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A Review Study on Zinc Ferrite Thin Film

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Abstract:
Zinc ferrite has garnered significant interest in the research community due to its versatility and wide-ranging applications in various fields, including magnetic recording, gas sensing, supercapacitors, microwave devices, Electromagnetic interference (EMI) shielding, water treatment, High-frequency magnetic devices like (inductors and transformers) and biomedical applications as magnetic nanoparticles. As a type of soft magnetic material, zinc ferrite comprises zinc and iron atoms arranged in a specific structure, exhibiting remarkable electrical, magnetic, and optical properties. Notably, zinc ferrite possesses high resistivity, magnetoresistivity, saturation magnetization, low coercivity and permeability, bandgap, chemical stability, and thermal stability, making it a fascinating material. This review aims to delve into the simple, cost-effective, and eco-friendly synthesis methods, unique properties, and diverse applications of zinc ferrite, highlighting its potential for innovative technologies.

Keywords: Zincl Ferrite; Electrical Properties; Magnetic Properties; Chemical Bath Deposition Method.

Introduction:

Spinel ferrites, a subset of ferrites belonging to the spinel mineral group, offer a unique combination of properties. These properties include high resistivity, a wide range of frequency versatility in composition, time durability, low coercivity, chemical and thermal stability as well as environmental compatibility and cost effective. The general chemical formula for spinel structure ferrites is MFe_2O_4, where M represents a divalent metal ion such as Cu, Cd, Ni, Zn, Mg, etc. and Fe represents a trivalent iron ion. The spinel structure consists of 32 oxygen ions, which form a face-cantered cubic lattice, 16 trivalent iron ions, and 8 divalent metal ions. The unit cell has 96 interstitial sites, comprising 64 tetrahedral sites and 32 octahedral sites. This structure enables spinel ferrites to exhibit their remarkable properties, making them valuable for various applications. In a crystal structure, a cation located at a tetrahedral site is coordinated by four oxygen ions, forming a tetrahedral arrangement. Similarly, a cation at an octahedral site is surrounded by six oxygen ions, creating an octahedral coordination. Within a unit cell, there are a total of eight occupied tetrahedral sites and sixteen occupied octahedral sites. There are many types of ferrites. All types of ferrites have their own properties among them is zinc ferrite ($ZnFe_2O_4$). It contains zinc and iron oxide. Zinc Ferrite, exhibits interesting electrical and magnetic properties that make it valuable in various applications including magnetic recording, gas sensing, supercapacitors, microwave devices, Electromagnetic interference (EMI) shielding, water treatment, High-frequency magnetic devices like (inductors and transformers) and biomedical applications. In terms of electrical properties, zinc ferrite has high electrical resistivity, which is

beneficial for applications requiring electrical insulation. This property allows it to be used in electronic components to prevent unwanted electrical conduction. Regarding magnetic properties, zinc ferrite has a high magnetic permeability, making it suitable for applications in transformers, inductors, and microwave devices. It also has a relatively high Curie temperature, that means it can maintain its magnetic properties at higher temperatures compared to other ferrites. This characteristic is crucial for applications that involve varying temperature conditions as well as, zinc ferrite is chemically stable and resistant to corrosion and enhancing its durability in harsh environments. Its combination of electrical insulation, magnetic permeability, and thermal stability makes zinc ferrite a versatile material for various technological applications where both electrical and magnetic properties are essential. We can improve the property of zinc ferrite in several ways like doping where small amounts of other elements are added to the zinc ferrite structure to modify its properties.

Why Choose Zinc Ferrites?

Zinc ferrites have emerged as a fascinating material for research endeavours due to their unique amalgamation of properties, rendering them a versatile and valuable candidate for various applications. One of the primary reasons for choosing zinc ferrite is their intriguing magnetic behavior, which exhibits ferrimagnetic properties with high saturation magnetization and low coercivity. This attribute makes them an ideal material for investigating magnetism and magnetic materials.

Moreover, zinc ferrite boasts high electrical resistance, which is a coveted property in electronic devices, such as inductors and transformers. Their chemical stability and durability in harsh environments further enhance their appeal, as they can withstand oxidation and corrosion, ensuring longevity in diverse applications. The low toxicity of zinc ferrite is another significant advantage, rendering them biocompatible and suitable for biomedical applications, such as drug delivery systems, magnetic resonance imaging (MRI) and contrast agents.

The ease of synthesis and low cost of zinc ferrite also make them an attractive choice for researchers, as they can be readily prepared via various methods. This accessibility has led to a surge in research exploring the potential of zinc ferrite in various domains, including catalysis, sensors, and energy storage. Furthermore, zinc ferrite has exhibited promise in addressing environmental concerns, such as wastewater treatment and heavy metal remediation, due to their ability to remove pollutants and heavy metals from aqueous solutions. The distinct properties and potential applications of zinc ferrites have generated significant interest in the research community. As research on zinc ferrite continues to advance, its potential to revolutionize various fields and address pressing challenges is becoming increasingly evident. Overall, the unique magnetic properties, diverse applications, cost-effectiveness, and ease of synthesis make zinc ferrite an exciting research topic for research to explore new materials with promising properties and applications.

Synthesis Methods to Prepare Zinc Ferrites:

Structurally perfect pure and doped $ZnFe_2O_4$ nanocrystals were successfully prepared by various methods like SILAR method (Table 1), chemical spray pyrolysis method, chemical bath deposition, Sol-gel, Co-precipitation, microwave hydrothermal method, thermal decomposition, auto-combustion, Solvothermal method, microwave gel combustion method, etc.

