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Magnetoresistive and Magneto-optical Properties of Fragment Spin-Valve Structures Based on the Ordered Arrays of Fe_3O_4 Nanoparticles

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A complex investigation of the properties of fragments of the spin-valve structures based on ordered arrays of Fe_3O_4 nanoparticles embedded in a conductive Cu or Au matrix was carried out. The effect of the orientation of an external magnetic field on the value of magnetoresistance and coercivity was established. The influence of the annealing temperature on the surface morphology and magneto-optical Kerr effect of these structures was studied.

Keywords: Nanoparticles, Spin-valve, Magnetoresistance, Kerr effect.

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1. INTRODUCTION

The question concerning the optimal selection of materials with necessary parameters for the construction of multilayer spin-valve structures and magnetic multilayers, which recently have found a wide application in the instrument base of micro- and nanoelectronics, remains topical today in the field of spintronics. The problem of embedding of the ordered two-dimensional arrays of nanoparticles (NPs) to the structure of spin-valve system instead of one of magnetic layers is also a new and little-studied. Investigation of novel features of the systems thus obtained opens new possibilities of application of the combined devices based on the structures of the array of NPs/multilayer films type.

An intensive study of the magnetic NPs began with the discovery of their special magnetic properties. First of all, interest to magnetic particles is induced by their single-domain state.

A large number of methods for obtaining NPs which can be divided into physical methods and chemical synthesis is developed for today. A variety of techniques of the material condensation, such as thermal condensation (see, for example, [1]), laser evaporation [2] and plasma condensation methods [3], is used for their production. Depending on the substrate temperature (as a rule, this is a low temperature), on which the material is condensed, and evaporation rate, one can obtain NPs of different size and stoichiometry [4]. However, there exist methods of thermal production of NPs without cooling of the substrate. In this case, a polymer layer, which has a low adhesion to the condensed film, is used as the substrate [5]. In the condensation of the material and further annealing of the sample, arrays of NPs are formed on the polymer substrate surface. Depending on the condensed film thickness and annealing temperature, it is possible to obtain NPs of different sizes in the range of 1-50 nm. Nanodispersion and electrolytic erosion are other physical and chemical methods for obtaining NPs.

To widespread methods for obtaining arrays of NPs one can ascribe the chemical methods when metal-containing compounds (MCC) and metal salts are used as the initial substances for chemical synthesis. The following techniques are applied for the synthesis: thermolysis or decomposition of MCC under the ultrasound action, magnetic materials recovery, sol-gel method, synthesis of magnetic on the gaseous/liquid phases interface and heterometallic NPs [6-9].

To study the phase and elemental composition, surface morphology and sizes of NPs, they use a package of methods, such as X-ray microanalysis [10], transmission electron microscopy (TEM), electron and X-ray diffractometry, scanning tunneling and atomic-force microscopy (AFM). Here, the peculiarities of these investigations by the abovementioned methods take place. For example, in the X-ray phase analysis of nanomaterials it fails to obtain the X-ray diffraction patterns with a set of narrow reflexes that cannot allow to definitely identify the NPs composition. In the study by the AFM [10, 11] or scanning electron microscopy methods one can investigate the surface morphology and estimate the real NPs sizes. In the study by the TEM method, one can evaluate the sizes of metallic nucleus, but it is impossible to determine with accuracy the thickness of NPs shell [12], if NPs covered by a polymer layer are studied. Therefore, in the study of the structural and phase state, in order to obtain more reliable results, several methods which supplement each other are used.

The aim of the carried out investigations was to obtain the experimental data concerning the possibility of usage of the ordered arrays of magnetic NPs as the elements of the spin-valve structures. The main attention was devoted to the morphological, magnetoresistive and magneto-optical properties and their dependence on the conditions of thermal treatment.

