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ABSTRACT

Studies of magnetic properties and GMI effect of amorphous Co-Fe rich microwires reveal that they present GMI effect at GHz frequencies. Magnetic field dependences of GMI effect are affected by the post-processing conditions. In particular, we observed that in Co-Fe rich microwires stress-annealing allows improvement of frequency dependence of GMI ratio at high frequencies. We discussed observed experimental dependences considering both different magnetic structure and the anisotropy in the bulk and near the surface and close analogy between giant magnetoimpedance and ferromagnetic resonance.

I. INTRODUCTION

Studies of the Giant magnetoimpedance (GMI) effect have attracted considerable attention together with the development of amorphous wires[1,2] although in fact, it was previously observed in permalloy wires.[3]

The most attractive feature of the GMI effect is quite large sensitivity to magnetic field (up to 10%/A/m): in fact one of the largest among the non-cryogenic effects.[4–8]

The most common value used for characterization of the GMI effect is the GMI ratio, $\Delta Z/Z$, defined as:

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

where H is the applied axial DC magnetic field and H_{max}, - a maximum field typically up to few kA/m.

The $\Delta Z/Z$ - value and the magnetic field dependence are intrinsically related to the type of magnetic anisotropy: in magnetic wires with circumferential easy axis a double-peak magnetic field dependence of the real component of wire impedance (and consequently of the GMI ratio) is observed.[9] However, in magnetic wires with axial magnetic anisotropy a monotonic decay of the GMI ratio from H=0 is predicted and experimentally reported.[9,10] Consequently, maximum GMI ratio, $\Delta Z/Z_m$, can be observed in $\Delta Z/Z(H)$ dependence either for H=0 (in magnetic wires with axial magnetic anisotropy) or at some magnetic field, H_{max}.[5–10] The highest GMI ratios (up to 650%) as a rule have been observed in amorphous magnetic wires exhibiting also high circumferential magnetic permeability.[5–8,10]

The origin of the GMI effect has been successfully explained in terms of the skin effect of a soft magnetic conductor.[1,2,6–10]

The development of novel industrial applications requires the GMI material miniaturization. Therefore, the tendency to reduce the magnetic wires diameter stimulated technological progress in the development of fabrication processes of thin wires.[11–16]

It was predicted that, the diameter reduction must be associated with rising of the optimal GMI frequency range.[17] Indeed, the main prerequisite for the GMI effect observation is that the skin depth must be thinner that the wire radius.

Additionally, at high enough frequencies the domain walls are strongly damped. Therefore, only the magnetization rotation is responsible for the magnetic permeability variation upon external magnetic field at high frequencies.[17,18] Furthermore, at GHz frequencies range the link between the GMI and ferromagnetic resonance (FMR) is discussed.[17,19]

One of the parameters affected by the frequency is the maximum GMI ratio, $\Delta Z/Z_m$.[7,19,20] From previous experimental studies on frequency dependence of maximum GMI ratio in different families of magnetic wires it is found that the optimal frequency for the thicker wires (with the diameter of about 120 μm) prepared using in-rotating water technique (the frequency at which $\Delta Z/Z_m$ presents maximum values) is of the order of MHz,[20] however, for the thinner wires prepared using Taylor-Ulitovsky method (with the diameter of about 15 μm) maximum $\Delta Z/Z_m$ is observed in the frequency range between 100 and 200 MHz.[5,10]

However, the wire radius is not the unique parameter affecting the GMI effect value and magnetic field dependence: the other parameters are the magnetic anisotropy and its radial distribution and the magnetic softness. The magnetic anisotropy distribution of amorphous materials is linked to the magnetostriction coefficient sign and value (mostly determined by the chemical composition) and to the internal stresses value and distribution (related to the preparation method).[5,10]

Recently, we have developed novel post-processing methods allowing to tune the magnetic softness and the magnetic anisotropy distribution of thin microwires by specially designed annealing (i.e., stress-annealing).[21]

The aim of this report is to provide recent results on the effect of induced magnetic anisotropy on frequency dependence of GMI effect in magnetic microwires.

II. EXPERIMENTAL DETAILS

We studied GMI effect in $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ (d=22.8μm; D=23.2μm) microwire prepared using the Taylor-Ulitovsky technique described elsewhere.[14] Studied microwire presents vanishing magnetostriction coefficient, λ_s, ($\lambda_s \approx -1.0 \times 10^{-7}$).[22,23]

The impedance, Z, and its magnetic field dependence have been measured using vector network analyzer from the reflection coefficient S_{11} using a micro-strip sample holder described elsewhere.[19]

From Z values obtained for different magnetic fields, *H*, we evaluated the magnetic field dependences of the GMI ratio, $\Delta Z/Z$, in agreement with equation (1).

