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Study of Dielectric and Magnetic Properties for $ZnFe_2O_4$ Nanoparticles Synthesized Using High-current Exploding Technique

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Abstract

The current article uses the exploding wire technique to examine the magnetic, electrical, and dielectric properties of nanoscale zinc copper ferrite ($ZnFe_2O_4$). The SEM micrographs confirm the almost uniform size distribution of the nanoparticles. The Mossbauer spectrum of the nanoparticles was recorded with an externally applied magnetic field at room temperature. The ferromagnetic behavior of the ZFO sample was determined through VSM measurements at ambient temperature, and the M-H loop analysis yielded information on the magnitude of remanence, coercivity, and optimum magnetization. Our findings indicate that the ZFO sample is ideal for applications requiring switching magnetic properties between ferromagnetic and paramagnetic states. The dielectric properties, including the frequency-dependent dielectric parameters, were determined using an LCR meter, and the dielectric relaxation phenomenon was found to be governed by a technique similar to Arrhenius. Additionally, we plan to investigate the magnetodielectric response (MDR) of the $ZnFe_2O_4$ nanoparticles under different external magnetic field strengths at specified frequencies and temperatures. Overall, the facile and economical nano ferrite produced through a high-output synthesis technique is highly appealing for electronic devices requiring fine-tuning magnetodielectric features.

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INTRODUCTION

In the course of investigating the characteristics of multiple-layered metallic magnetic and non-magnetic materials, a remarkable correlation between electrical hindrance and the magnetization alignment of adjacent layers (either unidirectional or opposite) was discovered. This phenomenon was named 'Giant Magnetoresistance' (GMR). Subsequently, the concept of a 'spin valve' was introduced, featuring two magnetic metallic layers parted by a non-magnetic spacer. Subsequently, magnetic field sensors, operational at ambient condition, were developed using spin valves, surpassing the capabilities of earlier anisotropic magnetoresistance (AMR) devices. In 1997, IBM incorporated GMR-supported magnetic read-pointers into their marketable diskdrive devices, leading to a widespread adoption of GMR-based read heads over AMR-assisted alternatives by other disk-drive companies. Out of the broader field investigating the influence of magnetic field-strength on electronic movement, known as 'magneto-electronics,' which encompasses AMR and numerous other effects, emerged a distinct subfield known as 'spintronics.' Within this realm of spintronics, a fundamental physics discovery swiftly catalyzed the growth of a substantial commercial sector, with sales exceeding $3 billion by 2005.

Significant advancements have been made in the realm of spinel-arranged ($M^{2+}M_2^{+3}O_4$) substances, primarily because of their outstanding chemical constancy and diverse utilities. The chemical formula MFe_2O_4 is typically consigned to these materials and they are collectively known as ferrites. Among the various ferrites, such as those like M = Fe, Co, Zn, Ni, Mn, etc., $ZnFe_2O_4$ (ZFO) stands out for its exceptional constancy thermally and chemically, coupled with impressive trails of electrical and magnetic parameters. The adjustability of its partially-conducting characteristics and its phase changeover characteristics under various surroundings create CFO as a prominent candidate amongst promising ferrites. Researchers have reported on the utility of ZFO in applications like catalysts and gas sensors [1–5]. It can be employed in magneto-optic memory devices, Lithium ion batteries, ferro-fluids, bio-sensors, picturing, and magnetic cooling devices [4]. The Al production industry extensively employs ZFO due to its excellent conducting ability, catalytic characteristics, and thermal steadiness [1]. In general, ferrites are renowned for distinctive attributes, including feeble dielectric loss, short in conductance (direct current), large value of permittivity, and spontaneous magnetization saturation (Ms). Such properties render ferrites appropriate for microwave absorbance. ZFO can exist in two possible structures: cubic and tetragonal. It adopts a tetragonal crystalline structure when slowly cooled, resulting in a (c/a) lattice structure proportion of roughly 1.06. The tetragonal phase of ZFO features an inverse spinel structure, with most Zn^{2+}ions residing in octahedral sub-lattice positions, while Fe^{3+} ions are evenly distributed between octahedral and tetrahedral sites [5]. Ineach unit cell of the tetragonal arrangement of ZFO, 8 Cu^{2+} ions are positioned at octahedral (B-site) sites, with 16 Fe^{3+} ions equally shared amongst tetrahedral and octahedral sites [6–8, 9]. This tetragonal arrangement remains stable at room temperature (300 K) and undergoes a transition to a cubic structure at temperatures of 633 K and higher, primarily driven by Jahn-Teller distortion. Magnetic properties play a pivotal role in this phase transformation, as the higher number intensity of Zn^{2+} ions at tetrahedral vacancies in the cubic structure leads to a higher value of magnetic dipole as compared to that of the tetragonal state**.**

