Magnetic Properties and GMI Effect in Multilayered Co-rich Microwires

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***Abstract*—The influence of magnetic and non-magnetic layers deposited by magnetic sputtering onto glass-coated amorphous Co-rich microwires on magnetic properties and Giant Magnetoimpedance (GMI) effect has been analyzed. The magnetic and non-magnetic layers affect both the hysteresis loop and the magnetic field dependence of the GMI ratio. The contributions from the internal stresses originated by the sputtered layer as well as the magnetostatic interaction between the amorphous ferromagnetic nucleus and deposited magnetic layers are discussed.**

Keywords- magnetic microwires; magnetic softness; hysteresis loops; internal stresses; magnetic anisotropy.

I. INTRODUCTION

Amorphous materials can present excellent soft magnetic properties together with superior mechanical properties and, hence, are suitable for various applications including magnetic sensors or non-destructive wireless monitoring of composites [1]-[5].

The most unusual properties of amorphous wire are magnetic bistability associated with remagnetization process running through single and large Barkhausen jump [6]-[8] or giant magnetoimpedance, GMI, effect [9]-[12]. The GMI effect has attracted attention due to the extremely high impedance sensitivity to an external magnetic field (up to 10%/A/m) observed in magnetic microwires [12] [13]. Therefore, several high-performance magnetic sensors and magnetometers have been developed [9] [14].

The above-mentioned GMI effect consists of a noticeable change in the impedance Z of the magnetic material under the influence of an external magnetic field, H [9]-[11].

The GMI effect typically represented through the GMI ratio, $\Delta Z/Z$, defined as [9]-[11]:

$$\Delta Z/Z=[Z(H)-Z(H_{max})]/Z(H_{max})\cdot 100 \qquad (1)$$

being H_{max} the maximum applied DC magnetic field (typically a few kA/m).

The $\Delta Z/Z$ –values are substantially affected by several parameters, such as H-value as well as frequency, f, of AC current, AC current amplitude, H_{max} –value, applied and internal stress, magnetic anisotropy of studied material, etc. [9]-[11]. Therefore, for optimization of $\Delta Z/Z$ –values and achievement of maximum $\Delta Z/Z$ –values, $\Delta Z/Z_m$, several parameters must be considered. Thus, at fixed f,-value the $\Delta Z/Z(H)$ dependence can have the maximum either at H=0 or can present symmetric double-peak dependence with two maxima at H-value attributed to transverse magnetic anisotropy field. Meanwhile, the optimum frequency, f_o, is related to the diameter of magnetic wire: for 120 μm diameter amorphous wires, a f_o of the order of 1 MHz is reported [12], whereas for magnetic microwires with diameters of about 15-20 μm, f_o of the order of 100 MHz is reported [11]. Accordingly, a decrease in diameter is associated with an increase in the optimal frequency range of the GMI effect [15]. Consequently, for each magnetic wire with given geometrical parameters and magnetic anisotropy type (wire diameter and chemical composition), there are optimal conditions at which the highest GMI ratio, $\Delta Z/Z_m$, is observed [11].

In amorphous magnetic wires, the best magnetic softness and, hence, the highest $\Delta Z/Z$ –values ($\Delta Z/Z_m$ about 200-300%) are typically observed in Co-rich compositions with vanishing magnetostriction coefficients, λ_s [11]. The $\Delta Z/Z_m$ –values can be further improved by appropriate post-processing. In properly post-processed magnetic microwires, $\Delta Z/Z_m$ –values of the order 600- 700% have been reported [12] [13] [17].

Recently, a new approach allowing tailoring the magnetic anisotropy of magnetic wires by depositing magnetic and non-magnetic layers onto the glass-coating was reported [18] [19].

Evidently, the performance of sensors and devices based on the GMI effect can be significantly improved by using materials with a higher GMI effect. Therefore, tuning of the

GMI effect through the modification of the magnetic anisotropy of the magnetic materials attracted substantial attention is presently [19]-[21].

Accordingly, we shall provide our latest results on tailoring of the GMI effect and magnetic properties of amorphous glass-coated microwires by magnetic (Permalloy) and non-magnetic (Cu) layers deposited by magnetic sputtering onto glass-coating.

