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Giant magneto-impedance effect in thin amorphous wires at elevated frequencies

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We report on novel results on observation of the giant magneto-impedance effect in amorphous microwires with different magnetostriction constant (Fe-rich, with positive magnetostriction constant, Co-rich with negative magnetostriction constant and Co-Fe-rich with nearly-zero magnetostriction constant) in the high frequency region (between 10 MHz and 500 MHz). The observed dependencies have been interpreted in terms of different magneto-elastic energy induced by the fabrication process.

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1. Introduction

The giant magneto-impedance effect GMI rediscovered in 90-th attracts continuous attention of researchers in the field of applied magnetism owing to the large sensitivity (up to 600%) of the electrical impedance to the *DC* magnetic field at high enough frequency of electrical current flowing along the magnetic conductor [1,2]. It is well established that the GMI effect is the highest in soft magnetic wires with vanishing magnetostriction constant [1-3]. Such studies mainly have been performed at frequencies in the range between 100 kHz and 20 MHz. At these frequencies the GMI effect in magnetic materials with high magnetostriction constant is much smaller (of the order of few %). Few attempts to improve the GMI ratio in both Co-rich and Fe-rich materials with non-zero magnetostriction constant have been performed using special materials processing (mostly thermal treatment) [4,5].

On the other hand the alternative tendency is related with the miniaturization of the magnetic sensing elements. Therefore glass-coated wires produced by the Taylor-Ulitovsky method with reduced diameter (1 ÷ 30 μm diameter of metallic nucleus and 1-20 μm thickness of the glass coating) attracted recently considered attention. These thin wires are composite materials consisting on a metallic nucleus coated by an insulating glass coating. Such glass coating introduces additional internal stresses deteriorating somehow the magnetic softness of the samples. Initially the GMI effect even in nearly-zero magnetostriction glass-coated wires achieved only few percents. Recently significant progress in tailoring of Co-rich glass coated microwires with vanishing magnetostriction constant, λ_s, allowed to improve significantly both their magnetic softness and the GMI ratio (up to about 600% at about 10-20 MHz) [4]. However at these frequencies (< 30 MHz) Fe-rich amorphous microwires with $\lambda_s>0$ and rectangular hysteresis loop exhibit rather poor initial magnetic permeability and low GMI effect without special annealing [4, 5].

Growing interest in the application of the GMI effect requires amplification of the frequency range till GHz frequencies [6,7]. But special care is needed to perform correct measurements at frequencies above 10 MHz, regarding the sample holder design, the electrical cables length and special HF specifications.

Initially the GMI effect was interpreted as the classical skin effect in a magnetic conductor assuming scalar character for the magnetic permeability. Consequently the change of the penetration depth of the *AC* current, δ, caused by the *dc* applied magnetic field is given by:

$$\delta = (\pi \, \sigma \, \mu_\phi \, f)^{-1/2} \tag{1}$$

where f the frequency of the current along the sample, σ is the electric conductivity and μ_ϕ the circular magnetic permeability assumed to be scalar. Thus the *dc* applied magnetic field affects the circular permeability, μ_ϕ changing in this way the impedance, Z [1-3].

Recently the tensor origin of the magnetic permeability and magneto impedance have been taken into account in order to describe more detailed the phenomenology [8,9]. It was theoretically shown in [8], that the axial dependence of the GMI spectra is mainly determined by the type of magnetic anisotropy: the circumferential anisotropy leads to the observation of the maximum of the real component of wire impedance (and consequently of the GMI ratio) versus the external magnetic field. If the sample possess an axial magnetic anisotropy, the maximum value of the GMI ratio corresponds at zero magnetic field, i.e. results in a monotonic decay of the GMI ratio with the axial magnetic field [8]. Non-diagonal components of the magnetic permeability tensor and impedance tensor introduced in [8,9] allow to describe such circumferential anisotropy. The highest GMI effect is predicted for the smallest magnetic anisotropy.

