Tunning the Giant Magnetoimpedance Effect in Fe-rich Magnetic Microwires by Stress-annealing

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Abstract— **The Giant Magneto-Impedance (GMI) effect is one of the most promising phenomena for creation of miniaturized magnetic sensors and magnetometers. We propose a route for development of cost-effective magnetically soft microwires for GMI applications. Stress-annealing of the Fe-rich glass-coated microwire allows considerable improvement of magnetic softness and giant Magneto-Impedance effect. Observed experimental dependencies are discussed considering various factors affecting the magnetic properties of the studied microwire upon stress-annealing: induced magnetic anisotropy and internal stresses relaxation.**

Keywords- giant magnetoimpedance effect; magnetic microwires; magnetic softness.

I. INTRODUCTION

Studies of Giant Magneto-Impedance (GMI) effect have attracted considerable attention of the scientific community and industries over the past two decades owing to a number of technological applications such as magnetic sensors, memories and devices, smart composites for remote stress and temperature monitoring, health monitoring, etc. [1]-[5].

Usually, magnetic field dependences of impedance, Z, is expressed through the GMI ratio [6][7], $\Delta Z/Z$, defined as:

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

where H_{max} is the maximum applied DC magnetic field.

The GMI effect is one of the most promising phenomena for creation of sensitive and inexpensive magnetic sensors and magnetometers. The main interest in GMI effect is related to one of the largest magnetic field sensitivities (up to 10 %/A/m) among non-cryogenic effects [1]-[5][8][9].

The development of magnetic materials presenting the highest GMI effect is essentially relevant for aforementioned applications of the GMI effect in magnetic sensors and devices [1]-[5]. The highest GMI effect is reported for Co-rich magnetic wires where $\Delta Z/Z$ -values of about 600% are achieved [8][9]. But, for most industrial applications, the use of Co-based alloys might be an obstacle since Co belongs to critical materials, being therefore at risk of supply constraints, financially costly and price volatile [10].

On the other hand, for most of emerging applications, the miniaturized magnetic sensors are requested [3]-[5]. Therefore, the development of cost-effective magnetically soft microwires without Co is highly demanded for prospective applications [1][6].

Less expensive Fe-rich glass-coated microwires are good candidates. However, usually highly magnetostrictive as-prepared Fe-rich amorphous glass-coated microwires present rectangular hysteresis loop characterized by low circumferential magnetic permeability and therefore present low GMI effect [3][5][9]. Experimentally, it was confirmed that the domain structure of Fe-rich microwires consists of a large axially magnetized single domain surrounded by the outer domains with radial magnetization orientation [11]. Such domain structure is related to a magnetoelastic anisotropy, i.e., high internal stresses with preferentially axial component and high and positive magnetostriction coefficient.

One of the possibilities is the diminishing of the magnetostriction coefficient by devitrification of amorphous precursor after appropriate annealing [12]-[14]. However, Finemet-type nanocrystalline materials are rather brittle.

Recently, an alternative method has been reported, allowing magnetic softening of Fe-rich microwires through the induced magnetic [15][16]. One of the main advantages of this method is that excellent mechanical properties of amorphous microwires are maintained.

Consequently, in this paper, we present our recent experimental results on effect of stress-annealing on magnetic properties and high frequency GMI effect of Fe-rich glass-coated microwires.

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In the section Experimental details, we present the description of the experimental techniques used for the sample preparation and characterization, while in the Experimental results and discussion we describe the results on the effect of conventional and stress annealing on hysteretic properties and GMI effect of Fe-based microwires.

II. EXPERIMENTAL DETAILS

We studied the influence of stress-annealing on magnetic properties and GMI effect of $Fe_{75}B_9Si_{12}C_4$ amorphous glass-coated microwires (total diameter, D = 26.6 μm, metallic nucleus diameter, d = 25.6 μm) prepared by Taylor-Ulitovsky method described elsewhere [5][9].

The samples have been annealed using a conventional furnace. In the case of stress-annealing, the mechanical load has been attached to the end of the sample during the anneling.

The values of stresses applied during the annealing have been calculated as previously described elsewhere [16]:

$$\sigma_m = \frac{K.P}{K\ S_m + S_{gl}};\ \sigma_{gl} = \frac{P}{K\ S_m + S_{gl}} \qquad (2)$$

where $k = E_2/E_1$, E_2 is the Young modulus of the metal, E_1 is the Young modulus of the glass at room temperature, P is the mechanical load applied during the annealing, and S_m and S_{gl} are the cross sections of the metallic nucleus and glass coating respectively. The estimated values of applied stress are calculated using (2) is $\sigma_m \approx 900$ MPa.

The hysteresis loops were measured by the fluxmetric method as described in previous publications on magnetic microwires [5]. We represent the hysteresis loops as the dependence of normalized magnetization, M/M_{Hmax} (where M is the sample´s magnetic moment at given magnetic field, H, and M_{Hmax} is the sample´s magnetic moment at the maximum magnetic field amplitude, H_m) versus magnetic field, H.

