1.1 INTRODUCTION TO FERRITES

Ferrites are an important class of magnetic materials which have many applications, ranging from radio frequency and microwave frequency. They can be used in transformers, inductors, antenna rod, memory chip etc. Recently, they have find applications in sensor [1], green anode materials, drug delivery. The most important property of ferrite is its high electrical resistivity, low eddy current and dielectric losses. Ferrites are extremely used in microwave devices, computers, high frequencies, magnetic refrigerators [2, 3].

Ferrites that are used in transformer or electromagnetic cores contain nickel, zinc or manganese compounds. They have a low coercivity and are called as soft ferrites. Because of their comparatively low losses at high frequencies, they are extensively used in the cores of
switched mode power supply (SMPS) and RF transformers and inductors.

Ferrite cores are used in electronic inductors, transformers, and electromagnets where the high electrical resistance of the ferrite leads to very low eddy current losses. They are commonly seen as a lump in a computer cable, called ferrite bead, which helps to prevent high frequency electrical noise, (radio frequency interference) from exiting or entering the equipment.

Early computer memories stored data in the residual magnetic fields of hard ferrite cores which were assumable into arrays of core memory. Ferrite powders are used in coating of magnetic recording tapes. One such type of material is iron (III) oxide.

The magnetically "hard" ferrites are characterized chiefly by their high coercive force, somewhat low remanent induction, and an appreciably lower value of $B_H$ (max) compared with the more conventional metal magnets. They are magnetically very stable and difficult to demagnetize either by external magnetic fields or by mechanical shock.
The electrical resistivity of these materials is very large, frequently exceeding $10^6$ ohm-m. This can be a value in application where a permanent magnet is required to polarize the core of the inductor or transformer carrying alternating fields, for eddy current losses in a ferrite magnet are usually negligible.

From the magnetic point of view of all natural substances may be classified as diamagnetic, paramagnetic or ferromagnetic. The magnetic permeability of the materials in the first two groups however differ so little from that of free space that to the technologist, they are non magnetic but quite different are the ferromagnetic elements, nickel, cobalt and iron, which display magnetism to extraordinary degree with these elements as constituents as a wide range of ferromagnetic alloy of practical importance also may be made through there are some, the Heusler alloys which include only non-ferromagnetic components.

Ferrites are the only relevant magnetic material that can have numerous applications in various field, so extensive work has been carried out to investigate and improve their fundamental properties. Recently there have
been great interests in nano-size ferrites because of their unusual properties, which are different than its bulk counter part.

Ferrites are usually semiconducting ferrimagnetic ceramic compounds derived from iron oxides such a hematite (Fe$_2$O$_3$) or Magnetite (Fe$_2$O$_4$) as well as oxides of other metals. Ferrites are, like most other ceramics, hard and brittle.

In terms of the magnetic properties, ferrites are often classified as "soft" and "hard" which refers to their low or high coercivity of their magnetism respectively.

1.2 HISTORY OF FERRITES

The history of (magnetic oxides) began centuries back with the discovery of stones that would attract iron. The most plentiful deposits of these stones were found in the district of Magnesia in Asia Minor hence the mineral name became magnetite (Fe$_2$O$_4$)

The first application of magnetite was as ‘Lodestones’ to the ancients, the first usable modern ferrite was made in 1946 used by early navigators to locate magnetic north. In
1600 William Gilbert published *De magnetic*, the first scientific study of magnetism. In 1819 Hans Christian Oersted observed that an electric current in a wire affected a magnetic compass needle. With further contribution by Faraday, Maxwell, Hertz and many others, the new science of electromagnetism developed.

Naturally occurring magnetite is a weak hard ferrite. Hard ferrite possesses magnetism which is essentially permanent.

During the 1930's research on soft ferrite continued primarily in Japan and Netherlands. However, it was not until 1945 that J. L. Snoek [4] of the Phillips research laboratories in the Netherlands succeeded in producing a "Soft ferrite" for commercial application.

Ferrites are used predominately in three areas of electronics (i) Low level application (ii) Power application (iii) Electromagnetic interference (EMI) suppression.