Recognizing the possible applications of nano-sized ferrites, we have used an innovative synthesis procedure known as the 'exploding wire technique' to synthesize nano-sized ZFO. Nano-size spinel ferrites, including Copper-Zinc, Manganese-Zinc, Nickel-Zinc, Nickel-Copper, and Nickel-Calcium, are investigated [10, 11, 9]. The dielectric parameters are influenced by a combination of inter-grain, intra-grain, and electrode processes, which affect charge transport. The creation of space charge, reassemble/repositioning and dislocation of electrical charges collectivelylead to charge displacement [9]. The extent of electron interchange is determined by the presence of Fe^{2+}/Fe^{3+}ions at octahedral (B-site) positions in spinel ZFO, with the intensity of Fe^{2+}/Fe^{3+}cation pairs increasing as Zn oxidizes to Zn^{2+} [3]."

EXPERIMENTAL

This approach involves an exploration of the nonlinear behaviors within metallic wires, such as iron (Fe), copper (Cu), and zinc (Zn), with the aim of explaining the phenomenon of electro-explosion. Electro-explosion occurs when an extremely high current density, typically ranging from 10^6 to 10^8 Am², is abruptly applied to a conductive wire.

The typical sequence of events in the process of wire explosion and fragmentation can be summarized as follows: (a) The wire undergoes melting due to Joule heating, (b) the metal evaporates, causing the formation of a highly dense core surrounded by plasma, (c) the core contracts due to self-induced magnetism, and (d) the explosion fragments undergo rapid spatial expansion, leading to the formation of shock waves.

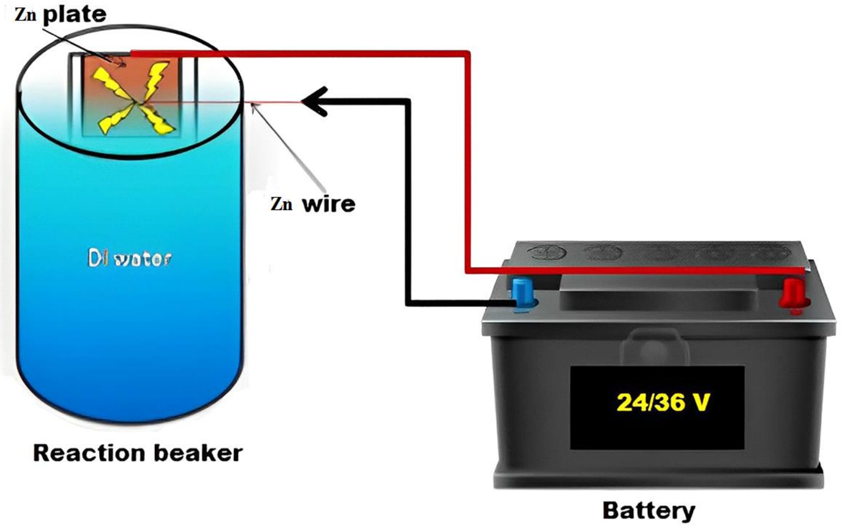

Figure 1. Experimental set up of exploding wire technique used to synthesize ZFO ($ZnFe_2O_4$) nanoparticles.

Despite significant efforts to understand the physics of explosive events, further research is necessary to gain a comprehensive understanding of the bursting characteristics exhibited by various types of wire materials.

