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The Effect of Gamma Irradiation on the Structure and Dielectric Properties of $MnFe_2O_4$ Nanoparticles

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The article considers the compound $MnFe_2O_4$ (nanopowder with true density of 4.96 g/cm^3, particle size of 60 nm, and a purity of 98.5%, SkySpring Nanomaterials, USA), which is widely used and considered a promising material today. These particles in powder form are pressed at a temperature of 293 K and a pressure of 50 kg/cm^2 and formed into a sample in the form of a tablet measuring 4×15×5 mm. In this article, we took an unirradiated sample and a sample irradiated for 1 and 10 hours, maintaining the consistency in dose. The radiation intensity is $\dot{D} = 1.41$ gray/sec, and the radiation dose is of 50 grays. We investigate the structural and dielectric properties of the samples and consider the influence of gamma rays on these properties.

Key words: manganese ferrite, nanostructured materials, intermolecular interactions, dielectric properties.

У статті розглянуто сполуку $MnFe_2O_4$ (нанопорошок зі справжньою густиною в 4,96 г/см^3, розміром частинок у 60 нм і чистотою у 98,5%, SkySpring

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Nanomaterials, США), яка на сьогоднішній день є широко використовуваною та вважається перспективним матеріялом. Ці частинки у вигляді порошку пресували за температури у 293 К і тиску у 50 кг/см^2 і формували зразок у формі таблетки розмірами 4×15×5 мм. У цій статті ми взяли неопромінений зразок, а також зразок, опромінений упродовж 1 і 10 годин, зберігаючи постійність дози. Інтенсивність випромінення становила $\dot{D} = 1{,}41$ грей/с, доза опромінення — 50 грей. Ми дослідили структурні та діелектричні властивості зразків, а також розглянули вплив гамма-променів на ці властивості.

Ключові слова: ферит манґану, наноструктурні матеріяли, міжмолекулярні взаємодії, діелектричні властивості.

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1. INTRODUCTION

It is known that the compound $MnFe_2O_4$, which has led to interesting studies and demonstrates higher magnetic and electromagnetic properties, is among the most studied materials in our time. $MnFe_2O_4$ nanoparticle is the main and important member of ferrites. Materials made from manganese ferrite nanoparticles mainly exhibit extreme paramagnetism, magnetization, single-domain effect, *etc.*—unusual magnetic properties. The nanoparticles we mentioned have higher mechanical, luminescence and magnetic properties than other existing magnetic ferrite nanoparticles. One of the main goals is to study the magnetic nature of nanoparticles in magnetic materials. Spinel-structured $MnFe_2O_4$ oxides with special magnetic transitions are widely studied in industry and medical biology. Among the factors that affect the physical and chemical properties of nanoparticles, we can cite several researches on the synthesis of nanomaterials, the surface effect with ferrite nanocrystals as a large surface-to-volume ratio and quantum confinement effects as properties dependent on the size. Ferrite nanocrystals with magnetic and spinel structures are considered two of the most important inorganic nanomaterials [1, 2]. These nanocrystals have possible optical, catalytic, electrical, electronic and magnetic properties, each of which is different from the other. Among spinel ferrites, manganese ferrite ($MnFe_2O_4$) nanoparticles have proven themselves in a large number of magnetic applications due to their significant properties. These applications include biosensors and MRI technology, recording media devices, drug delivery and contrast enhancement agents for ferrofluids [3–10].

In the presented work, the structural and dielectric properties of non-irradiated and irradiated samples under the influence of γ-rays for 1 and 10 hours were investigated. From the analyses carried out during the research, it can be assumed that after exposure to gamma rays, ferrite nanostructures acquire many new properties. This allows them to be used as a very good magnetic material.

