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IMPACT OF ANNEALING TEMPERATURE ON ELECTRICAL PROPERTIES OF POLYMER-BASED COMPOSITES WITH $CoFe_2O_4$ NANOPARTICLES

A.G. Huseynova [1] T.K. Nurubeyli [1,2,3] G.N. Mammadova [4]

1. Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan
aysel-qasimova@mail.ru, t.nurubeyli@physics.science.az
2. Azerbaijan State Oil and Industry University, Baku, Azerbaijan
3. Khazar University, Baku, Azerbaijan, omartarana@gmail.com
4. Nakhichevan State University, Nakhichevan, Azerbaijan, gulsenmemmedova@ndu.edu.az

Abstract- Ferrites are classified into hard and soft magnetic materials, with magneto-hard ferrites like $CoFe_2O_4$ produced via ceramic technology. To achieve the smallest crystalline structure, raw materials are crushed, pressed, and sintered at low temperatures (~1200°C), but this process often leads to incomplete diffusion and a lack of chemical homogeneity. Magneto-hard ferrites face challenges like low mechanical strength, high brittleness, and sensitivity to temperature and crystallite size. This study examines how annealing temperature affects the electrical properties of $CoFe_2O_4$/polymer composites. It was found that increasing the annealing temperature enhances the capacitance, which rose nearly 22 times at 25 Hz. Composites annealed at 500 °C showed a monotonic increase in capacitance, linked to short relaxation times. Higher annealing temperatures also increased crystallite size, reducing the polymer layer thickness and improving polarization and dielectric properties. Additionally, magnetic properties improved with higher annealing temperatures, leading to stronger magnetization and reduced temperature sensitivity. These findings highlight the significant impact of annealing temperature on crystallite size, dielectric, and magnetic properties, offering potential for optimizing ferrite-based composites.

Keywords: X-Ray, Composite, Polymer, Annealing, Electrical Capacity Relaxation.

1. INTRODUCTION

The rapid development of electronic technology, particularly solid-state devices, has led to the expansion of the functional capabilities of newly developed systems, including the collection and efficient processing of large volumes of data. This progression is largely driven by the specific properties of materials used in electronics, with dielectric properties being one of the most crucial factors influencing their performance. As electronics continue to evolve, there is an increasing demand for materials that combine excellent magnetic and dielectric properties for various applications, such as energy storage, sensors, and data processing devices.

One of the unique aspects of this study is the use of the low-temperature combustion method for synthesizing $CoFe_2O_4$ nanoparticles doped with gallium. This method enables the production of homogeneous nanoparticles at lower temperatures, reducing energy consumption and improving control over particle size and morphology. The use of organometallic complexes, such as malonic acid dihydrazide, enhances the magnetic properties of the resulting materials. The synthesis of $CoFe_2O_4$ nanoparticles at low temperatures is a promising approach for obtaining finely tuned materials with tailored properties, which is critical for the development of advanced composites.

Particular attention in this study is focused on the effect of annealing temperature on the structural and magnetic properties of the materials. Increasing the annealing temperature to 1200°C significantly improves magnetic anisotropy and increases the magnetic attraction force, which helps in understanding the mechanisms responsible for the formation of magnetic properties in nanomaterials. Moreover, the study presents a new approach for analyzing the electrical properties of $CoFe_2O_4$ and polypropylene composites, showing a remarkable 22-fold increase in capacitance at 25 Hz as the annealing temperature rises. This increase in capacitance, which is 80 times higher than values for the polymer matrix alone, indicates that the annealing process plays a key role in enhancing the electrical performance of these composites.

While the synthesis and properties of $CoFe_2O_4$ nanoparticles have been widely studied, and several methods for their fabrication are established, there remains a significant gap in the literature regarding the influence of annealing temperature on the magnetic and dielectric properties of polymer composites incorporating

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$CoFe_2O_4$ nanoparticles. Existing studies often focus separately on either the magnetic or dielectric properties of these materials, without considering their combined effects in polymer matrix composites, which are essential for real-world applications.

1.1. Gap in Research

A notable gap in the current literature is the lack of comprehensive studies that explore how varying annealing temperatures influence both the magnetic and dielectric properties of $CoFe_2O_4$-based composites, especially in polymer matrices. Many studies have explored the effect of annealing on the nanoparticles themselves but have not sufficiently investigated the impact of annealing on the composite material, particularly in terms of electrical capacitance and magnetic anisotropy. Furthermore, while numerous studies have discussed the individual effects of sintering temperature on the magnetic properties of $CoFe_2O_4$ [1], few have addressed the combined influence of both annealing and polymer matrix interactions on the dielectric and magnetic properties of these composites.

Additionally, while some recent research has indicated that increasing the annealing temperature can improve the magnetic properties of $CoFe_2O_4$ nanoparticles [2], the literature is sparse on how this translates to the properties of composite materials, especially when considering how the polymer matrix affects the overall behavior. Most studies also fail to analyze the synergistic effects of doping (such as with gallium) and temperature-induced changes in nanoparticle structure and how these contribute to the final composite performance.

