Determination of Transient Radiative Excess Carrier Lifetimes in Direct Band Gap Semiconductors in the Presence and Absence of Illumination

By

Senait Ketema

A Thesis Submitted to

The department of Applied Physics

School of Applied Natural Science

Presented in Partial fulfillment of the requirements for the degree of Master's in Physics

Office of Graduate Studies

Adama science and Technology University

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Declaration

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

Name: Senait Ketema

Signature……...

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

Name: Dr. Megersa Wodajo Shura

Signature……...

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Abstract

In this thesis, we models the optical generation and transient radiative recombination excess carrier lifetimes in direct band gap semiconductors (GaSb) during illumination and after switching off the illumination by calculating the absorption coefficient and also describe the significance of gallium antimonide (GaSb). The time dependence of excess carrier density and excess carrier lifetimes are determined by using the doping level 10^{17} cm^{-3} and absorption rate $1.21x10^{24}$ $cm^{-3}s^{-1}$.The transient mean times for each excess carrier lifetimes to reach their steady-state values are determined. In addition to this the excess carrier lifetime, as well as being of direct relevance to device performance, is also a critical parameter in determining the quality of the semiconductor system as it can provide information on the electrical activity of defects present in material.

I. Introduction

1.1 Background

The beginning of semiconductor research is marked by Faraday's 1833 report on negative temperature coefficient of resistance of silver sulfide. This is the first observation of any semiconductor property. As it appears from most of the historical reviews of semiconductor research, semiconductor devices-preceded by the adjectives early and primitive usually, refer to the crystal rectifiers used for wireless applications in the early 1900's. In this sense, early 1900's is regarded as the time when the semiconductor devices first came into application. An investigation into the history of semiconductor research unveils even more primitive and earlier semiconductor devices- they are the semiconductor devices of the 19th century. Pearson and Brattain outlined the developments in semiconductor research before 1900 [1)]. The next important decade in the semiconductor research is the decade of 1870. During this period selenium was discovered as a semiconductor, rectification at metal semiconductor interface came into scientists' notice. In 1873, Willoughby Smith arrived at the discovery of photoconductivity of selenium [5]. He was initially working with submarine cables. He set into experiments with selenium for its high resistance, which speared suitable for his submarine telegraphy. Various experimenters measured the resistance of selenium bars, but the resistance as measured by them under different conditions did not agree at all. Then Smith discovered that the resistance actually depended on the intensity of incident light. When the selenium bars were put inside a box with the sliding cover closed, the resistance was the highest. When glasses of various colures were placed in the way of light, the resistance varied according to the amount of light passing through the glass. But when the cover was removed, the conductivity increased. He also found that the effect was not due to temperature variation.

In 1874 came the most significant discovery in semiconductor field of the 19thcentury- the discovery of rectification at the contact between certain materials, especially naturally occurring sulfide crystals[9]. Braun's discovery was related to natural crystals and Schuster's discovery to contacts between tarnished and untarnished copper wire. In Schuster's experiment the copper oxide layer on the untarnished wire presumably acted as

the semiconductor giving the contact a rectification property [10]. Braun's experiments were more conclusive and systematic, so well approached that this is generally acknowledged as the first systematically approached study of metal semiconductor contacts. The first observation of photovoltaic effects in a solid system was made in 1876 [11] . The semiconductor substance was again selenium. 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. In 1883, Charles Edger Fritts a New York electrician built a selenium solar cell [12]. It consisted of thin selenium wafers covered with very thin semi-transparent gold wires and a protective sheet of glass. It is to be noted that, this was the first large area metal semiconductor junction device. However, it was very inefficient (η < 1%) in converting solar energy into electrical energy.

Semiconductors are II-VI and III-V crystalline or amorphous solids with distinct electrical characteristics [13]. Semiconductors in their natural state are poor conductors because a current requires the flow of electrons, and semiconductors have their valence bands filled, preventing the entry flow of new electrons. There are several developed techniques that allow semiconducting materials to behave like conducting materials, such as doping. These modifications have two outcomes: n-type and p-type. These refer to the excess or shortage of electrons, respectively. An unbalanced number of electrons would cause a current to flow through the material [14]. Large direct band gap semiconductors are material with energy band gap ranged from1 eV to 3.5 eV, like Gallium arsenide (GaAs), Indium phosphide (InP), Cadmium sulfide (CdS) [15]. In direct band gap material such as Gallium arsenide and indium phosphide recombination is radiative considered as very important. Small direct band semiconductors with energy band gap ranged from 0.3 to1.0 eV, like indium arsenide (InAs), gallium antimonide, GaSb, indium antimonide, InSb [16].are characterized by the absence or small amount of impurity materials, presence of very high charge carrier concentration and high charge carrier mobility. Small-band gap semiconductors such as find application as detectors in the medium-to-far infrared; medium-band gap semiconductors such as GaInAs are used in optical communication systems where the photon energy corresponds with that for minimum absorption of near infrared light in optical fibers Large-band gap semiconductors $E_g \geq 2$eV come into their

own in the manipulation of visible and ultraviolet light. Another important effect of the size of the energy gap is on the temperature dependence of the population of electrons in the conduction band. This population must be kept low in photo detectors so that the effect of photo excited electrons is large, and this means that small-band gap semiconductors can work only at low temperatures. 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. Some of these semiconductors are also used as booster cells in solar cell clusters to improve the efficiency of photovoltaic and thermo-photovoltaic (TPV) cells [17].

Generation in semiconductors refers to the process by which electron-hole pairs are created. The energy require for the excitation of an electron from valence band processor through the absorption of photons. 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 an unoccupied state in valence band. The excess energy and the change in the momentum released are either as photons or phonons or transferred to other carriers, which ensure energy and momentum conservation for the individual processes of electron hole recombination.

Radiative recombination is simply the direct annihilation of an electron-hole pair. It is the inverse process to optical generation, the excess energy being released mainly as a photon with energy close to that of the band gap. It involves a conduction band electron falling from an allowed conduction band state into a vacant valence band state (a hole). The radiative recombination rate, U_R, therefore, depends on the concentration of free electrons, n, and free holes, p *[18]* .while radiative recombination is typically the dominant recombination process in direct semiconductors, where it forms the basis for the operation of light-emitting diodes, it is considered to be small or even negligible compared to other recombination processes in indirect semiconductors such as silicon. Evaluation of the excess (photo-generated) carriers' effective lifetime is very important in the determination of the photoconductivity of the semiconductors [19].

Evaluation of the lifetime also requires knowledge of the determination of the carriers' mobility's, the thermal carrier concentrations for both holes and electrons and the determination of the density of photo-generated carriers which is directly related to the

intensity and the spectral properties of the incident photon [23].Due to the small amount of thermal carrier concentration, the minority carriers' lifetime is highly affected by carrier traps in the semiconductor than the majority carrier lifetime. In the absence of carriers trap both the majority and the minority carriers have equal effective lifetime [25]. small direct band semiconductors with energy band gap ranged from 0.3 eV to1.0 eV, like indium arsenide (InAs), indium antimonide (InSb) and gallium antimonide (GaSb) *etc*., are characterized by the absence or small amount of impurity materials, presence of very high charge carrier concentration and high charge carrier mobility [27]. This makes direct small band gap semiconductors to be very important for the use in various.

Domains of optoelectronic devices, such as pollutant detection and infrared thermal imaging, using a variety of device architectures, including near infrared photo-detectors, resonant tunneling structures and other quantum devices, infrared thermal imaging [29].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. The excess carrier lifetime is in general determined by the recombination rate of the minority charge carriers in the bulk of the material and at the surface. Recombination is a mechanism by which opposite free charge carriers annihilate each other at the valence or conduction bands or the impurity levels.

