Diluted Magnetic Semiconductors (DMSs) and Their Applications

By

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Gebremichael Gurmessa challa
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Dedication

This Project Work is dedicated to :

My Father: **Gurmessa Challa Bayan**

and

My Mother: **Bizunesh Taddese Yadessa**

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Abstract

Magnetic semiconductors are semiconductor materials that exhibit both ferromagnetism and useful semiconductor properties. If implemented in devices, these materials could provide a new type of control of conduction. Whereas traditional electronics are based on control of charge carriers (n- or p-type), practical magnetic semiconductors would also allow control of quantum spin state (up or down), which is an important property for spintronics applications. High Curie temperature (T_c above room temperature) DMS is required for practical applications and it is still challenging. This work reviews, magnetism, and transport properties of diluted magnetic semiconductors for applications as storage and data processing. Hence, a brief of information on the property and mechanism of incorporating magnetic impurities into semiconductors to get a hybrid that demonstrates miniaturized system will be explained. Moreover, two effects of impurity concentration x on magnon dispersion and fractional change of magnetization is plotted and discussed.

Introduction

0.1 Introduction

In most of semiconductor devices like the Bipolar junction transistors, FETs, MOSFETs etc. electronic charge is controlled by doping with acceptor or donor impurities [1, 2, 3, 4, 5]. The electronic spin can also be utilized for expanding their applications. In order to achieve such devices, the electrons must be spin-polarized and their polarization largely preserved as they travel through the semiconductor material. The spin polarized carriers can be created by doping ferromagnetic impurities such as transition metals like Mn, Co, Cr and rare earth metals such as Pd, Eu etc. [6, 7, 8, 9]. The variety of such semiconductors is called Diluted Magnetic Semiconductors which have combination of both magnetic and semiconducting properties. Such a compound is an alloy between a non-magnetic semiconductor and a magnetic element like the transition and rare-elements. The interesting room temperature ferromagnetism in many diluted magnetic semiconductor oxide systems (O-DMS), has opened up a route for spintronic devices. Diluted magnetic semiconductors have been studied by the researchers for identifying DMSs which have strong ferromagnetism at room temperature. Initially II-VI semiconductor alloys like $Zn_{1-x}Mn_xTe$ and $Cd_{1-x}Mn_xTe$ were studied but they showed very weak ferromagnetism and low Curie temperature (T_c). More recently, the Mn- doped III-V semiconductors like $In_{1-x}Mn_xAs$ and $Ga_{1-x}Mn_xAs$ has been studied and they have shown ferromagnetism at higher Curie temperature. The temperature is still too low for practical applications [10]. In all these materials ferromagnetism has been proven to be carrier mediated, which enables the modification of magnetic behavior through charge manipulation. It has motivated a continuous search for materials with even higher T_c. It has led to discovery of oxide based DMSs like ZnO and $In_{1.8}Sn_{0.2}O_3$ etc. which are wide band gap semiconductors ($> 3eV$) and can add an optoelectronic dimension to the new generation of spintronic devices [11, 12, 13]. The first generation of spintronics devices were based on passive magnetoresistive sensor and memory elements using electrodes made from alloys of ferromagnetic 3d metals. Their development was later boosted by the discovery of giant magnetoresistance, in (Fe/Cr)n multilayers, and tunnelling magnetoresistance [14]. Next generation is expected to consist on active spin-based devices that will necessarily comprise the creation and manipulation of spin polarized electrons in a host semiconductor [15, 16]. In order to achieve an operational device, the electrons must be spin-polarized and their polarization largely preserved as they travel through the semiconductor material. The most obvious way for spin injection would be injecting from a FM metal in a metal/SC junction. Transition metal magnetic ions are deliberately injected into non magnetic semiconductors such that the magnetic spin states (up and down spin states) are utilized for the transfer and storage of information by charge carriers (electrons and holes) and by spin states. This type of heterostructures have been extensively studied; however, it has been shown that it is difficult to preserve the electron spin across the interface, mainly due to the large mismatch in electrical conductivity between the two materials [17]. This work reviews, the highlights of magnetism, traditional semiconductors, diluted magnetic semiconductors, spin wave (magnon energy and dispersion) and application of DMS for the comparisons of conventional semiconductors and spin polarized DMSs.

Chapter 1

Highlights of Magnetism

The origin of magnetism lies in the orbital and spin motions of electrons and how the electrons interact with one another. The best way to introduce the different types of magnetism is to describe how materials respond to magnetic fields. This may be surprising to some, but all matter is magnetic. It's just that some materials are much more magnetic than others. The main distinction is that in some materials there is no collective interaction of atomic magnetic moments, whereas in other materials there is a very strong interaction between atomic moments [18]. The magnetic behavior of materials can be classified into the following five major groups:
1. Diamagnetism 2. Paramagnetism 3. Ferromagnetism 4. Ferrimagnetism
5. Antiferromagnetism

1.1 Diamagnetism

Diamagnetism is a fundamental property of all matter, although it is usually very weak. It is due to the non-cooperative behavior of orbiting electrons when exposed to an applied magnetic field. Diamagnetic substances are composed of atoms which have no net magnetic moments (i.e., all the orbital shells are filled and there are no unpaired electrons). However, when exposed to a field, a negative magnetization is produced and thus the susceptibility is negative [18].

1.2 Paramagnetism

In this class of materials, some of the atoms or ions in the material have a net magnetic moment due to unpaired electrons in partially filled orbital. One of the most important atoms with unpaired electrons is iron. However, the individual magnetic moments do not interact magnetically, and like diamagnetism, the magnetization is zero when the field is removed. In the presence of a field, there is now a partial alignment of the atomic magnetic moments in the direction of the field, resulting in a net positive magnetization and positive susceptibility as shown in Fig. 1.1 [18].

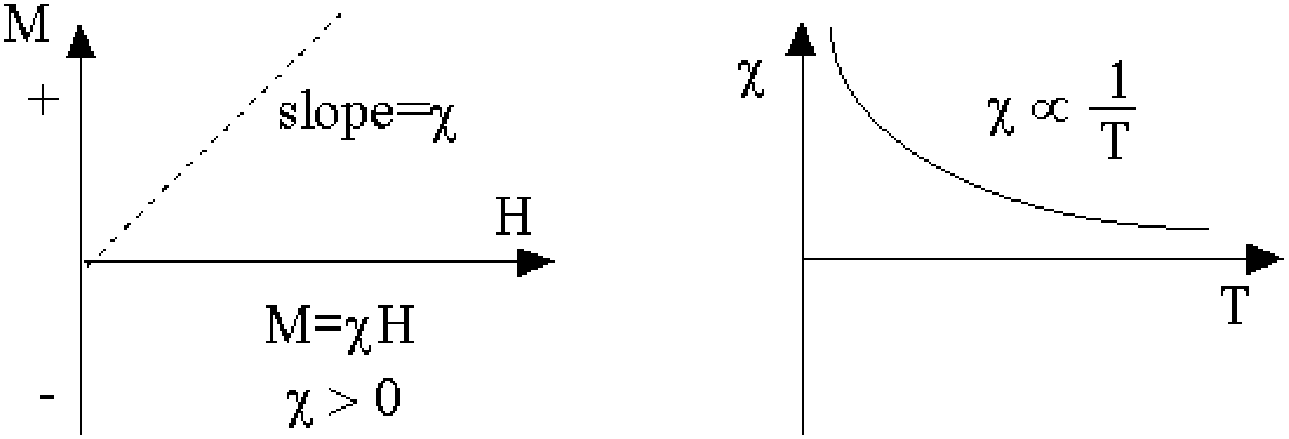

Figure 1.1: Paramagnetism [18].

In addition, the efficiency of the field in aligning the moments is opposed by the randomizing effects of temperature. This results in a temperature dependent susceptibility, known as the Curie Law. At normal temperatures and in moderate fields, the paramagnetic susceptibility is small (but larger than the diamagnetic contribution). Unless the temperature is very low ($<< 100K$) or the field is very high paramagnetic susceptibility is independent of the applied field. Under these conditions, paramagnetic susceptibility is proportional to the total iron content [18].

1.3 Ferromagnetism

Unlike paramagnetic materials, the atomic moments in these materials exhibit very strong interactions. These interactions are produced by electronic exchange forces and result in a parallel alignment of atomic moments. Exchange forces are very large, equivalent to a field on the order of 10^3 Tesla. The exchange force is a quantum mechanical phenomenon due to the relative orientation of the spins of two electrons. Ferromagnetic materials exhibit parallel alignment of moments resulting in large net magnetization even in the absence of magnetic field as shown in Fig. 1.2. The elements Fe, Ni, and Co and many of their alloys are typical ferromagnetic materials. Two distinct characteristics of ferromagnetic materials are their (1) spontaneous magnetization and, (2) the existence of magnetic ordering temperature [18].

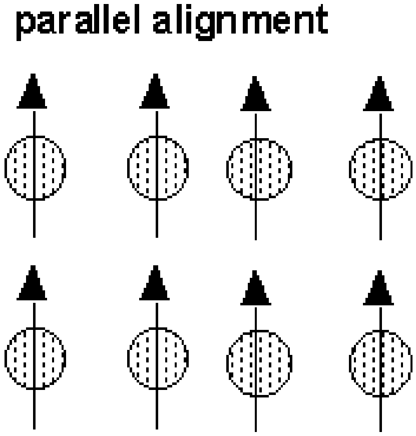

Figure 1.2: Ferromagnetism [18].

1.3.1 Spontaneous Magnetization:

The spontaneous magnetization is the net magnetization that exists inside a uniformly magnetized microscopic volume in the absence of a field. The magnitude of this magnetization, at 0 K, is dependent on the spin magnetic moments of electrons. A related term is the saturation magnetization which can be measured in a laboratory. The saturation magnetization is the maximum induced magnetic moment that can be obtained in a magnetic field (H_{sat}); beyond this field no further increase in magnetization occurs as shown in Fig. 1.3.

The difference between spontaneous magnetization and the saturation magnetization has to do with magnetic domains. Saturation magnetization is an intrinsic property, independent on particle size but dependent on temperature [18].