In this paper we study the GMI effect in the high frequency region (between 10 MHz and 500 MHz) in different families of amorphous microwires (Fe-rich, with positive magnetostriction constant, λ_s, Co-rich with $\lambda_s < 0$ and Co-Fe-rich with $\lambda_s \simeq 0$) fabricated by the Taylor-Ulitovsky method [4].

2. Experimental details

Different compositions of glass-coated amorphous microwires fabricated by the Taylor-Ulitovsky method by TAMAG Iberica Co have been studied. Particularly typical compositions with different magnetostriction have been selected: $Fe_{76}B_{13}Si_{11}$ (total diameter 20.4 μm, metallic nucleus diameter – 17.2 μm), $Co_{77.5}B_{15}Si_{7.5}$ (total diameter 21 μm, metallic nucleus diameter – 17 μm) and $Co_{68.5}Fe_{3.5}Cr_{3}B_{14}Si_{11}$ (total diameter 27.4 μm, metallic nucleus diameter – 16.4 μm).

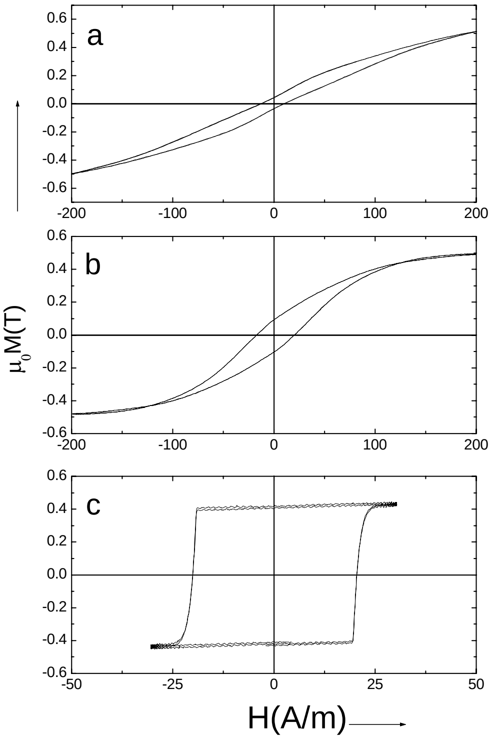

Fig. 1. Hysteresis loops of thin glass-coated microwires with different magnetosctriction constant: (a) Co-rich composition with $\lambda_s < 0$, (b) Co-Fe-Cr-based composition with $\lambda_s \simeq 0$ and (c) Fe-rich composition with $\lambda_s > 0$.

The impedance was evaluated using an impedance analyzer HP4192A at frequencies 10 - 500 MHz. The cylindrical sample holder made from a highly conductive (Al) shielding surrounding the central conductor which terminates in a short circuit has been used. After being soldered to the SMA microwave connector contact (electrical contact 1) the wire is inserted into the sample holder until the wire edge reaches a fine hole (contact 2) at the edge of the sample holder cavity. The SMA connector is then screwed to the sample holder and the electrical contact 2 is made by the silver paint. The measurements have been made according to the procedure described elsewhere [10]. The magnetoimpedance ratio, ΔZ/Z, has been defined as:

$$\Delta Z/Z = [(Z(H) - Z(H_{max})] / Z(H_{max}) \qquad (2)$$

where the maximum dc axial applied field, H_{max}, supplied by a solenoid is up to 30 kA/M.

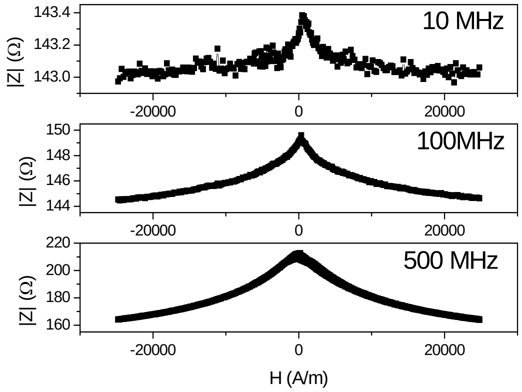

Fig. 2. DC magnetic field dependence of the impedance of $Fe_{76}B_{13}Si_{11}$ glass-coated amorphous microwires.