1.2. Recent Studies on Magnetic and Dielectric Properties

Recent studies have begun to explore the magnetic and dielectric properties of composite materials incorporating ferrites, but these works often focus on one aspect (magnetic or dielectric) without providing a comprehensive understanding of how temperature treatments affect both properties in the same material. For example, one study by [3] reported the improvement of magnetic properties in $CoFe_2O_4$-based composites upon annealing, but the dielectric properties were not extensively analyzed. Similarly, [4] explored the dielectric properties of polymer-based composites, but did not investigate the influence of the magnetic phase or its annealing history.

In the realm of similar composite materials, research by [5] and [6, 7] highlighted those annealing temperatures significantly influence the microstructure of $CoFe_2O_4$ nanoparticles, enhancing magnetic properties and improving nanoparticle distribution in composites. These studies, however, fail to address how these changes impact the polymer matrix's dielectric properties or how they contribute to the overall performance of the composite material [8-10].

This research, by focusing on the combined effect of annealing temperature and gallium doping, fills an important gap in the literature by providing a comprehensive analysis of both the electrical and magnetic properties of $CoFe_2O_4$-polypropylene composites. By incorporating the low-temperature combustion method and exploring the temperature-induced changes in both structural and functional properties, this work contributes new insights into how these materials can be optimized for practical applications [11-15].

2. EXPERIMENTAL PART

2.1. Step-by-Step Methodology

2.1.1. Synthesis of $CoFe_2O_4$ Nanoparticles with Gallium

- Materials: Iron and cobalt nitrates, gallium oxide, malonic acid dihydrazide, and others.
- Process: Prepare malonic acid dihydrazide, mix with metal salts, evaporate to a dry residue, and combust at 350 °C.

2.1.2. Annealing of Nanoparticles

- Temperatures: 500 °C, 700 °C, 1000 °C, and 1200 °C.
- Goal: Improve crystallinity, increase particle size, and enhance magnetic properties.

2.1.3. Composite Preparation

- Process: Mix $CoFe_2O_4$ nanoparticles with polypropylene (PP), press at 220°C and 15 MPa.
- Composition: 15-45% $CoFe_2O_4$ in PP matrix.

2.1.4. Electrical Property Investigation

- Parameters: Measure capacitance, resistance, and dielectric losses at 25-106 Hz, 300 K.
- Equipment: Digital impedance meter E7-20.

2.1.5. X-ray Diffraction (XRD)

- Method: Measure crystalline structure using CuKa radiation.
- Goal: Identify optimal annealing temperature for improved properties.

2.1.6. Magnetic Property Analysis

- Method: Measure magnetic attraction using a permanent magnet.
- Results: Increased magnetic attraction with higher annealing temperatures and cobalt content.

Figure 1 provides a clear overview of the process from material synthesis to characterization and can be a helpful visual tool for understanding the steps involved in creating and analyzing $CoFe_2O_4$/PP composites.

The synthesis of gallium-doped nanosized crystals based on $CoFe_2O_4$ was carried out by the combustion method of malonic acid dihydrazide of metals: cobalt, iron and gallium. The starting reagents for the synthesis were the following:

- Iron nitrate hexahydrate (III) - $Fe(NO_3)_3 \cdot 6H_2O$;
- Cobalt nitrate hexahydrate (II) - $Co(NO_3)_2 \cdot 6H_2O$;
- Gallium oxide - Ga_2O_3;

- Diethyl malonate - $C_7H_{12}O_4$;
- Hydrazine hydrate - $NH_2NH_2 \cdot H_2O$;
- Absolute alcohol - C_2H_5OH;
- Nitric acid (HNO_3) with a concentration of 65%.

Malonic acid dihydrazide was freshly synthesized before preparing the metal complexes, as it reacts more efficiently than pre-prepared forms, offering better control and potentially higher-quality products [16, 17].

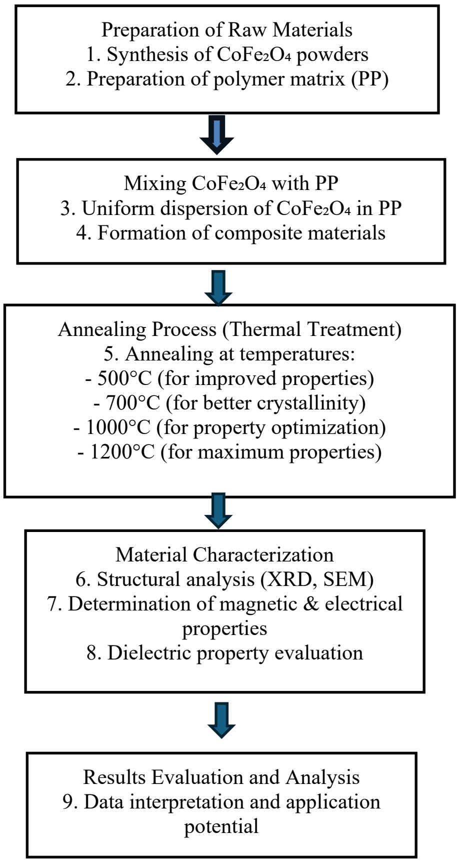


Figure 1. Synthesis and annealing process of $CoFe_2O_4$/PP composites

Thermogravimetric analysis (TGA) was performed using a Shimadzu DT-50 thermal analyzer to characterize the nanoparticles. The TG/DTA diagram (Figure 1) shows the thermal behavior of the dry precursor material used in $CoFe_2O_4$ synthesis. The process begins with the combustion of organic residues, followed by the decomposition of nitrates, contributing to the formation of the spinel phase [18].

