Giant Magnetoimpedance Effect in Nanocrystalline Microwires

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Abstract— We studied GMI effect and magnetic properties of Finemet-type FeCuNbSiB microwires. We observed that GMI magnetic field and frequency dependences and magnetic softness of composite microwires produced by the Taylor-Ulitovski technique can be tailored either controlling magnetoelastic anisotropy of as-prepared FeCuNbSiB microwires or controlling their structure by heat treatment or changing the fabrication conditions. GMI effect has been observed in as-prepared Fe-rich microwires with nanocrystalline structure.

1. INTRODUCTION

Studies of glass coated ferromagnetic microwires (typically of 5–30 μm in diameter) have attracted growing attention in the last few years owing to their outstanding soft magnetic properties (magnetic bistability, enhanced magnetic softness, GMI effect, fast domain wall propagation) and possibility to obtain glass-coated microwires with different structure (amorphous, nanocrystalline, granular) [1, 2]. Particularly, recent studies have demonstrated that optimization of soft magnetic properties and GMI effect of amorphous glass coated microwires is possible choosing the appropriate chemical composition of metallic nucleus and adequate annealing conditions [1].

In some cases, nanocrystallization allows achieving good magnetic softness and enhanced GMI effect in ferromagnetic microwires. Such soft magnetic character is usually attributed to vanishing magnetocrystalline anisotropy and the very small magnetostriction value when the grain size approaches 10 nm [3, 4]. Like for conventional nanocrystalline materials, average anisotropy for randomly oriented α-Fe(Si) grains is negligibly small when the average grain is about 10–20 nm. Consequently, low values of coercivity in the nanocrystalline microwires were ascribed to small effective magnetic anisotropy. In addition to the suppressed magnetocrystalline anisotropy, low magnetostriction values provide the basis for the superior soft magnetic properties observed in particular compositions [3, 4]. Low values of the magnetostriction are essential to avoid magnetoelastic anisotropies arising from internal or external mechanical stresses.

Generally magnetic properties and overall shape of hysteresis loops of amorphous ferromagnetic microwires depend on the composition of the metallic nucleus as well as on the composition and thickness of the glass coating. As discovered before, shape of hysteresis loops changes from rectangular, typical for amorphous Fe-rich compositions, to inclined, typical for Co-rich compositions [5]. Amorphous microwires with vanishing magnetostriction exhibit quite soft magnetic properties.

Such strong dependence of the hysteresis loops on these parameters should be attributed to the magnetoelastic energy given by:

$$K_{me} \approx 3/2\lambda_s\sigma_i, \tag{1}$$

where λ_s is the saturation magnetostriction and σ_i is the internal stress. The magnetostriction constant depends mostly on the chemical composition and is vanishing in amorphous Fe-Co based alloys with Co/Fe $\approx$ 70/5 [5–7]. One of the peculiarities of the fabrication technique of glass-coated microwires is that it involves the simultaneous solidification of composite microwire consisting of ferromagnetic nucleus surrounded by glass coating. Quite different thermal expansion coefficients of the glass and the metallic alloys introduce considerable internal stresses inside the ferromagnetic nucleus during simultaneous fast solidification of the composite microwire [1, 6, 8, 9]. The estimated values of the internal stresses in these glass coated microwires arising from the difference in the thermal expansion coefficients of metallic nucleus and glass coating are of the order of 100–1000 MPa, depending strongly on the ratio between the glass coating thickness and metallic core diameter [8–11], increasing with the glass coating thickness. Such large internal stresses give rise to a drastic change of the magnetoelastic energy, K_{me}, even for small changes of the glass-coating thickness at fixed metallic core diameter. Additionally, such a change of the ρ-ratio should be related to the change of the magnetostriction constant with applied stress [6, 12]:

$$\lambda_s = (\mu_o M_s/3)(dH_k/d\sigma), \tag{2}$$

where $\mu_o M_s$ is the saturation magnetization.

It is worth mentioning, that residual stresses of glass-coated microwires arising during simultaneous solidification of metallic nucleus and glass coating, mostly have been estimated from the simulations of the process of simultaneous solidification of metallic nucleus inside the glass tube [6–8] and experimental determination of such residual stresses is rather complex. One of the experimental evidence of existence of such stresses is the dependence of hysteresis loops and particularly magnetic properties (coercivity, remanent magnetization) on ρ-ratio [6, 8].

Consequently, tailoring of the magnetoelastic energy, K_{me}, is essentially important for optimization of magnetic properties of glass-coated microwires [1, 6, 8].

Accordingly, any method allowing estimation of internal stresses in glass-coated microwires is quite suitable for soft magnetic properties optimization.

In the case of glass-coated microwires, existence of the outer glass-coating with physical properties completely different from metallic nucleus alloys (different thermal conductivity, thermal expansion coefficients ...) in some cases drastically affects structure and magnetic properties of glass-coated microwires [1]. Thus, crystalline structure, crystallization temperature and magnetic properties of nanocrystalline microwires are rather different from nanocrystalline ribbons of the same composition [1–3].