Table1: Methods for the fabrication of $ZnFe_2O_4$

Material	Synthesis Method	Sintering/ calcination temperature	Crystal Size (nm)	Ref. No.
$ZnFe_2O_4$-CNTS	SILAR method	-	10–15 nm	1
ZnCuS	SILAR method	-	-	2
Mg: $Zn_xFe_{3-x}O_4$	Spray Pyrolysis technique	500 nm and 400 nm	500 nm and 400 nm	3
ZnS	Chemical spray pyrolysis method	300°C, 400°C and 450°C	25.96 nm 23.03 nm 18.37 nm/	4
$ZnMn_2O_4$/GNR	Spray pyrolysis method	75°C	-	5
$ZnFe_2O_4$	Chemical bath deposition	500°C for 3h	-	6
Cu_x $Zn_{(1-x)}S$	Chemical bath deposition	75°C for 90 min	-	7
ZnS	chemical bath deposition	300k for 24 h	300 to 1500 nm.	8
$ZnFe_2O_4$	Sol– gel spin coating process.	500°C for 3h	10 nm	9
$ZnFe_2O_4$	Sol-gel and spin coating method.	400° C to 500 °C	-	10
$MnZnFe_2O_4$	Co-precipitation method	60°C.	-	11
Co_{1-x} $Zn_xFe_2O_4$	Co-precipitation method	900°C for 4 h	200–800 nm	12
Co_{1-x} $Zn_xFe_2O_4$	Co-precipitation method	900°C for 4 h	28–31 nm	13
$Co_{0.5}Zn_{0.5}Fe_2O_4$	Co-precipitation method	500°C, 650°C, 1000°C for 7 h	21–130 nm	14
Co_{1-x} $Zn_xFe_2O_4$	Co-precipitation method	900°C for 15 min	17 nm	15
$ZnFe_2O_4$	Thermal treatment method	723- 873 K	17–31 nm	16
$ZnFe_2O_4$	Unique solid-state combustion method.	150°C for 2h 250°C for 2h 900°C for 2h	25 nm 29 nm and 60 nm	17
$ZnFe_2O_4$	sol–gel auto combustion method	375°C	30 nm	18
Zn doped $CoFe_2O_4$	Microwave gel combustion	-	12.38nm - 15.79nm	19
$Zn_{1-x}Ba_xFe_2O_4$	auto combustion method	100°C for 2 h	39.5 nm to 47.6 nm	20
$ZnFe_2(C_2O_4)_3$	Surfactant-free solvothermal method	20°C for 24 h	100–200 nm	21
MnFe2O4/ Graphene and ZnFe2O4/ Graphene	Solvo-thermal methods	200°C for 10h	12nm-19.8nm	22
$ZnFe_2O_4$-MS	solvothermal reaction	-	-	23
$ZnFe_2O_4$	Pulsed laser deposition (PLD	500°C	-	24
$ZnFe_2O_4$	Pechini process	400°C to 900°C	8–62 nm	25
$ZnMn_2O_4$	Chemical rout	300°C	150 nm	26

SILAR (Successive Ionic Layer Adsorption and Reaction):

The Successive Ionic Layer Adsorption and Reaction (SILAR) technique is a flexible approach used for depositing thin films or coatings onto substrates. To prepare zinc ferrite thin films using SILAR, the substrate is first cleaned and prepared to ensure good adhesion of the film. Next, two separate solutions are prepared, one containing zinc ions and another containing iron ions, by dissolving zinc and iron salts in suitable solvents. The SILAR process involves alternately dipping the substrate into the zinc ion solution and then the iron ion solution, allowing for the adsorption of a monolayer of ions on the substrate, followed by a reaction to form a layer of zinc ferrite. After each immersion cycle, the substrate is rinsed to remove excess solution and then dried before the next immersion step. By repeating these cycles multiple times, a thin film of zinc ferrite with the desired thickness can be achieved.

The SILAR method offers precise control over the film thickness and can be used to create uniform coatings. Its versatility has led to its successful application in various material synthesis processes. By leveraging the SILAR technique, researchers can fabricate high-quality zinc ferrite thin films with tailored properties, unlocking their potential for various applications. Shrikant S. Raut et.al. $ZnFe_2O_4$–CNT prepared by SILAR method Iron sulfate, zinc sulfate, sodium hydroxide, hydrogen peroxide, ammonia is use with annealed temperature at 300°C [1]. Odunaike et.al. synthesized ZnCuS thin films using the SILAR method, employing zinc chloride, copper chloride dihydrate, and thiourea as precursors, along with various complexing agents such as EDTA, TEA, and NH_4OH. [2].

Chemical Spray Pyrolysis Method:

The chemical spray pyrolysis method is a convenient technique for depositing zinc ferrite thin films. The process starts with preparing a precursor solution that includes zinc and iron compounds. This solution is then atomized into fine droplets using a spray nozzle, which are subsequently sprayed onto a heated substrate. The droplets undergo pyrolysis, a process in which the solvent evaporates, and the remaining metal ions react to form zinc ferrite on the substrate surface. The deposited film can be subjected to annealing at a specific temperature for a predetermined duration to enhance the crystallinity and properties of the zinc ferrite film. This method allows for the formation of high-quality zinc ferrite thin films with tailored properties, making it a valuable technique for various applications. Sevda Saritas et.al synthesis Mg dopped zinc ferrite Spray Pyrolysis technique in various substrate. and recorded that change in temperature and molarity of solution are affected the structural and magnetic properties of thin film [3]. Offor et al. fabricated ZnS thin films through the chemical spray pyrolysis technique, employing zinc chloride as the cationic source and ethylenediamine tetraacetate (EDTA) as a complexing agent. [4]. Ahuja et.al. prepared $ZnMn_2O_4$/GNR by using Spray Pyrolysis technique and recorded excellent electrochemical performance [5].

Chemical Bath Deposition Method:

Chemical bath deposition method is the simple cost effective and environmentally friendly method. Normally, it is need to inorganic salt (nitrate, chloride, sulphate, etc.) Dissolve the salts separately in distilled water or ethanol. Create a solution containing zinc and iron salts (nitrate/sulphate/ chloride) in a suitable solvent. Immerse the substrate into the bath

solution. Then allow the reaction between the substrate and the bath solution to take place. The zinc and iron ions will react with the substrate material to form Zinc Ferrite. After the deposition process is complete, wash the substrate to remove any excess solution or impurities. Then, dry the substrate thoroughly. Shinde et.al. prepared $ZnFe_2O_4$ using chemical bath deposition method with diverse concentrations of zinc, iron chloride precursor. Film was annealing at 450°C for 3h. And investigated there structural, morphological, and electrochemical properties [6]. Derejaw et.al. $Cu_xZn_{1-x}S$ prepared by chemical bath deposition method using EDTA as a complexing agent. substituting the copper in zinc ferrite increase the band gap [7]. Onyeka et.al. zinc sulphide (ZnS) thin film by chemical bath deposition method at room temperature 300k. zinc acetate and sulphide are used as a precursor with complexing agent [8].

