

Effects of Illumination on the Room Temperature Performances of the Bulk of Gallium Antimonide (GaSb) Semiconductor



By

Bikila Jalde Begna

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Bikila Jalde Begna

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Advisor

Dr. Megersa Wodajo Shura

Adama, Ethiopia

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As thesis research advisor, I hereby certify that I has read and evaluated this thesis entitled: **“Effects of Illumination on the Room Temperature Performances of the Bulk of Gallium Antimonide (GaSb) Semiconductor”** prepared under my guidance by **Bikila Jalde Begna**. I recommend that it can be submitted as fulfilling the thesis requirement.

Dr. Megersa Wodajo Shura

Advisor

Signature

Date

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

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Name of candidate: **Bikila Jalde Begna**

Signature: _____

Place: Adama Science and Technology University, Adama

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List of Symbols and Abbreviations

T	Temperature (K)
k_B	Boltzmann's constant (J/K)
E_g	Energy band gap (eV)
$E_g(0)$	Band gap energy at absolute zero on the Kelvin (eV)
$E_g(T)$	Band gap energy at any temperature (eV)
E_{ph}	Energy of photon (eV)
eV	Electro volt
GaSb	Gallium Antimonide
E_C, E_V	Energy of conduction band and valance band (eV)
α	Absorption coefficient (cm^{-1})
β	Beta (K)
λ	Photon Wavelength (nm)
c	Speed of light (m/s)
h	Plank's constant (Js)
$\hbar$	Reduced plank's constant (Js)
EHP	Electron hole pairs
K	Kelvin
ν	Photon frequency (s^{-1})
k	Wave number
C_R	Carriers radiative capture coefficient (cm^3s^{-1})
E_i	Intrinsic Fermi energy (eV)
E_F	Fermi energy (eV)
E_{BF}	Bulk Fermi energy (eV)
Φ_0	Incident photon flux density ($cm^{-2}s^{-1}$)
$\Delta\Phi$	Absorbed photon flux density ($cm^{-2}s^{-1}$)
Φ_s	Photon flux density entering the illuminated surface ($cm^{-2}s^{-1}$)
Δx	Change in thickness (m)
b	Thickness of layer (m)
Δt	Time interval (s)
A	Area (cm^{-2})
l	Length of layer (cm)
w	Width of layer (cm)
ΔN_{ph}	Number of photon absorbed
G_{th}	Thermal equilibrium Generation rate Electron and hole ($cm^{-3}s^{-1}$)
G_0	Photon absorption rate ($cm^{-3}s^{-1}$)

G	Total generation rate ($cm^{-3}s^{-1}$)
R	Total recombination rate
U	Net recombination rate
U_R	Radiative recombination rate
τ_n, τ_p	Lifetime for electron and holes (s)
m_n^*, m_p^*	Electron and hole effective mass (kg)
m_0	Rest mass of the electron (kg)
e	Elementary charge (c)
n_i	Intrinsic carrier density (cm^{-3})
n_0, p_0	Thermal equilibrium concentration of electron and hole (cm^{-3})
n, p	Non-thermal equilibrium concentration of electron and hole (cm^{-3})
$\delta n, \delta p$	Excess charge carrier concentration for electron and hole density (cm^{-3})
N_C, N_V	Effective density in the conduction and valence band (cm^{-3})
N_a	Acceptor concentration (cm^{-3})
n	Index of refraction
R	Reflectivity
x	Depth below the illuminated surface
x_p	Penetration depth of the light (m)
k_∞	Dielectric constant
ϵ_0	Permittivity of free space (c^2/Jm)
π	Pi
τ_R	Radiative excess carrier lifetime(s)
τ_k	Time constant of the radiative recombination (s)
τ_g	Excess generation carrier lifetime (s)
v_{th}	Thermal velocity of the electrons
α_R	Carrier capture cross section

Abstract

In this study, the effects of illumination on the room temperature performances of the bulk of Gallium Antimonide semiconductor are investigated under different conditions. First, by using the illumination mechanism, the photon absorption rate as function of absorption coefficient and depth below the illuminated surface in the bulk of the semiconductor were determined. Second, using the steady state condition of the free carrier generation-recombination mechanism, the radiative excess carrier lifetime of the free carrier is described in the bulk of semiconductor as function of the depth below the illuminated surface, absorption coefficients and injection levels. Next, the excess carrier lifetime is described at different photon flux density and energy of photons illumination. The obtained result indicates that, photon absorption rate and the free carrier's generation rate in general decreases with increasing the depth below the illuminated surface. Then, the variation of photo-response of the thick semiconductor is to be in general dominated by high injection levels and high energy of the illumination but, low injection levels and low energy illuminations cannot be detected the photo-response of the deep bulk and it becomes dominant at very high injection level.

Chapter 1 : Introduction

1.1 Background

Semiconducting materials have been of scientific interest for almost 200 years. 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. In 1873, Willoughby Smith arrived at the discovery of photoconductivity of Selenium. He set into experiments with Selenium high resistance, which appeared suitable for his submarine telegraphy [1]. Semiconductors in devices followed the discovery of a preferential direction for current flow through metal contacts made to naturally occurring crystals by Carl Braun in 1874. This observation was in distinction from the usual properties of metals and electrolytes in whose case resistance increase with temperature [2].

The next important decade in the semiconductor research is the decade of 1870. During this period selenium was discovered as a semiconductor, rectification at metal semiconductor interface came into scientists notice [3]. The first observation of photovoltaic effects in a solid system was made in 1876 [4]. Again, W. G. Adams, along with his student R. E. Day was investigating the photoelectric properties of Selenium at Cambridge. They discovered that illuminating a junction between Selenium and Platinum had a photovoltaic effect [3]. Although the most significant observations of the 19th century came during the period 1870-1885, the semiconductors had not received any device application for any practical purpose yet. It was not used until 1890's for any practical application. Wireless communication is the first field to employ these materials for practical application and then in the 1930s a complete theoretical foundation of semiconductors was established [5]. In recent years, considerable progress has been made in the fabrication of optoelectronic devices working at different frequency ranges in the infrared region using small band gap materials. Small band gap materials are used in various domains, such as pollutant detection and infrared thermal imaging, using a variety of device architectures, including near infrared photo-detectors, resonant tunneling structures and other quantum devices [6]. Some of these semiconductors are also used as booster cells in

solar cell clusters to improve the efficiency of photovoltaic and thermo-photovoltaic cells. By the beginning of the 20th century the five properties now associated with semiconductors had been discovered but, scarcely characterized such as: negative temperature coefficients, photoconductivity, rectification, photovoltaic effect and electroluminescence (excitation by current) [7].

Semiconductor material which conduct electricity conditionally, ranging between a conductor and an insulator. The existence of the energy band gap, high density of charge carrier and high mobility of a charge in semiconductor makes them very important in this aspect. The energy band gap of semiconductor ranges from 0.3 to 3.5 eV, small and direct band gap is ranging from 0.3 eV to 1.1 eV. The band gap for GaSb is ranged from 0.727 eV at room temperature to 0.813 eV an absolute zero [8]. Band gaps are one of the most important properties of modern semiconductor applications in photovoltaic, micro-processing, lighting source and for designing and discovering new applications. The conductivity of these materials can be varied over orders of magnitude by changes in temperature, optical excitation, and impurity content without altering the band-gap and other basic parameter of the host material and by simply doping it with acceptor or donor impurities [9]. At low temperature, pure semiconductors may become a perfect electrical insulator and the room temperature mobility of electrons for most semiconductors is ranged, since its valence band is totally filled with valence electrons and the conduction band is completely empty. However, as the temperature rises, a fraction of the valence electrons is excited into the conduction band by the thermal energy, thus creating free holes in the valence band [10].