2. EXPERIMENTAL TECHNIQUE

In the study we have used the samples representing the structure of one or several layers of magnetic Fe_3O_4 or FeO NPs embedded in a non-magnetic conductive Cu or Au matrix. Ordered arrays of NPs were formed by the dripping method [13] on SiO_2 substrates of 10 % solution of NPs in toluene. Such concentration was chosen solely by experiment for a more uniform distribution of NPs on the silicon substrate surface. Along with the evident simplicity of the selected NPs deposition method, a number of difficulties appear, such as the strong dependence of the NPs properties on their sizes, storage and deposition conditions [14] including air purity and humidity, solvent quality, degree of hydrophilicity of the substrate and its purity. Therefore, when dealing with NPs it is necessary to use high-precision control systems of the NPs deposition parameters. This gives the possibility to increase the repeatability of the results and significantly enhance the quality of the samples.

Formation of a conductive matrix over the array of NPs occurred by thermal evaporation of Cu or Au in the vacuum chamber VUP-5M at the pressure of residual atmosphere of 10^{-3}-10^{-4} Pa. Thickness of the deposited material was controlled using quartz resonator entering into the composition of an automated complex and was equal to 20 nm. Influence of the annealing temperature on the structural and phase state of NPs on the polymer substrates is described in detail in the work [13], where investigations were performed using the electron microscope PEM-125K. To measure the change in the magnetoresistance (MR) value we used the automated system which allows to conduct investigations at the CIP (Current in plane) geometry of the current flow in a variable configuration of the applied external magnetic field. Study of the surface morphology of the formed samples was carried out using the AFM method (in the contact mode). Investigations of the magneto-optical Kerr effect (MOKE) were also performed.

3. ANALYSIS OF THE RESULTS

The AFM-images represented in Fig.1 illustrate the surface morphology on the formation stages of the sample based on the ordered arrays of Fe_3O_4 NPs embedded in a conductive Cu matrix with further thermal treatment to 900 K. Analysis of the images gives a clear idea about the distribution of NPs on the silicon substrate surface directly after their deposition by the dripping method at room temperature (Fig. 1a), after deposition of a conductive non-magnetic Cu matrix (Fig. 1b) and thermal treatment to 900 K (Fig. 1c). As a result of annealing of the array of NPs, which is not covered by a conductive matrix, to 700 K (Fig. 2a) one observes its some ordering without a significant increase in the NPs sizes. At further annealing to 900 K, the average NPs size appreciably increases from 10 nm to 20 nm at the cost of the NPs unification (Fig. 2b). In this case, we should note that in the study by the AFM method in the contact mode of the arrays of NPs, which are not embedded in a conductive matrix, not very correct results concerning the surface morphology can be observed due to a weak adhesion of NPs to the substrate surface. Moreover, analyzing the data of the NPs geometry, one should take into account the effect of probe convolution in the scanning of NPs whose radius is comparable with the radius of probe curvature.

In Fig. 3 we present the AFM-images of the pre-annealed to 700K Fe_3O_4 NPs embedded in a conductive Au matrix and after re-annealing of the formed structure to 900K. Analysis of the obtained images implies a complete disorder of the formed structure consisting of the ordered arrays of NPs in a conductive matrix after annealing to 900 K. This can be argued by the fact that conductive matrix under the temperature action is dispersed and forms islands which involve NPs that leads

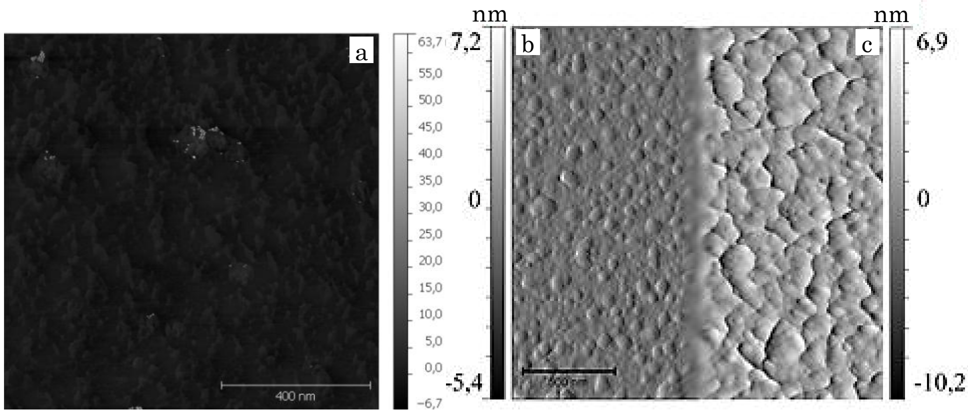

Fig. 1 – AFM-images of Fe_3O_4 NPs before annealing (a) without deposition of a conductive layer embedded in a conductive Cu matrix (b) and with further annealing to 900 K (c)