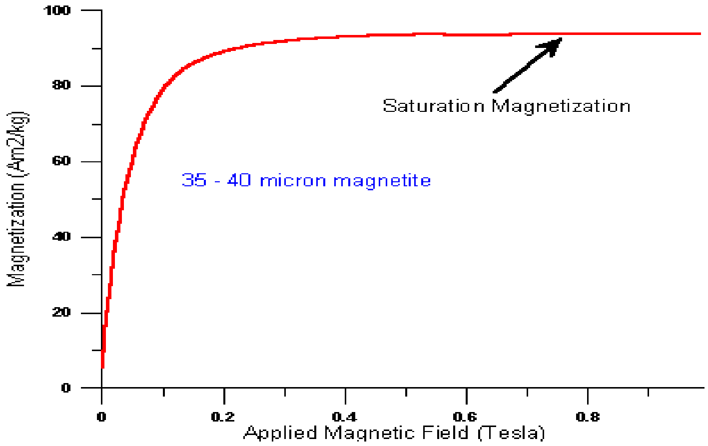

Figure 1.3: Saturation magnetization [18].

1.3.2 Curie Temperature:

Even though electronic exchange forces in ferromagnetism are very large, thermal energy eventually overcomes the exchange and produces a randomizing effect. This occurs at a particular temperature called the Curie temperature T_c. Below the Curie temperature, the ferromagnetism is ordered and above it, disordered. The saturation magnetization goes to zero at the Curie temperature. A typical plot of magnetization versus temperature for magnetite is shown in Fig.1.4 below. The Curie temperature is also an intrinsic property and is a diagnostic parameter that can be used for mineral identification. However, it is not foolproof because different magnetic minerals, in principle, can have the same Curie temperature [18].

1.3.3 Hysteresis:

In addition to the Curie temperature and saturation magnetization, ferromagnetism can retain a memory of an applied field once it is removed. This behavior is called hysteresis

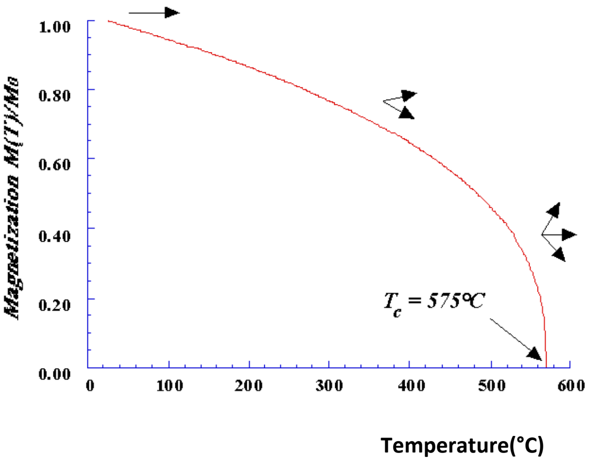

Figure 1.4: magnetization versus temperature for magnetite (Fe_3O_4) [18].

and a plot of the variation of magnetization with magnetic field is called a hysteresis loop as shown in Fig. 1.5 [18]. Another hysteresis property is the coercivity of remanence (H_r). This is the reverse field which, when applied and then removed, reduces the saturation remanence to zero. It is always larger than the coercive force. The various hysteresis parameters are not solely intrinsic properties but are dependent on grain size, domain state, stresses, and temperature. Because hysteresis parameters are dependent on grain size, they are useful for magnetic grain sizing of natural samples [18].

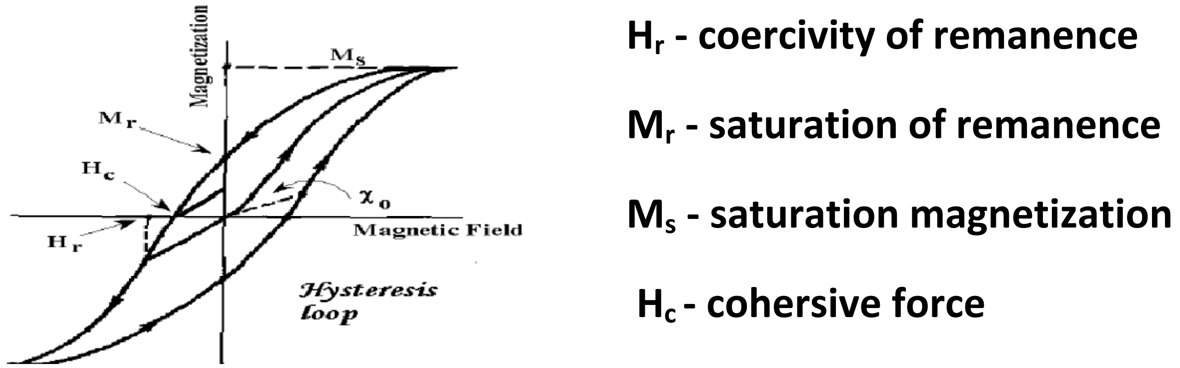

Figure 1.5: Hysteresis [18].

1.4 Ferrimagnetism

In ionic compounds, such as oxides, more complex forms of magnetic ordering can occur as a result of the crystal structure. One type of magnetic ordering is called ferrimagnetism. A simple representation of the magnetic spins in a ferrimagnetic oxide is shown here in Fig. 1.6. The magnetic structure is composed of two magnetic sub lattices (called A and B) separated by oxygen. The exchange interactions are mediated by the oxygen anions. When this happens, the interactions are called indirect or super exchange interactions. The strongest super exchange interactions result in an anti-parallel alignment of spins between the A and B sublattice. In ferrimagnetism, the magnetic moments of the A and B sublattices are not equal and result in a net magnetic moment. Ferrimagnetism is therefore similar to ferromagnetism. It exhibits all the hallmarks of ferromagnetic behavior-spontaneous magnetization, Curie temperatures, hysteresis, and remanence. However, ferromagnetism and ferrimagnetism have very different magnetic ordering. Magnetite is a well known ferrimagnetic material. Indeed, magnetite was considered a ferromagnetic until *Néel* in the 1940's, provided the theoretical framework for understanding ferrimagnetism [18].

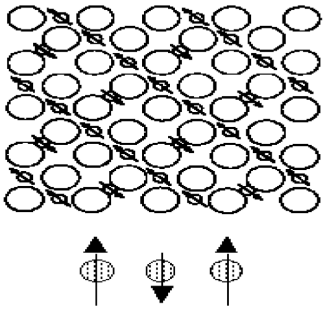

Figure 1.6: Ferrimagnetism [18].

1.5 Antiferromagnetism

If the A and B sublattice moments are exactly equal but opposite, the net moment is zero. This type of magnetic ordering is called antiferromagnetism as shown in Fig. 1.7.

The clue to antiferromagnetism is the behavior of susceptibility (χ) above a critical

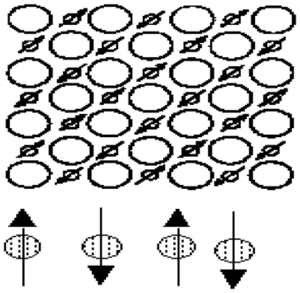

Figure 1.7: Antiferromagnetism [18].

temperature, called the *Néel* temperature (T_N) as shown in Fig. 1.8 . Above T_N, the susceptibility obeys the Curie-Weiss law ($\chi = \frac{C}{T-T_c}$); $T_c = C\lambda$ for paramagnets but with a negative intercept indicating negative exchange interactions. (λ-is a constant independent of temperature) [18].

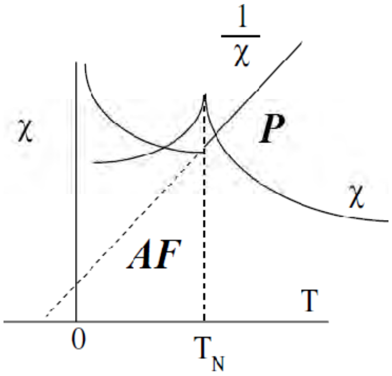

Figure 1.8: susceptibility (χ) versus temperature (T) [18].

Chapter 2

Traditional Semiconductors

The main factors that determine basic properties (e.g., optical and electrical properties) of semiconductors are related to the chemical composition and the (crystallographic) structure, the presence of various defects and impurities (both intentional and unintentional), and the dimensions of the semiconductor or semiconductor structure (i.e., related to the quantum confinement regime). The chemical composition and the (crystallographic) structure determine the electronic band structure (e.g., the magnitude and the type of energy gap, and the carrier effective mass), which has the major influence on the semiconductor properties [19]. The electrical conductivity of semiconductors can be varied (in both sign and magnitude) widely as a function of (i) impurity content (e.g., doping), (ii) temperature (i.e., thermal excitation), (iii) optical excitation (i.e., excitation with photons having energies greater than the energy gap, E_g), and (iv) excess charge carrier injection (e.g., in semiconductor devices). It is this capability of controlling the electrical conductivity in semiconductors that offers myriad applications of these materials in a wide variety of electronic and optoelectronic devices [19].

2.1 Semiconductor Crystals

2.1.1 Intrinsic Conductivity

Carrier concentrations representative of metals, semimetals, and semiconductors are shown in Fig. 2.1. Semiconductors are generally classified by their electrical resistivity at room temperature, with values in the range of 10^{-2} to 10^{9} ohm-cm, and strongly dependent on temperature. At absolute zero a pure, perfect crystal of most semiconductors will be an insulator, if we arbitrarily define an insulator as having a resistivity above 10^{14} ohm-cm [20]. Devices based on semiconductors include transistors, switches, diodes, photovoltaic cells, detectors, and thermistors. These may be used as single circuit elements or as components of integrated circuits.

Some useful nomenclature:

Semiconductor compounds of chemical formula AB, where A is a trivalent element and B is a pentavalent element, are called III-V (three-five) compounds. Examples are indium antimonide and gallium arsenide. When A is divalent and B is hexavalent, the compound is called a II-VI compound. Examples are zinc sulfide and cadmium sulfide. Silicon and germanium are sometimes called diamond-type semiconductors, because they have the crystal structure of diamond. Diamond itself is more an insulator rather than a semiconductor. Silicon carbide SiC is a IV-IV compound [20]. In semiconductors, the energy

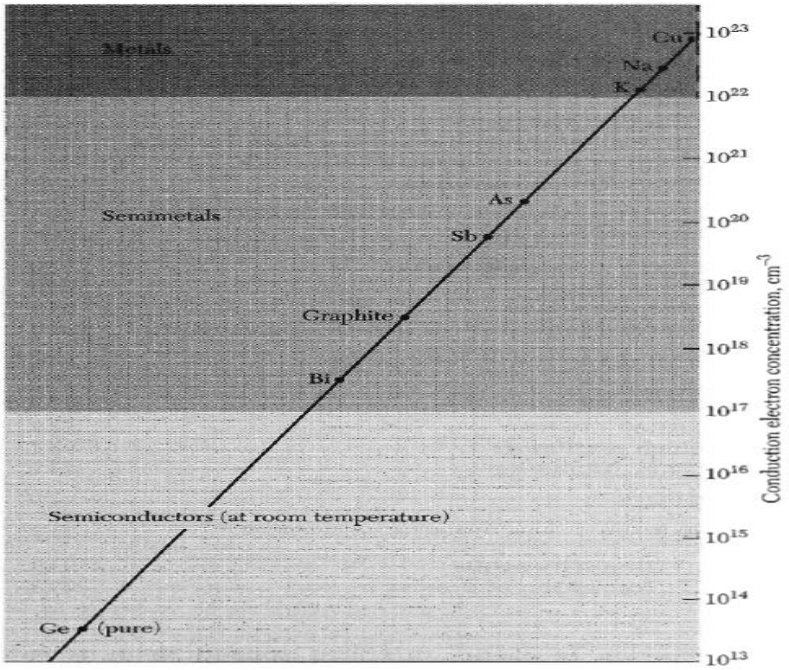

Figure 2.1: Carrier concentrations for metals, semimetals, and semiconductors. The semiconductor range may be extended upward by increasing the impurity concentration and the range can be extended downward to merge eventually with the insulator range [20].

gap is sufficiently small, so that at room temperature the electrons from the top of the valence band are thermally excited to the conduction band, where they can contribute to the carrier transport in a material. In insulators, the energy gap is so much greater (as compared to semiconductors) that at room temperature the probability of thermal excitation of an electron from the valence band to the conduction band is very low. In Fig. 2.2, the Fermi energy, or Fermi level defines the reference energy for the probability of occupation of electron states. Thus, in metals Fermi level is located within a partially filled allowed band, whereas in semiconductors and insulators Fermi level is positioned within the forbidden band [19].