In the section Experimental details, we present the description of the experimental techniques, while in the Experimental results and discussion section we describe the results on effect of magnetic (Permalloy) and non-magnetic (Cu) layers deposited by magnetic sputtering onto glass-coating on hysteresis loops and GMI effect of the microwires.

II. EXPERIMENTAL DETAILS

We prepared and studied hysteresis loops and GMI effect of coated microwire with magnetic (Permalloy) or non-magnetic (Cu) layers up to 600 nm thick deposited on a glass coating. Studied amorphous $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ glass-coated microwire prepared by Taylor-Ulitovsky technique, described earlier elsewhere [15].

The axial hysteresis loops were measured using the fluxmetric method [21], as well as using the Physical Property Magnetic System (PPMS) vibrating-sample magnetometer. For a better comparison of the studied samples, the hysteresis loops were presented as the normalized magnetization M/M_o versus H dependencies (being M - the magnetic moment at given H and M_o - the magnetic moment at the maximum employed magnetic field amplitude).

The $\Delta Z/Z\ (H)$ dependencies were evaluated using (1) from the experimentally measured $Z(H)$ dependence. Z-values were obtained from the reflection coefficient S_{11} measured using a specially designed microstrip sample holder and a vector network analyzer, as described earlier [22].

The magnetostriction coefficient, λ_s, of studied microwire was measured using the so-called Small Angle Magnetization Rotation (SAMR) method [23], recently successfully adapted for glass-coated microwires of reduced diameter [23]. The low and negative λ_s –value ($-3\cdot10^{-6}$) was obtained for studied microwire.

Thin Permalloy (Py) and copper (Cu) layers were deposited by Radio Frequency magnetron sputtering onto the glass coating of both microwires. The sample holder geometry and the deposition system allowed the continuous rotation of the sample holder (at 14 r.p.m.). Accordingly, a homogenous deposition on the surface of the glass-coating of microwire (excepting the fixed extremes) was achieved. The thickness of the thin films was 600 nm.

Hysteresis loops of single microwires have been measured using the fluxmetric method previously described in detail elsewhere [32]. In order to compare the samples with different compositions and subjected to different post-processing, we represent the hysteresis loops as the normalized magnetization, M/M_0, versus magnetic field, H, where M is the magnetic moment at a given magnetic field and M_0 is the magnetic moment of the sample at the maximum magnetic field amplitude, H_m.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The hysteresis loops of studied sample prior depositing of magnetic (Permalloy) or non-magnetic (Cu) layers is typical for amorphous microwire with low negative λ_s –values. The coercivity, H_c, is about 40 A/m, as evidenced from the hysteresis loops (see Figure 1).

The contribution of magnetic layers on hysteresis loops of studied sample is shown in Figures 2 (a,b) and 3. After deposition of the layers, the low-field hysteresis loops generally tend to be more rectangular (see Figures 2 a,b). The presence of non-magnetic (Cu) layers is reflected by a

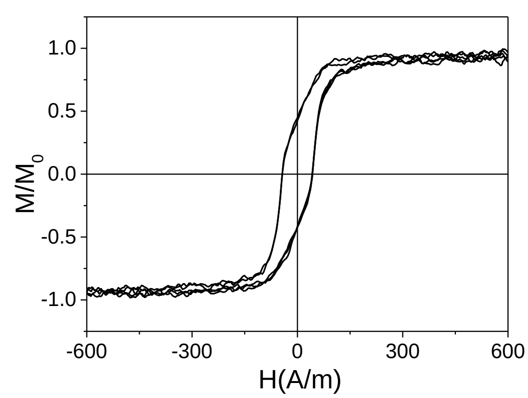

Figure 1. Hysteresis loop of as-prepared sample.

more rectangular hysteresis loop (see Figure 1). On the other hand, the presence of hysteresis observed up to rather high magnetic field must be attributed to the contribution of magnetic layer (see Figure 3).

$\Delta Z/Z(H)$ dependencies of as-prepared sample and after depositing of magnetic or non-magnetic layers are shown in Figure 4. As expected from the influence of deposited layers on hysteresis loops, the GMI ratio, $\Delta Z/Z$ and $\Delta Z/Z(H)$ dependencies are affected by the deposited layers (see Figure 4). In particular, the GMI ratio becomes generally lower after depositing any magnetic or non-magnetic layers. However, the highest GMI ratio and sharper peaks on $\Delta Z/Z(H)$ dependencies are observed in the sample with Permalloy layer.

