Optimization of Giant Magnetoimpedance Effect in Co-rich Magnetic Microwires

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Abstract—**Processing of the Co-rich glass-coated microwire by Joule-heating allows considerable improvement of magnetic softness and Giant Magneto-Impedance (GMI) effect. At optimal Joule heating conditions, we observed GMI ratio up to 650%, low magnetic anisotropy field of about 25 A/m and coercivity of about 2 A/m. Observed experimental dependencies are discussed considering various factors affecting the magnetic properties of studied microwire upon Joule heating: induced magnetic anisotropy, internal stresses relaxation and radial distribution of magnetic anisotropy.**

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

I. INTRODUCTION

Giant Magneto-Impedance (GMI) effect presenting one of the highest sensitivities to applied magnetic field has become a topic of great attention owing to it interest for development of cost effective magnetic field sensors and devices [1]-[7].

In most of publications [1]-[8], the expression for the GMI effect through the GMI ratio, $\Delta Z/Z$, defined as:

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

is used.

The highest GMI ratio up to 650 %, as well as magnetic field sensitivity up to 10%/A/m were reported experimentally for amorphous magnetic Co-rich microwires [9] [10]. These achievements allowed to develop a number of extremely sensitive magnetic sensors and magnetometers using magnetic wire presenting GMI effect [5][6][11]-[13].

Theoretically predicted maximum GMI ratio is about 3000% [14] that is few times superior to the experimentally reported maximum $\Delta Z/Z$-values [9][10]. Therefore, it is expected that experimentally reported GMI effect can be considerably improved by preparation technology improvement, as well as by using of effective post-processing methods. It is clear that the use of magnetic materials with higher GMI effect can improve the performance of magnetic devices. Consequently, considerable efforts have been paid to study the post-processing on GMI ratio of various magnetic materials [4] [7][15]-[18].

Developed GMI sensors present excellent magnetic field sensitivity, quick response and low power consumption [5]. However, one of the weak points of the GMI sensors is the size [5][19]. The demagnetizing factor and hence the diameter of magnetic wires is the limiting factor [7][20]. Therefore, thin magnetically soft wires are highly demanded for development of the GMI sensors.

The thinnest magnetic wires with ferromagnetic metallic nucleus diameter from 0.05 to 80 μm covered by glass coating can be prepared using Taylor-Ulitovsky method [4] [7][21].

Presence of glass-coating results in elevated magnetoelastic anisotropy [22]-[25]. The common way for improvement of the magnetic softness is a careful selection of chemical composition of metallic alloy allowing achievement of vanishing magnetostriction coefficient [4] [10]. However, experimentally observed GMI ratio values are still considerably lower than theoretically predicted optimized GMI ratio (about 3000%) [14][26]. As showed elsewhere, the value of GMI ratio is intrinsically related to magnetic softness [27]. Therefore, further efforts for optimization of magnetic softness are expected to improve the GMI ratio in amorphous wires.

The most common post-processing of magnetic materials usually consists of annealing [4]. However, conventional annealing of Co-rich originates considerable magnetic hardening hence deterioration of GMI effect [4][7][10][28]. Observed changes of magnetic properties induced by the conventional annealing in Co-rich microwires have been explained considering change of the magnetostriction coefficient value and sign as well as modification of the

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domain structure and remagnetization process mechanism related to the stresses relaxation [10][28].

On the other hand, GMI ratio enhancement has been reported after stress-annealing or Joule heating of Co-rich microwires at certain annealing conditions [7]. This difference has been associated to the induced magnetic anisotropy. The origin of the anisotropy induced by stress or magnetic field annealing of amorphous materials has been previously attributed the directional ordering of atomic pairs, compositional and topological short- range ordering or back stresses [29]-[31].

Consequently, it is expected that the GMI ratio can by improved by the Joule. Up to now, only a few experimental results on effect of Joule heating on GMI effect have been reported [7]

Consequently, in this paper we systematically studied the influence of Joule heating on magnetic properties and GMI effect of Co-rich glass-coated microwires.