The microwire impedance, Z, was evaluated from the reflection coefficient S_{11} measured by the vector network analyzer using the micro-strip sample holder as previously described [16][17]. This technique allows to extend the frequency range for GMI characterization up to GHz range.

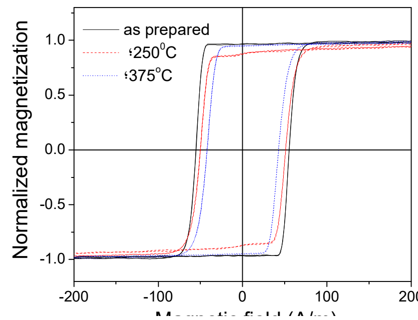
The GMI ratio, $\Delta Z/Z$, is defined using (1).

III. EXPERIMENTAL RESULTS AND DISCUSSION

As expected from previous knowledge on magnetic properties of Fe-rich microwires [16], as-prepared $Fe_{75}B_9Si_{12}C_4$ microwires present perfectly rectangular hysteresis loops (Figure 1).

Conventional annealing (without stress) does not affect the overall hysteresis loop shape, although some decrease of coercivity after annealing is appreciated (Figure 1).

However, after stress-annealing, we observed drastic changes of hysteresis loops and hence magnetic properties of studied $Fe_{75}B_9Si_{12}C_4$ microwires. The hysteresis loops change from perfectly rectangular to linear with quite low coercivity (see Figures 2a-2c). The coercivity, H_c, and remanent magnetization decrease with increasing of the annealing temperature, T_{ann}.



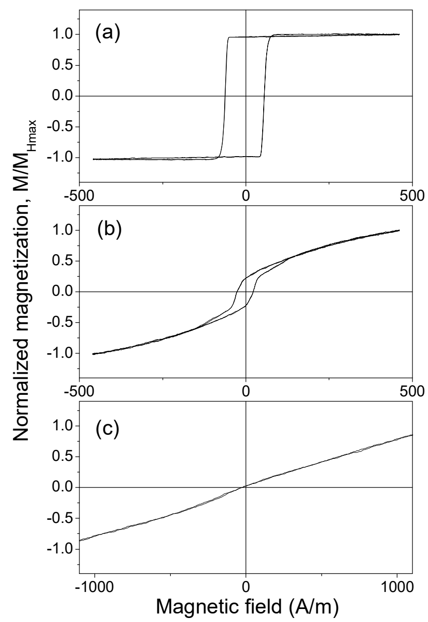


Figure 2. Hysteresis loops as-prepared (a), annealed at 250 ºC (b), and 300 ºC (c) for 1 h $Fe_{75}B_9Si_{12}C_4$ microwires.

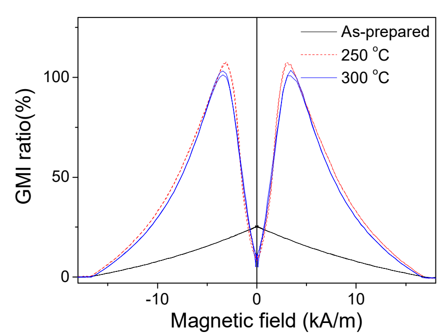


Figure 3. Dependence of GMI ratio, on annealing temperature measured for $Fe_{75}B_9Si_{12}C_4$ microwires at 700 MHz.

The observed modification of the hysteresis loops reflects change of magnetic anisotropy from axial to transverse. Consequently, the hysteresis loops of stress-annealed Fe-rich microwires are quite similar those of Co-rich microwires in which the remagnetization process in axial direction is associated to the magnetization rotation [16].

It is worth mentioning that the transversal magnetic anisotropy in stress-annealed Fe-rich microwires can be tuned by the temperature of stress-annealing (see Figure 1).

As reported elsewhere, magnetic field dependence of GMI ratio is intrinsically related to the type of magnetic anisotropy [18][19]. Therefore, as expected, the GMI ratio value and the magnetic field dependence of studied microwires are rather different. Drastic increasing of GMI ratio after stress-annealing can be appreciated from Figure 3.

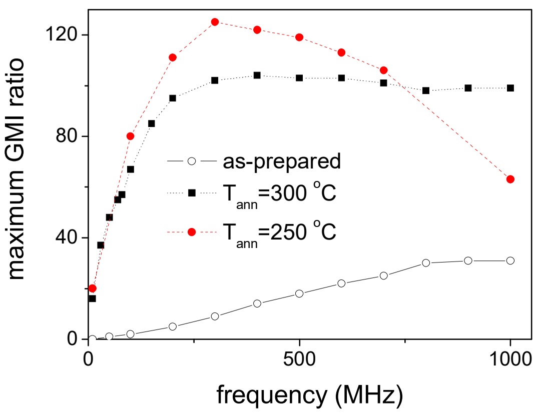


Figure 4. Frequency dependence of maximum GMI ratio for as-prepared and stress-annealed $Fe_{75}B_9Si_{12}C_4$ microwires.