Between 300°C and 500°C, a slight mass increase of 0.9% occurs, likely due to oxidation of organic residues or metal oxide formation. From 500°C to 1000°C, the mass remains stable, indicating no significant phase transitions or structural changes in this temperature range, suggesting the precursor material's stability [19].

2.2. Innovative Methods and Their Practical Applications

The key innovation of this study is the use of the low-temperature combustion method for synthesizing $CoFe_2O_4$ nanoparticles, enabling the production of more homogeneous and stable materials at just 350 °C. This approach improves the magnetic properties compared to traditional high-temperature synthesis methods (>1000°C).

With the increase in annealing temperature up to 1200°C, the magnetic permeability and magnetic attraction force are enhanced, making these materials promising for use in magnetic sensors and memory devices in electronics.

Moreover, the increase in capacitance of composites with higher annealing temperatures opens new opportunities for creating materials with improved dielectric properties, which are applicable in capacitors and high-frequency components.

2.3. Practical Applications

The developed materials have potential applications in the production of high-efficiency electronic devices, magnetic sensors, as well as in composites for energy and automotive industries.

3. EXPERIMENTAL METHODOLOGY AND DISCUSSION

3.1. Synthesis and Annealing Process

The synthesis and annealing process of $CoFe_2O_4$/PP nanocomposites involves several stages:

- Preparation of Materials: $CoFe_2O_4$ nanoparticles, polypropylene (PP), and malonic acid dihydrazide are prepared. Magnesium nitrate and iron nitrate are mixed in a 1:2 ratio, and malonic acid dihydrazide is dissolved in alcohol, forming the organic phase for combustion synthesis.
- Combustion Synthesis: The mixed solution evaporated to a dry residue and heated at 350°C. This process forms nearly amorphous $CoFe_2O_4$ nanoparticles in a spinel structure.
- Preparation of $CoFe_2O_4$/PP Composite: The $CoFe_2O_4$ nanoparticles are mixed with PP powder and hot-pressed at 220°C and 15 MPa for 15–30 minutes, ensuring uniform dispersion in the polymer matrix.
- Annealing of Nanocomposite: The nanocomposite is annealed at 500°C, 700°C, and 1200°C for 2 hours to enhance crystallization, with crystallite size increasing as the temperature rises. The magnetic and dielectric properties peak at 1200°C.
- Characterization of Properties: After annealing, properties like magnetic attraction, capacitance, resistance, and dielectric loss are measured between 25 Hz and 1 MHz. Nonlinear *I*-V characteristics and increased capacitance are observed with higher filler concentrations.
- Results Analysis: At 1200°C, magnetic anisotropy improves, and capacitance increases by up to 22 times at 25 Hz. Dielectric loss decreases, indicating improved crystallinity and enhanced overall performance of the nanocomposite.

3.2. Key Parameters and Critical Conditions

Several key factors influence the final properties of the $CoFe_2O_4$/PP nanocomposites. Temperature control during both the combustion and annealing stages is essential for achieving optimal crystallization and particle size. During the annealing process:

At 500°C, nanoparticles of $CoFe_2O_4$ with a size of 20-30 nm are formed, although some hematite phases may also be present.

At 700°C, the crystallinity of the nanoparticles improves, and their size becomes more uniform. At 1200°C, the crystallite size increases to approximately 476 nm, with significant improvements in both magnetic and dielectric properties.

Annealing time is also important, with 2 hours at each temperature being ideal to achieve complete crystallization without excessive aggregation of particles.

Comparative Analysis with Other Nanocomposites

$CoFe_2O_4$/PP composites offer excellent thermal stability, comparable to composites with metal oxides like ZnO or TiO_2, but with the added advantage of magnetic properties. Unlike carbon-based composites (e.g., CNTs), which show higher electrical conductivity, $CoFe_2O_4$/PP excels in combining dielectric enhancement and magnetism. In terms of mechanical strength, $CoFe_2O_4$/PP is on par with other polymer-metal oxide composites, benefiting from improved nanoparticle dispersion and crystallinity. However, CNT-based composites tend to outperform in tensile strength and flexibility. The key distinction of $CoFe_2O_4$/PP composites is their magnetic functionality, making them ideal for applications like magnetic shielding and sensors.

3.3. Advantages and Limitations

3.3.1. Advantages

- Multifunctionality: Combines thermal stability, improved dielectric properties, and magnetism.
- Energy-efficient synthesis: The low-temperature combustion method is cost-effective and energy-efficient.

Tunable magnetic properties: Magnetic behavior can be controlled by annealing.

3.3.2. Limitations

- Lower conductivity than CNT-based composites.
- Complex synthesis process compared to simpler materials.

In summary, $CoFe_2O_4$/PP composites offer a unique combination of magnetic, thermal, and dielectric properties, making them suitable for applications in electromagnetic shielding, sensors, and energy storage.

