy levels while it is low at the recombination centers. SRH lifetime is uniformly decreases from acceptor region to their recombination center in both and an excess electron SRH lifetime rapidly increases after recombination while excess holes SRH lifetime somewhat smoothly increases then rapidly increases to the donor region. In figure 4.4 (a) & (b) similarly, at the room temperature at $G_0 > 0$ level injection trapping effect for excess electrons and holes is low at lower and higher localized energy levels and reach maximum value at a localized state closer to 0.65eV at the same time.

Independent of the energy position of an SRH centers (in the upper or in the lower half of the gap) the charge state of the two possible occupation states governs whether a center is donor- or acceptor-like. If the charge state changes between ^{0} and $^+$ (for being occupied by an electron or not), it is a donor, and if the charge state changes between ^{0} and $^-$ (for being occupied by a hole or not), it is an acceptor. Hence, donor-like levels are, in ionized state (if occupied by a hole), electro statically attractive for electrons, hence for them $C_{nT} \gg$

C_{pT} holds, and acceptor-like levels are, if occupied by an electron, attractive for holes, leading to $C_{nT} \ll C_{pT}$. Therefore, the often-made assumption $C_{nT} = C_{pT}$ or ($\tau_{n0} = \tau_{p0}$) for a mid-gap level. In the limit of small excess concentrations δn, $\tau_{SRH} = \tau_{n0}$ always holds. If δn increases, the behavior depends on the ratio $\frac{\tau_{n0}}{\tau_{p0}} = \frac{\sigma_p}{\sigma_n}$. for $\tau_{n0} \gg \tau_{p0}$(acceptor-like center) in p-material also for high emissions levels $\tau_{SRH} = \tau_{n0}$ holds, since the center remains mainly occupied by a hole. For $\tau_{p0} \gg \tau_{n0}$ (donor-like center), however, with increasing δn the hole occupancy factor according to Eq. (2-99) decreases. The τ_{SRH} increases with increasing δn. If the lifetimes strongly deviate from each other, in a certain excess carrier concentration regime τ_{SRH}increases proportional to δn and($\delta n = \delta p$). In figure 4.4(a) & (b) in the limit of high injection level ($G_0 \to \infty$), $\tau_{SRH} = \tau_{n0} + \tau_{p0}$ holds, and then the lifetime is governed by the larger of the two lifetimes. This makes the center less recombination-active to incoming electrons. This effect is called "saturation of a SRH center." The result in both Figure (a) & (b) are exactly V-shapes which are done due to the saturation factor on the samples as high injection level was introduced.

4.5 Effects of density of localized state versus doping level on Shockley-Read-Hall lifetimes

Figure 4.5 illustrates the SRH lifetimes at total density of localized state and doping level as a function of localized state energy for (a) total density of localized state greater than doping level and (b) total density of localized state less than doping level and (c) total density of localized state equal to doping level. These result analyzed by fixing the temperature at room (300K) and at low injection level. As predicted in Figure 4.5 (a), (b) and (c) since the recombination and the trapping of carriers are negligible for localized levels near the valence and conduction band edges, the magnitude of both SRH lifetimes reaches a maximum value in these regions.

