Technological Chain for Tuning of Magnetic Properties of Glass Covered Microwire for Sensor Application

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Abstract—**The technological chain of precise tuning of magnetic properties of amorphous microwires has been established for the first time. The main elements of chain are the chemical composition, geometrical proportions, thermal annealing, mechanical stress and crossed magnetic fields. The relevance and importance of the establishment of the tuning chain is determined by the wide application of magnetic microwires is magnetic sensors.**

Keywords-Soft magnetic materials; Amorphous magnetic wires; Magneto-optic Kerr effect.

I. INTRODUCTION

Amorphous magnetic wires present a number of properties suitable for technical applications, such as giant magnetoimpedance (GMI) effect or magnetic bistability associated with fast domain wall propagation [1]–[4]. Amorphous magnetic wires are also important when using new highly accurate switching sensing devices. Consequently, various types of magnetic wires have been widely investigated during last years [1]–[9].

Our study was directed to select the essential properties to establish a repeatable control of the key technological parameters of magnetic microwires. We recognized that, at each steps of the chain, we change and manipulate the limited number of the properties. Therefore, by increasing the number of the elements of the technological chain, we make the magneto-electric system of the microwire more predictable.

The main idea of our work is the presentation of the technological chain providing the tuning of the basic properties of glass covered microwires. Preliminary, we selected microwire samples with different compositions and geometry to establish in the best way the each step of the process chain.

The structure of the paper is the following: Section II is devoted to the experimental details, Section III – to the composition and annealing, Section IV – influence of torsion stress, Section V – influence of crossed magnetic field, Section VI – conclusions.

II. EXPERIMENTAL DETAILS

The study of the magnetization reversal in the surface of microwires has been performed by means of the optical polarizing microscopy working in reflective mode using the longitudinal magneto-optical Kerr effect (MOKE) configuration [10] [11]. The surface hysteresis loops were obtained from the MOKE intensity for different values of the external magnetic field applied in the axial direction (H_{ax}) as a result of the MOKE images processing [10].

A pair of Helmholtz coils provided an axial magnetic field H_{ax}. The circular magnetic field was originated by the electric current flowing along the microwire. The mechanical torsion stress has been applied. While one of the wire ends was mechanically fixed the second end was rotary stressed to apply the stress with different angle.

Samples annealing has been performed in a conventional furnace below the crystallization temperature and Curie temperature. All the thermal treatments were performed in air because metallic nucleus is coated by the insulating and continuous glass coating. The microwire was heated, annealed and slowly cooled with the furnace under the tensile stress.

Bulk hysteresis loops have been measured by flux-metric method. We represent the normalized magnetization, M/M_s as a function of the axial magnetic field, H, where M is the magnetic moment at given magnetic field and M_s is the magnetic moment of the sample at the maximum magnetic field amplitude. We measured the dependence of the impedance, Z, and GMI ratio, $\Delta Z/Z$, on the magnetic field by using specially designed micro-strip sample holder placed inside a sufficiently long solenoid that creates a homogeneous magnetic field. Z_{MAX} is the value of the impedance measured when the axial magnetic field H was maximal.

III. COMPOSITION AND ANNEALING

The selection of nominal composition and the conditions of the thermal annealing are the basic steps of technological chain. At the first step of the technological route, we demonstrate the role of the microwire composition. Taking into account that the Co-based and Fe-based wires (that is, a wire in which the Co or Fe content is maximal relative to other chemical elements) are the main elements of the wire-based sensors we selected the following samples: $Co_{69.16}Fe_{4.1}B_{11.81}Si_{13.84}Cr_{1.09}$ with metallic nucleus diameter d=25,6 μm and total diameter D=30,2 μm (sample I) and $Fe_{65}B_{15}Si_{15}C_5$ with d=30 μm and D=34,4 μm (sample II). The sample II was annealed in the presence of tensile stress.

Figure 1 shows the magnetic hysteresis loops (Fig. 1a)) and GMI dependencies (Fig. 1b)) of the sample I while the Figure 2 presents the experimental dependencies obtained in the sample II.

The magnetic behaviour is different for these microwires. The magnetization reversal in the as-cast sample I reflects the magnetization rotation contribution while as-cast sample II demonstrates the magnetic bistability. The annealing process reverses the picture: the annealed sample I becomes magnetically bistable while the annealed sample II looses the bistability.