In this paper, we studied the effect of the nanocrystallization on magnetic properties, structure and GMI of Finemet-type amorphous and nanocrystalline microwires.

2. EXPERIMENTAL

We studied Finemet-type $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$, $Fe_{71.8}Cu_1Nb_{3.1}Si_{15}B_{9.1}$, $Fe_{73.8}Cu_1Nb_{3.1}Si_{13}B_{9.1}$ and $Fe_{70.8}Cu_1Nb_{3.1}Si_{16}B_{9.1}$ glass-coated microwires with different metallic nucleus diameter, d, and total microwire diameter, D, were produced by modified Taylor-Ulitovsky method [1–3]. It is worth mentioning, that the strength of internal stresses is determined by ratio ρ [6, 9]. Therefore, controllable change of the ρ-ratio allowed us to control the residual stresses.

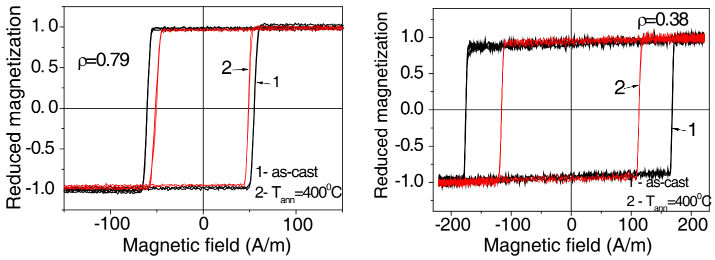
Hysteresis loops have been determined by flux-metric method, as described elsewhere [1, 2]. We measured magnetic field dependences of impedance, Z, and GMI ratio, $\Delta Z/Z$, for as-prepared samples and after heat treatments. We used specially designed micro-strip sample holder. The sample holder was placed inside a sufficiently long solenoid that creates a homogeneous magnetic field, H. The sample impedance Z was measured using vector network analyzer from reflection coefficient S_{11}. The DC bias current I_B was applied to the sample through a bias-tee element. All experimental graphs show both ascending and descending branches of the field dependencies of the real part of impedance Z so that the magnetic hysteresis can be evaluated. More details on experimental technique can be found in Ref. [1].

Structure and phase composition have been checked using a BRUKER (D8 Advance) X-ray diffractometer with Cu K_α ($\lambda = 1.54$ Å) radiation.

3. RESULTS AND DISCUSSION

All as-prepared and even annealed Finemet-type microwires at annealing temperature, T_{ann}, below first crystallization process, present squared hysteresis loops similar to Fe-rich amorphous microwires (Fig. 1).

As expected from previous studies of Fe-rich amorphous microwires [1], coercivity, H_C, of as-prepared Finemet-type microwires depends on ratio $\rho = d/D$ (Fig. 2). Annealing temperature dependence of coercivity of $Fe_{71.8}Cu_1Nb_{3.1}Si_{15}B_{9.1}$ microwires shown in Fig. 3 present considerable magnetic softening at annealing temperatures, T_{ann}, between 800 and 900 K as previously observed in other Finemet-type materials and Finemet-type microwires [1, 13]. Consequently, although GMI effect in as-prepared Fe-rich microwires is rather small, after annealing we observed increasing of the GMI effect (Figs. 4(a) and 4(b)). Enhancement of the $\Delta Z/Z$ ratio is related with magnetic softening of studied microwires after annealing and internal stress relaxation. Indeed applied and internal stresses considerably affect GMI effect [12]. Generally, measurements of the GMI effect in nanocrystalline microwires involve preparation of the electrical connections of rather brittle nanocrystalline samples.



(a) (b)

Figure 1: Hysteresis loops of as-prepared and after the heat treatment $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$ microwires with different $\rho = d/D$ ratios: (a) $\rho = 0.79$, (b) $\rho = 0.38$.

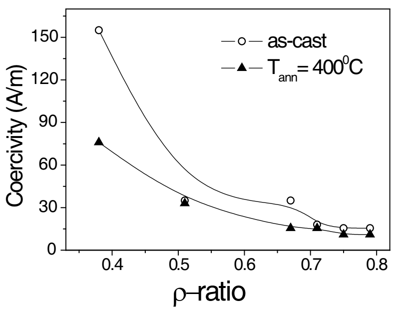


Figure 2: Coercivity dependence on ρ-ratio for as-prepared $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$ microwires.