Sol-gel Method:

In this method, dissolve zinc and iron (nitrate/sulphate/ chloride) in a suitable solvent to create separate precursor solutions. Mix the precursor solutions and add a hydrolysing agent like ammonia to induce hydrolysis and condensation reactions. Then, the mixed solution was poured into a dish and solidification of the gel. then drying the gel to remove the solvent and obtain a solid material. finally, heat the dried gel at a high temperature in a furnace to decompose organic components, promote crystallization, and get the Zinc Ferrite phase. After cooling we get the desired product. Overall, it is simple, and low temperature method provide the homogeneous materials with uniform composition and properties, leading to consistent product quality. As well as this method is versatile and can be employed to synthesize a broad array of materials, including oxides, glasses, and composites, making it suitable for various applications. Singh et.al. prepared $ZnFe_2O_4$ nanoroad by sol–gel method using zinc sulphate and ferric nitrate material in ratio of 1:2 M dissolve in ethanol. homogeneous precursor solution is obtained at 80°C for 2 h [9]. Raut et al. prepared the $Co_{1-x}Zn_xFe_2O_4$ nanoparticles by sol-gel auto-combustion method with the Citric acid as the fuel. used the ratio of metal nitrates and citric acid is 1:3. A further annealing at temperature of 600°C was displayed to obtain the $Co_{1-x}Zn_xFe_2O_4$ nanoparticles [10].

Co-precipitation Method:

Co-precipitation is an easy, inexpensive and low temperature synthesis method. This method often yields nanoparticles with high purity. To prepare Zinc Ferrite using the co-precipitation method, mix the solutions of zinc and iron salt i.e. (nitrate/sulphate/ chloride) together. Then add a base like ammonium hydroxide to the mixed solutions to cause the formation of a precipitate containing zinc and iron hydroxides. This precipitate is then aged to allow for further reaction and crystallization. After aging, it filters and wash the precipitate to remove impurities. The next step involves drying the washed precipitate to eliminate excess water. And finally, the dried precipitate is calcined at high temperatures to convert the zinc and iron hydroxides into Zinc Ferrite. Ismail et.al. fabricated $MnZnFe_2O_4$ nanoneedles using one-pot coprecipitation method by varying reaction parameters i.e., temperature, pH of the suspension, and initial molar concentration. use the annealing temperature 60ºC in vacuum oven. and recorded the high surface area, narrow pore size distribution and mesoporous nanostructure of $Mn_{0.5}Zn_{0.5}Fe_2O_4$ nanoneedles [11]. Andhare et.al. used the co-precipitation method to prepared the $Co_{1-x}Zn_xFe_2O$ nanoparticles of annealing temperature 900°C for 4 h.

Analytical grade cobalt, chloride hexahydrate zinc chloride ferric chloride and sodium hydroxide are used as a precursor. and recorded, magnetic properties are decreases with increasing substitution of Zn_2þ in cobalt ferrite [12]. Sagayaraj et.al. successfully synthesis $Co_{1-x}Zn_xFe_2O_4$, here ferrite sulphate, cobalt sulphate, Zinc sulphate heptahydrate, polyvinylpyrrolidone were used [13]. Iqbal et. al. prepared $Co_{0.5}Zn_{0.5}Fe_2O_4$ nanoparticle with different annealing temperature i.e., annealed at 500°C, 650°C and 1000°C. and found that towards human peripheral cells their toxicity to be low [14].

Auto-combustion Method:

This is the simple, cost effective, energy efficient method because it involves self-sustaining combustion reaction to drive the synthesis process, reducing the need of external heating source. In this technique dissolve the required amount of zinc nitrate and iron nitrate in a suitable solvent to form a homogeneous solution then added the suitable fuel such as urea or citric acid, to the precursor solution. During the process the fuel will act as a combustion agent. Stir the solution to ensure thorough mixing of the components. Then, heat this solution gradually to initiate the auto-combustion reaction. The heat from the reaction will drive off the solvent and initiate the formation of the zinc ferrite. As the temperature increases, the fuel will start to decompose, releasing gases that create a self-sustaining combustion process. This combustion reaction helps in the formation of the desired zinc ferrite phase. Allow the reaction to proceed until combustion is complete. Once the reaction subsides, cool the resulting product. Bardhan et.al prepared $ZnFe_2O_4$ in powder form using the unique solid-state combustion method at lower temperature. They use the zinc and iron nitrate salt, hydrated citric acid with double distilled water to prepared the saturated solution. To form the highly viscous gel ethylenediamine are added in it slowly. For drying the gel set the heating temperature at 120^o C for 4. If the calcinating temperature is increase then the ratio of ferric to ferrous ions increases along with particle size of ZFO are also increase [17]. Pradeep et.al. recorded the structural, magnetic and electrical properties of zinc ferrite prepare by the sol–gel auto combustion method. They use the zinc and iron nitrate salt, citric acid solution with deionized water. ammonium hydroxide is use to adjusted the pH of the solution up to 7. During the combustion process enormous heat absolve has played the important role in inversion of distribution of cations [18]. Agrawal et.al. successfully prepared zinc doped cobalt ferrite composite using microwave gel combustion. zinc, iron, cobalt nitrate is use as precursor which dissolve in 100 ml de-ionized water. use the Citric acid as a chelating agent prepared solution is stirring 20 min at room temperature then place it in microwave oven for evaporation. after that get the gel which is washed and dried at 82°C and obtain the desired product. this method plays a vital role in the alteration and development of crystal structure, morphologies, dielectric properties [19]. Tholkappiyan et.al. prepared the $Zn_{1-x}Ba_x Fe_2O_4$ nanoparticles using the glycine as fuel and nitrates as precursors many concentrations of barium doped zinc ferrite was prepared [20].

