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Optimization of high frequency magnetoimpedance effect of Fe-rich microwires by stress-annealing

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ABSTRACT

We present comparative studies of magnetic properties and giant magnetoimpedance (GMI) effect of Fe and Co-rich microwires. As-prepared Co-rich microwires present much higher GMI ratio. The impact of the stress-annealing on magnetic softness and high frequency magnetoimpedance effect of Fe-rich microwires has been studied. The large improvement of the magnetoimpedance response in a wide frequency range by the stress-annealing is observed. We have achieved GMI ratio increase by an order of magnitude after stress-annealing of Fe-rich microwire. Observed stress-induced anisotropy and related changes of magnetic properties are discussed considering internal stresses relaxation and “back-stresses”.

1. Introduction

Magnetic wires have attracted growing interest of the researchers and engineers owing to magnetic properties attractive for development of cost effective and high performance magnetic sensors and magnetometers [1–4]. The giant magnetoimpedance (GMI) effect as well as controllable domain wall (DW) propagation considered among the most promising magnetic properties of different families of wires [1–6].

Although aforementioned versatile properties of magnetic wires are not restricted to wires with amorphous structure, amorphous materials prepared using rapid quenching from the melt present various advantages, such as combination of fast and inexpensive fabrication method and excellent magnetic, mechanical and corrosion properties [5,7–9].

Recently a few novel rapid quenching methods suitable for preparation of micrometric and even sub-micrometric cast amorphous wires have been developed [10–14].

The Taylor-Ulitovsky technique known since 60-s [15,16] and allows preparation of thinnest rapidly quenched glass-coated microwires (with metallic nucleus diameters of 0.5–40 μm coated by glass-coating with thickness of 0.5–20 μm) have attracted recently growing interest [1,10,11,17].

One of the most attractive properties of amorphous wires is aforementioned GMI effect presenting quite large sensitivity to an applied magnetic field (up to 10%/A/m) and therefore suitable for development of magnetic sensors, magnetometers, memories and devices, smart composites for remote stress and temperature monitoring, health monitoring etc [5,18–23]. For technical applications the most common expression for GMI effect is the GMI ratio, $\Delta Z/Z$, defined as:

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

where Z is impedance of the wire, H and $H_{\max}$ are the applied and maximum DC magnetic field.

Although the highest experimentally reported GMI ratio is about 600% [22,23], the theoretical maximum GMI ratio is about 3000% [24]. Additionally the soft magnets suitable for GMI effect optimization must be about one order thicker than the minimal skin depth (about 0.3 μm) and present low magnetic anisotropy [25,26].

Up to now the highest GMI ratio is reported for Co-based glass-coated microwires with metallic nucleus of nearly-zero magnetostriction coefficient and micrometric diameters [22,23,27]. Upon joule heating the magnetic softness and GMI ratio of Co-rich microwires can

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be improved [22].

On the other hand for large scale applications a high-performance, cost effective and less expensive microwires are highly demanded.

Therefore certain attention has been paid to optimization of magnetic softness of less expensive Fe-rich amorphous glass-coated microwires [28–30]. As-prepared amorphous Fe-based microwires present higher magnetostriction coefficient than Co-based microwires and therefore usually have rectangular hysteresis loop with low magnetic permeability and hence poor GMI effect [11]. This character of hysteresis loop is related to rather peculiar domain structure of Fe-based as-prepared amorphous microwires consisting of a single domain inner core with axial magnetization surrounded by an outer domains shell with radial magnetization orientation [31,32].

Magnetic softness and GMI effect of Fe-based amorphous alloys doped by Cu and Nb can be considerably improved by the nanocrystallization allowing decreasing of the magnetostriction coefficient [7,28,29]. But such nanocrystalline materials are rather fragile.

Induced magnetic anisotropy is the alternative route of processing of amorphous Fe- and Co-based alloys allowing in some cases improvement of magnetic softening without deterioration of mechanical properties [30,33]. A few successful attempts on tuning of hysteresis loop and low frequency (10 MHz) GMI are reported for Fe-based glass-coated microwires [30]. Arising of transverse magnetic anisotropy and improvement of GMI ratio at 10 MHz are reported in stress-annealed Fe-based microwires [30,34]. It is worth mentioning that up to now studies of GMI effect of stress-annealed Fe-based microwires have been limited to low frequency, f, (f = 10 MHz) band [30,34]. But for micrometric wires the optimal GMI frequency band is shifted towards high frequencies range (f = 100 MHz-1 GHz) [27,35]. Studies of the influence of stress-induced magnetic anisotropy on high frequency GMI effect are limited to a few quite recent experimental results obtained mostly for Co-based microwires [33,36]. Thus for Co-based microwires enhancement of the GMI effect after stress-annealing at 100–500 MHz is reported [33]. Accordingly studies of the effect of stress-annealing on GMI effect at frequencies above 10 MHz in Fe-based microwires are particularly interesting and relevant for prospective applications.

Consequently, in this paper we present our recent experimental results on influence of stress-annealing on magnetic properties and GMI effect at elevated frequencies of Fe-based glass-coated microwires and comparison to similar studies in Co-based microwires.

