CHAPTER 1

INTRODUCTION

1.1: Magnetic Materials

This project mainly deals with the characterization of a magnetic particle system. Let us focus on some basics of magnetism. In this chapter different types of magnetism will be discussed and the materials that were encountered in this research (magnetite) will be given corresponding reference. Finally, this chapter will conclude with a discussion on the actual method of particle synthesis and how it was modified for use in this project. Important magnetic properties that are relevant to this work will be explained. In this chapter current magnetic particle systems will be discussed and the usage of composite particles of this research in similar applications.

Magnetic Basics

The response of a material when subjected to an external magnetic field is the root of magnetism. The spinning electrons in the material behave like tiny magnets. These tiny magnets are aligned in the direction of applied magnetic field and thereby the material is magnetized. First let us define certain basic magnetic properties. An applied magnetic field \( H \) incites a response from a
material called magnetic induction $B$. The relationship between $B$ and $H$ can be defined by equation 1-1.1,

$$B = \mu_0 H + \mu_0 I \quad (1-1.1)$$

Where $I$ is the magnetic moment per unit volume.

$\mu_0$ is a constant called the permeability of free space. There are also common terms for ratios between some of these different quantities because the magnetic properties of a material are often defined by how they vary with an applied magnetic field. So, the ratio of $I$ to $H$ is called the susceptibility and is indicative of the ease with which a material can be magnetized by an applied magnetic field. Equation 1-1.3 gives the definition of susceptibility

$$\chi = \frac{I}{H} \quad (1-1.3)$$

The ratio of $B$ to $H$ is called the permeability and it is the property of the material which allows magnetic lines of force (field) to penetrate the material. Equation 1-1.4 defines magnetic permeability.

$$\mu = \frac{B}{H} \quad (1-1.4)$$

From equation 1-1.3 and 1-1.4 we can derive a relationship between the susceptibility and the permeability,

$$\frac{\mu}{\mu_0} = 1 + \chi \quad (1-1.5)$$
The following section describes the different types of magnetism and will reference these properties, so it is important to keep them and their relationships with each other in mind.

1.2: Types of Magnetic Materials

The orbital and spin motion of electrons and interaction between these electrons is the origin of magnetism. Different types of magnetic materials are due to differences in their response to external magnetic fields. Some materials are much more magnetic than others. The reason is in some materials there is a strong interaction between the atomic magnets, whereas in other materials there is no interaction between the atomic magnets. Depending upon the magnetic behavior of materials, they can be classified into the following five major groups:

1. DIAMAGNETIC SUBSTANCES

2. PARAMAGNETIC SUBSTANCES

3. FERRO MAGNETIC SUBSTANCES

4. FERRI MAGNETIC SUBSTANCES

5. ANTI FERRO MAGNETIC SUBSTANCES
Diamagnetism

Diamagnetism is a weak magnetism and is the fundamental property of all matter. Diamagnetism is mainly due to the non-cooperative behavior of the orbital electrons under the application of external magnetic field. In diamagnetic substances, all the atoms have paired electrons and there are no unpaired electrons in the shells. Thus the net magnetic moment of the atom of a diamagnetic substance is zero. However, when an external magnetic field is applied on these substances, these materials are magnetized opposite to the field direction. Thus they have negative magnetization. That means for diamagnetic substances the susceptibility is negative. If we plot \( M \) vs. \( H \), we see:

Figure 1.2.1: Plot of \( M \) vs. \( H \) for diamagnetism
From the above plot it can be understood that the magnetization is zero when the applied is zero. The other characteristic behavior of diamagnetic substances is that their susceptibility is independent of temperature.

**Paramagnetism**

In these materials, the atoms or ions have unpaired electrons in partially filled orbitals. That means each atom in a paramagnetic substance has a small net magnetic moment. But, there is no interaction between these atomic magnets. In the presence of an external magnetic field there will be a partial alignment of these atomic magnetic moments in the direction of applied magnetic field resulting in a net positive magnetization and positive susceptibility. When the applied field is zero, the magnetization also becomes zero.

