Optimization of GMI Effect and Magnetic Softness of Co-rich Microwires

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***Abstract*—We provide our attempts to improve the Giant Magneto-Impedance (GMI) effect and magnetic softness of Co-rich glass-coated magnetic microwires by annealing. We studied the effect of annealing on the hysteresis loops and the GMI ratio of Co-rich microwires. A remarkable GMI ratio improvement up to 735% is observed after annealing of Co-rich microwires under appropriate conditions. The observed magnetic softening and GMI ratio improvement are discussed considering the internal stresses relaxation and a change in the magnetostriction coefficient sign and values after annealing.**

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

I. INTRODUCTION

The main interest in amorphous magnetic materials is an excellent magnetic softness combined with superior mechanical and corrosion properties [1][2]. The most common method for preparation of amorphous materials is rapid quenching from the melt [1]-[3]. Such technique allows preparation of either amorphous ribbons or wires [3] [4].

The main interest in amorphous wires is related to the highest Giant Magneto-Impedance, GMI, effect [4]-[6] commonly 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 [4]-[6]:

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

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 Oe).

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 wires [6]-[8].

There are several fabrication processes involving rapid melt quenching allowing preparation of amorphous magnetic wires. Recently the main attention is paid to studies of glass-coated microwires. The main reasons are the most extended range of metallic nucleus diameters (from 0.1 to 100 μm), as well as better corrosion properties and biocompatibility related to the presence of flexible and insulating glass-coating [9]-[12]. 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 [9]-[14].

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 [7][8].

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.

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II. EXPERIMENTAL DETAILS

We prepared Co-rich $Co_{72}Fe_4B_{13}Si_{11}$ glass-coated amorphous microwires with metallic nucleus diameter, *d*, of about 40 µm and a total diameter, *D*, of about 45 µm by the aforementioned Taylor-Ulitovsky method [9]-[12]. 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 [15] [16].

Axial hysteresis loops were measured using the fluxmetric method, developed for studies of soft magnetic microwires with reduced diameters [17]. All the measurements were performed at room temperature. The electromotive force, ϵ, in the pick-up coil with N turns produced by the change of magnetic flux, ϕ, is given by [17]:

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

The change in magnetic flux originates by the sample magnetization, M, and by the applied magnetic field, H. The compensation coil was used to eliminate the magnetic flux component originated by the applied magnetic field. This compensation coil is connected in series- opposition with the pick-up coil. In numerous previous studies this experimental setup was successfully used for measurements of the hysteresis loops of extremely soft magnetic microwires allowing mA/m resolution of coercivity [6][8][17]. 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, $\Delta Z/Z$, 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 [17].

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

A recently developed setup designed to evaluate the λ_s of magnetic microwires using the so-called Small Angle Magnetization Rotation (SAMR) method was used for λ_s measurements [19].

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), 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.

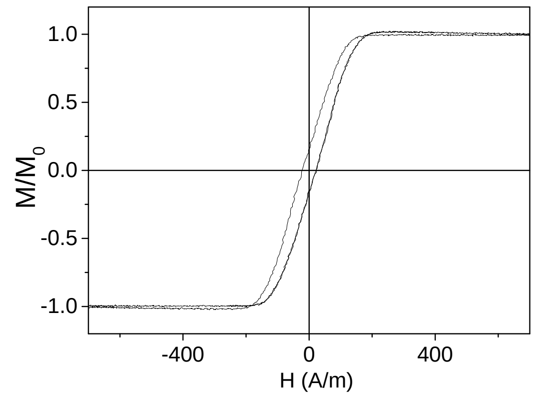

Figure 1. Hysteresis loops of $Co_{72}Fe_4B_{13}Si_{11}$ microwires with d=40µm, D=45 µm.