The breadth of application of ferrites circuitry continues to grow. The wide range of possible geometries, the continuing improvements in material characteristics and
their relative cost effectiveness make ferrite components the choice for the both conventional and innovative applications.

The study of ferrite comprises a very extensive activity in the field of magnetism. Ferrites are being mixed metallic oxides of high resistivity are members of the semiconductor family. This may be attributed in part to the demand for magnetic materials with low core losses in carrier. Activities in microwave ferrites commenced at a still later date Polder [5] in 1949, first derived the ferrite permeability tensor which lead the groundwork for the understanding of ferrite behavior at microwave frequency. In 1952, Hogan [10] constructed the first workable ferrite microwave gyrator. At the end of 1953 the first commercially available ferrite devices the ‘uniline’ a ferrite loaded waveguide which has different attenuation in the two opposite direction of propagation, appeared in the market. Since then, the study of ferrites has been the subjects of many symposia and of the large number of articles. The study of microwave ferrite has given impetus to the renewal of interest in solid state physics. In recent years, from the study of microwave ferrites, we have gained a better insight into the nature of
the interaction between the electromagnetic wave and the electron spin of the atom in the solid state.

Ferrites are being studied from last 5-6 decades to understand their basic structural, electrical and magnetic properties. Large number of researcher pursues the research on enhancement of properties of ferrite either by introducing variety of cations at tetrahedral (A) site or octahedral [B] site or by changing the method of preparation. Recently, wet chemical methods are being commonly used for the preparation of nano particles of ferrite.

1.3 STRUCTURE OF FERRITE

Ferrites are ceramic ferromagnetic materials with the general chemical formula MO.\( \text{Fe}_2\text{O}_3 \) where M is a divalent metal such as iron, manganese, magnesium, nickel, zinc, cadmium, cobalt, copper, aluminum or a mixture of these, the ferrites crystallize into the spinel structure which is named after the mineral spinel MgAl\(_2\)O\(_4\).

The spinel crystal structure is determined primarily by the oxygen ion lattice. The radii of the oxygen ions are several times larger than radii of the metallic ions in the
compound as can be seen from Table 1.1. Consequently, the crystal structure can be thought of as being made up of the closest possible packing of layers of oxygen ions, with the metallic ions fit in at the interstices.

The unit cell is cubic; each unit cell contains eight MeFe$_2^{3+}$O$_4$ molecules. The space group of spinel ferrite is $Fd\overline{3}m0^7$. The oxygen ions form a nearly closed packed cubic structure and the metal ions are distributed over the tetrahedral and octahedral sites. In a unit cell, eight tetrahedral and sixteen octahedral sites are occupied by the metal ions. The tetrahedral and octahedral sites are conventionally called A and B sites respectively. The oxygen ion positions are defined by a crystallographic parameter ‘u’, which generally lays between 0.375 A.U. and 0.400 A.U.

The ion packing situation is indicated in Fig. 1.1 (a), where, the solid lines represent the top layer of oxygen spheres while the dotted lines represent the bottom layer of oxygen spheres. Upon close examination, it can be seen that there are two kinds of interstices, denoted by letters A and B. A metallic ion located at the A site has four nearest
oxygen ion neighbors, three oxygen ions in the bottom layers and one oxygen ion in the top layer (Fig. 1.1. b).

Fig. 1.1 Atomic arrangement at tetrahedral (A) and octahedral [B] site in spinel structure

In other words, it is in a site of tetrahedral co-ordination. If the metallic ion is located at B site, it has six nearest oxygen ion neighbours. These oxygen ions are situated at the corners of an octahedron (Fig. 1.1. C). Thus, the metallic ion is in a site of octahedral co-ordination. For zinc and cadmium ferrites, the divalent metallic ions Zn$^{++}$ or Cd$^{++}$ are at the A site, while the two trivalent ferric ions
2Fe^{+++} are at the B site. This structure is same as that of normal spinel.

Fig. 1.2 Crystal structure of spinel ferrite

A diagram of the unit cell of the spinel crystal structure is shown in Fig. 1.2 where the Mg^{++}, Al^{+++}, and O^{2-} ions are represented by spheres of different sizes and shapes. Actually, most of the simple ferrites, e.g. NiFe_2O_4 are of the inverse spinel structure in which one trivalent ferric ion (Fe^{+++}) is at the A site while the remaining trivalent ferric ion (Fe^{+++}) and the divalent metallic ion (M^{++}) are at the B site.

