

# Journal Pre-proof

Controlling the domain wall dynamics in Fe-, Ni- and Co-based magnetic microwires

P. Corte-León, L. Gonzalez-Legarreta, V. Zhukova, M. Ipatov, J.M. Blanco, M. Churyukanova, S. Taskaev, A. Zhukov



PII: S0925-8388(20)31533-4

DOI: <https://doi.org/10.1016/j.jallcom.2020.155170>

Reference: JALCOM 155170

To appear in: *Journal of Alloys and Compounds*

Received Date: 18 February 2020

Revised Date: 9 April 2020

Accepted Date: 11 April 2020

Please cite this article as: P. Corte-León, L. Gonzalez-Legarreta, V. Zhukova, M. Ipatov, J.M. Blanco, M. Churyukanova, S. Taskaev, A. Zhukov, Controlling the domain wall dynamics in Fe-, Ni- and Co-based magnetic microwires, *Journal of Alloys and Compounds* (2020), doi: <https://doi.org/10.1016/j.jallcom.2020.155170>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier B.V.

© 2020. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>



DEPARTAMENTO DE  
FISICA DE MATERIALES  
UNIVERSIDAD DEL PAIS VASCO  
EUSKAL HERRIKO UNIBERTSITATEA

FACULTAD DE QUIMICA  
Pº Manuel de Lardizabal, 3  
Apartado 1072  
20080 SAN SEBASTIAN (SPAIN)  
Tel.: (+ 34 943) 0186 11  
Telefax: (+ 34 43) 017130

San Sebastián, April 9-th, 2020

Dear Editor,

Please find the Credit Author Statement of our submission “Controlling the domain wall dynamics in Fe-, Ni- and Co- based magnetic microwires” (Ref. . JALCOM-D-20-02648) by P. Corte-León, L. Gonzalez-Legarreta, V.Zhukova, M. Ipatov, J. M. Blanco, M.Churyukanova, S. Taskaev and A. Zhukov under consideration for it publication in J. Alloys Compound.

**Author contributions.**

Each author of the paper has essential contribution in the present manuscript.

Paula Corte-León: Data curation, Investigation, Visualization.

Lorena Gonzalez-Legarreta :Data curation, Investigation, Writing - review & editing

Valentina Zhukova: Methodology, Resources, Data curation, Investigation.

Mihail Ipatov: Investigation, Methodology, Software, Data curation

Juan Maria Blanco: Investigation, Methodology, Data curation

Margarita Churyukanova: Investigation, Data curation.

Sergey Taskaev: Investigation.

Arkady Zhukov: Conceptualization, Funding acquisition, Supervision, Writing - review & editing, Writing - original draft.

On behalf of the authors

Sincerely yours,

Dr. A. Zhukov

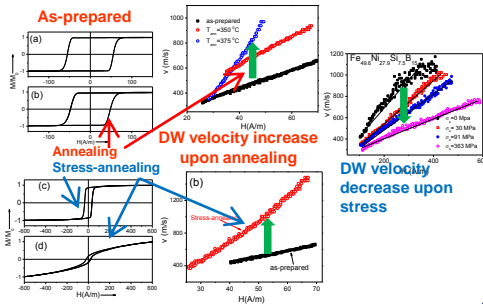
E-mail: [arkadi.joukov@ehu.es](mailto:arkadi.joukov@ehu.es)

Tel: 34-943-018611

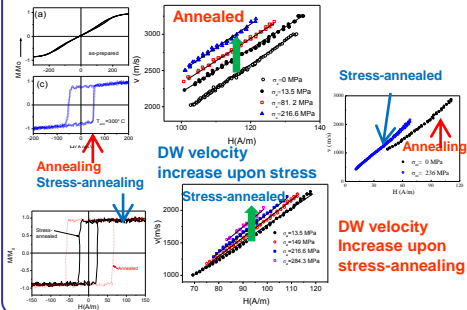
Fax: 34-943-017130

# Magnetically bistable glass-coated microwire

## Spontaneous magnetic bistability ( $\lambda s > 0$ ) microwires



## Induced magnetic bistability ( $\lambda s \approx 0$ ) microwires



## Controlling the domain wall dynamics in Fe-, Ni- and Co- based magnetic microwires

P. Corte-León<sup>1</sup>, L. Gonzalez-Legarreta<sup>1,2</sup>, V. Zhukova<sup>1,3</sup>, M. Ipatov<sup>1,3</sup>, J. M. Blanco<sup>3</sup>,  
M. Churyukanova<sup>4</sup>, S. Taskaev<sup>5</sup> and A. Zhukov<sup>1,3,6,\*</sup>

<sup>1</sup>Dpto. Física de Materiales, Fac. Químicas, UPV/EHU, 20018 San Sebastián, Spain

<sup>2</sup>Dpto. QUIPRE, Inorganic Chemistry-University of Cantabria, Nanomedice-IDIVAL, Avda. de Los Castros 46, 39005 Santander, Spain.