Then, the effects of the injection level and the energy photon illuminations produced in a direct band gap in the bulk semiconductor Gallium Antimonide during illumination with a light of photon energy is greater than the energy band gap semiconductor. When the light of energy of individual photons greater than the semiconductor band gap is shining on the surface of a semiconductor sample, the photons can be absorbed, transferring their energy to an electron and the electron can be excited from the valence band to the conduction band [11]. The free electrons and holes produced due to illumination in the material raises the electrical conductivity of the semiconductor, the electrical conductivity in semiconductor

depends on the concentration of electrons and holes and their mobility [12]. The concentration of electrons and holes within the conduction or valence band can be affected by the light energy and injection level (photon flux density). The incident photon flux density Φ_0 is a measure of how many photons are attacking an area on the surface of the material per a unit time. Photons incident on the surface of a semiconductor will be either reflected from the top surface, or will be absorbed, scattered in the material, or transmitted through the material [13]. The performance of the material depends on the lifetime of free charge carriers generated by interaction of light with the material, referred to as the excess carrier lifetime [14, 15]. In a direct band gap material, optical absorption occurs near surface of the materials where as for the material having indirect band gap, light penetrates much deeper into the material [16].

The excess carriers in semiconductor is a crucial issue in study of the performance of the material. The performance of the material in this case depends on the excess carrier lifetime of free charge carriers generated by the interaction of photon with the material. Many researchers reported the effects of the illumination in the bulk of semiconductor and compared the theoretical and experimental values. Using the steady state photoconductivity along with the relations describing the excess carriers' lifetimes in the bulk of the semiconductors. The theoretical values of the excess carrier lifetime radiative recombination in the materials were also calculated. The radiative lifetime in the deep bulk of the material is constant at low injection, but decreases and continues to decrease as the injection level increases [17]. Stollwerk *et al.* [18] Reported that, the room temperature carrier lifetimes in the bulk the gallium antimonide photovoltaic cells is varying from 6 ns down to 10ps across the 10^{18}cm^{-3} to 10^{20}cm^{-3} doping range. Hilsum *et al.* [19] also reported that, a lifetime of roughly $1\mu\text{m}$ for GaSb, whereas Svensson *et al.* [20] measured a lifetime of 150 ns in undoped GaSb using photoconductivity measurements alone. The result of the excess carrier lifetime obtained from the steady state photoconductivity measurements revealed that the lifetime strongly decreases with increasing injection levels. Many of the researchers studied the photo responses of the bulk material in their previous works by using the experimental and theoretical methods. But the excess carrier lifetime is not measured and difficult to measure at each depth below the illuminated surface. In

this study, the photo response of in the bulk of Gallium Antimonide is described as function of the depths and absorption coefficients under different conditions.

1.2 Objectives of the study

The general objective of this study is to determine the effects of illumination on the room temperature performances of the bulk of Gallium Antimonide semiconductor. The specific objectives of the study were:

- to determine the effects of photon energy and the depth below the illuminate surface on the room temperature photon absorption rate in bulk semiconductor,
- to investigate effects of photon energy, photon flux density and the depth below the illuminate surface on the room photo-response (excess carrier lifetime) in bulk semiconductor.

1.3 Thesis outlines

This thesis organized into five chapters. Chapter is about review of related literatures. It mainly deals with the theory of energy bands, thermal equilibrium properties and the photo-response of semiconductors. Chapter three presents the overall method of data analysis in this work. Chapter four covers the results and discussion of the study. Chapter gives the overall conclusions of the results obtained in chapter 4.

Chapter 2 : Basic Semiconductors properties

In semiconductors, the electron-hole pairs can be created by either thermal or optical. At thermal equilibrium, these concentrations are constant. 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. This is called electron-hole recombination mechanism. Since the net carrier concentrations are constant at 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 as shown in Figure

2-1 below [21]. The band gap is also known as forbidden energy band and electrons are absent in the band gap. Band gap is defined as the minimum energy needed for an electron to shift from the valence band to the conduction band or *vice versa*. Band gap in semiconductors usually ranges between 1 and 4 eV, less than the band gap in insulators, while more than the band gap in conductors [23]. 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, under the effect of an externally applied electric field, the electrons can act as mobile carriers. They are drifted in the crystal lattice and thereby contribute to the electric current, allowing the remaining electrons in the valence band to exchange places with each [24]. Excess electron-hole pairs can also be generated in a semiconductor by the absorption of photons with energies greater than the band gap energy [25].

2.1 Thermal Equilibrium properties of Semiconductor

In this section, the description of some common properties of semiconductor materials like the energies, charge carrier densities and the photo-response will be discussed.

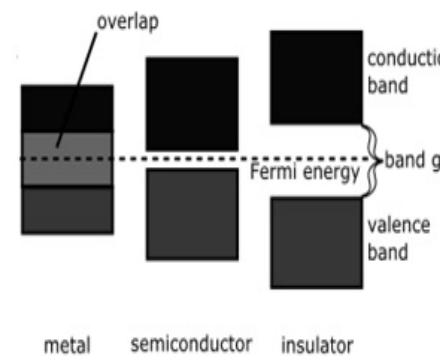


Figure 2-1: This figure shows the difference between the band gap of metal, semiconductor and insulator [21, 22].

2.1.1 Energy band gap of Semiconductor

The respective conduction and valence bands can be thermally populated with both electrons and holes, respectively as the Fermi energy level is near enough to both bands. There are two types' band structures in semiconductors: direct or indirect band. A direct band semiconductor is distinguished by having the minimum conduction band and maximum valence band edges aligned in at the same wave vector value, k , so that an electron can easily transit from the maximum edge of the valence band to the minimum edge of the conduction band. On

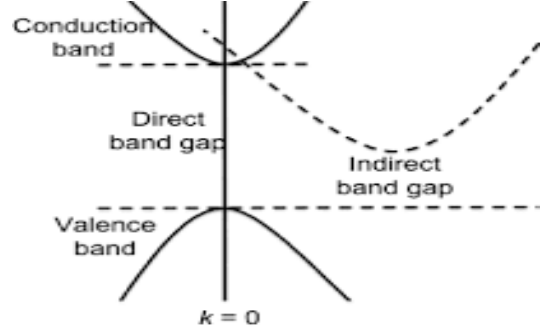


Figure 2-2: Direct and indirect band gap semiconductors [26].

the other hand, in the indirect band semiconductors, the band edges are not aligned at the same value of k , so that the electron does not transit directly to the conduction band minimum edge, both a photon and a phonon production mechanism are involved. In crystalline solids, the energy band gap, E_g between the valence band maximum, E_V and conduction band minimum, E_C is referred to as energy band gap [27]:

$$E_g = E_C - E_V. \quad (2-1)$$

When band gap light is absorbed by a semiconductor, charges move between the valence band and conduction band. A contraction of the crystal lattice with decreasing temperature usually leads to a strengthening of the interatomic bonds and associated increase in the band gap energy. The first empirical relation for the band gap shift with temperature, T was developed by Varshini *et al.* as [28, 29]:

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

where α and β are constants and $E_g(0)$ is the limiting value of the band at zero kelvin, the typical values of $E_g(0)$, α and β are 0.813 eV, 3.78×10^{-4} eV/K and 94 K, respectively.

