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# High-frequency GMI effect in glass-coated amorphous wires

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ABSTRACT

The giant magneto-impedance (GMI) attracted growing attention especially owing to the large sensitivity of the electrical impedance to the *DC* magnetic field, when the relatively high-frequency electrical current flows along the magnetic conductor. Such GMI effect is the highest in soft magnetic wires with vanishing magnetostriction constant. The last strong tendency in miniaturization of the magnetic sensing elements has resulted in the development of the thinner glass-coated wires produced by the Taylor–Ulitovsky method (1–30 μm in diameter). Recent significant progress in tailoring of magnetically soft Co-rich glass-coated microwires allows to enhance significantly the GMI ratio (up to about 600%) in compositions with vanishing magnetostriction constant, $\lambda_s$, at frequencies between 100 kHz and 20 MHz. In this paper we report novel results on the GMI effect at high-frequency region (between 10 MHz and 500 MHz) in different families of amorphous microwires (Fe-rich, with positive magnetostriction constant, Co-rich with negative magnetostriction constant and Co–Fe-rich with nearly-zero magnetostriction constant) fabricated by the Taylor–Ulitovsky method. The differences in observed dependencies for these families of compositions have been interpreted in terms of difference in the magnetoelastic anisotropy.

## 1. Introduction

The giant magneto-impedance (GMI) attracted growing attention since 90-th especially owing to the large sensitivity (up to 600%) of the electrical impedance to the *DC* magnetic field, when the relatively high-frequency electrical current flows along the magnetic conductor [1,2]. Such GMI effect is the highest in soft magnetic wires with vanishing magnetostriction constant [1–3] at frequencies of between 100 kHz and 20 MHz. At these frequencies the GMI effect in magnetic materials with considerable 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].

The last strong tendency in miniaturization of the magnetic sensing elements has resulted in the development of the thinner wires produced by the Taylor–Ulitovsky method (1–30 μm in diameter). These thin wires are the composite materials consisting on metallic nucleus coated by an insulating glass coating. Recent significant progress in tailoring of magnetically soft Co-rich glass-coated microwires fabricated by this method enabled to enhance significantly the GMI ratio (up to about 600%) [4] in metallic nucleus compositions with vanishing magnetostriction constant, $\lambda_s$. Fe-rich amorphous microwires with $\lambda_s > 0$ possessing rectangular hysteresis loop exhibit rather poor initial magnetic permeability and low GMI effect without special processing due to the strong longitudinal magnetic anisotropy [4,5].

The *AC* current frequency should be high enough (usually above 100 kHz) in order to observe significant change of the electrical impedance. On the other hand special care is needed in order to study GMI effect at frequencies above 10 MHz. Particularly, the sample holder should have special design and the electrical cables should be as shorter as possible and should possess special HF specifications.

GMI effect already found industrial applications in GMI and SI (stress impedance) sensors with the CMOC IC circuitry with advantageous features comparing with conventional magnetic sensors developed by different companies [6]. Main applications are related with the detection of the magnetic fields, small weights and vibrations mostly in the car industry and in medicine.

As has been mentioned, initially the GMI effect was interpreted in terms of the classical skin effect in a magnetic conductor assuming scalar character for the magnetic permeability, as a consequence of the change in the penetration depth of the *AC* current caused by the *DC* applied magnetic field. The electrical impedance, *Z*, of a

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magnetic conductor in this case is given by [1,2]:

$$Z = \frac{R_{DC} kr J_o(kr)}{2J_1(kr)} \tag{1}$$

with $k = (1+j)/\delta$, where $J_o$ and $J_1$ are the Bessel functions, $r$ the wire's radius and $\delta$ the penetration depth given by:

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

where $\sigma$ is the electrical conductivity, $f$ the frequency of the current along the sample, and $\mu_\phi$ the circular magnetic permeability assumed to be scalar. The *DC* applied magnetic field introduces significant changes in the circular permeability, $\mu_\phi$. Therefore, the penetration depth also changes through and finally results in a change of $Z$ [1,3].