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 Joule heating on hysteretic properties and the GMI effect of Co-rich microwires.

II. EXPERIMENTAL DETAILS

We studied the influence of Joule heating on magnetic properties and GMI effect of $Co_{67}Fe_{3.9}Ni_{1.4}B_{11.5}Si_{14.5}Mo_{1.6}$ amorphous glass-coated microwires (total diameter, D= 26.6 μm, metallic nucleus diameter, d=25.6 μm) prepared by Taylor-Ulitovsky method described elsewhere [1][4][7].

The hysteresis loops were measured by the fluxmetric method as described in previous publications on magnetic microwires [7]. 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.

We employed the DC current values, I, of 30 and 40 mA selected in order to avoid the deterioration of magnetic properties related to the crystallization. Employed current densities (58.3 and 77.7 A/mm^2 for 30 and 40 mA respectively) were clearly below the value that can produce magnetic hardening and/or crystallization of the samples [32].

All the measurements have been performed for the same sample. We have measured the hysteresis loops and GMI effect in the as-prepared sample, then the same sample has been annealed. All the measurements have been performed after each annealing and then the same sample has been annealed again. Finally, we obtained the dependencies of maximum GMI ratio, $\Delta Z/Z_{max}$ on frequency, f, at different annealing time, t_{ann}.

The impedance and its magnetic field dependence were evaluated using the micro-strip sample holder previously described elsewhere [16][26]. The microwire impedance, Z, was evaluated from the reflection coefficient S_{11} measured by the vector network analyzer (Agilent N5230A).

The GMI ratio, $\Delta Z/Z$, is defined using eq. (1). Use of aforementioned technique allows to measure GMI effect in the extended frequency range (up to 1 GHz).

III. EXPERIMENTAL RESULTS AND DISCUSSION

As-prepared $Co_{67}Fe_{3.9}Ni_{1.5}B_{11.5}Si_{14.5}Mo_{1.6}$ microwire presents quite soft magnetic properties characterized by hysteresis loop with low coercivity (about 7 A/m) typical for glass-coated microwires with low and negative magnetostriction coefficient (see Figure 1).

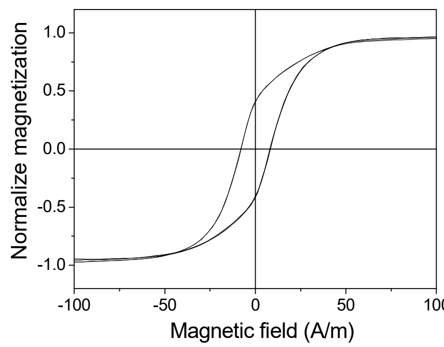

Figure 1. Hysteresis loop of as-prepared $Co_{67}Fe_{3.9}Ni_{1.5}B_{11.5}Si_{14.5}Mo_{1.6}$ amorphous glass-coated microwire.

Consequently, high GMI ratio (with $\Delta Z/Z_{max}$≈550% at f=300 MHz) is observed, even for as-prepared $Co_{67}Fe_{3.9}Ni_{1.4}B_{11.5}Si_{14.5}Mo_{1.6}$ microwire (see Figure 2).

As-prepared $Co_{67}Fe_{3.9}Ni_{1.4}B_{11.5}Si_{14.5}Mo_{1.6}$ microwire presents double-peak $\Delta Z/Z(H)$ dependence previously reported for Co-rich magnetic wires with low negative magnetostriction coefficient usually associated to weak circumferential magnetic anisotropy [4][7][27].