If M^{++} is a ferrous ion, then the ferrite Fe_3O_4 can be represented in the ionic form Fe_3O_4 = FeO. Fe_2O_3 = Fe^{+++} (Fe^{+++} Fe^{++}) O_4^{-}. 
It is interesting to note here that if electrons were to transfer from the divalent ferrous ion (Fe^{++}) at the B site to the trivalent ferric ion (Fe^{+++}) at the B site, the compound would remain completely unchanged. Thus, it might be expected that electron flow would be facilitated, giving rise to high conductivity or low resistivity. The resistivity of iron ferrite Fe_{3}O_{4} is about 10^{-4} ohm-m which is three orders of magnitude higher than that of iron, is still too low for high frequency application. However, if the ferrous ion Fe^{++} is replaced by the nickel ion Ni^{++}, for example, the chemical formula would be:

NiO.Fe_{2}O_{3} = Fe^{+++} (Fe^{+++} Ni^{++}) O_{4}^{-}

It is now no longer possible for electrons to be interchanged between the Fe^{+++} and Ni^{++} ions at the B sites without having the final state different from initial one. Indeed, by substituting a metallic ion such as Ni^{++} for the ferrous ion in Fe_{3}O_{4} (Magnetic), the resistivity can be increased to as high a value as 10^{7} ohm-m.

There are notable exceptions to the MO.Fe_{2}O_{3} formula for ferrites. For e.g., Ferroxdure, a ferrite used for permanent magnets, has the chemical formula BaO.6Fe_{2}O_{3}.  

______________________

(11)
It has a hexagonal structure rather than the cubic crystal structure of the spinel, giving rise to high uniaxial anisotropy. Because of its high anisotropy field, itself resonates with no externally applied field at about 50 Kilo mega cycles/sec. Consequently, this material can be utilized to build light and compact resonance isolators at these high frequencies. Rare earth garnets are hard ferrites and also have large applications in many fields. They have the general chemical formula \(5\text{Fe}_2\text{O}_3.3\text{M}_2\text{O}_3\) where M represents yttrium or some other rare earth ions from samarium to lutetium. This structure differs from the spinel lattice of the conventional ferrites in several respects.

\[1.4 \quad \text{TYPES OF FERRITES}\]

Mixed metal oxides with iron (III) oxides as their main component are ferrites. On the basis of the cations distribution ferrite crystal are classified into three types (i) Spinel (ii) Garnet (iii) Magnetoplumbite.

The interesting electric and magnetic properties of these compounds are governed critically by their chemical
composition. Hence preparation of ferrite composites with specific properties has gain much importance.

The simplest among the ferrite are the spinel type. Simple ferrite spinels (A\textsuperscript{II}Fe\textsubscript{2}O\textsubscript{4}) as well as mixed ferrite spinels of the general composition (A\textsuperscript{II}\textsubscript{1-x}B\textsuperscript{x}Fe\textsubscript{2}O\textsubscript{4}) are known.

1) **Spinel Ferrite**

Spinel ferrites are described by the chemical formula MFe\textsubscript{2}O\textsubscript{4} where M stands for divalent metal ions. The crystal structure of spinel ferrite possess two interstitial sites namely tetrahedral (A) and octahedral [B]. A variety of cations can accommodate at tetrahedral (A) site and octahedral [B] site enabling wide variation in the properties of ferrites.