Accordingly, a rather high GMI ratio of about 400 % is observed even in as-prepared sample (see Figure 2). The highest GMI ratio, $\Delta Z/Z_{max}$, (≈400 %) is observed at f=200 MHz. A double-peak $\Delta Z/Z(H)$ dependence, typical for

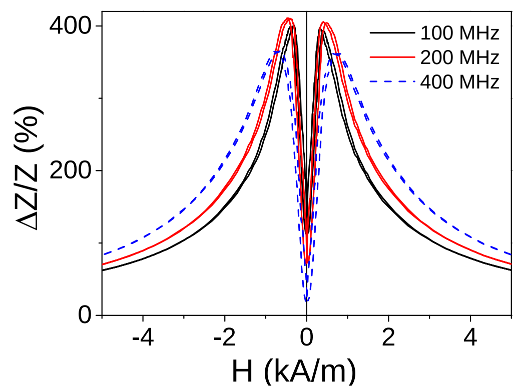

Figure 2. $\Delta Z/Z(H)$ dependencies at different frequencies in studied microwires.

magnetic wires with circumferential magnetic anisotropy [19], is observed at all measured frequencies (see Figure 2). Such features of the GMI effect correlate with the hysteresis loop, particularly with low H_c and H_k -values.

Previously, substantial improvement of the GMI effect was observed after annealing at 300 ºC [12]. Therefore, we studied the effect of annealing at 300 ºC on hysteresis loops, $\Delta Z/Z_{max}$, and $\Delta Z/Z(H)$ dependence of the studied microwire. The evolution of the hysteresis loops of $Co_{72}Fe_4B_{13}Si_{11}$ microwire after the annealing at T_{ann} =300 °C (60 min) is provided in Figure 3. The main change of the hysteresis loops consists of a decrease in H_k –value up to H_k≈75 A/m, while the H_c remains almost unchanged (H_c≈24 A/m).

The $\Delta Z/Z(H)$ dependencies measured in annealed $Co_{72}Fe_4B_{13}Si_{11}$ microwire are shown in Figure 4. Compared to the as-prepared $Co_{72}Fe_4B_{13}Si_{11}$ microwire, a substantial increase in $\Delta Z/Z_{max}$ –values is observed in the annealed samples. Similarly to the as-prepared $Co_{72}Fe_4B_{13}Si_{11}$ sample, the $\Delta Z/Z(H)$ dependences of annealed $Co_{72}Fe_4B_{13}Si_{11}$

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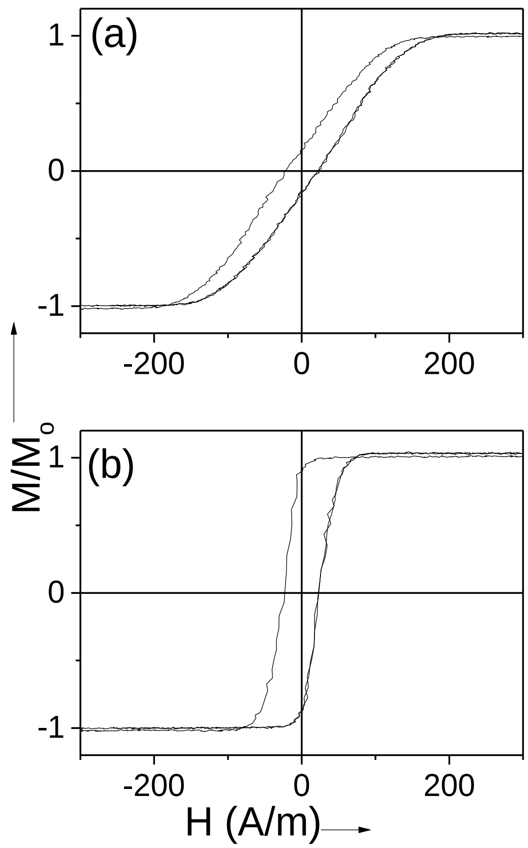

Figure 3. Hysteresis loops of as-prepared (a) and annealed at T_{ann}= = 300 ºC (b) $Co_{72}Fe_4B_{13}Si_{11}$ sample.

