CHAPTER-I
INTRODUCTION AND SCOPE OF INVESTIGATIONS

1.1 Introduction

Different features associated with the space charge region and with surface states at the surface of semiconductor bulk systems or step-junction were generally discussed in terms of the surface potential and of the electrochemical potentials of holes and electrons. Various attempts were made to use the theoretical concept for the interpretation of experimental results on the surfaces of semiconductor bulk systems \([1-3]\)\. In this context, relationship between space charge, carrier concentration and electric field at a semiconductor surface as a function of the change in electrostatic potential from bulk to the surface region was developed. One of the techniques dealt with the numerical integration of Poisson's equation through the use of Boltzmann statistics and the results were obtained in graphical form through which the correspondence with the surface properties of semiconductors were built \([4]\)\. The results were expressed as a function of the deviations of Fermi energy from its intrinsic value in the bulk and at the surface, and have been used for any non-degenerate semiconductor at any temperature where the donor and acceptor levels were completely ionised. On the basis of

*The number within the square bracket corresponds to reference given at the end of the thesis. This convention will be followed all through.
this method, different solutions were obtained — all of those had appropriate uses [5-8]. There was other approach where the relationship among different parameters had been calculated theoretically by assuming some dopant distribution or band structure and then the computed relationship was compared with the results of the experimental curves [9]. Within the inversion regime, an analogous approximate analytical relationship among different parameters was presented [10]. For degenerate cases, Fermi-Dirac statistics is being used and the transport equations are modified due to heavy doping effects [11-14].

Important works have been reported during the last few years in connection with the studies of heavy doping effects in the performance of semiconductor devices using p-n junctions. The analysis of heavily doped semiconductor devices is complicated by changes in the energy bands which occur in the regions of high dopant density. The resulting non-uniform band structure is generally considered in order to model p-n junction devices accurately. For degenerated materials with non-uniform band structure, the theory of electron and hole motions and density of states are modified than the situation of non-degenerated cases. Various problems have been tackled to include materials of semiconductor bulk systems with graded composition, like heterojunctions and high-low junctions having non-uniform temperature or strain and devices with highly doped region [12, 15-18]. In heterostructures, various heavy doping effects are studied using
approximate methods [12,19-21].

In course of various investigations, it is found that open circuit voltage decay is used as one of the techniques for determining minority carrier lifetime in semiconductor devices [22-26]. Open circuit voltage decay measurement provides information about the effective back-surface recombination velocity and the minority carrier lifetime. In a heavily doped region, the recombination process reduces the dimension of the doped region and yields higher power conversion efficiency. Its value depends on the physical and chemical states of the surface, viz., free, oxidised, metallised, etc. [27-29]. Recombination is assumed to take place [27,30-35] via deep traps either at or close to the surface. These traps may direct the Fermi level at the free surface [32]. It is assumed that under heavy doping conditions, the surface recombination is a combination of the Shockley-Read-Hall (SRH) process through surface states in the band gap and the band-to-band Auger recombination process, due to which the recombination rate [36] depends on the density of surface states, the distribution of band bending, etc.

There are numerous semiconductor devices, viz., bipolar transistors, solar cell, LED, etc., where carrier flow is controlled by injection and diffusion of minority carriers, contain active regions with doping levels above $10^{18}$ cm$^{-3}$. The recombination effects in these situations play an important role in the behaviour of certain
characteristics of the devices. In the modelling of minority carrier controlled devices, surface recombination velocity (S) act as a parameter which characterizes surface recombination. Surface recombination is highly affected owing to the influence of heavy doping, particularly through band gap narrowing. Moreover, surface recombination velocity depends on injection of carriers. Thus, S changes under different physical conditions. The junction leakage current with the variation of injection level of a high-low junction has been modelled by the effective surface recombination velocity. The variation of surface recombination velocity with dopant density for n⁺-n junction is being investigated.

Built-in field at high-low junction has influence over the value of S like the other factors, e.g., minority carrier recombination in the highly doped region and the minority carrier recombination in the space charge layer at the high-low junction. Earlier workers derived the expression of effective recombination velocity taking into account the influence of those factors partially.

Different approaches have been made to analyse various compositionally non-uniform semiconductor devices since the last three decades. Earlier workers obtained solutions in case of abrupt graded junctions based on depletion approximations. Heavy doping effects in heterojunctions have been investigated where transport equations are derived in
terms of non-uniform band structure [12,21,52]. In the fabrication of devices for mm-wave amplification, and microwave integrated circuits, different applications of heterojunction bipolar transistors (HBTs) are known. The properties of III-V HBTs have been studied in terms of their breakdown voltage, output conductance and band gap. The different studies in GaAlAs/GaAs, InGaP/GaAs are made by different workers [53-56].

