Magnetic Properties and the Giant Magnetoimpedance of Amorphous Co-Based Wires with a Carbon Coating

E. V. Golubeva, E. A. Stepanova, K. G. Balymov, S. O. Volchkov, and G. V. Kurlyandskaya

Ural Federal University, Laboratory of Magnetic Sensorics, Ekaterinburg, 620002 Russia
Universidad del País Vasco UPV-EHU, Depto Electricidad y Electrónica, 48940, Leioa, Spain
*E-mail: golubeva.elizaveta@urfu.ru

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Abstract—A comparative analysis of the magnetic properties and specific features of the giant magnetoimpedance has been carried out for amorphous rapidly quenched wires with a composition of (Co0.94Fe0.06)72.5Si12.5B15 in the initial state and after the deposition of a carbon coating. The deposition of the defective graphene-like carbon layer was carried out under normal conditions during the exposure in toluene (methylbenzene). The method of the energy-dispersive X-ray spectroscopy made it possible to reliably show that after the modification in toluene, the carbon content on the surface significantly exceeds the natural amount of carbon. The deposition of the carbon coating induced changes in the distribution of the initial quenching stresses in the near-surface layer of amorphous wires. A comparative analysis of the magnetic and magnetoimpedance properties of the samples before and after exposure in the aromatic solvent confirms the occurrence of changes in the effective magnetic anisotropy as a result of this surface treatment.

Keywords: giant magnetoimpedance, rapidly quenched amorphous wires, effective magnetic anisotropy, carbon coating, low-temperature condensation of carbon

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INTRODUCTION

Carbon-based nanostructures are interesting from both fundamental and applied points of view [1]. Usually, the self-organized carbon structures are obtained by laser deposition in an inert-gas atmosphere or in vacuum [2]. The studies of the creation of graphene-like nanostructures on metallic surfaces [3] are of special interest. In addition, in a number of works, much attention is focused on the process of low-temperature condensation of carbon on nonpassivated surfaces under normal conditions upon the interaction with aromatic solvents, such as methylbenzene (toluene) [4, 5]. Even in the first works performed on Fe and Ni nanoparticles and Fe and FeNi films, a possible mechanism for creating the graphene-like coating in the form of polycyclic aromatic hydrocarbons formed by the mechanism of cationic polymerization was proposed [4]. However, a number of important issues remained unclear. At present, in the scientific literature, there are data on the possibility of the formation of carbon coatings on the surface of Fe and Ni nanoparticles [4], 3d-metal films (Fe and FeNi) [4, 5], and amorphous rapidly quenched cobalt-based ribbons [6] under normal conditions when interacting with the aromatic solvent methylbenzene.

Functional carbon coatings are promising in terms of their use in various sensor devices, including magnetic biosensors for marker and markerless detection [7–9]. It is assumed that they can be used for the functionalization of magnetic markers and as functional coatings of sensor elements. The deposition of graphene-like nanostructures onto the metallic surfaces of nanoparticles can be an important step in the development of new-generation markers, since these coatings can provide a high degree of deaggregation. As the functional coatings of sensor elements, the carbon coatings can play an important role in optimizing the processes of self-organization of biocomponents and biomarkers.

The use of the effect of the giant magnetoimpedance (GMI) for determining the concentration of magnetic markers is promising because of the high sensitivity of this effect to the external magnetic fields of small strength [10, 11]. The effect of the GMI consists in the change of the overall impedance of a ferromagnetic conductor as a function of frequency of the current flowing through the sample and of the strength of the external dc magnetic field [11, 12]. The GMI phenomenon is described using classical electrodynamics based on the dependence of the total impedance ($Z$) on the depth of the skin layer, which in turn depends on the frequency of the excitation current ($f$),
the circular magnetic permeability ($\mu$), and the dc resistivity ($\rho$) [13]. Thus, the GMI can be used to analyze the changes in magnetic properties and effective magnetic anisotropy (MA) in the near-surface layer of the sample.

Amorphous and nanocrystalline rapidly quenched materials (both ribbons and wires) are promising soft magnetic materials for application as sensitive elements of magnetic sensors. They possess characteristics suitable for such applications, including the high sensitivity of the GMI effect with respect to external magnetic fields [14–16].