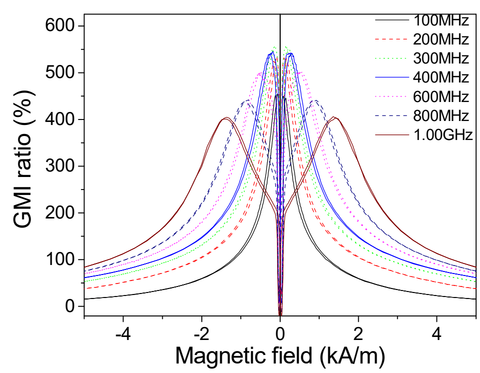

Figure 2. $\Delta Z/Z$(H) dependencies measured in as-prepared $Co_{67}Fe_{3.9}Ni_{1.4}B_{11.5}Si_{14.5}Mo_{1.6}$ microwire at different frequencies.

After Joule heating at certain conditions, we observed increase of maximum GMI ratio, $\Delta Z/Z_{max}$, as shown for example for the sample annealed at 40 mA for 3 and 5 min (Figures.3a and 3b). At this annealing condition $\Delta Z/Z_{max}$ ≈650% is observed. However, increasing the annealing time $\Delta Z/Z_{max}$ decreases (see Figure. 3c for 40 mA, t_{ann}=10 min).

Similarly, considered magnetic softening is observed after Joule heating at certain conditions: as-compared to as-

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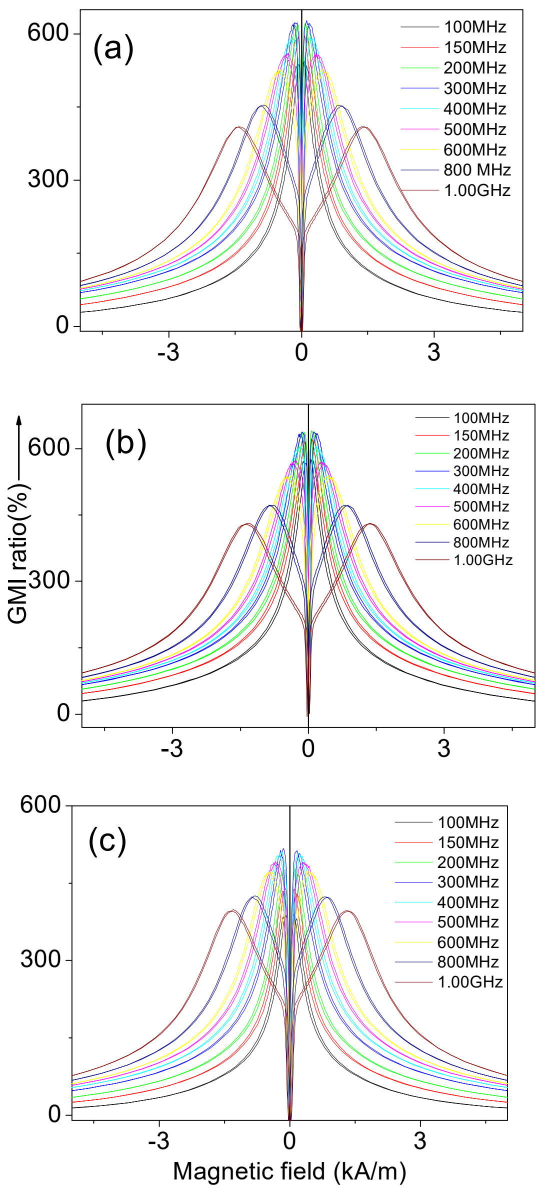

Figure 3. $\Delta Z/Z$(H) dependencies measured in annealed at 40 mA for 3 min (a), 5 min (b) and 10 min (c) $Co_{67}Fe_{3.9}Ni_{1.4}B_{11.5}Si_{14.5}Mo_{1.6}$ microwire at different frequencies.

prepared sample Joule heated sample present lower coercivity, of about 2 A/m (see Figure 4a).