Minority carrier lifetime is an important parameter in light emitting diodes (LEDs), photovoltaic cells, bipolar transistors, heterojunction lasers and other devices. In photovoltaic devices, the minority carrier lifetime is determined by different methods [23,25,57]. Carrier lifetime in silicon is usually found by using pulse optical excitation and photoconductivity decay technique. The illumination-effects on AlGaAs/GaAs modulation-doped-field-effect-transistor (MODFET) structure are known [58]. Heavy doping effects produce high emitter efficiency in bipolar transistors and high open circuit voltage in solar cells. Lifetimes for high carrier concentrations are important in band-band processes.

The In$_{1-x}$Ga$_x$AsP$_{1-y}$ quaternary alloy system is considered to be the most promising for optical communication in the 0.95 - 1.75 μm wavelength range [59-62] because the epitaxial layer of this quaternary lattice matches InP substrates over a wide range of band gaps for which devices such as LEDs, lasers, photodetectors, etc. can be produced. By proper choice of composition [63,64], the band gap Eg can
be chosen from a wide range. Laser performance shows poor temperature dependence characteristics of the threshold current [65]. Carrier leakage from the InGaAsP active region to the InP confining layers shows a steep temperature dependence of the threshold current [66] which is interpreted in terms of the Auger process [67].

Band-band Auger lifetimes in heavily doped quaternary alloy as a function of dopant concentration and temperature are useful parameters for device design work and analysis [25, 68, 69]. The qualitative theory of Auger lifetime was first given by Beatie and Landsberg [70] on the basis of a simple band structure. Beatie and Smith [71] offered a more detailed theory considering band structure consisting of conduction, heavy hole, and light hole bands (called the CHLH process). Takeshima [72] calculated Auger lifetimes considering transition through the conduction band-heavy hole band-spin split-off band mechanism (called the CHSH process). It includes two heavy hole bands, a conduction band, and an Auger excited split-off band. Spin split-off band in the Auger process is an important factor; it helps to choose an alloy for devices. The Auger lifetime is very short. When the band gap energy approaches the spin-orbit splitting, the alloy will be unsuitable for light emitting diode (LED) devices.

Energy conversion efficiency in solar cell depends upon the minority carrier lifetime. There are numerous
silicon devices \([73-76]\) with doping levels of the order of \(10^{18} \text{ cm}^{-3}\), based on the injection of minority carriers. Device performances in these cases depend upon the transport of the minority carriers through the heavily doped regions. Several earlier works considered the effects of heavy doping \([11,77-79]\) on the basic parameters, e.g., energy gap, minority carrier diffusion constant, carrier mobility, and minority carrier diffusion length.

In the limit of physical sizes approaching dimensions comparable to an electron wavelength in semiconductors and metals, quantum size effects become predominant. It has been clear over the past decade that even single abrupt heterostructure interfaces contain a sufficient energy band discontinuity so that the effects of reduced dimensionality must be considered for both optical and electronic device structures. The variation of these effects on size, composition, and applied fields, and the extension of these effects to several interfaces or the very large number of interfaces in a superlattice results in high possibilities for device structures. From practical point of view, sophisticated modern epitaxial growth techniques have provided with the high quality materials and ultrathin layer structures necessary to explore this emerging technology.

Fabrication of quantum well heterostructures have allowed tailoring of optical and electronic responses of the semiconductor materials, which initiates more towards the
development of electronic and optoelectronic devices. Semiconductor superlattices and quantum well heterostructures form an important new class of electronic/optoelectronic materials, since the properties of these layered structures are in many ways superior to those of bulk materials. Optical and electronic properties of thin layered structures are being studied intensively [80-90]. Optical properties of quantum well heterostructures including non-linear optical properties and injection lasers of both lattice-matched and mismatched materials systems are being studied. Both experimental and theoretical studies on excitonic transitions in quantum wells are well known [84, 91-95]. The excitonic studies offer a direct probe into the quasi-two-dimensional physics of quantum well structures and have been useful in applications ranging from characterization of interface quality to optical modulators. By using non-variational numerical techniques, the properties of effective-mass excitons in quantum wells in the presence of strain, transverse electric fields, and free-carriers are studied extensively [96].

The phenomena of recombination processes of carriers associated with continuous-wave (CW) intensity dependent photoluminescence and the physical characteristics of highly excited semiconductor quantum well have been the subject of recent investigations [97-101]. Photoluminescence spectroscopy is an useful technique for obtaining informations concerning the semiconductor alloys which give important aspects of
optoelectronic and microwave devices. Both experimental studies as well as theoretical models of luminescence linewidths of excitons in different quantum wells are reported during the last decade \([102-106]\). Various processes of interactions have been considered to explore the contributions to the linewidth of the exciton luminescence.