2. EXPERIMENTAL DETAILS

In this research, we used a nanopowder sample with a true density of 4.96 g/cm^3, a particle size of 60 nm, and a purity of 98.5% (SkySpring Nanomaterials, USA). The $MnFe_2O_4$ nanoparticle has a spherical shape depending on the synthesis process. These particles in the form of powder are produced by pressing. Pressing process Model No. FTIR hydraulic press with ATHP-15 is made. The process was carried out in full-fledged laboratory conditions. For this, the nanoparticle in the form of powder was poured into a special mould with a width of 4 mm, a length of 15 mm, and a height of 5 mm. High temperatures were not required, since our goal when pressing powdered nanoparticles was only to shape the sample. The temperature of 293 K was enough to give our nanoparticle a tablet shape. The pressing pressure was 50 kg/cm^2. The samples, obtained in pill form, were irradiated at room temperature ($T = 293$ K) in an MPX-γ-25M device with a ^{60}Co radiation source, with a radiation intensity of $\dot{D} = 1.41$ gray/sec and a radiation dose of 50 grays. It was irradiated for 1 and 10 hours with dose sequencing. The dielectric loss tangent was measured using an E8-4 automatic bridge at a frequency of 1 kHz in the temperature range 300–500 K.

3. RESULTS AND DISCUSSION

Recently, interest in nanomaterials has increased in various directions and in various fields. In this regard, it is very important to know the characteristics of nanoparticles produced in many directions. Because the properties of nanocomposites depend on the nanoparticles, the structural and dielectric properties of $MnFe_2O_4$ nanoparticles were studied in the research work. Thus, initially, the dielectric properties of the $MnFe_2O_4$ nanoparticles were determined using measuring devices. The chemical structure of the $MnFe_2O_4$ nanoparticle is as shown in Fig. 1.

This type of structure allows the generation of cyclization-intramolecular bonds and radiation-oxidation reactions, *i.e.*, chemical changes due to the influence of radiation in the nanoparticles after exposure to gamma rays. These properties are used in the preparation of nanomaterials with new types of dielectric properties.

The $MnFe_2O_4$ nanoparticle was first irradiated with gamma rays for 1 hour and then for 10 hours. At that time, the dose rate was 1.41 gray/sec. Following irradiation, the nanoparticle absorbed a dose of 50 grays ($\cong 50.76$). Then, the value of the evolution of the electrical capacitance of the nanoparticle irradiated with gamma rays and the non-

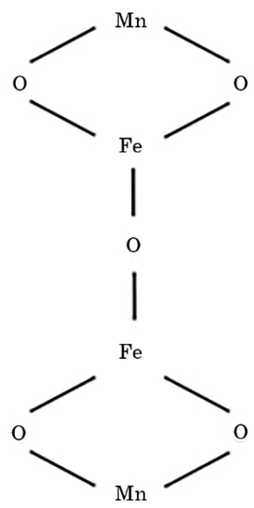

Fig. 1. Chemical structure of $MnFe_2O_4$ nanoparticle.

irradiated nanoparticle as a function of temperature was measured for 1 hour and 10 hours. According to the obtained results, the temperature dependence graph of the electrical capacitance of the sample was determined.

As shown in the graph, there is no big change in the electrical capacitance value of the non-irradiated $MnFe_2O_4$ nanoparticle (Fig. 2). However, after irradiating the sample for 1 hour, its electrical capacitance value increased and although the electrical capacitance value decreased to some extent at intermediate temperature values, a sharp increase was observed at high temperature values. The same situation was observed in the temperature dependence graph of its electrical capacity after gamma irradiation for 10 hours. Thus, although the price of electrical capacity increased sharply at the initial temperature values, the price of electrical capacity subsequently became somewhat stable. This change in the nanoparticle may be due to cyclization, *i.e.*, formation of intramolecular bonds, and radiation-oxidation reactions, *i.e.*, chemical changes caused by radiation. At the same time, gamma rays can cause the formation of free radicals in nanoparticles, and free electrons and other particles created during irradiation can also affect such a change in the electrical capacitance value.

Dielectric losses are the electrical energy spent to heat the dielectric located in an electric field. In dielectrics, losses occur in alternating and constant electric fields. To characterize electrical losses in dielectrics, the notion of dielectric electrical loss angle δ or tangent of the dielectric electrical loss angle $tg\delta$ is used.

