Development of Magnetic Microwires with High Magneto-Impedance Effect

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***Abstract*— Giant Magneto-Impedance (GMI) effect is ideal for developing high-performance magnetic sensors due to its high sensitivity to magnetic fields and the ease of manufacturing magnetic sensors. We provide our attempts to improve the GMI effect and magnetic softness of Co-rich glass-coated magnetic microwires. We studied the GMI effect and magnetic properties of Co-rich glass-coated magnetic microwires with two different diameters. Substantially different frequency dependence of GMI effect is observed in studied microwires. A high GMI ratio of about 625% is observed in thinner Co-rich microwire at about 300 MHz.**

Keywords- magnetic microwires; magnetic softness; GMI effect; magnetic anisotropy.

I. INTRODUCTION

The main interest in amorphous wires is related to the GMI effect suitable for development of magnetic sensors [1]-[6]. Commonly, the GMI effect is attributed to high circumferential magnetic permeability, μ_ϕ, of amorphous wires and substantial μ_ϕ dependence on the applied magnetic field.

The most common way to represent the GMI effect is the GMI ratio, $\Delta Z/Z$, given as [1]-[6]:

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

where Z is the sample impedance, H is the applied magnetic field and H_{max} is the maximum applied Direct Current (DC) magnetic field (usually below a few kA/m).

Typically, $\Delta Z/Z$ –values of about 200-300% are reported in Co-rich magnetic wires with vanishing magnetostriction coefficients, λ_s [4]-[6]. In several publications, $\Delta Z/Z$ –values above 600% have been achieved in carefully processed Co-rich glass-coated microwires [4][7]. Such glass-coated microwires can be prepared using the so-called modified Taylor-Ulitovsky (also known as quenching-and-drawing method), actually known since the 60s and intensively studied since the 90s [7]-[9].

The performance of sensors and devices based on use of the GMI effect is substantially affected by the $\Delta Z/Z$ - value. Therefore, great attention was paid to studies of the magnetic wires with improved magnetic softness and optimization of the GMI effect by thermal treatment [4][7].

Consequently, in this paper we provide our latest attempt on optimization of the magnetic softness and GMI effect in Co-rich glass-coated magnetic microwires.

In Section 2, we present the description of the experimental methods and samples, while in Section 3, we describe the results on effect of annealing on hysteresis loops and GMI effect of Co-rich microwires. We conclude our work in Section 4.

II. EXPERIMENTAL DETAILS

We studied magnetic properties and GMI effect in amorphous $Co_{72}Fe_4B_{13}Si_{11}$ glass-coated microwires with metallic nucleus diameters, d, of about 40 µm and a total diameter, D, of about 45 µm (sample 1) and $d \approx 25.8$ µm $D \approx 29.2$ µm (sample2) manufactured by the aforementioned Taylor-Ulitovsky method. Briefly, the Taylor-Ulitovsky technique involves melting a metallic alloy inside a Duran-type glass tube using a high-frequency inductor, forming the glass capillary, drawing of such capillary filled with the molten metallic alloy surrounded by a softened glass, and winding of the solidified glass-coated microwires onto a rotating bobbin [8]-[10]. In fact, this fabrication technique is known since the 60s [11][12], however it was considerably modified during the last years [8]-[10]. The chemical composition was selected considering nearly-zero magnetostriction coefficient, λ_s ($\lambda_s \approx 10^{-7}$) of Co-rich Co-Fe based amorphous alloys [13][14].

Axial hysteresis loops were measured using the fluxmetric method, developed for studies of soft magnetic microwires with reduced diameters [15]. In this method, the electromotive force, ε, is induced in the pick-up coil with number of turns, *N*, due to a change in the magnetic flux, ϕ, when the magnetization reversal of a sample with magnetization M occurs [15]. Such ε is given as:

$$\varepsilon = -N\frac{d\phi}{dt} \qquad (2)$$

The magnetic flux, ϕ, is produced by both the applied field, *H*, and by the sample magnetization, *M*, [15]:

$$\phi == \mu_0[A_c H + A_s M] \qquad (3)$$

where A_c and A_s are the coil and sample cross-section areas. The use of compensation coil allows to remove the applied field contribution [15]. Finally, the magnetization, *M*, can be obtained by integrating the ε, as follows:

$$M = \frac{1}{N\mu_0 A_s}\int \varepsilon\, dt \qquad (4)$$

The hysteresis loops represented as the normalized magnetization M/M_o versus applied magnetic field, *H* (being M_o -the magnetic moment of the samples at maximum amplitude H_o of magnetic field) allows better comparison of magnetic properties of studied microwires with different chemical compositions and diameters.