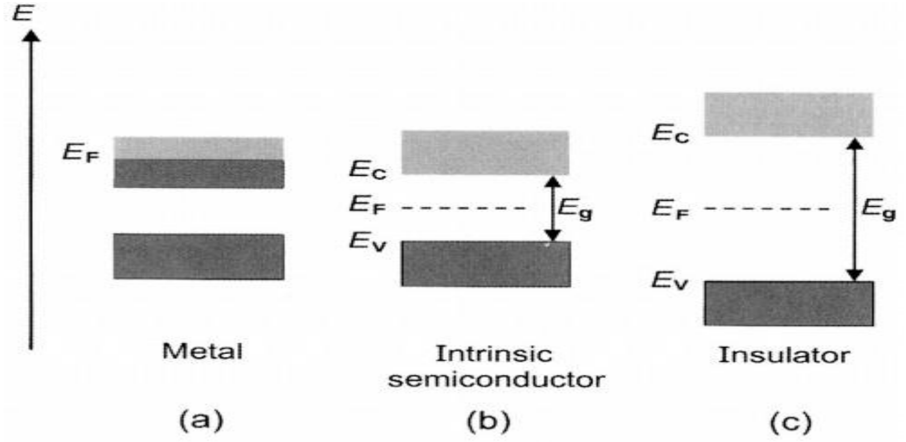

Figure 2.2: Schematic illustration of typical band diagram for (a) a metal, (b) an intrinsic semiconductor ($T = 0K$), and (c) an insulator [19].

In Fig. 2.2 dashed lines represent the Fermi level; darker regions represent filled bands, whereas lighter regions correspond to the empty bands [19]. A highly purified semiconductor exhibits intrinsic conductivity, as distinguished from the impurity conductivity of less pure specimens. In the intrinsic temperature range the electrical properties of a semiconductor are not essentially modified by impurities in the crystal. An electronic band scheme leading to intrinsic conductivity is indicated in Fig. 2.4. The conduction band is vacant at absolute zero and is separated by an energy gap, E_g from the filled valence band [20].

At 0 K the conductivity is zero because all states in valence band are filled and all the states in the conduction band are vacant. As the temperature is increased, electrons are thermally excited from the valence band to the conduction band, where they become

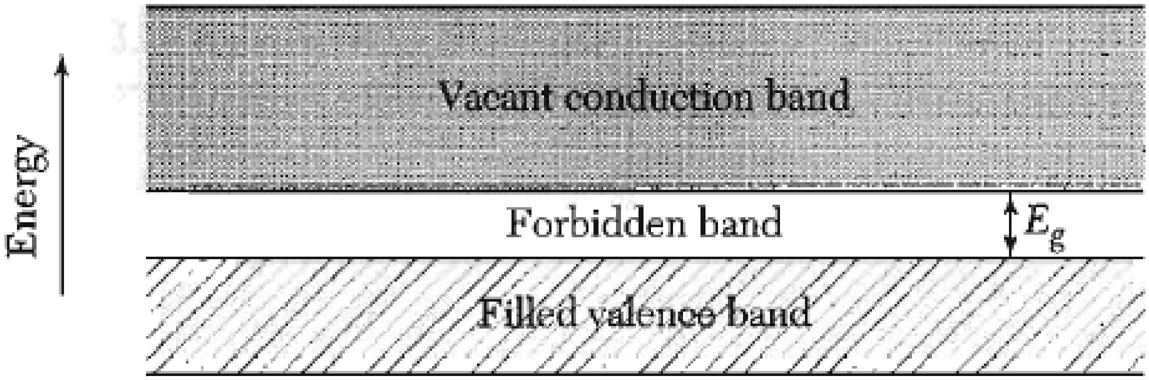

Figure 2.3: Band scheme for intrinsic conductivity in a semiconductor [19].

mobile. Such carriers are called "intrinsic". The band gap is the difference in energy between the lowest point of the conduction band and the highest point of the valence band. The lowest point in the conduction band is called the conduction band edge; the highest point in the valence band is called the valence band edge. As the temperature is increased, electrons are thermally excited from the valence band to the conduction band. Both the electrons in the conduction band and the vacant orbital or holes left behind in the valence band contribute to the electrical conductivity [20].

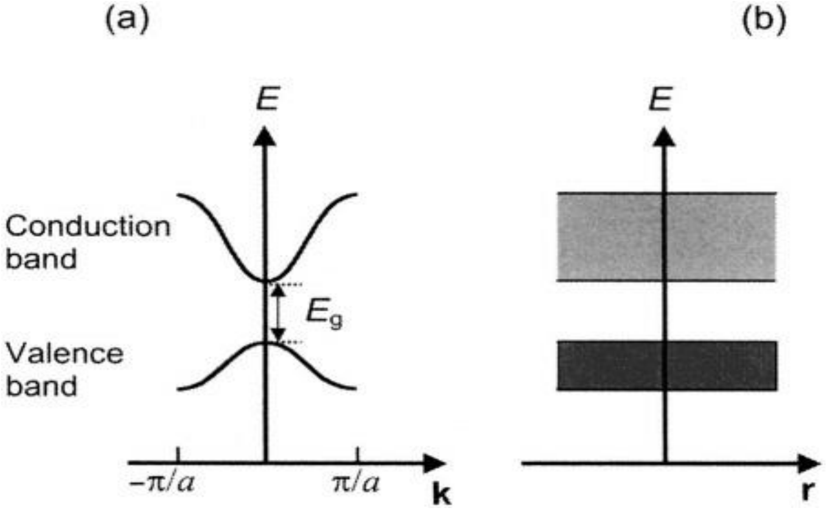

Figure 2.4: Schematic diagram of the electronic energy bands in (a) k-space (the reduced-zone representation) and (b) in real space as a function of r [19].

Band Gap

The intrinsic conductivity and intrinsic carrier concentrations are largely controlled by $\frac{E_g}{k_B T}$, the ratio of the band gap to the temperature. When this ratio is large, the concentration of intrinsic carriers will be low and the conductivity will be low [20]. The density of states of electrons ($D_e(\varepsilon)$) in 3D and Fermi-Dirac distribution function (f_e) are given by,

$$D_e(\varepsilon) = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{\frac{3}{2}}(\varepsilon - E_c)^{\frac{1}{2}} \tag{2.1.1}$$

and

$$f_e \cong \exp\left(\frac{\mu - \varepsilon}{K_B T}\right). \tag{2.1.2}$$

The concentration of electrons (n) in the conduction band is then given by,

$$n = \int_{E_c}^{\infty} D_e(\varepsilon) f_e(\varepsilon) d\varepsilon = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{\frac{3}{2}} exp\left(\frac{\mu}{k_B T}\right)\int_{E_c}^{\infty}(\varepsilon - E_c) exp\left(\frac{-\varepsilon}{k_B T}\right) d\varepsilon. \tag{2.1.3}$$

which integrates to give

$$n = 2\left(\frac{m_e^* k_B T}{2\pi\hbar^2}\right)^{\frac{3}{2}} \exp\left(\frac{\mu - E_c}{k_B T}\right). \tag{2.1.4}$$

In a similar way, the density of hole states ($D_h(\varepsilon)$) and the Fermi-Dirac distribution function (f_h) are given by,

$$D_h(\varepsilon) = \frac{1}{2\pi^2}\left(\frac{2m_h^*}{\hbar^2}\right)^{\frac{3}{2}}\left(E_v - \varepsilon\right)^{\frac{1}{2}} \tag{2.1.5}$$

and

$$f_h \cong \exp\left(\frac{\varepsilon - \mu}{k_B T}\right); \tag{2.1.6}$$

where E_v is the energy at the valence band edge.

Therefore,

$$p = \int_{-\infty}^{E_v} D_h(\varepsilon) f_h(\varepsilon) d\varepsilon = 2\left(\frac{m_h^* K_B T}{2\pi\hbar^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_v - \mu}{k_B T}\right) \tag{2.1.7}$$

for the concentration p of holes in the valence band. For the intrinsic semiconductors the electrons concentration in the conduction band is equal the hole concentration in the valence band. This leads to the carrier concentration (n_i)

$$(n_i) = n = p = 2\left(\frac{k_B T}{(2\pi\hbar^2)(m_e^* m_h^*)^{\frac{3}{4}}}\right)^{\frac{3}{4}} \exp\left(\frac{E_g}{2k_B T}\right). \tag{2.1.8}$$

This last equation is carriers concentration for the intrinsic semiconductors [20].

2.1.2 Impurity or Extrinsic Conductivity

Certain impurities and imperfections drastically affect the electrical properties of a semiconductor. The addition of boron to silicon in the proportion of 1 boron atom to 10^5 silicon atoms increases the conductivity of pure silicon at room temperature by a factor of 1000. In a compound a stoichiometric deficiency of one constituent will act as an impurity; such semiconductors are known as deficit semiconductors. The deliberate addition of impurities to a semiconductor is called doping. We consider the effect of impurities in silicon and germanium. These elements crystallize in the diamond structure. Each atom forms four covalent bonds, one with each of its nearest neighbors, corresponding to the chemical valence four. If an impurity atom of valence five, such as phosphorus, arsenic, or antimony, is substituted in the lattice in place of a normal atom, there will be one valence electron from the impurity atom left over after the four covalent bonds are established with the nearest neighbors, that is, after the impurity atom has been accommodated in the structure with as little disturbance as possible. Impurity atoms that can give up an electron are called donors [20].