![Paramagnetism](image)

Figure 1.2.2: Plot of M vs. H for paramagnetism
If the temperature of the paramagnetic substance increases, then alignment of the atomic magnets will be disturbed. That means the magnetic susceptibility depends on temperature. The magnetic susceptibility of is inversely proportional to the absolute temperature. This law is called curies law.

When a moderate magnetic field is applied on a paramagnetic substance, at room temperature, then the susceptibility is inversely proportional to the absolute temperature. But, still it is greater than the susceptibility of a diamagnetic substance. If the temperature of a paramagnetic substance is brought to a low temperature(<<100K) or the magnetic applied on the substance is very high, then the susceptibility of the paramagnetic substance does not depend on the applied magnetic field. In such situation, the susceptibility of the paramagnetic substance depends on the total iron content in the substance. At room temperature, most of the minerals containing iron are paramagnetic.

The Para magnetism of the matrix minerals in natural samples can be significant if the concentration of magnetite is very small. In this case, a paramagnetic correction may be needed.
Superparamagnetism

Superparamagnetism is an interesting phenomenon that comes into play when ferromagnetic or ferromagnetic particles become very small. At particle sizes of about 10 nanometers, these materials begin to exhibit paramagnetic behavior, even when they are below their curie temperature. This is because, below curie temperature, the thermal agitations are not strong enough. The interaction forces between the individual atoms dominate the thermal agitations. But, the thermal agitations succeed in changing the direction of magnetization of the entire particle. As a result, the directions of magnetic moments of the particles in the crystal are arranged randomly. Thus the net magnetic moment is zero.

This phenomenon gives rise to the limitation of how small magnetic recording media can get because superparamagnetism will cause the particles to lose their memory from thermal influences. Superparamagnetic particles are therefore often used in many magnetic systems in the biomedical field because not only are they small, but they also do not retain any magnetic remanence. The latter reason is important because it means that the particles will not aggregate due to magnetic forces, however the trade-off is that the particles are paramagnetic in behavior and therefore it is more difficult to achieve a high magnetization. For these reasons, this research aimed to use particles that were in the size range of a few hundred nanometers, thus allowing them to retain their ferromagnetic properties yet still be small enough.
to flow through blood capillaries if necessary. As we will see in the experimental chapter, the particles are very soft magnets and have only a small remnant magnetization.

**Ferromagnetism**

When we think of magnetic materials, the most common materials that come into our mind are iron, nickel, and magnetite. These are generally called ferromagnetic substances. In these substances, there exists a strong interaction between the atomic magnets. These interaction forces are exchange type of forces. The interaction force between the atoms is due to exchange of electrons. The exchange type of forces are very large and are of magnitude 1000 Tesla. This strength is almost $10^8$ times the strength of the earth’s magnetic field. Atomic magnets are aligned parallel to each other under the influence of these exchange forces.

A spinning electron behaves as a tiny magnet. In ferromagnetic materials, the spins of the two neighboring electrons are oriented such that a strong interaction develops between the atoms containing these electrons. This is a quantum mechanical effect. That’s the reason why these atomic magnets
are aligned parallel to each other, even in the absence of external, magnetic field.

The peculiar characteristics of ferromagnetic materials are

a) Spontaneous magnetization

b) Critical temperature (also called Curie temperature)

Figure 1.2.3: parallel alignment in ferromagnetism

Spontaneous Magnetization

The net magnetization existing in a uniformly magnetized microscopic volume under the absence of external magnetic field. The magnitude
of spontaneous magnetization depends on the spin magnetic moments of spinning electrons.

The measurable property corresponding to spontaneous magnetization is saturation magnetization. The saturation magnetization is the maximum, induced magnetic moment that can be induced by a magnetic field ($H_{sat}$); beyond this field there will be no further increase in the magnetization.