Additionally, from Figure 4a, it can be observed that current annealed sample presents lower magnetic anisotropy field, H_k, of about 25 A/m. Similar magnetic properties ($H_c \approx$ 2 A/m and $H_k \approx$32 A/m) are also observed for current annealed microwire at 30 mA for 3 min (see Figure 4b). But further increasing of annealing time (at I= 30 mA) results in slight increasing of coercivity (up to 6 A/m at t_{ann}= 20 min) and of magnetic anisotropy field (up to 75 A/m) (see Figure. 4c).

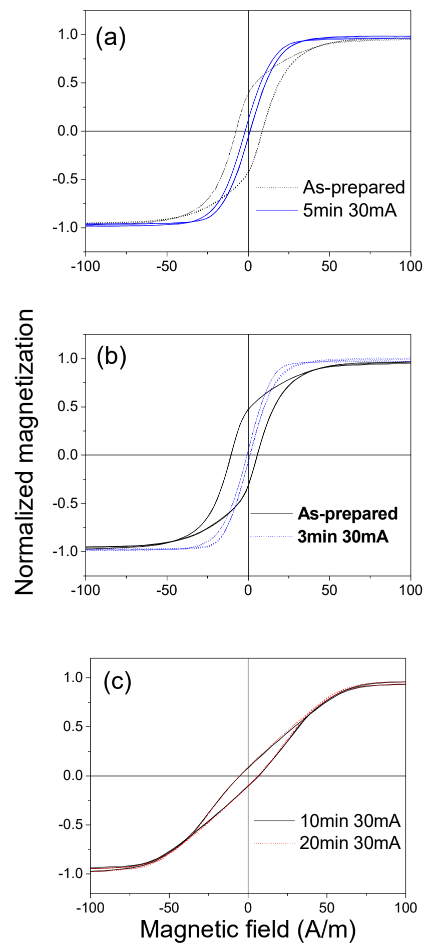

Figure 4. Hysteresis loops of as-prepared and current annealed at 30 mA and 40 mA for 5 min (a), 3 min (b) 10 and 20 min (c) $Co_{67}Fe_{3.9}Ni_{1.5}B_{11.5}Si_{14.5}Mo_{1.6}$ amorphous glass-coated microwire

The evolution of the magnetic anisotropy field, H_k, after current annealing is presented in Figure 5.

The observed results are summarized in Figure 6 where the maximum GMI ratio $\Delta Z/Z_{max}$, is plotted versus the

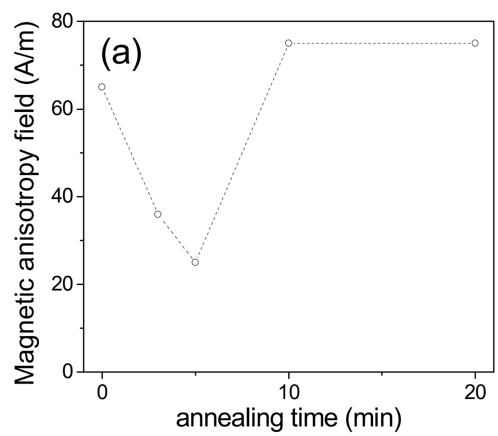

Figure 5. Dependence of the magnetic anisotropy field on Joule annealing time at I=30 mA for $Co_{67}Fe_{3.9}Ni_{1.4}B_{11.5}Si_{14.5}Mo_{1.6}$ microwire.

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frequency, $\Delta Z/Z_{max}(f)$, for different annealing conditions. As it can be observed, we achieved remarkable improvement of $\Delta Z/Z_{max}$ from 550% (observed for as-prepared sample) up to 650% (achieved after current annealing at 30mA or 40 mA for short annealing time of 3 and 5 min). Superior $\Delta Z/Z_{max}$ is observed in a whole frequency range, although the optimum frequency where $\Delta Z/Z_{max}$ ≈650% in current annealed samples is about 200 MHz, while for as-prepared samples the highest $\Delta Z/Z_{max}$ ≈550% is observed at about 300 MHz (see Figure 6).