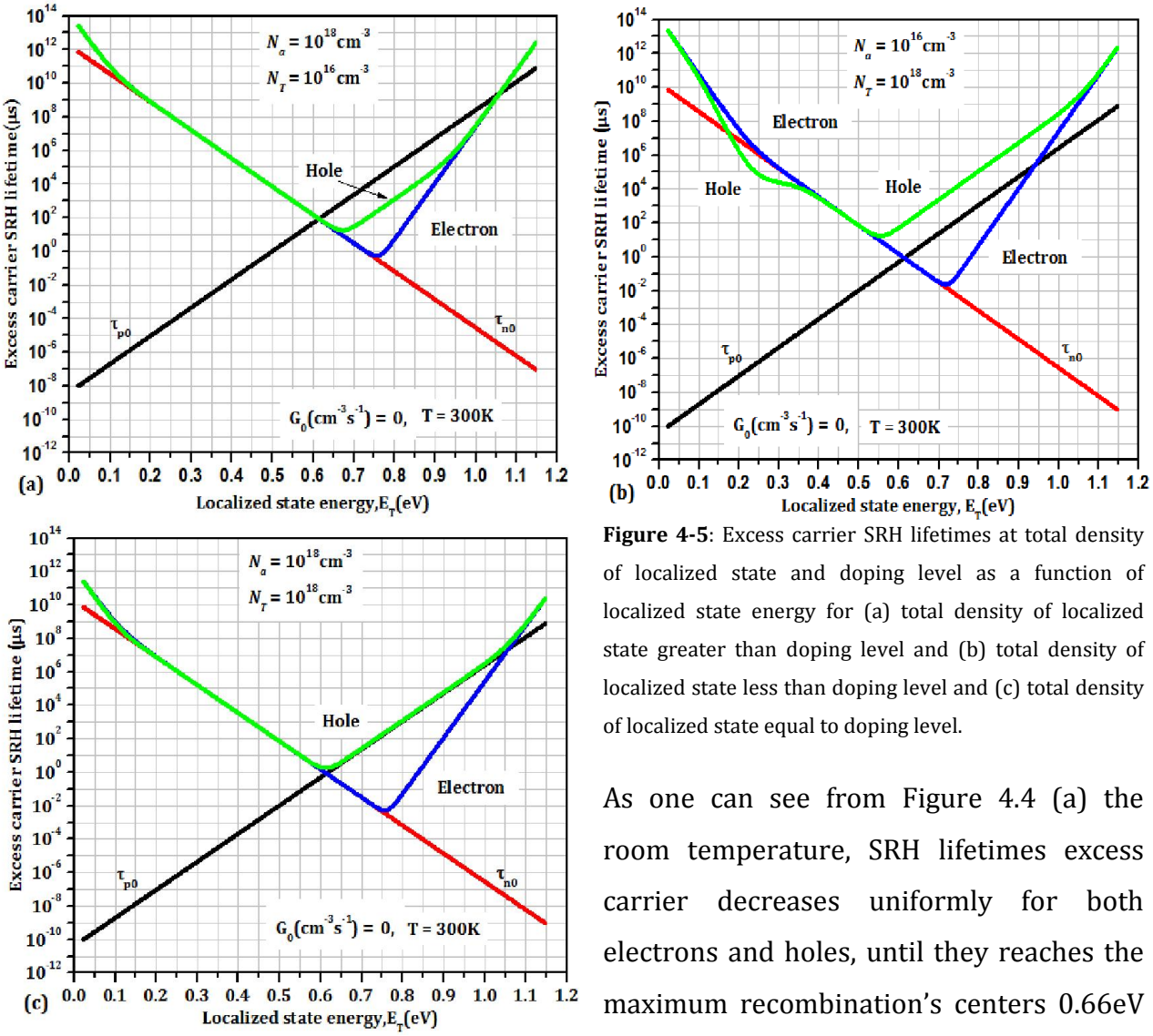

Figure 4-5: Excess carrier SRH lifetimes at total density of localized state and doping level as a function of localized state energy for (a) total density of localized state greater than doping level and (b) total density of localized state less than doping level and (c) total density of localized state equal to doping level.

As one can see from Figure 4.4 (a) the room temperature, SRH lifetimes excess carrier decreases uniformly for both electrons and holes, until they reaches the maximum recombination's centers 0.66eV for holes and 0.76eV electrons. After recombination center in the donor trap regions due to imbalances of both electrons and holes, SRH lifetime for the hole is show as majority carrier lifetime while the electron is show the minority carrier lifetime (insufficiency holes and excess electrons). In figure 4.5(b) we see that the holes re-emission is takes place which is called the trap, with cause of total density state exceeds the doping level. The SRH lifetime for holes and electrons decreases up to the recombination centers 0.55eV and 0.76eV, respectively. SRH lifetime for the hole is majority carrier lifetime while the electron is the minority carrier lifetime (i.e. due to more insufficiency of holes and excess of electrons).

In figure 4.5(c) both holes and electrons SRH lifetime decreases before they reaches recombination's centers while both are increases after recombination. Again in the donor region, SRH lifetime for the hole is majority carrier while for electrons is minority carrier. In three cases trap is increases to the mid-gap and decreases after the recombination center to the conduction band. The total density state of parameter more shows the increases and decreases of the traps.