M can be replaced by other divalent metal ions and we can have number of spinel ferrites. Fe\textsuperscript{3+} ions can be replaced by other trivalent ions like Al\textsuperscript{3+}, Cr\textsuperscript{3+}, Ga\textsuperscript{3+} etc. Fe\textsuperscript{3+} ions can also be replaced by combination of divalent and tetravalent ions. The basic electric and magnetic properties of some spinel ferrites are summarized in Table 1.3.
2) Garnet

The chemical formula for ferrimagnetic garnet is $\text{Me}_3\text{Fe}_5\text{O}_{12}$ where Me is a trivalent ion such as rare earth or yttrium. The unit cell is cubic and contains eight molecules of $\text{Me}_3\text{Fe}_5\text{O}_{12}$ i.e. 160 atoms. The metal ions are distributed over three types of sites. The Me ions occupy the dodecahedral sites (called c sites), where they are surrounded by eight oxygen ions, the $\text{Fe}^{3+}$ ions distributed over the tetrahedral (d) and octahedral (a) sites in the ratio $3 : 2$. Thus, the cation distribution of $\text{M}_3\text{Fe}_5\text{O}_{12}$ can be written as $\text{Me}^\text{c}_3\text{Fe}^\text{d}_3\text{Fe}^\text{a}^\text{d}\text{O}_{12}$.

As in the case of spinels, the magnetic alignment results from super exchange interaction via the intervening oxygen ions, and the interaction is expected to be greater for the shorter the Me-O distance and the closer the Me-O-Me angle is to $180^\circ$. On this basis it is concluded that the interaction between the d and a cations are relatively strong (both negative). These interactions central the magnetic alignments in the solid, resulting in the following spin arrangement.
\[ \text{Me}^c_3 \text{Fe}^a_2 \text{Fe}^d_3 \text{O}_{12} \] for magnetic Me ion

\[ \text{Me}^c_3 \text{Fe}^a_2 \text{Fe}^d_3 \text{O}_{12} \] for non-magnetic Me ion

The total magnetic moments on the a and d ions are aligned antiparallel and the moments on the c-ions are antiparallel to those on the d-ion. Thus, for the formula \((3\text{M}_2\text{O}_3)^c(2\text{Fe}_2\text{O}_3)^a (2\text{Fe}_2\text{O}_3)^d\) the arrangement is \(6\text{Fe}^d, 4\text{Fe}^d, 6\text{Me}^c\). The net magnetic moment \(m\) (in Bohr magneton per unit formula) is

\[
m = 6m_c - (6m_d - 4m_a) = 6m_c - 10 \mu_B \tag{1.1}
\]

assuming a magnetic moment of \(5\mu_B\) per Fe ion. In terms of the unit formula \(\text{M}_3\text{Fe}_5\text{O}_{12}\) equation 1.1 becomes

\[
m = (3m_c - 5\mu_B) \tag{1.2}
\]

where, \(m_c\) is the magnetic moment per Me ion.

3) **Ortho-ferrites**

Ortho-ferrites have the general formula \(\text{MeFeO}_3\), where Me is a large trivalent metal ion, such as rare-earth ion or yttrium. They crystallize in a distorted pervoskite structure with an orthorhombic unit cell. These ortho-ferrites show a weak ferromagnetism, which has been attributed to the small canting in the alignment of two anti-
ferromagnetically coupled lattices. The canting angle is of the order of $10^{-2}$ rad but is sufficient to introduce a small net ferromagnetic moment perpendicular to the antiferromagnetic axis. The direction of spin orientation of the Fe ion in HOFeO$_3$ and ErFeO$_3$ has been experimentally determined at room temperature and found to be parallel to the (100) axis on lowering the temperature the spin axis rotates, and at 1.25K the direction is (001) for HOFeO$_3$ and (110) for ErFeO$_3$. The spin moment on the rare earth ion gets ordered at a much lower Neel temperature [6.5 K for HO Fe O$_3$ and 4.3 K for ErFeO$_3$].

4) Hexagonal ferrites

There are number of ferrites that crystallize in hexagonal structure, and some of them have gained considerable technological importance in recent years. These ferrites are further sub-classified into M, W, Y, Z and U compounds. All these have different, though related, crystal structures. The M compounds have the simplest structure. Barium ferrite, the well known hard ferrites, belongs to this class. These compounds have the general formula MeFe$_{12}$O$_{19}$
where Me is a divalent ion of a large ionic radius, such as Ba$^{2+}$, Sr$^{2+}$ or Pb$^{2+}$. Some compounds with trivalent Me (e.g. La$^{3+}$, Al, Ga, Cr, Fe) are also known. In these, one iron per formula unit is present as Fe$^{2+}$ to allow for the charge compensation.