The difference between spontaneous magnetization and the saturation magnetization has to do something with magnetic domains. Saturation magnetization is an intrinsic property, that is independent of particle size but is dependent on temperature. Paramagnetic susceptibility is slightly greater than 1 and is positive but, ferromagnetic susceptibility is high and positive. When compared with paramagnetic materials, the magnetization in ferromagnetic materials is going to be saturated in moderate magnetic fields, at high (room-temperature) temperatures:
In ferromagnetic substances, at a particular temperature called Curie temperature, thermal agitations overcome the electronic exchange interaction energy between the atomic magnets. This produces a randomizing effect. Above Curie temperature, the ferromagnet is disordered. But below Curie temperature, it is ordered. The saturation magnetization becomes zero at the Curie temperature. Fig 1.2.4 shows a graph between the magnetization and applied magnetic field.

The Curie temperature is an intrinsic and characteristic property of the given substance. Curie temperature helps us in identifying the minerals...
present in the given sample. But, this method is not a 100% reliable method, because some magnetic materials may have the same Curie temperature.

**Hysteresis**

In addition to the Curie temperature, saturation magnetization, ferromagnets can retain certain amount of magnetism, even after the removal of the applied field. This behavior is called hysteresis and graph between the variation of magnetization with applied magnetic field is called a hysteresis curve. The amount of magnetism remaining in the ferromagnetic sample, when the applied field is zero, is called retentivity. The reverse magnetic field that should be applied on the ferromagnetic sample to reduce the saturation magnetization to zero is called coercivity.

Hysteresis parameters like retentivity and coercivity etc, are not purely intrinsic properties. They depend on the grain size, domain state, stress, temperature. That means these hysteresis parameters are useful in magnetic grain sizing of natural samples.
Ferrimagnetism

In some ionic compounds (certain oxides of Fe) a complex form of magnetic ordering is observed due to crystal structure of those oxides. One such type of magnetic ordering is called ferrimagnetism. A simple orientation of magnetic spins in a ferrimagnetic oxide is shown in Fig 1.2.6.

The magnetic structure in a ferrimagnetic oxide consists of two magnetic sub lattices separated by oxygen. The exchange interaction between the two sub lattices are communicated by oxygen anions and these interactions are called super exchange interactions. As a result of these super exchange interactions the spins of the sub lattices are aligned antiparallel. But, magnetic
moments of sub lattices are not equal. Therefore there will be net magnetic moment.

Ferrimagnetic substance also exhibits spontaneous magnetization, Curie temperature, Hysteresis and Retentivity.

Figure 1.2.6: Magnetic ordering ferromagnetic material

**Antiferromagnetism**

If the magnetic moments of A and B sub lattices shown in figure 1.2.7 are equal in magnitude and opposite in direction, the net magnetic moment is zero. This type of magnetic alignment is called antiferromagnetism.
1.3: Advantages of nano-magnetic materials:

Magnetic nanoparticles have many advantages and applications in the fields of biology and medicine. First, their sizes can be controlled from a few nanometers up to tens of nanometer. These sizes are comparable to those of a cell (10–100 µm), a virus (20–450 nm), a protein, (5–50 nm) and a gene (2 nm wide). These magnetic nano particles have the required size and ability to interact with a given biological entity. Since magnetic nanoparticles have magnetic nature, they obey coulomb’s inverse square law. That means these particles can be made to respond to an external magnetic field. This idea can
be used in the transport and immobilization of, magnetic nanoparticles. In this manner drugs can be delivered to infected regions of the body like cancer tissues, tumors etc. Third, nanoparticles have a large surface area. Chemical and biological agents can be attached to them by modifying their surface area. Nano magnetic particles can also be coated with chemical and biochemical molecules to make them bind to a biological entity. If time varying magnetic fields are applied on nano particle, energy is transferred from the field to the nano particle under resonance condition. As a result of this, the nano particle heats up. This property enables them to be used as hyperthermia agents. They deliver thermal energy to the targeted bodies such as tumors. The above mentioned potential applications are possible in biomedicine due to the novel physical properties the above discussed magnetic nano particles.

