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Magnetic properties of nanocomposites based on opal matrices with embedded ferrite-spinel nanoparticles

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ABSTRACT

Magnetic properties of nanocomposites based on opal matrices with ferrite-spinel nanoparticles embedded have been investigated in temperature range from 2 to 300 K. The magnetization curves and hysteresis loops as well as the temperature dependence of magnetic moment and the temperature and frequency dependences of AC susceptibility have been measured. The results of magnetic measurements are compared to X-ray analysis and electron microscopy investigations.

1. Introduction

Magnetic properties of oxides and ferrites nanoparticles are the object of detailed studies [1,2]. Magnetic oxide nanoparticles have been studied to elucidate the effects of nanoscale finite size on the magnetic behavior. Magnetite nanoparticles synthesized by co-precipitation show superparamagnetism at room temperature [3]. The magnetization of nanoparticles often obeys the Langevin function. The reduced magnetization can be consistently explained by a spin-disordered surface layer. The dynamical properties of 7 nm $\gamma - Fe_2O_3$ particles, dispersed in a polymer, were investigated by AC susceptibility [4]. A model which accounts for interparticle interactions by a statistical calculation of the dipolar energy satisfactorily describes the variation of the average blocking temperature as a function of the measuring time. The concentration dependence of the remanent magnetization, the coercive field and the blocking temperature of a three-dimensional random assembly of ferromagnetic nanoparticles interacting via exchange and dipolar forces is studied by Monte Carlo simulations [5]. It has been found that interactions always suppress the coercivity. The zero-field-cooled/field cooled (ZFC/FC) curves are calculated. The peak of the ZFC curve provides the blocking temperature (T_b) of the system. Interparticle interactions cause an increase of T_b.

Magnetic properties of the ferrites depend on composition and cation distribution. According to the occupancy of cations in tetrahedral and octahedral sites, they can exhibit ferromagnetic, antiferromagnetic, and paramagnetic behavior [6]. The chemical composition and particle size plays a crucial role in determining the magnetic properties of the nanoparticles and possible applications. MFe_2O_4 nanoparticles (where M is Co, Mg, Mn and Ni) were obtained using ricinoil solution as a surfactant and their structural characterization and magnetic properties were studied [7]. The room temperature M–H hysteresis loops show ferromagnetic behavior of the calcined samples, with specific saturation magnetization values ranging between 11 and 53 emu/g. Nanoparticles of $Co_{0.5}Ni_{0.5-2x}Li_xFe_{2+x}O_4$ were prepared by using a citrate precursor method [8]. The change in magnetic properties by adding Li^+ ions is explained that is dependent on many factors such as crystallite size, measured density, porosity, expected cation distribution, exchange interactions, and magnetocrystalline anisotropy. Manganese ferrite nanoparticles, in the size range 3.3–9.0 nm, are prepared by a hydrothermal co-precipitation process. The magnetization curves recorded at room temperature on diluted colloidal sols allow characterizing the distribution of magnetic moment by using a simple Langevin formalism [9]. The magnetic dynamics behavior is investigated by measurements of magnetic hysteretic properties and temperature dependence of the ZFC susceptibility.

Manganese zinc iron magnetic nanoparticles were synthesized by a co-precipitation method [10]. The magnetic properties being investigated including Curie temperature, saturation magnetization, remanent magnetization, coercive field, and hysteresis loop.

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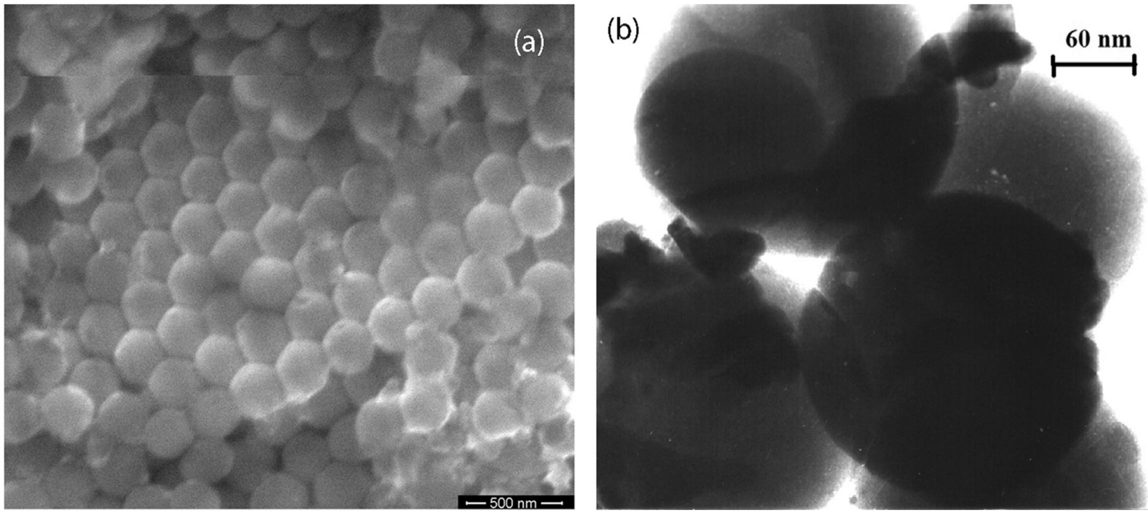

Fig. 1. The TEM images of opal matrices with $Ni_{0.5}Zn_{0.5}Fe_2O_4$ nanoparticles (a) and $Ni_{0.35}Zn_{0.65}Fe_2O_4$ nanoparticles (b).