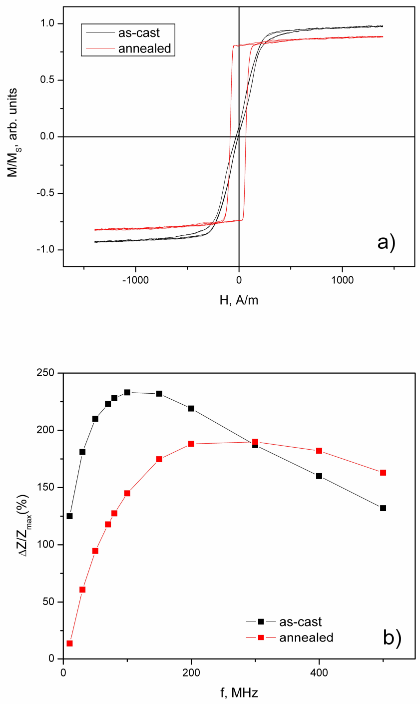

Figure 1. a) bulk hysteresis loops and b) GMI of as-cast and annealed microwire obtained in sample I.

The annealing influences in the opposite manner on the GMI effect in two studied samples (Figs. 1b and 2b). For Co-rich wire, the GMI (Fig. 1b)) of annealed microwire is basically lower than of the as-cast sample [12]. It is associated with to the axial magnetic anisotropy induced by the thermal annealing.

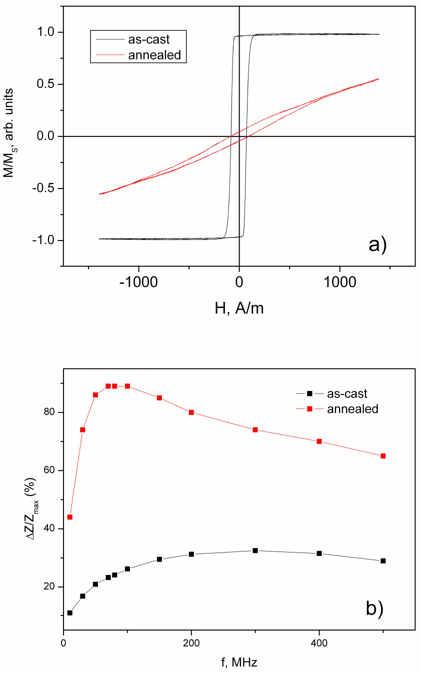

Figure 2. a) bulk hysteresis loops and b) GMI of as-cast and annealed microwire obtained in sample II.

The wire annealed in the presence of the tensile stress demonstrates the rectangular hysteresis loop (Fig. 1a) normally observed in the wires with positive magnetostriction constant. For Fe-rich wire, the increase of GMI ratio (Fig. 2b)) is related to the partial crystallization and change of sign of the magnetostriction constant [13]. The annealing in the presence of stress is related to stress relaxation and considerable effect of internal stresses on magnetostriction [14] [15]. We assume that the stress relaxation induced by annealing can change the magnetostriction sign. On the other, hand under applying stresses we can reduce the magnetostriction constant.

IV. TORSION STRESS

Here, we present the influence of the torsion stress on the magnetization reversal. First, we have demonstrated that the magnetization reversal in the surface of the wire repeats the magnetization reversal in the volume both for as-cast and annealed samples. Figure 3 presents the longitudinal MOKE hysteresis loops for the as-cast and annealed sample I. The shape of these curves coincides with the shape of magnetic hysteresis (Fig. 1a)).

Applying the torsion stress we have demonstrated the possibility of the transformation of the hysteresis of type a) to the hysteresis of type b).