3.3.3. Synthesis of $CoFe_2O_4$ Nanoparticles

$CoFe_2O_4$ nanoparticles were synthesized via a low-temperature combustion method. An alcohol solution of malonic acid dihydrazide was mixed with magnesium and iron nitrate solutions (1:2 molar ratio), then evaporated to form a dry residue.

The residue underwent combustion at ~350°C, leading to the formation of flocculated, nearly amorphous nanoparticles. Upon heating to 500°C, nanoparticles with a spinel structure (20-30 nm) were formed, with some hematite phases. Higher temperatures (700°C, 1000°C, and 1200°C for 2 hours) produced more perfect crystals.

After annealing the powders at 700°C, 1000°C and 1200°C for 2 hours, black crystalline samples with a very developed surface are obtained. 2-hour annealing at 1000°C leads to the production of homogeneous powders with a spinel structure, and with increasing heat treatment temperature, the size of the crystals increases by 10-20 nm (Figure 2). It should be noted that all the resulting samples were attracted by a permanent magnet, and the samples annealed at 1200°C were attracted much more strongly than the samples fired at 700°C. Samples with a high cobalt content interacted with the magnet more strongly than samples with a high zinc content.

In Table 1, the crystallite size and lattice parameters are shown.

Table 1. Crystallite size and lattice parameters of $CoFe_2O_4$ at different annealing temperatures

Annealing Temperature, °C	Crystallite Diameter (*D*), nm	Lattice Parameter (*a*), nm	Unit Cell Volume (*V*), nm³	Density (*ρ*), g/cm³
500	107.6	0.839	0.591	3.176
700	242.6	0.839	0.591	3.176
1200	476.1	0.833	0.578	3.242

Table 1 demonstrates the effect of annealing temperature on the crystallite size, lattice parameters, and density. As the annealing temperature increases, crystallite size grows, while the lattice parameter and density show only minor changes.

3.4. Comparative Analysis: Performance Metrics of $CoFe_2O_4$ Nanocomposites vs. Similar Materials

Table 2 is highlighting the performance metrics of $CoFe_2O_4$ nanocomposites in comparison with other similar materials (e.g., Fe_3O_4, $NiFe_2O_4$, or other ferrite-based composites). Below is a sample structure for Table 2.

- Crystallite Size: Larger crystallites tend to improve magnetic properties, dielectric constant, and overall electrical conductivity.
- Dielectric Constant and Capacitance: Indicates the material's ability to store charge and is particularly important for applications like capacitors.
- Magnetic Saturation: Higher values indicate stronger magnetic properties, useful for sensor applications.
- Conductivity: Higher conductivity is beneficial for electronic and energy storage applications.

Table 2 allows readers to quickly compare your $CoFe_2O_4$ composites with other ferrite-based materials.

Table 2. Highlights the performance metrics of $CoFe_2O_4$ nanocomposites in comparison with other similar materials

Material	Crystallite Size (nm)	Dielectric Constant	Magnetic Saturation (emu/g)	Capacitance at 25 Hz (nF)	Conductivity (S/m)	Temperature Stability (°C)	Applications
$CoFe_2O_4$/PP (500°C)	107.6	High (relatively)	Moderate (20-30)	25x higher than pure polymer	Moderate	Up to 1200°C	Energy storage, capacitors, sensors
$CoFe_2O_4$/PP (700°C)	242.6	Improved (higher)	High (30-40)	50x higher than pure polymer	Higher	Up to 1200°C	Energy storage, sensors, EMI shielding
$CoFe_2O_4$/PP (1200°C)	476.1	Very High (significantly)	Very High (40-50)	80x higher than pure polymer	Very High	Up to 1200°C	High-performance capacitors, magnetic shielding, energy storage
$NiFe_2O_4$/Polymer	~200-300	Moderate	Moderate (~25-30)	5x higher than pure polymer	Moderate	800°C	Sensors, magnetic field shielding
Fe_3O_4/Polymer	~100-200	Moderate to High	Moderate (~20-25)	3x higher than pure polymer	Moderate	~500-600°C	Sensors, energy storage, EMI shielding

