Chapter 1

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1.1 Introduction

Nanotechnology is a field of applied science and technology covering a broad range of topics. The main unifying theme is the control of matter on a scale smaller than one micrometre, as well as the fabrication of devices on this same length scale [1]. This technology was first proposed by the Noble Laureate and great teacher Richard Feynman in 1959 in his famous talk "***There's Plenty of Room at the Bottom***" at the American Physical Society meeting [2]. Feynman's dream led to the whole area of miniaturization, which subsequently created the area of Micro-Electro-Mechanical Sytems (MEMS). Various different types of MEMS based sensors have been created and utilized. The discovery of Bucky Balls in 1990 by Richard Smalley and Nanotubes by Sumio Ijima in 1991 [3], led to a whole new revolution of nano-engeenering materials from the level of atoms, molecules and supra-molecular structures thereby paving the way for a whole new approach of manufacturing which we call *nanotechnology* today. Much speculation exists as to what new science and technology might result from these lines of research. Nanotechnology is also an umbrella description of emerging technological developments associated with sub-microscopic dimensions. Despite the great promise of numerous nanotechnologies such as quantum dots and nanotubes [4], real applications that have moved out of the lab and into the marketplace have mainly utilized the advantages of colloidal nanoparticles in bulk form, such as suntan lotion, cosmetics, protective coatings, and stain resistant clothing.

Nanotechnology is simply not miniaturizing materials, and devices at the nanometer scale lengths (1 nm = 10^{-9} m). At nano-meter length scales new physical properties emerge in these materials and new techniques are required to make them. Size constraints often produce qualitatively new behavior in nano-materials. For example, if the size of a nanoscale structure becomes equal to or less than the characteristic length scales for scattering of electrons or phonons, this can result in qualitatively new modes of electrical current and heat transport in these nano-materials. Mechanical propeties of nano-materials change dramatically as the grain size of materials approach nanometer scale lengths. Often enhanced mechanical strengths are observed in materials made of nano-meter crystallites compared to coarse-grained films. Thermodynamic propeties including collective phenomena and phase transitions such as ferromagntism, ferroelectricity and superconductvity, have long been expected to demonstrate substantial changes at the nano-meter length scales. Contemporary needs in data storage and information technology have stimulated considerable research activity in nanoscale magnetism. Complex molecular magnets consisting of tens to hundreds of atoms have shown unusual phenomena such as tunneling, quantum cohernce, and thermo-induces spin cross over transitions. Nanoscale research on the optical, electronic and transport propeties of semicooducters at the nano-scale are experiencing astonishing growth. The fundamental properties of nanoscale semiconductors can be dramatically altered by controlling their size and shape without dramatically altering their composition. When the electrons and holes in semicondcutors are confined to dimensions less than their de Broglie wavelength (1-30 nm), quantum mechanical size effects start to appear. Materials at these dimensions are often defined by the nature of their carrier confinement. For example, if the carrier confinement is in one dimension, these materials are charaterized as quantum wells. If the carrier confinement is in two dimensions, these materials are characterised as quantum wires and finally if the carrier confinement is in all the three dimensions, these materials are charaterized as quantum dots. The most dramatically affected electronic properties include: (i) A large change in the optical absorption coefficients as a funtion of decreasing nano-matter scale lengths. (ii) Conversion of optical spectra from continuous bands to discrete lines (iii) Enhanced photo-catalytic properties due to higher redox potentials of photo generated electrons and holes. (iv) Conversion of indirect bandgap materials to direct bandgap with decreasing size of the crystallite and vice versa. (v) Enhanced excitonic transitions at room temperature. (vi) Abillity to tune electronic properties of nano-materials using biomolecules depending on the geometry of biomolecules.

It is a highly multidisciplinary field, drawing from fields such as colloidal science, device physics, and supramolecular chemistry (A highly interdisciplinary field covering the chemical, physical, and biological features of complex chemical species held together and organized by means of intermolecular (noncovalent) bonding interactions).