There are three types of recombination mechanisms in the bulk of a given semiconductor. 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. Once an excess of minority charge carriers (e.g. electrons in p-type material) is created, it will take some time for the system to come back to thermal equilibrium. Excess carriers could, for example, be created by a pulse of light shining onto the semiconductor. The transition back to equilibrium is due to recombination of the excess minority carriers (electrons) with the majority carriers (holes). There are two

principal categories of carrier lifetimes: recombination lifetimes and generation lifetimes. The con-cept of recombination lifetime τ_R holds when excess carriers decay as a result of recombination. Generation lifetime τ_g applies when there is a paucity of carriers, as in the space- charge region of a reverse-biased device and the device tries to attain equilibrium. The recombination lifetime is a property of the carriers within the semiconductor, rather than a property of the semiconductor itself. As such, it is a weighted average then across all the carriers, whose individual behavior's may be influenced by different factors, including surfaces, bulk defects and the density of carriers, besides the fundamental properties of the semiconductor material. Interpreting the recombination lifetime can, therefore, be difficult as it represents a number of specific recombination mechanisms occurring simultaneously within the bulk and at the surfaces. For this reason, the recombination lifetime is often referred to as an effective lifetime.

The concepts of carrier lifetime in semiconductor materials and average life expectancy in demography are similar. Like common mortals, electrons (and holes) die after some time and the average of this time is called the minority carrier life time. The free carriers' generation rate is affected by the photon flux density and the energy of illuminating sample; and the thickness of the sample. The absorbed photons create excess electron-hole pairs and as a result the densities of electrons and holes increase above their equilibrium value. This also results in the increment of the conductivity of material. This increment in the conductivity of the material due to illumination by light is called photoconductivity of material .The lifetime measurement is normally used in one way or another to assess material quality. High lifetimes are indicative of good material, while low lifetimes might point to problems such as inadequate crystal growth techniques that introduce dislocations or high concentrations of impurities in the semiconductor material.

Processing of various semiconductor devices can also be effectively monitored and improved by systematic lifetime measurements. Previously the study of semiconductor materials, devices and circuits, lifetime measurements were useful in gaining a better understanding of generation and recombination mechanisms. With improved fabrication technology, the focus shifted away from theoretical studies to processing-related lifetime testing. However, with the new devices such as large area power devices, metal oxide–semiconductor MOS devices and high-efficiency solar cells; there has been a considerable

interest in lifetime measurements that gives an explanation to the physical recombination processes within the device. However, the measurement of carrier lifetime in silicon wafers was studied in the past three decades. This parameter is still required to be determined accurately for new composites and nano-materials. On the other hand, the conductivity modulation could alter the distribution of charge carriers available for conduction. Thus, the excess conduction loss can occur as conductivity modulation proceeds.

The present work discusses the evaluation of carrier lifetimes based on a method developed earlier by Elani *et al.* (2005) and more recently by Elani (2008). It will be concluded that the conductivity modulation (conductivity changes) measurement can lead to the determination of carrier lifetime. Parameter is very important for silicon fabrication in many electronic devices such as solar cells, sensors, nuclear detectors, switches and other bipolar or opto-devices. The other benefit of the current research work lies within the improvement of the computerized in-line carrier lifetime systems, such as the microwave relax meter and wafer lifetime tester. The performance of semiconductor material depends on the lifetime of free charge carriers generated by the interaction of light with the material, referred to as the excess carriers' lifetime [30]. The excess carrier lifetime is in general determined by the recombination rate of the minority charge carriers in the bulk of the material and at the surface.

The concepts of carrier lifetime in semiconductor materials and average life expectancy in demography are similar. Like common mortals, electrons (and holes) die after some time and the average of this time is called the minority carrier recombination life time (τ_R). In this context, light often includes invisible forms of radiation such as Γ-rays, x-rays, ultraviolet and infrared, in addition to visible light.

Optoelectronic devices are electrical-to-optical or optical-to-electrical transducers, or instruments that use such devices in their operation. Electro-optics is often erroneously used as a synonym, but is a wider branch of physics that concerns all interactions between light and electric fields, whether or not they form part of an electronic device.

In this work, first the time dependence of the radiative recombination and generation excess carrier lifetimes in direct band gap semiconductors during illumination are determined, then the time dependence of the radiative recombination lifetime after switching off the illumination is determined.

1.3 Objectives

1.3.1 General Objectives

The general objective of this study is to determine the optical generation and radiative recombination excess carrier lifetimes in direct band gap semiconductors during illumination and after switching off the illumination.

1.3.2 Specific Objectives

The specific objectives of this study are:

- to determine the generation lifetimes for photo-generated carriers in direct band gap semiconductors during illumination of the sample,
- to determine the radiative recombination lifetimes for photo-generated carriers in direct band gap semiconductors during illumination and after switching the light,
- to describe the competition between generation and recombination effects in the presence of illumination and
- to study the doping effect of semiconductors on the transient and steady-state conditions of free carriers generation-recombination processes.

II. Literature Reviews

2.1 Optical generation of carriers

The term “photo-conductivity” refers to a change in conductivity of a semiconductor when illuminated by photons. The generation of excess electron-hole pairs in a semiconductor is known as the injection of excess carriers [31]. At thermal equilibrium, the valence band contains many electrons and the conduction band has many empty states into which electrons may be excited. When photons with energies equal to or greater than the band gap are incident on semiconductor materials, the photons are absorbed by the formation of electron-hole pairs. While the photo-generated carriers exist in their respective bands, they are free to contribute to the conductivity of the material. The electron-hole pairs generated by photon absorption are known as photo-generated carriers. In the case of a pure semiconductor, photons with energy less than the band gap energy will not be enough to excite an electron from the valence band to the conduction band and it will pass through the semiconductor without being absorbed [32] .This explains why some materials are transparent in certain wave length ranges. It is possible to "see through" certain insulators, such as a good NaCl crystal, because of a large energy gap containing no or very few impurity states. The technique of measuring the absorption of incident photons is important for the determination of the band gap energy of a semiconductor.

Optoelectronics is the study and application of electronic devices and systems that source detect and control light, usually considered a sub-field of photonics. 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. The photo-generated electrons and holes change the total electron and hole concentrations in the semiconductor to new values n and p, respectively, given by:

$$n = n_0 + \delta n\,, \qquad p = p_0 + \delta p, \tag{1}$$

where n_0 and p_0 are the densities of thermally generated electron and hole concentrations, respectively; and δn and δp are the photo-generated electron and hole concentrations, respectively. The carrier injection level in a semiconductor is determined by the concentration of excess carriers injected into it. If the non-thermal equilibrium concentration is much greater than the thermal equilibrium majority carrier concentration (that is $p \gg p_0$ or $\delta p = p$) in p-type material, the system is said to be under a high injection *level*. Conversely, the term low injection level is a situation in which the majority carrier concentration remains essentially unperturbed that is $p = p_0$ or $\delta p \ll p_0$. Since the free carrier density is affected by the photon flux density and the energy of illuminating light, the photoconductivity is also affected by the illumination. Absorption of a photon in a material corresponds to an optical transition of one electron from the ground state (valence band) to the excited state (conduction band). The transition, in fact, generates two oppositely charged carriers, since simultaneously a hole is created in the valence band. The two elementary charges physically emerge at the same part in space within the crystal. Therefore, due to their mutual Coulomb attraction, electron and hole engage into a correlated motion and appear in energy levels within the material band-gap. This elementary excitation comprising correlated charged particles is treated as a new particle: an exciton. The photon with the energy exceeding the band gap energy of semiconductor can be absorbed. The absorbed photon energy excites the electron from the valence band into the conduction band. As result, one electron-hole-pair (EHP) is being created. The generation of excess carriers in a semiconductor may be accomplished by either electrical or optical means. For example, EHPs are created in a semiconductor when photons with energies exceeding the band gap energy of the semiconductor are absorbed. The rate of optical generation of minority carriers is represented by G_0 and is given as the ratio of δn to the radiative minority carriers' generation lifetime, τ_G:

$$G_0 = \frac{\delta n}{\tau_G}. \tag{2}$$

2.2 Radiative recombination of carriers

When the excited electron meets the hole in the valence band, it may occupy that place. As a result the EHP disappears; this process is called recombination. Recombination is the inverse process to the generation of excess carriers in a semiconductor. The annihilation of excess carriers generated by optical or electrical means in a semiconductor may take place via different recombination mechanisms. Depending on the ways in which the energy of an excess carrier is removed during a recombination process, there are three basic recombination mechanisms, which are responsible for carrier annihilation in a semiconductor. They are: (1) the band-to-band radiative recombination, (2) the Shockley-ead-Hall (SRH) recombination (or the multi phonon process) and (3) the Auger recombination (kinetic energy is transferred to other carriers during recombination). The recombination mechanism, band-to-band radiative recombination is usually the predominant process occurring in direct band gap semiconductors such as GaAs and InP [33].In this case, the recombination of EHPs is accompanied by the release of a photon with the energy close to the band gap energy of the semiconductor. Radiative recombination process is occurring in small-band gap semiconductors such as InSb and HgCdTe materials. The band-to-band radiative recombination in a semiconductor is the inverse process of optical absorption and generation of EHPs. Emission of photons due to band-to-band radiative recombination is a common phenomenon observed in a direct band gap semiconductor such as GaAs, InP, or InAs [34]. The total thermal recombination rate (R_{th}) is directly proportional to the product of the thermally generated concentration of electrons n_0 available in the conduction band and the thermally generated concentration of holes p_0 available in the valence band:

$$R_{th} = C_R n_0 p_0, \tag{3}$$

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

$$C_R = \sigma_R \vartheta_{th}. \tag{4}$$

The capture cross-section, σ_R can be thought of as the volume swept out per unit time by a particle. When the dispersion in the dielectric constant is ignored, the band-to-band

capture coefficient for bands with spherical symmetry was shown by van Roosbroeck and Shockley to depend on the absorption coefficient through the relation [35].

$$C_R = e\pi\sqrt{k_\infty}\left(\frac{m_n}{m_n^* + m_p^*}\frac{300}{T}\right)^{3/2}\left(1 + \frac{m_n}{m_n^*} + \frac{m_n}{m_p^*}\right)\left(E_g^2 + 3E_g k_B T + 3.75 k_B^2 T^2\right), \quad (5)$$

Where e is elementary charge, k_∞, high frequency dielectric constant, m_n, rest electron mass, m_n^*, effective mass of electron, m_p^*, effective mass of hole, T, temperature of the system, E_g, energy band gap of the material and k_B is the Boltzmann constant. Since $E_g \gg k_B T$, the term E_g^2 is dominant in large band gap materials. The total non-thermal recombination rate (R) during illumination is also directly proportional to the product of the non-thermal concentrations of electrons n available in the conduction band holes p available in the valence band:

$$R = C_R np, \quad (6)$$

where n and p are discussed in relation (1) above. The rate at which free photo-generated minority carriers disappear or recombine in this is represented by U_R and is by the difference between the non-thermal recombination rate, R and the thermal recombination rate, R_{th}. Then, subtraction of relation (3) from relation (6) in the absence of carriers trap ($\delta p = \delta n$) yields:

$$U_R = C_R[((p_0 + n_o)\delta n + \delta n^2)] = \frac{\delta n}{\tau_{R0}} + C_R \delta n^2, \quad (7)$$

Where τ_{R0} is a time constant given by:

$$\tau_{R0} = \frac{1}{C_R(n_0 + p_0)}. \quad (8)$$

For low injection level system, when $\delta n \ll p_0$, the quadratic term in δn on the right side of relation (7) can be neglected and hence:

$$U_R = \frac{\delta n}{\tau_{R0}}. \quad (9)$$

For high injection level system, when $\delta n \gg p_0$, the linear term in δn on the right side of relation (7) can be neglected and:

$$U_R = C_R \delta n^2. \quad (10)$$

2.3 Radiative excess carrier lifetimes

The radiative recombination rate of photo-generated minority carriers is also given as the ratio of the density of photo-generated electrons, δn to the radiative minority carriers' recombination lifetime, τ_R:

$$U_R = \frac{\delta n}{\tau_R}. \tag{11}$$

2.3.1 Excess carrier lifetimes with illuminations

The rate of accumulation of the photo-generated electrons in the conduction band is given by the difference between the free carriers' generation rate, G_0 and the recombination rates, U_R:

$$\frac{d\delta n}{dt} = G_0 - U_R. \tag{12}$$

As can be seen from relations (2), (11) and (12), in order for the free electrons to be accumulated, the generation lifetime must be less than the radiative recombination lifetime(or $\tau_G < \tau_R$). At a steady-state condition, the generation and recombination rates are perfectly balanced ($\tau_R = \tau_G$) [36].

Assuming that, one photon ejects one electron-hole pair during illumination; it is possible to determine the density of photo-generated electron hole pairs as function of the absorbed photon flux density, G_0. The density of photo-generated electron-hole pairs in the bulk of the semiconductor is hence a function of the natures of the material and the illuminating radiation [37] .A very important parameter of detector-grade semiconductor material is the charge-carrier lifetime and there needs to be a distinction between recombination and generation lifetime. These terms describe the transient behavior from a non-equilibrium charge distribution obtained either by injection of additional carriers or by their removal, back to an equilibrium condition. Consider for instance the case where a direct p-type semiconductor is in thermal equilibrium. Although the concentration of electrons and holes does (on average) not change, thermal generation and recombination of electron–hole pairs is continuously occurring. Under illumination with light there is an additional generation rat, G_0, and both minority and majority carrier concentrations will be

increased from their thermal equilibrium values by the same amount δn as electrons and holes are created in pair. The significance of the lifetime τ_R can be illustrated by considering a sudden turnoff of the light source. Then the excess recombination rate U_R will be proportional to the excess minority carrier density δn. Generally, the effective excess carrier lifetimes are determined using the recombination mechanisms. Using the carrier capture coefficients by different energy states representing these recombination mechanisms in different semiconductors were determined by different researchers to be $10^{-10}\text{cm}^3\text{s}^{-1}$ for radiative recombination mechanism [38] .In general, the radiative excess carrier lifetime varies with time for high injection levels. In order to calculate the time dependences of τ_R and τ_g, the relation describes the variation of U_R with the excess carrier concentration, δn, relation (6) is very important. Substitution of relation (7) into relation (12) gives:

$$\frac{d\delta n}{dt} = G_0 - \left(\frac{\delta n}{\tau_{R0}} + C_R \delta n^2\right). \tag{13}$$

Taking the initial free carrier density to be zero initially just when the illumination begins, relation (13) can be rearranged as:

$$\int_0^{\delta n(t)} \frac{d\delta n}{\delta n^2 + \frac{\delta n}{C_R \tau_{R0}} - \frac{G_o}{C_R}} = -C_R \int_0^t dt, \tag{14}$$

Upon factorizing the denominator of the left side of relation (14) and integrating the term on the right side, we have:

$$\int_0^{\delta n(t)} \frac{d\delta n}{(\delta n + k_1)(\delta n + k_2)} = -C_R t, \tag{15}$$

where k_1 and k_2 are arbitrary constants to be determined by comparing relations (14) and (15) as:

$$k_1 = \frac{2G_o \tau_{Ro} \tau_k}{\tau_{Ro} - \tau_K}, \qquad k_2 = -\frac{2G_o \tau_{Ro} \tau_K}{\tau_{Ro} + \tau_k}, \tag{16}$$

