CHAPTER – I
INTRODUCTION
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Ferrites are a group of technologically important magnetic materials. Due to their useful electromagnetic characters ferrites have a large number of applications ranging from millimeter wave integrated circuitry to transformer cores and magnetic recording [1-4]. But the performance of these materials in their bulk form is limited. Because of technological importance of these materials, ferrites are revisited in nanoregime. The synthesis of ferrite nano particles with controlled size and tailorable magnetic properties along with the understanding of the structure -property correlations have become one of the topics of fundamental scientific importance [5].

1.1 Ferrites

Ferrites are ferrimagnetic materials, which are composed of oxides containing ferric ions as the main constituent. Nanoferrites are significantly used for a wide range of applications like high density magnetic information storage, magnetic resonance imaging, targeted drug delivery, etc.

1.1.1 Structure of ferrites:

Ferrites are mixed metal oxides with iron (III) oxides as their main component. Ferrites crystallize in three different crystal types namely spinel, garnet and magneto-plumbite [6, 7].

<table>
<thead>
<tr>
<th>Type</th>
<th>Structure</th>
<th>General formula</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinel</td>
<td>Cubic</td>
<td>$M^{2+}Fe_2O_4$</td>
<td>$M^{2+} = Cd, Co, Mg, Ni and Zn</td>
</tr>
<tr>
<td>Garnet</td>
<td>Cubic</td>
<td>$Ln^{3+}Fe_5O_{12}$</td>
<td>$Ln^{3+} = Y, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Lu.</td>
</tr>
<tr>
<td>Magneto-plumbite</td>
<td>Hexagonal</td>
<td>$M^{2+}Fe_{12}O_{19}$</td>
<td>$M^{2+} = Ba or Sr</td>
</tr>
</tbody>
</table>


1.1.2 Spinel ferrite:

Spinel ferrites are mixed oxides with general formula $AB_2O_4$, where A is a divalent metal ion and B is $Fe^{3+}$ ion. Spinel ferrite is isostructural with the mineral $MgAl_2O_4$. The unit cell consists of 8 unit formula $(8 \times M^{2+}Fe_2O_4)$.

$$8 \times M^{2+}Fe_2O_4 = (8M + 16Fe) \text{ cations} + 32 \text{ Oxygen anions} = 56 \text{ ions}$$

The 32 oxygen anions are closely packed into face centered cubic lattice in which two kinds of interstitial sites are present namely tetrahedral sites or A-sites and octahedral sites or B-sites. The tetrahedral (A) and octahedral (B) sites are shown in the Fig1.1. There are 64 tetrahedral sites out of which 8 are occupied and 32 octahedral sites out of which 16 are occupied [7,8,9].

The magnetic and electrical properties of the spinel are governed by the distribution of iron and metal ions among the tetrahedral and octahedral sites of the spinel structure. The size and valency of the cations and the oxygen parameter of the anions are the important factors for the site occupancy, the calculations of ionic radii are in the ranges.

$$0.055 < R_{tet} < 0.067 \text{nm}$$

$$0.070 < R_{oct} < 0.075 \text{nm}$$

These factors are not enough to give complete picture of cation distribution. The different electron environments surrounding the A and B sites are also influence the distribution of $M^{2+}$ and $Fe^{3+}$ cations. There are three possible distributions for cations (1) the normal spinel $( M^{2+})[Fe^{3+}]O_4$ in which all of the $M^{2+}$ cations reside on the tetrahedral sites (2) the inverse spinel $(Fe^{3+})[ M^{2+} \text{ Fe}^{3+}]O_4$ in which the $M^{2+}$ cations are on octahedral sites and (3) the mixed spinel in which the divalent cations are distributed between both tetrahedral and octahedral sites which gives distribution of cations. The cation distribution is represented by $(M^{2+}_xFe^{3+}_{1-x})[ M^{2+}_{1-x}Fe^{3+}_{1+x}]O_4$ Where the
Fig 1.1 Tetrahedral (A) and Octahedral (B) sites in spinel structure [10].
ions inside the brackets are located in octahedral sites and ions outside the brackets in tetrahedral sites. For x=1 is called normal spinel (zinc ferrite) and for x=0, is called inverse spinel (nickel ferrite). For random distribution x=1/3. The cation distribution is dependent on the method of preparation and is variable with temperature of synthesis or annealing, consequently influences the electrical and magnetic properties of these materials.

