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Giant magneto-impedance effect in diamagnetic organic thin film coated amorphous ribbons

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ABSTRACT

We grew a diamagnetic thin film on the surface of Co-based amorphous ribbon ($Fe_{5.85}Co_{70.15}Mo_4B_{15}Si_5$) to investigate the effect of this coating on giant magneto-impedance (GMI). We investigated GMI over a frequency range of 0.1–3.0 MHz and under a static magnetic field. The results show that GMI for amorphous ribbons can be enhanced by this coating process. A changing in GMI as high as 90% was observed in diamagnetic organic thin film coated Co-based amorphous ribbons at 2 MHz. The very large enhancement of the GMI value is a consequence of the closed magnetic flux path under the organic film layer. In this work, we concentrated on enhancing the GMI effect. First, we show that sensitivities of the ribbons can be improved by using the coating technique. In addition, the surfaces of these samples were imaged and analyzed by an atomic force microscopy.

1. Introduction

The giant magneto-impedance (GMI) effect implies a strong dependence of the impedance of a conductor on the external magnetic field. GMI has been observed in a wide range of soft magnetic materials. This effect is promising due to its possible application in the development of the highly sensitive magnetic field sensors [1–4]. Cobalt-based amorphous magnetic alloy ribbons have attracted considerable attention since 1980s, because of their applications in electronic devices—specially, magnetic field sensors and magnetic recording heads. GMI has been extensively studied since its discovery, first in soft amorphous ferromagnetic wire, and then in ribbon and film [5–9]. Interest in these ribbons has increased following the observation of the GMI effect in the mid-1990s [10,11]. The origin of the GMI effect is attributed to a combination of the skin effect with some particular domain structures in soft ferromagnetic material [12]. The effect has a classical electromagnetic explanation related to changes in the dynamics of the magnetization process. Such changes affect the magnetic permeability of the specimen and consequently affect the frequency dependence of the penetration depth of AC current through the magnetic conductor. The aim of this work is to emphasize the effect of a thin-film coating on impedance changes.

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2. Materials and methods

2.1. Sample preparation and GMI measurements

A solution of $CoCl_2{\cdot}6H_2O$ (1 mmol) in 20 mL ethanol was added to a solution of the ligand (2 mmol) in 30 mL ethanol. The ligand is (2E)-3-Aza-1-(hydroxyimino)-2,4-diphenylpent-2-ene (HL), which was synthesized by the reaction of isonitrosoacetophenone with 1-phenyl-1-aminoethane in 1:1 molar ratio. The detailed synthesis scheme, analytical and physical data for the HL ligand ($C_{16}H_{16}N_2O$) are given in Ref. [13]. The solutions were continuously stirred for 3 h, during which the metal complexes precipitated. The resulting precipitates were filtered, washed first with cold ethanol and then with diethylether, and dried in air. While obtaining the Co (III) complex, the addition of a cobalt (II) chloride solution prepared in ethanol to an alcoholic solution of the ligand resulted in an orange colored complex because of air oxidation [14].

The thin films of the compounds were prepared by evaporating the solvent from a solution. The solution of the compounds was homogenized for 3 h and was rotated for homogenous mixing. The films were determined to be about 1 μm thick using spectroscopic ellipsometry.

Co-based amorphous ribbons were cut into strips measuring 13 mm in length and 5 mm in width. A conventional setup was designed to measure GMI [15]. In order to measure the GMI amorphous ribbons were placed in the center of a solenoid supplied with a constant dc current of 10 mA. This current was passed from a circuit and generated a dc magnetic field in the solenoid. The applied dc magnetic field causes an ac voltage variation in the ribbon, which

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was measured with an Agilent 3458 A digital multimeter in the frequency range of 0.1–3.0 MHz. To measure GMI, the dc magnetic field was applied along the longitudinal direction of the ribbon over a range from −8 to +8 kA/m. The result of the experimental data has been plotted as the percentage change of magneto-impedance with applied magnetic field, and is expressed as

$$\frac{\Delta Z}{Z_{\max}}(\%) = \frac{Z(H) - Z(H_{\max})}{Z(H_{\max})} \times 100 \quad (1)$$

where $\Delta Z/Z_{\max}$, $Z(H)$ and $Z(H_{\max})$ are the GMI ratio, magneto-impedance at magnetic field H, and magneto-impedance at maximum magnetic field, respectively. GMI% values, under an applied dc magnetic field, H_{dc}, were calculated by using Eq. (1).