2.1.2 Thermal equilibrium carrier concentration

The thermal equilibrium concentration of electrons and holes in semiconductor are determined by many factor including the band structure of the semiconductor, types and concentrations of the impurities doped in semiconductor. The thermal

equilibrium is used to describe the unperturbed state of system, to which no external illumination, or other perturbing forces are applied [30, 31]. Therefore, the thermal equilibrium concentration of electron and hole in conduction and valence band are always remained constant. At thermal equilibrium, electron-hole pairs are constantly being created and annihilated. For a semiconductor under thermal equilibrium, the concentration of electrons and holes in the conduction and valence bands are represented by n_0 and p_0 , respectively. The thermal equilibrium carrier concentrations, n_0 and n_p in the non-degenerate semiconductor case can be given by [32]:

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

where E_F is the Fermi-level energy, k_B , Boltzmann constant, N_C and N_V are the effective densities of conduction valence band states, respectively that are described as:

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

where h is Planck's constant, m_n^* and m_p^* are effective mass of electrons holes in conduction and valence bands, respectively and given in GaSb semiconductor given as [33, 34].

$$m_p^* = 0.35m_n \quad \text{and} \quad m_n^* = 0.047m_n, \quad (2-5)$$

where m_n is the rest mass of electron.

2.1.3 Intrinsic Semiconductors

Un-doped semiconductors (i.e., semiconductors with no intentional doping) or a perfect semiconductor crystal with no impurities or lattice defects is called an intrinsic semiconductor. A semiconductor may be considered as an intrinsic semiconductor if its thermally generated carrier density represented by n_i is much larger than the background doping or residual impurity densities. At $T = 0$ K, an intrinsic semiconductor behaves like an insulator because the conduction band states are totally empty and the valence band states are completely filled. However, as the temperature increases, some of the electrons in the valence band states are excited into the conduction band states by thermal energy, leaving behind an equal number

of holes in the valence band and the electron-hole pairs are produced. These electron-hole pairs (EHPs) are the only charge carriers in intrinsic material. Therefore, the intrinsic carrier density increases with increasing temperature. Suppose that $\mathfrak{N}$ is the concentration of electron-hole pairs thermally generated in the respective bands and $\mathfrak{N}_R$ is part of the intrinsic concentration of electron-hole pairs annihilated after the generation, the free carrier concentrations in the conduction and valence bands adjust for the intrinsic semiconductor to [35]:

$$n_0 \approx \mathfrak{N} - \mathfrak{N}_R = n_i = p_0. \quad (2-6)$$

In the above section, the electron-hole pairs in an intrinsic semiconductor are generated by thermal excitation. Therefore, for intrinsic semiconductors with an energy band gap on the order of 1 eV or higher, the intrinsic carrier density is usually very small at low temperature below 100 K. As a result, the resistivity for these intrinsic semiconductors is expected to be very high at low temperatures. For intrinsic semiconductor when both n_0 and p_0 are equal to the intrinsic concentration, n_i (or $n_0 = p_0$), the Fermi-level, E_F is converged to the intrinsic energy, E_i in relation (2-3) above, so that:

$$n_i = N_C \exp\left(-\frac{E_C - E_i}{k_B T}\right) = N_V \exp\left(-\frac{E_i - E_V}{k_B T}\right), \quad (2-7)$$

Upon squaring relation (2-7), we obtain:

$$n_i = \sqrt{N_C N_V} \exp\left(-\frac{E_g}{2k_B T}\right). \quad (2-8)$$

The intrinsic energy level can be determined taking into account the two terms on the left side of relation (2-7) and relation (2-4) as:

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

2.1.4 Extrinsic Semiconductors

In addition to the intrinsic carriers generated thermally, it is possible to create carriers in semiconductors by purposely introducing impurities into the crystal. This is called doping. Doping is the most common technique for varying the conductivity of semiconductors. 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 0 K, and very little thermal energy is required to excite these electrons to the conduction band. 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 [36]. 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 adding in the two exponential terms in relation (2-3) and taking into account relation (2-7) we get a very known relation between the intrinsic and the thermal equilibrium carrier densities [37]:

$$n_0 = n_i \exp\left(-\frac{E_i - E_F}{k_B T}\right) \quad \text{and} \quad p_0 = n_i \exp\left(-\frac{E_F - E_i}{k_B T}\right). \quad (2-10)$$

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

Upon multiplying the two expressions in relation (2-10) above and taking into account the expressions in relation (2-3), we get:

$$n_i = \sqrt{p_0 n_0} = \sqrt{N_V N_C} \exp\left(\frac{E_g}{k_B T}\right). \quad (2-11)$$

Eqn. (2-11) is called the *law of mass action* [38]. Upon eliminating n_i in between the two expressions in (2-10), we obtain the extrinsic Fermi-level, E_F to be:

$$E_F = E_i - k_B T \ln\left(\frac{p_0}{n_i}\right). \quad (2-12)$$

As the charge carrier concentrations change, the position of the extrinsic Fermi energy level varies within the band gap until the system reaches thermal equilibrium.

Eqn. (2-12) shows that E_F lies above E_i for n -type material ($n_i > p_0$) and below the E_i for p -type material ($n_i < p_0$) [39].

When free electron-hole pairs annihilate through recombination in extrinsic semiconductor, the free carrier concentrations in the conduction and valence bands adjust for the intrinsic semiconductor to [35]:

$$n_0 \approx N_d^+ + \mathfrak{N} - n_R \quad (2-13)$$

and

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

where 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, n_R is the concentration of total electron-hole pairs involved in the recombination process after the donors and the acceptors are being ionized. Upon eliminating $\mathfrak{N} - n_R$ in Eqn. (2-14), the well-known neutrality relationship is obtained:

$$n_0 + N_a^- = p_0 + N_d^+. \quad (2-15)$$

The law of mass action, relation (2-11), along with relation (2-15) for highly doped semiconductor ($N_a^- \gg N_d^+$) yields:

$$p_0 = \frac{N_a^-}{2} \left(1 + \sqrt{1 + \left(\frac{2n_i}{N_a^-} \right)^2} \right). \quad (2-16)$$

2.2 Photo-response of semiconductors

When photons with energies equal to or greater than the band gap energy ($h\nu \geq E_g$) are incident on semiconductor materials, the photons are absorbed by the formation of electron-hole pairs, where ν is the frequency of the light. While the photo-generated carriers exist in their respective bands, they are free to contribute to the conductivity of the material. The electron-hole pairs generated by photon absorption are known as photo-generated carriers. In the case of a pure semiconductor, photons with energy less than the band gap energy ($h\nu < E_g$) will not be enough to excite an electron from the valence band to the conduction band and it will pass through the semiconductor without being absorbed. 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

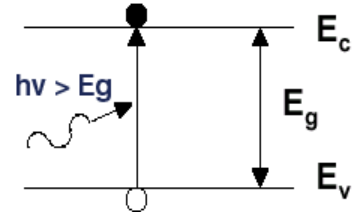


Figure 2-3: Absorption of photon in semiconductors [40].

exist in their respective bands, they are free to contribute to the conductivity of the material. The energy of each absorbed photon is consumed by raising a valence band electron in to the conduction band and creating electron-hole pair. Photon with $h\nu < E_g$ are basically not absorbed by the semiconductor and cannot generate electron-hole pair [41].