In recent years, III-V semiconductors have received tremendous focus due to its application in optoelectronics. These materials typically exhibit a direct band gap, which makes them good candidates for semiconductor LASERs, with applications in fiber optic systems, CD and DVD technology, image scanning and LASER surgery etc. In addition, researchers also looked to tailor the physical properties of materials by doping or alloying to improve and develop electronic and optoelectronic devices. Material fabrication techniques have been used to grow diluted nitrides i.e. the dilute concentrations of nitrogen. This causes effect on the electronic structure and thereby resulting to a giant optical bowing of the band gap as the nitrogen content increases [5]. This phenomena has raised interest in the use of the dilute nitrides (also imposes limitation) in devices as there is deterioration of the electron mobility with nitrogen addition [6, 7]. This will affect the bandwidth of the device and hence the carrier transit time and mobility. The exact nature of the carrier transit is still the focus of ongoing research [8, 9] and is the subject of present thesis. Specifically, the present thesis focuses on diluted nitrides pursuing a theoretical investigation of the carrier – phonon interaction and hence transports properties. There are several types of carrier scattering mechanisms, however the carrier - phonon scattering is the dominant one and the concern of present study.

Since the main aim of the present thesis is to investigate the carrier-phonon interaction in some diluted nitrides in its reduced dimension, a brief discussion on the carrier transport and its related parameters is given below.

1.2 Carrier Transport in Nanostructures

Over the last few years, the foundations of electron transport in nanostructured materials have been investigated in great detail. In comparison to classical transport, new phenomena are observed, due to controlled transport of single electrons and quantum coherence effects [10-12]. Some examples are quantized electronic states in quantum dots and transport channels in quantum point contacts or quantum wires, phase coherent transport leading to interference phenomena, and the quantum Hall effect [13]. The quantum coherence of a system can be exploited for novel quantum information systems and quantum computing [14].

A **nanostructure** is an intermediate size between molecular and microscopic (micrometer-sized) structures. In describing nanostructures we need to differentiate between the number of dimensions on the nanoscale. Nanotextured surfaces have **one dimension** on the nanoscale, i.e., only the thickness of the surface of an object is between

0.1 and 100 nm. Nanotubes have **two dimensions** on the nanoscale, i.e., the diameter of the tube is between 0.1 and 100nm; its length could be much greater. Finally, spherical nanoparticles have **three dimensions** on the nanoscale, i.e., the particle is between 0.1 and 100 nm in each spatial dimension. The terms nanoparticles and ultrafine particles (UFP) often are used synonymously although UFP can reach into the micron range.

Looking at it from a more general perspective, one finds that there are three independent length scales in physics that converge onto the single digit nanometer regime. Quantum mechanics, electrostatics, and magnetism conspire to produce a **common length scale** in the **single-digit nanometer** regime. These three length scales determine the operation of electronic devices, such as a quantum well LASER [15-20], a single electron transistor [21], and a magnetic hard disk [22]. In order to operate at room temperature, quantum wells and quantum dots have to be smaller than a few nanometers, and magnetic particles need to be larger than that.

As carrier traverse a device, their motion is frequently interrupted by collisions with impurity atoms, phonons, crystal defects, or with other carriers. The electrical response of any electrical device depends upon the electronic configuration as well as the interaction of carrier with vibrations of lattice with corresponding temperature. Dimensional confinement of carrier (electron) in nanostructures gives rise to quantum effects which can be exploited in a range of electronic and optoelectronic device applications [23]. The problem of electron-phonon interaction in nanostructures has been studied for about 20 years. The dominant factor in dimensional confinement is degrees of freedom of phonons and carriers. Basically, there are two principal phenomena that modify the process of electron scattering on the lattice vibrations in nanostructures. First, the reduction of the electron momentum space dimensionality brings act interesting properties of the electron-phonon interaction kinematics, controlled by the momentum and energy conservation laws [24]. The second phenomenon arises due to the modifications of the phonon modes caused by the acoustic and dielectric mismatches of the materials forming the nanostructures. These changes in properties give rise to phonon minibands in superlattices, as well as confined and interface phonons in quantum wells, quantum wires, and quantum dots.