2.2. Atomic force microscopy

The topography of the sample surfaces was imaged by an NMI Atomic Force Microscope manufactured by NanoMagnetics Instruments Ltd., Oxford, UK. The AFM was operated in tapping mode at room temperature. Aluminum coated silicon probes, manufactured by Nanosensors, were used for tapping. The technical specifications of the silicon AFM probe are as follows: resistivity, 0.01–0.02 Ω cm; resonance frequency, 204–497 kHz; thickness, 4.0 μm; length, 125 μm; width, 30 μm; force constant, 10–15 N/μm. The resonance frequency we used for imaging was 298.4 kHz.

The AFM images are typically quantified by three numbers at the microscopic scale: the mean roughness, RMS value and z scale. The mean roughness, R_a of an AFM image is defined as in [16]:

$$R_a = \frac{\sum_{i=1}^{N} |h_i - \bar{h}|}{N} \quad (2)$$

where h_i indicates the surface roughness data at the point i, $\bar{h}$ is the mean surface roughness, and N is the number of data points for the image. The simplest and most common metric to quantify changes in surface topography is called the root mean square (RMS) roughness calculation (R_q). The image RMS, R_q is the root mean square average of the height deviations taken from the mean data plane and is expressed as in [16]:

$$R_q = \sqrt{\frac{\sum_{i=1}^{N} |h_i - \bar{h}|^2}{N}} \quad (3)$$

The z scale gives the vertical distance between the highest and the lowest point of the image.

3. Results and discussion

3.1. GMI effect

For high frequencies, the intensity of the applied dc magnetic field modifies the field penetration depth. In the presence of an applied magnetic field, the magnetic characteristics of the ribbons cause an impedance change in the circuit and a corresponding change in ac voltage output. Consequently, the current distribution within the conductor is changed, and the impedance changes accordingly. The largest GMI ratio of 13.70% for the coated sample is observed at 2 MHz (Fig. 1). Table 1 summarizes the GMI% values for the uncoated samples and for the samples coated with organic thin film.

Figs. 2 and 3 demonstrate the field dependence of the GMI ratio for the Co-based amorphous ribbons over a frequency range from 1.0 to 3.0 MHz. Fig. 3 also shows the coating effect on the samples. The GMI effect can be improved by measuring at a reasonable frequency that gives maximum enhancement. In general, the coating the sample surface with organic thin film has also improved the GMI ratio at all frequencies. This behavior can easily be seen by comparing Figs. 2 and 3, or by comparing the second and third columns in Table 1. It is believed that the thin film coating causes some stress on the surface, altering the domain structure. The diamagnetic thin film layer also suppressed the magnetic field passing through the sample. Therefore, the magnetic field penetrates better into the sample, compared to the uncoated sample.

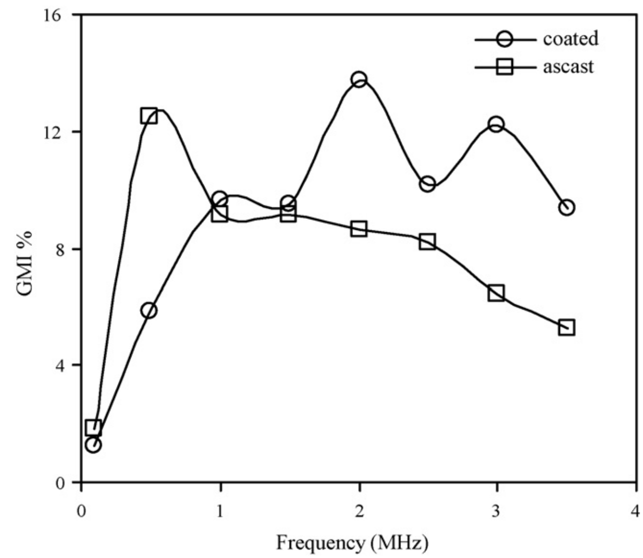

Fig. 1. The frequency dependence of the GMI ratio for the Co-based amorphous ribbons.