Photons incident on the surface of a bulk semiconductor are either reflected from the top surface or absorbed in the material. When the surface of a semiconductor is illuminated by a light source with $h\nu > E_g$ with incident photon flux density, Φ_0 (which is equivalent to the number of incident photon per unit area per unit time), the fraction of the photons flux density reflected back is given by $\Phi_0 R$ and the fraction entering the sample is $\Phi_0(1 - R)$, where R is the reflection coefficient (reflectivity) and can be defined in terms of the index of refraction of the media on either side of the surfaces (interfaces). Hence, it is calculated by using the relation [17] :

$$R = \left(\frac{n - 1}{n + 1} \right)^2. \quad (2-17)$$

Relation (2-17) assumes the refractive index, n remains constant for the entire wavelength range under consideration, i.e. $\lambda < 20 \mu m$ and the refractive index was taken as 3.8 for Gallium Antimonide [42, 43]. This results in a typical value of R to be approximately 0.34.

2.2.1 Absorption in infinitely thick (bulk) semiconductor

Next, we wish to investigate a photon absorption rate at different depths in the bulk of a very thick semiconductor. Thick (bulk) semiconductor refers to the case when the thickness of the semiconductor, b is infinitely large ($b \rightarrow \infty$). Figure 2-4 shows a

photon beam of flux density Φ_0 directed at the upper surface of a portion of a semiconductor sample of width w and infinitely large thickness. It is assumed that the beam contains only photons of energy $h\nu \geq E_g$. As the beam passes through the sample, the photon flux density at a distance x from the surface can be calculated by considering the probability of absorption within any infinitesimal thickness dx . The photon absorption rate, g_0 at depth x for a given wavelength is proportional to the photon flux density, $\Phi(x)$ remaining at x after being absorbed in the preceding section of the material [44].

$$g_0 = \frac{d\Phi(x)}{dx} = -\alpha\Phi(x), \quad (2-18)$$

where α is a constant called the absorption coefficient, which is related to the dielectric properties of the material and the wavelength of the incident photon. The absorption coefficient is determined using its dependence on the photon and the band gap energies, by Bardeen *et al* [45] as:

$$\alpha(\omega) = \frac{2^{\frac{2}{3}} m_n e^2}{3 \hbar^2 \sqrt{k_\infty}} \left(\frac{m_n^* m_p^*}{m_n (m_n^* + m_p^*)} \right)^{\frac{3}{2}} \left(1 + \frac{m_n}{m_n^*} + \frac{m_n}{m_p^*} \right) \left(\frac{\hbar\omega - E_g}{m_n c^2} \right)^{\frac{1}{2}}. \quad (2-19)$$

The negative (-) sign in Eqn. (2-18) indicates the decrease g_0 of with increasing x . Taking into account the reflection of photon flux density $\Phi_0 R$ back to the vacuum or air, the photon flux density entering the illuminated surface is given by the difference between the incident and the reflected photon flux densities:

$$\Phi_s(0) = \Phi_0(1 - R). \quad (2-20)$$

The total photon flux density remained at depth, x below the surface is described by the integration of relation (2-18) from the surface to depth, x as:

$$\int_{\Phi_s}^{\Phi} \frac{d\Phi'}{\Phi'} = -\alpha \int_0^x dx' \quad (2-21)$$

and hence is given by:

$$\Phi(x) = \Phi_0(1 - R) \exp(-\alpha x). \quad (2-22)$$

The total photon flux density decreases with increasing the depth below the surface. Relation (2-22) is known as Beer's law [46].

Next, we wish to describe the photon absorption rate, g_0 at different depths in a given portion of thick semiconductor. Figure 2-4 illustrates the photon absorption in a layer of thickness Δx at depth x in infinitely thick or bulk semiconductor ($b \rightarrow \infty$) of width and length w and l , respectively.

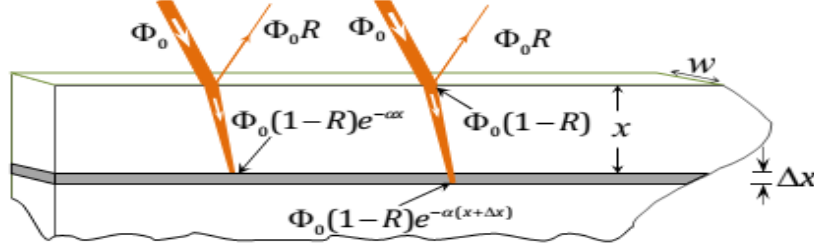


Figure 2-4: Photon Absorption in infinitely thick semiconductor [35].

The photon absorption rate (g_0) in entire volume of the given illuminated area (A) and thickness (Δx) is defined as the total number of absorbed photons per unit volume per unit time:

$$g_0 = \frac{\Delta N_{ph}}{A \Delta x \Delta t} = \frac{\Delta \Phi}{\Delta x}, \quad (2-23)$$

where ΔN_{ph} is the number of absorbed photons, Δt the time, A , illuminated surface area and $\Delta \Phi$ the absorbed photon flux density given as:

$$\Delta \Phi = \frac{\Delta N_{ph}}{A \Delta t}. \quad (2-24)$$

The photon absorption rate, g_0 at depth, x below the surface can be determined from relation (2-18) as:

$$g_0(\alpha, x) = -\alpha \Phi_0 (1 - R) \exp(-\alpha x) = -\alpha \Phi(x) \quad (2-25)$$

or

$$\frac{g_0(\alpha, x)}{\Phi_0} = \alpha (1 - R) \exp(-\alpha x). \quad (2-26)$$

The photon absorption rate in relation (2-26) also depends on the depth, x and the absorption coefficient, α . As one can see from relation (2-26), the linear term dominates for lower values of α , while the exponential term dominates for higher values of α . The absorption rate, g_0 has hence maximum value for intermediate values α . When relation (2-26) is differentiated with respect to α and the result is equated to zero as:

$$\frac{dg_0(\alpha, x)}{d\alpha} = (1 - \alpha x)\Phi(x) = 0. \quad (2-27)$$

The photon flux density $\Phi(x)$ cannot be zero at all point inside the material and therefore $1 = \alpha x$. This defines a depth x_p below the illuminated surface where the maximum absorption rate occurs for specific absorption coefficient. The depth (x_p) at which $g_0(\alpha, x)$, has a maximum value for a given photon energy is called the penetration depth, x_p of that photon and is given by:

$$x_p = \frac{1}{\alpha}, \quad (2-28)$$

Taking into account Eqn.(2-26) along with Eqn.(2-28) yields the position dependence of the absorption rate of a photon of absorption depth, x_p as:

$$g_0(x) = \frac{\Phi_0(1 - R)}{x_p} \exp\left(-\frac{x}{x_p}\right). \quad (2-29)$$