The GMI ratio, *ΔZ/Z*, was defined using (1) from the *Z(H)* dependence. *Z*-values were evaluated using a vector network analyzer from the reflection coefficient S_{11}, as described elsewhere [16].

The amorphous state studied sample has been confirmed by a broad halo in the X-ray spectra obtained using X-ray diffraction.

The magnetostriction coefficient, λ_s, of both studied samples was evaluated using the so-called Small Angle Magnetization Rotation (SAMR) method. In both samples, low and negative λ_s-values of about -0.9×10^{-6} are obtained.

We studied as-prepared microwires and microwires annealed in conventional furnace at 300 ºC.

III. EXPERIMENTAL RESULTS AND DISCUSSION

As can be seen from the hysteresis loop (see Figure 1), both as-prepared microwires present rather soft magnetic properties with coercivities, H_c, about 20 A/m and magnetic anisotropy fields, H_k, below 200 A/m.

This behavior is typical for amorphous microwire with low negative λ_s –values. The *ΔZ/Z(H)* dependencies of both studied samples measured at various frequencies, *f*, are provided in Figures 2 (a) and (b). Double-peak *ΔZ/Z(H)* dependencies, typical for magnetic wires with circumferential magnetic anisotropy [17], are observed at all measured frequencies in both samples (see Figure 2). Such features of the GMI effect correlate with the hysteresis loop, particularly with low H_c and H_k -values.

In both studied samples, a rather high GMI effect, i.e. high maximum *ΔZ/Z* ratio, $\Delta Z/Z_{max}$, (≈600 %) is observed (see Figure 2). The achieved high $\Delta Z/Z_{max}$ –values are relevant for obtaining of high magnetic field sensitivity, *η*, given as [1] [3] [18]:

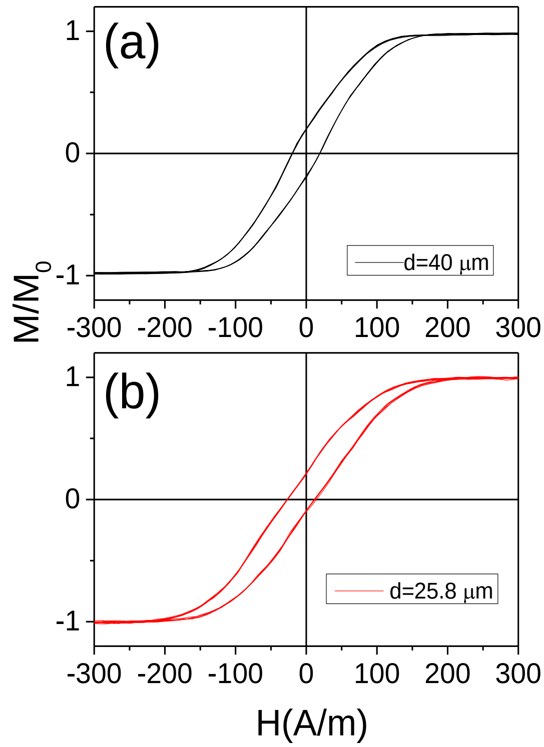

Figure 1. Hysteresis loops of the sample 1 (a) and 2 (b).

$$\eta = \frac{\partial\left(\frac{\Delta Z}{Z}\right)}{\partial H} \qquad (5)$$

Obviously, the η-value given by (5) is one of the important parameters for the GMI materials performance. From the relationship between η and $\partial\left(\frac{\Delta Z}{Z}\right)$, given by (5), it follows that the higher $\Delta Z/Z_{max}$ –values, the higher the η-values. Therefore, a comparison of the $\Delta Z/Z_{max}$ –values and their frequency dependencies is meaningful for assessing the effectiveness of the GMI effect in studied samples.

As follows from Figure 2, $\Delta Z/Z_{max}$ –values are observed at each frequency, *f*. As previously already discussed, $\Delta Z/Z_{max}$ ratio in magnetic wires usually exhibits maximum value at some optimum frequency, f_o [3][16]. As observed from Figure 2, $\Delta Z/Z_{max}$ –values are affected by *f*, being higher at 100≤ *f* ≤400 MHz (see Figure 2).