Table 1
The GMI ratio for the uncoated and organic thin film coated samples.

Frequency (MHz)	GMI% (uncoated)	GMI% (coated)
0.1	1.78	1.24
0.5	12.40	5.81
1.0	9.15	9.65
1.5	9.13	9.51
2.0	8.64	13.70
2.5	8.19	10.15
3.0	6.40	12.17

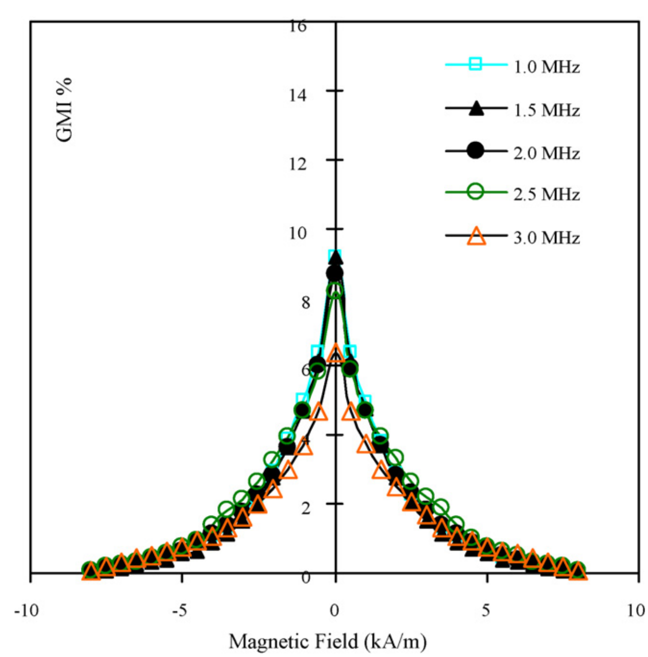

Fig. 2. The magnetic field dependence of the GMI ratio for the uncoated samples.

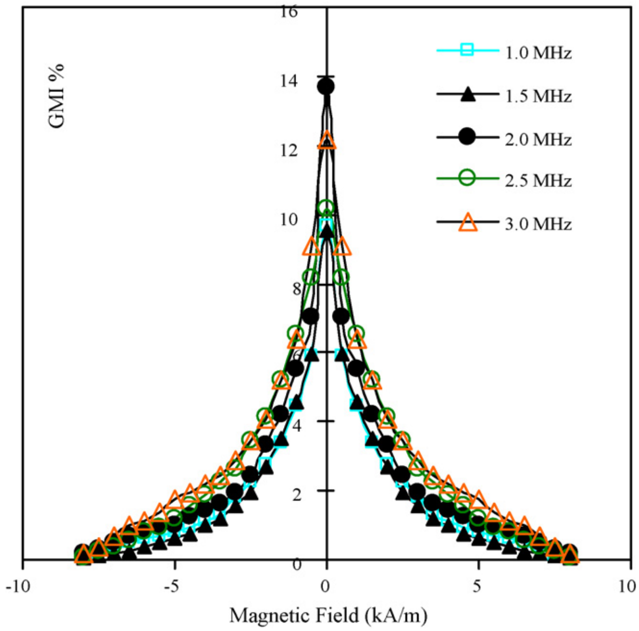

Fig. 3. The magnetic field dependence of the GMI ratio for the diamagnetic organic thin film coated samples.

Table 2
Surface roughness analysis of the samples.

Sample	Mean roughness (R_a) (nm)	RMS (R_q) (nm)	z Scale (nm)
Uncoated	183.6	184.1	448.0
Organic coated	204.3	209.8	580.0

3.2. AFM images

The statistics for the samples with and without the organic coating are summarized in Table 2. The mean roughness and RMS values for the uncoated samples are found to be lower than those for the coated samples. Although the R_a, R_q and z-scale increased on the coated samples, the GMI effect was also increased on these samples. The mean surface roughness increased by 11.3% after the samples were coated, and the GMI improved 0.6% at 1.0 MHz, 0.4% at 1.5 MHz, 57% at 2.0 MHz, 24% at 2.5 MHz, 90% at 3.0 MHz, indicating the effect of the coating.