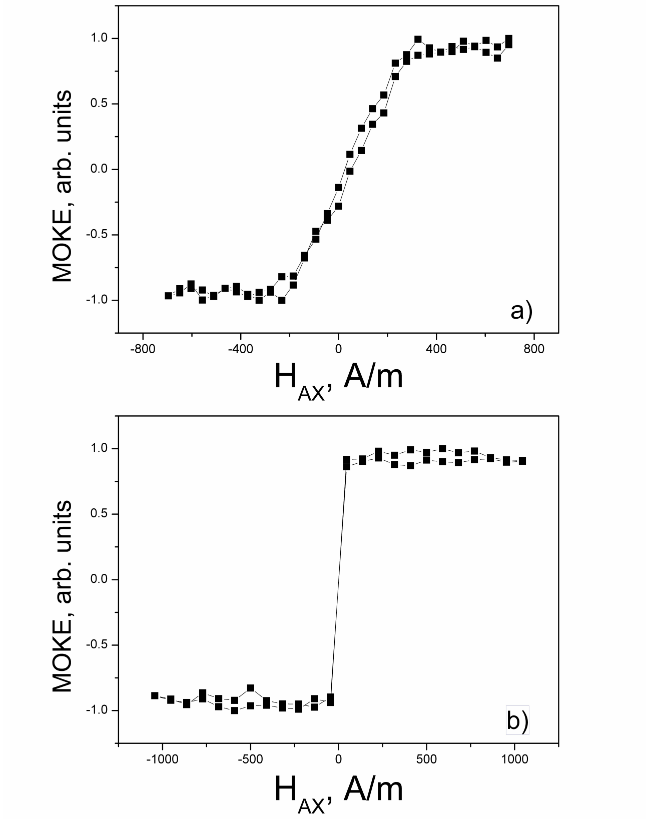

Figure 3. Surface MOKE hysteresis loops obtained in a) as-cast sample I, b) annealed sample I.

Taking into account the importance of thermal stability of the sensors operation, we could remark the following. Generally, the hysteresis loop consists of fluent rotation of the magnetization and sharp jumps. The relation between these two parts of magnetization reversal depends on the temperature. In some wires this effect is observed even when approaching only 50 ^{O}C.

Figure 4 shows the stress induced transformation of the MOKE hysteresis of the as-cast sample I. In the presence of the stress, the jump of the magnetization appears and increases. In such a way, the hysteresis loop takes the shape of the annealed wire (Fig. 3b). The evident jumps of the surface magnetization are observed in the presence of the high torsion stress (the curve with “star” points in the Fig. 4).

V. CROSSED MAGNETIC FIELD

The final step of the tuning is the application of the crossed magnetic field. Figure 5 shows the MOKE dependencies on circular magnetic field with the presence of DC axial magnetic field acted as an external parameter.

Without the axial field the jump between two circularly magnetized states takes place (line with rectangular black points). The DC axial magnetic field moves the hysteresis loop along the circular field axis. The direction and the value of the shift depend definitely on the sign and the value of the axial field. This shift reflects the change of the angle of helicality of surface magnetic structure.

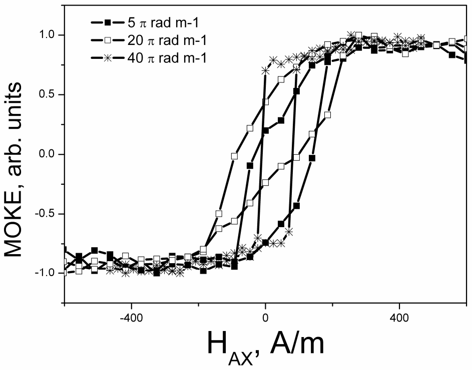

Figure 4. Surface MOKE hysteresis loops obtained in presence of torsion stress of different value in as cast sample I.

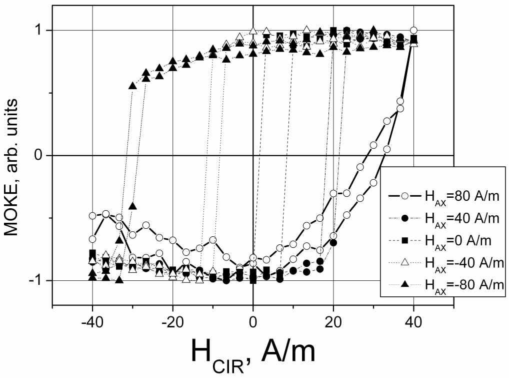

Figure 5. Surface MOKE hysteresis reflecting the magnetization reversal process obtained in a circular field in the presence of DC axial field H_{AX}. Sample I.

The angle between the circular axis of the wire and surface magnetization changes in the presence of axial filed. In such a way, the angle of surface helical structure is smoothly and reversibly adjusted by the DC axial field. This fine tuning of the helical structure is considered as a key method of the control of GMI sensor because the applied experimental configuration of “circular field + DC axial field” is totally coincide with the field configuration of the GMI sensors.

VI. CONCLUSIONS

The technical chain of the adjustment of the magnetic and electric properties of magnetic microwire for sensor application is demonstrated. The un-reversible elements of the chain are the chemical composition, geometric metal-glass proportion and the thermal treatment. The reversible units necessary for the fine tuning are the mechanical stress, in particular torsion stress, and the vector sum of crossed circular and axial magnetic fields.

Creation of such type of chains extends the possibility of the control of the main properties of microwires permitting the realization of the predicted parameters of magnetic sensors. The main parameters which could be predicted are the frequency and magnetic field ranges of the stable operation of sensors. Also the range of the sensitivity to external stresses and the level of stress saturation could be determined.

The disadvantage of the proposed scenario is the impossibility of the creation of the universal chain. Different types of the microwires need different elements of the technical chain.