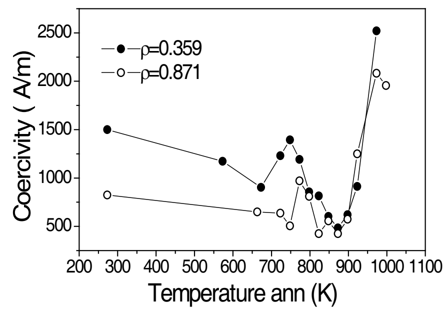
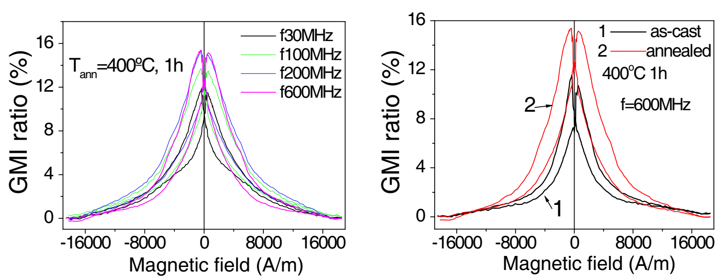


Figure 3: Annealing temperature dependence of coercivity of $Fe_{71.8}Cu_1Nb_{3.1}Si_{15}B_{9.1}$ microwires with different ρ-ratios.



(a) (b)

Figure 4: (a) $\Delta Z/Z(H)$ dependences of $Fe_{73.8}Cu_1Nb_{3.1}Si_{13}B_{9.1}$ amorphous microwires annealed at 400°C measured at different frequencies and (b) $\Delta Z/Z(H)$ dependences of $Fe_{73.8}Cu_1Nb_{3.1}Si_{13}B_{9.1}$ amorphous microwires measured in as-prepared and annealed at 400C samples at 600 MHz.

X-ray studies show, that as-prepared $Fe_{73.8}Cu_1Nb_{3.1}Si_{13}B_{9.1}$ microwire exhibit nanocrystalline structure. The structure consists of of α-Fe nanocrystallites with average grain size about 12 nm and amorphous matrix (Fig. 5(a)). The grain size has been estimated the average grain size can be estimated from the width of the crystalline peak using the Debye-Scherrer equation. For comparison X-ray diffraction pattern of completely amorphous as-prepared $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$ microwire is shown in Fgi. 5(b). In as-prepared $Fe_{73.8}Cu_1Nb_{3.1}Si_{13}B_{9.1}$ microwires we observed considerable GMI effect (up to $\Delta Z/Z \approx 30\%$ at $f = 100$ MHz, see Fig. 5(c)). Observed considerable GMI effect in as-prepared $Fe_{73.8}Cu_1Nb_{3.1}Si_{13}B_{9.1}$ microwires is much higher that of $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$. This difference must be attributed to amorphous structure of $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$ and nanocrystalline structure of $Fe_{73.8}Cu_1Nb_{3.1}Si_{13}B_{9.1}$ microwires.

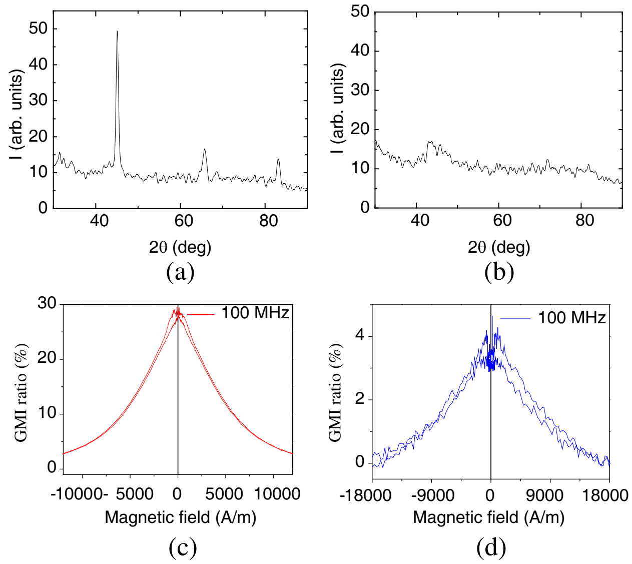


Figure 5: (a) X-ray diffraction patterns of as-prepared $Fe_{73.8}Cu_1Nb_{3.1}Si_{13}B_{9.1}$ ($\rho = 0.6$) and (b) $Fe_{70.8}Cu_1Nb_{3.1}Si_{14.5}B_{10.6}$ ($\rho = 0,87$) microwires and (c), (d) GMI effect in the same samples.

4. CONCLUSIONS

The study of magnetic and thermal properties of nano-scaled Finemet-type FeCuNbSiB and Co-Cu glass-coated microwires reveals that increase of stresses in the amorphous metallic nucleus considerably affect magnetic properties of these materials. In Finemet-type FeCuNbSiB the reduction of the ρ-ratio, results in the rise of coercivity. We observed magnetic softening and considerable GMI effect in Finemet-type FeCuNbSiB with nanocrystalline structure. Magnetoelastic anisotropy affects soft magnetic properties and GMI effect of FeCuNbSiB micrfowires.

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