High Frequency Giant Magnetoimpedance Effect of amorphous microwires for magnetic sensors applications

A. Zhukov
Dpto. Fisica de Materiales
Basque Country University, UPV/EHU, and
IKERBASQUE, San Sebastian and Bilbao, Spain
arkadi.joukov@ehu.es

A. Talaat, M. Ipatov, V. Zhukova
Dpto. Fisica de Materiales
Basque Country University, UPV/EHU, Spain
valentina.zhukova@ehu.es

Abstract—**We studied the Giant magnetoimpedance (GMI) effect and magnetic properties of amorphous Fe-Co rich magnetic microwires prepared by the Taylor-Ulitovski technique. We observed that these properties can be tailored either controlling magnetoelastic anisotropy of as-prepared Co-rich microwires or controlling their magnetic anisotropy by heat treatment. High GMI effect even at GHz frequencies has been observed in Co-rich microwires.**

Keywords: magnetic microwires; GMI effect; magnetic softness; magnetoelastic anisotropy

I. Introduction

Studies of glass coated ferromagnetic microwires (typically of 1-30 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].

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 [1]. Such strong dependence of the hysteresis loops on these parameters has been attributed to the magnetoelastic energy given by:

$$K_{me} \approx 3/2\ \lambda_s \sigma_i, \qquad (1)$$

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 ≈70/5 [1-3].

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 [1-5]. Strength of these internal stresses depends on ρ-ratio defined as the ρ=d/D, where d is the metallic nucleus diameter and D-total microwire diameter. 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 [4-7], 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 [1]:

$$\lambda_s = (\mu_o M_\sigma/3)(dH_K/d\sigma), \qquad (2)$$

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 [4-7] 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 [1,8].

Consequently, tailoring of the magnetoelastic energy, K_{me}, is essentially important for optimization of magnetic properties of glass-coated microwires [1,2]

The aforementioned GMI effect usually observed in soft magnetic materials phenomenologically consists of the change of the AC impedance, $Z = Z_1 + iZ_2$ (where Z_1 is the real part, or resistance, and Z_2 is the imaginary part, or reactance), when submitted to an external magnetic field, H_0. The GMI effect was well interpreted in terms of the classical skin effect in a magnetic conductor assuming the dependence of the penetration depth of the *ac* current flowing through the magnetically soft conductor on the *dc* applied magnetic field [9-11]. The extremely high sensitivity of the GMI effect to even low magnetic field attracted great interest in the field of applied magnetism basically for applications for low magnetic field detection.

Generally, the GMI effect was interpreted assuming scalar character for the magnetic permeability. The origin of the GMI effect has been explained considering the change in the penetration depth of the *ac* current caused by the *dc* applied magnetic field. The electrical impedance, *Z*, of a magnetic conductor in this case is given by [10,11]:

$$Z = R_{dc}\, krJ_0(kr)/2J_1(kr) \qquad (3)$$

with $k = (1 + j)/\delta$, where J_0 and J_1 are the Bessel functions, r – wire's radius and δ the penetration depth given by:

$$\delta = 1/\sqrt{\pi\sigma\mu_{\phi} f} \qquad (4)$$

where σ 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 [9-11].

Usually for quantification of the GMI effect the magneto impedance ratio, $\Delta Z/Z$, is used. GMI ratio, $\Delta Z/Z$, is defined as:

$$\Delta Z/Z = [Z(H) - Z(H_{max})] / Z(H_{max}), \qquad (5)$$

where H_{max} is the axial *DC*-field with maximum value up to few kA/m.

The main features of the GMI effect are the following:

1. Large change in the total impedance usually above 100%. Usually for the case of amorphous wires with high circumferential permeability the highest GMI effect is reported [1,2,9-11]. Thus, we tailoring magnetic anisotropy through the geometry of amorphous microwires few researchers reported on achievement of about 600% GMI ratio observation in Co-rich microwires with vanishing magnetostriction constant [1,2,12]. In this case, it is quite promising for the application of magnetic sensors.
2. The GMI materials usually present extremely soft magnetic properties. Indeed previously reported that the good magnetic softness is directly related to the GMI effect: the magnetic field dependence of the GMI ratio is mainly determined by the type of magnetic anisotropy[13,14].
3. The AC and DC currents play an important part in the GMI effect. The main reason is that llike magnetic permeability, GMI effect presents tensor character [15-17]. The AC and DC current flowing through the sample creates circumferential magnetic field. Additionally current produces the Joule heating [18].