Recently this "scalar" model was significantly modified taking into account the tensor origin of the magnetic permeability and magneto-impedance [7,8]. For instance, it was theoretically shown in [7], that the axial dependence of the GMI spectra is mainly determined by the type of magnetic anisotropy. It was shown particularly, that the circumferential anisotropy leads to the observation of the maximum of the real component of wire impedance (and consequently of the GMI ratio) as a function of the external magnetic field. In contrast, in the case of axial magnetic anisotropy the maximum value of the GMI ratio corresponds at zero magnetic field [7], i.e. results in a monotonic decay of the GMI ratio with the axial magnetic field. Consequently, non-diagonal components of the magnetic permeability tensor and impedance tensor were introduced in [7,8] in order to describe such circumferential anisotropy. In order to achieve highest GMI effect the magnetic anisotropy should be as smaller as possible.

In this paper we report novel results on the GMI effect at high-frequency region (between 10 MHz and 500 MHz) in different families of amorphous microwires (Fe-rich, with positive magnetostriction constant, Co-rich with negative magnetostriction constant and Co–Fe-rich with nearly-zero magnetostriction constant) fabricated by the Taylor–Ulitovsky method [4].

## 2. Experimental details

Different compositions of amorphous glass-coated microwires fabricated by the Taylor–Ulitovsky method have been studied. Generally, Fe-rich compositions with positive magnetostriction constant, $\lambda_s$, Co-rich compositions with $\lambda_s < 0$ and Co–Fe-rich compositions with vanishing $\lambda_s$ have been studied. The impedance was evaluated using impedance analyzer HP4192A at frequencies 10–500 MHz. The magneto-impedance ratio, $\Delta Z/Z$, has been defined as:

$$\frac{\Delta Z}{Z} = \frac{Z(H) - Z(H_{\max})}{Z(H_{\max})} \tag{3}$$

where the maximum *DC* axial applied field, $H_{\max}$, supplied by a solenoid is up to 30 kA/m.

In the case of high-frequency measurements (10 MHz–3 GHz) the cylindrical sample holder is made from a highly conductive (Al) shielding surrounding the central conductor which terminates in a short circuit. 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 Network Analyzer supplies an electromagnetic wave propagating in a TEM mode, which is the same as that for a wire carrying a radio frequency current. The reflection coefficient is measured, allowing the determination of the input impedance, $Z_{in}$. The impedance, $Z$, ha been determined as described elsewhere [9].

## 3. Results and discussion

The GMI effect is related intrinsically with the hysteresis loops of the samples. Typical hysteresis loops of three compositions of studied microwires (Fe-rich with positive magnetostriction constant, Co-rich with negative magnetostriction constant and Co–Fe-rich with vanishing magnetostriction) are presented in Fig. 1.

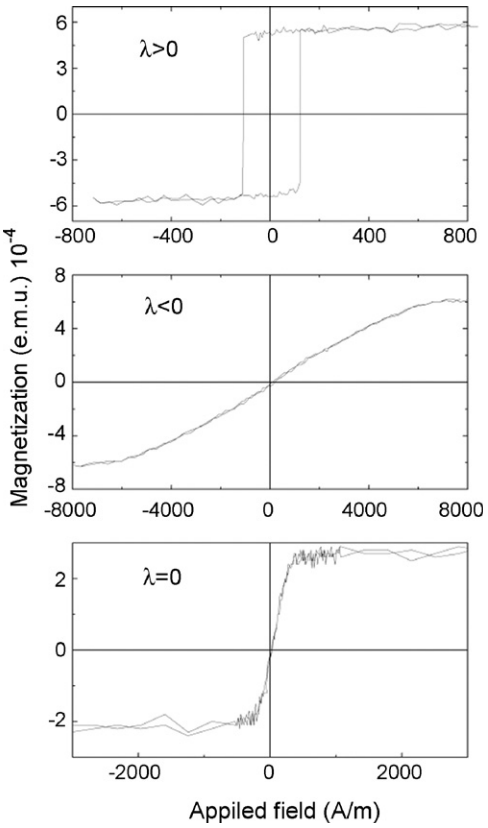

**Fig. 1.** Hysteresis loops of thin glass-coated microwires with different magnetostriction constant. Magnetization as a function of applied field.