For comparison of the frequency dependence of the GMI effect we plotted frequency, *f*, dependence of a maximum GMI ratio, $\Delta Z/Z_m$, defined as a maximum $\Delta Z/Z$ obtained at a given frequency.

Hysteresis loops have been measured using the fluxmetric method previously successfully employed for characterization of magnetic microwires.[24] For better comparison of microwires annealed at different conditions we represent 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.

We measured aforementioned properties in as-prepared and annealed microwires. For conventional and stress annealing we used a conventional furnace. During the stress- annealing, a mechanical load has been attached to one end of the microwire and axially placed via the furnace nozzle. Such mechanical load allowed to apply tensile stress during the annealing, σ_a, up to 500 MPa. All the annealing processes have been performed at temperatures, T_{ann}, below the crystallization, observed at above 450-500 °C.

The stress value during the annealing, σ, within the metallic nucleus and glass shell has been evaluated as described elsewhere.[21]

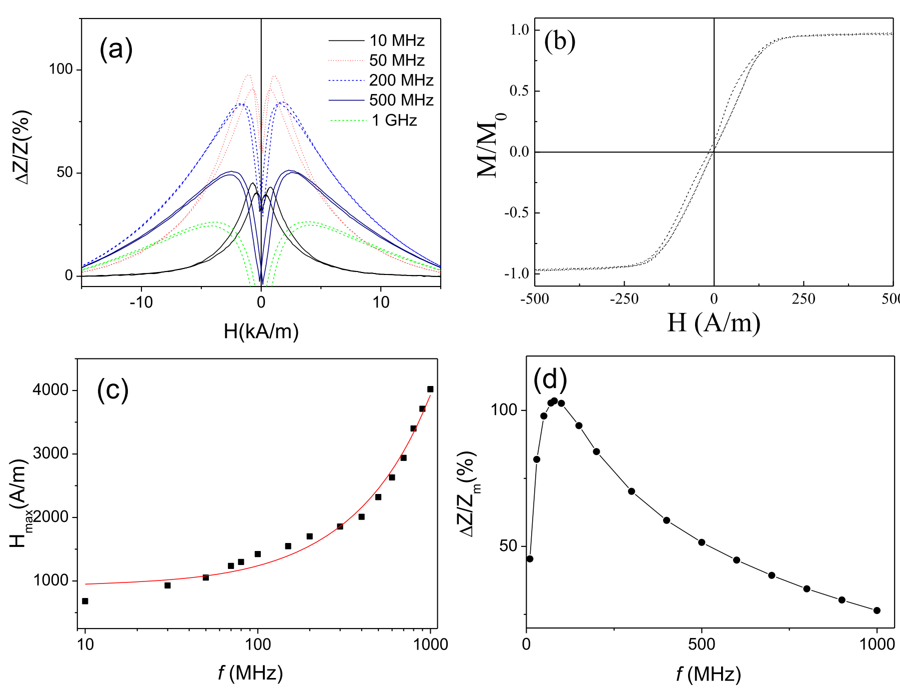

FIG. 1. *ΔZ/Z (H)* dependences (a), hysteresis loops (b), $H_{max}(f)$ (c) and $\Delta Z/Z_m(f)$ (d) dependencies of as-prepared $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires.

III. RESULTS AND DISCUSSION

ΔZ/Z (H) dependencies of as-prepared $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires present the double-peak character (for $10 \le f \le 1$ GHz) typical for wires with circumferential magnetic anisotropy (see Fig. 1a). Such circumferential magnetic anisotropy is confirmed by the hysteresis loop (Fig. 1b) presenting almost linear shape with low (about 5 A/m) coercivity, H_c, remanence, M_r/M_o (M/M_o at H=0), and magnetic anisotropy field, H_k. The magnetic field corresponding to GMI ratio maximum, H_{max}, considerably increases at high frequencies (see Fig. 1c). At elevated (nearly GHz) frequencies H_{max} –values (about 2000-3000 A/m) are considerably higher than magnetic anisotropy field, H_k, that can be estimated as $H_k \approx 170$ A/m. Similar behavior: increase of H_{max} and observation of H_{max} superior to H_k –values have been reported for various families of magnetic wires.[19,25,26] $H_{max}(f)$ dependence presents rapid H_{max} rising at elevated frequencies (see Fig. 1d).