It must be underlined, that the GMI effect origin has been explained based on the theory of classical electrodynamics. The skin effect, which is responsible for GMI at medium and high frequencies, is a phenomenon well described by the classical electrodynamics [10,11].

Cylindrical shape and high circumferential permeability observed in amorphous wires are quite favorable for achievement of high GMI effect [1,2]. As a rule, better soft magnetic properties are observed for nearly-zero magnetostrictive compositions. It is worth mentioning, that the magnetostriction constant, λs, in system $(Co_xFe_{1-x})_{75}Si_{15}B_{10}$ changes with x from -5×10^{-6} at x= 1, to $\lambda s \approx 35\ \times10^{-6}$ at $x \approx 0.2$, achieving nearly-zero values at Co/Fe about 70/5 [1,19-21].

Depending on the frequency *f* of the driving AC current *I*ac flowing through the sample, the giant magnetoimpedance can be roughly four different regimes might be considered. In fact we should consider mostly comparison of the skin depth with the radius or half thickness of the sample:

(*i*) At low frequency range of 1-10 kHz when the skin depth is larger than the radius or half thickness of the sample (rather weak skin effect) the Matteucci effect and magnetoinductive effect have been observed. In particular sharp voltage peaks measured between the sample's ends were attributed to the sample remagnetization considering circular magnetization reversal [1,9]. The changes of impedance are due to a circular magnetization process exclusively. Therefore considering that the origin of GMI effect is associated with the skin effect of magnetic conductor, observed phenomena might not be considered properly as the GMI effect.

(*ii*) At frequencies, ranging from 10-100 kHz to 1-10 MHz, the frequency range where the GMI effect has been first reported and described, the giant magnetoimpedance, originates basically from variations of the magnetic penetration depth due to strong changes of the effective magnetic permeability caused by a DC magnetic field [1,9-11]. It is widely believed that in this case both domain walls and magnetization rotation contribute to changes of the circular permeability and consequently to the skin effect.

(*iii*) For frequencies ranging in the MHz band (from 1-10 MHz to 100-1000MHz depending on the geometry of the sample), the GMI effect is also originated by the skin effect of the soft magnetic conductor, i.e. must be attributed to the GMI. But at these frequencies the domain walls are strongly damped. Therefore the magnetization rotation must be considered as responsible for the magnetic permeability change induced by an external magnetic field [1,2,9].

(*iv*) At high frequencies, of the order of GHz, the magnetization rotation is strongly influenced by the gyromagnetic effect. With increasing the frequency the GMI peaks are shifted to higher fields where sample is magnetically saturated. At this frequency range strong changes of the sample's impedance have been attributed to the ferromagnetic resonance (FMR)[9,22].

Recently major attention is focused on high frequencies(GHz range) GMI applications owing to the development of thin magnetically soft materials and recent tendency in miniaturization of magnetic field sensors [23,24]

Therefore, the purpose of this paper is to study the GMI effect in thin amorphous magnetically soft microwires suitable for miniaturized GMI based magnetic field sensors paying attention to the high frequency GMI effect.

II. EXPERIMENTAL DETAILS

We studied Co-Fe rich microwires with nominal compositions $Co_{67.1}Fe_{3.8}Ni_{1.4}Si_{14.5}B_{11.5}Mo_{1.7}$, $Co_{67.71}Fe_{4.28}Ni_{1.57}Si_{11.24}B_{12.4}Mo_{1.25}C_{1.55}$ and $Co_{66}Cr_{3.5}Fe_{3.5}B_{16}Si_{11}$ different diameters of metallic nucleus, d, total diameters, D, and consequently different ρ - ratios (ρ=d/D) fabricated by the Taylor-Ulitovsky method [1-3] (see schematic picture in Fig.1).

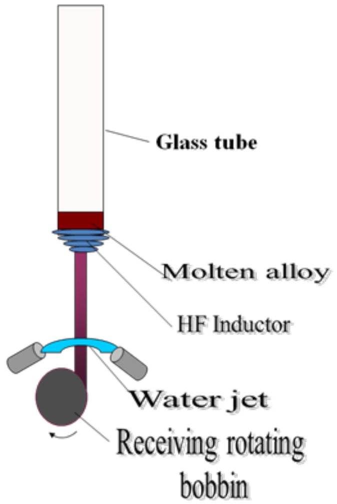


Figure 1. Schematic picture of the fabrication process allowing preparation of glass-coated microwires

Hysteresis loops have been determined by flux-metric method, as described elsewhere [2]. A corresponding schematic picture is shown in Fig.2.