Donor States:

The structure in Fig. 2.5 has a positive charge on the impurity atom (which has lost one electron). Lattice constant studies have verified that the pentavalent impurities enter the lattice by substitution for normal atoms, and not in interstitial positions. The crystal as a whole remains neutral because the electron remains in the crystal. The extra electron moves in the coulomb potential $\frac{e}{\varepsilon r}$ of the impurity ion, where ε in a covalent crystal is the static dielectric constant of the medium. The factor $\frac{1}{\varepsilon}$ takes account of the reduction in the coulomb force between charges caused by the electronic polarization of the medium. This treatment is valid for orbits large in comparison with the distance between atoms, and for slow motions of the electron such that the orbital frequency is low in comparison with the frequency (ω_g) corresponding to the energy gap. These conditions are satisfied quite well in Ge and Si by the donor electron of P, As, or Sb [20].

Arsenic has five valence electrons, but silicon has only four valence electrons. Thus four electrons on the arsenic form tetrahedral covalent bonds similar to silicon, and the

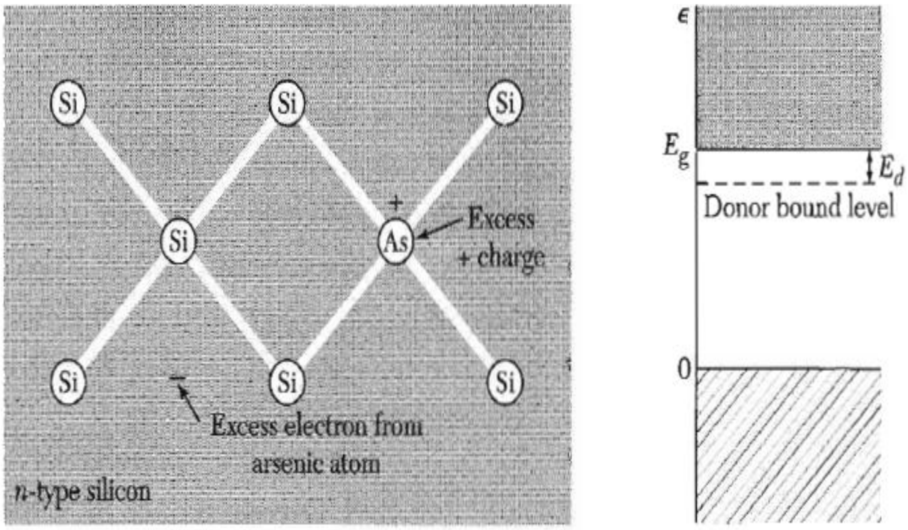

Figure 2.5: Charges associated with an arsenic impurity atom in silicon [20].

fifth electron is available for conduction. The arsenic atom is called a donor because when ionized it donates an electron to the conduction band.

Acceptor States:

A hole may be bound to a trivalent impurity in germanium or silicon, just as an electron is bound to a pentavalent impurity. Trivalent impurities such as B, Al, Ga, and In are called acceptors because they accept electrons from the valence band in order to complete the covalent bonds with neighbor atoms, leaving holes in the band. The semiconductor can conduct in the impurity band by electrons hopping from donor to donor. The process of impurity band conduction sets in at lower donor concentration levels if there are also some acceptor atoms present, so that some of the donors are always ionized. It is easier for a donor electron to hop to an ionized (unoccupied) donor than to an occupied donor atom, in order that two electrons will not have to occupy the same site during charge transport [20].

Boron has only three valence electrons; it can complete its tetrahedral bonds only by taking an electron from a Si-Si bond, leaving behind a hole in the silicon valence band as shown in Fig. 3.1. The positive hole is then available for conduction. The boron atom is called an acceptor because when ionized it accepts an electron from the valence [20].

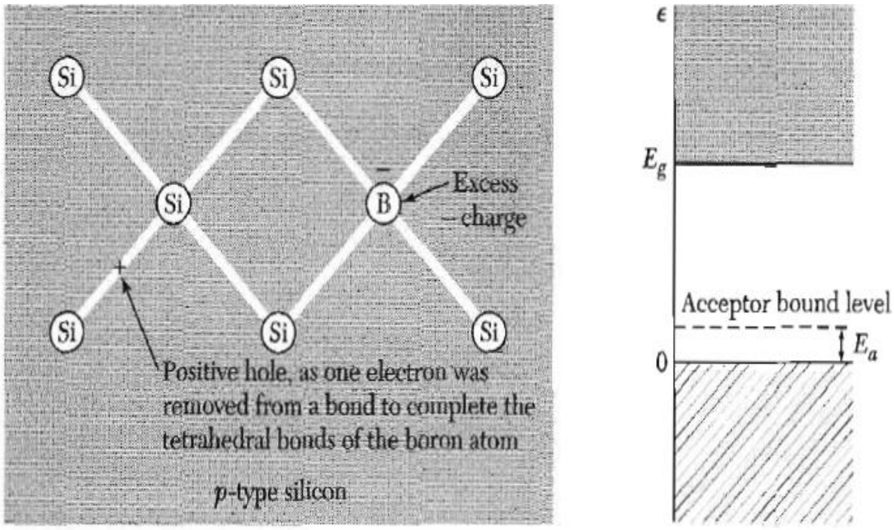

Figure 2.6: Charges associated with a boron impurity atom in silicon [20].

2.2 Applications of Semiconductors

The main applications of semiconductors in various devices are related to the effects produced by the controlled addition (to a semiconductor material) of dopants that facilitate the formation of built-in electric fields and corresponding junction devices. A wide range of semiconductor devices based on such junctions are typically employed as rectifying elements (e.g., p-n diodes), or as parts in various transistors that can be employed as current (or voltage) controlled switches and amplifiers in microelectronics technology, or as optoelectronic devices that are employed in photonics technology. In the p-n junction, the depletion region and the internal (built-in) potential are formed, resulting in a rectifying diode characteristic, which allows the flow of electrical current in one direction but not in the another depending on the forward-bias or reverse-bias conditions of such a device as shown in Fig. 2.7. This behavior of the p-n junction is employed in various electronic device applications. Other junctions include metal-semiconductor junctions (or Schottky barriers), and heterojunctions that are formed between two dissimilar semiconductors. The important properties of heterostructures are related to their ability to control the carrier transport by controlling the energy barriers and potential variations and their ability to confine the optical radiation, which is especially important in optoelectronic devices. The two main types of transistors are bipolar junction transistors (BJTs) and field effect transistors (FETs). These are extensively employed in computer technology as fast on-off switches, or in devices for amplification of a current or voltage. The light-emitting devices employ radiative recombination of injected minority carriers with the majority carriers and subsequent emission of light from the forward-biased junction. In such devices, the energy gap of a semiconductor determines the energy (or wavelength) of the emitted photon, and the availability of a wide variety of semiconductors with appropriate energy gaps makes such devices suitable for the emission of light in the desired wavelength ranges. The photodiode is a semiconductor device that produces a photocurrent in response to absorbed incident optical power. Unlike light-emitting devices that are forward biased, in order to make these devices more sensitive and faster, semiconductor junctions in photodiodes are reverse biased [19].

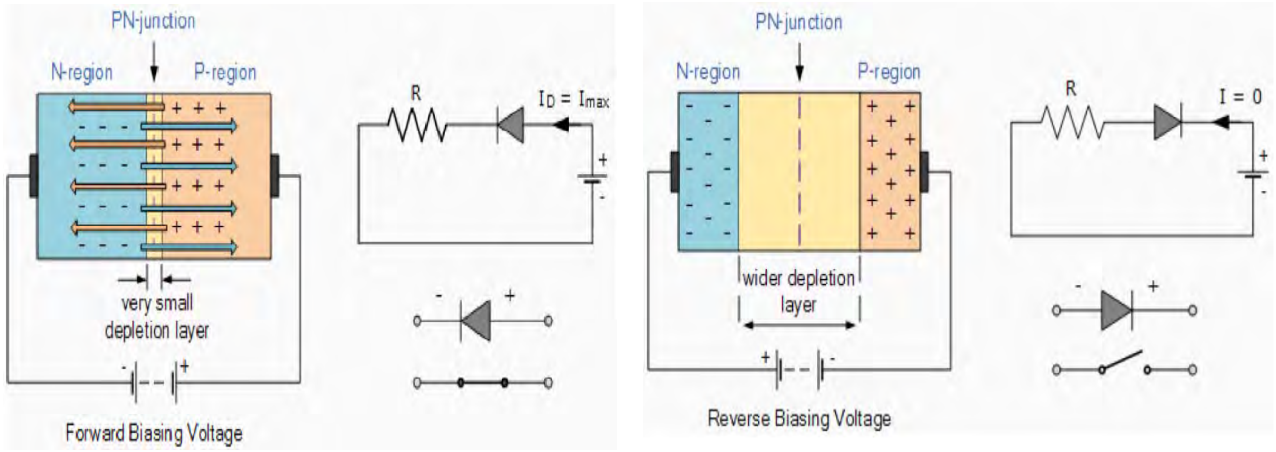

Figure 2.7: The p-n junctions; the two main types of transistors, BJTs and FETs, are extensively employed in computer technology as fast on-off switches, or in devices for amplification of a current or voltage [21].

Chapter 3

Diluted Magnetic Semiconductors

Diluted magnetic semiconductors (DMSs) have been of much interest and have been studied actively for the purpose of the use of both charge and spin of electrons in semiconductors. Spin injection into nonmagnetic semiconductors was tried by many research groups due to the potential to create new classes of spintronics devices. Previous efforts were focused on the direct electrical injection of spin polarized electrons using a ferromagnetic metal-coated on metal-semiconductor junction [22]. DMSs are semiconductors in which transition-metal ions substitute cations of the host semiconductor materials as shown in Fig. 3.1. Localized d electrons of the magnetic ions couple with the extended electrons in the semiconducting band. These couplings lead to a number of peculiar and interesting properties, such as magneto-optical and magneto-electrical effects [23]. Dietl et al [24, 25] suggested GaN and ZnO as candidates having a high T_c and a large magnetization, and lately a few experimental results were reported [26, 27, 28, 29, 30]. $Zn_{1-x}Co_xO$ is interesting not only in terms of its room temperature ferromagnetism [15], but also in its ferromagnetic transport properties. In addition, Sato et al [31] suggested theoretically that the ferromagnetic state in Mn-, Fe-, Co-, and Ni- doped ZnO-DMS can be stabilized.