3. Results and discussion

The magnetic anisotropy and consequently the GMI effect are intrinsically related with the axial hysteresis loops of the samples. Typical hysteresis loops of three compositions of the studied microwires (Fe-rich with positive magnetostriction constant, Co-rich with negative magnetostriction constant and Co-Fe-rich with vanishing magnetostriction) are shown in Fig.1. Generally, Fe-rich compositions with positive magnetostriction constant, λ_s, exhibit rectangular hysteresis loop (see Fig. 1), Co-rich compositions with $\lambda_s < 0$ show almost unhysteretic hysteresis loop and Co-Fe-rich compositions with vanishing λ_s show best magnetic softenss (Fig. 1). It means that the chemical composition of glass-coated microwires drastically affects their magnetic behavior.

The magnetic field dependence of the impedance has been also measured in three different thin glass-coated microwires at the same frequency range (10-500 MHz) (see Figs. 2-4). At 10 MHz the GMI effect of Fe-rich microwires is small, but increasing the frequency the GMI effect significantly increases (Fig. 2). The shape of the Z(H) shows roughly the decay with the *DC* applied magnetic field. Co-rich ($Co_{77.5}B_{15}Si_{7.5}$) microwires exhibit much higher GMI effect at all frequencies and the shape of the Z(H) dependence is typical for the materials with circular magnetic anisotropy, i.e. with a maximum at a certain *DC* axial magnetic field (Fig. 3). Finally,

$Co_{68.5}Fe_{3.5}Cr_3B_{14}Si_{11}$ microwires with vanishing magnetostriction exhibit the highest GMI effect. The shape of the Z(H) dependence is similar to that of microwires $Co_{77.5}B_{15}Si_{7.5}$, but the field corresponding to the maximum is much lower at all the frequencies (see Fig. 4).

These results are summarized in Figs. 5 and 6 where $\Delta Z/Z_{max}$ (f) and H_m(f) dependences are shown. The main features in ΔZ/Z(H) dependences for the three different compositions of the amorphous glass-coated thin wires can be summarized as following: i) the GMI ratio increases with frequency between 10 and 500 MHz in all compositions of glass-coated microwires; ii) even the Fe-rich cold-drawn amorphous wires exhibit considerable GMI effect at high frequencies.

A remarkable difference in the magnetic field dependence of the GMI effect can be attributed to the different magnetoelastic anisotropy of these three compositions of the microwires. Thus, Fe-rich microwires possess highest magnetostriction constant (of the order of $20\cdot10^{-6}$) [4,11]. Alternatively, Co-rich compositions possess lower and negative magnetostriction constant of the order of $-3\cdot10^{-6}$ [11-13]. Finally Co-Fe-rich possess vanishing magnetostriction constant of the order of $-(1-3)\cdot10^{-7}$ [11-13].

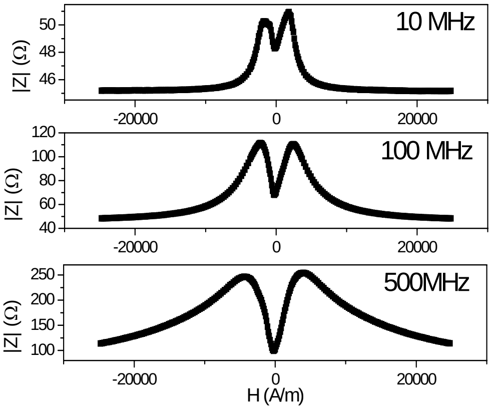

Fig. 3. DC magnetic field dependence of the impedance of $Co_{77.5}B_{15}Si_{7.5}$ glass-coated amorphous microwires.