The limiting cases for the photon absorption rate in a very thick (bulk) semiconductor can be concluded as:

$$g_0(x_p) = \begin{cases} \alpha\Phi_0(1 - R), & \text{for } x \ll x_p, \\ 0.37\alpha\Phi_0(1 - R), & \text{for } x \approx x_p, \\ 0, & \text{for } x \gg x_p. \end{cases} \quad (2-30)$$

2.2.2 Radiative Recombination:

Radiative recombination is the opposite of the optical generation of charge carriers. It occurs when the energy of the excited electron is emitted by the formation of photon during the annihilation of an electron-hole pairs. This steady state excess carrier lifetime is given by: The Radiative recombination rate depends on the concentration of free electrons (n) and holes (p) is obtained as follows [48, 49, 50, and 51].

$$U_R = C_R(np - n_i^2), \quad (2-31)$$

where C_R is the electron and hole radiative carrier capture coefficient by the respective bands given by [52, 53, 54, 55 and 56]:

$$C_R = e\pi\sqrt{k_\infty} \left(\frac{m_n}{m_n^* + m_p^*} \frac{300}{T} \right)^{\frac{3}{2}} \left(1 + \frac{m_n}{m_n^*} + \frac{m_n}{m_p^*} \right) [E_g^2 + 3E_g k_B T + 3.75 k_B^2 T^2], \quad (2-32)$$

and n and p are the non-equilibrium electron and hole concentrations, respectively given by:

$$n = n_0 + \delta n \quad (2-33)$$

and

$$p = p_0 + \delta n \quad (2-34)$$

and δn is the photo-generated electron-hole concentrations. Substitution of relations (2-33) and (2-34) into relation (2-31) gives [57, 58]:

$$U_R = C_R \delta n (\delta n + p_0 + n_0), \quad (2-35)$$

The radiative excess carrier lifetime, τ_R takes the form:

$$\tau_R = \frac{\delta n}{U_R} = \frac{\tau_{R0}}{1 + C_R \tau_{R0} \delta n}. \quad (2-36)$$

where τ_{R0} is a time constant given by [59, 60]:

$$\tau_{R0} = \frac{1}{C_R (n_0 + p_0)}. \quad (2-37)$$

Since $U_R = G_0$ at steady state, the radiative excess carrier lifetime can be given by:

$$\tau_R = \frac{2\tau_k \tau_{R0}}{\tau_{R0} + \tau_k}, \quad (2-38)$$

where τ_k a time constant given by:

$$\tau_k = \frac{\tau_{R0}}{\sqrt{1 + 4C_R G_0 \tau_{R0}^2}}. \quad (2-39)$$

For a system under low injection level ($G_0 \rightarrow 0$), we have:

$$\tau_k = \tau_{R0} \quad (2-40)$$

and hence,

$$\tau_R = \tau_{R0}. \quad (2-41)$$

For under high injection level ($G_0 \rightarrow \infty$), then:

$$\tau_k = \frac{1}{2\sqrt{C_R G_0}} \ll \tau_{R0} \quad (2-42)$$

and

$$\delta n = 2G_0 \tau_k \quad \text{and} \quad \tau_R = 2\tau_k. \quad (2-43)$$

Chapter 3 : Methodology

This chapter gives the details explanation about the method used to analyze the results of this research work. First, a model of bulk Gallium Antimonide sample with known dimensions and majority carrier concentration is selected as the one in Figure 2-4.

The temperature dependence Hall measurements data was obtained from Nelson Mandela University, South Africa. The minority carrier concentration, n_0 is determined from majority carrier concentration p_0 and the intrinsic carrier concentration using the law of mass action given in relation (2-11).

Table 3-1 depicts all the constants and parameters used in the description of the results in this work.

Table 3-1: Constants and parameters used in the description of the results in this work.

No	Quantity	Symbols	Amount
1	Band gap at absolute zero	E_{g0}	0.813 meV
2	Band gap temperature coefficient	α	3.78×10^{-4} eV/K
3	Elementary charge	e	$1.602 \times 10^{-19}c$
4	Band gap temperature constant	β	94 K
5	Rest mass of electron	m_n	$9.11 \times 10^{31}kg$
6	Effective mass of electron in conduction band	m_n^*	$0.047m_n$
7	Effective mass of hole in valence band	m_p^*	$0.35m_n$
8	Planck's constant	h	$6.626 \times 10^{-34}Js$
9	Boltzmann constant	k_B	$1.38 \times 10^{-23}JK^{-1}$
10	Majority carrier concentration	p_0	$10^{17}cm^{-3}$
11	Intrinsic carrier concentration	n_i	$9.07 \times 10^{11}cm^{-3}$
12	Intrinsic Fermi energy	E_i	0.445 eV
13	Extrinsic Fermi energy	E_F	0.147 eV
14	Radiative capture coefficient	C_R	$1.01 \times 10^{-10}cm^3s^{-1}$

Next, the photon absorption rate as function of the depth, x and the absorption coefficient, α in the entire sample were investigated in detail using relation (2-29). The absorption coefficient dependence of the absorption rate is determined by varying the depth below the surface. The position dependence of the absorption rate below the illuminated surface is also determined by varying the absorption

coefficient of the material. In all the analysis of the results of the description of the photon absorption rates in the material, the vertical axes of the photon absorption rate and the horizontal the axes of the absorption coefficient and depth below the surface were taken as semi-log scales.

Using the steady-state conditions for radiative excess carrier lifetimes in relation (2-38), the excess carrier lifetime as functions of the depth below the illuminated surface and the absorption coefficient. The radiative carrier capture coefficient used in the analysis was calculated at room temperature using relation (2-32). In the description of excess carrier lifetimes as function of the absorption coefficients, the depth below the illuminated surfaces and the flux density of the photons are varied as required. In the description of excess carrier lifetimes as function of the depth below the illuminated surface, the absorption coefficient and the flux density of the photons are varied.

Chapter 4: Results and discussion

This chapter deals with the analysis and discussion of the entire results of this thesis. First, the photon absorption rates as function of depths and absorption coefficients in the bulk of semiconductor were presented. Then, the radiative excess carrier lifetime as function of absorption coefficient and depth below the illuminated surface were analyzed injection level under different condition.

4.1 Photon absorption rate

Figure 3-1 shows the normalized photon absorption rate (ratio of the optical absorption rate per incident photon flux density (g_0/Φ_0)) in the entire sample (brown lines) as a function of (a) absorption coefficient for different depths and (b) depths below the illuminated surface at different absorption coefficients. As one can see from Figure 3-1 (a), the normalized photon absorption rate has maximum value of $\alpha(1 - R)$ for $x \rightarrow 0$ or near the illuminated surface of the sample as shown by red line. The values of the photon absorption rates at the surface corresponding to photons with absorption coefficients α are shown by the intersection points of the horizontal red lines and the slanted red line just above the peak of each curve in Figure 3-1 (a). If a point at depth x below the illuminated surface is illuminated by photons of all energies (absorption coefficients), photons with the absorption coefficients equal to the reciprocal of x ($x = 1/\alpha$) has maximum absorption rate equal to 37% of its maximum value at the surface, or $0.37\alpha(1 - R)$ shown by green line in Figure 3-1 (a). Other photons with absorption coefficients less than x (or $1/\alpha < x$) and greater than x (or $1/\alpha > x$) have photon absorption rate less than $0.37\alpha(1 - R)$. The values of the photon absorption rates at the surface corresponding to photons with absorption coefficients α are shown by the intersection points of the horizontal red lines and the slanted red line just above the peak of each curve in Figure 3-1 (a).