1.1.3 Magnetic interactions in ferrites:

In ferrites the metallic ions occupy tetrahedral (A) sites and octahedral (B) sites. The possible three kinds of magnetic interactions A-O-B, B-O-B, and A-O-A in ferrites are due to the interactions of metallic ions through non-magnetic $O^{2-}$ ions by superexchange mechanism. The exchange interactions A-B, B-B, and A-A are negative. The strength of these interactions are determined by degree of overlapping of oxygen and the transition metal ion orbitals. The strength of interaction depends on the distance between the metal ions and M-O-M bands angle. The important interaction in spinel ferrite is A-B interaction while the other interactions B-B and A-A are negligible. The interaction is such that antiparallel alignment occurs when both ions have 5 or more 3d electrons or 4 or fewer 3d electrons. Parallel alignment occurs when one ion has less than or equal to 4 electrons and the second ion has greater than or equal to 5 electrons. The common ferrite ions have more than 5d electrons, hence the magnetic moments are aligned antiparallel between A and B sites. There are twice as many B sites occupied as A sites, so the B site will dominate over A site resulting in ferrimagnetism. The value of saturation magnetic moment of B site ($M_B$) is greater than that of the A site ($M_A$), so that the net saturation magnetization is equal to the vector sum of the magnetic moments of two sub lattices [7, 26].

$$M_S = M_B - M_A$$  ......................................................... (1.1)
Unlike in anti-ferromagnetism, a resultant magnetization is observed due to the difference in the magnitudes of the magnetic moments between sublattices.

1.1.4 Site preference in ferrites:

The original expectation of normal and inverse site selection is based on ionic valancies. The other factors such as cation size, crystal field and valance play a role in site selection. Consider magnetite which has two Fe$^{3+}$ ions and one Fe$^{2+}$ ion. It can be seen that the Fe$^{3+}$ ion has much stronger tetrahedral site preference than Fe$^{2+}$. One of the Fe$^{3+}$ ions occupies the A site and regulates the other two ions (Fe$^{3+}$ and Fe$^{2+}$) to the B sites per formula unit. Hence the magnetite has the inverse site occupations. It is important to notice that Zn$^{2+}$ has by far the strongest preference for A site occupation. Consider divalent transition metal substitution for iron [12]

$$\text{Fe}_3\text{O}_4 = \text{Fe}^{2+}\text{O}^2^- (\text{Fe}^{3+})_2 (\text{O}^{2-})_3 \rightarrow \text{T}^{2+}\text{O}^2^- (\text{Fe}^{3+})_2 (\text{O}^{2-})_3$$

Considering that the A and B sublattices are antiferromagnetically coupled, the Fe$^{3+}$ moments cancel for the compounds, leaving only the T$^{2+}$ moments. There is initial increase in moment observed with Zn substitution in

$$\text{TO.Fe}_2\text{O}_3 \rightarrow (\text{T}^{2+})_{1-x}(\text{Zn}^{2+})_x (\text{Fe}^{3+})_2\text{O}.$$ When Zn$^{2+}$ substitutes for T$^{2+}$, the iron ions are forced to the B sites as $x$ increases. Taking the sign of the B site moments to be positive, the net moment per FU becomes [27]

$$\mu_n = 5(1 + x) + \mu_T(1 - x) - 5(1 - x) = 10x + \mu_T(1 - x) \text{ ..................... (1.2)}$$