An important requirement for biosensors is that they operate stably in a biocorrosive environment, which can be achieved by applying polymer coatings. However, due to the poor mutual compatibility of the surface of the rapidly quenched material and the polymer, polymer coatings very often form with a number of defects and have short lifetimes. It has been suggested that, to increase the adhesion between the polymer and the metal, a graphene-like coating can be used that was obtained, e.g., by the low-temperature condensation of carbon in aromatic solvents.

Since studies of this type of coatings on amorphous materials in the form of wires have not been carried out previously, the main purpose of this work was to establish the possibility of forming a carbon coating in the process of low-temperature condensation of carbon in methylbenzene on the surface of cobalt-based amorphous wires, as well as to study the influence of this coating on their magnetic and magnetoimpedance properties.

EXPERIMENTAL

The object of this study was amorphous wires of the composition (Co$_{0.94}$Fe$_{0.06}$)$_{72.5}$Si$_{12.5}$B$_{15}$ 150 $\mu$m in diameter and 6 mm long obtained by rapid quenching in water [15, 16]. Wires of this composition have a negative constant of saturation magnetostriction $\lambda_s$; therefore, their magnetic domain structure consists of two substructures, i.e., a central part (core) with an axially directed magnetic anisotropy (AMA) and a shell with a circularly directed AMA [15–17].

To create graphene-like coatings on the surfaces of the samples, the wires were placed in an aromatic solvent, methylbenzene, under normal conditions (atmospheric pressure was about 760 mmHg, ambient temperature was about 25°C) for one month without any preliminary treatments. For surface modification, the samples were placed in glass containers with volumes many times greater than that of the sample, and the solvent was agitated once a day. The entire surface of the sample was completely covered with methylbenzene without the possibility of direct contact with atmospheric oxygen. The samples in the initial state were designated as W-0; the samples with the modified surface were designated as W-1.

The surface features of the wire samples were examined by the scanning electron microscopy (SEM) using a JEOL (JSM-7000F, Japan) microscope and X-ray energy dispersive spectroscopy (X-Act EDX INCA X-sight Series Si(Li) penta FET (Oxford Instruments, United Kingdom)).

The magnetic properties of the samples were measured using a 7407 VSM vibrating-sample magnetometer (Lake Shore Cryotronics) with a measurement error of no more than 3%.

The measurements of the frequency and magnetic-field dependences of the impedance were carried out using an automated complex of magnetoimpedance spectroscopy [18]. The studies were carried out in a frequency range of alternating current ($f$) of 1–400 MHz; the external magnetic field with a strength in the range of $-100$ to $+100$ Oe was applied along the axis of the wire. The basis of the complex is a precision impedance analyzer (Agilent E4991A); the measurement error does not exceed 3% in the frequency range studied. The sample is connected to a single measuring circuit using the high-conductive silver-based adhesive high-frequency connectors, such as SMA, high-frequency Agilent wires, and a loading resistor. The automation of the measuring complex was carried out by combining the impedance analyzer and the Fluke PM2813 current source in the Labview 2010 software package.

An external quasi-static magnetic field was created using a solenoid. To reduce the effect of earth field, the solenoid was located perpendicular to its force lines. All magnetic measurements were carried out under normal conditions. The relative change in the total impedance in the external magnetic field (GMI ratio) was calculated using the formula

$$\Delta Z/Z = 100\% [Z(H) - Z(H_{max})]/Z(H_{max}),$$

where $H_{max} = 100$ Oe. The maximum value of the total impedance for each frequency was denoted as $\Delta Z_{max}$. An important characteristic of the GMI effect is its sensitivity to the external magnetic field

$$S(\Delta Z/Z) = d(\Delta Z/Z)/dH.$$

RESULTS AND DISCUSSION

The appearance of the end part of the amorphous wire (Co$_{0.94}$Fe$_{0.06}$)$_{72.5}$Si$_{12.5}$B$_{15}$ is shown in Fig. 1a. The features of the morphology of the vitreous fracture are confirmed by the data of X-ray diffraction (in the present work, data are not shown) on the amorphous structure of the obtained samples. As can be seen from the quasi-static magnetic hysteresis loops (Fig. 1b), even in the range of high fields (on the order of 100 Oe for soft magnetic materials), the W-0 sample is not magnetized to saturation. This behavior is quite understandable in view of the high level of hardening stresses. It is also worth noting that the samples both before and after the deposition of the carbon coating...