Chapter 5 : Conclusions

In this study, the effects of deep levels optical emissions of free carriers on the photo-responses semiconductor at different localized state are calculated inside the sample of silicon (Si). Then, the effect of temperature on the trap effect and on SRH lifetimes, and injection, and total trap density state and doping level on the 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 regions 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. $\sigma_n \gg \sigma_p$ 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 traps 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 0.77 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, at high injection level to low level and if total trap density is greater than doping level. Only deep levels can trap free carriers at higher temperatures and trap is decreases with increasing temperature as function of localized state energies. In all case SRH lifetimes as function of localized state energies in lower temperatures is dominated in the semiconductor silicon sample. It has been shown that, the trapping value varies with temperature. At low temperatures, free carrier traps are

relatively more active. The minority carrier traps farther away above the intrinsic level become more effective with decreasing temperature. Free carrier traps are more effective at low temperatures, when compared to high temperatures. The probability of emission of carriers by the center increases with increasing temperature. The electron trap localized centers become the most dominant electron trap centers at lower temperatures. SRH lifetime becomes to be saturated as injection level goes to infinite.

References

[1] G.L Pearson and W. H.Brattain, "History of semiconductor research," *Pre-1900 Semiconductor Research and Semiconductor Device,* vol. 43, pp. 1794-1806, 1955.

[2] R.N.Hall, "Recombinatio process in semiconductors," *proc,* vol. 106B, pp. 923-931, March, 1960.

[3] D. K. Schroder, *Semiconductor Material and Device Characterization 2nd edition John Wiley and Sons,* 1998.

[4] Vikram,Rupavatharam, "Modeling of QE, I-V Characteristics of MSM (Metal-Semiconductor-Metal)," *Mercuric Iodide Thin Films with MEDICITM,* 2004.

[5] I. A. Y. Lubiaiker, "Direct band and indirect band semiconductors depend on temperure," p. 38, 1995.

[6] Sheng S. Li, "Semiconductor Physical Electronics Second Edition, USA: Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA," 2006.

[7] L.W.BridEman, "Hall Effect," *The thermodynamics of Electrical Phenomena in Metals,* 1934.

[8] T. Trupke, M. A. Green, P. Wurfel, P. P. Altermatt, A. Wang, J. Zhao, and R.Corkish, "Temperature dependence of the radiative recombination coefficient of intrinsic crystalline silicon," *J. Appl. Phys,* vol. 94, pp. 4930-4937, 2003.

[9] A. Mitonneau, A. Mircea, G.M. Martin, D. Pons, "Electron and hole capture cross sections at deep centers in gallium arsenids," *HAL,* pp. 853-860, 1979.

[10] M. W. Shura, "Band-to-band Auger effect in GaSb and InAs lasers," 2013.

[11] M. W. Shura, V. Wagener, J. R. Botha and M. C. Wagener, "Non-linear injection level dependence of the excess carrier lifetime of p-type GaSb thin films: A two-layer model," *J. Appl. Phys,* p. 113104, 111 (2012).

[12] Chen, M. C. Wu and C. C., "Photoluminescence of high-quality GaSb grown from GaSb rich solutions

by liquid phase epitaxial," *Journal of applied physics,* vol. 72, pp. 4275-4280, 1992.

[13] W. J. Turner et. al, "Exciton absorption and emmission in InP," *Physical review A,* vol. 136, pp. 1467-1470, 1964.

[14] C. W. Hsien and P. H. Lai, "Temperature effect on empact ionization characteristics metamorphic high electron mobilty transistors," 2006.

[15] A. Many and R. Bray, "Lifetime of excess carriers in semicondoctors. London: Heywood and Co," pp. 117-151, 1985.

[16] C. Kittel, "Introduction to solid state physics, Wiley, seventh edition," 2010.

[17] Y. P. Varshni, "Temperature dependence of the energy gap in semiconductors," *Physica,* vol. 34, p. 149, 1967.

[18] J. P. McKelvey, "Solid-state and semiconductor physics, 2nd ed., Harper & Row. New York," 1966.

[19] S. S. Li, "Semiconductor Physical electronics (Springer, New York)," 2006.

[20] C. Kittel, "Introduction to solid state physics, 8th ed, John Wiley & Sons, Inc," 2005.