Where $\mu_T$ is the moment of the divalent transition metal ion for which Zinc is substituted. At $x = 0$, the equation describes the moment of divalent transition metal ion. With increasing $x$, the net moment is predicted to increase linearly towards 10 $\mu_B$. But this linearity fairly followed until $x \sim 0.3$– 0.4 and after the net moment decreased. This argues that at large Zn concentration the antiferromagnetic B – B interaction start flipping those B site Fe$^{3+}$ moments that are farthest from an A moment. It is also a factor that A – B exchange
interaction is weakened as Zn content increases. In nanoregime the ions are randomly distributed among the tetrahedral (A) and octahedral (B) sites which influence the electrical and magnetic properties of ferrites.

1.2 Concept of magnetism

The magnetic moment of an atom was originated from orbital motion and spin motion of electron. The net magnetic moment is the vector sum of orbital and spin moments of the electron, and two possibilities arise [11 - 14]

1. The magnetic moments of all the electrons are so oriented that they cancel one another out, and the atom as a whole has no net magnetic moment.
2. The cancellation of electronic moments is only partial and the atom is left with a net magnetic moment. Magnetic moment is measured in Bohr magneton.

Bohr magneton $\mu_B = \frac{eh}{4\pi m}$ ........................................ (1.3)

Bohr magneton equals to $9.273 \times 10^{-24}$ A/m$^2$, is the fundamental unit of magnetic moment

1.2.1 Magnetization and Susceptibility:

Magnetization is a quantity descriptive of the extent to which the magnetic materials are magnetized and is defined as total magnetic moment per unit volume.

$$\vec{I} = \frac{\sum \vec{\mu}}{V} \hspace{1cm} ........................................ (1.4)$$

Where $V$ is the volume of the sample and $\vec{\mu}$ is magnetic moment of each particle.
The magnetic properties of a material are not only characterized by the magnitude and sign of magnetization, but also depends on the variation of $\vec{I}$ with applied magnetic field $\overline{H}$. The ratio of magnetization to the applied magnetic field is the magnetic susceptibility.

$$\chi = \frac{\vec{I}}{\overline{H}}$$ ............................................ (1.5)

Magnetic susceptibility describes the response of a magnetic material in a magnetic field.

1.3 Classification of magnetic materials

Magnetic materials are classified as diamagnetic, paramagnetic, ferromagnetic, anti-ferromagnetic and ferrimagnetic.

Diamagnetism is an inherent result of the cancellation of orbital and spin magnetic moments of paired electrons in the orbitals. In the presence of applied field, the orbital motion generates magnetization opposite to the applied field, described by negative susceptibility.

According to Langevin theory of diamagnetism the susceptibility can be given by

$$\chi = \frac{-\mu_0 N Ze^2}{6m} \langle r^2 \rangle$$ ............................................ (1.6)

Where is $\mu_0$ permeability, $N$ is concentration of atoms, $m$ is mass of the electron and $r$ is radius of electron distribution with in the atom.

Paramagnetism is a result of incomplete cancellation of orbital and spin magnetic moments, hence there is some net magnetic moment. When field is applied there is complete alignment of atomic magnetic moments, but thermal agitation randomizes the atomic moments, results in small net magnetization and positive susceptibility.
According to Langevin theory of paramagnetism, the susceptibility can be given by

\[ \chi = \frac{-\mu N \mu_0}{3K_B T} = \frac{C}{T} \]  

(1.7)

Where \( C = \frac{-\mu N \mu_0}{3K_B} \) is Curie constant, \( \mu_0 \) is permeability, \( N \) is concentration of atoms and \( \mu \) is atomic magnetic moment.

Ferromagnetism is a result of parallel alignment of atomic magnetic moments due to strong electron exchange interactions, leaves very high and spontaneous magnetization. The susceptibility of these materials infinite at a characteristic temperature \( (T_C) \) is known as Curie temperature. The temperature dependence of ferromagnetic material is given by the equation

\[ \chi = \frac{C}{T - \theta} \]  

(1.8)

This is known as Curie – Weiss law. Here ‘\( \theta \)’ is Curie temperature and \( C \) is Curie constant.