Although enormous amount of work has been done to study different properties of semiconductor bulk systems and quantum well heterostructures, there remain still different aspects which need further efforts to extract more informations about their nature and characteristics. In this thesis, the outcome of theoretical investigations of some of these stated areas has been presented.

The influence of heavy doping on open circuit voltage decay in an abrupt \(p^+-n\) junction silicon semiconductor diode may be investigated. The analysis should include the contribution to decay characteristic of the holes and electrons that come from the junction space charge region. The results of numerical computations may be used to study the open circuit voltage decay characteristic of the diode.

Since the surface recombination rate \([36]\) under heavily doped condition depends on the density of surface states, the distribution of band bending and the other parameters, some investigations may be carried out to study the variation of surface recombination velocity with dopant density. The
results could be compared with earlier works. Further attempt may be made to investigate the variation of charge control transit-time with surface recombination velocity of the minority carriers under heavily doped condition.

Surface recombination velocity \( S \) has been used as a fitting parameter in different devices [107,108]. An expression for the built-in potential in a heavily doped high-low (p⁺-p) junction may be derived through model calculation. The variation of surface recombination velocity with dopant density could be numerically estimated taking into account the variation of built-in potential.

Some properties of semiconductor heterojunctions under heavily doped condition may be explored through different models. The potential distribution of a semiconductor heterojunction in equilibrium could be studied where many-body effects and non-ideal behaviours of electrons at the junction interface would be considered as heavy doping effects along with band gap narrowing and carrier degeneracy. The results may be depicted graphically. Further investigations can be carried out on some characteristics of heavily doped heterojunction structures through Poisson-Boltzmann integral equation. The variation of conduction band/Fermi level separation and carrier concentration distribution with depth may be studied through the derived result.

Different works are reported in connection with the studies of heavy doping effects in the performance of
heterojunctions \[12,20,109\]. The effect of exponentially graded base doping on the performance of GaAs/AlGaAs HBTs have been reported \[110\]. An expression of the collector leakage current of heavily doped AlGaAs/InGaAs and AlGaAs/GaAs HBT structures may be derived through which common-emitter I-V characteristics of InGaAs and GaAs collector regions could be studied. The results could be compared with earlier works.

Minority carrier lifetime in III-V semiconductors is determined by time-resolved photoluminescence technique \[111\]. A model may be developed to study the variation of photoluminescence lifetime with concentration in heavily doped double heterostructures under focussed powers and also under unfocussed power. The results could be presented graphically.

Threshold current density in a semiconductor laser alters as the material would be changed by mixing \[112\]. GaAs material produces GaAs\(_{1-x}\)P\(_x\) at 77 K when mixed with GaP. It shows a sharp rise of the threshold current density. Knowledge of Auger effects, under heavy doping condition, is helpful in VLSI and transistor technology. In heavily doped semiconductors, the Auger effects leads to lifetime broadening of the electronic states at the band edge, unless it is screened by Coulomb interaction \[113\]. There are several works that predict experimentally measured lifetimes \[111,114-116\] of heavily doped GaAs and InGaAsP to study the Auger effects. Considering the anisotropy of some band
parameters, the Auger recombination rate in InGaAsP has been calculated [117]. Different works are published on the determination of recombination rates in the material under various situations [118-120]. There are several works about Auger recombination in light emitting devices and in other materials [111,113,116,121-135].

The influences of doping on lifetime, diffusion length and mobility of minority carriers have been studied theoretically as well as experimentally. There are different complexities in device fabrication and in the choice of doping materials, which are resolved by making assumptions. There are attempts to overcome the disagreement between theoretical results and experimental values by proper choice of transport equations. The carrier lifetime and quantum efficiency in heavily doped InGaAsP may be investigated through modelling works. The variation of carrier lifetime and quantum efficiency with nominal current density at a given temperature could be studied through numerical analysis. The variations of minority carrier lifetime with dopant density and temperature can be studied through some model calculations. Also, an expression for Auger lifetime may be derived for a heavily doped Hg$_{1-x}$Cd$_x$Te through which the variation of Auger lifetime with temperature can be understood through numerical analysis.

A theoretical analysis on some physical characteristics of GaAs-(Ga,Al)As quantum well photoluminescence may be investigated. A quantum mechanical formalism would be adopted
for theoretical investigations of some physical characteristics in GaAs-(Ga,Al)As quantum well under steady-state optical excitation conditions based on the dependence of photoluminescence on laser intensity. The variations of carrier density with laser intensity and electron-hole (e-h) recombination decay-time may be studied. Radiative recombination of electrons with free holes and holes bound at neutral acceptors can be considered in the analysis along with the contribution of Auger processes and excitonic recombination.