The synthesis of spinel ZFO shown in Figure 1 was achieved using the exploding wire technique (EWT), which involved striking a copper wire (one millimeter diameter) against a plate made of Copper metal (5 millimeter thick) that was immersed in a constantly stirring aqueous solution of Fe_2O_3. The Zinc wire and Zinc plate were attached to the +ve and -ve terminals of a 12 Volt, 80 AmpHours DC power supply. The Zn wire explosion and Zn plate corrosion caused by electrical sparking generated nanoparticles of ZFO, which settled at the bottom of the beaker. Further details on the synthesis technique can be found in the referenced paper [5]. XRD analysis of ZFO was conducted at room temperature using Cu Lyman-α radiation having wavelength of 1.54Å. The data was scanned for the range 20° to 80° with step size of 0.02°. SEM images were acquired using a scanning electron microscope (XL-Philips 20). Alpha-A High Performance Frequency Analyzer with model Novo-control Technologies were used to obtain the complex impedance parameters. Dielectric analysis was performed using pallet form CFO, and a vibrating sample magnetometer with make and model, EG&G PARC and 4500, respectively were utilized for magnetization measurements.

RESULTS AND DISCUSSION

In Figure 2, the SEM image of ZFO displays uniform and small nanospheres arranged in a regular pattern to form spherical structures. The particle size ranges between micro to nanometers, with the majority falling within the range of 60±40 nm. Agglomeration of powder results in the formation of some small plate-like grains. The formation of larger grains may be due to enhance in the formation of crystallite hence leading to densification. The spectrum of EDAX supports the presence of Iron, Zinc, and Oxygen elements in the sample of ZFO. Table 1 displays the atoms present and weight percentages of constituent elements in CFO.

The dielectric constant (ε′) of the ZFO sample was measured at room temperature, using an LCR meter, as a function of frequency. The ε′ was calculated using the equation $\varepsilon' = C/(Ad)$, where C was the capacitance, d was the thickness and A was the flat surface area of the pallet. Figure 3(a) represents that the ε′ decreases as the frequency increases. The data is shown for the frequency ranging from 0 Hz-10 MHz. It was observed that the ZFO sample exhibits rapid dispersion of dielectric constant value at low frequencies and becomes independent of frequency variation at higher frequencies. This behavior can be described by Koop's theory and polarization of Wagner interfacial type. In accordance to the mentioned theories the conductive grains of the dielectric medium were separated by the high resistive grain boundaries. Here, the grains are effective at high frequency, whereas the grain boundaries are at low frequencies,