As can be observed, the chemical composition of glass-coated microwires drastically affects their magnetization curves: the hysteresis loop changes from rectangular for Fe-rich compositions to almost unhysteretic in Co-rich compositions.

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 Fig. 2). At 10 MHz the GMI of Fe-rich microwires is small enough, but increasing the frequency the GMI effect significantly increases. The shape of the $Z(H)$ shows roughly the decay with *DC* applied magnetic field. Small maximum can be appreciated at about 500 MHz. Co-rich 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 the a maximum at certain *DC* axial magnetic field, $H_m$, as previously observed in [1,2]. Finally, Co–Fe-rich microwires present generally similar behavior with Co-rich microwires, but the $H_m$ is significantly lower.

The main features in $\Delta Z/Z(H)$ dependences for three different compositions of amorphous glass-coated thin wires is that the GMI ratio increases with frequency between 10 MHz and 500 MHz in all compositions of glass-coated microwires.

These results are summarized in Figs. 3 and 4 where $\Delta Z/Z_{\max}(f)$ and $H_m(f)$ dependences are shown.

A remarkable difference in 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 $20 \times 10^{-6}$) [10]. As can be appreciated from Fig. 1, such microwires posses the axial magnetic anisotropy and therefore the shape of the $\Delta Z/Z(H)$ dependences is different from Co-rich microwires possessing negative magnetostriction constant and, consequently transverse magnetic anisotropy (Fig. 2c).

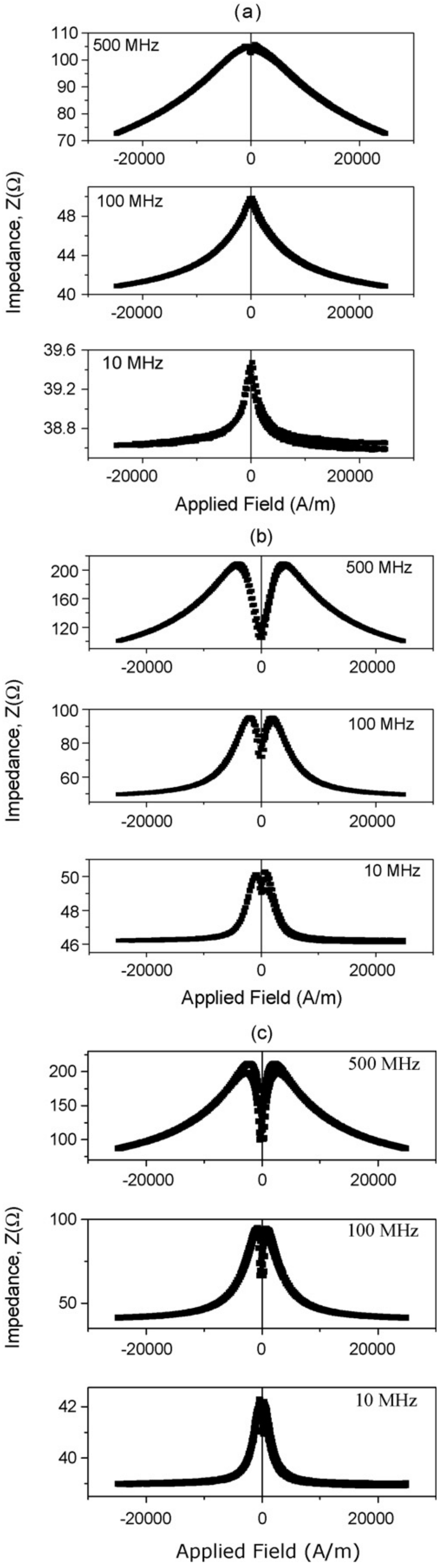

**Fig. 2.** DC magnetic field dependence of the impedance of $Fe_{75.5}B_{13}Si_{11}Mo_{0.5}$ (a), $Fe_{3.7}Co_{69.8}Ni_1Si_{11}B_{13}Mo_{1.5}$ (b) and $Co_{77.5}Si_{7.5}B_{15}$ (c) glass-coated amorphous microwires with metallic nucleus diameter of about 15–20 μm.