The crystal structure of barium ferrite is hexagonal with the unit cell made up of two unit formulae. The structure is related to the spinel structure in which the oxygen lattice, f.c.c., consist of a series of hexagonal layers of oxygen lying perpendicular to the (111) direction.

### 1.5 APPLICATIONS OF FERRITE

Ferrites are used at both radio and microwave frequencies. Ferrite applications at below microwave frequencies are numerous. The deflection yoke core in a television picture tube is an example of the use of ferrites of the nickel-zinc-iron or manganese-zinc-iron variety. The deflection yoke consist of wire coils wound to fit around the neck of television picture tube. The ferrite cores are molded so that they can be assembled tightly around these coils. The complete structure slips over the neck a television
picture tube. When high frequency current from the tubes of the television set pass through these coils, the electron beam of the picture tube is deflected vertically and horizontally, thus projecting a picture. Because of their high resistivity and the consequent low eddy current loss, use of ferrite cores here greatly increases the efficiency of the operation. For the same reason, cores for fly back transformers used in television scanning are made of ferities. Further examples could be given, when a ferrite rod is inserted into a coil of wire acting as an antenna, it concentrates the electromagnetic energy in the core because of its high permeability. This greatly increases the energy received by a receiving antenna. The high resistivity of ferrites combined with their high permeability also makes them suitable for filter inductor applications. Ferrites are also used in cores for magnetic memories and switches. These applications involve the use of microsecond pulses for transmitting, storing and reading information expressed in the binary code. Other non-microwave applications are IF transformers and tuned inductors.
Ferrites are used at microwave frequencies for somewhat different reasons. At these frequencies, they exhibit non-reciprocal properties, i.e., the attenuation and phase shift of microwaves propagating through them have different values for the two opposite directions of propagation in a waveguide.

A rather pronounced Faraday effect is observed at microwave frequencies, i.e., the plane of polarization of the wave is rotated as it travels through an axially magnetized ferrite pencil in a circular waveguide. This effect can be utilized to build a whole class of non-reciprocal devices such as Unilines, gyrators, differential phase shifters, etc.

If a sample of ferrite is placed at the point of circular polarization in a rectangular waveguide, i.e., at the point where the magnetic field is a rotating vector of constant amplitude, and magnetized transverse to the direction of propagation, non-reciprocal attenuation and phase shift can be attained.

The resonance isolators based on the non-reciprocal attenuation principle can be used to isolate source and load, thereby stabilizing the frequency of a klystron or magnetron.
oscillator by absorbing much of the energy reflected from the load without introducing excessive insertion loss in the forward (oscillator to load) direction. The non-reciprocal phase shifter can form the core of a microwave circulator. Such a device can be used to guide the transmitter energy to the antenna and to direct the received energy from the antenna to the receiver.

At large signal levels, the permeability of ferrites at microwave frequencies is a function of signal level, i.e., the attenuation of a ferrite-containing unit is a function of power incident upon it. Since the attenuation of such a device rises with power, if the ferrite is magnetized by an appropriate value of d.c. field, it can function as a power limiter. Other applications are cut-off switches utilizing the fact that the equivalent permeability of ferrites can go negative when the ferrite is appropriately magnetized, causing the energy incident upon it to be reflected.

1.6 LITERATURE SURVEY

Ferrites continued to be very attractive materials for technological applications due to their unique electrical and
magnetic properties. The basic electrical and magnetic properties depends on many factors such as preparative method, sintering temperature, amount and type of substitution. The spinel structure affords a particularly good opportunity to explain the relative stabilities of ions in available sties \((\text{tetrahedral (A) and Octahedral } B)\) and study of transition metal oxides particularly spinel ferrite is of great importance from both the fundamental and applied research points of view. The interesting physical and chemical properties of ferro-spinels arise from the ability to distribute the cations among the available tetrahedral (A) and octahedral [B] sties. In addition, the variations in preparative condition also cause large changes in some extrinsic properties. The variation of different physical properties with method of preparation \([7,8]\) has made ferrite, a most versatile and technological material. The magnetic properties of ferrites depend on chemical composition, cation distribution, porosity and grain size. Cadmium substituted spinel ferrites show good magnetic properties for technical applications. The knowledge of
cation distribution and spin alignment is essential to understand the magnetic properties of spinel ferrites.