2. Experimental details

Amorphous $Fe_{75}B_9Si_{12}C_4$ (metallic nucleus diameter, d = 15.2 µm, total diameter, D = 17.2 µm) and $Co_{50.7}Fe_{8.1}Ni_{17.6}B_{13.3}Si_{10.3}$ (d = 12.8 µm, D = 15.8 µm) glass-coated microwires with positive and low negative magnetostriction coefficients, λ_s, respectively prepared using Taylor-Ulitovky technique described elsewhere [10,11,14–17].

Structure and phase composition have been evaluated by X-ray Diffraction (XRD) employing a BRUKER (D8 Advance) X-ray diffractometer with Cu K_α (λ = 1.54 Å) radiation.

DSC measurements were performed using DSC 204 F1 Netzsch calorimeter in Ar atmosphere at a heating rate of 10 K/min.

Samples annealing has been performed in a conventional furnace.

All the as-prepared and annealed samples presented XRD patterns with broad halo typical for completely amorphous materials (see Fig. 1).

The crystallization temperature, T_{cr1}, (determined as the beginning of the first crystallization peak) evaluated by DSC for as-prepared and stress-annealed $Fe_{75}B_9Si_{12}C_4$ samples is about 522 °C (see Fig. 2). DSC measurements allow also estimating the Curie temperature, T_c (about 413 °C).

The employed annealing temperatures, T_{ann}, were below the T_{cr1} and T_c [24].

The tensile stress has been applied during the annealing as well as during the sample cooling with the furnace. The mechanical load has been attached to the microwire during the annealing and slow cooling with the furnace.

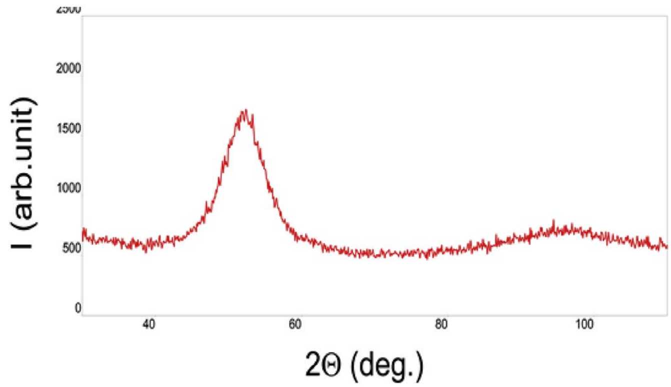

Fig. 1. XRD patterns of as-prepared $Fe_{75}B_9Si_{12}C_4$ microwires.

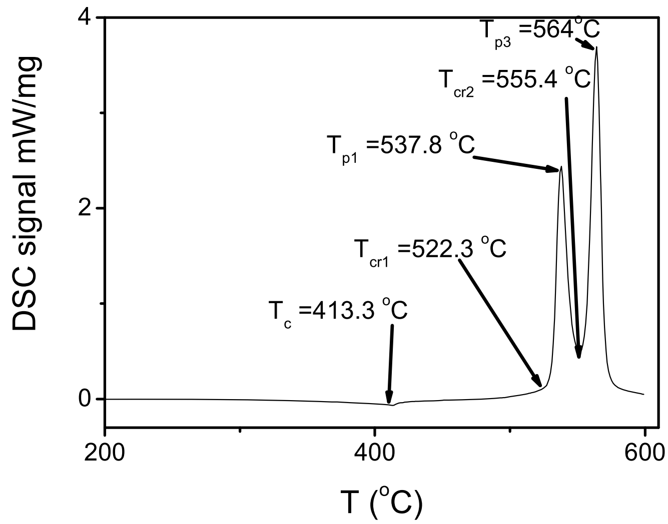

Fig. 2. DSC curves of as-prepared $Fe_{75}B_9Si_{12}C_4$ microwire.

The stress value during the annealing within the metallic nucleus and glass shell has been evaluated as described earlier [33]:

$$\sigma_m = \frac{K \cdot P}{K\ S_m + S_{gl}},\ \sigma_{gl} = \frac{P}{K\ S_m + S_{gl}} \tag{2}$$

where $K = E_2/E_1$, Ei are the Young's moduli of the metal (E_2) and the glass (E_1) at room temperature, P is the applied mechanical load, and S_m and S_{gl} respectively are the cross sections of the metallic nucleus and glass coating. We fixed the applied tensile stress $\sigma_m \approx 900$ MPa and annealing temperature, $T_{ann} = 200°$ C and annealing time, t_{ann} = 120 min.

Employed tensile stress was similar or even slightly higher than that previously used for stress-annealing of Fe-based microwires [30], while to prevent the crystallization and glass-coating damage we kept the annealing temperature as low as possible (200 °C). Consequently we do not observe any change of XRD pattern and stress-annealed samples can be easily bended and twisted.

Hysteresis loops have been measured using fluxmetric method previously described elsewhere [37]. We represent the normalized magnetization, M/M_0 versus magnetic field, H, where M is the magnetic moment at given magnetic field and M_0 is the magnetic moment of the sample at the maximum magnetic field amplitude, H_m.

For GMI characterization we used GMI ratio, $\Delta Z/Z$, defined by eq. (1)

As previously described [25,27], we used micro-strip sample holder placed inside a sufficiently long solenoid that creates a homogeneous