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REFERENCES

[1] Novel Functional Magnetic Materials, Fundamentals and Applications (editor A. Zhukov), Springer Series in Materials Science, vol. 231, Springer International Publishing, 2016, ISSN 0933–033X.

[2] L. V. Panina and K. Mohri, "Magneto-impedance effect in amorphous wires," Appl. Phys. Lett., vol. 65, pp. 1189-1191, Aug. 1994, doi:10.1063/1.112104.

[3] A. Zhukov, M. Ipatov and V. Zhukova, Advances in Giant Magnetoimpedance of Materials, Handbook of Magnetic Materials, ed. K. H. J. Buschow, 24: chapter 2, pp. 139–236, 2015.

[4] I. Ogasawara and S. Ueno, "Preparation and properties of amorphous wires," IEEE Trans. Magn., vol. 31, pp. 1219-1223, Feb. 1995, doi: 10.1109/20.364811.

[5] P. Rudkowski, G. Rudkowska and J. O. Strom-Olsen, "The fabrication of fine metallic fibers by continuous melt-extraction and their magnetic and mechanical properties," Mater. Sci. Eng., vol. A 133, pp. 158-161, Mar. 1991, dpi: 10.1016/0921-5093(91)90038-O.

[6] V. Zhukova, A. Zhukov, V. Kraposhin, A. Prokoshin and J. Gonzalez, "Magnetic properties and GMI of soft melt-extracted magnetic amorphous fibers," Sensors and Actuators (A), vol. 106, pp. 225-229, Sept. 2003, doi: 10.1016/S0924-4247(03)00172-9.

[7] K. Mohri, T. Uchiyama, L. P. Shen, C. M. Cai and L. V. Panina, "Amorphous wire an CMOS IC-based sensitive micro-magnetic sensors (MI sensor and SI sensor) for intelligent measurements and controls," J. Magn. Magn. Mater., vol. 249, pp. 351-356, Aug. 2001, doi: 10.1016/S0304-8853(02)00558-9.

[8] V. Matko V. and R. Šafarič, "Major improvements of quartz crystal pulling sensitivity and linearity using series reactance," Sensors, vol. 9, pp. 8263-8270, Oct. 2009, doi: 10.3390/s91008263.

[9] V. Matko, "Next generation AT-cut quartz crystal sensing devices," Sensors, 2011, vol. 5, pp. 4474-4482, Apr. 2011, doi: 10.3390/s110504474.

[10] A. Stupakiewicz, A. Chizhik, M. Tekielak, A. Zhukov, J. Gonzalez and A. Maziewski, "Direct imaging of the magnetization reversal in microwires using all-MOKE microscopy," Rev. Sci. Instrum., vol. 85, id. 103702, Oct. 2014, doi: 10.1063/1.4896758.

[11] A. Chizhik and J. Gonzalez, Magnetic Microwires: A Magneto-Optical Study. Pan Stanford Publishing Pte. Ltd., Singapore, 2014, ISBN 978-981-4411-26-4.

[12] A. Zhukov, K. Chichay, A. Talaat, V. Rodionova, J. M. Blanco, M. Ipatov and V. Zhukova, "Manipulation of magnetic properties of glass-coated microwires by annealing," J. Magn. Magn. Mater., vol. 383, pp. 232-236, June 2015, doi: 10.1016/j.jmmm.2014.10.003.

[13] V. Zhukova, J. M. Blanco, M. Ipatov, M. Churyukanova, S. Taskaev and A. Zhukov, "Tailoring of magnetoimpedance effect and magnetic softness of Fe-rich glass-coated microwires by stress- annealing," Sci. Reports, vol. 8, id. 3202, Feb. 2018, doi: 10.1038/s41598-018-21356-3.

[14] A. Zhukov, M. Churyukanova, S. Kaloshkin, V. Semenkova, S. Gudoshnikov, M. Ipatov, A. Talaat, J.M. Blanco and V. Zhukova, "Effect of annealing on magnetic properties and magnetostriction coefficient of Fe Ni-based amorphous microwires", J. Alloys and Compounds, vol. 651, pp. 718-723, Aug. 2015, doi: 10.1016/j.jallcom.2015.08.151.

[15] M. Churyukanova, V. Zhukova, A. Talaat, J.J. del Val, S. Kaloshkin, E. Kostitcyna, E. Shuvaeva, V. Sudarchikova and A. Zhukov, "Studies of thermal and magnetic properties of Fe-based amorphous and nanocrystalline glass coated microwires," J. Alloys and Compounds, vol. 615, pp. S256-S260, Jan. 2014, doi: 10.1016/j.jallcom.2013.12.030.