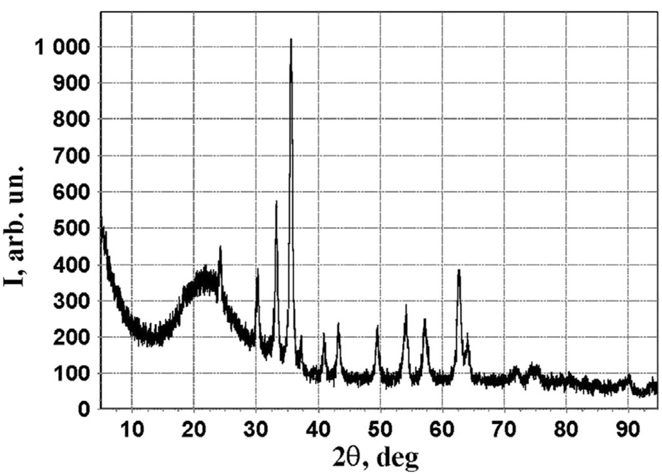

Fig. 2. X-ray diffraction pattern of the sample of opal matrix with synthesized chemical compounds based on Ni, Zn and Fe in the inter-spherical nano-voids.

$Co_xZn_yFe_{3-x-y}O_4$ ferrite nanoparticles have been synthesized by the reverse microemulsion method [11]. As was established, the Curie temperature decreases with increasing concentration of Zn. Single phase zinc ferrite ($ZnFe_2O_4$) nanoparticles have been prepared by the co-precipitation method [12]. The effects of precipitation temperature in the range 20–80 °C on the structural and the magnetic properties of zinc ferrite nanoparticles were investigated. The magnetic measurements exhibited that the zinc ferrite nanoparticles synthesized at 40 °C were superparamagnetic. The maximum saturation magnetization of Ni–Zn ferrite powders increased with combustion temperature indicating the growth of grain size, while remanent magnetization and coercive force decreased [13]. Effects of nanocrystalline ferrite particles addition on densification behavior and magnetic properties of the NiCuZn ferrites were investigated [14].

They regard radiofrequency and microwave devices as one of the most valuable applications of ferrites. Signal processing requires broadband, low-loss, low-cost microwave devices (circulators, isolators, phase shifters, absorbers). Magnetic properties, specific to operation in high-frequency electromagnetic fields, are discussed in the paper [15]. For a magnetic material to be applied in microwave devices, the most important static magnetic properties, to be controlled, are as follows: the saturation magnetization and anisotropy constants. A low-coercivity, high-remanence, soft magnetic material, having a square hysteresis loop, is required for microwave operation.

The most frequently used microwave ferrites are the spinels. Typically, spinels can be used up to 30 GHz. The microwave and magnetic properties of $Ni_{0.35}Cu_{0.15}Zn_{0.5}Fe_2O_4$ spherical particles have been compared with [16]. For 3D opal-based nanocomposites with Ni–Zn ferrite particles full saturation of the magnetization curve was not exceeded even in fields up to 30 kOe [17]. The latter work confirms the presence of the fine superparamagnetic properties or at any rate strongly interacting particles.

In this paper the magnetic properties of the nanocomposites based on the opal matrices with iron spinel particles embedded in the inter-spherical voids have been studied. The materials of this sort have unique microwave properties [17]. As is well known, the resonant microwave properties are mainly determined by the magnetic field dependence of magnetization. The magnetization curves, hysteresis loops, temperature dependences of magnetic moment and AC-susceptibility of nanocomposites with nickel zinc, manganese zinc, cobalt zinc and neodymium cobalt zinc iron ferrites have been measured. Magnetic properties have been studied along with the structural and X-ray phase analysis.

2. Preparation of samples and structural data

As is known, few methods of synthesis of opal matrices, inverse opal matrices and films on their base were developed [18,19]. Insertion of the ferrite nanoparticles in the inter-sphere voids was fulfilled by means of repeated impregnation. The technology which permits us to fabricate the opal matrix packages with improved mechanical properties, partially with better adhesion between spheres has been described in the paper [17]. The opal matrix packages with SiO_2 sphere diameter of 250 nm were firstly obtained as a result of hydrolysis reaction between tetra-ether of ortho-silicon acid $Si(OC_2H_5)_4$ and ethanol C_2H_5OH. In the polycondensation process the spherical monodisperse silicon dioxide particles were obtained. After precipitation and drying the opal matrix obtained was thermally treated in order to strengthening and removing of residual water. Characterization of structural perfection of the opal packages obtained was carried out optically through the shape and width of Bragg reflection bands.

The method of impregnation uses precursors that have good solubility in water and have to convert into oxides at moderate temperatures. Annealing is carried out at temperatures from 770 to 870. Impregnations and afterheats were repeated up to 20 times resulting in gradual infill of the inter-sphere voids. The TEM