According to Heisenberg the exchange energy due to exchange interactions between the neighbouring spins is given by

\[ E_{ex} = -2J_{ex} S_i \cdot S_j \]  

(1.9)

Where \( J_{ex} \) exchange integral, and \( S_i \), \( S_j \) are neighboring spins. If \( J_{ex} > 0 \) magnetic moments are parallel results ferromagnetism and if \( J_{ex} < 0 \) results antiparallel configuration.

Antiferro magnetism is a result of antiparallel alignment of atomic magnetic moments due to exchange interactions between the neighboring moments and exchange integral \( J_{ex} \) is negative according to Heisenberg-Hamiltonian theory. This antiparallel alignment causes a small
positive susceptibility. Antiferromagnetism occurs below a critical temperature is known as Neel temperature \( (T_N) \) and above \( T_N \) antiferromagnetic becomes paramagnetic material. The susceptibility is given by

\[
\chi = \frac{C}{T + \theta} \hspace{1cm} \text{................................. (1.10)}
\]

Ferrimagnetism is similar to antiferromagnetism character but due to the difference in magnetisation of the two sublattices, results a net magnetism. The spontaneous magnetism exhibits below a critical temperature is known as Curie temperature and above this is overcome by the thermal agitation and system is paramagnetic. Ferrites are the major class of ferromagnetic materials. The susceptibility is given by

\[
\frac{1}{\chi} = \frac{T}{C} + \frac{1}{\chi_0} - \frac{b}{T - \theta} \hspace{1cm} \text{................................. (1.11)}
\]

The magnetic orders of magnetic moments in different magnetic materials are shown in Fig 1.2.

**1.4 Hysteresis curve**

When the applied field is decreased from saturation, the magnetization curve of the material doesn’t retrace its original path i.e., the magnetization is not reduced to zero. This is due to the fact that some energy is lost during Barkhausen jumps \([14]\) so that the domain walls can’t move back across the sample. When the field direction is reversed, the domain walls begin to move across the sample. However, the loss of energy during the Barkhausen jumps prevents the motion of domain walls back to their original position i.e., direction at which \( \vec{H} = 0 \). Consequently, there remains some magnetization in the material even when field approaches zero, i.e., the magnetization curve of the material doesn’t retrace its path with decreasing \( \vec{H} \). This is called Hysteresis. This amount of residual magnetization remaining in the material
Fig 1.2 Alignment of magnetic moments in (a) paramagnetic material (b) ferromagnetic material (c) anti-ferromagnetic material and (d) ferrimagnetic material.
when \( \overline{H} = 0 \) is called the remanence (\( \overline{M_r} \)). The magnetic materials with higher \( \overline{M_r} \) values are preferred for preparing permanent magnets. The reverse magnetic field needed to restore magnetization to zero is called coercivity \( \overline{H_c} \). It is a good measure of the ease or difficulty of magnetizing a material. Soft magnetic materials have lower values of \( \overline{M_r} \) and \( \overline{H_c} \).

If the reverse field is further increased, the sample reaches saturation point in the reverse direction, \( -\overline{M_s} \). When the field is then decreased to zero and increased in the positive direction, the magnetization curve approaches \( +\overline{M_s} \) through \( -\overline{M_r} \). Now the loop traced out is called major hysteresis loop shown in Fig1.3.

The soft and hard magnetic materials are classified on the basis of the shape of the hysteresis. Spinel ferrites, in SDP states, exhibit superparamagnetic state for which both \( \overline{M_r} \) and \( \overline{H_c} \) of the sample vanish.