As discussed elsewhere, the origin of H_{max} is usually linked to the magnetic anisotropy field, H_k.[1,2,7,8,10]

One of the origins explaining this discrepancy can be related to rather different macroscopic magnetic anisotropy, reflected in bulk hysteresis loops and in thin surface layer responsible for GMI effect. This difference might be associated with the interfacial layer between the metallic nucleus and glass-coating recently observed in Fe- and Co-rich microwires.[27,28]

However, observed difference between the H_{max} and H_k –values is quite high. Indeed, H_k –value deduced from Fig. 1b gives about 200 A/m, while H_{max} –values obtained from the *ΔZ/Z(H)* dependencies measured for f>500 MHz provide values superior to 2000 A/m (see Figs. 1c, d)

Frequency dependence of maximum GMI ratio, $\Delta Z/Z_m$ *(f)* in as-prepared $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires presents a maximum at about 100 MHz (see Fig. 1d). Consequently, as-prepared sample presents relatively low GMI effect at GHz frequencies.

Upon annealing at T_{ann}=300 °C (see Fig. 2) the hysteresis loops of as-prepared microwires have been considerably modified. Similarly to that reported for Co-rich microwires with vanishing λ_s –values remarkable magnetic hardening (coercivity growth from about 5 A/m to 50 A/m) is observed upon annealing (see Fig. 2a). Additionally, annealed at T_{ann}=300 °C $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires present rectangular hysteresis loops (see Fig. 2a). However, stress-annealing at the same T_{ann} allows considerable coercivity decreasing (Fig. 2b). Furthermore, at high enough stress applied during the annealing the hysteresis loop loses its rectangular character and coercivity drops up to $H_c \approx 12$ A/m (Fig. 2c). Consequently, the same sample with exactly the same geometry can present completely different magnetic anisotropy.

The domain structure of magnetic microwires is usually discussed considering core-shell model experimentally confirmed by various direct and indirect methods.[29–33]

This model allows simple evaluation of the domain structure modification from the squareness ratio, M_r/M_o, as:

$$R_c = R(M_r/M_o)^{1/2} \tag{2}$$

where R is the metallic nucleus radius and R_c – is the radius of the inner axially magnetized core.[32]

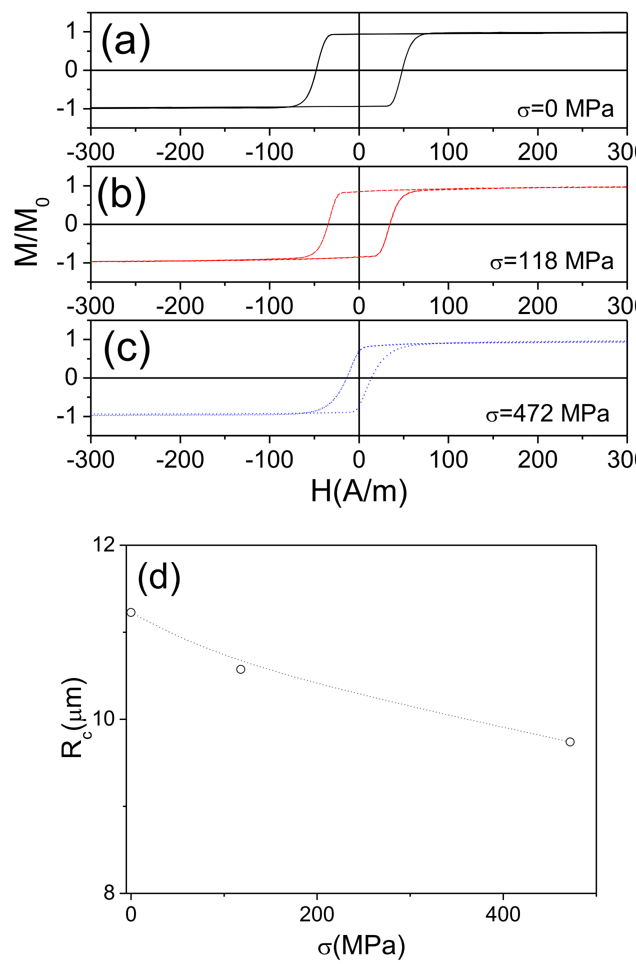

FIG. 2. Hysteresis loops of annealed (a) and stress-annealed (b, c) at T_{ann} = 300 °C for different σ and R_c (σ) dependence (d) of $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires.

A remarkable modification of the squareness ratio, M_r/M_o, can be appreciated from evolution of the hysteresis loops upon stress annealing (see Figs. 2a–c). Considering eq. (2) we have evaluated the evolution of R_c –values versus stress applied during the annealing (see Fig. 2d). From Fig. 2d we can deduce that the stress-annealing allows a decrease in the inner axially magnetized core volume and hence rising of the outer domain shell volume with transverse magnetization orientation.