Where τ_k is another time constant given by:

$$\tau_k = \frac{\tau_{Ro}}{\sqrt{1 + 4C_R G_o \tau_{Ro}^2}}. \tag{17}$$

Then by using partial fraction integration method relation (15) becomes:

$$\int_0^{\delta n(t)} \left(\frac{A}{\delta n + k_1} + \frac{B}{\delta n + k_2}\right) d\delta n = -C_R t, \tag{18}$$

where A and B are also arbitrary constants. Upon comparing relations (15) and (18) and taking into accounts the constants in relation (16), we have:

$$B = -A = C_R \tau_k \tag{19}$$

Substitution of relation (19) into relation (18) and performing the integrations gives:

$$\delta n(t) = \frac{2G_0 \tau_{R0} \tau_k \left(1 - \exp\left(-\frac{t}{\tau_k}\right)\right)}{\tau_{R0}\left[1 + \exp\left(-\frac{t}{\tau_k}\right)\right] + \tau_k \left[1 - \exp\left(-\frac{t}{\tau_k}\right)\right]}. \tag{20}$$

The radiative recombination lifetime, τ_{R1} with illumination is determined as function of time by using relation (20) along with relations (6) and (11) as:

$$\tau_{R1}(t) = \frac{2\tau_{R0}\tau_k \left[\tau_{R0}\left(1 + \exp\left(-\frac{t}{\tau_k}\right)\right) + \tau_k \left(1 - \exp\left(-\frac{t}{\tau_k}\right)\right)\right]}{(\tau_{R0}^2 + \tau_k^2)\left[1 - \exp\left(-\frac{t}{\tau_k}\right)\right] + 2\tau_{R0}\tau_k \left[1 + \exp\left(-\frac{t}{\tau_k}\right)\right]}. \tag{21}$$

The excess carrier generation lifetime is also determined using relations (20) and (2) as:

$$\tau_g(t) = \frac{2\tau_{R0} \tau_k \left(1 - \exp\left(-\frac{t}{\tau_k}\right)\right)}{\tau_{R0}\left[1 + \exp\left(-\frac{t}{\tau_k}\right)\right] + \tau_k \left[1 - \exp\left(-\frac{t}{\tau_k}\right)\right]}. \tag{22}$$

- Initially, for $t/\tau_k \ll 1$, by expanding the exponential terms in relations (20) to (22) and taking the first two dominant terms, we get:

$$\begin{aligned} U_R(t) &= \frac{G_0}{\tau_{R0}} t, \\ \delta n(t) &= G_0 t, \\ \tau_{R1}(t) &= \tau_{R0}\left(1 - \frac{(\tau_{R0}^2 - \tau_k^2)}{4\tau_{R0}\tau_k^2} t\right), \\ \tau_g(t) &= t. \end{aligned} \tag{23}$$

  For $t/\tau_k \to 0$:

$$U_R(t) = 0, \qquad \delta n(t) = 0, \qquad \tau_g(t) = 0, \qquad \tau_{R1}(t) = \tau_{R0}. \tag{24}$$

- At steady-state, as $t \to \infty$, again, we have:

$$U_R(t) = G_0, \qquad \delta n = \frac{2G_0\tau_k\tau_{R0}}{\tau_{R0} + \tau_k}, \qquad \tau_{R1} = \tau_g \approx \frac{2\tau_k\tau_{R0}}{\tau_{R0} + \tau_k}. \tag{25}$$

A close examination of relations (23) and (25) reveals that, as the changes of the quantities in relations (20) to (22) keep their initial values throughout the process with illumination as in relations (23) and (25), $U_R(t)$ reaches its steady-state value at time τ_{R0}, $\delta n(t)$ and $\tau_g(t)$ reach their steady-state values at the steady-state of time of τ_{R1} and $\tau_{R1}(t)$ reaches its steady-state at the time equal to ratio of the square of the steady state of τ_g to τ_{R0}:

$$\tau' = \frac{4\tau_{R0}\tau_k^2}{(\tau_{R0}+\tau_k)^2} = \frac{\tau_g^2}{\tau_{R0}}. \tag{26}$$

Hence, the transient time for δn(t) and $\tau_g(t)$ is the steady-state value of τ_{R1} and the transient time for $\tau_{R1}(t)$ is the time given in relation (26).

I. low injection level system:

For low injection level system . $G_0 \to 0$ and $\tau_k \approx \tau_{R0}$, we have from relations (20) to (22) that:

$$\delta n(t) = G_0\tau_{R0}\left[1-\exp\left(-\frac{t}{\tau_{R0}}\right)\right], \qquad U_R(t) = G_0\tau_{R0}\left[1-\exp\left(-\frac{t}{\tau_{R0}}\right)\right], \tag{27}$$

$$\tau_{R1}(t) = \tau_{R0}, \qquad \tau_g(t) = \tau_{R0}\left[1-\exp\left(-\frac{t}{\tau_{R0}}\right)\right]. \tag{28}$$

- Initially, when $t \to 0$,

$$\delta n(t) = G_0 t \to 0, \qquad \tau_{R1}(t) = \tau_{R0},$$
$$\tau_g(t) = t \to 0, \qquad U_R(t) = 0. \tag{29}$$

- At steady-state:

$$\delta n(t) = G_0\tau_{R0}, \qquad \tau_{R1}(t) = \tau_g(t) = \tau_{R0}, \qquad U_R(t) = G_0. \tag{30}$$

II. High injection level system:

For high injection level system under illumination, $\tau_k \ll \tau_{R0}$, relations (20) to (22) are simplified to:

$$\delta n(t) = \frac{2G_0\tau_k\left(1-\exp\left(-\frac{t}{\tau_k}\right)\right)}{1+\exp\left(-\frac{t}{\tau_k}\right)}, \tag{31}$$

$$\tau_{R1}(t) = \frac{2\tau_{R0}\tau_k\left[1+\exp\left(-\frac{t}{\tau_k}\right)\right]}{\tau_{R0}\left[1-\exp\left(-\frac{t}{\tau_{R0}}\right)\right]+2\tau_k\left[1+\exp\left(-\frac{t}{\tau_{R0}}\right)\right]}, \tag{32}$$

$$\tau_g(t) = \frac{2\tau_k\left(1 - \exp\left(-\frac{t}{\tau_k}\right)\right)}{1 + \exp\left(-\frac{t}{\tau_k}\right)}. \tag{33}$$

- Initially:

$$\delta n(t) = G_0 t, \qquad \tau_{R1}(t) = \tau_{R0}\left(1 - \frac{\tau_{R0}}{4\tau_k^2}t\right),$$
$$\tau_g(t) = t, \qquad U_R(t) = \frac{G_0}{\tau_{R0}}t. \tag{34}$$

- At steady-state:

$$\delta n(t) = 2G_0\tau_k, \qquad \tau_{R1}(t) = \tau_g(t) = 2\tau_k, \qquad U_R(t) = G_0. \tag{35}$$

2.3.2 Excess carrier lifetime without illuminations

On turning off the illumination (or $G_0 = 0$) after the system has reached a steady state after a total illumination time, τ, relation (11) becomes:

$$\frac{d\delta n}{dt} = -U_R = -\left(\frac{\delta n}{\tau_{Ro}} + C_R\delta n^2\right). \tag{36}$$

Following the same procedure we used to integrate the differential equation in relation (13) to integrate the differential equation in relation (36) for δn from the initial steady state value during illumination, relation (25) to $\delta n(t)$ and for the time from the total illumination time, τ to the later time, t, we get:

$$\delta n(t) = \frac{4G_0\tau_{R0}\tau_k^2\exp\left(-\frac{t-\tau}{\tau_{R0}}\right)}{(\tau_{R0} + \tau_k)^2 - (\tau_{R0}^2 - \tau_k^2)\exp\left(-\frac{t-\tau}{\tau_{R0}}\right)}. \tag{37}$$