1.5 Magnetic anisotropy

Magnetic anisotropy is the function of direction of preference for the magnetization. The energy difference between the easy and hard axis results from different kinds of magnetic anisotropies, which can be distinguished to their origin as 1. magnetocrystalline anisotropy 2. shape anisotropy 3. surface anisotropy 4. Induced anisotropy. Magnetic anisotropy is this property of the magnetic materials which determines their magnetic parameters such as magnetic susceptibility, permeability, shape of the hysteresis loop and frequency of the ferromagnetic resonance.

a) Magnetocrystalline anisotropy:

Magnetocrystalline anisotropy is an intrinsic property and is regarded as a force which tends to bind the magnetization to directions of a
Figure 1.3 Typical Hysteresis Curve

For a cubic crystal $E_a$ is related to two anisotropy constants $K_1$ and $K_2$ is given by

$$E_a = K_0 + K_1 \left( \alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2 \right) + K_2 \alpha_1^2 \alpha_2^2 \alpha_3^2 \quad ........... (1.12)$$

Where $\alpha_1$, $\alpha_2$ and $\alpha_3$ are the direction cosines of the magnetization vector relative to the crystallographic axes and $K_0$ is an isotropic constant.

For crystal with hexagonal close packed structure such as CoFe$_2$O$_4$ and Hexagonal Barium Ferrite, which are called semi axial crystals, there exists a single angle $\theta$ between magnetization vector and the semi- major axis (c-axis). Then the anisotropy energy can be expressed as

$$E_A = K_1 \sin^2 \theta + K_2 \sin^4 \theta + K_3 \sin^6 \theta + ... \quad ............ (1.13)$$

b) Shape anisotropy:

Shape is a source of magnetic anisotropy. In a non-spherical specimen it will be easier to magnetize along long axis than along short axis, because the demagnetizing field is less along long axis[15]. For spherical sample there is no spherical anisotropy. The magnetic energy density can be written as [11]

$$E = \frac{1}{2} \mu_0 N_d M_S \quad ........................................... (1.14)$$

Where $N_d$ is demagnetizing factor and $M_S$ is the saturation magnetism.

c) Surface anisotropy:

Surface effects are major source of anisotropy in small magnetic nanoparticles. The two effects, namely, breaking of the symmetry and reduction in the symmetry around the atoms on the surface are considered to be the potential causes for the surface anisotropy. The reduced symmetry represents the discontinuity for magnetic interactions. Surface effects are more significant in nanoparticles, because of increasing numbers of atoms are on
the surface layer of a particle, leading to a change of the electronic environment on the particle surface. Hence the spins at surface are dictated by the local crystal field, reduction of coordination number and a broken magnetic exchange bond, thus the surface spins are often canted or disordered.

For a spherical particle, the nanoparticle size, an effective anisotropy constant, which induces the surface anisotropy are related as

\[ K_{ef} = K + \left( \frac{6}{D} \right) K_s \] ................................. (1.14)

Where \( K_s \) surface anisotropy constant, \( K \) is magnetic crystalline anisotropy constant and ‘\( D \)’ is particle diameter. Surface anisotropy leads the surface magnetically harder than the core of the particle.

**d) Induced magnetic anisotropy:**

Induced magnetic anisotropy is produced by the treatment techniques such as magnetic annealing, stress annealing, plastic deformation and magnetic irradiation [12]. The influence of stress affects the preferred directions of magnetization due to the magneto-elastic interactions.

**1.6 Particle size dependence of coercivity**

As the particle size is reduced, it is typically found that the coercivity increases, goes through a maximum and then tends towards zero. In multidomain particles, magnetization changes by domain wall motion. The size dependence of coercivity is experimentally found to be given by the approximation [11, 16]. Figure 1.4 is a schematic of the variation in coercivity with particle diameter.

\[ H_{ci} = a + \frac{b}{D} \] ......................................................... (1.15)

Where \( a \) and \( b \) are constants and \( D \) is the particle diameter.
Fig. 1.4 Dependence of coercivity on particle size[11]
Below a critical particle size $D_C$, the particles becomes single domain and the coercivity reaches a maximum. The particles with size equal to or smaller than $D_C$, change their magnetization by spin rotation.