We measured magnetic field dependences of impedance, Z, and GMI ratio, ΔZ/Z, for as-prepared samples and after heat treatments.

Schematic picture showing principles for revealing the impedance matrix elements: diagonal, ς_{zz}, and off-diagonal, $\varsigma_{z\varphi}$, are shown in Fig. 3

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

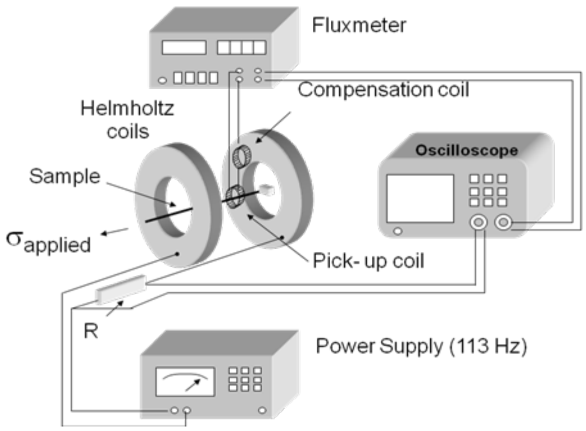


Figure 2. Schematic picture of the experimental set-up for measurements of hysteresis loops

This work was supported by Spanish Ministry of Science and Innovation, MICINN under Project MAT2010-18914, by the Basque Government under Saiotek 13 PROMAGMI (S-PE13UN014) and DURADMAG (S-PE13UN007) projects and by the *MISIS* grant under project K3-2014-028.

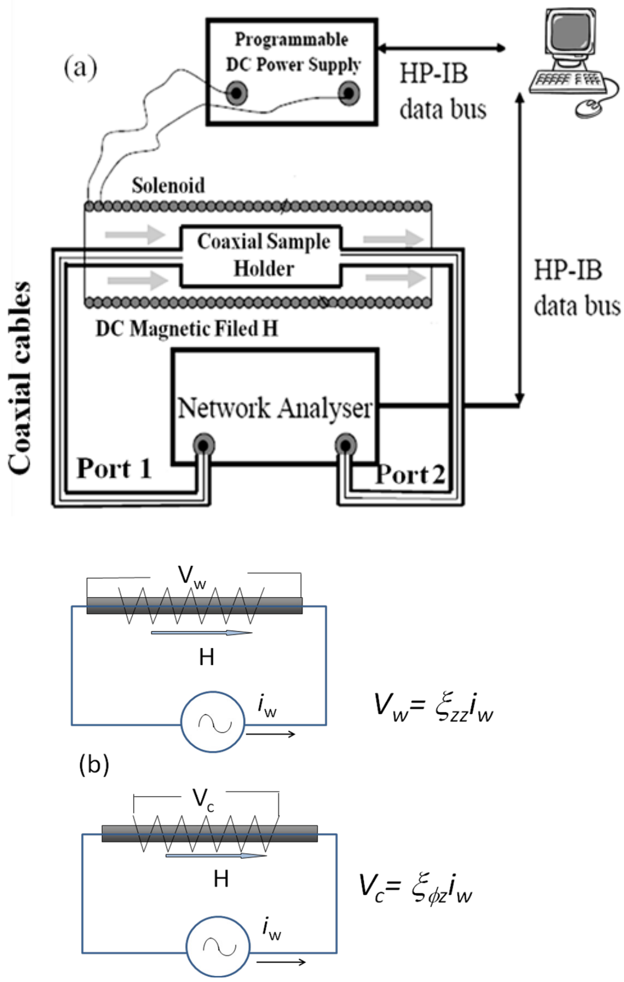


Figure 3. Schematic picture of the experimental set-up for measurements of GMI effect (a) and principles for revealing of the diagonal, ς_{zz}, and off-diagonal, $\varsigma_{z\varphi}$, impedance matrix elements (b)

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 refs. (1, 3, 15, 17).

III. RESULTS AND DISCUSSION

As-prepared $Co_{69.2}Fe_{4.1}B_{11.8}Si_{13.8}C_{1.1}$ microwires present soft magnetic behavior with very low coercivity (about 4 A/m) similar to other Co-rich amorphous microwires with nearly-zero negative magnetostriction constant (Fig.4a,b). As can be observed, all studied of $Co_{67.1}Fe_{3.8}Ni_{1.4}$ $Si_{14.5}$ $B_{11.5}$ $Mo_{1.7}$ microwires present low coercivity values, although magnetic anisotropy field depends on ρ–ratio (see Figs 4 a,b).