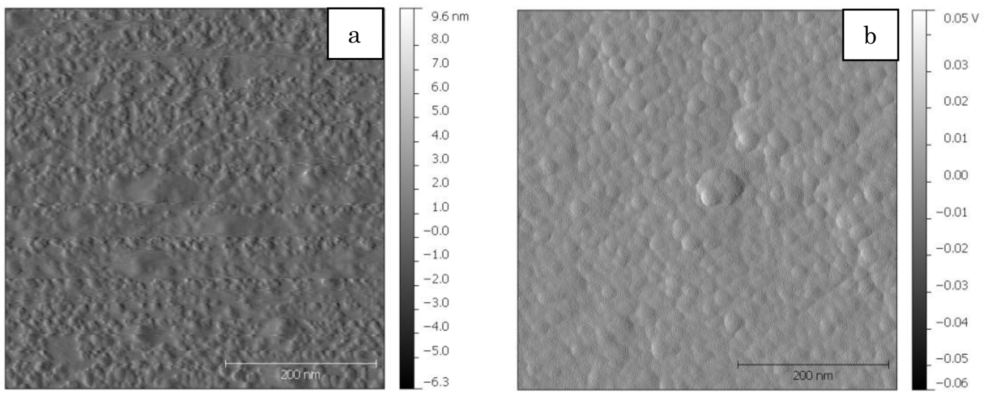

Fig. 2 – AFM-images of Fe_3O_4 NPs after annealing to 700 K (a) and to 900 K (b) without deposition of a conductive matrix

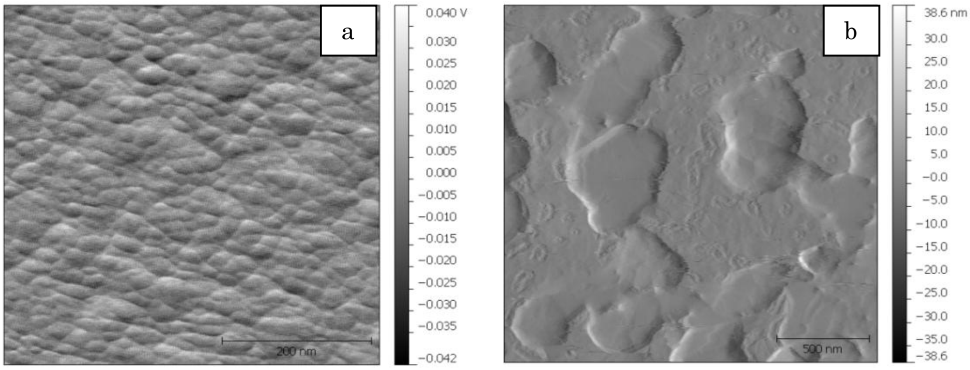

Fig. 3 – AFM-images of the pre-annealed to 700 K Fe_3O_4 NPs embedded in a conductive Au matrix (a) and after re-annealing of the formed structure to 900 K (b)

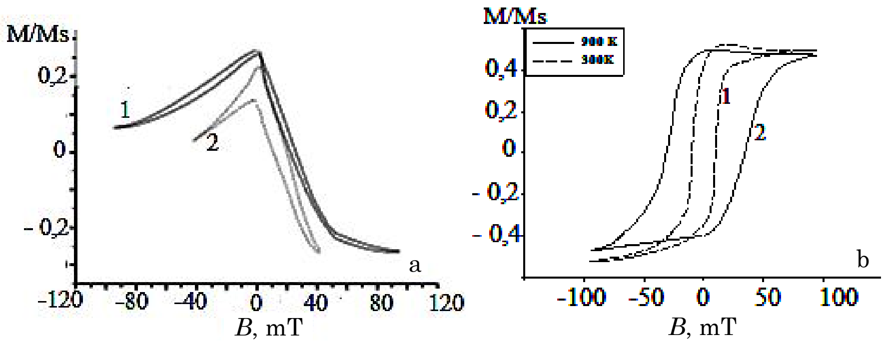

Fig. 4 – MOKE for the annealed to 700 K Fe_3O_4 NPs (a, curve 1) further embedded in a conductive Au(20) matrix (a, curve 2) and for the $Au(2)/Cu(20)/Fe_3O_4(NPs)/SiO_2$ system at room temperature and after annealing to 900 K (b)