As the particle size decreases below $D_C$ and coercivity decreases, because of thermal effects according to the relation

$$H_{ci} = g - \frac{h}{D^{3/2}}$$

(1.16)

Where $g$ and $h$ are constants.

Below a critical diameter $D_p$, the coercivity becomes zero and thermal effects become strong enough to spontaneously demagnetize a previously saturated assembly of particles. Such particles are called superparamagnetic and the phenomenon is known as superparamagnetism.

### 1.7 Single Domain Particles and Superparamagnetism

The magnetostatic energy associated with a crystalline material decreases as the crystal is divided into smaller domains. But the division into smaller domains cannot continue indefinitely as the energy associated with domain wall formation increases. Each crystal will be characterized by an equilibrium domain size which gives rise to minimum magnetostatic energy in the crystal. If the crystal sizes itself decreases to this equilibrium domain size (say less than 100 nm) the crystallite is called a single domain particle and there are no domain walls [11]. Below the critical size, the remanent magnetization is no longer fixed in the direction dictated by particle size or crystal anisotropy, ambient thermal energy may be large enough to spontaneously demagnetize saturated assembly of particles. Such particles are called superparamagnetic and phenomenon is the superparamagnetism [12,17]. Superparamagnetism can be observed in the particles of critical size given as
Where $V_p$ is the volume of the particle, $k_B$ is Boltzman’s constant, $T$ is temperature and $K$ is the anisotropy constant. The net spin within each particle cannot fluctuate randomly from thermal vibrations if energy barrier $KV$ is greater than $25k_BT$ and they are considered as stable. Increasing the anisotropy of a material will increase the activation energy barrier and results in a smaller critical size for superparamagnetism [18]. Particles that are superparamagnetic can became stable when the temperature is below a critical temperature is called the blocking temperature $T_B$.

$$T_B = \frac{KV}{25k_B} \quad \text{(1.18)}$$

The blocking temperature is defined as the temperature for which the relaxation time $\tau$ is equal to the characteristic time of the technique. For magnetic and $^{57}\text{Fe}$ Mössbauer measurements it is $100$ to $10^{-8}$ s respectively [19].

The superparamagnetic properties of the nanoparticles are determined by the magnetocrystalline anisotropy which owes its origin to the L - S coupling at crystal lattices. According to the Stoner – Wohlfarth theory, the magnetocrystalline anisotropy energy $E_A$ of a single domain particle can be written as

$$E_A = KV_p \sin^2 \theta \quad \text{.......................... (1.19)}$$

Where $K$ is the magnetocrystalline anisotropy constant and $V_p$ is the volume of the nanoparticle. The superparamagnetic properties of nanoparticles can be controlled by adjusting anisotropy energy $E_A$ and hence the anisotropy constant $K$ which is an indication of strength of L -S coupling. The strength of these couplings is different in A and B sublattices of the spinel structure .Thus anisotropy energy and hence L-S coupling will have strong influence on the
superparamagnetism of nanoparticles. Both intrinsic anisotropy such as magnetocrystalline anisotropy and extrinsic anisotropies such as shape, surface anisotropies including induced anisotropies will have a bearing on the superparamagnetism.

1.8 Nanoscience and Nanotechnology

Nanoscience is the study of the fundamental principles of molecules and structures with at least one dimension roughly between 1 and 100nm. Nanotechnology is the application of these nanostructures that involves study, control and manipulation of nano materials [20-22]. This is a multidisciplinary area of research and development bringing together the disciplines of chemistry, biology, engineering and medicine. Nanomaterials because of novel electrical and magnetic properties they have wide applications in modern technology [23].