Magnetic field, H, dependence of real part, Z_1 of the longitudinal wire impedance Z_{zz} (Z_{zz} = Z_1+iZ_2), measured up

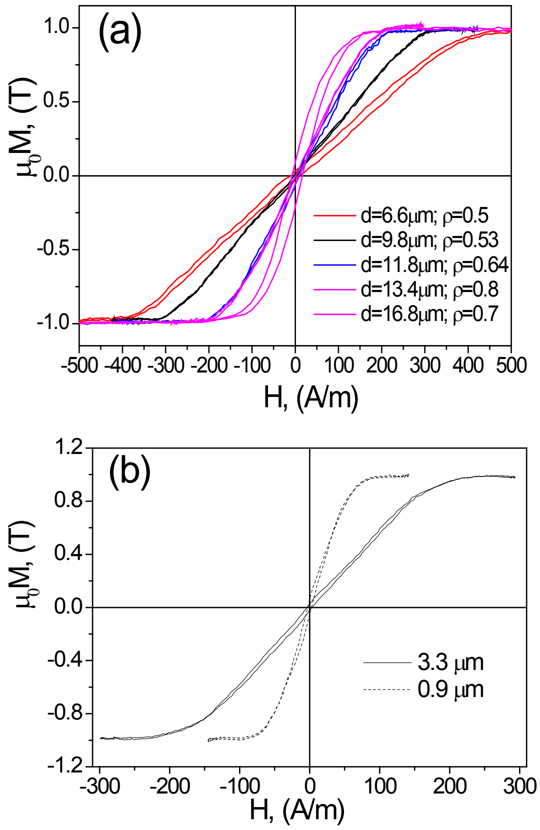


Figure 4. Hysteresis loops of $Co_{67.1}Fe_{3.8}Ni_{1.4}$ $Si_{14.5}$ $B_{11.5}$ $Mo_{1.7}$ microwires with different metallic nucleus diameter and ρ–ratio (a) and the same metallic nucleus diameter and different glass-coating thickness (b).

to 4 GHz in $Co_{66}Cr_{3.5}Fe_{3.5}B_{16}Si_{11}$ $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ and $Co_{67.71}Fe_{4.28}Ni_{1.57}Si_{11.24}B_{12.4}Mo_{1.25}C_{1.55}$ microwires are shown in Fig.5. General features of these dependences is that the magnetic field of maximum shifts to the higher field region increasing the *f*. High enough magnetic field sensitivity, i.e. GMI effect till GHz- range frequencies should be also underlined. On the other hand, if the maximum applied magnetic field is not high enough, impedance change induced by applied magnetic field at high frequencies decreases starting from some frequency. For example, for most studied microwires the optimum frequency for achievement of highest GMI ratio is about 300 MHz (see Fig.6).

From the point of view of applications in magnetic field sensors anti-symmetrical magnetic field dependence exhibited by the off-diagonal GMI component is quite attractive for determination the magnetic field direction in real sensor devices [1-3, 15].

Off-diagonal of GMI, measured in $Co_{67.71}Fe_{4.28}Ni_{1.57}Si_{11.24}B_{12.4}Mo_{1.25}C_{1.55}$ microwire (d=10.8 µm, D=13.8 µm) are shown in Fig.7. As can be appreciated from Fig.7, considerable hysteresis of off-diagonal impedance is observed for studied microwire. Under application of bias current (2mA) the GMI hysteresis decreases the amplitude of S21 parameter increases and magnetic field dependence becomes antisymmetric (Fig.7).