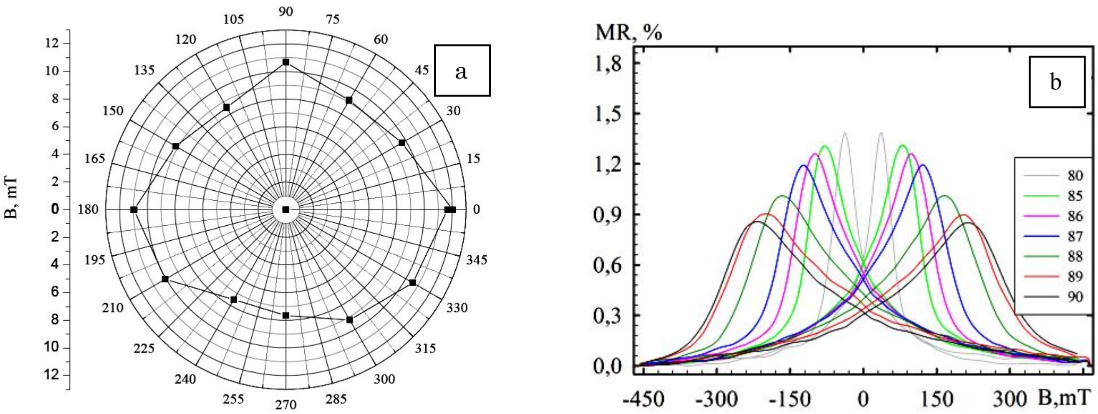

Fig. 5 – Circle diagram of the change in the coercive force (a) and dependence of the MR value on the geometry of the external magnetic field application (b)

to the destruction of the earlier formed ordered array. One of the consequences of this is a sharp decrease in the MR value after annealing to this temperature that is described in detail in the work [13].

Dependence shows in Fig. 4a describes the MOKE for the annealed to 700 K Fe_3O_4 NPs further embedded in a conductive Au matrix. Analysis of the results demonstrates that deposition of a conductive matrix slightly increases the coercive force value. For the system $Au(2)/Cu(20)/Fe_3O_4(NPs)/SiO_2$ the investigation results of the temperature influence on the MOKE are shown in Fig. 4b. After thermal treatment of this system to 900 K, a considerable increase in the coercive force is observed. Circle diagram (Fig. 5a) illustrates the dependence of the coercive force on the measurement geometry for the unannealed sample.

Dependences shown in Fig. 5b illustrate the sharp increase in the coercive force from 60 mT to 480 mT and decrease in the MR value from 1.3 % to 0.85 % at the angle change from 80° to 90° of the external magnetic field application. Such behavior of the dependences can indicate the presence of the heavy magnetization axis in the range of these angles. With further decrease in the angle one observes stabilization of both the coercive force (about 60 mT) and the MR (1.2-1.3 %) that can be explained by the presence of the easy magnetization axis.

4. CONCLUSIONS

The analysis of the surface morphology of the structures composed of the ordered arrays of Fe_3O_4 NPs in a conductive Cu or Au matrix on the stages of their formation and depending on the annealing temperature is performed by the AFM method. The temperature influence on the MR change and MOKE is studied. A sharp increase in the coercive force from 60 mT to 480 mT and MR decrease from 1.3 % to 0.85 % in the range of angles of 80^0-90^0 are analyzed. The investigation results of the MR represented in the work [13], namely, a sharp decrease in the MR value after annealing to 900 K, are confirmed by the AFM method. The results of the performed magnetoresistive investigations correlate with the data obtained by the MOKE method and with the studies carried our earlier.

Based on the analyzed data, it was concluded about the possibility of the use of the ordered arrays of Fe_3O_4 NPs embedded in a conductive Cu or Au matrix as the sensitive elements of magnetic field sensors, rotating sensors, commutation elements in electronics.

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