The materials challenge is great because both magnetic and electronic doping is required, and the interaction between magnetic dopant spins and free carriers must be engineered to achieve thermally robust dopant spin carrier coupling [32]. Magnetism and semiconducting properties are known to coexist in some ferromagnetic semiconductors, such as europium chalcogenides and ferrimagnetic or ferromagnetic semiconducting spinels [33]. The first DMSs to be identified were II-VI semiconductor alloys like

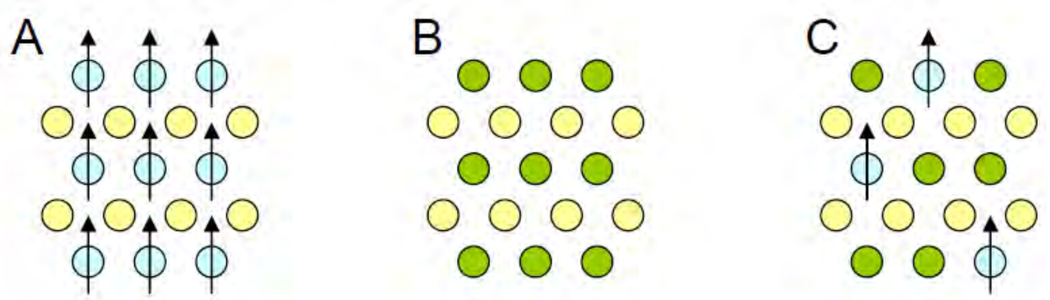

Figure 3.1: Schematic showing (A) a magnetic semiconductor, (B) a non-magnetic semiconductor, and (C) a diluted magnetic semiconductor [34].

$Zn_{1-x}Mn_xTe$ and $Cd_{1-x}Mn_xTe$ [35]. They were studied in the 1980s, presenting either spinglass behavior or weak ferromagnetism, with Curie temperatures (T_c) of only a few $\boldsymbol{K}$ [36] and therefore, completely inadequate for applications requiring ferromagnetic order at room temperature (RT). More recently, the Mn-doped III-V semiconductors $In_{1-x}Mn_xAs$ [37, 38] and $Ga_{1-x}Mn_xAs$ [39] showed ferromagnetism at higher temperature. A T_c of 173 K was achieved in Mn-doped GaAs by using low temperature annealing techniques which is quite promising [40], although still too low for the envisaged room temperature applications. In all these materials ferromagnetism has been proven to be carrier mediated, which enables the modification of magnetic behavior through charge manipulation. This has motivated a continuous search for materials with even higher T_c and carrier mediated ferromagnetism, and led to the conjecture that oxide-based DMS would be key materials in the development of spintronic devices. Indeed, it was pointed out that the capability of high electron doping and the rather heavy effective electron mass of oxide semiconductors could be quite efficient to realize high Curie temperatures [41]. Moreover, most of the foreseen oxide based DMSs are wide band gap semiconductors ($> 3eV$) which can add an optoelectronic dimension to the new generation of spintronic devices. The groundbreaking was the discovery of room temperature ferromagnetism in the $Co : TiO_2$ system by Matsumoto et al [42, 43], which has triggered a considerable number of investigations in other oxide-based DMS such as TM-doped ZnO [44], SnO_2 [45], Cu_2O [46] and $In_{1.8}Sn_{0.2}O_3$ [47]. Table 3.1 summarizes the magnetic moments and T_c values reported in literature for thin films of these oxide-based DMSs.

Table 3.1: Some reports on high T_c oxide based DMS [48] .

Material	Doping(x)	Moment ($\mu_B/3d$ ion)	$T_c(K)$
TiO_2	$Co, 1-2\%$	0.3	> 300
	$Co, 7\%$	1.4	$650-700$
	$V, 5\%$	4.2	> 400
	$Fe, 2\%$	2.4	> 300
ZnO	$Co, 10\%$	2.0	$280-300$
	$V, 15\%$	0.5	> 350
	$Mn, 2.2\%$	0.16	> 300
	$Fe, 5\% - Cu, 1\%$	0.75	550
	Ni,0.9%	0.06	> 300
SnO_2	$Co, 5\%$	7.5	650
	$Fe, 5\%$	1.8	610
Cu_2O	$Co, 5\% - Al, 0.5\%$	0.2	> 300
$In_{1.8}Sn_{0.2}O_3$	$Mn, 5\%$	0.8	> 300

3.1 Applications of DMS

Since the discovery of the giant magnetoresistance (GMR) in 1988 in thin film structures consisting of alternating ferromagnetic and nonmagnetic layers, increasing efforts have been made to combine the spin and charge degrees of freedom of the electrons in commercial microelectronic elements. Utilizing the electron's spin combined with, or without its charge has the potential advantage of non-volatility, increased data processing speed, decreased electric power consumption, and increased integration densities compared with conventional semiconductor based integrated circuits. The proposed multifunctional spintronic device concepts envisions spin field effect transistors with ultra low power use, magnetic diodes with gain, integrated reprogrammable logic and memory chips and light emitting spin diodes with polarized output [17].

The spin-electronics also called spintronics, is where the spin of an electron is controlled by an external magnetic field and polarize the electrons. These polarized electrons are used to control the electric current. The goal of spintronics is to develop a semiconductor that can manipulate the magnetism of an electron. Once we add the spin degree of freedom to electronics, it will provide significant versatility and functionality to future electronic products. Magnetic spin properties of electrons are used in many applications such as magnetic memory, magneticrecording (read, write heads), etc. [49].

Therealizationof semiconductors that are ferromagnetic above room temperature will potentially lead to anewgeneration of spintronic devices withrevolutionary electrical andoptical properties. The field of spintronics was born in thelate 1980s with the discovery of the"giant magnetoresistance effect". The giant magnetoresistance (GMR) effect occurs when a magnetic field is used to align the spin of electrons in the material, inducing a large change in the resistance of a material. Anew generation of miniature electronic devices like computer chips, light-emitting devices for displays, and sensors to detect radiation, air pollutants, light and magnetic fieldsare possible with the new generation of spintronic materials [49].

In electronic devices, informationis storedandtransmitted by theflowof electricity inthe form of negatively charged subatomic particles calledelectrons. The zeroesand ones of computer binary code are represented by thepresence or absence of electrons within asemiconductor or other material. In spintronics, information is storedand transmittedusinganother property of electronscalled spin. Spin is the intrinsic angular momentumof anelectron, each electron actslikeatiny bar magnet, like a compass needle, that pointseither up or downto represent thespinof an electron. Electrons moving through anonmagnetic material normally have random spins, so the net effect is zero. External magnetic fieldscanbe applied so that the spins are aligned (all up or alldown), allowing a new wayto store binary data in the formof ones (all spins up) and zeroes (all spins down). The effect was first discovered in a device made of multiple layers of electrically conducting materials: alternating magnetic and nonmagnetic layers. The device was known as a "spin valve" because when a magnetic field was applied to the device, the spin of its electrons went from all up toall down, changing its resistanceso that the device acted like avalve to increase or decrease the flow ofelectricalcurrent, called spin Valves [49]. In the spin-FET shown in Fig. 3.3 source and drain constitute dilute magnetic semiconductor, connected by a narrow semiconductor channel. The spins of electrons injected into the semiconductor, are set parallel to the magnetization source. Thus, from its source to the drain spin-polarized current flows if the drain and source are magnetized in one direction. In the spin-LED spin-polarized carriers are injected from the contact, combined with composite materials such as nanowires $Ga_{1-x}Mn_xN$. Spin-LED can be used to transmit information using the spin-codes. Emitting light of a certain polarization depending on the orientation of the spin, spin-LED allows you to encode the information carried by polarized light. The first scheme of spintronics device based on the metal oxide semiconductor technology was the first field effect spin transistor proposed in 1989 by Suprio Datta and Biswajit Das of Purdue University.

In their device, a structuremade from indium-aluminum-arsenide and Indium-gallium-arsenide, as shown in Fig. 3.2, provides a channel for two dimensional electron transport between two ferromagnetic electrodes. One electrode acts as an emitter and the other as a collector. The emitter emits electrons with their spins oriented along the direction of electrodes magnetization, while the collector acts as a spin filter and accepts electrons with the same spin only. In the absence of any change to the spins during transport, every emitted electron enters the collector [49].

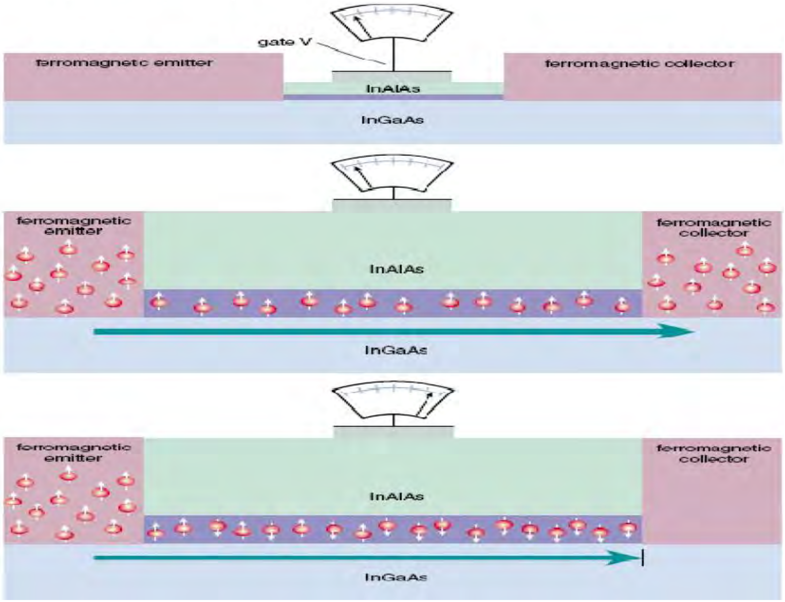

Figure 3.2: Datta-Das spin transistor was the first spintronic device to be proposed for fabrication in a metal-oxide-semiconductor geometry familiar in conventional microelectronics [50].

Datta-Das spin transistor was the first spintronic device to be proposed for fabrication in a metal-oxide-semiconductor geometry familiar in conventional microelectronics. An electrode made of a ferromagnetic material (purple) emitsspin-aligned electrons (red spheres), which pass through a narrow channel (blue) controlled by the gate electrode(gold) and arecollected by another ferromagnetic electrode (top). With the gate voltage off, the aligned spins pass through the channel and are collected at theotherside (middle). With the gate voltage on, the field produces magnetic interaction that causes the spins to precess, like spinning tops in a gravity field. If the spins are not aligned with the direction of magnetization of the collector, no current can pass. In this way, the emitter-collector current is modulated by the gate electrode. As yet, no convincinglysuccessfulapplication of this proposal has been demonstrated [50].