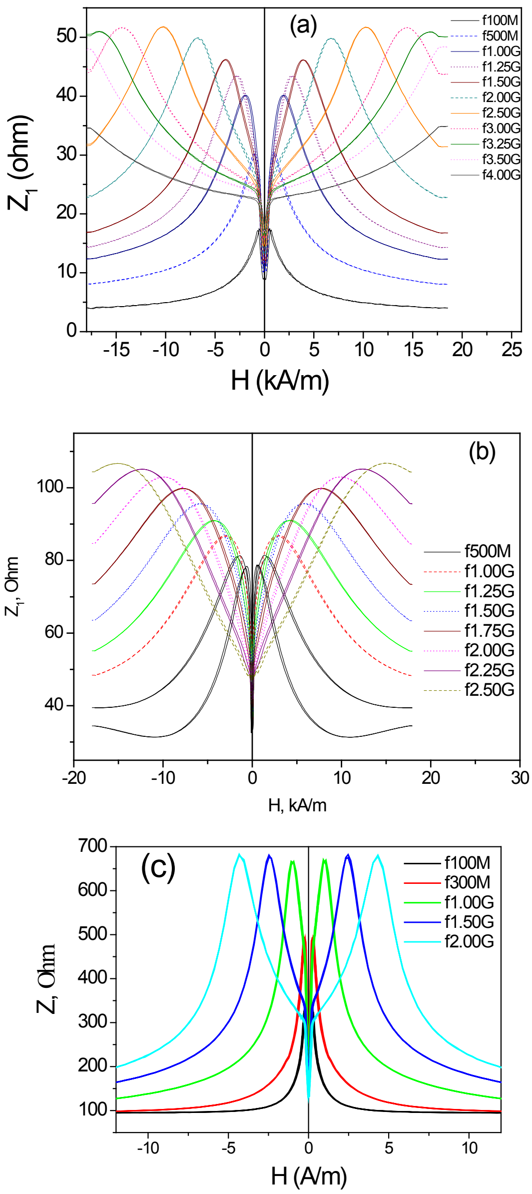


Figure 5. Z(H) dependences of $Co_{66}Cr_{3.5}Fe_{3.5}B_{16}Si_{11}$ (a) $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$(b) and $Co_{67.71}Fe_{4.28}Ni_{1.57}Si_{11.24}B_{12.4}Mo_{1.25}C_{1.55}$ (c) microwires measured at different frequencies

Magnetic field dependence of the off-diagonal voltage response, V_{out} measured using pulsed scheme, also presents anti-symmetrical magnetic field dependence $Co_{67.1}Fe_{3.8}Ni_{1.4}Si_{14.5}B_{11.5}Mo_{1.7}$ ($\lambda_s \approx 3 \cdot 10^{-7}$) microwire (Fig.8). It should noted from Fig.4 that the $V_{out}(H)$ curves exhibit nearly linear growth within the field range from —H_m to H_m. The H_m limits the working range of MI sensor to 240 A/m and should be associated with the anisotropy field.

This excitation scheme described elsewhere [15] is presently used in existing magnetic field sensor devices based on GMI effect [15, 23]. Recently periodic excitation with bias current allowing decreasing of the GMI hysteresis has been also proposed for the GMI magnetometer [26].

Observed above (Fig.4) dependence of hysteresis loops on ρ– ratio must be attributed to the magnetoelastic anisotropy

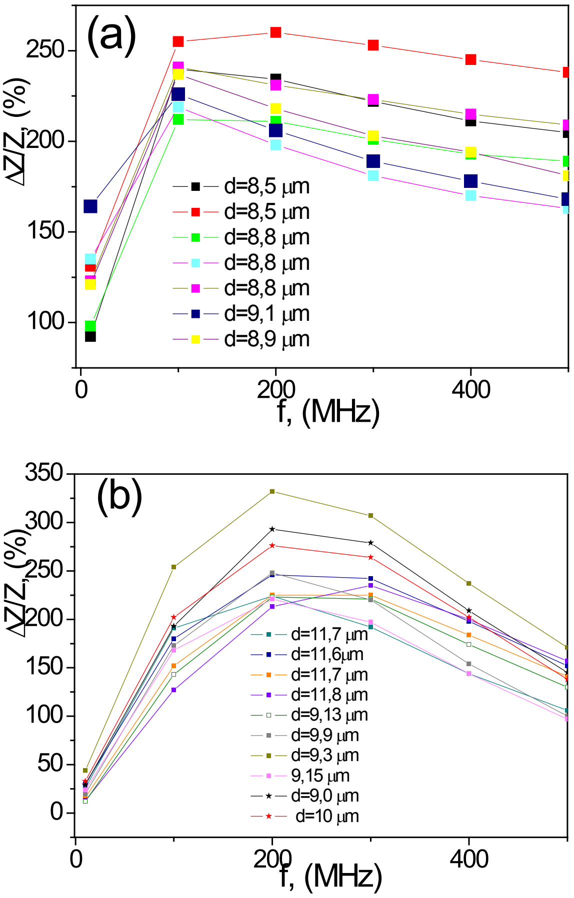


Figure 6. Frequency dependence of $Co_{66.87}Fe_{3.66}C_{0.98}Si_{11.47}B_{13.36}Mo_{1.52}$ microwires with different metallic nucleus diameters

related with the internal stresses. The strength of internal stresses, σ_i, arising during simultaneous rapid quenching of metallic nucleus surrounding by the glass coating can be controlled by the ρ–ratio: strength of internal stresses increases decreasing ρ–ratio (i.e. increases with increasing of the glass volume) [4-7]. Consequently magnetic field dependences of both Z_{zz} and $Z_{\varphi z}$ can be controlled by the