The recombination excess carrier lifetime in the absence of illumination in this case is also determined by substituting relation (37) into relation (11) as:

$$\tau_{R2}(t) = \tau_{R0}\left[1 - \frac{(\tau_{R0} - \tau_k)\exp\left(-\frac{t-\tau}{\tau_{R0}}\right)}{\tau_{R0} + \tau_k}\right]. \tag{38}$$

1) Initially, for $(t - \tau)/\tau_{R0} \ll 1$, we have:

$$U_R(t) = G_0\left(1 - \frac{t-\tau}{\tau_k}\right), \tag{39}$$

$$\delta n(t) = \frac{2G_0\tau_{R0}\tau_k}{\tau_{R0}+\tau_k}\left(1 - \frac{\tau_{R0}+\tau_k}{2\tau_{R0}\tau_k}(t-\tau)\right), \tag{40}$$

$$\tau_{R2}(t) = \frac{2\tau_{R0}\tau_k + (\tau_{R0} - \tau_k)(t-\tau)}{\tau_{R0} + \tau_k}. \tag{41}$$

For $t - \tau \to 0$:

$$\delta n(t) = \frac{2G_0\tau_{R0}\tau_k}{\tau_{R0}+\tau_k}, \qquad \tau_{R2}(t) = \frac{2\tau_{R0}\tau_k}{\tau_{R0}+\tau_k}. \tag{42}$$

2) At steady state, when $t - \tau \to \infty$, we get from relations (37) and (38) that:

$$U_R(t) = 0, \qquad \delta n(t) = 0 \qquad \text{and} \qquad \tau_{R2}(t) = \tau_{R0}. \tag{43}$$

As the changes of the quantities in relations (37) and (38) keep their initial values throughout the process after the switching of the illumination as in relations (39) to (41), $U_R(t)$ reaches its state-state at time, τ_k, $\delta n(t)$ reache its steady-state in the time equal to the steady-state value of τ_{R1} and $\tau_{R2}(t)$ reach its steady-state in time, $t - \tau = \tau_{R0}$. Hence, τ_{R0} is the transient time of $\tau_{R2}(t)$ and the steady-state value of τ_{R1} is the transient time for $\delta n(t)$ and τ_k is the transient time for $U_R(t)$ in the absence of illumination.

I. low injection level system:

For low injection level system in the absence of illumination, $\tau_k = \tau_{R0}$, from relations (37) and (38) we have:

$$\delta n(t) = G_0\tau_{R0}\exp\left(-\frac{t-\tau}{\tau_{R0}}\right), \tag{44}$$

$$\tau_{R2}(t) = \tau_{R0}, \qquad U_R(t) = G_0\exp\left(-\frac{t-\tau}{\tau_{R0}}\right). \tag{45}$$

Initially:

$$\delta n(t) = G_0\tau_{R0}, \qquad \tau_{R2}(t) = \tau_{R0}, \qquad U_R(t) = G_0. \tag{46}$$

At steady-state:

$$\delta n(t) = 0, \qquad \tau_{R2}(t) = \tau_{R0}, \qquad U_R(t) = 0. \tag{47}$$

II. High injection level system:

For a system under high injection level ($\tau_k \ll \tau_{R0}$) in the absence of illumination, we have from relations (37) and (38) that:

$$\delta n(t) = \frac{4G_0\tau_{R0}\tau_k^2 \exp\left(-\frac{t-\tau}{\tau_{R0}}\right)}{2\tau_{R0}\tau_k + \tau_{R0}^2\left[1-\exp\left(-\frac{t-\tau}{\tau_{R0}}\right)\right] + \tau_k^2\left[1+\exp\left(-\frac{t-\tau}{\tau_{R0}}\right)\right]}, \tag{48}$$

$$\tau_{R2}(t) = \tau_{R0}\left[1-\exp\left(-\frac{t-\tau}{\tau_{R0}}\right)\right] + \tau_k\left[1+\exp\left(-\frac{t-\tau}{\tau_{R0}}\right)\right]. \tag{49}$$

Initially:

$$\delta n(t) = 2G_0\tau_k, \qquad \tau_{R2}(t) = 2\tau_k, \qquad U_R(t) = G_0. \tag{50}$$

At steady-state:

$$\delta n(t) = 0, \qquad \tau_{R2}(t) = \tau_{R0}, \qquad U_R(t) = 0. \tag{51}$$

III. Methodology

The primary task on this work was to select an appropriate semiconductor sample in which radiative generation-recombination mechanisms dominate the entire generation-recombination processes. The electrical and optical properties of GaSb were studied through literature reviews. Literature research consists of physics journal articles on the subject matter through a search of online library. In addition, the hand book of physical science and physics were used as a primary reference for much of the initial information. The next task was to collect important data for the determination of the optical generation-recombination excess carrier lifetimes in this semiconductor. Next, by assuming that, one photon ejects one electron-hole pair during illumination; the rate of accumulation of free electron-hole pairs in the respective conduction and valence bands was formulated for the optical generation-recombination mechanisms. Upon solving the differential equation for the rate of accumulation of free carriers in the respective valence and conduction bands as function of time, the time dependence of the free carrier concentration could be obtained during illumination and upon switching of the illumination. Then, using the generation and recombination mechanism relations, it was possible to determine the time dependence of both the recombination and generation free carrier lifetimes as function of time during illumination and upon switching of the illumination. Then substitute the typical values for some parameters related to the electrical and optical properties of the selected semiconductor, one could study the transient effect of the response of the semiconductor. This could be done by varying the doping level, energy of the illumination and injection level (incident photo flux density) of the samples.

IV. Result and Discussion

In this study, the time dependences of the radiative recombination and the optical generation excess carrier lifetimes during illumination and after switching off the illumination in GaSb are determined. The transient properties of all the excess carrier lifetimes before attaining the steady-state conditions are described in detail. The optical excess carrier generation rate G_0 is kept at constant non-zero value during illumination and kept at zero after switching of the illumination.

4.1 Time dependence of excess carrier density

Figure 1 depicts the time dependence (a) optical carrier generation rate and; excess carrier concentration in p-type GaSb sample of doping level 10^{17} cm^{-3} when it is illuminated by photons of optical carrier generation rates (b) 10^{18} $cm^{-3}s^{-1}$(c) 8×10^{14} $cm^{-3}s^{-}1$ and (d) 10^{19} $cm^{-3}s^{-1}$. The time dependent of the normalized G_0 in Figure 1 (a) is drawn by keeping its magnitude constant at 1 for the total time interval between 0 and τ to represent constant illumination and; then by making the magnitude of G_0 zero to represent the switching off the illumination in the next time interval between τ and 2τ. The time dependent of the excess carrier densities in Figure 1 (b) to (d) are also drawn using the expression of the time dependence excess carrier density in relation (20) during illumination for the time interval between 0 and τ; and the expression of the time dependence excess carrier density in relation (37) after switching of the illumination for the time interval between τ and 2τ. To normalize the excess carrier densities the obtained results are divided by the respective maximum constant values of the excess carrier densities at steady state during illumination described in relation (25).When the semiconductor is under constant illumination of relatively low injection level as in Figure 1 (a) for time, τ, the absorbed photons also generate EHPs at constant rate. Hence, the concentration of EHPs must linearly increase with time in the initial stage (for time t close to 0) after switching on the light as illustrated by line L_1 in Figure 1 (b). That is, for t close to 0, the excess carrier concentration is very small and the effect of recombination is negligible; a constant G_0 dominates the accumulation process. The slope of line L_1 (see relation (29)) gives the constant optical excess carrier generation rate, G_0. Recombination,

on the other hand, tries to reduce the excess carrier concentrations to zero. As more EHPs are generated, the recombination rate starts to influence the accumulation process and the rate at which excess carriers accumulate (see Eqn. (12)) decreases exponentially and finally becomes zero (at steady-state). As the value of the recombination rate increases and approaches G_0 at steady state, the low injection level excess carrier density during illumination reaches its maximum constant value at steady-state (relation (30)) as shown in Figure 1 (b).