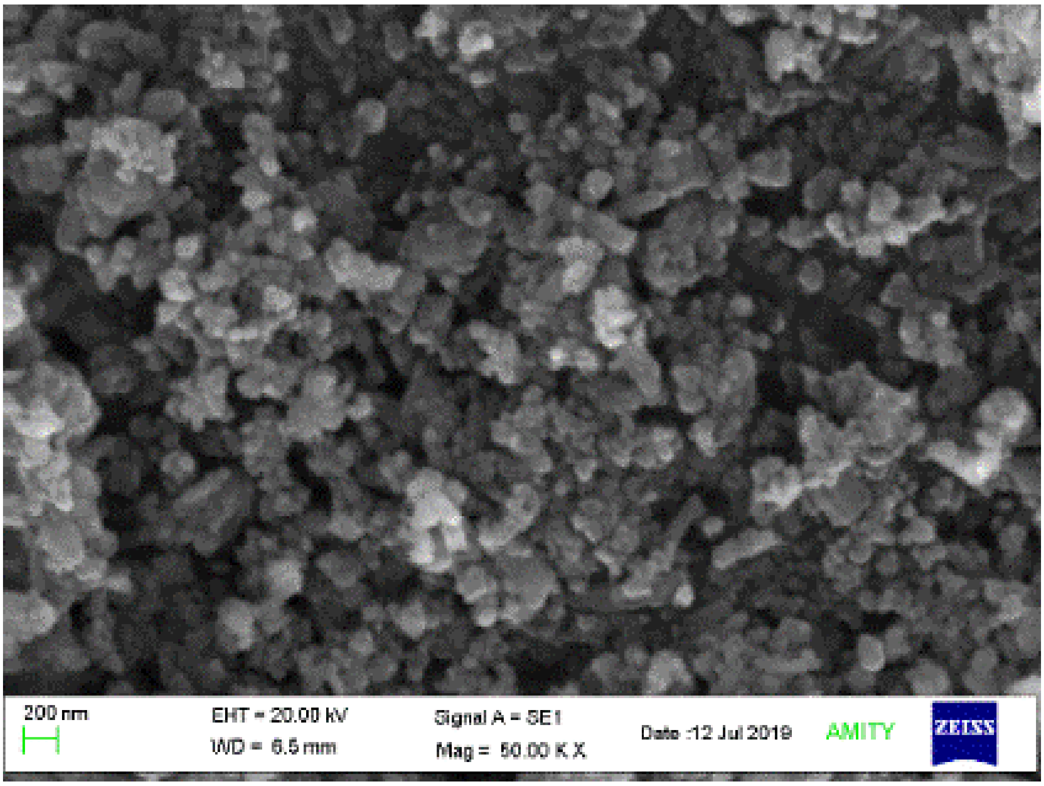

Figure 2. SEM micrographs of ZFO ($ZnFe_2O_4$) nanoparticles annealed at 650° for 7 hours.

Table 1. EDAX data of ZFO ($ZnFe_2O_4$) nanoparticles annealed at 650° for 7 hours

Elements	Weight %	Atomic %
O (K)	20.2	50.9
Fe (K)	49.21	33.42
Zn (K)	29.	16.
Total	100	100

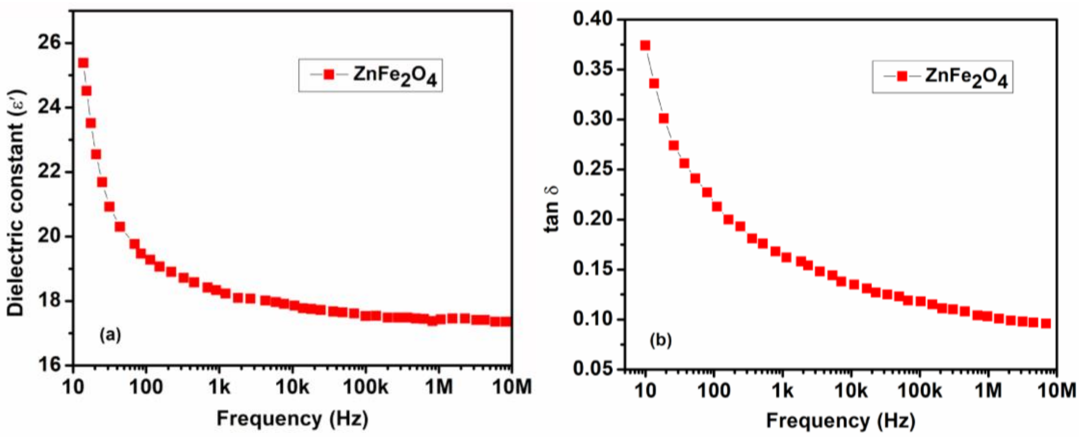

Figure 3. (a) Real part of electric constant (ε′) of ZFO ($ZnFe_2O_4$) nanoparticles annealed at 650° for 7 hours as function of frequency (b) tan δ versus frequency of ZFO ($ZnFe_2O_4$) nanoparticles annealed at 650° for 7 hours.