Consequently, by stress-annealing we are able to tune the domain structure of studied microwires varying the stress applied during the annealing.

Accordingly, *ΔZ/Z (H)* dependencies of annealed and stress-annealed $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires present considerable difference. Single-peak *ΔZ/Z(H)* dependence with maximum at $H \approx 0$ is observed for annealed microwire for low enough frequencies ($f \le 100$ MHz) (Fig. 3a). While a double-peak *ΔZ/Z(H)* dependence with *ΔZ/Z* maximums at $H \neq 0$ is presented by stress-annealed sample (see Fig. 3b).

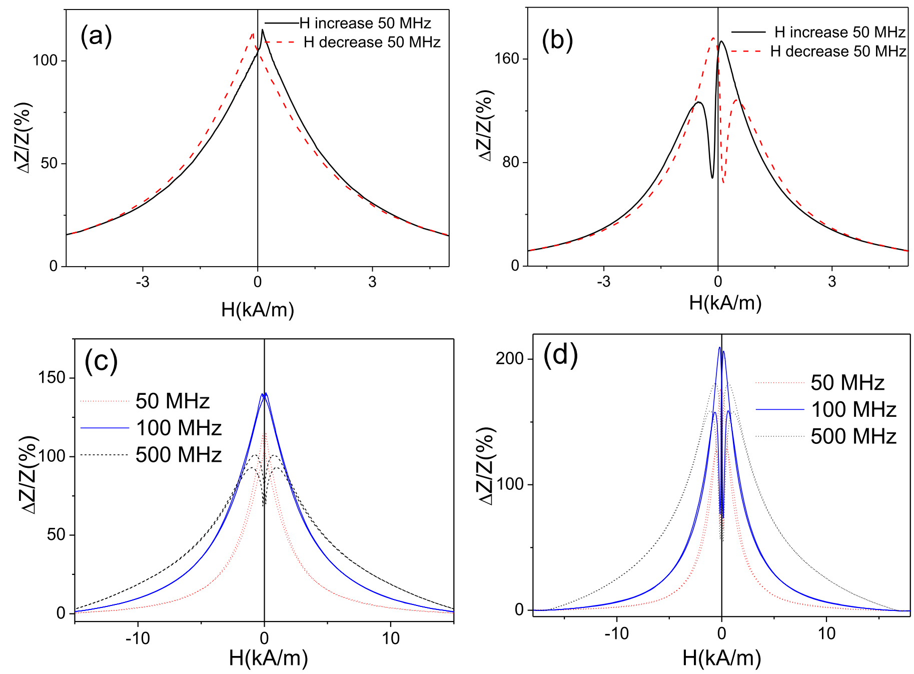

FIG. 3. *ΔZ/Z (H)* dependencies of annealed (a, c) and stress- annealed for σ =472 MPa at 300 °C (b, d) $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires measured at different frequencies.

However, for elevated frequency (f = 500 MHz) double-peak $\Delta Z/Z$ *(H)* dependence is observed for the same sample (see Fig. 3c). Upon stress annealing double-peak $\Delta Z/Z$ *(H)* dependence becomes more visible (even for low f) increasing the stress, σ, applied during the annealing (see Fig. 3d). Additionally, GMI hysteresis becomes more appreciable in low magnetic field region in stress-annealed samples (see Fig. 3a).

Frequency dependence of maximum GMI ratio, $\Delta Z/Z_m$, for as-prepared and annealed samples presents considerable difference too (see Fig. 4). For as-prepared $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_1$ microwire the optimal frequency (at which $\Delta Z/Z_m$ presents maximum) is about 100 MHz. In annealed samples the optimal frequency shifts to 150 MHz. Additionally, annealing and especially stress-annealing allows improvement of $\Delta Z/Z_m$ for wide frequency range. $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires stress-annealed at σ= 472 MPa present $\Delta Z/Z_m$ > 100% for frequencies up to 1 GHz (see Fig. 4a).

Observation of double-peak $\Delta Z/Z(H)$ dependencies at high frequency and high enough GMI ratio in annealed $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwire (presenting rectangular hysteresis loop as can be seen in Fig. 3a) can be interpreted considering the existence of a thin outer layer with circumferential magnetic anisotropy.[28]

Similarly to the case of as-prepared samples $H_{max}(f)$ dependencies of annealed and stress-annealed $Fe_{3.6}Co_{69.2}Ni_1B_{12.5}Si_{11}Mo_{1.5}C_{1.2}$ microwires present H_{max} rising at elevated frequencies (see Fig. 4b). However, observed H_{max} –values are at least twice lower than those of as-prepared samples.