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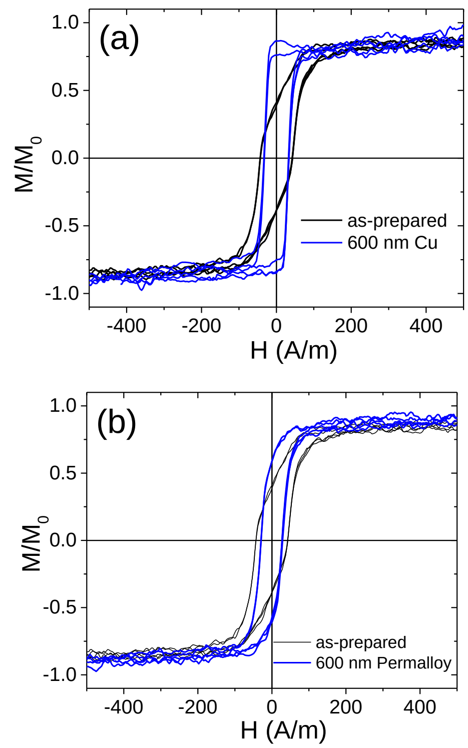

Figure 2. Low field hysteresis loop with deposited 600 nm thick non-magnetic Cu (a) and Permalloy (b) layers.

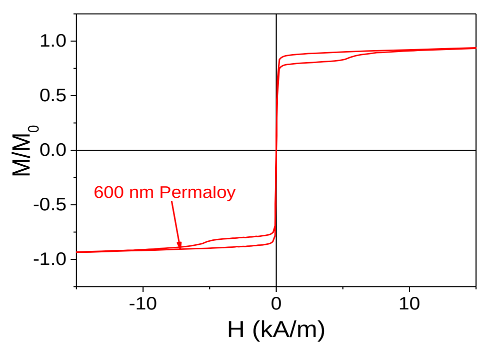

Figure 3. Hysteresis loops of magnetic microwires with Co- and Permalloy layers of the same thickness measured up to 20 kA/m.

All the $\Delta Z/Z(H)$ dependencies have double-peak character with maximum GMI ratio values, $\Delta Z/Z_m$, at $H \neq 0$ (see Figure 4). The evolution of $\Delta Z/Z(H)$ dependencies with frequency are rather different. Thus, in as-prepared sample the highest $\Delta Z/Z_m$ is observed at f=100 MHz, whereas in the samples with Cu-layer the highest $\Delta Z/Z_m$ –value is observed at f =80 MHz.

The evolution of $\Delta Z/Z_m$(f) dependencies provided in Figure 5 allows to compare the influence of the magnetic or non-magnetic deposited layers on $\Delta Z/Z_m$ –value and select optimal conditions for each sample.

For as-prepared sample and sample with Permalloy layer, the optimal frequency is about 100 MHz, where