The $\Delta Z/Z_{max}$ (*f*) dependencies obtained from *ΔZ/Z(H)* dependencies measured in the frequency range up to 800 MHz are shown in Figure 3. As can be seen from Figure 3, slightly higher $\Delta Z/Z_{max}$– values are obtained for sample 1 at *f* < 100 MHz. However, at *f* ≥100 MHz higher $\Delta Z/Z_m$– values are observed for sample 2.

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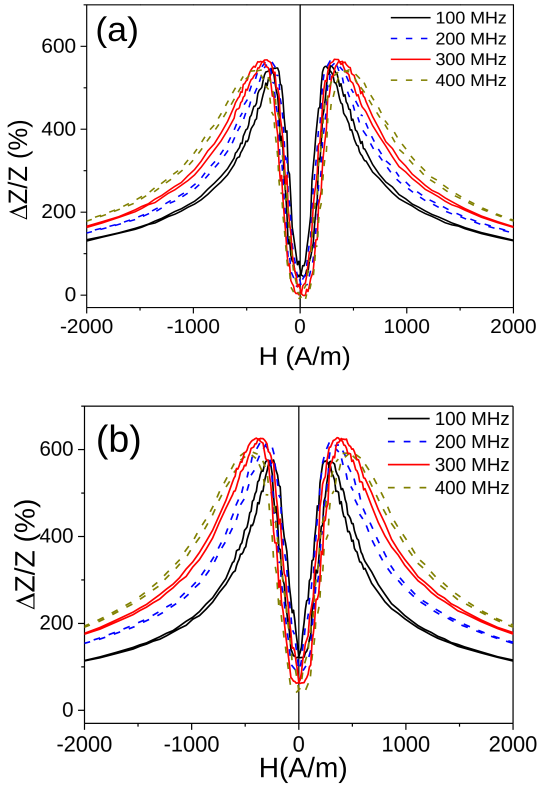

Figure 2. *ΔZ/Z(H)* dependencies measured at different frequencies in sample 1 (a) and 2 (b).

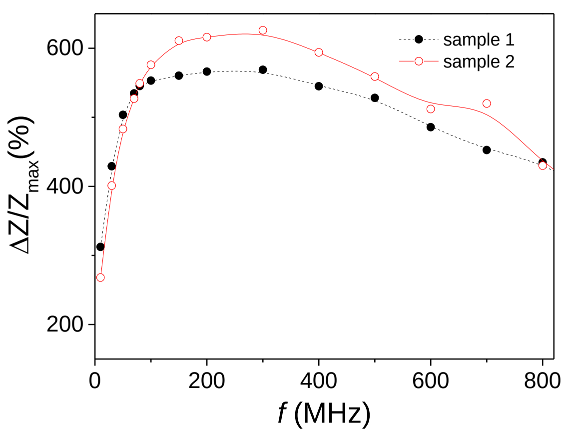

Figure 3. $\Delta Z/Z_m(f)$ dependencies evaluated from *ΔZ/Z(H)* dependencies for both studied samples.

The $\Delta Z/Z_{max}$ -value and the frequency, f_o, at which $\Delta Z/Z_{max}$ is observed are related to the wire diameter and to the magnetoelastic anisotropy [3][19]. Thus, a decrease in magnetic wire diameter is associated with an increase in the f_o –value [19]. The $\Delta Z/Z_{max}$ –values obtained for the sample 2 ($\Delta Z/Z_{max}$ ≈625%) observed at f_o ≈300 MHz are among the highest reported for as-prepared glass-coated microwires [4[[7]. Considering that appropriate annealing usually allows further $\Delta Z/Z_{max}$ –value improvement, future research on effect of annealing on GMI effect will be carried out.

IV. CONCLUSIONS AND FUTURE WORK

We studied magnetic properties and GMI effect in two $Co_{72}Fe_4B_{13}Si_{11}$ glass-coated amorphous microwires with different metallic nucleus diameters. The studied samples of the same chemical composition but different diameters exhibit different frequency dependences of the maximum GMI ratio. Quite high maximum GMI ratio (up to 625%) is observed in thinner Co-rich microwires at 300 MHz. Future studies of the appropriate annealing on $\Delta Z/Z_{max}$ –value might be helpful for further improvement of the GMI effect.

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