The spinel ferrites with divalent non magnetic substitutes like Zn$^{2+}$ and Cd$^{2+}$ have been the subject of many investigators [9-12], because of their magnetic properties resulting from a particular configuration. It is known that Zn$^{2+}$ and Cd$^{2+}$ ions invariably go to the tetrahedral (A) and there by diluting A site. A large number of research papers are available in the literature on Zn$^{2+}$ substituted mixed spinel ferrite [13,14].

Nickel ferrite is an important magnetic material for the application in radio frequency microwave application. Nickel ferrite possesses inverse spinel structure. The study of nickel and nickel substituted ferrite is of great importance,

The modification in electrical and magnetic properties of nickel ferrites by substitution of different ions have been the subject of many researchers [15, 16].

Usually, the spinel ferrites are prepared by ceramic technology which has some drawbacks. Recently, some wet chemical methods like co-precipitation [17], sol-gel [18],
auto-combustion [19], Solvent evaporation method [20], hydrothermal method [21], citrate method [22], combustion method [23] etc. have been used for synthesis of spinel ferrites.

The advantage of wet chemical method is that they produce particles of nano meter dimension. To our knowledge no systematic investigations have been found in the literature on the size dependent, structural electrical and magnetic properties of nickel–cadmium ferrites prepared by both ceramic as well as sol-gel technique. Therefore, detail investigation of the structural, electrical and magnetic properties of Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ (where x = 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0) synthesized by ceramic and sol-gel technique have been carried out in the present investigation.

1.7 AIM OF THE PRESENT WORK

The aim of the present work is to study the size dependent properties of Ni$_{1-x}$Cd$_x$Fe$_2$O$_4$ spinel ferrite system. The varying size of samples was obtained by preparing material by ceramic and sol-gel method.
The samples of Ni-Cd spinel ferrites of varying particle sizes have been successfully prepared by sol-gel and ceramic method. The structural properties were investigated by means of X-ray diffraction technique (XRD), scanning electron microscopy (SEM), infrared spectroscopy (IR) etc.

The magnetic properties were investigated by means of pulse field magnetization technique and the a.c. susceptibility technique.

The electric properties like D.C. resistivity of all the samples of both the system (ceramic as well as sol-gel) has been studied as a function of composition of temperature range (300 to 900 K).

The electric and dielectric properties were investigated by two probe technique as a function of composition, frequency and temperature.

The dielectric constant ($\varepsilon'$) and dielectric loss tangent (tan$\delta$) were measured at room temperature as function of frequency in the range (100Hz – 1MHz)
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   Lima Miguel A. Navak, R Paulo, well Jr.,  
Table 1.1

Ionic Radii of Several Elements\(^a\)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Radius $\text{Å} = 10^{-8} \text{ cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$^-$</td>
<td>1.32(^b)</td>
</tr>
<tr>
<td>Fe$^{++}$</td>
<td>0.67</td>
</tr>
<tr>
<td>Fe$^{+}$</td>
<td>0.83</td>
</tr>
<tr>
<td>Mn$^{++}$</td>
<td>0.91</td>
</tr>
<tr>
<td>Mg$^{++}$</td>
<td>0.78</td>
</tr>
<tr>
<td>Ni$^{++}$</td>
<td>0.78</td>
</tr>
<tr>
<td>Zn$^{++}$</td>
<td>0.83</td>
</tr>
<tr>
<td>Cd$^{++}$</td>
<td>1.03</td>
</tr>
<tr>
<td>Co$^{++}$</td>
<td>0.82</td>
</tr>
<tr>
<td>Cu$^{++}$</td>
<td>0.70</td>
</tr>
<tr>
<td>Al$^{+++}$</td>
<td>0.57</td>
</tr>
</tbody>
</table>


\(b\) Computed by Goldschmidt on the basis of empirical assumptions.