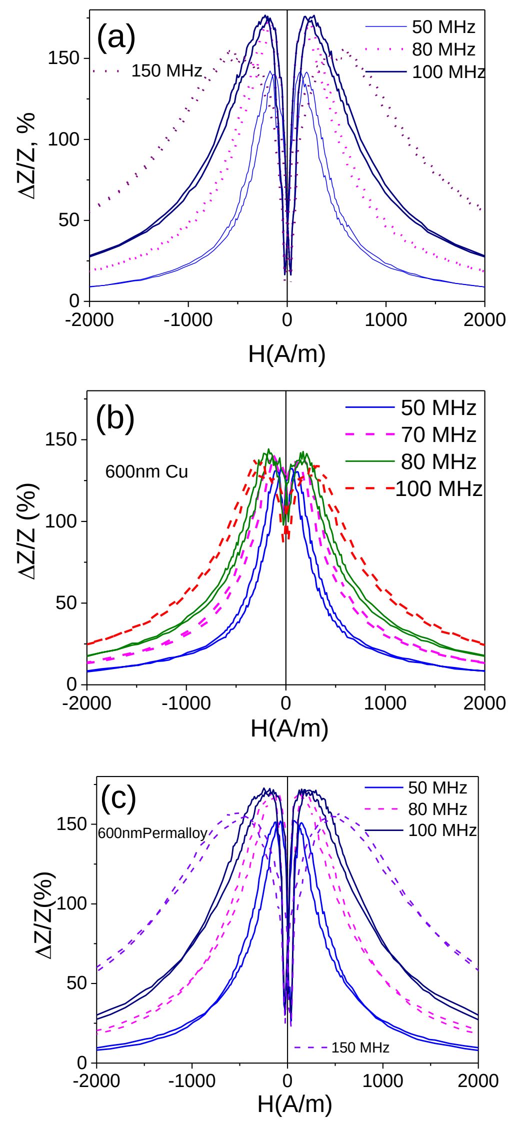

Figure 4. $\Delta Z/Z(H)$ dependencies of as-prepared $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ microwires (a) and of the same sample with deposited 600 nm thick layers of Cu (b) and Permalloy (c).

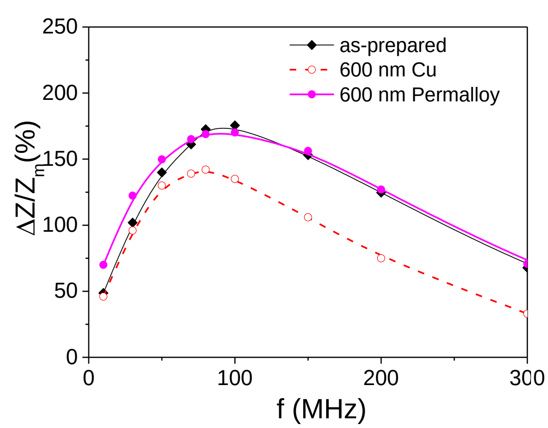

Figure 5. $\Delta Z/Z_m(f)$ dependencies of as-prepared microwire and after depositing of magnetic and non-magnetic layers.

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$\Delta Z/Z_m$ ≈175% are observed. Meanwhile, for the samples with Cu layer, the optimal frequency is about 80 at which $\Delta Z/Z_m$ ≈145% are observed. In the frequency band f≤100 MHz, the sample with a permalloy layer has the highest $\Delta Z/Z_m$ –values.

For interpretation of the obtained experimental results, we must consider two types of effects. Thus, both magnetic and non-magnetic layers deposited on the glass-coating affect the internal stresses distribution inside the metallic nucleus arising during the glass-coated microwires preparation. As previously shown [19][25], the presence of the metallic layers deposited on the glass-coating results in the onset of the additional compressive stresses. The compressive nature of the stresses induced by the deposited metallic layers is confirmed by the modification of the hysteresis loops (see Figure 2): after the deposition of metallic layers, all low-field hysteresis loops become more rectangular.

On the other hand, the different character of the hysteresis loops, $\Delta Z/Z_m$ –values and $\Delta Z/Z(H)$ dependencies in the samples with non-magnetic (Cu) and magnetic (Permalloy) must be related to the magnetic properties of the layer deposited on the glass-coating. Thus, a magnetic layer in its remanence state can produce a stray field that should affect both hysteresis loops and GMI behavior of amorphous magnetically soft nucleus. The existence of the magnetostatic interaction between two magnetic microwires with different magnetic properties has been recently experimentally observed in array consisting of magnetically soft Co-rich microwire and magnetically harder Fe-rich microwire [26].

IV. CONCLUSIONS AND FUTURE WORK

We showed that the magnetic properties and GMI effect of amorphous magnetic microwires can be tuned by magnetic and non-magnetic layers deposited onto glass-coating. In studying Co-rich microwires with deposited magnetic and non-magnetic layers, we observed substantial effect of deposited magnetic and non-magnetic layers on GMI effect and hysteresis loops. Low field hysteresis loops of studied microwire present systematic change upon deposition of non-magnetic and magnetic layers towards more rectangular hysteresis loops. The GMI ratio and its magnetic field dependencies are affected by the presence of magnetic and non-magnetic layers deposited onto glass-coating. The observed experimental dependencies are discussed considering both change of the internal stresses originated by the deposited layers as well as the magnetostatic interaction between the amorphous ferromagnetic nucleus and deposited magnetic layer. In the future, the influence of magnetically harder layers deposited onto the glass-coating and effect of the deposited magnetic layer thickness on hysteresis loops and GMI effect will be studied. It is expected to tune the magnetostatic interaction between the amorphous ferromagnetic nucleus and deposited magnetic layer and thus modify the magnetic field dependence of the GMI ratio.

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