Giant Magnetoimpedance effect at GHz frequencies in amorphous microwires

Arcady Zhukov1,2,3,4, Mihail Ipatov1,2, Paula Corte-Leon1,2,3, Juan Maria Blanco2,3 and Valentina Zhukova1,2,3

1Dept. Polym. and Adv. Mater., Univ. Basque Country, UPV/EHU, 20018 San Sebastian, Spain, valentina.zhukova@ehu.es
2Dept. Appl. Phys., University of Basque Country, EIG, UPV/EHU, 20018 San Sebastian, Spain, juanmaria.blanco@ehu.es
3EHU Quantum Center, University of the Basque Country, UPV/EHU, Spain, paula.corte@ehu.es
4IKERBASQUE, Basque Foundation for Science, 48011 Bilbao, Spain, arkadi.joukov@ehu.es

Magnetic properties and GMI effect of amorphous Co-rich microwires reveal that they present GMI effect at GHz frequencies. Frequency dependence of maximum GMI ratio has been evaluated. Magnetic field dependences of GMI ratio and frequency dependence of maximum GMI ratio are affected by the post-processing conditions. In particular, we observed that stress-annealing allows improvement of magnetic softness, GMI ratio and affects the frequency dependence of GMI ratio.

Index Terms—Amorphous magnetic materials, Coercive force, Magnetic hysteresis

I. INTRODUCTION

Studies of Giant Magnetoimpedance (GMI) effect in different kind of magnetic materials have attracted considerable attention from the point of view of various technological applications as well as from the point of view of basic research [1-4]. One of the main tasks in this field is the achievement of the highest GMI effect that will allow improvement of the sensitivity of the magnetic sensors and devices utilizing GMI effect. In particularly small size and high magnetic field resolution are the features of magnetic field sensors made from thin magnetically soft microwires that have been proposed for magnetic compass applications in Cell phones [5]. Additionally, high frequency GMI effect is suitable for development of smart composites with tunable magnetic permittivity [2,6].

Accordingly, development of thin magnetically soft wires is a key for GMI applications. It must be underlined that the diameter reduction must be associated with the increasing of the optimal GMI frequency range: a trade-off between dimension and frequency is required in order to obtain a maximum effect [4]. Consequently development of thin soft magnetic materials required for miniaturization of the sensors and devices requires an extension of the frequency range for the impedance toward the higher frequencies (GHz range). On the other hand for a given chemical composition and geometry the optimal frequency for GMI effect is reported [2].

Accordingly, the purpose of this paper is to study the GMI effect in thin amorphous magnetically soft microwires extending the frequency range up to GHz band.

II. EXPERIMENTAL TECHNIQUE

We studied the GMI effect in extended frequency range up to GHz frequencies in Fe50,Co50,2Ni12,5Si1,5Mo1,5C1,2 (metallic nucleus diameter, d=22.8μm; total diameter, D=23.2μm) microwire with low negative magnetostriiction coefficients, λs, prepared using the Taylor-Ulitovsky technique [2]. The impedance, Z, and its magnetic field, H, dependence have been measured from the reflection coefficient, S11, evaluated by the vector network analyzer as described elsewhere [7]. From Z values obtained for different H-values we evaluated the magnetic field dependences of the GMI ratio, ΔZ/Z, defined as:

\[
\Delta Z/Z = \left[ \frac{Z(H)}{Z(H_0)} - 1 \right] \times 100
\]

being \( Z(H_{max}) \) -Z-values at maximum magnetic field, \( H_{max} \).

The frequency dependence of the maximum GMI ratio, \( \Delta ZZ_f \), defined as a maximum ΔZ/Z obtained at a given frequency, f, is also evaluated.

Hysteresis loops have been measured using the fluxmetric method previously successfully employed for characterization of magnetic microwires [8]. For better comparison we represent the normalized magnetization, \( M/M_0 \), versus magnetic field, \( H \), where \( M \) is the magnetic moment at a given \( H \) and \( M_0 \) is the magnetic moment of the sample at the maximum magnetic field amplitude \( H_{max} \). We measured aforementioned properties in as-prepared and annealed microwires. For conventional and stress annealing we used a conventional furnace and annealing temperature, \( T_{ann} \), 350 °C.

The magnetostriiction coefficient, \( \lambda_s \), has been evaluated by Small Angle Magnetization Rotation (SAMR) method using the set-up developed for the \( \lambda_s \) evaluation in magnetic microwires [9]. Studied microwire present vanishing \( \lambda_s \) (\( \lambda_s \approx 0 \)).