The values of the photon absorption rates at the absorption depth of each photon with absorption coefficients α are shown by the intersection points of the horizontal green lines and the slanted green line just at the peak of each curve in Figure 3-1 (a). In addition, at a given depth, the photon absorption rate has very small values at very small and large values of α . The photon absorption rate has very large (maximum

value) at the intermediate value of α . The points of intersection of blue slanted line and horizontal blue lines indicates the maximum value of the normalized photon absorption rate (α) at the surface in the absence of surface reflectivity, R .

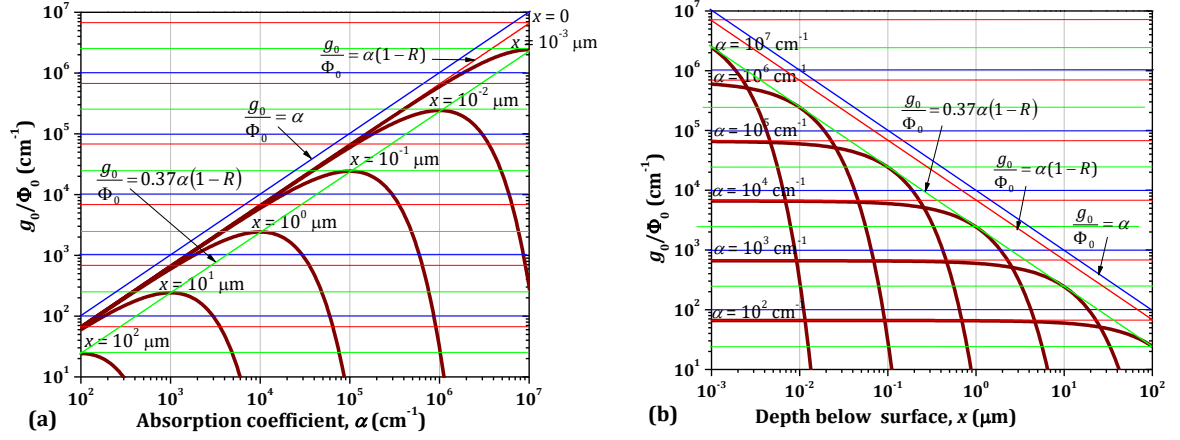


Figure 3-1: Normalized photon absorption rate (ratio of the optical absorption rate per incident photon flux density) in the bulk of semiconductor (brown lines) as (a) a function of absorption coefficient at different depths in the material and (b) as a function of depth for photons with different absorption coefficients.

The normalized photon absorption rate with surface reflectivity, R cannot attain the maximum value, α . Surface reflectivity, R changes the maximum value of the normalized photon absorption rate from its value α to $\alpha(1 - R)$. This value again reduced to $0.37\alpha(1 - R)$ at the penetration depths of each photon. The green slanted line in Figure 3-1 (a) shows the coordinates of the values at the penetration depths of the photons ($\alpha, 0.37\alpha(1 - R)$). The red slanted line depicts the coordinates of the points at the surface in the presence of reflectivity ($\alpha, \alpha(1 - R)$). The blue slanted line depicts the coordinates of the points at the surface in the absence of reflectivity (α, α) that cannot be attained in this case.

As shown in Figure 3-1 (b), photons with very large absorption coefficient (energy) have very high absorption rate near the surface. Photons with very large absorption coefficient (energy) have very low and constant absorption rate near the surface. The maximum values of the normalized absorption rates near the illuminated surface for all of the photons represented by absorption coefficients, α are shown by horizontal red lines with values at $\alpha(1 - R)$. The horizontal blue lines indicates the maximum values of the normalized absorption rates at the surface (α) in the absence of reflectivity, R . The normalized absorption rates at the surface cannot attain the value α indicated by the horizontal green lines with the presence of the surface reflectivity. Reflectivity reduces the maximum values of the normalized absorption rates from α to $\alpha(1 - R)$. The values the normalized absorption rates again falls to $0.37\alpha(1 - R)$ at

the penetration depths of the photons in the material as shown by horizontal green lines in Figure 3-1 (b). The green slanted line in Figure 3-1 (b) shows the values at the penetration depths of the photons $(x, 0.37\alpha(1 - R))$. The red slanted line indicates the coordinates of the points at the surface in the presence of reflectivity $(x, \alpha(1 - R))$. The blue slanted line depicts the coordinates of the points at the surface in the absence of reflectivity (x, α) that cannot be attained in this case also.

Figure 3-1 in general describes that, photons with very high absorption coefficients (energy) have maximum photon absorption rate near the surface and hence have the probability to be absorbed fully near the surface. Nevertheless, photons with very low absorption coefficients (energy) have very low and constant photon absorption rate near the surface and hence have the probability to be penetrated into the deep bulk of the semiconductor.

The results obtained for variation of the photon absorption rate as function of absorption coefficients and depths below the illuminated surface of GaSb is in good agreement with that of M.W. Shura in his work of photoconductive spectroscopy of p-type GaSb films [35].

4.2 Excess Carrier Lifetime

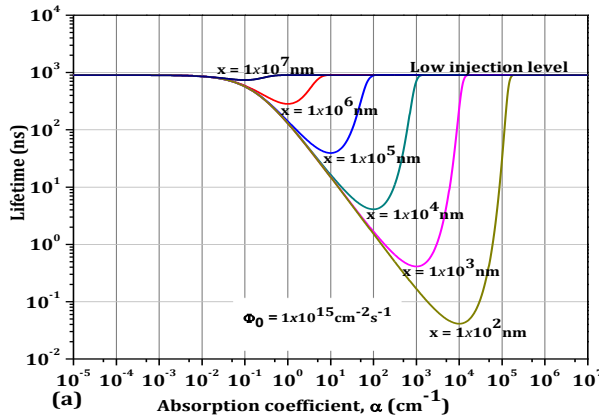


Figure 3-2: Room temperature low injection level radiative excess carrier lifetime at different depth below the illuminated as function of absorption coefficient for a sample with doping level of $1 \times 10^{17} \text{ cm}^{-3}$.

Figure 3-2 illustrates the room temperature with injection level for the radiative excess carrier lifetime at different depth below the illuminated surface as function of absorption coefficient for a sample with doping level of $1 \times 10^{17} \text{ cm}^{-3}$ and the photon flux density is $1 \times 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$. Since the radiative excess carrier lifetime is very suitable for the

effects illumination on the photo-response of the material, the analysis for this result is performed by using radiative recombination mechanism in bulk semiconductor. Then, we wish to investigate the effects of the energy of the illumination at different

positions in a given sample. Then, the doping is adjusted at room temperature, the photon flux density made to be slightly low, $1 \times 10^{15} \text{cm}^{-2} \text{s}^{-1}$ and the absorption coefficient is varied from very low to very high values as depicted in Figure 3-2. For a point located just at the surface, the excess carrier lifetime remains its maximum constant value at very low energy regime and decreases with increasing the absorption depth. As the depth increases more, the excess carrier lifetime remains its maximum constant value as above the $x = 1 \times 10^7 \text{nm}$ and it becomes low injection level region, reaches its minimum value at the penetration depth of the position of the illumination and again reaches the maximum value at the surface in the high energy regimes (high absorption coefficients) carrier lifetimes formed at the penetration depths between the two plateaus at very low and very high energy illumination regimes is related to the inverse of the hills of absorption rates as discussed in Figure 3-1(a) in the bulk of gallium antimonide semiconductor. Then as result obtained from Figure 3-2, the excess carrier lifetimes remains at its maximum constant value with very low energy and high energy regimes, but its minimum values as the depth below the illuminated surface slightly decreases. The variation of the excess carrier lifetimes with the absorption coefficients varied from 10^{-2}ns to 10^3ns in case of this figure.