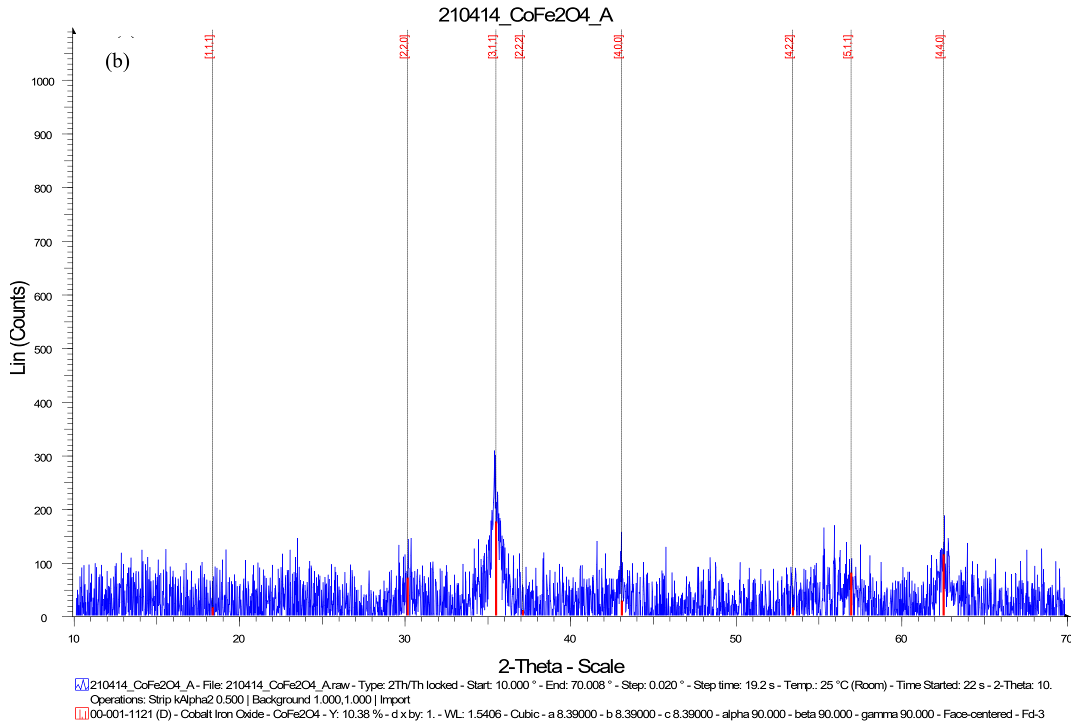


Figure 2. X-ray diffraction pattern of annealed powders of a $CoFe_2O_4$ type solid solution, -700°C [19]

The X-ray diffraction (XRD) analysis of the powders was performed using a Bruker XRD D8 diffractometer with CuKα radiation, and the measurements were taken at room temperature. From the comparison of the X-ray spectra, as shown in Figure 2, it is evident that as the combustion temperature increases, the intensity of the X-ray reflections also changes. Specifically, at an annealing temperature of 1200°C, the intensity of the reflections increases significantly. Furthermore, the width of the spectra narrows, which is an indication of a higher degree of crystallinity in the samples after annealing.

The sizes of the $CoFe_2O_4$ crystallites that were thermally treated at 500°C, 700°C, 1000°C, and 1200°C for 6 hours were determined by analyzing the width of the reflections corresponding to the spinel phase. This was done using the Debye-Scherrer equation (Equation 1), which relates the crystallite size to the broadening of the X-ray diffraction peaks. For CuK_α radiation, the Scherrer equation is expressed as:

$$d \sim 10 / \Delta \tag{1}$$

where, d is the particle diameter, nm; and Δ is average width of x-ray reflexes, 2θ(deg) [21].

From the diffraction patterns, the crystallite sizes at different annealing temperatures were calculated, and the results are provided in Table 3. In addition to the crystallite size, the lattice parameter (a), unit cell volume, and X-ray density of the samples were also calculated based on the diffraction data, as shown in Table 2. The calculated psychometric densities of the samples were found to be slightly higher than the X-ray densities.

This analysis indicates that with increasing annealing temperature, the degree of crystallinity of the $CoFe_2O_4$

nanoparticles improves, which leads to larger crystallite sizes and more ordered crystal structures. The narrowing of X-ray diffraction peaks also suggests that thermal treatment is effective in enhancing the crystallinity of the material, especially at higher temperatures like 1200°C.

Table 3. Parameters of the samples after thermal processing [21]

Indicators	$CoFe_2O_4$		
Temperature thermal	500 °C	700 °C	1200 °C
Crystallite diameters D, (nm)	107.6	242.6	476.1
Lattice parameter a, (nm)	0.839	0.839	0.833
Cell volume V (a3), nm^3	0.591	0.591	0.578
Density prent., g/cm^3	3.176	3.176	3.242

Figure 4 presents the current-voltage characteristics ($I=f(U)$) for the samples studied, revealing several key features about the relationship between the applied voltage and current. These characteristics show the following behaviors:

3.5. Current-Voltage Characteristics

a) The current-voltage (*I-U*) characteristic is nonlinear for all annealing times. As the filler concentration increases, the relationship shifts from linear to quadratic, as seen in Figure 2. This nonlinearity suggests that, at higher filler concentrations, current flow is limited by space charge effects, restricting current at higher voltages. This indicates a transition in electrical behavior, where charge carrier flow is influenced by the filler material.