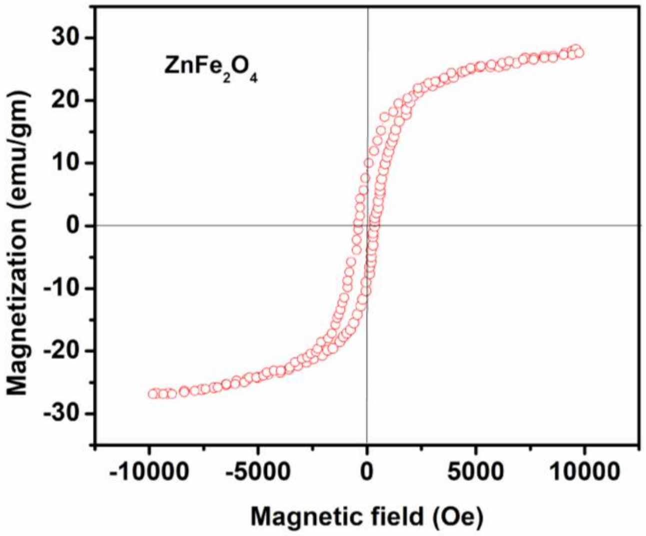

Figure 4. M verses H graph of ZFO ($ZnFe_2O_4$) nanoparticles annealed at 650° for 7 hours.

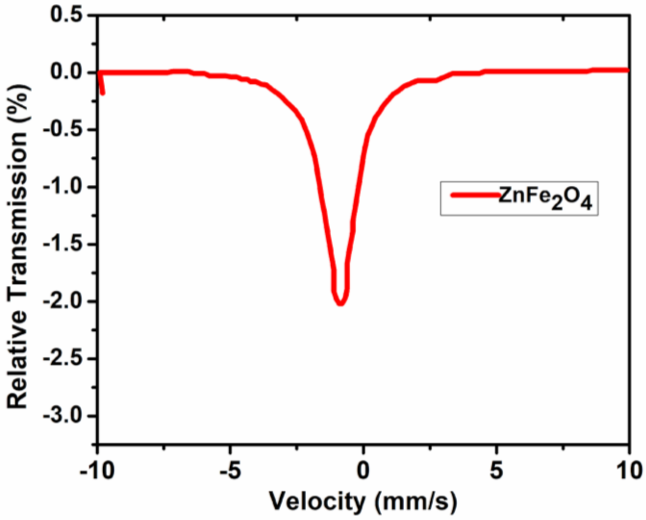

Figure 5. Mossbauer spectra of ZFO ($ZnFe_2O_4$) nanoparticles annealed at 650° for 7 hours

The Figure 3(b) displays the plot of tan δ as a function of frequency for ZFO nanoparticles. The tan δ value represents the dielectric loss, which is the loss of energy from the applied field that is converted into heat within the ZFO material. The movement of domain walls and polarization rotation both contribute to the tangent loss. At lower frequencies, there is a significant dissipation of heat due to the field following the domain wall. At the higher frequencies, tan δ are found to be decreasing and becomes independent on frequency, indicating that the rotation in polarization is not able to follow the applied electric field [3, 4].

The magnetization behavior of annealed ZFO nanoparticles was studied by measuring the M-H plot at room temperature, as shown in Figure 4. The sample, which was annealed at 650°C for 7 hours, exhibited a saturation magnetization of 28 emu/gm. This improvement in magnetic properties can be attributed to several factors, such as an increase in grain size, reduction in impurities and defects, and modification in cation distribution resulting from the annealing process [6–8]. The coercivity and remanence values for the sample were evaluate to be 366 Oe and 9 emu/gm, respectively.

The typical Mossbauer spectra of iron has sextets as it is magnetic. Here, In Figure5 all sextets collapse to single due to the non-magnetic behavior of Zinc (Zn).

SUMMARY AND CONCLUSION

A sample of pure ZFO nanoparticles with an average grain size of 95 nanometer and an average lattice parameter of 8.41 was synthesized by exploding the wire with high current to achieve an inverse spinal crystalline structure. The SEM micrograph confirms the particle size within the range of 60±40 nm. The spectrum of EDAX supports the existence of Iron, Zinc and Oxygen elements in the sample. At low frequencies, the dielectric dispersion of the sample is high and become independent at higher frequencies, and can be explained by the Koop's theory in addition with the Wagner interfacial type polarization. The sample exhibits a large tangent loss, which in consequence dissipates heat in the material at low frequencies. The sample reaches a saturation magnetization of 28 emu/gm, with 9 emu/gm remanence and 366 Oe coercivity.

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