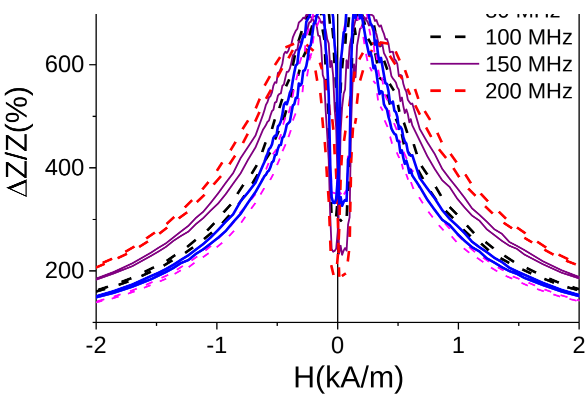

Figure 4. *ΔZ/Z*(*H*) dependencies measured in annealed at 300 ºC sample measured at frequencies 70-200 MHz.

microwires have a two-peak character. However, the difference is that the magnetic field H_m, at which $\Delta Z/Z_{max}$ is observed, becomes lower. Thus, for f=100 MHz H_m decreases from 0.35kA/m (for as-prepared sample) to 0.15 kA/m (for all annealed $Co_{72}Fe_4B_{13}Si_{11}$ samples). The magnetic field of maximum, H_m, in *ΔZ/Z(H)* dependencies is commonly associated with the magnetic anisotropy field [4][19]. Therefore, the observed change in *ΔZ/Z(H)* dependencies after annealing correlates with the evolution of the hysteresis loops upon annealing. On the other hand, higher $\Delta Z/Z_{max}$ –values, observed in annealed $Co_{72}Fe_4B_{13}Si_{11}$ samples must be related to a decrease in magnetic anisotropy field after annealing and internal stresses relaxation.

As observed in Figure 3, the change in the hysteresis loops of the studied microwire towards an increase in the remanent magnetization, M_r/M_0, after annealing is similar to that previously observed for various Co-rich [20]. Such behavior was discussed in terms of the relationship between the λ_s-value, the internal stresses relaxation and the structural relaxation [20]. The characteristic feature of studied glass-coated microwires is the elevated internal stresses related to the preparation method involving rapid solidification of the metallic alloy inside the glass tube [9][10][21]. It has been theoretically predicted and shown experimentally (i.e., by the glass etching) that the largest component of such internal stresses, associated with the difference in the thermal expansion coefficients of the metal alloy and glass, is axial [9][10][22]. Accordingly, a negative λ_s-value, together with the axial character of internal stresses, leads to the transverse magnetic anisotropy of Co-rich microwires with vanishing and negative λ_s, as shown in Figure 3.

Our measurements show that after annealing there is a change in the λ_s-value from low negative (λ_s-≈-9x10^{-7}) to low positive (λ_s-≈11x10^{-7}). Such changes in the λ_s-value can explain the change in the hysteresis loops and the *ΔZ/Z(H)* dependencies.

The double-peak *ΔZ/Z(H)* dependencies observed for all annealed $Co_{72}Fe_4B_{13}Si_{11}$ sample (see Figure 4) suggest the presence of the transverse magnetic anisotropy in the surface layer of the studied microwires. It looks surprising considering low positive λ_s. The origin of such weak transverse anisotropy on the surface of the studied microwire can be attributed to the presence of an interface layer between the metal core and the glass coating and, consequently, a different chemical composition in the thin surface interface layer. Such an interface layer was previously observed experimentally [23].

IV. CONCLUSIONS

We showed that the GMI effect of Co-rich amorphous magnetic microwires can be substantially improved by appropriate annealing. Quite a high maximum GMI ratio (up to 735%) is observed after annealing of Co-rich microwires. The effect of annealing is discussed in terms of internal stresses relaxation, a change in the magnetostriction coefficient sign and the value upon annealing. Weak transverse magnetic anisotropy evidenced from the obtained hysteresis loops by the shape of *ΔZ/Z(H)* dependencies is explained by the presence of the interface layer between the metallic nucleus and the glass-coating.

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