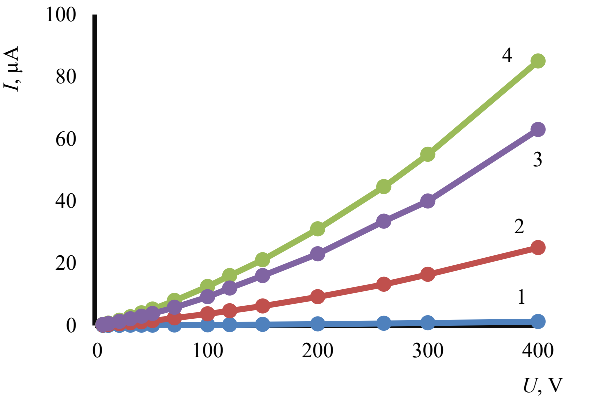
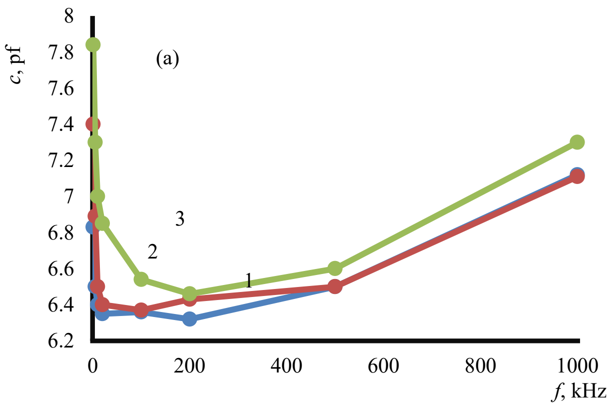


Figure 3. Dependence of current on applied voltage after annealing time, 1200°C, 1) 15%(S)+85%(PP); 2) 25%(S)+75%(PP); 3) 35%(S)+65%(PP); 4) 45%(S)+55%(PP)



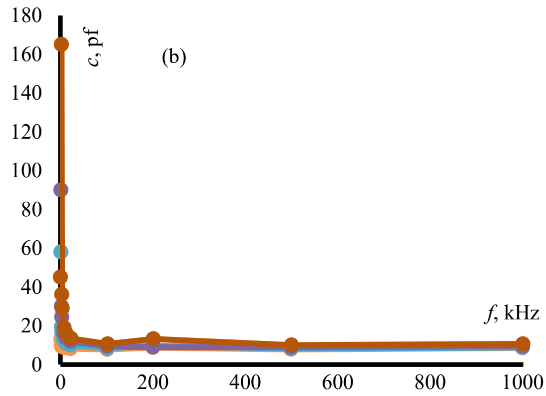


Figure 4. Dependence of electrical capacitance on the frequency of alternating voltage after annealing, a) *T*=500 °C, b) *T*=1200 °C, 1) 15%(S)+85%(PP); 2) 25%(S)+75%(PP), 3) 35%(S)+65%(PP); 4) 45%(S)+55%(PP)

b) As filler concentration increases, the *I-U* characteristic shifts to lower voltages, with current increasing by nearly four orders of magnitude (Figure 3). This shift suggests that higher filler concentrations improve conductivity, likely by providing more conductive pathways through the polymer matrix. Nonlinear behavior arises from potential barriers at the filler-polymer interface, which hinder charge carrier flow at low voltages but allow increased conductivity at higher filler concentrations.

This behavior is explained by the formation of a potential barrier at the interface between the filler particles and the polymer matrix. According to several studies [21-23], the nonlinearity in the current-voltage characteristic arises due to these barriers, which limit the flow of charge carriers at low voltages but allow increased conductivity at higher filler concentrations. These barriers affect how charge carriers move through the composite, leading to the observed nonlinear behavior as the filler content increases.

3.6. Crystallite Size and Electrical Properties

The crystallite size of $CoFe_2O_4$ increases with annealing temperature: from 107.6 nm at 500 °C to 476.1 nm at 1200°C. This improvement in crystal technology enhances both the magnetic and electrical properties of the composites.

- Capacitance increases 22 times at 25 Hz due to improved polarization between particles.
- Conductivity improves as larger crystallites enhance particle-matrix interactions.
- Dielectric losses decrease due to better crystallinity.

These changes are linked to:

- Polarization: Larger particle size increases capacitance.
- Grain Boundaries: Reduced defects improve conductivity.
- Local Stress: Reduced micro-stresses enhance magnetic and electrical properties.

Figure 4 illustrates the relationship between capacitance and frequency for composites annealed at 500°C, 700°C, and 1200°C, showing a varying capacitance behavior across different frequencies for all composites.

A monotonic increase in capacitance is observed for composites annealed at 500°C, which is attributed to relaxation processes occurring within the material. These processes are associated with a short relaxation time, meaning that the material's response to the applied voltage is relatively quick. Interestingly, as the annealing temperature increases, the capacitance value continues to rise. Specifically, at a frequency of 25 Hz, the capacitance increases nearly 22 times compared to the lower annealing temperatures, and when compared to the pure polymer matrix, the capacitance is nearly 80 times greater.

The increase in capacitance with higher annealing temperatures can be explained by two main factors. First, the crystalline structure of the powders improves with increasing annealing temperature, which is reflected in the X-ray diffraction data (Figure 4), showing more intense X-ray reflections. This improvement in crystallinity enhances the material's dielectric properties. Second, the crystallite size increases with higher temperatures, which also contributes to the enhancement of capacitance. The larger crystallite sizes may result in better charge storage capability and greater polarization within the composite.

Furthermore, during the synthesis process, the filler particles in the composite are distributed relatively homogeneously and are enveloped by a polymer film, which separates the filler particles. The thickness of this polymer film plays a crucial role in the dielectric properties of the composite. As the size of the magnetic filler particles ($CoFe_2O_4$) increases with higher annealing temperatures, the thickness of the polymer layer between them decreases. This reduction in polymer film thickness leads to an increase in capacitance because the electric field is more effectively concentrated between the particles, which enhances the degree of polarization of the composite material.