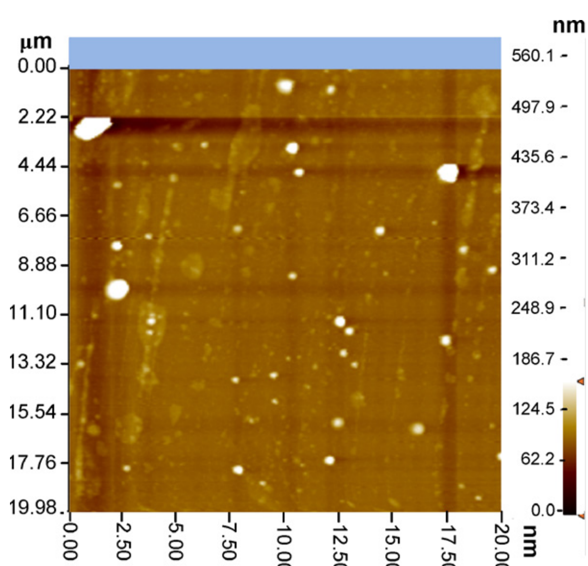

Fig. 4. 2D topography image of uncoated Co-based amorphous ribbon. The image size is 20 µm × 20 µm.

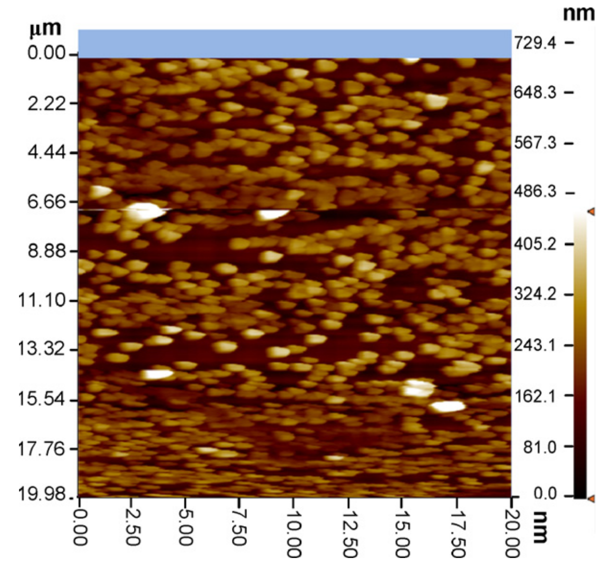

Fig. 5. 2D topography image of organic coated Co-based amorphous ribbon. The image size is 20 µm × 20 µm.

Fig. 4 shows 2D surface variations on the uncoated samples obtained using the AFM. Large and small spherical agglomerations were observed on the surface of the organic film layer (Fig. 5). The microstructure of this layer may cause a closed magnetic flux path along the ribbon axis. Thus, the coated samples may have a large effective relative permeability, resulting in a considerable enhancement in the GMI. The surface of the uncoated sample is smoother than the coated sample. The mean roughness parameters of the uncoated and coated samples are 183.6 and 204.3, respectively, within an area of 20 µm × 20 µm. The RMS and z scale values of these samples corroborate these measurements (Table 2).

4. Conclusions

The GMI effect in 13 mm × 5 mm samples of Co-ribbon, with and without an organic thin-film coating, was studied as a function of frequency and applied magnetic field strength. The highest GMI ratio was found to be 13.70% at 2 MHz in the organic thin film coated samples. The interaction between the magnetic field, alternating current and surface domain structure has an important effect on the GMI ratio of coated and as-cast samples.

In this study, a significant enhancement of the GMI effect can be obtained by adding a diamagnetic layer to the surface of the Co-based amorphous ribbons. To our knowledge, such an experimental study on the GMI effect of any diamagnetic thin film coated Co-based amorphous ribbon has never been reported previously in the literature. Such enhancements on GMI response enable the manufacturing of new types of highly sensitive magnetic field sensors.

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