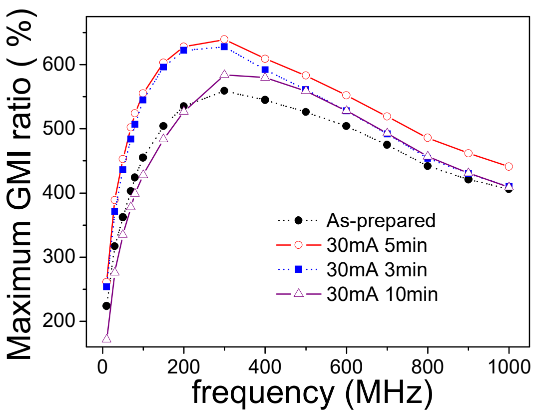

Figure 6. $\Delta Z/Z_{max}(f)$ dependences observed in $Co_{67}Fe_{3.9}Ni_{1.4}B_{11.5}Si_{14.5}Mo_{1.6}$ microwire current annealed at different annealing conditions

The observed influence of current annealing on magnetic softness of $Co_{67}Fe_{3.9}Ni_{1.5}B_{11.5}Si_{14.5}Mo_{1.6}$ glass-coated microwire must be attributed not only to the sample heating, but also to the circumferential magnetic field H_{circ} (associated to the current I flowing through the sample).

The aforementioned circumferential magnetic field, H_{circ}, produced by the current (Oersted field) in the surface of the metallic nucleus can be evaluated as following:

$$H_{circ}=I/2\pi r \qquad (2)$$

where I is the current value, r- radial distance.

Evaluated values of H_{circ} on the surface of studied microwire are H_{circ} ≈ 0.375 kA/m and 0.5 kA/m for I=30 mA and 40 mA respectively for studied microwire. These H_{circ} –values are clearly superior to the H_k–values evaluated from the hysteresis loops (see Figure 2) and hence can affect the magnetization near the surface during the current annealing.

It is worth mentioning that the Oersted field changes from 0 in the microwire axis to its maximum value in the surface. Therefore, the thin layer in the surface of metallic nucleus is affected by the Oersted magnetic field during the Joule heating. In fact, this layer is involved in the GMI effect.

As mentioned above, it is known that the annealing in presence of magnetic field can considerably affect the magnetic anisotropy of amorphous materials [29]-[36]. The macroscopic magnetic anisotropy is originated by a preferred magnetization direction during the annealing and previously discussed considering the directional ordering of atomic pairs or compositional short- range ordering, as well as the topological short-range ordering [29]-[36].

For the present studies of microwire containing Fe, Co and Ni, the pair ordering looks rather reasonable. We must assume that the evolution of magnetic properties and GMI effect must be affected by the competition of induced magnetic anisotropy related to the presence of the Oersted field as well as stress relaxation and related change of the magnetostriction coefficient reported for conventional furnace annealing [7].

Therefore, it is expected that the current annealing can considerably affect the GMI performance and the hysteresis loops of the studied microwires. We believe that this circumferential magnetic field does not allow magnetic hardening previously reported for conventional furnace annealing of Co-rich microwires [7][18][28].

IV. CONCLUSIONS

We have investigated the influence of Joule heating on GMI ratio of $Co_{67}Fe_{3.9}Ni_{1.5}B_{11.5}Si_{14.5}Mo_{1.6}$ glass-coated microwire. From the obtained dependence, we determined the optimal current annealing conditions and obtained considerable improvement of $\Delta Z/Z_{max}$ –values from 550% to about 650% after appropriate current annealing conditions. Additionally, current annealed microwires present excellent magnetic softness with low magnetic anisotropy field of about 25 A/m and coercivity of 2 A/m.

The observed dependencies have been discussed considering magnetic anisotropy induced by circular magnetic anisotropy during current annealing, internal stresses relaxation and radial distribution of magnetic anisotropy.

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