1.4 About $\text{Mg}_x\text{Fe}_{(1-x)}\text{O}$

Nano crystalline spinel ferrites have many applications in non-resonant devices, high quality filters, radio frequency circuits, transformer cores, rod antennas, read/write heads for high-speed digital tapes. Because of their potential application capability, they have been investigated intensively from recent past.
**Why MgO doped into Fe₃O₄?**

Between MgO and Fe₃O₄ the lattice mismatch is very small. That is why MgO is ideal substrate for epitaxy of Fe₃O₄. Many investigations have been done on the growth of thin epitaxial films of Fe₃O₄ on MgO substrate using different deposition methods. MgAl₂O₄, Si and GaAs substrates, sapphire substrates can also be used for the growth of Fe₃O₄ thin epitaxial films. The lattice mismatch between the thin epitaxial film and substrate, crystal structure symmetry between thin film and the substrate are the factors on which strain rate of thin epitaxial film depends. In earlier experiments done by some researchers, it is revealed that, when MgO(100) is used as a substrate, the Fe₃O₄ films show a sluggish strain relaxation behavior and these partially above the critical strain relaxation thickness. Even at a thickness of 660 Å, the relaxation was partial. But, till now no effort was made to understand this behavior.

There is a cubic symmetry between the crystal structures of MgO and Fe₃O₄. Both have face centered cubic (FCC) structure with oxygen sub lattice. MgO has rock salt structure with lattice constant of 0.4213 nm. MgO belongs to Fm3m symmetry group. Fe₃O₄ has cubic inverse spinel structure. It’s lattice constant is 0.8397 nm. Fe₃O₄ belongs to Fd3m symmetry. The oxygen sub lattice size differences in the MgO substrate and Fe₃O₄ thin epitaxial film gives causes a small lattice mismatch of 0.33%. There are two different ways of symmetry breaking in Fe₃O₄/MgO heteroepitaxy. The lattice
parameter of MgO is half that of Fe$_3$O$_4$. This leads to translation symmetry disruption. The Fd3m crystal structure of Fe$_3$O$_4$ is low in symmetry than the Fm3m crystal structure in MgO. As a result of this, the unit cell is rotated by 90° about an axis normal to the lattice, but Fe$_3$O$_4$ does not. Therefore antiphase boundaries are formed. The crystal structure differences and differences in the symmetry of MgO and Fe$_3$O$_4$ have made us to look at the strain relaxation behavior of Fe$_3$O$_4$ thin epitaxial films. This information will be very useful for design of future spintronic devices and magnetite based nanostructures.

MgO has a rock salt structure. It’s lattice constant is equal to 4.212 Å. The lattice constant of MgO is nearly equal to half the lattice constant of Fe$_3$O$_4$ (8.3987 Å). Due to this reason antiphase boundaries are formed. During the growth, two adjacent Fe$_3$O$_4$ islands can be shifted by $1/4$h110i or $1/2$h100i has shown in figure 1.4. The other reason for the formation of APB’s is due to the fact that Fe$_3$O$_4$ islands can be rotated with respect to each other by 90°. Here the oxygen sub lattice is continuous and is not disturbed across anti phase boundary. But the cation sub lattice is shift at anti phase boundary. The second reason leading to the formation of APBs, is that the Fe$_3$O$_4$ islands can be rotated with respect to each other by 90°. It is worth noticing here that the oxygen sub lattice is continuous and it is not disturbed across the APB. Only the cations sub lattice is shifted at an APB. Eerenstein et al. have reported that the domain size in Fe$_3$O$_4$ films grown using
molecular beam epitaxy (MBE) decreases with decreasing thickness. The domain size depends, not only on the film thickness, but also from the growth conditions. Higher growth or post annealing temperature favors larger domains, due to the annealing out of the APBs via a diffusive mechanism. High resolution X-ray diffraction (HR-XRD) and transmission electron microscopy (TEM) strain relaxation studies on epitaxial Fe$_3$O$_4$/MgO(001) thin films grown by MBE and magnetron sputtering [18], have shown that the films remain in a fully strained state up to 700 nm. The critical thickness for strain relaxation, in this case, is estimated to be about 70 nm. The anomalous strain relaxation behavior has been attributed to the presence of APBs which by alternating tensile and compressive strains developed within the growth islands and the APBs respectively, account for the anomalous accommodation of the strain in the films.
Properties of magnetic particles depend on their size. That is the reason why they have been used in applications like catalysis, energy storage, high density data storage. Magnetic nanoparticles have wide applications in the field of biotechnology also. These applications are magnetic separation, magnetic resonance imaging and magnetic hyperthermia treatment[17]. Magnetic hyperthermia treatment involves the breakdown of cancer cells at 42 – 45°C. When external magnetic field is applied, the magnetic particles generate heat. The size of magnetic particles and their properties are the parameters on which magnetic heating depends. In magnetic hyperthermia
treatment, magnetite and hematite are best suitable to be used as candidate particles. They have the potential biological compatibility and suitable magnetic properties. It is observed that MgFe$_2$O$_4$ having micrometer size exhibit greater magnetic heating than the other ferrites. Recently it was investigated that magnetic hyperthermia treatment can be combined with a drug delivery system. As a result of this, only cancer tissue can be heated. For this use, the main requirement is, the particle size should be within the limit of 10-100nm.