4.2.1 At different absorption coefficients and high photon flux

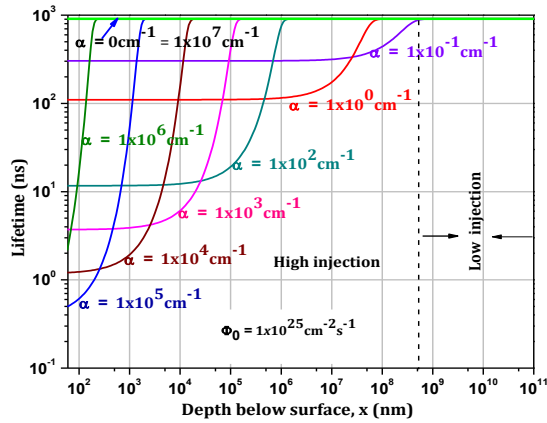


Figure 3-3: Variation of radiative excess carrier lifetimes with depth below the illuminated surface for different absorption coefficients and high photon flux for GaSb doping level $1 \times 10^{17} \text{cm}^{-3}$.

In this Figure the absorption coefficients are varied from very low to very high value at high photon flux density. Then, under high injection level for all the photon energy illuminations except at 0cm^{-1} and $1 \times 10^7 \text{cm}^{-1}$ with depth below the illuminated surface. While, the bulk is under low injection level only for two values of 0cm^{-1} and $1 \times 10^7 \text{cm}^{-1}$ energy of photon illuminations with high photon flux density $1 \times 10^{25} \text{cm}^{-2} \text{s}^{-1}$ then, the

radiative excess carrier lifetime remains constant maximum value at each depth below the illuminated surface. Since, a photon with low and high energy of illumination can pass through a material with a low absorption rate and it is

maximum photon absorption rate at equal the penetration depth as discussed in Figure 3-1 (b) reciprocal of the excess carrier lifetime. As discussed the above the bulk is low energy photon with constant low absorption rate at all points inside the bulk material and the absorption rate of a photon with high energy is very high closer to the illuminated surface, so that the photo-response of the bulk materials at low and high energy of photon illumination remains constant and maximum values in Figure 3-3 and has maximum absorption rate pick of at the value depth equal to the reciprocal of absorption coefficients. But, in this case the radiative excess carrier lifetime is the inverse of the hills of the photons absorption rate in Figure 3-1(b). Therefore, the value of the absorption rate diminishes with increasing the depth below the illuminated surface. Then, the value of the radiative excess carrier lifetime constant maximum values with very large the depth below the illuminated surface.

4.2.2 At different photon flux density and with photon energy

Figure 3-4: shows the room temperature (300K) for all the samples with single doping level of the variation of radiative excess minority carrier lifetimes with the depth below the illuminated surface at different photon flux density as low and high photon energy illumination is determined using relation Eqn. (2-26). Then, Figure 3-4 (a), the absorption coefficient is very low is value of 10^{-2}cm^{-1} and the photon flux density injection levels is varied from $1 \times 10^{15}\text{cm}^2\text{s}^{-1}$ to $1 \times 10^{30}\text{cm}^2\text{s}^{-1}$.

As can be seen from Figure 3-4 (a) the bulk material under low injection level for the illumination less than $10^{25}\text{cm}^2\text{s}^{-1}$ photon flux density, while, under high injection level for the four photon flux density $1 \times 10^{25}\text{cm}^2\text{s}^{-1}$, $1 \times 10^{27}\text{cm}^2\text{s}^{-1}$, $1 \times 10^{29}\text{cm}^2\text{s}^{-1}$ and $1 \times 10^{30}\text{cm}^2\text{s}^{-1}$. Since the deep bulk with very high thermal equilibrium majority carrier concentration, $p_o > \delta n$ still remains under low injection level as depicted by the low photon flux density $1 \times 10^{15}\text{cm}^2\text{s}^{-1}$ as shown in the Figure 3-4 (a). Then, the excess carrier lifetimes becomes constant at low illumination photon flux density as shown can be seen from Figure 3-4 (a), until the increasing the injection level of the photon flux density that can generate free carriers concentration more than the thermal equilibrium carrier concentrations in the bulk $p_o < \delta n$ as indicated by the four higher injection levels $1 \times 10^{25}\text{cm}^2\text{s}^{-1}$, $1 \times 10^{27}\text{cm}^2\text{s}^{-1}$, $1 \times 10^{29}\text{cm}^2\text{s}^{-1}$ and $1 \times 10^{30}\text{cm}^2\text{s}^{-1}$. Hence, effects of high injection level and low energy photons can be detected in the deep bulk towards the illuminated surface,

while the effects of the low injection level and low energy photons cannot be detected in the deep bulk. So, the excess carrier lifetime is decreases with increasing the injection level and with large thickness low injection level.

As shown in Figure 3-4 (b), the absorption coefficient is kept at high value 6×10^4 and with room temperature as already seen in Figure 3-4 (b), the excess carrier lifetime remains maximum constant value under low injection level for $1 \times 10^{15} \text{ cm}^2 \text{ s}^{-1}$ photon flux density at all depth below the illuminated surface, while for high injection level and high energy of photon illumination and the photon flux densities varied from $1 \times 10^{20} \text{ cm}^2 \text{ s}^{-1}$ to $1 \times 10^{30} \text{ cm}^2 \text{ s}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$.

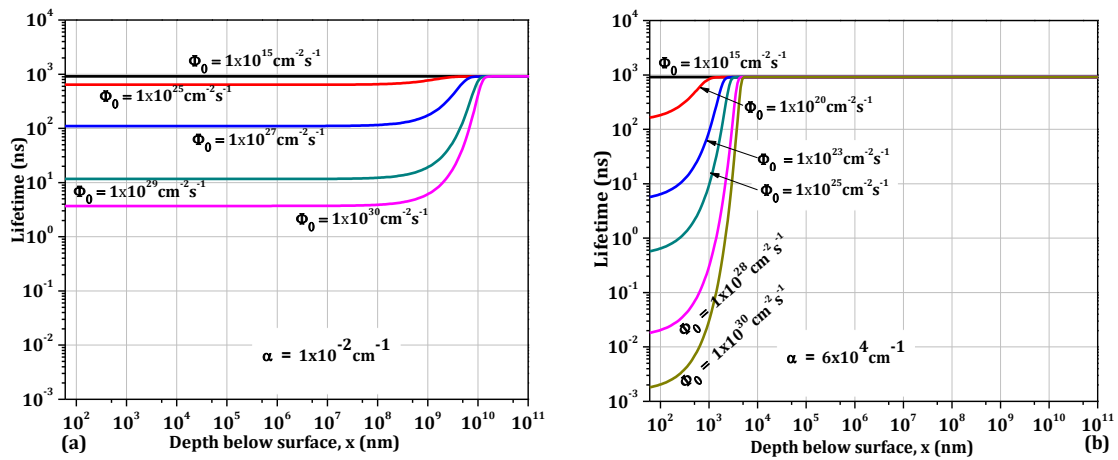


Figure 3-4: Variation of the radiative excess carrier lifetimes with depth below the illuminated surface for (a) at different flux and low absorption coefficients, (b) at different flux and high absorption coefficients for GaSb doping level $1 \times 10^{17} \text{ cm}^{-3}$.