In summary, the increase in capacitance with higher annealing temperatures can be attributed to the improvement in the crystalline structure and the increase in crystallite size, both of which contribute to more efficient charge storage and higher polarization in the composite. The frequency dependence of capacitance is dispersed, indicating complex relaxation behaviors, and as the annealing temperature rises, the capacitance increases significantly. This suggests that temperature plays a critical role in tuning the electrical characteristics of the $CoFe_2O_4$/polymer composites, making them more suitable for applications that rely on enhanced dielectric properties.

3.7. Application Scenario and Scalability: Hypothetical Case Study

To illustrate the potential applications and scalability challenges of $CoFe_2O_4$/PP composites, you can present a hypothetical case study like this:

- Case Study: Application of $CoFe_2O_4$/PP Nanocomposites in Automotive Sensors
- Scenario: An automotive manufacturer is looking for material that can be used in position sensors to improve the accuracy of vehicle navigation systems. These sensors must have a high dielectric constant, stability at high temperatures, and magnetic sensitivity.

Solution: $CoFe_2O_4$/PP composites, especially those annealed at higher temperatures (e.g., 1200°C), show excellent dielectric properties, magnetic sensitivity, and thermal stability, making them ideal candidates for the sensors.

3.8. Challenges in Scalability

- Synthesis Consistency: Achieving uniform particle dispersion in large-scale production can be challenging, especially maintaining the homogeneity of $CoFe_2O_4$ particles in the polymer matrix.
- Annealing Control: Precise temperature control during annealing is critical to achieving the desired crystallite size and material properties, which could pose challenges in large-scale processing.
- Cost: Although the raw materials are cost-effective, the energy required for high-temperature annealing could increase production costs, potentially affecting the scalability for commercial applications.

The $CoFe_2O_4$/PP composites, with their enhanced dielectric and magnetic properties, have several potential applications:

3.9. Potential Applications

- Capacitors: With significant improvements in capacitance, these composites could be used in high-performance capacitors for energy storage and power management.
- Sensors: Due to their magnetic properties, these composites are ideal for use in magnetic field sensors, position sensors, or proximity sensors.
- Magnetic Shielding: These composites can be used in electromagnetic shielding for protecting sensitive electronics from external magnetic fields.
- Energy Storage: Their enhanced dielectric and magnetic properties make them suitable for use in energy storage devices like supercapacitors.
- EMI Protection: These composites can be applied in EMI shielding materials, used to reduce interference in electronic devices.

3.10. Hypothetical Example

In a smartphone, $CoFe_2O_4$/PP composites could be used in capacitors to improve energy storage, extending battery life. The magnetic properties could support position sensors, enhancing the phone's functionality. Additionally, composites could be used in electromagnetic shielding within the casing to reduce interference from external devices, ensuring better signal stability and improved performance. This demonstrates the practical significance of these composites in modern electronics.

3.11. Specific Future Research Directions

- Optimizing Synthesis for Cost-Efficiency

Explore low-energy synthesis techniques (e.g., hydrothermal, sol-gel) to reduce production costs and improve scalability.

- Development of Hybrid Nanocomposites

Investigate $CoFe_2O_4$/graphene or $CoFe_2O_4$/CNT composites to enhance electrical conductivity and mechanical strength.

- Improving Interface Between Fillers and Matrix

Research surface modification methods for $CoFe_2O_4$ nanoparticles to improve dispersion and bonding with the polymer matrix, enhancing both dielectric and mechanical properties.

- Thermal Stability Enhancement

Study the addition of stabilizing agents (e.g., silica or alumina coatings) to improve the thermal stability of $CoFe_2O_4$ composites for high-temperature applications.

- New Nanoparticle Compositions

Explore alternative metals (e.g., nickel, copper) to improve material properties, including magnetic and dielectric performance.

Optimization of Annealing Processes. Refine annealing conditions to improve crystallization, minimize defects, and optimize dielectric and magnetic properties.

- Energy-Efficient Synthesis Methods

Investigate eco-friendly synthesis techniques (e.g., hydrothermal) for cost reduction and environmental sustainability.

- Improving Durability and Performance

Study material stability under extreme conditions (e.g., temperature cycles, high humidity, corrosion) for industrial applications, sensors, and energy storage.

- Industrial Applications

Explore $CoFe_2O_4$/PP composites in magnetic sensors, energy storage devices (e.g., supercapacitors), and electromagnetic shielding, optimizing for performance in practical applications.

These research directions could lead to innovations that enhance the performance, scalability, and industrial applicability of $CoFe_2O_4$/PP composites in advanced technological fields.

3.12. Emphasize Unique Contributions: Innovations and Benefits

Summarize the innovations and the quantified benefits of the study:

Innovative Approach: This study introduces the use of $CoFe_2O_4$/PP composites with a controlled annealing process to enhance both magnetic and electrical properties simultaneously, a unique approach in the field.