Spintronic Devices:

Recording devices, such as computer hard disks, already employ the unique properties of magnetic materials. Data are recorded and stored as tiny areas of magnetized iron or chromium oxides. A "read head" can read this information by detecting minute changes in the magnetic field as the disk rotates underneath it. This induces changes in the heads electrical resistance also known as magnetoresistance. Spintronic devices, also known as magnetoelectronics, are expected to become the ideal memory media for computing and main operating media for future quantum computing. The first widely acknowledged breakthrough in Spintronics was the use of GMR, used in read heads of most hard drives already mentioned above. A popular device that exploits the Spintronics is, for example, the Apple iPod 60 GB. Measuring a little more than half an inch in thickness, this pocket filling device has a spintronics based read head [51, 52]. Recent discovery of tunneling magnetoresistance (TMR) has led to the idea of a magnetic tunnel junction that has been utilized for the MRAM (Magnetic Random Access Memory). Here, one has two magnetic layers separated by an insulating metal-oxide layer. Electrons are able to tunnel from one layer to the other only when magnetization of the layers are aligned in the same direction. The resistance is otherwise very high, in fact, 1000 times higher than in the standard GMR devices, known as spin valves. spintronic devices, combining the advantages of magnetic materials and semiconductors, are expected to be fast, non-volatile and consume less power. They are smaller than 100 nanometers in size, more versatile and more robust than the conventional ones making up silicon chips and circuit elements [53, 54].

Why Spintronics?

The miniaturization of microelectronic components by roughly a factor of 40 has taken place from the early days of integrated circuits, starting around 1970. Over this time, microelectronics has advanced from the first integrated circuits to present day computer chips containing 100 million transistors. It is now well recognized that further shrinking of the physical size of semiconductor electronics will soon approach a fundamental barrier. The fundamental physical laws that govern the behavior of transistors will preclude them from being shrunk any further and packed in even greater number on computer chips. The continual shrinking of transistors will result in various problems related to electric current leakage, power consumption and heat [51].

On the other hand, miniaturization of semiconductor electronic devices is making device engineers and physicists feel the looming presence of quantum mechanics a brilliant physics concept developed in the last century where counter intuitive ideas such as wavelike behavior, is more dominant for particles such as the electron. Electron spin is, after all, a quantum phenomenon. Many experts agree that spintronics, combined with nanotechnology would offer the best possible solution to the problems associated with miniaturization mentioned above. Nanoscience and nanotechnology involve the study of extremely tiny devices and related phenomena on a spatial scale of less than one-thousandth the diameter of a human hair or roughly half the diameter of a DNA molecule [51].

Semiconductor Spintronics:

Inspite of the rapid advances in metal-based spintronics devices (such as GMR devices), a major focus for researchers has been to find novel ways to generate and utilize spin-polarized currents in semiconductors. These include the investigation of spin-transport in semiconductors and the exploration of possibilities for making semiconductors function as spin polarizers and spin valves. This is important because semiconductor-based Spintronics devices can easily be integrated with traditional semiconductor technology; they also can serve as multi-functional devices. Further, spins in semiconductors can be more easily manipulated and controlled. Visionaries claim a merger of electronics, photonics, and magnetics will provide novel spin-based multi-functional devices such as spin-FETs (field-effect transistors), spin-LEDs (light-emitting diodes), spin-RTDs (resonant tunneling devices), optical switches operating at tera hertz frequencies, modulators, quantum computation, etc., just to name a few. The progress in these developments of course, crucially depends on our understanding and control of the spin degrees of freedom in semiconductors, semiconductor heterostructures, and ferromagnets [51].

Spin transistor:

The basic idea of a spin transistor, as proposed by Suprio Datta and Biswajit Das (Purdue University, USA) is to control the spin orientation by applying a gate voltage. A spin-FET, as depicted in Fig. 3.3, consists of ferromagnetic electrodes and a semiconductor channel that contains a layer of electrons and a gate electrode attached to the semiconductor. The source and drain electrodes are ferromagnetic (FM) metals [51].

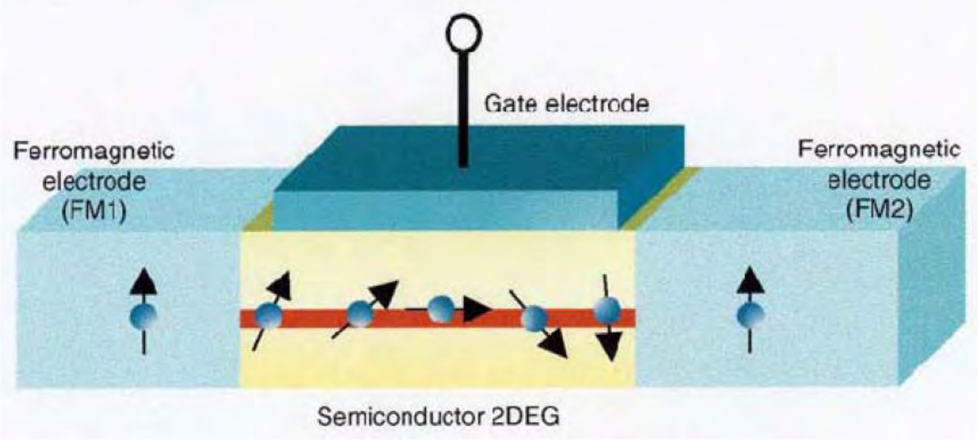

Figure 3.3: Datta-Das spin Transistor [51].

The spin-polarized electrons are injected from the FM source electrode (FM1), and after entering the semiconductor channel they begin to rotate. The rotation is caused by an effect due to spin-orbit coupling that occurs when electrons move through the semiconductor crystal in the presence of an electric field. The rotation can be controlled, in principle, by an applied electric field through the gate electrode. If the spin orientation of the electron channel is aligned to the FM drain electrode, electrons are able to flow in to the FM drain electrode. However, if the spin orientation is flipped in the electron layer (as in the Fig. 3.3), electrons cannot enter the drain electrode (FM2). In this way, with the gate electrode the rotation of the electron spin can be controlled. Therefore, in a spin-FET the current flow is modified by the spin precession angle. Since the spin-FET concept was published in 1990, there has been a world-wide effort to develop such a transistor. The success of such a project crucially depends on efficient injection of spin currents from a ferromagnetic metal into a semiconductor, a seemingly formidable task. Intense research is under way to circumvent this problem by using Ferromagnetic semiconductors such as GaMnAs [51].

Quantum dots: Spin-based computers:

Modern nanofabrication techniques and materials engineering have reached a level where it is now possible to fabricate advanced semiconductor devices at atomic scales. The most remarkable ones are the quantum dots in which electron motion is quantized along all directions and conducting electrons are confined within the nanometer distances [48]. The dots contain typically one to several hundred electrons and experiments have shown effective control over both the charge and spin degree of freedom of these confined electrons. Quantum dots have been found to be very useful as electronic and optical devices such as the quantum dot laser, memory chips, and in quantum cryptography, quantum computer, etc. It has been proposed that the spin of an electron confined to quantum dots can be used as quantum bits and an array of quantum dots could serve as a quantum computer. In principle, a computer that processes the quantum states instead of conventional classical information will be able to solve problems for which there is no efficient classical algorithm. Quantum operations in the quantum dots would be possible by coupling electron spins in neighboring quantum dots. Fundamental understanding of the role of electron spins in quantum-confined structures is crucial in this effort [51].

Chapter 4

Determination of Magnon Energy and Dispersion in Diluted Magnetic Semiconductors

4.1 Spin Waves

Let the low-lying energy states of spin systems (the fractional spin reversal is small), coupled by exchange interactions are wave like, as shown originally by Bloch for ferromagnets. The waves are called spin waves as shown in Fig. 4.1; the energy of a spin wave is quantized, and the unit of energy of a spin wave is called a magnon [56].

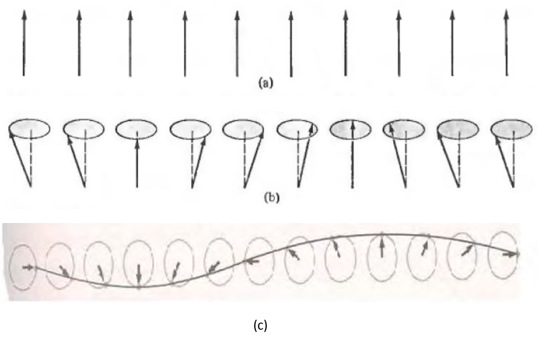

Figure 4.1: Schematic representations of the orientations in a row of spins in (a) the ferromagnetic ground state, (b) a spin wave state (the low-lying elementary excitations are spin waves). The ends of the spin vectors precess on the surface of cones, with successive spins advanced in phase by a constant angle and (c) The spins viewed from above showing one wave length. The wave is drawn through the ends of the spin vectors [20, 55, 56].

4.2 The Model Hamiltonian

Let the Heisenberg ferromagnetic interaction Hamiltonian $\hat{H}$ in the presence of small external magnetic field $H^{'}$ in the z-direction be written as [56, 57, 58],

$$\hat{H} = -\sum_{ij} J_{ij} S_i S_j - g\mu_B H^{'} \sum_i S_i^z \quad , \tag{4.2.1}$$

where S_i and S_j are the spins at the lattice sites i and j respectively, each of magnitude S in units of $\hbar$ and g is Landé g factor, μ_B is the Bhor magneton; J_{ij} is the exchange integral which is positive for ferromagnetic ordering. The Hamiltonian $\hat{H}$ describes diluted magnetic semiconductor which is known to show ferromagnetism experimentally brought by holes interaction with Mn ion. By use of Holstein-Primakoff transformation, and replacing the spin with boson creation and annihilation operators an attempt can be done to transform the spin problem to a many-body interaction [59].
The transformations are:

$$S_i^+ = S_{ix} + iS_{iy} = (2S)^{\frac{1}{2}}[1 - \frac{a_i^+ a_i}{2S}]^{\frac{1}{2}} a_i \quad , \tag{4.2.2}$$

$$S_i^- = S_{ix} - iS_{iy} = (2S)^{\frac{1}{2}} a_i^+ [1 - \frac{a_i^+ a_i}{2S}]^{\frac{1}{2}} \quad , \tag{4.2.3}$$

$$S_i^z = S - a_i^+ a_i \quad . \tag{4.2.4}$$

It is possible to verify that the definitions $S^{\pm}$ gives the correct commutation relations $[S_x, S_y] = iS_z$ if the boson commutation relations $[a, a^+] = 1$ are obeyed on the given lattice site since the system is periodic, and looking for excitations, which can be characterized by a well-defined momentum (crystal momentum) $\boldsymbol{k}$, so defining the Fourier variables as,

$$a_i = \frac{1}{\sqrt{N}} \sum_k e^{-ik.r} b_k \ ; \qquad a_i^+ = \frac{1}{\sqrt{N}} \sum_k e^{ik.r} b_k^+ \ ; \tag{4.2.5}$$

where the Fourier transformation variables also satisfy the bosonic relations $[b_k, b_k^+] = \delta_{kk'}$, ... e.t.c. We possibly see that the operators b_k^+ and b_k create and destroy a magnon or spin-wave excitations of the ferromagnet. These turn out to be excitations where the spins locally deviate only a small amount from their ground state value as the "spin wave" passes by. Holstein and Primakoff therefore suggested expanding the nasty (unpleasant) square root in equations (4.2.2) and (4.2.3), that gives:

$$S_i^+ = (2S)^{\frac{1}{2}}[a_i - \frac{a_i^+ a_i a_i}{4S} + ...] = ((2S)^{\frac{1}{2}})\left[1 - \frac{a_i^+ a_i}{4S} + ...\right] a_i \ . \tag{4.2.6}$$