The effects of these high injection levels and high photon energy can be detected in the bulk and near to the illuminated surface. Since the photon absorption rates of a photon with high energy (absorption coefficient) is closer to the illuminated surface and decreases with increasing the depth below the illuminated surface as already discussed in Figure 3-1 (b). Then under high injection levels regions condition for $p_0 < \delta n$, then the excess carrier concentration δn shows different response as function depth below the illuminated surface with high injection levels and the higher photon energy. Due to the presence of maximum free carrier concentration under the illuminated surface, the excess carrier lifetime also has decreases value with increasing photon flux density. The value of the excess carrier lifetime corresponding to maximum remains constant values at each depth and low injection level, but, decreases with the depth below the illuminated surface decreases and attains

minimum value at very high injection levels. Hence, the effects of an illumination with high energy and high injection level can be detected at different points inside a material with various photo-responses. However, the effects of illumination energy with low photon flux density cannot be detected in the material and the excess carrier lifetime remains constants value as shown in Figure 3-4 (a) and (b). In general the performance of the material is determined under high photon illumination energy rather than low photon illumination energy.

4.2.3 Effects of injection level with the excess carrier lifetime as function of absorption coefficients

In general, photo-generated carriers can be recombined both with opposite photo-generated carriers and thermally-generated carriers in the material. Each of the recombination rates for photo-generated carriers discussed above is hence the sum of the recombination rate of a photo-generated carrier with opposite photo-generated carriers and thermally-generated carriers. The net recombination rate of photo-

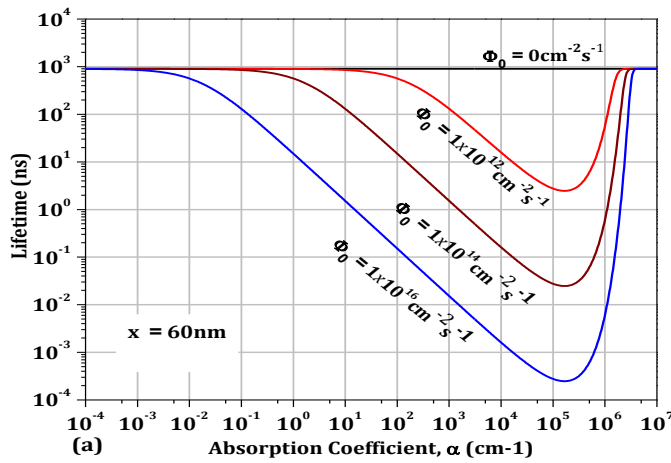


Figure 3-5: Variation of radiative excess carrier lifetimes as function of absorption coefficients with different injection levels for small depth below the illuminated surface for GaSb.

generated carriers is dominant in high injection level material, while the net recombination rate of a photo-generated carrier with the thermally generated carriers is dominant in low injection level material. As a result, the excess carrier lifetimes given in Eqns. (2-36) (2-39) and (2-38) remain only a function of photo-generated carrier concentrations in high injection level system and only a

function of thermally-generated carrier concentrations in low injection level materials in Eqn. (2-37). The description of the injection level dependence of the excess carrier lifetimes can be predicted by varying the photo-generated carriers in relations Eqns. (2-36), (2-37) and (2-38). Then, Figure 3-5 illustrated that the injection level with excess carrier lifetime for p-type of the gallium antimonide as function of the absorption coefficients or the photon energy of illuminations, then the regions of the excess carrier lifetime is divided in two in this case. The first regions

where the excess carrier lifetimes remains constant maximum value with very low photon energy the region where the thermal equilibrium carriers concentration dominate the entire recombination mechanism ($p_0 > \delta n$). This condition is called *low injection level*. The regions where the excess carrier lifetimes decreases with increasing the photon flux density, where the injection levels dominate the entire recombination mechanism ($\delta n > p_0$) and this condition is called *high injection level*. As can be seen from Figure 3-5 above the excess carrier lifetime decreases slightly with increasing photon flux density in radiative recombination and constants maximum values with very low photon illumination energy and also very high photon illumination energies. The excess carrier lifetime is displaying distinctive decreases with increasing photon flux density and it becomes constant at very low photon flux density. The results obtained for the excess carrier lifetimes in Figure 3-5 for injection levels were varied from 10^{-4} ns to the value to 10^3 ns. Then, the results obtained for the variation of the excess carrier lifetimes with the injection level is in good agreements with the reports of several authors [17, 47, 48].

Chapter 5: Conclusion

In this study, the effects of the energies of the illuminations on the photon absorption rate at different locations below the illuminated surface inside GaSb sample are described. Then, the effects of energy of illumination and photon flux density on the photo-responses of bulk of gallium antimonide semiconductor at different depth below the illuminated surface is investigated. The results obtained from the description of photon absorption rates, shows that; photons with different energies have different absorption rates at a given depth. So that the absorption rate forms a hill of maximum height equal 37% its value at the surface. High energy photons are highly absorbed near the illuminated surface and low energy photons are penetrating into the deep bulk without being absorbed (or with less absorption). Photons with very high energies are absorbed at very high rate and photons with very low energy are passing unabsorbed through the material. The value of the absorption rate goes to zero for very large and small energy of illumination and maximum at the penetration depth, whereas, the rate of absorption is increases with decreasing thickness, but it is absorbed with different rate in thick semiconductor.

The excess carrier lifetimes in GaSb have been studied as function of the energy illumination and depths below the illuminated surface with injection level have been studied using steady-state and illumination mechanism. The excess carrier lifetime remains its maximum constant value at very low and very high energy of illuminations and as the depth, x increases more the excess carrier lifetime remains at its maximum constant value reaches and its minimum values as the depth below the illuminated surface slightly decreases and reaches, its minimum value at the penetration depth of the illumination. The excess carrier lifetime displays distinctive decreases with increasing photon flux density. When the excess carrier lifetime also become constant at very low illumination photon flux density and varying with photon flux density at high injection level. As the injection level increases, the photo-responses it becomes decreases and the deep bulk becomes dominant at very high injection level. The variation of photo-response of the thick semiconductor is to be in general dominated by high injection level and high energy photon illumination, but, low injection level and low energy photon illuminations cannot be detected in deep bulk semiconductor or the lifetimes it remains constant maximum value. Then,

the excess carrier lifetimes also become constant at very low illumination photon flux density and varying with photon flux density at high injection level as function depths below the illuminated surface and absorption coefficients.

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