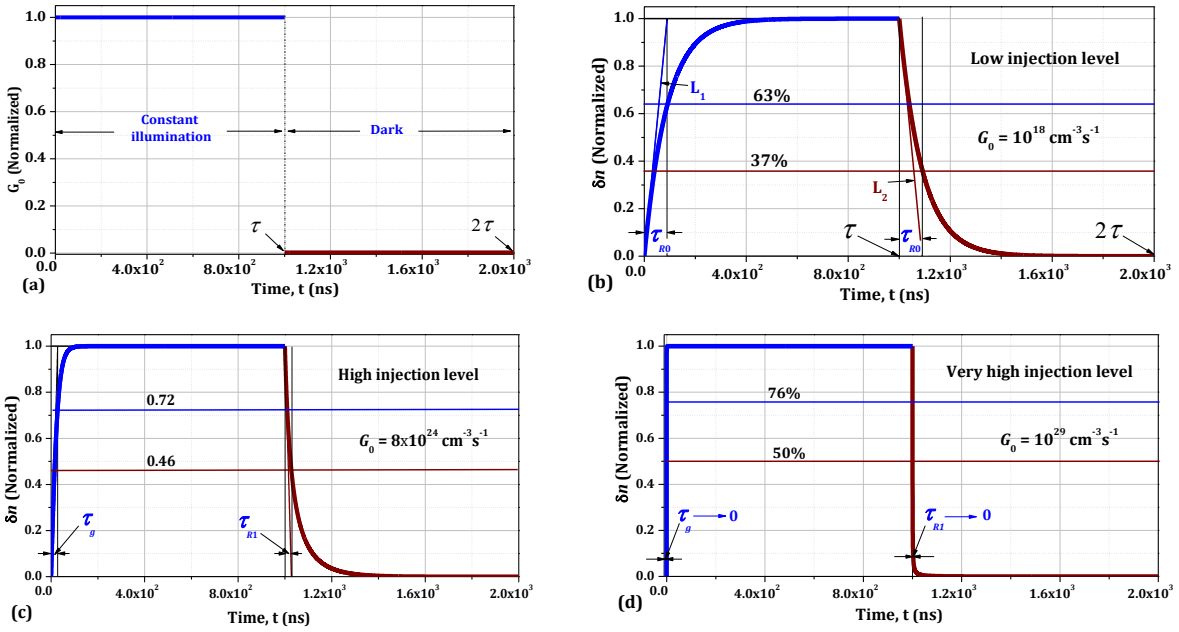

Figure 1: Variations of the normalize (a) optical carrier generation rate and; excess carrier concentration in p-type GaSb sample of doping level 10^{17} cm^{-3} when it is illuminated by photons of optical carrier generation rates (b) 10^{18} cm^{-3}s^{-1}(c) 8×10^{14} cm^{-3}s^{-1} and (d) 10^{19} cm^{-3}s^{-1}.

When the steady-state low injection excess carrier lifetime in relation (30) is substituted in the expression for low injection level excess carrier density during illumination in relation (27), the excess carrier density attains the value $1-\exp(-1)$ or 63% of its maximum value at the steady state, $G_0\tau_{R0}$. However, if the variation in the excess carrier density keeps its initial condition as in relation (23) or (29) throughout the process, $\delta n(t)$ reaches its maximum value, $G_0\tau_{R0}$ at the steady-state in the same time interval as in relation (27) as indicated by L_1 in Figure 1 (b). The transient mean time, τ_{R0} for $\delta n(t)$ to attain its maximum value in a system under low injection level during illumination is hence, defined as the time in which $\delta n(t)$ increases from 0 to 63% of its value at the steady-state,

or the time taken for $\delta n(t)$ to rise to its steady-state value, if the carriers continue to increase at the initial rate of accumulation.

Upon turning the illumination off ($G_0 = 0$) after the system has reached a steady-state after time, τ, only the recombination rate dominates the entire process, so that the free carriers densities in the respective bands fall at the rate given in relation (36). The decay rate is very fast at the beginning and the time dependence of the excess carrier density can be approximated as linear as in relation (46) for a system under low injection level. If the recombination rate keeps its initial value throughout the process, $\delta n(t)$ will fall to 0 in a time equal to the low injection level steady-state value excess carrier lifetime, τ_{R0} described in relation (47). However, since the excess carrier concentration decreases, subsequent slower decay follows and $\delta n(t)$ drops exponentially to 37% of its maximum initial value in time, $t - \tau = \tau_{R0}$. The transient mean time, τ_{R0} for $\delta n(t)$ in a dark system in this case is therefore defined as the time taken for the excess carrier concentration to decrease to 37% of its maximum value, or the time taken for excess carrier concentration to decrease to zero, provided the carriers continue to decay at their initial rate of recombination. As the injection level increases, the steady-state value of $\delta n(t)$ for a system under illumination increases to the value described in relation (25) or (35). The transient mean times for $\delta n(t)$ to reach the steady-state during illumination and after switching of the illumination remain the same and their value are reduced to that of the steady-state values of τ_g and τ_{R1} described in relation (25) or (35) depending on the level of injection. As the injection (illumination) level highly increases, the transient mean times for $\delta n(t)$ to reach the steady-state during illumination and after switching of the illumination goes to zero as depicted in Figure 1 (c) and (d). The ranges of both the steady-state conditions during illumination and after switching of the illumination for $\delta n(t)$ increase with increasing the injection level as shown in Figure 1 (c) and (d). For a system under slightly high injection level during illumination as the one shown in Figure 1 (c), $\delta n(t)$ increases from 0 to 72% of its value at the steady-state, in the mean transient time, τ_g given in relation (25), while it drops exponentially to 46% of its maximum initial value in the same time after switching of the illumination. For a system under very high injection level during illumination, $\delta n(t)$ increases from 0 to 76% of its value at the steady-state, in a very small transient mean

time, τ_g given in relation (35) as depicted on the left side of Figure 1 (d). For a system undergoing very high injection level, $\delta n(t)$ also drops exponentially to 50% of its maximum initial value in a very small transient mean time after switching of the illumination as illustrated on the right side of Figure 1 (d).

4.2 Time dependence of excess carrier lifetimes.

Figure 2 depicts the time dependences of (a) radiative recombination carrier lifetime during illumination, τ_{R1} (blue line), (b) optical generation carrier lifetime, τ_g (green line) and (c) radiative recombination carrier lifetime after switching off the illumination, τ_{R2} (wine line). The transient mean times for each excess carrier lifetimes to reach their steady-state values are shown at the initial stages of each graph. The doping level of the sample used is 10^{17} cm^{-3} and the absorption rate used is 1.21×10^{24} cm^{-3}s^{-1}. All the graphs in Figure 2 (a) to (c) are drawn using the generation expressions of time dependent of each excess carrier lifetimes described using relations (32), (33) and (38).