Note that the expansion is formally an expansion in $\frac{1}{S}$. Substituting for a_i from eq. (4.2.5) and considering low temperature excitations it reduces to:

$$S_i^+ = (2S)^{\frac{1}{2}} a_i = \left(\frac{2S}{N}\right)^{\frac{1}{2}} \sum_k e^{-ik.r_i} b_k \ . \tag{4.2.7}$$

similarly,

$$S_i^- = (2S)^{\frac{1}{2}} a_i^+ = \left(\frac{2S}{N}\right)^{\frac{1}{2}} \sum_k e^{ik.r_i} b_k^+ \ , \tag{4.2.8}$$

and

$$S_j^+ = (2S)^{\frac{1}{2}} a_j = \left(\frac{2S}{N}\right)^{\frac{1}{2}} \sum_k e^{-ik.r_j} b_k \ , \tag{4.2.9}$$

$$S_j^- = (2S)^{\frac{1}{2}} a_j^+ = \left(\frac{2S}{N}\right)^{\frac{1}{2}} \sum_k e^{ik.r_j} b_k^+ \ , \tag{4.2.10}$$

$$S_i^z = S - a_i^+ a_i = S - \frac{1}{N} \sum_{k,k'} e^{i(k-k')r_i} b_k^+ b_{k'} \ , \tag{4.2.11}$$

$$S_j^z = S - a_j^+ a_j = S - \frac{1}{N} \sum_{k,k'} e^{i(k-k')r_j} b_k^+ b_{k'} \ , \tag{4.2.12}$$

where a_i and a_j are taken for convenience to be as k' dependent. But,

$$S = S_x \hat{\imath} + S_y \hat{\jmath} + S_z \hat{k} \ . \tag{4.2.13}$$

From equations (4.2.2) and (4.2.3), we can find S_x and S_y as:

$$S_x = \frac{S^+ + S^-}{2} \ , \tag{4.2.14}$$

$$S_y = \frac{S^+ - S^-}{2i} \ , \tag{4.2.15}$$

$$S = \left(\frac{S^+ + S^-}{2}\right)\hat{\imath} + \left(\frac{S^+ - S^-}{2i}\right)\hat{\jmath} + S_z \hat{k} \ , \tag{4.2.16}$$

where

$$S_i = \left(\frac{S_i^+ + S_i^-}{2}\right)\hat{\imath} + \left(\frac{S_i^+ - S_i^-}{2i}\right)\hat{\jmath} + S_i^z \hat{k} \ , \tag{4.2.17}$$

and

$$S_j = \left(\frac{S_j^+ + S_j^-}{2}\right)\hat{\jmath} + \left(\frac{S_j^+ - S_j^-}{2i}\right)\hat{\jmath} + S_j^z \hat{k} \ , \tag{4.2.18}$$

and

$$\begin{aligned} S_i.S_j &= \left[\left(\frac{S_i^+ + S_i^-}{2}\right)\hat{i} + \left(\frac{S_i^+ - S_i^-}{2i}\right)\hat{j} + S_i^z\hat{k}\right].\left[\left(\frac{S_j^+ + S_j^-}{2}\right)\hat{i} + \left(\frac{S_j^+ - S_j^-}{2i}\right)\hat{j} + S_j^z\hat{k}\right], \\ &= \frac{1}{2}\left(S_i^+S_j^- + S_i^-S_j^+\right) + S_i^zS_j^z \ . \qquad (4.2.19) \end{aligned}$$

Substituting equation (4.2.19) in equation (4.2.1) we get;

$$\hat{H} = -\sum_{ij} J_{ij}[\frac{1}{2}(S_i^+S_j^- + S_i^-S_j^+) + S_i^zS_j^z] - g\mu_B H' \sum_i S_i^z \qquad (4.2.20)$$

and again substituting eq. (4.2.7)- (4.2.13) in eq. (4.2.20), for S^+, S^- and S

$$\hat{H} = -\sum_{ij} J_{ij}S^2 - \sum_{ij} J_{ij}S\left[a_i^+a_j + a_ia_j^+ - a_i^+a_i - a_j^+a_j + a_i^+a_ia_j^+a_j\right] - g\mu_B H' \sum_i S_i + g\mu_B H' \sum_i a_i^+a_i \qquad (4.2.21)$$

where the first term in this equation is energy of the ground state, and the terms in the square bracket are operators expressing explicitly the handing on of spin deviations from one site to the next. The term of order $a_i^+a_ia_j^+a_j$ is ignored by the reason in eq. (4.2.6). Therefore, denoting the sum of this energy by H_0;
i.e, $H_0 = -\sum_{ij} J_{ij}S^2 - g\mu_B H' \sum_i S_i$ and substituting eq. (4.2.5) in to eq. (4.2.21) we get,

$$\begin{aligned} \hat{H} - H_0 = \hat{H}_{magnon} = -\sum_{ilkk'} \frac{J(l)S}{N}&\left[e^{-i(k-k').r_i}e^{ik'.l}b_kb_{k'}^+ + e^{i(k-k')r_i}e^{-ik'.l}b_k^+b_{k'}\right. \\ &\left. -e^{i(k-k').r_i}b_k^+b_{k'} - e^{-i(k-k').r_i}b_k^+b_{k'}\right] + \frac{g\mu_B H'}{N}\sum_{ikk'} e^{i(k-k')r_i}b_k^+b_{k'} \ . \qquad (4.2.22) \end{aligned}$$

At $k' = k$, equation (4.2.22) can be reduced to

$$\hat{H}_{magnon} = -\sum_l J(l)ZS \sum_k \left[\gamma_k b_kb_k^+ + \gamma_{-k}b_k^+b_k - 2b_k^+b_k\right] + g\mu_B H'^{\sum_k b_k^+b_k} \qquad (4.2.23)$$

$$\begin{aligned} \hat{H}_{magnon} &= -\sum_l J(l)ZS \sum_k \left[\gamma_k(1 + b_k^+b_k) + \gamma_{-k}b_k^+b_k - 2b_k^+b_k\right] + g\mu_B H'^{\sum_k b_k^+b_k} \\ &= -\sum_l J(l)ZS \sum_k \gamma_k - \sum_l J(l)ZS \sum_k \left[\gamma_k b_k^+b_k + \gamma_{-k}b_k^+b_k - 2b_k^+b_k\right] + g\mu_B H'^{\sum_k b_k^+b_k} \\ &= -\sum_l J(l)ZS \sum_k \left[\gamma_k(b_k^+b_k + b_k^+b_k) - 2b_k^+b_k\right] + g\mu_B H'^{\sum_k b_k^+b_k} \qquad (4.2.24) \end{aligned}$$

Noting that $\sum_l \gamma_k = 0$ and $\gamma_k = \gamma_{-k}$ if there is a center of symmetry [57]. And

$$\begin{aligned}\hat{H}_{magnon} &= -\sum_l J(l)ZS\sum_k\Big[\gamma_k(2b_k^+b_k - 2b_k^+b_k\Big] + g\mu_B H^{'\sum_k b_k^+ b_k} \\ &= -\sum_l 2J(l)ZS\sum_k\Big[(\gamma_k - 1)b_k^+b_k\Big] + g\mu_B H^{'\sum_k b_k^+ b_k} \qquad (4.2.25)\end{aligned}$$

where,

$$\gamma_k = \frac{1}{Z}\sum_\ell e^{ik.l} \;\; and \;\; \gamma_{-k} = \frac{1}{Z}\sum_\ell e^{-ik.l}\ . \qquad (4.2.26)$$

which is the dispersion function depending only on the positions of the nearest neighbor spin in the approximation for lattice with inversion symmetry and $\gamma_k = \gamma_{-k}$. From equation (4.2.23), the term with $g\mu_B H^{'}$ can be neglected for negligibly small external magnetic field $H^{'}$ and we have put $r_i - r_j = \ell$; $J_{ij} = J(\ell)$ where z-is the number of nearest neighbors (for example $z = 6$ for simple cubic structure); N-total number of spins , $S^z = S$ and $\sum S^Z = NS$

$$\hat{H}_{magnon} = \sum_k\Big[2\sum_l J(\ell)ZS(1-\gamma_k)\Big]b_k^+b_k \qquad (4.2.27)$$

Since the frequency is real in (4.2.26), only the real part of the exponential is retained so that $\gamma_k = \frac{1}{Z}\sum_l cos(k.\ell) \cong \frac{1}{Z}\sum_\ell(1 - \frac{(k.\ell)^2}{2})$ $=1 - \frac{1}{Z}\sum_\ell \frac{(k.\ell)^2}{2}$ by summing over the Z vectors denoted by ℓ which join the center atom to the nearest neighbors. Substituting the value of γ_k in equation (4.2.27), we get

$$\hat{H}_{magnon} = \sum_{k,\ell}(J(\ell)S(k.\ell)^2 b_k^+b_k = \sum_k(JSa^2k^2)b_k^+b_k \qquad (4.2.28)$$

where $\ell \cong a$.