Further work may be carried out on energy-gap discontinuities between conduction and valence bands for GaAs-Al$_x$Ga$_{1-x}$As quantum wells. From the analyses, the energies of the various light- and heavy-hole exciton transitions can be calculated as the function of well width for square-wells.

Moreover, theoretical investigations on the enhanced refractive index change in asymmetrical quantum well with an applied electric field could be investigated. The numerical results of the change of refractive index with an applied electric field due to subband transition in the graded gap quantum well could be presented using suitable transformation of the absorption coefficient. The ground state to the first excited state transition in the conduction band of quantum well structure may be considered. For numerical analysis, some known quantum well structure would be chosen. The influence of Stark shift for the change in refractive index due to the larger change in transition energy may be understood. The calculations can be initiated considering CO$_2$ laser as
incident radiation.

1.2 Scope of Investigations

On the basis of previous discussion, the investigations which have been carried out are presented in the forthcoming chapters.

Chapter-II deals with the investigations of the influence of heavy doping on open circuit voltage decay in an abrupt $p^+\!-\!n$ junction silicon semiconductor diode [136]. Band gap narrowing and carrier degeneracy are taken into consideration as heavy doping effects. The variations of open circuit voltage decay with time is studied through numerical analysis.

In Chapter-III, some studies are made on surface recombination velocity and its effects on some parameters in heavily doped $n^+\!-\!p$ junction device. Section 3.2 deals with the derivation of an analytical expression for the surface recombination velocity in a $n^+\!-\!p$ junction under heavily doped condition [137]. The variation of surface recombination velocity as a function of dopant density has been presented graphically along with the results of an earlier work [34]. In Section 3.3, the effect of surface recombination on the transit-time in heavily doped $n^+\!-\!p$ junction silicon solar cell is investigated through a model [138]. The numerical results have been compared graphically with an earlier experimental work [36].
Chapter-IV is related to high-low junction where the influence of built-in potential on the effective surface recombination velocity has been investigated [139]. In the analysis, dopant density dependent dielectric constant and the effect of carrier lifetime across the junction are taken into account along with other heavy doping effects. The results of numerical analyses are shown through graphs.

Some studies on semiconductor heterojunctions under heavily doped condition are made in Chapter-V. Section 5.2 concerns with a model calculation for investigating the potential distribution of a heavily doped semiconductor heterojunction in equilibrium [140]. The variation of normalized potential with dopant density has been depicted through a graph. In Section 5.3, a model is developed for studying the characteristics of heavily doped n⁺-GaAs/n-Ge heterojunction structures through the use of Poisson-Boltzmann integral equation [141]. The equation has been used to investigate some characteristics of the heterojunction.

In Chapter-VI, an expression for the collector leakage current is derived which has been made useful to study the common emitter I-V characteristics of In₀.₅₃Ga₀.₄₇As and GaAs collector regions of heavily doped heterojunction bipolar transistors (HBTs). The results have been presented graphically [142] and compared with an earlier work [143].

A model has been developed in Chapter-VII to study the variation of photoluminescence lifetime with concentration in
heavily doped $\text{Al}_{x}\text{Ga}_{1-x}\text{As/GaAs}$ double heterostructure (DH). The results of computational analyses are presented through graphs [144].

Heavy doping effects, e.g., band gap narrowing, non-parabolicity of band structure, carrier degeneracy and the distribution of states in the forbidden gap greatly influence the recombination processes. In Chapter-VIII, some models will be presented to investigate the different lifetimes of some compound semiconductors. In Section 8.2, a model is developed for a heavily doped InGaAsP to investigate the variation of carrier lifetime and quantum efficiency with nominal current densities [145]. Section 8.3 deals with the studies on temperature and concentration dependent minority carrier lifetime in heavily doped InGaAsP through an empirical lifetime model [146]. The results are shown graphically. The study has been extended to the case of $\text{Hg}_{1-x}\text{Cd}_{x}\text{Te}$ where the temperature dependence of Auger lifetime for different fixed values of carrier densities are presented through graphs under heavily doped as well as lightly doped situations [147].

In Chapter-IX, the results of some theoretical investigations of the dependence of carrier density on laser intensity for GaAs-(Ga,Al)As quantum well in CW laser photoluminescence treatment has been presented [148]. From the analyses, the variations of carrier density with laser intensity and recombination lifetime with carrier density for the quantum well under different compositions are
numerically estimated. These have been shown graphically along with the results of some previous works [100,101].

In Chapter-X, the variation of refractive index of a graded gap quantum well (GGQW) with an applied electric field has been investigated [149]. The change of Stark shift with the applied electric field is also estimated. The results of numerical computations have been presented graphically along with the work of an earlier author [150].

Finally, a summary and some discussions are given in Chapter-XI about the various investigations which are presented in the different chapters of this thesis.