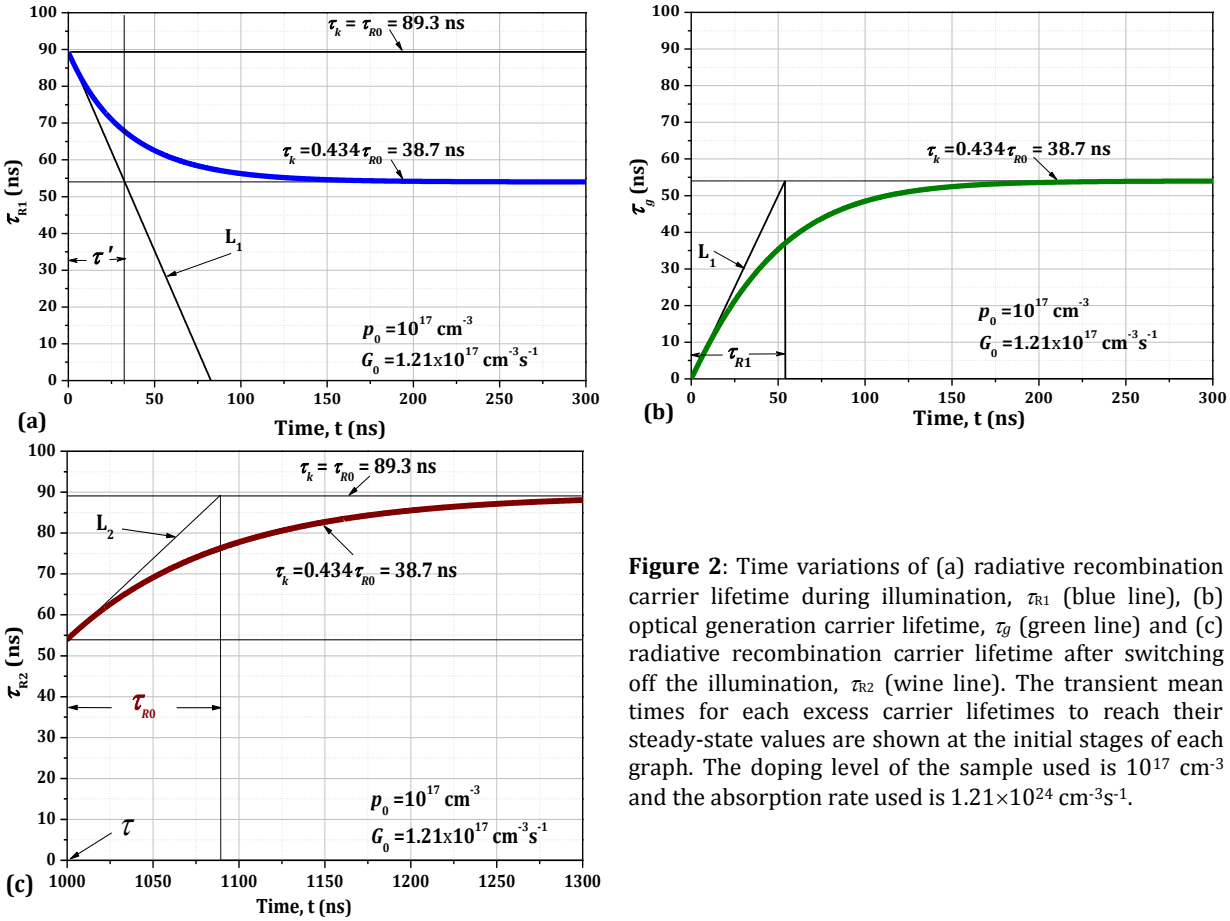

Figure 2: Time variations of (a) radiative recombination carrier lifetime during illumination, τ_{R1} (blue line), (b) optical generation carrier lifetime, τ_g (green line) and (c) radiative recombination carrier lifetime after switching off the illumination, τ_{R2} (wine line). The transient mean times for each excess carrier lifetimes to reach their steady-state values are shown at the initial stages of each graph. The doping level of the sample used is 10^{17} cm^{-3} and the absorption rate used is 1.21×10^{24} cm^{-3}s^{-1}.

In general, photo-generated carriers can be recombined both with opposite photo-generated carriers and thermally-generated carriers in the system. The net excess carrier recombination rate in relation (7) above is hence the sum of the recombination rate of a free carrier with opposite photo-generated and thermally-generated carriers. The net recombination rate of photo-generated carriers with other opposite photo-generated carriers is dominant in high injection level system as depicted in relation (10), while the net recombination rate of photo-generated carriers with the thermally generated carriers is dominant in low injection level system as shown in relation (9). As a result, all the excess carrier lifetimes $\tau_{R1}(t), \tau_g(t)$ and $\tau_{R2}(t)$ remain a function of G_0 in high injection level system as described relations (32), (33) and (49); and only a function of τ_{R0} in low injection level system as shown in relations (38) and (45). The maximum excess carrier density obtained using relation (25) by the illumination of photon absorption rate 1.21×10^{24} $cm^{-3}s^{-1}$ is approximately 6.53×10^{16} cm^{-3} and the value of the time constant, τ_k described in relation (17) has value 38.7 ns for all the curves in Figure 2 (a) to (c). Hence, the photo-generated carrier density is comparable with thermally generated carrier density and the system can be considered as slightly under high injection level. Initially, when the time, t approaches zero, the system can be considered as under low injection level (compare the expressions in relations (24) and (29)). The recombination excess carrier lifetime during illumination, τ_{R1} depicted in Figure 2 (a) hence decreases with time from its maximum value τ_{R0} (which is equivalent to the low injection value) to the steady state value described in relation (25). The generation excess carrier lifetime, τ_g illustrated in Figure 2 (b) also increases with time from its maximum value zero to the steady state value in relation (25). Both τ_{R1} and τ_g have the same steady state values. However, the recombination excess carrier lifetime after switching of the illumination, τ_{R2} shown in Figure 2 (c), increases with time from its high injection level value described in relation (25) at time, τ to the low injection value, τ_{R0} at steady state. If the variation of $\tau_{R1}(t)$ with time keeps its initial condition as in relation (23) throughout the process, it reaches its value at steady-state described in relation (25) in the time interval described in relation (26) as indicated by L_1 in Figure 2 (a). Similarly, if the variation of $\tau_g(t)$ with time keep its initial condition as in relation (23) throughout the process, it reaches its steady-state

value described in relation (25) in the time interval described in relation (25) as indicated by lines L_1 in Figure 2 (b). If the variation of $\tau_{R2}(t)$ with time keeps its initial condition as in relation (41) throughout the process, it reaches its value at steady-state, τ_{R0} in the time interval, τ_{R0} as indicated by L_2 in Figure 2 (c).Figure 3 illustrates the effects of injection level on the time dependences of (a) radiative recombination carrier lifetime during illumination, $\tau_{R1}(t)$ (blue line), (b) optical generation carrier lifetime, $\tau_g(t)$ (green line), (c) radiative recombination carrier lifetime after illumination is switched off, $\tau_{R2}(t)$ (wine line) and (d) when the excess carrier lifetimes $\tau_{R2}(t)$, $\tau_g(t)$ and $\tau_{R2}(t)$ are plotted all together for the sample used in Figure 2 above. In this case, three injection levels of optical carriers generation rates 10^{18} $cm^{-3}s^{-1}$, 1.21×10^{24} $cm^{-3}s^{-1}$ and 2.2×10^{25} $cm^{-3}s^{-1}$ that are considered as low, slightly high and very high injection levels, respectively. The values of the resulting time constant, τ_k corresponding to each illumination levels are 89.3 ns, 38.7 ns and 10 ns, respectively as shown in Figure 3 (a) to (c).