From observed frequency dependencies of H_{max} it is clear that at GHz frequencies H_{max} –values are about one order of magnitude superior than the macroscopic magnetic anisotropy field. Accordingly, all the studied samples are magnetically saturated when exhibit the impedance change at elevated frequencies.

Previously GMI effect at elevated frequencies has been explained considering the fundamental link between ferromagnetic resonance, FMR, and GMI.[17,25,26,34,35] However, it must be mentioned that the alternating Oersted field distribution is affected by the skin effect. Therefore, for the present case the FMR for the inhomogeneous driving field must be considered.[26]

Similarly to previous reports we plotted the dependence of the square of the frequency on H_{max} (Fig. 4c). The linear fit can be observed for high f and H_{max} –values. However, considerable deviations can be appreciated in low-field region for all the samples.

Additionally, the slopes of df^2/dH dependencies of as-prepared and annealed samples are considerably different. However, the saturation magnetization of amorphous materials depends on the chemical composition of the alloy.

The relation between the saturation magnetization, M_s, and the resonance frequency is given by the equation:

$$M_s = 0.805 * 10^{-9} df_0^{\,2}/dH \tag{3}$$

where f_0 is the resonant frequency, H is the applied magnetic field, M_s is the saturation magnetization.

Consequently, from provided analysis we can deduce that some features of high frequency GMI effect can be described using FMR-like approximation. However, low frequency GMI cannot be described considering the FMR approach and the FMR approach provides rather different M_s –values for as-prepared and annealed samples. The origins of observed discrepancies must be clarified in the future.

Magnetic anisotropy of as-prepared glass-coated microwires is commonly discussed considering the magnetoelastic anisotropy, i.e., the magnetostriction coefficient sign and value and the internal stresses distribution and value.[36–38]

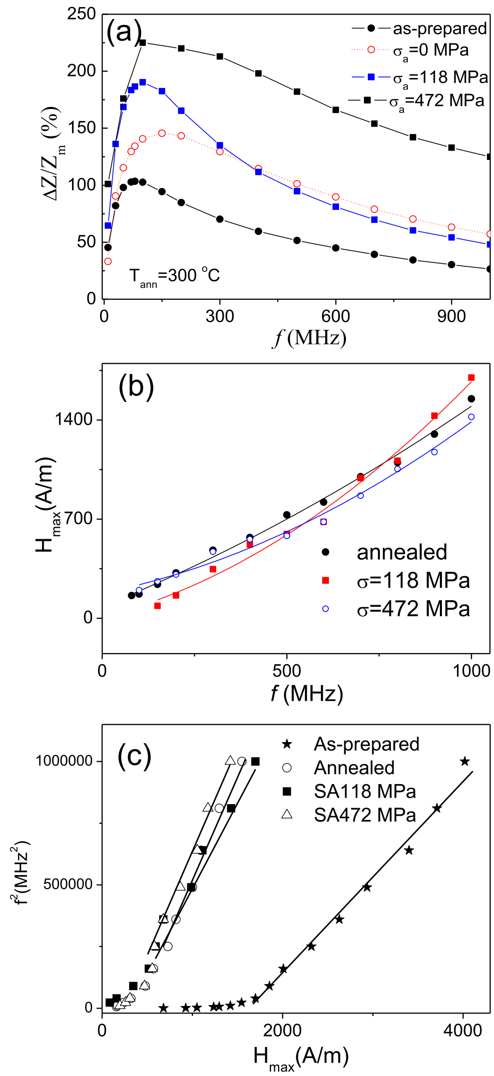

FIG. 4. $\Delta Z/Z_m(f)$ dependencies (a), $H_{max}(f)$ dependencies (b) and $f^{2}(H_{max})$ dependencies (c) for as-prepared, annealed and stress-annealed microwires.

Observed experimental results on influence of post-processing can be explained considering the internal stresses relaxation upon annealing and redistribution of the stresses within the metallic nucleus upon stress-annealing.

IV. CONCLUSIONS

We provide comparative studies of GMI effect at elevated frequencies in as-prepared and post-processed Co-based microwires.

Magnetic field dependences of GMI effect are affected by the post-processing conditions. Stress annealing allows remarkable improvement of frequency dependence of GMI ratio.

In particular, we observed that in Co-Fe-rich microwires stress-annealing allows improvement of frequency dependence of GMI ratio. We discussed observed experimental dependences considering both different magnetic structure and the anisotropy in the bulk and near the surface and close analogy between giant magnetoimpedance and ferromagnetic resonance.

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