$\cos(k.\ell) = (\cos k_x\ell + \cos k_y\ell + \cos k_z\ell)/3$, by averaging over the three degrees of freedom along x,y and z.

$$\hat{H}_{magnon} = \frac{1}{3}\Big[\sum_{k,\ell} J(\ell)S(k.\ell)^2 b_k^+b_k\Big]. \qquad (4.2.29)$$

For $k.\ell << 1$, equation (4.2.28) can be rewritten as

$$\hat{H}_{magnon} = \sum_k\Big[\frac{1}{3}JS(2k^2a^2)\Big]b_k^+b_k\ , \qquad (4.2.30)$$

where $\sum_\ell(k.\ell)^2 = 2k^2a^2$, having two nearest neighbors. Averaging over the impurities concentration x, where x is the percentage of dopant impurity that replaced the group III elements (i.e, $x = \frac{N_{imp}}{N_{total}}$) in the compound, gives the following :

$$< \hat{H}_{magnon} >=< \sum_k [\frac{2}{3} xJSa^2k^2] b_k^+ b_k > \quad . \tag{4.2.31}$$

under these assumptions, the magnon part of the Hamiltonian can simply be written like a harmonic oscillator or phonon type Hamiltonian;

$$< \hat{H}_{magnon} >= \sum_k n_k \omega_k \quad . \tag{4.2.32}$$

where, $n_k = b_k^+ b_k$ is the number of magnons in state **k**, and

$$\omega_k = \frac{2}{3} xJSa^2k^2 \quad . \tag{4.2.33}$$

is the magnon dispersion for the magnetic impurity concentration x.

4.3 Result and Discussion

Denoting the coefficient of xk^2 by a constant D we can rewrite equation (4.2.33) as $\omega_k = Dxk^2$. The graph of ω_k versus $\boldsymbol{k}$ for $D = 1$ and different values of concentration x is shown in Fig. 4.2 in the first Brillouin zone. From the graph we note that the magnon dispersion increases with increasing concentration x for a fixed value of $\boldsymbol{k}$, and dispersion also increases with increasing wave number $\boldsymbol{k}$ at a fixed value of concentration x. Using equation (4.2.32) the average value of the number of magnons exited in the mode $\boldsymbol{k}$ at thermal equilibrium can be given by the Plank distribution [20, 56] as: $< n_k >= \frac{1}{e^{\beta\hbar\omega_k - 1}}$, where $\beta = \frac{1}{k_BT}$ which would give the total number as,

$$\sum_k n_k = \frac{1}{4\pi^2} \left(\frac{k_BT}{2xJsa^2} \right)^{\frac{3}{2}} \int_0^\infty dy \frac{y^{\frac{1}{2}}}{e^y - 1} = R \left(\frac{k_BT}{2xJsa^2} \right)^{\frac{3}{2}} \tag{4.3.1}$$

where, $R = \frac{1}{4\pi^2} \int_0^\infty dy \frac{y^{\frac{1}{2}}}{e^y - 1} = 0.0587$ and $y = \beta\omega_k\hbar$. This leads to determination of the magnetization using the standard relation,

$$M(T) = M(0) - \frac{g\mu_B}{nS} \Sigma_k n_k = g\mu_B nS - g\mu_B \Sigma_k < n_k >= g\mu_B nS \left(1 - \frac{1}{nS} \Sigma_k < n_k > \right) , \tag{4.3.2}$$

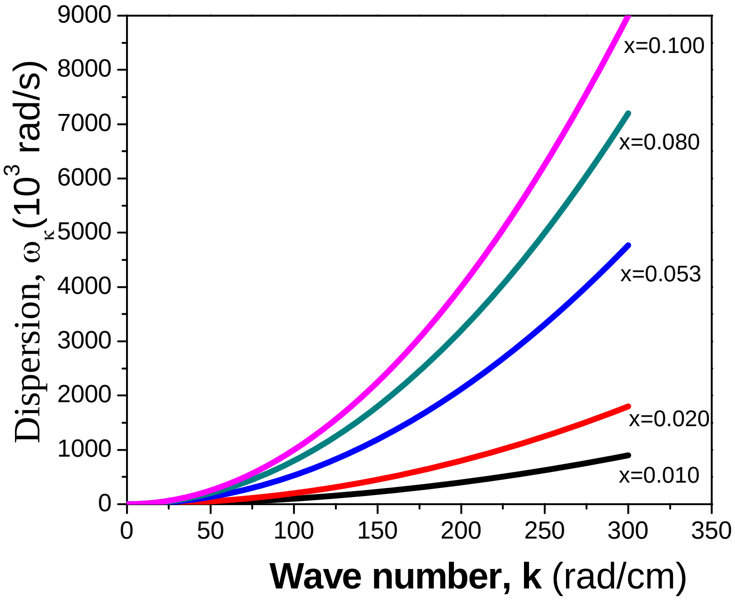

Figure 4.2: Dispersion relation for magnons in a ferromagnet in one dimension with nearest-neighbor interactions.

where, $g\mu_B nS = M(0) = M_s$ which is the saturation magnetization.

Hence,

$$\frac{M(T)}{M(0)} = 1 - \frac{1}{nS}\Sigma_k < n_k >= 1 - \frac{0.0587}{SQ}\left(\frac{k_BT}{2xJS}\right)^{\frac{3}{2}} . \tag{4.3.3}$$

The number of atoms per unit volume (n), $n = Q/a^3$, where Q=1, 2, 4 for sc, bcc, fcc lattices respectively. Now $(\Sigma_k n_k)/nS$ is equal to the fractional change of magnetization $\Delta M(T)/M(0)$, whence [20].

$$\frac{\Delta M(T)}{M(0)} = \frac{0.0587}{SQ}\left(\frac{k_BT}{2xJS}\right)^{\frac{3}{2}} , \tag{4.3.4}$$

which gives the Bloch's $T^{3/2}$ law and has been confirmed experimentally [20]. Equation (4.3.4) can be rewritten as equation (4.3.5) below to show the variation of fractional change of magnetization with impurity concentration x.

$$\frac{\Delta M(T)}{M(0)} = (constant)\left(\frac{T}{x}\right)^{\frac{3}{2}} . \tag{4.3.5}$$

Denoting the coefficient of $\left(\frac{T}{x}\right)^{\frac{3}{2}}$ by a constant $(say, constant = 1)$, we can plot the graph of fractional change of magnetization, $\frac{\Delta M(T)}{M(0)}$ versus temperature (T) to show the variation of fractional change of magnetization with impurity concentration x as shown in Fig. 4.3. It is clear from this Fig. that, increasing impurity concentration x at a fixed temperature decreases the fractional change of magnetization, $\frac{\Delta M(T)}{M(0)} = 1 - \frac{M(T)}{M(0)}$. The decrease in $\frac{\Delta M(T)}{M(0)}$ confirms the increase in $M(T)$ which increases with increasing concentration x.

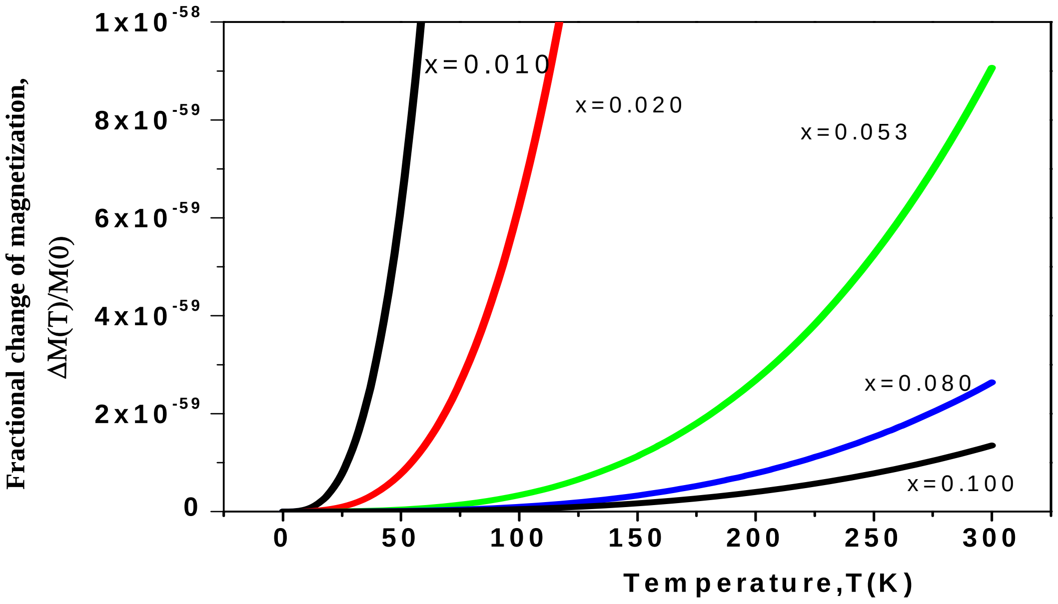

Figure 4.3: $\frac{\Delta M(T)}{M(0)}$ versus temperature (T) in K.

The spin of electrons in spin-polarized diluted magnetic semiconductors give additional degree of freedom for storage and information transfer in microelectronics. This is possible if the ferromagnetic property is maintained in the semiconductor at room temperature and above by spin polarized electrons that preserve their polarization throughout the semiconductor material for the achievement of practical spintronic devices. The increase of magnetic ions as impurity in a nonmagnetic semiconductor, however, increases the dispersion (ω_k) of the spin wave (magnon). Moreover, the increase in ferromagnetic ion concentration x decreases the fractional change of magnetization and increases the magnetization of the DMSs. The increase in the magnon dispersion, also increases the temperature of the spin wave. The increase in temperature on the other hand, depolarizes the spin-polarized electrons and, therefore, this challenges the success of the proposed spintronic devices by Datta-Das due to the lose of information in a very short time at the hetro-junctions at the collector electrode. The above challenges will be solved if DMSs work at room temperature in a single crystal to overcome the injection and detection of spin-polarized electrons at the hetro-interfaces which results in data lose at the interfaces due to the large mismatch in the Fermi levels at the interfaces.

Chapter 5

Conclusion

The finding of diluted magnetic semiconductors is significant in the sense that it opens up a completely new paradigm for next generation microelectronics which takes advantages of the spin properties in addition to the charge transport property. The material will be really useful if it works at room temperature. Our findings also indicate that the dispersion and magnetization would enhance with increment of impurity concentration whereas the fractional change of magnetization decreases, at constant temperature. The most fundamental challenges in the realization of practical spintronic devices address the achievement of sufficiently long spin lifetimes, injection of spin-polarized carriers at the hetro-interfaces and the detection of spin coherence in nanoscale structures, which are preferably compatible with the fabrication methods and well understood semiconductor compounds applied nowadays in microelectronics industry; and it is still formidable task [60].

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DECLARATION

I hereby declare that this M.Sc dissertation is my original work and has not been presented for a degree in any other universities, and that all sources of material used for the dissertation have been duly acknowledged.

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Signature: ____________________

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Signature: ____________________

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