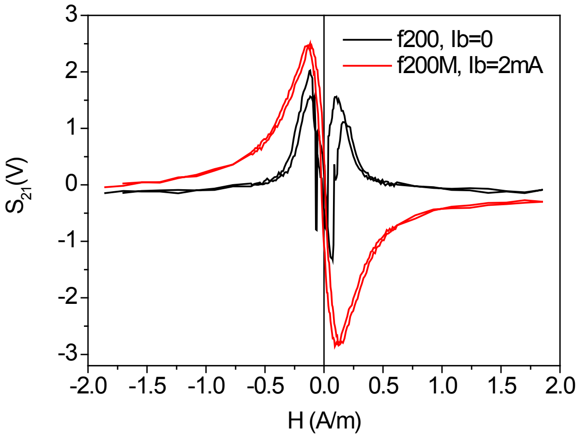


Figure 7. Effect of bias current on magnetic field dependence of S_{21} parameter measured at 200 MHz in $Co_{67.71}Fe_{4.28}Ni_{1.57}Si_{11.24}B_{12.4}Mo_{1.25}C_{1.55}$ microwires

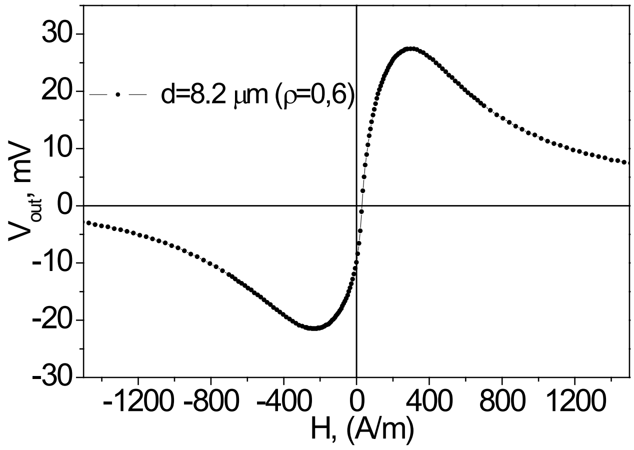


Figure 8. V_{out}(H) response of $Co_{67,1}Fe_{3,8}Ni_{1,4}Si_{14,5}B_{11,5}Mo_{1,7}$ microwires

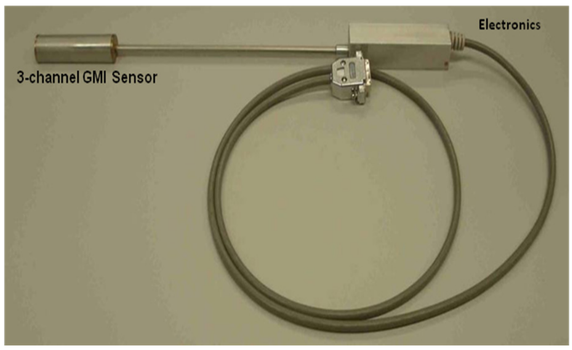
magnetoelastic anisotropy through the ρ–ratio.

The origin of observed low field hysteresis on S_{21} (H) (Fig 7) is directly related with deviation of the anisotropy easy axis from transversal direction [27,28]. Therefore, application of circular bias magnetic field H_B produced by DC current I_B running through the wire affects the hysteresis and asymmetry of the MI dependence, suppressing this hysteresis when I_B is high enough. In fact in pulsed exciting scheme when the sharp pulses with pulse edge time about 5 ns are produced by passing square wave multi-vibrator pulses through the differentiating circuit, overall pulsed current contains a DC component that produces bias circular magnetic field [15,26]. In this way low field hysteresis can be surpassed selecting adequate pulse amplitude.

IV. SHORT DESCRIPTION OF THE GMI MAGNETOMETER

Recently we reported on design and performance of a magnetometer based on the off-diagonal GMI effect in Co-rich glass-coated microwire [26]. A special GMI-holder has been developed to measure the diagonal and off-diagonal GMI components of a microwire (see Fig.9). The GMI-holder was connected to the measuring system with a shielded twisted pair of 0.5 m length and was placed inside a solenoid within a magnetic shield made of permalloy.