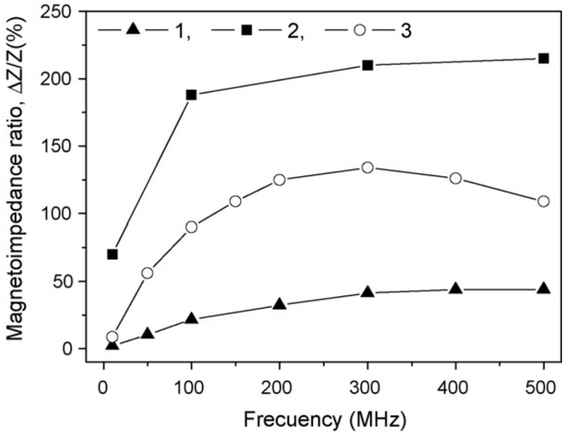

**Fig. 3.** Frequency dependence of the $\Delta Z/Z_{\max}$ on frequency for different glass-coated thin amorphous wires: (1) $Fe_{75.5}B_{13}Si_{11}Mo_{0.5}$; (2) $Fe_{3.7}Co_{69.8}Ni_1Si_{11}B_{13}Mo_{1.5}$ and (3) $Co_{77.5}Si_{7.5}B_{15}$ compositions.

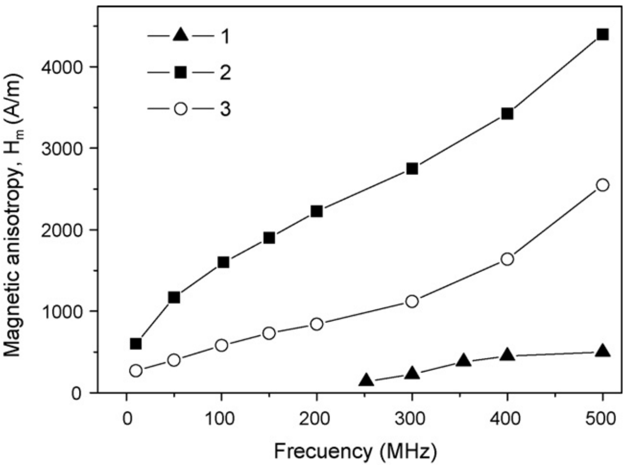

**Fig. 4.** Frequency dependence of the $H_m$ in different compositions of thin glass-coated amorphous wires: (1) $Fe_{75.5}B_{13}Si_{11}Mo_{0.5}$; (2) $Co_{77.5}Si_{7.5}B_{15}$ and (3) $Fe_{3.7}Co_{69.8}Ni_1Si_{11}B_{13}Mo_{1.5}$ compositions.

Alternatively, Co-rich compositions possess lower and negative magnetostriction constant of the order of $-3 \times 10^{-6}$ [10]. Therefore the magnetic anisotropy field, $H_k$, associated with the field, $H_m$, at which the maximum on the $Z(H)$ dependence takes place [11,1,12], is higher than in the case of Co–Fe-rich microwires with vanishing magnetostriction constant. Finally Co–Fe-rich possess vanishing magnetostriction constant of the order of $-10^{-7}$ [10,12].

Besides, glass-coated wires are the composite materials. Consequently the glass-coating technology gives rise to the internal stresses due to 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.

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 MHz and 500 MHz. A remarkable difference in magnetic field dependence of the GMI effect can be attributed to the different magnetoelastic anisotropy of these three compositions of the microwires.

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