Moreover, the $\Delta Z/Z(H)$ dependencies of as-prepared and stress-annealed samples are essentially different. Stress-annealed samples present double-peak $\Delta Z/Z(H)$ dependencies predicted for the samples with transverse magnetic anisotropy, while decay of $\Delta Z/Z$ versus H typical for axial magnetic anisotropy is observed in as-prepared sample.

As previously reported elsewhere, for each particular magnetic material, there is an optimal frequency range where the GMI effect presents the highest values [16][17][20]. The optimal frequency is related to the sample dimensions (diameter), as well as to the magnetic anisotropy. The observed improvement of GMI ratio is present in a wide frequency range. For comparison, frequency dependencies of maximum GMI ratio on measured frequency are presented in Figure 4.

As can be appreciated from Figure 4, GMI ratio in $Fe_{75}B_9Si_{12}C_4$ microwires stress-annealed at all studied conditions (T_{ann}) is almost one order of magnitude higher than in as-prepared $Fe_{75}B_9Si_{12}C_4$ microwires. The most noticeable is the enhancement of $\Delta Z/Z_m$ -values observed for the frequency band of about 300 MHz, where more than one order increasing of the GMI ratio (up to $\Delta Z/Z_m \approx 125\%$) by stress-annealing is achieved (Figure 4). In the sample stress-annealed at T_{ann} = 300 °C for t_{ann} = 60 min the GMI ratio values of about 100% are observed in a wide frequency band from 200 MHz up to 1 GHz (Figure 4).

Considerable enhancement of GMI ratio observed in stress-annealed Fe-rich microwires must be attributed to transverse magnetic anisotropy evidenced from comparison of hysteresis loops of as-prepared and stress –annealed microwires and $\Delta Z/Z(H)$ dependencies (Figures 2, 3).

The rectangular hysteresis loop observed in as-prepared Fe-rich microwires (Figures 1, 2a) with positive magnetostriction coefficient is commonly attributed to the axial magnetic anisotropy related to the magnetoelastic anisotropy [21]-[23]. From provided simulation [23][24], as well as from indirect experimental studies involving change of magnetic properties upon chemical etching [5][25] of glass-coating or stress relaxation by annealing [5][26], it is confirmed that the axial internal stresses in glass-coated microwires arising during the preparation process are the highest within the most part of the metallic nucleus.

From previous studies, it is known that stresses and/or magnetic field annealing considerably affects the magnetic properties of amorphous materials originated by a macroscopic induced magnetic anisotropy [27]-[29].

The origin of induced magnetic anisotropy of amorphous materials has been discussed in terms of the directional ordering of atomic pairs or compositional short- range ordering [27]-[31], as well as the compositional and topological short range ordering [30][31]. The mentioned pair ordering is commonly considered for amorphous alloys containing at least two magnetic elements [27]-[29]. However, topological short range ordering (also known as structural anisotropy) involves the angular distribution of the atomic bonds and small anisotropic structural rearrangements at temperatures near the glass transition temperature [30].

For the present case of $Fe_{75}B_9Si_{12}C_4$ amorphous microwires containing only one magnetic element (Fe) the pair ordering and the compositional short- range ordering mechanisms of stress- induced magnetic anisotropy are not very likely. Therefore, the contribution of topological short range ordering looks more likely. Additionally, in the case of glass-coated microwires, the presence of the glass-coating associated to strong internal stresses [21]-[23] is relevant for formation of the macroscopic magnetic anisotropy. Consequently, previously the origin of stress-induced anisotropy in Fe-rich ($Fe_{74}B_{13}Si_{11}C_2$) amorphous microwires has been discussed considering “back stresses” giving rise to the redistribution of the internal stresses after stress-annealing [32].

Consequently, the observed transversal magnetic anisotropy induced by stress annealing can be explained considering either increasing to back stresses or aforementioned topological short range ordering.

The advantage of above described effective approach allowing improvement of magnetic softness and high frequency GMI effect of Fe-rich microwires is that the proposed stress-annealing allows to retain superior mechanical properties of amorphous materials, i.e., plasticity and flexibility.

It is worth mentioning that the observed stress-induced anisotropy is rather stable and cannot be removed completely by the subsequent annealing: as recently described [16], only a portion of such stress-annealing induced anisotropy can be eliminated by subsequent annealing without stress.

IV. CONCLUSION

In this work, we present studies of magnetic properties and GMI effect of Fe o-rich microwires.

Considerable enhancement of magnetic softness and GMI effect of Fe-rich microwires has been observed after stress- annealing. For the interpretation of the observed effect of stress annealing, we considered internal stresses relaxation after annealing and interplay of compressive stresses and axial internal stresses after stress annealing. Consequently, appropriate annealing is the effective method for improvement of magnetic softness, domain wall dynamics and GMI effect of glass-coated microwire.

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