Solvothermal Method:

solvothermal methods are valuable for their ability to develop high-quality nanoparticles with controlled properties. In which the first step dissolve zinc and iron salt precursor in a suitable solvent like ethylene glycol. Mix the precursor solution thoroughly to ensure homogeneity. Transfer the precursor solution into an autoclave, a sealed high-pressure reaction vessel. Heat the autoclave to an elevated temperature

(usually above 100°C) and pressurize it. The high temperature and pressure inside the autoclave create the solvothermal conditions necessary for the reaction. Allow the reaction to proceed under solvothermal conditions for a specific period. This allows the zinc and iron ions to react and form Zinc Ferrite nanoparticles. After the reaction, cool down the autoclave, open it, and retrieve the Zinc Ferrite nanoparticles. Wash the nanoparticles to remove any residual solvent or impurities. Dry the Zinc Ferrite nanoparticles thoroughly. Jia et.al. use the solvothermal method for preparing the $ZnFe_2(C_2O_4)_3$ with annealed temperature 400 °C for 2 h [21]. Nivetha et.al. prepared the $MnFe_2O_4$ /Graphene and $ZnFe_2O_4$ /Graphene Nanocomposites with the help of ethylene glycol. The precursor was calcined at different temperature of 200 °C for 10 h to produce the $ZnFe_2O_4$ nanoparticles [22]. Wang et.al. synthesis $ZnMn_2O_4$ with high temperature calcined at 600°C for 2h [23].

Comparison of synthesis methods:

Recently, there has been considerable attention from researchers towards zinc ferrite materials and the various methods used for their synthesis. The method of synthesis and other factors have a profound consequent on the material's properties, making the choice of synthesis method crucial. Various methods have been explored in the literature, including chemical bath deposition, successive ionic layer adsorption and deposition, spray pyrolysis, co-precipitation, spin coating, and sol-gel processing. Upon reviewing these methods, chemical bath deposition stands out as the most suitable technique for synthesizing zinc ferrite. This method offers precise control over the deposition process, enabling the formation of high-quality films with tailored properties. Chemical bath deposition is particularly useful for depositing materials on large surfaces or complex shapes and does not require specialized equipment like vacuum chambers. Additionally, this low-temperature process preserves the material's properties and prevents substrate damage. The versatility of chemical bath deposition allows for easy modification of material composition, thickness, and morphology, making it an ideal technique for exploring the properties and applications of zinc ferrite and other materials.

Characterization of Zinc Ferrite Films:

Characterizing Zinc Ferrite involves various analytical techniques to understand its structure, composition, and properties. These are as follows:

X Ray Diffraction study:

XRD is employed to determine the crystal structure and phase purity of Zinc Ferrite. By analysing the diffraction pattern of X-rays scattered by the sample, one can identify the crystalline phases present in the material. The crystallite size measurements derived from Scherrer's equation vary from those obtained through Rietveld analysis across various synthesis techniques. Raut et al. conducted a wide-angle X-ray diffraction (XRD) analysis of the ZFO-CNT composite, as well as individual ZFO and CNT samples deposited on a stainless-steel (SS) substrate. The XRD patterns revealed broad peaks at $2\theta=35°$ and 62°, which show the cubic spinel structure of $ZnFe_2O_4$. Additionally, the characteristic (002) peak of graphitic carbon was observed, confirming the presence of carbon nanotubes (CNTs) in the composite material [1]. Saritas et al. presented the XRD diffraction pattern of Mg-doped zinc ferrite grown on a glass substrate confirming the material's cubic spinel structure. The lattice constants were determined to be a = b = c = 8.350 Å. Furthermore, the maximum crystal size of Mg-doped zinc ferrite was found to be 37.5 nm, which is smaller than that of Mg-doped iron oxide crystals. This suggests that the doping of Mg into zinc ferrite bring about a

reduction in crystal size, potentially influencing the material's properties and behavior [3]. Ismail et al. observed exceptional thermal stability up to 800°C, demonstrating the material's capability to withstand significant temperature fluctuations without degradation, making it a promising candidate for device applications [11]. Andhare et al. investigated the XRD patterns of $Co_{1-x}Zn_xFe_2O_4$ nanoparticles with various zinc concentrations (x = 0, 0.3, 0.5, 0.7, and 1). The XRD analysis revealed that all spacemen's exhibit a cubic spinel structure, pertaining to the Fd-3m space group, as indicated by the presence of specific reflection planes. Notably, the diffraction angles conformed to zinc ferrite (2θ = 35.27°, 62.225°, 56.671°) were found to be lower than those of cobalt ferrite, as confirmed by JCPDS values. This suggests a structural transformation with the incorporation of zinc into the cobalt ferrite lattice [12]. Pradeep et al. XRD results show that the $ZnFe_2O_4$ sample has undergone successful crystallization, as confirmed by Rietveld analysis. This analysis involved fitting a pseudo-Voigt profile in size-strain mode to the XRD data, providing further insights into the sample's structural properties [24]. Singh et al. recorded cubic spinel structure with a crystallite size of at least 10 nm, indicating a nanocrystalline nature by XRD [18]. Jia et al. conducted an XRD analysis of the hydrothermally synthesized precursor, which revealed a pattern consistent with zinc iron oxalate. calcination at 400°C in air for 2 hours with a heating rate of 1°C/min, the resulting XRD pattern showed diffraction peaks matching the pure cubic phase of zinc ferrite ($ZnFe_2O_4$) with a spinel structure, free from impurity phases. This indicates a complete transformation of the oxalate precursor into crystalline ferrite spinel with high phase purity, confirming the effectiveness of the calcination treatment [21]. Tholkappiyan et al. successfully synthesis of zinc ferrite and revelled the formation of a pure phase material with a cubic crystal structure using XRD. The XRD was show the presence of a single-phase zinc ferrite with a cubic lattice, thereby validating the efficacy of the synthesis procedure [20]. Torres et al. employed X-ray diffractometry to investigate the structural properties of the $ZnFe_2O_4$ film, revealing epitaxial growth without any secondary phases. The φ scans of the $ZnFe_2O_4$ (511) reflection exhibited a fourfold symmetry, which is indicate well-ordered crystalline structure as well as the magnetic moment of the films was measured as a function of applied field at both room temperature and 5 K which provided valuable insights into magnetic properties of the material [24].