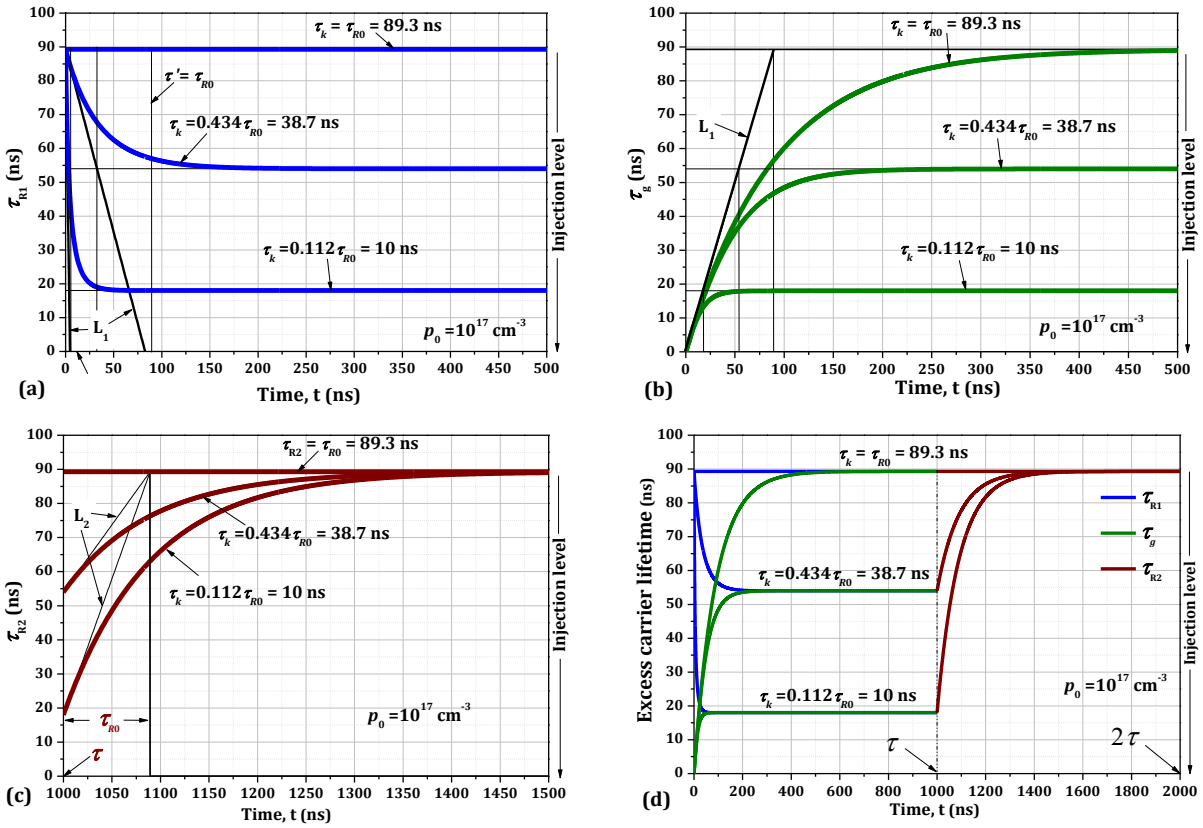

Figure 3: Effects of injection level on the time dependences (a) for radiative recombination carrier lifetime during illumination, τ_{R1} (blue line), (b) for generation carrier lifetime, τ_g (green line), (c) for radiative recombination carrier lifetime after illumination is switched off, τ_{R2} (wine line) and (d) when the excess carrier lifetimes τ_{R1}, τ_g and τ_{R2} are plotted all together for the sample used in Figure 2 above. The sample is illuminated by photons of three injection levels of optical carrier generation rates of 10^{18} $cm^{-3}s^{-1}$, 1.21×10^{24} $cm^{-3}s^{-1}$ and 2.2×10^{25} $cm^{-3}s^{-1}$ that are considered as

low, slightly high and very high injection levels, respectively.

As it can be seen from relations (23) and (41), the variations of $\tau_{R1}(t)$ and $\tau_{R2}(t)$ with time at the initial time for different injection levels are also varying, while the variation of $\tau_g(t)$ with time at the initial time remains the same for all injection levels. This is illustrated in Figure 3 (a) and (c) with slanted lines represented by L_1 and L_2 of different slopes tangent to the curves of $\tau_{R1}(t)$ and $\tau_{R2}(t)$ at the beginning for different injection levels. However, all the curves of $\tau_g(t)$ in Figure 3 (b) for different injection levels are parallel to each other at the initial time and the slanted line L_1 with slope 1 shown on the left side of the figure represents the similarity of the variation of all the curves with time at the beginning. The slope of line, L_1 at the beginning of Figure 3 (a) is varying with injection levels and given by $-(\tau_{R0}^2 - \tau_k^2)/4\tau_k^2$ (see relation (23)). The slope of L_1 is zero for low injection system ($\tau_{R0} = \tau_k$) and increases with increasing the injection level since τ_k decreases with injection level. The slope of line, L_2 at the beginning of Figure 3 (c) is also varying with injection levels and given by $(\tau_{R0} - \tau_k)/(\tau_{R0}+\tau_k)$. The slope of L_2 also zero at low injection level and increases with increasing the injection level until it reaches the value of 1 for very high injection level (see relation (41)). This leads to the proof of the premise that low injection level radiative recombination excess carrier lifetime is constant and has value τ_{R0} which is controlled only the thermal equilibrium properties of the material; and the low injection level optical generation excess carrier lifetime increases with time [39].Figure 3 (d) shows the relation between the radiative recombination lifetime and the optical generation lifetime. As can be seen from the figure, the low injection level recombination excess carrier lifetime remains constant at time, τ_{R0} for the entire time interval between 0 and 2τ, where τ, is the total illumination time. However, the low injection level optical generation excess carrier lifetime exponentially increases from zero to its steady-state value τ_{R0}. As the injection level increases, the recombination excess carrier lifetime exponentially decreases and reaches its steady state value described in relation (25); and as the illumination is switched off at time τ, the recombination excess carrier lifetime exponentially increases and reaches its steady state constant value, τ_{R0}. After time 2τ, the full process is repeated. The high injection level optical generation excess carrier lifetime again exponentially increases from zero to its steady-state value described

in relation (25) until time τ. Optical generation excess carrier lifetime does not exist between times τ and 2τ, because of there is no illumination. When each The constant value at very low injection level and the increasing of the values of the recombination excess carrier lifetime at the beginning ($t = 0$) and after switching off the illumination for the system under high injection level as shown in Figure 3 (d) indicates that, a semiconductor performs more when it is under low injection level.

V. Conclusion

In this paper, the time dependences of the radiative recombination and the optical generation excess carrier lifetimes during illumination and after switching off the illumination in GaSb are determined. The transient properties of all the excess carrier lifetimes before attaining the steady-state conditions are described in detail. The optical excess carrier generation rate G_0 is kept at constant non-zero value during illumination and kept at zero after switching of the illumination. Electron-hole pairs (EHPs) are continuously generated under illumination, and the excess charge carrier concentrations in the respective bands are increase. As more EHPs are generated, the recombination rate starts to influence the accumulation process and the rate at which excess carriers accumulate is exponentially decreases. As the value of the recombination rate increases and approaches G_0 at steady state, the generation lifetime, $\tau_g(t)$ also approaches toτ_R .The photo-generated carriers are recombined both opposite photo-generated carriers and thermally – generated carriers in the system. The net recombination rate of photo-generated carriers with other opposite photo-generated carriers is dominant in high injection level. For a system undergoing very high injection level, $\delta n(t)$ also drops exponentially to 50% of its maximum initial value in a very small transient mean time after switching of the illumination.. The photo-generated carrier density is comparable with thermally generated carrier density and the system can be considered as slightly under high injection level. The ranges of both the steady-state conditions during illumination and after switching of the illumination for $\delta n(t)$ increase with increasing the injection level. The optical generation excess carrier lifetime does not exist between times τ and 2τ, because of there is no illumination. In low injection level the radiative recombination excess carrier life time is constant and has valueτ_{R0}, which is controlled only the thermal equilibrium properties of the material. After switching off the illumination the recombination excess carrier lifetime exponationally increases and reaches its steady state constant value , τ_{R0}.

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