After 1 hour and 10 hours of irradiation, the value of the evolution of the dielectric loss angle of the nanoparticle having absorbed a dose

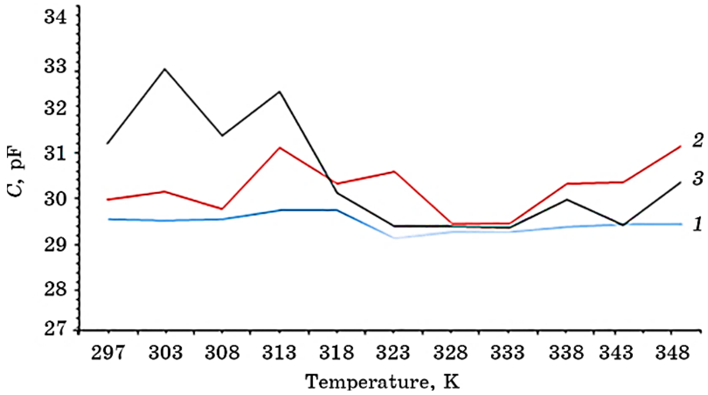

Fig. 2. Temperature dependence plot of electrical capacitance of $MnFe_2O_4$ nanoparticle: *1*) non-irradiated sample; *2*) for 1 hour and *3*) for 10 hours after being irradiated by gamma rays.

of 50 grays as a function of temperature was measured [11]. This device allows direct measurement of the tgδ parameter.

The temperature dependence of the dielectric loss angle parameters of the $MnFe_2O_4$ nanoparticle was studied (Fig. 3). As shown in the graph, there is no significant change in the dielectric loss angle value of the non-irradiated $MnFe_2O_4$ nanoparticle. However, after irradiating the sample for 1 hour, its dielectric loss angle value decreased. The same situation was observed in the temperature dependence graph of its dielectric loss angle after being irradiated with gamma rays for 10 hours.

It is observed in the dependences of $\mathrm{tg}\delta = f(t)$ that the decrease in the dielectric loss angle (tgδ) can be considered as a factor indicating the

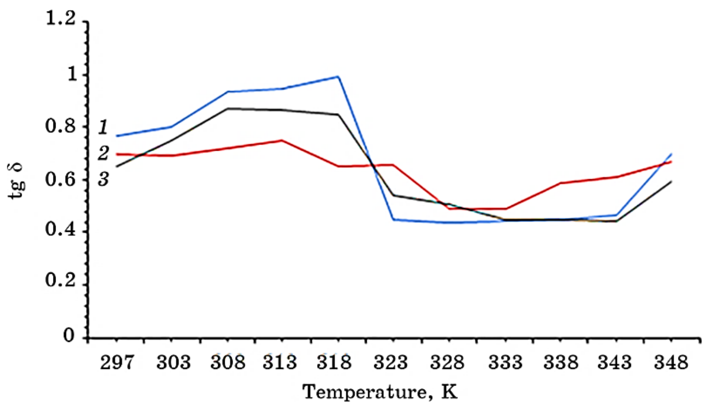

Fig. 3. Temperature dependence plot of dielectric loss angle (tgδ) of $MnFe_2O_4$ nanoparticle: *1*) non-irradiated sample; *2*) for 1 hour and *3*) for 10 hours after being irradiated with gamma rays.

weakening of the relaxation process. This is a factor that indicates the improvement of the electret properties of the $MnFe_2O_4$ nanoparticle after irradiation with gamma rays. At the same time, these results can be explained by the influence of the kinetics of nanoparticles under the influence of gamma rays.

After the $MnFe_2O_4$ nanoparticle is irradiated by gamma rays for 1 hour, its dielectric loss (tgδ) decreases and at the same time, the stability of electric charges decreases. The choice of Fe_2O_4 oxide is also due to the fact that the nanoparticles resulting from it are also antiradar, antistatic, *etc.*; they also have the same properties. This improves the electret properties of the nanoparticles and can lead to changes in their dielectric parameters after treatment in a magnetic field [12].

In general, dielectric permeability is related to the electric moment of a unit volume of the dielectric in an external electric field and is determined by the structure of the polymer and also depends on the frequency and temperature of the applied field. The error of the measurement results did not exceed ≅5%. Based on the measured capacitance C and the geometric dimensions of the samples, the value of the dielectric constant ε was calculated from the capacitance formula of a planar capacitor as follows: $\varepsilon = Cd/(\varepsilon_0 S)$; here, ε_0 is the dielectric constant, d is the thickness of the sample and S is the surface area of the electrodes.