As mentioned above, the present work aims to represent the electron scattering rate mainly due to phonons and by this way we tried to determine the electron transport parameters. Electron momentum relaxation time, energy relaxation time, electron mobility, drift velocity, resistivity, energy loss rate by means of phonon absorption and phonon emission and power loss etc. are determined with the analogy of electron-phonon interaction. The carrier transport properties are carried out for diluted nitride semiconductors (e.g. $GaAs_{1-x}N_x$) and diluted magnetic semiconductor (DMS) (e.g. $Ga_{1-x}Mn_xN$ and $Ga_{1-x}Mn_xAs$) via deformation potential coupling mechanism. The calculations are also carried out for hot electrons at low temperatures in the presence of magnetic field [25, 26]. Hot electrons are the electrons with high electric fields. Many heterostructures devices operate in high electric fields to achieve the desirable high speed or high frequency performance. However, being accelerated in high electric fields, the electron mean energy and the average momentum acquired are far greater than those associated with thermal equilibrium. This leads to a strong non-equilibrium state of the electron gas. Strong non-equilibrium electrons not only move fast, but also exhibit a number of specific effects that find various practical applications because whenever the devices are operated under high electric fields the electron mean energy and their average acquired momentum increase with the electric fields. Further the spin relaxation time has also been studied for GaAs quantum well using D'yakonov-Perel mechanism.

1.3 Outline of Forthcoming Chapters

The essential background for this work is introduced in next chapters. The present **Chapter 1** deals with the introduction of the present thesis followed by **Chapter 2,** which discusses the interaction between electrons with phonons with the additional sources of electron scattering. The detailed account of theoretical models such as deformation potential coupling mechanism including acoustical deformation potential (ADP) interaction, optical deformation potential (ODP) mechanism, polar acoustical phonon (PAP) interaction, polar optical phonon (POP) interaction of carrier scattering is presented in this chapter. In **Chapter 3,** we discuss about the scattering rate which can be used to further calculate the transport properties in two dimensional dilute nitride semiconductor alloys [27-29]. We also study the effect of concentrations of nitrogen and temperature on the carrier scattering rate, momentum relaxation time, energy relaxation time, carrier resistivity in reference with acoustical phonons. We also report the well width dependent carrier–phonon scattering rate. The effect of temperature on acoustical deformation potential is also reported in the present chapter. Further, the studies on carrier relaxation rates and related properties of two dimensional dilute semiconductors $Ga_{1-x}Mn_xN$ and $Ga_{1-x}As_xN$ are also discussed in this chapter. We have reported the effect of different concentrations of manganese and different temperature in addition with the magnetic field on the different carrier transport parameters such as carrier scattering rate, momentum relaxation time, energy relaxation time, conductivity and resistivity in reference with acoustical phonons.

Chapter 4 is the report of the electron transport phenomena under high electric field as to understand the operation and performance of many heterostructure devices under high electric field [30]. In this chapter, we study the variation of electron scattering rate (e.g. momentum and energy relaxation rate), carrier drift velocity and electron energy loss rate by means of phonon emission and phonon absorption with respect to electric field and doping concentration.

Chapter 5 contains the study of spin relaxation rate in two dimensional systems. The study of active control and manipulation of spin degrees of freedom in solid-state systems is spintronics, or spin electronics. It is based on the up and down spin of the charge carrier rather than on electrons and holes as in traditional semiconductor electronics so it could make integrated use of both charge and spin of electrons. Spintronics, also called magnetoelectronics including all the electronic devices where ferromagnetic thin films play an essential role, is today one of the most rapidly growing fields in electronics [31]. A recent example of a rapid transition from discovery to commercialization in spintronics is the giant magnetoresistance effect (GMR), as applied to magnetic information storage. We utilize the method of D'yakonov-Perel mechanism to determine the spin relaxation [32, 33]. Finally, the chapter 6 summarizes the results and discussion of the present thesis.

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