The electronic circuit consists of a power source creating the external uniform magnetic field, and the sources of the



Figue 9. Photo of the GMI magnetometer based on the off-diagonal GMI effect of $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ glass-coated microwire.

alternating current of the frequency *f* = 1 - 10 MHz and the dc bias current. High-frequency signals of diagonal and off-diagonal GMI components were amplified and then detected by corresponding lock-in detectors.

The sensing element of the GMI magnetometer is a 10 mm long piece of $Co_{67}Fe_{3.85}Ni_{1.45}B_{11.5}Si_{14.5}Mo_{1.7}$ microwire with a small pick-up coil of 85 turns wounded around the microwire. The electronics with a feedback circuit is used to register an electro-motive force proportional to external magnetic field applied along the wire axis. In the absence of the feedback current the magnetometer is capable to measure a narrow range of magnetic fields, ± 3.5 μT, in the frequency range of 0 - 1 kHz, the level of the equivalent magnetic noise being about 10 $pT/Hz^{1/2}$ at a frequency 300 Hz. The use of the feedback circuit increases the range of the measured magnetic fields up to ± 250 μT.

V. CONCLUSIONS

Studies of magnetic properties and GMI effect of amorphous Co-Fe rich microwires reveals that they present GMI effect at GHz frequencies. Hysteresis loops and magnetic field dependences of GMI effect are affected by microwires magnetic anisotropy. Magnetic properties and GMI effect can be tailored controlling magnetoelastic anisotropy of Co-rich microwires.

REFERENCES

[1] A. Zhukov, M. Ipatov, M. Churyukanova, S. Kaloshkin, V. Zhukova, “Giant magnetoimpedance in thin amorphous wires: From manipulation of magnetic field dependence to industrial applications”, J. Alloys Comp. Vol. 586, pp S279–S286, 2014.

[2] M. Vazquez, H. Chiriac, A. Zhukov, L. Panina, and T. Uchiyama, “On the state-of-the-art in magnetic microwires and expected trends for scientific and technological studies”, Phys. Status Solidi A, Vol. 208, pp. 493–501, 2011.

[3] A. Zhukov and V. Zhukova, “Magnetic Sensors and Applications Based on Thin Magnetically Soft Wires with Tuneable Magnetic Properties”, International Frequency Sensor Association Publishing, Barcelona, 2013, 164p.

[4] A S Antonov, V T Borisov, O V Borisov, A F Prokoshin and N A Usov, “Residual quenching stresses in glass-coated amorphous ferromagnetic microwires”,J. Phys. D: Appl. Phys. Vol. 33, pp1161-1168, 2000.

[5] H. Chiriac, T.-A- Ovari and A. Zhukov, ”Magnetoelastic anisotropy of amorphous microwires ”, J. Magn. Magn. Mater. Vol. 254-255, pp. 469-471, 2003.

[6] H. Chiriac, T. A. Ovari, and Gh. Pop, “Internal stress distribution in glass-covered amorphous magnetic wires”, Phys. Rev. B, vol .42, pp. 10105-10113, 1995.

[7] J. Velázquez, M. Vazquez and A. Zhukov, “Magnetoelastic anisotropy distribution in glass-coated microwires”, J. Mater. Res. Vol.11, No10 pp. 2499-2505, 1996.

[8] A. F. Cobeño, A. Zhukov, J. M. Blanco and J. Gonzalez, “Giant magneto-impedance effect in CoMnSiB amorphous microwires”, J. Magn. Magn. Mater. Vol. 234, pp.L359-L365, 2001.

[9] M.-H. Phan, H.-X. Peng, “Giant magnetoimpedance materials: Fundamentals and applications”, Prog.Mater. Science vol. 53, pp. 323–420, 2008

[10] L.V. Panina and K. Mohri,” “Magneto-impedance effect in amorphous wires”” Appl. Phys. Lett. Vol. 65, pp. 1189-1191, 1994.

[11] 10. R. Beach and A. Berkowitz, “Giant magnwetic field dependent impedance of amorphous FeCoSiB wire”, Appl. Phys. Lett. Vol. 64, pp 3652-3654, 1994.

[12] V. Zhukova , A. Chizhik, A. Zhukov, A. Torcunov, V. Larin, and J. Gonzalez, “Optimization of Giant Magnetoimpedance in Co-Rich Amorphous Microwires” IEEE Trans. Magn., vol. 38, pp. 3090-3092, 2002

[13] N. A. Usov, A. S. Antonov and A. N. Lagar`kov, ”Theory of giant magneto-impedance effect in amorphous wires with different types of magnetic anisotropy”, J Magn. Magn. Mater. Vol. 185, pp. 159-173, 1998.