Many properties of solids depend on the size range over which they are measured. When the dimensions of materials are brought to nanoregime, there are tremendous change in chemical and physical properties. As the size of the particle reduces to nanoscale surface to volume ratio increases. This affects the physical, chemical, magnetic and electrical properties this is where quantum size effects starts playing their role [24, 25]. With the emergence of nanotechnology ferrite nanoparticles with controllable dimensionality along with novel magnetic and electrical properties became one of the topic of fundamental scientific research.

The potential applications of magnetic materials have enabled significant advances in modern technologies. But the applications of bulk materials are limited, hence magnetic nanoparticles are emerged as potential candidates for wide applications and expectations. The objectives for undertaking this research are given along with motivation.
1.9 Motivation for Present Work

Ferrites have been widely studied for their broad range of applications [28, 29]. With the advances in nanotechnology, these materials are now being studied in nanoregime in which they exhibit novel properties and hence may find new and increased applications [30 - 34]. Ferrite particles in nanoscales can be produced by a large number of methods like (1) ball milling [35] (2) sol-gel synthesis [36 - 38] (3) hydrothermal synthesis [39,40] (4) co-precipitation [41 - 43], etc. All methods have their inherent advantages and disadvantages.

The material properties which are microstructure dependent are found to vary depending on the method of preparation. Hence we find in literature a large number of publications of the same material prepared through different routes. Of all the possible methods co-precipitation method seems to be the simplest method which offers reliability and reproducibility at relatively low temperature required for processing. Even in this method the material properties are found to be different depending on the starting materials used, the pH of the NaOH solution and the temperature at which the precipitation takes place.

There seems to be a great deal of variation in the results obtained in the studies of Ni-Zn ferrite prepared by co-precipitation method itself. For example Parvateeswara Rao et al. [44] prepared Ni$_{0.65}$Zn$_{0.35}$Fe$_2$O$_4$ nanoparticles using co-precipitation method in which they used a 0.2 M NaOH solution and maintained at 60ºC. They obtained nanoparticles of $\approx$ 16nm which showed a saturation magnetization of 23emu/g for an annealing temperature of 800ºC.

S.K.Date et al. [45] prepared Ni$_{0.8}$Zn$_{0.2}$Fe$_2$O$_4$ using co-precipitation method obtained a particle size of 16nm and a saturation magnetization of 60 emu/g for an annealing temperature of 800ºC.
Santhosh et al. [46] prepared $\text{Ni}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_4$ ($x = 0$ to 0.7 in steps of 0.1) by co-precipitation method using 2M NaOH and they obtained a particle size of around 25 nm.

In a recent publication Kandaswamy et al. [47] prepared $\text{Ni}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_4$ ($x = 0$ to 1 in steps of 0.1) using 0.63 M NaOH solution and obtained particle sizes of around 9 nm and a saturation magnetization of around 38 emu/g.

Ni-Zn ferrites have wide variety of applications because of low magnetic coercivity, high electric resistivity, low loss and relatively high saturation magnetization. They are technologically very important materials.

The co-precipitation method is a low cost, but reliable method of nanoparticle preparation. It is an attractive method for the large scale preparation of nano – ferrites. Hence efforts can be made to standardize this method. In the present studies it is proposed to prepare $\text{Ni}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ ($x = 0.5, 0.6, 0.7$) under co-precipitation method using parameters different from those reported in literature. In the present studies 0.4 M NaOH was used as a precipitating agent. Solution of precipitating agent as well as the mixture of cationic solutions were both kept at 60° C and mixed at once to obtain maximum yield. Since annealing temperature is supposed to increase the particle size and hence the saturation magnetization, it is proposed to study the effect of annealing temperature on the particle size and other properties. Annealing temperature more than 800° C was not used, so as to keep the particles in nano-regime. The ferrite samples so prepared were studied using XRD, FE-SEM, VSM, FC-ZFC, MÖSSBAUER and IR techniques and the results are discussed in the light of the available earlier literature.
REFERENCES