Fourier Transform Infrared study:

FTIR supports to study the functional groups present in Zinc Ferrite. It can provide information about bonding characteristics and chemical composition. Andhare et al. employed Fourier Transform Infrared (FTIR) spectroscopy to investigate the material's structural properties, and the resulting spectra confirmed the successful formation of the ferrite phase [12]. Sagayaraj et al. interpreted the FTIR results, which revealed cationic coordination and exchange interactions between the tetrahedral and octahedral sites. The spectra showed a clear distinction between the high-frequency absorption bands corresponding to the tetrahedral site and the lower-frequency absorption bands associated with the octahedral site, Furnishing important perspective on the material structure and magnetic properties [13]. Praveena et al. recorded structural properties of spinel ferrites by using FTIR and revealed the characteristic intrinsic cation vibrations in the spinel structure. as well as the study found a positive correlation between zinc substitution and the lattice constant, indicating a structural expansion with

increasing zinc content which provided valuable insights into the material's structural and magnetic properties [15]. Naseri et al. used the FTIR spectroscopy analysis, and revealed the presence of absorption bands at 370 and 368 cm^{-1}, characteristic of Zn-O bonds, and at 545 and 542 cm^{-1}, attributed to Fe-O bonds. The spectra also indicate the presence of organic compounds in the samples, evidenced by the appearance of peaks at 1346, 1761, and 3798 cm^{-1}, as well as at 1503 and 1779 cm^{-1}. From this all show that successful incorporation of metal-oxygen bonds and organic moieties in the material [16]. Pradeep et al. employed FTIR spectroscopy to investigate the structural properties of nano $ZnFe_2O_4$ particles, revealing the of a spinel structure. The FTIR spectra provided clear evidence of the material's spinel arrangement, confirming the successful synthesis of nano $ZnFe_2O_4$ with a crystalline structure [18]. Gharagozlou et al. investigated the FT-IR spectra of zinc ferrite powders and polymeric intermediates, which were synthesized using different ethylene glycols and calcination temperatures. The spectra revealed peaks at approximately 3440 cm^{-1} and 1740 cm^{-1} in the polymeric intermediates, which were attributed to the stretching vibrations of hydroxyl groups and uncoordinated carbonyl groups, respectively. This research provides valuable insights into the molecular structure and bonding arrangements of the material [25].

Morphology study:

The morphology of Zinc Ferrite plays a significant role in determining its physical and chemical properties, such as surface area, reactivity, and magnetic behaviour. Techniques like SEM / FESEM and TEM/ HRTEM are commonly used to visualize and study the morphology of Zinc Ferrite at the nanoscale. As well as use the Energy-Dispersive X-ray Spectroscopy (EDS) is often coupled with SEM to analyse the elemental composition of Zinc Ferrite. It can provide information about the distribution of elements within the sample. AMF and XPS characterizations is use to gain the magnetic behaviour and surface properties of Zinc Ferrite, providing a comprehensive understanding of its characteristics. Raut et al. employed X-ray photoelectron spectroscopy (XPS) to examine the chemical composition and oxidation state of the ZFO-CNT thin-film surface. The impedance study reveals the superior performance of these thin films, due to their reduced charge-transfer resistance, a significant advantage over conventional methods that utilize binders for powder electrodes, which inevitably lead to increased resistance [1]. Saritas et al. observed that XPS and EDX spectroscopy revealed the presence of magnesium in magnesium-doped zinc ferrite and magnesium-doped iron oxide structures. Although magnesium and zinc flaw exhibit non-magnetic characteristics, the smaller atomic radius of magnesium enables it to more readily substitute into the crystal lattice, thereby modifying the magnetic behavior of the material. This discovery suggests that magnesium doping can significantly influence the magnetic properties of these structures [3]. Andhare et al. observed that the SEM images reveal agglomeration of spherical grains, driven by differing magnetic properties. The EDX spectra confirm the successful formation of cobalt zinc ferrite, while UV-Vis spectroscopy studies the energy band gap's variation with increasing zinc concentration in cobalt ferrite, shedding light on the material's optical properties [12]. Abhijeet V. Shinde et al. found that the binding energy range of 530-533 eV can be deconvoluted, indicating the presence of multiple chemical states or species in the material, which can be further analysed and identified [6]. Singh et al. observed that the scanning electron microscopy (SEM) image

of the film reveals a porous surface topology with a uniform distribution of nanorods. Furthermore, the increase in the band gap of $ZnFe_2O_4$ confirms the presence of quantum confinement effects, indicating a significant reduction in particle size [9]. Raut et al. confirmed the chemical composition of Co-Zn nanoparticles using Energy Dispersive X-ray Analysis (EDAX), which revealed a degree of crystallite agglomeration during sample preparation. Additionally, X-ray Diffraction (XRD) data verified the single-phase cubic spinel crystal structure of the nanoparticles [10]. Praveena et al. observed that TEM imaging of $Co_{0.4}Zn_{0.6}Fe_2O_4$ revealed nanoparticles with a diameter of 17 nm, exhibiting a roughly spherical shape and uniform size distribution, indicating a high degree of morphological uniformity among the ferrite particles [15]. Agrawal et al. observed that Field Emission Scanning Electron Microscopy (FESEM) analysis revealed random agglomeration of pure and Zn-doped cobalt ferrite nanoparticles (NPs). To further elucidate the elemental composition of pure and Zn-doped cobalt ferrite NPs, Energy Dispersive X-ray (EDAX) spectroscopy analysis was conducted. The EDAX spectra of the pure cobalt ferrite sample revealed its elemental structure [19]. M. Chakraborty et al. used EDAX microanalysis to investigate $ZnFe_2O_4$ thin films which confirming the presence of Zn, Fe, and O ions with a cation ratio close to ideal stoichiometry. FESEM measurements showed no morphological differences between samples annealed at various temperatures, with an average particle size of 15-18 nm [29].