\(c\) Computed by Pauling on the basis of wave mechanics.
Table 1.2
For crystal types of ferrites.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Type</th>
<th>Structure</th>
<th>General Formula</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Spinel</td>
<td>Cubic</td>
<td>$\text{A}^{\text{II}}\text{Fe}_2\text{O}_4$</td>
<td>($\text{A}^{\text{II}}=$Cd,Co,Mg,Ni and Zn)</td>
</tr>
<tr>
<td>2</td>
<td>Garnet</td>
<td>Cubic</td>
<td>$\text{L}_3\text{III}_2\text{Fe}_2\text{O}_12$</td>
<td>($\text{Ln}^{\text{III}}=$ Y,Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Lu)</td>
</tr>
<tr>
<td>3</td>
<td>Magneto Plumbite</td>
<td>Hexagonal</td>
<td>$\text{A}^{\text{II}}\text{Fe}<em>{12}\text{O}</em>{19}$</td>
<td>$\text{BaFe}<em>{12}\text{O}</em>{19}$</td>
</tr>
</tbody>
</table>
Table 1.3
Magnetic and electrical data of some spinel ferrites

<table>
<thead>
<tr>
<th>Compound</th>
<th>Cation distribution</th>
<th>(a_0) (Å)</th>
<th>Resistivity, Ohm cm</th>
<th>(n_B) Cal.</th>
<th>(n_B) Obs</th>
<th>(\theta_c) °C</th>
<th>(K_1) ×10⁻³</th>
<th>(K_1) ×10⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnFe₂O₄</td>
<td>Zn²⁺ [Fe²⁺]O₄</td>
<td>8.44</td>
<td>10²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(antiferromagnetic (T_N = 9.5)K)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(n_B = 5)μB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MnFe₂O₄</td>
<td>Mn²⁺ [Fe²⁺]O₄</td>
<td>8.51</td>
<td>10⁴</td>
<td>5</td>
<td>4.55</td>
<td>300</td>
<td>-40</td>
<td>-5</td>
</tr>
<tr>
<td>Fe₃O₄ (Fe₂O₄)</td>
<td>Fe³⁺ [Fe²⁺ Fe³⁺]O₄</td>
<td>8.39</td>
<td>4×10⁻³</td>
<td>4</td>
<td>4.1</td>
<td>585</td>
<td>-130</td>
<td>40</td>
</tr>
<tr>
<td>CoFe₂O₄ (quenched)</td>
<td>Fe³⁺ [Co²⁺ Fe³⁺]O₄</td>
<td>8.38</td>
<td>10⁷</td>
<td>3</td>
<td>3.94</td>
<td>520</td>
<td>2000</td>
<td>-110</td>
</tr>
<tr>
<td>NiFe₂O₄ (quenched)</td>
<td>Fe³⁺ [Ni²⁺ Fe³⁺]O₄</td>
<td>8.34</td>
<td>10⁶-10⁴</td>
<td>2</td>
<td>2.3</td>
<td>585</td>
<td>-69</td>
<td>-17</td>
</tr>
<tr>
<td>CuFe₂O₄</td>
<td>Fe⁵⁺ [Cu²⁺ Fe³⁺]O₄</td>
<td>8.37</td>
<td>10⁵</td>
<td>1</td>
<td>2.3</td>
<td>455</td>
<td>-63</td>
<td>-10</td>
</tr>
<tr>
<td>MgFe₂O₄</td>
<td>Fe³⁺ [Mg²⁺ Fe³⁺]O₄</td>
<td>8.36</td>
<td>10⁷</td>
<td>0</td>
<td>1.1</td>
<td>440</td>
<td>-40</td>
<td>-6</td>
</tr>
<tr>
<td>Li₀.₅Fe₂.₅O₄</td>
<td>Fe³⁺ [Li₀.₅Fe₂.₅]O₄</td>
<td>8.33</td>
<td>10²</td>
<td>2.5</td>
<td>2.6</td>
<td>670</td>
<td>-83</td>
<td>-8</td>
</tr>
<tr>
<td>γ-Fe₂O₃</td>
<td>Fe³⁺ [Fe⁵⁺/₃ ⊗₁/₃] O₄</td>
<td>8.34</td>
<td>---</td>
<td>2.5</td>
<td>2.3</td>
<td>575</td>
<td>-</td>
<td>-</td>
</tr>
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