[14] J. M. Blanco, A. Zhukov and J. Gonzalez, “Effect of tensile and torsion on GMI effect in amorphous wire”, J. Magn. Magn. Mat. Vol. 196-197 pp.377-379, 1999.

[15]S. I. Sandacci, D. P. Makhnovskiy, L. V. Panina, K. Mohri, and Y. Honkura, ”Off-Diagonal Impedance in Amorphous Wires and Its Application to Linear Magnetic Sensors”, IEEE Trans Magn., vol. 35, pp. 3505-3510, 2004.

[16] P. Aragoneses, A. Zhukov, J. Gonzalez, J.M. Blanco and L. Dominguez “Effect of AC driving current on Magneto-Impedance effect**”** Sensors and Actuators A, vol. 81/1-3 pp.86-90, 2000.

[17] V. A. Zhukova, A. B. Chizhik, J. Gonzalez, D. P. Makhnovskiy, L. V. Panina, D. J. Mapps and A. P. Zhukov, "Effect of annealing under torsion stress on the field dependence of the impedance tensor in amorphous wire”, J. Magn. Magn. Mater. Vol. 249/1-2, pp. 318-323, 2002.

[18] V. Zhukova, A.F. Cobeño, A. Zhukov, J.M. Blanco, S. Puerta, J. Gonzalez and M. Vázquez, “Tailoring of magnetic properties of glass coated microwires by current annealing”, Non-crystalline solids vol. 287,pp. 31-36, 2001.

[19] A. Zhukov, V. Zhukova, J. M. Blanco, A. F. Cobeño, M. Vazquez, J. Gonzalez, „Magnetostriction in glass-coated magnetic microwires“, J. Magn. Magn. Mater. Vol. 258-259 pp.151-157, 2003.

[20]Y. Konno, K. Mohri, “Magnetostriction measurements for amorphous wires”, IEEE Trans Magn Vol. 25 No.5 pp. 3623-3625, 1989

[21]A.F. Cobeño, A. Zhukov, A.R. de Arellano - Lopez, F. Elías. J.M. Blanco, V. Larin and J. González, “Physical properties of nearly zero magnetostriction Co-rich glass-coated amorphous microwires” J. Mater. Res. Vol 14, pp. 3775-3783, 1999

[22]. D. Ménard, M. Britel, P. Ciureanu, and A. Yelon, “Giant magnetoimpedance in a cylindrical conductor,” *J. Appl. Phys.*, vol. 84, pp. 2805–2814, 1998.

[23] T. Uchiyama, K. Mohri, and Sh. Nakayama, “Measurement of Spontaneous Oscillatory Magnetic Field of Guinea-Pig Smooth Muscle Preparation Using Pico-Tesla Resolution Amorphous Wire Magneto-Impedance Sensor”**,** IEEE Trans. Magn., Vol. 47, NO. 10,pp3070-3073, 2011.

[24]L. Ding, S. Saez, C. Dolabdjian, L. G. C. Melo, A. Yelon, and D. Ménard, “Equivalent Magnetic Noise Limit of Low-Cost GMI Magnetometer”, IEEE *Sensors* J., vol. 9, No2, pp.159-168, 2009.

[25]M.J. Garcia Prieto, E. Pina, A.P. Zhukov, V. Larin, P. Marin, M. Vázquez and A. Hernando, “Glass coated Co-rich Amorphous Microwires with Improved Permeability”, Sensors & Actuators A vol. 81/1-3, pp. 227-231, 2000.

[26] S. Gudoshnikov, N. Usov, A.Nozdrin, M. Ipatov, A. Zhukov, and V. Zhukova, “Highly sensitive magnetometer based on the off-diagonal GMI effect in Co-rich glass-coated microwire”, Phys. Stat. Sol. (a), Vol. 211, No. 5, pp. 980–985, 2014.

[27] M. Ipatov, V. Zhukova, A. Zhukov, J. Gonzalez, and A. Zvezdin, “Low-field hysteresis in the magnetoimpedance of amorphous microwires”, Phys. Rev.B vol. 81, p. 134421, 2010

[28] M. Ipatov, V. Zhukova, J. Gonzalez and A. Zhukov, "Magnetoimpedance sensitive to DC bias current in amorphous microwires" Appl. Phys. Lett vol. 97, p. 252507, 2010.