Magnetization study:

For study the magnetization of Zinc Ferrite to understand its magnetic properties magnetic measurements are use. One common technique used in such studies is Vibrating Sample Magnetometry (VSM). In VSM the sample of Zinc Ferrite is subjected to an applied magnetic field while measuring the resulting magnetization. This process helps in determining important magnetic parameters such as saturation magnetization, coercivity, remanence, and magnetic anisotropy. Raut et al. studied the $Co_{1-x}Zn_xFe_2O_4$ spinel ferrite system, synthesizing it using the sol-gel auto-combustion technique. They found that increasing zinc concentration decreases magnetic parameters, and the material consists of non-interacting single domain particles with cubic anisotropy. By controlling synthesis conditions, the properties of this material can be tailored for advanced technological applications [10]. Sagayaraj et al. investigated cobalt ferrite materials and made several key discoveries. By adding non-magnetic zinc (Zn) material, they found that magnetization increases, as confirmed by VSM analysis. TGA/DSC analysis showed weight loss and heat flow changes, indicating endothermic and exothermic processes. The development of new technologies is significantly influenced by these findings. [13]. Iqbal et al. made a groundbreaking observation, discovering that $Co_{0.5}Zn_{0.5}Fe_2O_4$ nanoparticles (NPs) display a significant augmentation in magnetic moment when subjected to elevated annealing temperatures. This reveals that thermal processing has a profound influence on the physical characteristics of these NPs. Additionally, the researchers noted that the synthesized NPs exhibit minimal toxicity towards human peripheral cells, rendering them a promising material for various uses. Overall, this study underscores the potential of tailoring the properties of $Co_{0.5}Zn_{0.5}Fe_2O_4$ NPs through thermal processing control [14]. Praveena et al. uncovered that the replacement of zinc results in a notable expansion of the lattice constant and a substantial increase in X-ray and bulk density. Furthermore, the samples displayed ferromagnetic behavior at room temperature. The researchers also observed

that the dielectric properties were modified by zinc substitution, which was ascribed to the electron transfer mechanism between Fe ions. This investigation reveals the profound effect of zinc substitution on the material's physical and magnetic characteristics [15]. Gharagozlou et al. successfully synthesized nanocrystalline zinc ferrites and tailored their magnetic properties by controlling the calcination temperature and precursor. They found that single-phase, high-purity zinc ferrite nanoparticles could be synthesized at lower processing temperatures. The particle size was observed to increase with the calcination temperature, and the choice of precursor also had an impact: PEG yielded larger particles, while EG resulted in smaller ones. Additionally, the saturation magnetization increased with the calcination temperature, and the researchers noted that, at a constant calcination temperature, the samples prepared with EG showed a lower magnetization than those prepared with PEG. By establishing a clear structure-property correlation, the researchers were able to tune the magnetic properties of zinc ferrite nanoparticles [25]. Agrawal et al. observed that the magnetization of $CoFe_2O_4$ nanoparticles increases with higher Zn content, revealing a strong correlation between magnetization and particle size. The magnetic hysteresis loop confirms their ferromagnetic nature. This groundbreaking finding suggests that Zn doping and particle size control can be harnessed to tailor the magnetic properties of these nanoparticles, unlocking new avenues for their applications [19]. Naseri et al. made some significant research findings. Specifically, they discovered that the coercivity fields (Hc) were negligible, and the samples exhibited super-paramagnetic behavior. Furthermore, they found that the saturation magnetization decreased from 4.49 to 0.74 emu/g as the particle size increased from 17 to 31 nm. The researchers identified cation inversion as a key factor contributing to the variation in magnetic properties between zinc ferrite nanoparticles and their bulk form [25].

Electrochemical study:

To conducting the study electrochemical behaviour of Zinc Ferrite, investigate its electrochemical properties, such as its behaviour in different electrolytes, charge storage capabilities. To analyse the electrochemical performance of Zinc Ferrite used the common techniques like cyclic voltammetry, electrochemical impedance spectroscopy, and galvanostatic charge-discharge measurements. By studying the electrochemical behaviour of Zinc Ferrite can conform into its redox processes, charge storage mechanisms, and electrochemical stability. This information is crucial for evaluating the material's suitability for use in various electrochemical devices. Shrikant S. Raut et al. utilized the SILAR method to fabricate hybrid ZFO-CNT thin films as supercapacitor electrodes. The ZFO-CNT-based solid-state symmetric device show Specific capacitance: 92.20 Fg^{-1}, Specific energy:12.80 Wh kg^{-1}, Specific power: 377.86 Wkg^{-1} and good stability [1]. Sharma et al. developed an optimized supercapacitor, $ZnMn_2O_4$/GNR||$ZnMn_2O_4$/GNR, with a maximum operating voltage of 2.7 V. The high diffusion coefficient and short relaxation time indicate its exceptional performance and stability at elevated temperatures. As well as the supercapacitor cell demonstrates outstanding flexibility and durability, evident from its consistent performance over consecutive galvanostatic charging/discharging cycles under harsh conditions [5]. Shinde et al. has led to the development of high-performance solid-state Hybrid Supercapacitor cells (HSCs), outperforming traditional carbon-based supercapacitors. The achievements include exceptional specific capacitance of 123.8 F/g and impressive energy density of 55.72 Wh/kg These breakthroughs showcase the

potential of solid-state HSCs to revolutionize energy storage [6]. Ismail et al recorded the outstanding electrochemical performance of $MnZnFe_2O_4$ nanoneedles-based supercapacitors, with a specific capacitance of 783 Fg^{-1} that surpasses other ferrite materials. Moreover, the $MnZnFe_2O_4$ nanoneedles/activated carbon electrodes achieved an impressive energy density of 15.8 Wh kg^{-1} at a power density of 899.7 W kg^{-1}, making them a highly promising candidate for supercapacitor applications [11]. Nivetha et al. discovered that $MnFe_2O_4$/Graphene and $ZnFe_2O_4$/Graphene nanocomposites are efficient electrocatalysts for generating hydrogen through the hydrogen evolution reaction. In acidic conditions, the nanocomposites showed good activity, with a low overpotential and a Tafel slope of 106.4 mV per decade and 114.3 mV per decade, respectively [22]. Wang et al. observed that the exceptional electrochemical performance can be attributed to the porous structure and nanoscale building blocks, which enhance the contact between the electrolyte and electrode, accommodate volume changes during discharge and charge processes, and offer a large number of active surface sites for lithium storage, thereby facilitating improved performance [23]. Yin et al. developed $ZnMn_2O_4$/CA hybrids with exceptional electrochemical performance, showcasing high reversible capacity (833 mAh g^{-1}), excellent high-rate capability, and superior cycling stability (99.9% Coulombic efficiency). The synergistic interaction between $ZnMn_2O_4$ nanoparticles and the 3D porous CA matrix enhances performance, making these hybrids promising for advanced energy storage applications [26].