1.5: Applications of Magnetic nano particle:

The capabilities of creating nano and micro sized particles of magnetite have lead to use of these small magnetic particles in a range of applications. Many studies have been conducted to characterize the magnetic behavior of various sizes of magnetite particles. Because of its useful properties, magnetite has been the material of choice for many magnetic particle systems.

Ferro fluids are an interesting example of such systems. A ferro fluid is basically a colloidal solution of magnetic particles that are suspended in either a polar or non-polar liquid. Magnetite is commonly used as the magnetic material, but iron and cobalt particles have been used as well. The particles are typically on the order of about 10 nanometers so that they are super
paramagnetic. This is so that the fluid remains as stable suspension and the magnetic particles do not aggregate together and form clumps or settle in the absence of a magnetic field. When a magnetic field is applied, however, the particle will respond and are often used as a seal that can be applied or removed with a magnetic field. These fluids have been used in applications such as rotary seals for disk drives and dampers for audio speakers [28].

Recently researchers started showing interest in using ferro fluids for biomedical applications. For this application the fluid must be biocompatible. Such ferro fluid systems have been used for cell sorting. A biological effector is bound to the nano particle surface so that the particle can target specific cells. These cells can be sorted by applying the magnetic field to separate them. This system begins to appear very similar to the system characterized in this thesis because it entails that the magnetic particles are biologically functional. However this one system in particular uses particles of Fe$_2$O$_3$, a material that will not achieve a very high magnetization as compared to system with Fe$_3$O$_4$. In addition, where magnetite is used as the material of choice, the particles are still in the super paramagnetic size range, thus they will still not achieve a high magnetization as compared to larger particles that exhibit ferromagnetic behavior. This is a very important factor that will come into play especially for in vivo applications.
If an external alternating magnetic field is applied on magnetic nano particle, then they start heating up. This is an interesting property. That means these magnetic nano particles can be guided to a tumor. By applying an alternating magnetic field the tumor can be treated via magneto cytolysis. There has been some demonstrated success doing this, however many systems are also trying to incorporate a drug delivery mechanism to additionally treat specific areas of the body. When an oscillating magnetic field is applied, the diffusional release of the drug is increased.

Recent studies have revealed one more application of magnetic nano particles. They can be used as magnetic microspheres. Drugs can be attached to these microspheres for use as targeted drug delivery systems. The drugs can be either chemically or physically associated with these microspheres. In these kinds of applications, the common practice is to coat a cross linked protein or polysaccharide microsphere to microsphere. A large drawback to these systems is that they contain a small volume fraction of magnetic material, and this of course degrades overall magnetic capabilities.