III. EXPERIMENTAL RESULTS AND DISCUSSION

Excellent magnetic softness with coercivity, \( H_c \), of about 5 A/m and magnetic anisotropy field, \( H_a \), of about 150 A/m is observed in as-prepared sample (see Fig. 1a). Almost linear shape of hysteresis loops is characterized by almost zero remanence, \( M/M_0 \). In this sample ΔZZ(H) dependencies resent the double-peak character (for 10 ≤ f ≤1 GHz) typical for wires with circumferential magnetic anisotropy (see Fig. 1b). In spite of rather soft magnetic properties, ΔZZf is slightly above 100% (Figs 1b,c).

Similarly to other Co-rich microwires [2,10], a substantial magnetic hardening and transformation of the linear hysteresis loop into a rectangular is observed upon annealing at 350 °C.
However, stress-annealing at the same $T_{\text{ann}}$ allows to prevent such magnetic hardening and even achieve better magnetic softness with $H_{c} \approx 2 \text{ A/m}$ and $H_{k} \approx 70 \text{ A/m}$ (see Fig. 2a). Consequently, a remarkable improvement of $\Delta Z/Z_{m}$ up to 230% is observed upon stress-annealing (see Fig. 2b).

Frequency dependence of $\Delta Z/Z_{m}$ in as-prepared sample presents a maximum at about 80 MHz (see Fig. 2c). A superior $\Delta Z/Z_{m}$ values, observed in stress-annealed sample in the whole frequency range (up to 1 GHz) are evident for stress-annealed samples compared to as-prepared sample (see Fig. 2c). It is interesting that the optimum frequency for stress-annealed sample shifts to about 150 MHz (Fig. 2c).

**Conclusion**

We studied magnetic properties and GMI effect at elevated frequencies in as-prepared and stress-annealed Co-based microwires. Magnetic field dependences of GMI ratio are affected by the annealing conditions. Stress annealing allows remarkable improvement of the GMI ratio in extended frequency range.

**REFERENCES**

[1] L.V. Panina and K. Mohri, Magneto-impedance effect in amorphous wires, Appl. Phys. Lett., vol. 65, pp. 1189–1191, 1994

[2] A. Zhukov, M. Ipatov, P. Corte-León, L. Gonzalez-Legarreta, M. Churyukanova, J.M. Blanco, J. Gonzalez, S. Taskaev, B. Hernando and V. Zhukova, Giant magnetoimpedance in rapidly quenched materials, J. Alloy Compd., vol. 814, p. 152225, 2020

[3] M.H. Phan, H.X. Peng, Giant magnetoimpedance materials: Fundamentals and applications, Prog. Mater. Sci., vol. 53, pp. 323-420, 2008

[4] K. Mohri, T. Uchiyama, L. V. Panina, M. Yamanoto, and K. Bushida, Recent Advances of Amorphous Wire CMOS IC Magneto-Impedance Sensors: Innovative High-Performance Micromagnetic Sensor Chip,

**Journal of Sensors**, Article ID 718069, 2015

[5] D. Ménard, M. Britel, P. Cureanu and A. Yelon, Giant magnetoimpedance in a cylindrical magnetic conductor, J. Appl. Phys. vol. 84, pp. 2805–2814, 1998.

[6] D. Makhnovskiy, A. Zhukov, V. Zhukova, J. Gonzalez, Tunable and self-sensing microwave composite materials incorporating ferromagnetic microwires, Advances in Science and Technology, vol. 54, pp 201-210, 2008.

[7] A. Zhukov, M. Ipatov, P. Corte-León, J. M. Blanco, L. González-Legarreta and V. Zhukova, Routes for Optimization of Giant Magnetoimpedance Effect in Magnetic Microwires, IEEE Instrumentation & Measurement Magazine, vol. 23(1), pp. 56-63, 2020

[8] L. Gonzalez-Legarreta, P. Corte-Leon, V. Zhukova, M. Ipatov, J. M. Blanco, J. Gonzalez, A. Zhukov, Optimization of magnetic properties and GMI effect of Thin Co-rich Microwires for GMI Microsensors, Sensors, vol. 20, p.1558, 2020

[9] M. Churyukanova, V. Semenkova, S. Kaloshkin, E. Shuvaeva, S. Gadozhnikov, V. Zhukova, L. Shchetinin, and A. Zhukov, Magnetostriiction investigation of soft magnetic microwires, Phys. Status Solidi A, vol. 213(2), pp. 363–367, 2016.

[10] A. Zhukov, M. Ipatov, P. Corte-León, L. Gonzalez-Legarreta, J.M. Blanco and V. Zhukova, Soft Magnetic Microwires for Sensor Applications, J. Magn. Magn. Mater. vol. 498, p. 166180, 2020