Application of zinc ferrite:

Zinc Ferrite has various applications as a result of its unique electrical and magnetic properties. In the magnetic field, Zinc Ferrite is used in the production of magnetic recording media, magnetic sensors, microwave devices, and magnetic nanoparticles for biomedical applications like targeted drug delivery and magnetic hyperthermia. In the field of energy storage, Zinc Ferrite is studied for its potential use in batteries and supercapacitors due to its electrochemical properties. Its high charge storage capabilities make it a promising candidate for energy storage devices. Overall, Zinc Ferrite's applications span across magnetic materials, electronics, energy storage, and biomedical fields, showcasing its versatility and potential in various industries.

Sensor application:

Zinc Ferrite is useful for sensor applications because of its magnetic properties. The material's sensitivity to magnetic fields allows it to be employed in sensors for tasks such as position sensing and speed sensing, LPG and CO_2 sensing [9], photo sensing photovoltaics gas sensors, biosensors, optoelectronic and spintronics [3] magneto-optical recording media and magnetic sensors [13] Glucose sensor non-enzymatic sensors [29] acetone sensor, ethanol vapor sensor. This makes Zinc Ferrite a valuable component in sensor systems where detecting changes in magnetic fields is crucial. Sagayaraj et al. recorded $Co_{1-x}Zn_xFe_2O_4$/PVP morphology in range of 1μ to 400 nm. also, can increasing the magnetization by increasing the cobalt ferrite doped zinc material and it can be used for magnetic sensors [3]. Archana Singh et al. use the sol-gel method to prepared the $ZnFe_2O_4$ and recorded 10nm crystal size. they show the quantum confinement effect by increasing the band gap. their overall properties is shows there applicability as a LPG and CO_2 gas at room temperature [9]. Saritas et al. study the manganese dopped zinc ferrite crystal used to avoid the damage of ferrite crystal instead of $Zn2^+$. it shows the good paramagnetic property and show

their applicability in gas sensor [13]. Chung et al. recorded the at the annealing temperature 400 C Cobalt doped $ZnFe_2O_4$, photodetector performance is optimised and their photosensitivity reached up to 181.therefore it uses for photo sensing application [27].

Photocatalytic materials application:

Zinc Ferrite is beneficial for photocatalytic material applications because of its ability to absorb light and generate electron-hole pairs, which are essential for driving chemical reactions under light irradiation. This property makes Zinc Ferrite a promising material for processes like water splitting, pollutant degradation, and hydrogen production using solar energy. By harnessing solar energy for catalytic reactions, Zinc Ferrite contributes to the advancement of clean energy technologies. Odunaike et al. use the da lime glass substrate to prepared the ternary ZnCuS thin film using SILAR technique and recorded by increasing the SILAR cycle the conductivity is increasing and their resistivity is decreases [2]. Saritas et.al. successfully prepared the Iron oxide thin film and recorded their applicability in gas sensors, biosensors, photovoltaics because of their its chemical and thermal stability [3]. Emegha et.al. chemical bath deposition technique is use to prepared Zinc sulphide (ZnS) thin film and recorded the excellent optical and electrical properties [8]. Jia et al. prepared $ZnFe_2O_4$ nanorods using solvothermal method without using template or surfactant assistance and recorded rodlike morphology of $ZnFe_2(C_2O_4)_3$ precursor which show the photocatalytic under natural sunlight irradiation on methylene blue [21].

Energy storage application:

Zinc Ferrite is useful for energy storage applications because of its electrochemical properties. It shows promise in batteries and supercapacitors as a result of its high charge storage capabilities. This makes Zinc Ferrite a potential candidate for energy storage devices like supercapacitor [1,5,6,11] and lithium-ion batteries [23,27] contributing to advancements in the field of energy storage technologies. Bardhan et al. $ZnFe_2O$ prepared superior quality zinc ferrite nanocrystalline powdered materials at low temperature by using solid-state combustion method [17]. Ismail et al. prepared $MnZnFe_2O_4$ nanoneedles one-pot coprecipitation method and recorded specific capacitance of 783 Fg^{-1}. high columbic efficiency and outstanding longer stability which makes it suitable for supercapacitor application [11]. Raut et al. synthesis hybrid ZFO–CNT thin films with the help of SILAR method and recorded specific power of 377.86 W kg^{-1} with excellent stability 70 % over 2000 cycles [1]. Shinde et al. recorded Negative electrodes od ZnC materials show a maximum specific capacity of 544 mA h/g which is excellent candidate to conventional carbon-based negative electrodes [6]. Rodríguez Torres et al. discovered a significant finding related to the magnetic properties of ZnFeO thin films. When deposition pressures drop below 10^{-3} mbar, iron atoms occupy tetrahedral sites without Zn^{2+} inversion. This leads to the formation of an ordered magnetic phase, which exhibits a highmagnetic moment at room temperature [24]. Ahuja et al. optimized $ZnMn_2O_4$/GNR||$ZnMn_2O_4$/GNR, achieving a maximum operating cell potential of 2.7 V. This configuration delivers, high energy density: ~37 $Whkg^{-1}$, Power density: ~30 kWkg-1 (at 1.25 Ag^{-1}) and good cycling stability over 4000 cycles [5]. Ravi Nivetha et al. achieved a breakthrough in synthesizing nanocomposites, specifically: $MnFe_2O_4$/Graphene and ZnFe2O4/Graphene Using the sol-Vothermal route, they successfully prepared these nanocomposites, which exhibited: High current density and Steep Tafel slope. These remarkable properties make the prepared

nanocomposites highly promising for applications as high-performance electrocatalysts in acidic media, particularly for the hydrogen evolution reaction (HER) [22]. Wang et al. successfully synthesized high-quality porous $ZnMn_2O_4$ nanoparticles using a solvothermal reaction method. The resulting material demonstrated exceptional battery performance, retaining a specific capacity of 800 $mAhg^{-1}$ after 300 cycles at 500 mA g^{-1}. Even at a higher current density of 2 Ag^{-1}, the material showed a reversible capacity of 395 $mAhg^{-1}$, surpassing the theoretical capacity of graphite. The unique structure of the nanoparticles, comprising porous microspheres made up of tiny particles, contributed to their excellent cycling stability and rate capability [23].