Functional and site-specific magnetic particles are also of great interest to the field of magnetic resonance imaging (MRI). Magnetic particles serve as magnetic contrast agents. They reduce $T_1$ and $T_2$ relaxation times. For better imaging purpose, a contrast agent is necessary. This can be achieved by attaching antibodies to the magnetic particles. MRI just serves as one more
examples of a scientific field that can benefit from functional magnetic particles.

In conclusion, many of the studies of all these kinds of systems are not adequately focused on the magnetic properties of the particles. In many of the applications discussed above, the common difficulty is achieving large magnetization for guidance purposes. This difficulty deteriorates the efficiency of these systems. The main reason for this is due to coating of other materials, high mineral loading is not possible. In one study, particles with 23 to 29 weight percent mineral loading were used and their corresponding magnetization were 20 and 30 emu/gm\[35\. The composite particle system developed in this research, the ratio of magnetite to polymer is high and thereby the particles can achieve high magnetization. The composite particles are not super paramagnetic. That means they can attain a higher magnetization on the basis of intrinsic magnetic properties. In many of the targeted drug delivery systems, the main difficulty is to obtain magnetic force to retain super paramagnetic particles in deep tissues.

It should also be noted that the magnetic particle introduced in this thesis do not need to be limited to in vivo applications. These particles can also be used in targeting and retrieval in environmental applications. For example, we can eliminate anthrax spores. That has spread in a room. A magnetic system such as the one researched in this thesis could target these spores, binds them, and then removes them by retrieving the
particles. This is another example of the utility of these particles. Be it drug delivery or targeted MRI contrast, this new magnetic particle system is an improvement over existing systems and is useful for a wide range of applications.

1.6: Iron Oxide:

Iron oxide (FeO) or ferrous oxide is also known as würzite in its mineral form. As a powder this black oxide can cause explosions as it readily ignites.

* FeO, iron (II) oxide, (würzite)

* Fe₃O₄, iron (II, III) oxide, (magnetite)

* Fe₂O₃, iron (III) oxide, (hematite)

  • α-Fe₂O₃, hematite
  • β- Fe₂O₃
  • γ- Fe₂O₃, maghemite
  • ε- Fe₂O₃

Iron oxide nano particles have super paramagnetic properties and they have potential applications in many fields. Nickel, Cobalt, Copper are highly magnetic, but they are highly toxic and can be oxidized easily. Hence they have
limited applications. The two main forms of iron oxide nano particles, one is $\text{Fe}_3\text{O}_4$ and its oxidized form, maghemite($\gamma$-$\text{Fe}_2\text{O}_3$).

Iron oxide nano particles are used in catalysis, sensors, high sensitivity biomolecular magnetic resonance imaging (MRI), multi-tera bit storage device. In all these applications, the common requirement is the special surface modification of iron oxide nano particles. for this purposes, surface coating agents have to be used. Alkyl amines and long chain fatty acids can be used as surface coating agents. Magnetite and maghemite are bio compatible and non-toxic to human body. Iron oxide is easily degradable.

The particle size, shape, surface chemistry and magnetic properties of nano particles are dependent on the preparation methods of nano materials. In addition to that, structural defects and distribution of structural defects with in the particle are also dependent on the preparation methods. Recently many efforts have been made to prepare "mono dispersed colloids". These colloids consist of nano particles that are uniform both in size and shape.

Iron precursors decompose in the presence of hot organic surfactants. As a result of this, the samples of magnetite iron oxide nano particles are formed with a good size and crystallinity. The particle size plays a very important role in biomedical applications like magnetic resonance imaging, magnetic cell separation. Magnetic nanoparticles produced by the above described method are very useful in the above mentioned biomedical
applications. If iron precursors such as Fe(Cu)$_3$, Fe(CO)$_5$, or Fe(acac)$_3$ are decomposed in organic solvents at high temperature, then highly monodispersed nanoparticles can be produced.