At the end of the research work, the temperature dependence of the dielectric permeability parameters of the $MnFe_2O_4$ nanoparticle was studied (Fig. 4). As shown in the graph, the dielectric permeability value of the $MnFe_2O_4$ nanoparticle behaved very strangely after 1 hour

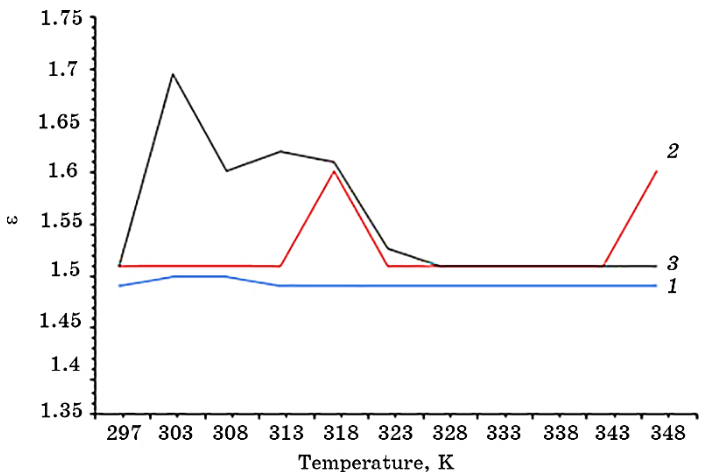

Fig. 4. Temperature dependence plot of dielectric permittivity (ε) of $MnFe_2O_4$ nanoparticle: *1*) non-irradiated sample; *2*) for 1 hour and *3*) for 10 hours after being irradiated with gamma rays.

of irradiation and strong symmetrical increases were observed at certain temperature values. After being irradiated for 10 hours, a sharp increase in initial temperature values was observed, but a decrease in subsequent values was observed.

It is observed in the dependence $\varepsilon = f(t)$ that the increase in the value of the dielectric permeability (ε) can be considered as a factor indicating the weakening of the relaxation process. This is a factor that indicates the improvement in the properties of the electret after irradiation of the nanoparticle with gamma rays.

During the research, it was also observed that, when the duration of the radiation absorption dose of the nanoparticle increased, the crystal structure of the $MnFe_2O_4$ nanoparticle disintegrated and turned into powder. This phenomenon can be explained as follows. Another important feature of the effect of γ irradiation on nanoparticles, which causes the crystal structure to disintegrate and turn into powder, may be the effect of the crystal structure of $MnFe_2O_4$ nanoparticle. Intramolecular coupling in nanoparticles disrupts their crystallinity at high absorption doses, which is an attenuation factor [13].

Although many scientific studies have been carried out in these directions, there are still processes that are not fully explained.

At the same time, the change in physical and mechanical characteristics can be attributed to the generation of excessive loads and their stabilization. It is important to note that the degree of modification of one or another characteristic of a nanoparticle is determined by its physical state before irradiation, conditions, type, power and dose of irradiation.

The research carried out shows that the study of the electret properties of the nanoparticle system after gamma irradiation is of particular importance for the modern era.

4. CONCLUSIONS

Structural and dielectric properties of $MnFe_2O_4$ nanoparticle were studied in the research work. So, initially, the dielectric properties of $MnFe_2O_4$ nanoparticle were determined with the help of measuring devices. Later, that nanoparticle was exposed to gamma rays. At this time, the research work was carried out by changing the absorption dose of the beam, but only by changing the absorption time of the beam. The nanoparticle samples absorbed 50 gray doses for 1 and 10 hours, and the dielectric parameters of the nanoparticle were determined with the help of measuring devices. The obtained results were presented in the form of a graph and analysed in a comparative manner. It was found that the various parameters of the nanoparticle changed in different ways. It has been noted that there are positive changes in some electrical parameters. After exposure to gamma rays, ferrite nanostructures have many new properties, which make it possible to use them as a good magnetic material. Such advantages of ferrite nanoparticles allow them to be used in various fields, such as magnetic fluids, information carriers, catalysts, gas analysers, sensors, electronics, radio engineering and information technology industries, as well as in biomedical devices for contrast enhancement.

AUTHORS' CONTRIBUTIONS

Aynura F. Gochuyeva participated in planning the experiments, analysed the obtained results, and contributed to the interpretation of the dielectrically and structural properties of $MnFe_2O_4$ nanoparticles. Durdana F. Rustamova supervised the research, formulated the main methodological and technological approaches, coordinated the study, and wrote the manuscript with contributions from all authors. Mauyey Bakytbek carried out the investigation and established the methodological framework of the study.

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