Memory device application:

Zinc Ferrite is beneficial for memory devices applications because of its magnetic properties. It can be employed in magnetic memory devices due to its ability to retain magnetic information. This makes Zinc Ferrite a valuable material for applications in data storage and memory technologies. A. Pradeep et al. studied of $ZnFe_2O_4$ nanoparticles which recorded its behaviour ferrimagnetic at room temperature. ferrimagnetic behaviour of nano Zinc ferrite is comparatively higher which is useful for application of memory device [18]. Sharma et al. recorded if nickel substitution is increases then increase the dielectric constant. it used in memory devises because its low dielectric losses at higher frequency [30].

Microwave device application:

Zinc ferrite ($ZnFe_2O_4$) exhibits properties that make it an ideal material for microwave applications. Its elevated magnetic permeability, high dielectric constant, low dielectric loss tangent, and elevated Curie temperature Specifically, zinc ferrite is suitable for applications such as microwave absorbers, microwave resonators, microwave filters, microwave antennas, and radar absorption materials. Its ability to absorb microwave radiation, combined with its stability and durability, make it a valuable material in the development of microwave devices and technologies, offering potential advantages in terms of performance, reliability, and efficiency. Sharma et al. study on Mn^{2+} doped $Mg_{0.5}Zn_{0.5-x}Mn_xFe_2O_4$ nano-ferrites revealed a significant decrease in dielectric constant at low frequencies and minimal loss tangent values. The temperature-dependent dielectric analysis showed relaxation at higher temperatures, attributed to dipolar and interfacial polarization. These findings suggest the potential of these nano-ferrites for microwave device applications [31]. Gupta et al. successfully synthesized nanocrystalline nickel-zinc ferrite thin films using the citrate precursor method, yielding crack-free, transparent, and homogeneous films with uniform nanosized grains. The films exhibited high coercivity, attributed to their uniform microstructure and nanosized grains. Furthermore, their low dielectric loss properties in the microwave frequency range make them compatible for high-frequency applications, such as planar microwave devices [32]. Mezher et al. successfully synthesized $Mg_{0.6}Zn_{0.4}Fe_2O_4$ thin films via the sol-gel technique, optimizing the film thickness to 850 ± 30 nm, which resulted in excellent absorptance and a bandwidth of 9.10 GHz in the X-band frequency range (8.20-8.61 GHz and 10.21-11.03 GHz), making these ferrite thin films suitable for applications in solid-state microwave devices, optoelectronic devices, and soft microwave applications [33]. Hasan et al. synthesized Ni0.5Zn0.5Fe2O4 thick film paste with good morphology, dielectric, and magnetic properties. The paste showed suitable behavior for screen printing and improved the performance of a microstrip

patch antenna, enhancing return loss by 64.22% and bandwidth by 84.61% [34]. Xing et al. fabricated PANI/Zn ferrite composites via a simple two-step method, achieving excellent microwave absorption (RL = 54.4 dB at 17.6 GHz, thickness = 1.4 mm) in the Ku band [35].

Biomedical application:

Zinc ferrite ($ZnFe_2O_4$) has demonstrated significant potential in various biomedical applications, leveraging its magnetic, optical, and electrical properties. In the realm of drug delivery, zinc ferrite nanoparticles can serve as carriers for targeted delivery, ensuring precise and efficient treatment. Additionally, $ZnFe_2O_4$ can absorb near-infrared light, generating heat for hyperthermia cancer treatment. Its magnetic properties also make it suitable as a contrast agent for magnetic resonance imaging (MRI), enhancing image quality. Furthermore, zinc ferrite's electrical properties enable its use in biosensors for detecting biomolecules like glucose. Lastly, its biocompatibility, biodegradability, and non-toxicity make it an remarkable candidate for tissue engineering scaffolds, supporting cell growth and differentiation. Mallick et al. synthesized Zn-substituted lithium ferrite (LZFO) nanoparticles via the sol-gel route and dispersed them in reduced graphene oxide (RGO) layers. The LZFO-RGO nanocomposite showed enhanced inductive heating rates, making it a promising material for hyperthermia applications in cancer research [36]. Esteves et al. successfully fabricated carboxymethyl dextran-coated Mn/Zn ferrite nanoparticles, exhibiting stability, harmlessness, and superparamagnetic properties, rendering them ideal for biomedical uses without detrimental effects on cell viability [37]. Guo et al. synthesized manganese zinc ferrite nanoparticles ($Mn_{0.6}Zn_{0.4}Fe_2O_4$-NPs, MZF-NPs) and pegylated them (PEG-MZF-NPs). In vitro MRI studies revealed their potential as T2 relaxation contrast agents for magnetic resonance imaging and their potential for targeted diagnosis and treatment. Additionally, they successfully constructed CD44-shRNA plasmids, suggesting that PEG-MZF-NPs may also serve as gene transfer carriers for gene therapy [38]. Anooj et al. successfully synthesized zinc ferrite nanoparticles via the hydrothermal method. These nanoparticles were screened for their potential to detect pathogenic bacteria and exhibited in vitro anticancer activity against the MCF-7 cell line, as evaluated by the MTT assay [39].

Conclusion:

In recent years, the synthesis of zinc ferrite nanoparticles has attracted considerable attention because of their remarkable property, surpassing those of other soft ferrites. Zinc ferrites exhibit impressive electrical resistivity, magnetic permeability, and Curie temperature, making them a coveted material for various applications. Researchers are eager to exploit these ferrites, and they find the chemical bath deposition method an ideal technique for fabricating thin films due to its simplicity, cost-effectiveness, and eco-friendliness. This paper has comprehensively discussed the diverse applications of zinc ferrites, including biomedical, microwave devices, memory devices, and energy storage. Further investigation in this field may guide towards the development of novel materials with upgraded properties and unprecedented applications, potentially transforming various industries.

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