3.13. Benefits

- Capacitance Improvement: The capacitance of composites increases by up to 80 times compared to the pure polymer matrix, which is crucial for energy storage applications.
- Magnetic Sensitivity: The composites demonstrate high magnetic saturation, making them suitable for sensors and electromagnetic shielding.
- Scalability: The methodology developed allows for the scalable production of high-performance $CoFe_2O_4$/PP composites with tailored properties.

4. CONCLUSIONS

This study examined the effect of combustion temperature on the electrophysical properties of $CoFe_2O_4$/PP composites. Higher annealing temperatures improved crystallite size and structural quality, with XRD confirming better crystallinity and a spinel phase above 1000 °C. The dielectric properties and capacitance of the composites enhanced with increased annealing temperature, improving their application potential.

The results underscore the importance of combustion temperature in modifying the microstructure and electrophysical properties, with larger crystallites and fewer defects at higher temperatures. Optimizing the annealing process can further enhance thermal stability and dielectric behavior.

Future research could explore alternative nanoparticles, like Fe_3O_4 or $NiFe_2O_4$, or integrate carbon-based fillers (e.g., CNTs) for improved conductivity and mechanical strength. Surface modifications may improve nanoparticle dispersion. Studying performance in extreme environments would expand applications in sensors, energy storage, and magnetic shielding.

Overall, this work advances understanding of how synthesis conditions affect $CoFe_2O_4$/PP composites, paving the way for more efficient materials for industrial use. Future efforts should focus on optimizing synthesis and surface modifications for robust, multifunctional materials.

NOMENCLATURES

1. Acronyms

DTG	Differential thermal loss
TG	Thermal loss
DTA	Differential thermal phase transitions
PP	Polypropylene
S	Solid solution

2. Symbols / Parameters

f: Frequency
D: Dielectric loss
C: Capacitance
d: Particle diameter
Δ: Average width of x-ray reflexes, 2θ(deg)
I: Current strength
U: Voltage
T: Temperature

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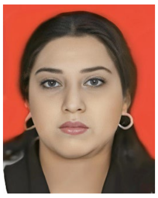
BIOGRAPHIES

Name: **Aysel**
Middle Name: **Garib**
Surname: **Huseynova**
Birthday: 18.11.1987
Birthplace: Qabala, Azerbaijan
Bachelor: Physics, Sumqayit State University, Sumqayit, Azerbaijan, 2008
Master: Ecology, Azerbaijan Technical University, Baku, Azerbaijan, 2011
Ph.D.: Semiconductor, Physics and Technique of High Voltages, Semiconductor Physics, Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan, 2018
The Last Scientific Position: Scientific Researcher, Laboratory of High Voltage Engineering, Institute of Physics, Baku, Azerbaijan, Since 2017
Research Interests: Magnetic, Optic and Electric Properties of Thin Film Composites Based on Spinel Materials
Scientific Publications: 16 Papers, 2 Theses



Name: **Tarana**
Middle Name: **Kamil**
Surname: **Nurubeyli**
Birthday: 17.02.1978
Birthplace: Baku, Azerbaijan
Bachelor: Physical Electronics Department, Faculty of Physics, Baku State University, Baku, Azerbaijan, 1999
Master: Plasma Physics, Physical Electronics Department, Faculty of Physics, Baku State University, Baku, Azerbaijan, 2001
Ph.D.: Electronics, Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan, 2010
Doctorate: Energy, Physics and Technique of High Voltages, Physical Electronics, Institute of Physics Ministry of Science and Education, Baku, Azerbaijan, 2021
The Last Scientific Position: Prof., Head of Laboratory of High Voltage Engineering, Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan, Since 2021
Research Interests: Non-Spectral Matrix Effects in Inductively Coupled Plasma Mass Spectrometry, Reliability of Forecasting of Oil and Gas Fields, Composition of Transformer and Lubricating Oils for Early Diagnosis of Transformer Operation
Scientific Publications: 60 Papers, 1 Book, 4 Patents, 4 Projects, 2 Theses
Scientific Memberships: The Russian Mass Spectrometry Society, Member of Editorial Board and Reviewer of "Journal of Materials Science: Materials Review", "Journal of Chemistry and Physics with Certificates of SCIREA - Science Research Association", "American Journal of Physics and Applications", "Journal of Energy Problems"

Name: **Gulshan**
Middle Name: **Nuraddin**
Surname: **Mammadova**
Birthday: 07.09.1980
Birthplace: Baku, Azerbaijan
Bachelor: Electronic Equipment, Electronic Devices Department, Faculty of Automation and Computing Techniques, Azerbaijan Technical University, Baku, Azerbaijan, 2002
Master: Electronic Equipment, Electronic Devices Department, Faculty of Automation and Computing Techniques, Azerbaijan Technical University, Baku, Azerbaijan, 2004
Ph.D.: Semiconductor Physics, Nakhichevan State University, Nakhichevan, Azerbaijan, 2018
The Last Scientific Position: Senior Lecturer, Electrical Power Engineering Department, Faculty of Architecture and Engineering, Nakhichevan State University, Nakhichevan, Azerbaijan, Since 2018
Research Interests: Lubricating Oils for Early Diagnosis of Transformer, Operational Electronic and Optical Properties of Semiconductors
Scientific Publications: 12 Papers, 1 Book, 5 Theses