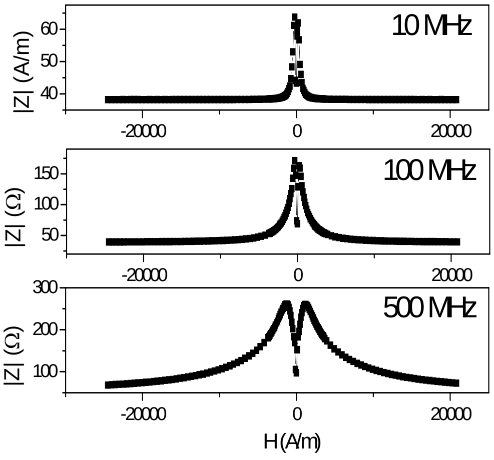

Fig. 4. DC magnetic field dependence of the impedance of $Co_{68.5}Fe_{3.5}Cr_3B_{14}Si_{11}$ glass-coated amorphous microwires.

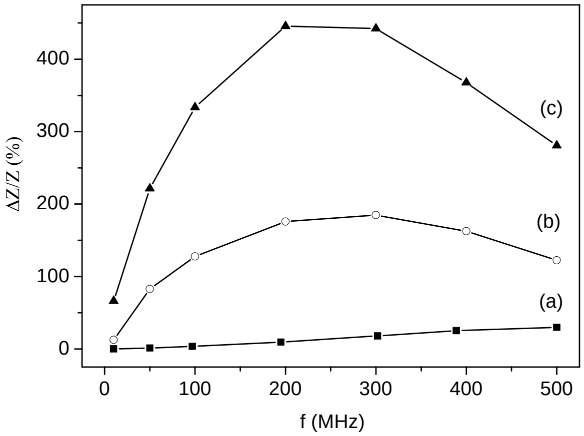

Fig. 5. Frequency dependence of the $\Delta Z/Z_{max}$ for different glass-coated thin amorphous wires: (a) $Fe_{76}Si_{11}B_{13}$; (b) $Co_{77.5}Si_{7.5}B_{15}$ and (c) $Co_{68.5}Fe_{3.5}Cr_3Si_{11}B_{14}$.

Besides, glass-coated wires are composite materials. Consequently the glass-coating technology gives rise to the additional internal stresses originated from the difference in the thermal expansion coefficients of the glass coating and metallic nucleus. This difference in the fabrication technique results in the different magnetic anisotropy in the surface and in different frequency dependence of the GMI effect.

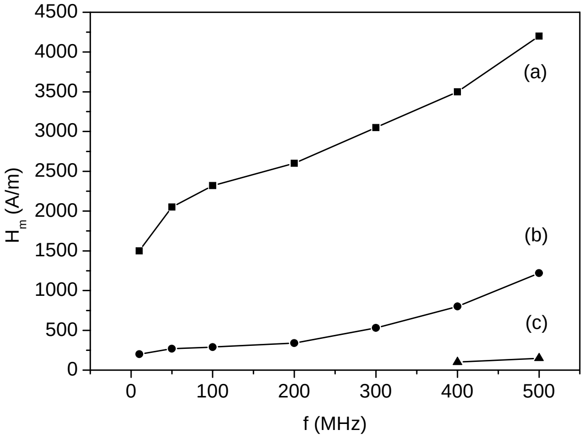

Fig. 6. Frequency dependence of the H_m for different glass-coated thin amorphous wires: (a) $Fe_{76}Si_{11}B_{13}$; (b) $Co_{77.5}Si_{7.5}B_{15}$ and (c) $Co_{68.5}Fe_{3.5}Cr_3Si_{11}B_{14}$.

4. Conclusions

The following conclusions can be drawn: the GMI effect of three different compositions of thin glass-coated amorphous microwires has been studied at frequencies between 10 and 500 MHz. A remarkable difference in the magnetic field dependence of the GMI effect can be attributed to the different magnetoelastic anisotropy of these three compositions of the microwires. Considerable GMI effect (up to 30%) is observed in Fe-rich microwirees at elevated frequencies.

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