[21] E. Rosencher and B.Vinter, "Opto-electronic, Thomson-CSF Masson," 1998.

[22] D. K. Schroder, "Carriers lifetime in silicon," *IEEE Transactions on electron devices,* vol. 44, 1997.

[23] Kaur.R, A.V.Singh, R.M.Mehra, Noncryst.Solids 352(2006)2335.

[24] A. Baraldi, F. Colonna, C. Ghezzi, R. Magnanini, A. Parisini, L. Tarricone, A. Bosacchi,and S. Franchi, "Semicond. Sci. Technol," p. 11, 1656 (1996).

[25] C. A. Wang and G. Nichols, "Auger and Radiative Recombination Coefficients in 0.55eV InGaAsSb," *Massachusetts Institute of Technology, Lexington,* 2004.

[26] F. Silva, "Impurity cluster effects in high and low doping semiconducotors Wiley," *International journal of quantum chemistry,* pp. 1-6, 2010.

[27] P. Blood and J. W. Orton, "The electrical characterization of semiconductors: majority carriers and electron states, Landon: Accadamic press," 1992.

[28] S. Wang, " Fundamentals of Semiconductor Theory and Device Physics (PrenticeHall)," 1989.

[29] G. H. L. a. H. H. w. bury, " Solid State Phys.," vol. 13, p. 223, 1962.

[30] Bourgoin and.M.Lanno point Defects in semiconductors II,Springer Verlag, New York(1983).

[31] Landsberg, "Recombination in Semiconductorss, Cambridge : Cambridge University Pres," 1991.

[32] V. K. Khanna, "carrier life times and recombination-generation mechanisms in semiconductor device physics," *solid state devices division,* pp. 223-224, 2004.

[33] C. T. Sah and W. Shockley, *Phys. Rev,* 1958.

[34] G. Kennler, K. Forberich, M. C. Scharber, C. J. Brabec, *J. of applied phys,* vol. 102, p. 054516, 2007.

[35] D. Macdonald, "Measuring and interpreting the life time of silicon wafers," *Sollar 39 energy,* pp. 255-262, 2004.

[36] R. Sinton and T. Mankad, "Contactless carrierlifetime measurement in silicon wafers," pp. 1-14, 2010.

[37] W. Shockley and W. T. Read, "statistical of the recombination of holes and electrons," *physical review 87(5),* Vols. 835-842, 1952.

[38] J. Okada, "Recombination Centers in Germanium," *J. Phys. Soc.,* vol. 13, pp. 793 - 800, Japan, 1958.

[39] W. K. a. J. Luttinger, *Phys. Rev.,* vol. B8, p. 915, 1955.

[40] Sze, S. M. (Ed.) ,Modern Semiconductor Device Physics, New York: Wiley, New York, 1998.

[41] J. F. Roller, Contactless Spectral-Dependent Measurement of Bulk Lifetime and Surface Recombination Velocity in silicon photovoltaic materials, 2016.

[42] R. Thomas, Harris, "Optical properties of Si, Ge,GaAs, InAs and InP at elevated tempratures," 2010.

[43] M. W. Shura, "Photoconductivity Spectroscopy of GaAs thin films," 2013.

[44] M. M . A.V. Dmitrie, "Recombination and ionization in narrow gap semiconductors," 1995.

[45] Audrius Alkauskas, Qimin Yan, and Chris G. Van de Walle,"First-principles theory of nonradiative carrier capture via multiphonon emission" Materials Department, University of California, Santa Barbara, California 93106-5050, USA, July 17, 2014.

[46] H. RN, "electron-hole recombination in germanium," *Phy Rev,* vol. 87, p. 387, 1952.

[47] J. Okada, "Effect of External Illumination on Carrier Lifetime in Semiconductors," *J.Phys. Soc. Japan,* vol. 14, pp. 1550-1557, 1959.

[48] B. R. Green, "Opto-electronic," *Hall Effect measurement for Semiconductors and material characterization,* 2011.

[49] M. Z. Rahman , and Bangladesh, "Modeling Minority Carrier's Recombination Lifetime of p-Si Solar Cell," *Dhaka 1208,* 2011.

[50] P. C. R. K, "A comparison of dominant recombination mechanisms in n-type InAsSb materials," *Banaras Hindu University, India,* 2006.