1.7: Crystal Structure of Magnetite:

Magnetite has been used as permanent magnet since ancient times and is the parent of ferrites used in modern magnetic recording and data storage devices. The electronic and magnetic properties of Fe$_3$O$_4$ are due to Fe$^{3+}$ and Fe$^{2+}$ mixed valent character. At room temperature (300K) Fe$_3$O$_4$ is ferromagnetic, metallic and has inverse cubic spinel structure (a=8.394Å). At 120K, it undergoes the Verwey transition at which it becomes insulating. At this transition it undergoes a structural distortion associated with charge ordering [4]. But, the full low temperature structure of Fe$_3$O$_4$ is still not known. The most definitive study was published in 1982 on the basis of 10K single crystal neutron diffraction results.

Magnetite has a cubic inverse spinel structure with oxygen forming a face centered cubic closed packing. In magnetite, Fe$^{3+}$ ions occupy all tetrahedral sites and Fe$^{3+}$ and Fe$^{2+}$ ions occupy octahedral sites. In maghemite, most of iron is in the trivalent state and octahedral sites are copied by cationic vacancies. Maghemite has a cubic unit cell in which each cell contains 32 O ions, 21 1/3 Fe$^{3+}$ ions and 2 1/3 vacancies. In the 8 tetrahedral
and 16 octahedral sites, cations are randomly distributed. Iron atoms acquire large magnetic movement due to the presence of four unpaired electrons in 3d shell. Hence, the crystals formed from iron atoms can be either in ferromagnetic or antiferromagnetic or ferrimagnetic states.

In cubic structure arrangement, the oxygen ions are closely packed. The Fe ions have comparatively small size than oxygen ions. The Fe ions fill the gaps between the oxygen ions. The gaps between oxygen ions occur in two ways.

A) Tetrahedral site

B) Octahedral site

The octahedral site Fe ion is surrounded by six oxygens. In tetrahedral site, Fe ion is surrounded by four oxygens. The tetrahedral sites form the magnetic sub lattice A and the octahedral sites form the magnetic sub lattice B. The spins of sub lattices A and B are aligned anti parallel to each other. As a result of this, a complex form of exchange forces are developed between the Fe ions in the two types of sites mentioned above.
The structural formula for magnetite is given by \([\text{Fe}^{3+}]A[\text{Fe}^{3+}, \text{Fe}^{2+}]B\text{O}_4\). This kind of arrangement of cations on A and B sublattices, is called an inverse spinel structure. With negative AB exchange interactions, the total magnetic moment of magnetite is mainly contributed by the B-site \(\text{Fe}^{2+}\).

1.8. NANO MAGNETIC MATERIALS FOR BIOMEDICAL APPLICATIONS

Magnetic nano particles with sizes ranging from nanometer to one micrometer are used in number of medical applications. Because they are non-toxic, bio compatible, injectable and due to their high level accumulation in the target tissue or organ. Magnetic nano particles have the potential to form self organized films and solids. This feature enables them to offer exciting opportunities at the interface between physic, chemistry and biology. Magnetic
nanoparticles modified with organic molecules have been widely used for biotechnological and biomedical applications.

Magnetic properties of magnetic nano particles can be controlled by applying an external magnetic field even after modifying them with organic molecules. Magnetic nano particles can also be used in biomedical applications like cell separation, automated DNA extraction, gene targeting, drug delivery etc. Magnetic force based tissue engineering is a novel application of magnetic nano particles. Researchers recently are paying their attention towards preparation methods for synthesizing nano particles of uniform size and shape.

Magnetic Nano particles show a high and uniform magnetization throughout the material. The FeCo nanoparticles are soft magnetic materials. When the applied magnetic field’s direction is reversed, they also switch the magnetization direction quickly. This feature makes them ideal for use in high frequency electric circuits like mobile phones. Recently self-organization of FePt magnetic nano particles was discovered. This property makes them suitable for potential application in data storage applications. The storage devices made from these magnetic materials have a high storage density of several tetrabits/cm$^2$. This storage capacity is much better than the most advanced computer hard drives.

CHAPTER-2