<sup>3</sup>Dpto. de Física Aplicada, EUPDS, UPV/EHU, 20018, San Sebastian, Spain

<sup>4</sup>National University of Science and Technology «MISIS», Moscow, 119049, Russia

<sup>5</sup>NRU South Ural State University (Chelyabinsk, Russia)

<sup>6</sup>IKERBASQUE, Basque Foundation for Science, 48011 Bilbao, Spain

\*Corresponding author, E-mail: arkadi.joukov@ehu.es, Tel: 34943018611, Fax: 34-943017130

### Abstract

We studied influence of post-processing (annealing and stress-annealing) on domain wall dynamics in Fe-, Ni- and Co- based magnetic microwires with spontaneous and induced magnetic bistability. As-prepared Co-based microwires with low and negative magnetostriction present linear hysteresis loops. Magnetic bistability in Co-based microwires has been induced by annealing. Minimizing magnetoelastic anisotropy either by adjusting the chemical composition with a low magnetostriction coefficient or by heat treatment is an appropriate route for the domain wall dynamics optimization in magnetic microwires. Stress-annealing allows further improvement of domain wall velocity and hence is a promising method allowing optimization of the DW dynamics in magnetic microwires. The beneficial influence of stress-annealing on the DW dynamics is explained considering an increase in the volume of outer domain shell with transverse magnetization orientation in expense of decrease in the radius of the inner axially magnetized core. Such transverse magnetic anisotropy can affect the DW dynamics in similar way as the applied transverse magnetic field and hence is beneficial for the DW dynamics optimization. Thus, stress-annealing allows designing the magnetic anisotropy distribution more favorable for the DW dynamics improvement. Co-rich microwires with magnetic bistability induced by annealing present a considerable enhancement in the DW velocity upon applied tensile stress: exactly the opposite to the case of magnetic microwires with spontaneous magnetic bistability. Observed dependence has been explained considering decrease in the magnetostriction coefficient under effect of the applied stress.

**Keywords:** Magnetic microwires, domain wall propagation, magnetic anisotropy, magnetostriction, annealing, internal stresses.

## 1. Introduction

Development of magnetic sensors is essentially influenced by technological progress in the field of magnetic materials [1-3]. Indeed, the features of magnetic sensors are determined by selection of appropriate magnetic material. A significant portion of magnetic sensors use soft magnetic materials [3].

One of the most promising families of soft magnetic materials with a number of advantages, such as excellent magnetic softness, fast and inexpensive manufacturing process, dimensionality suitable for various sensor applications, and good mechanical properties, is a family of amorphous and nanocrystalline materials obtained using rapid quenching from the melt. [4-6].

Such advanced functional magnetic properties have been reported in amorphous materials with either planar (ribbons) or cylindrical (wires) geometry [4-6]. However, each family of amorphous materials presents specific features making them suitable for rather different applications. Thus, planar (ribbon-shaped) materials with low magnetic losses and high saturation magnetization values are good applications in transformers [4]. On the other hand, amorphous wires can present quite peculiar magnetic properties, like spontaneous magnetic bistability associated with single and large Barkhausen jump [7-9] or giant magnetoimpedance, GMI, effect [10-13]. Although it is worth mentioning that in fact, large Barkhausen and GMI effect can be observed either in crystalline wires [14,15] as well as in properly heat treated amorphous ribbons [16,17].

However, high GMI effect and extremely fast single domain wall, DW, propagation can be realized in amorphous magnetic wires in a most simple way (i.e. even without additional post-processing) [18-20].

These features can be attributed to the fact that the cylindrical geometry together with the internal stresses distribution typical for the rapid quenching from the melt provide the unique features, like core-shell domain structure presenting either high circumferential magnetic permeability (in negative magnetostrictive Co-rich compositions) or existence of axially magnetized single inner domain responsible for observation of the single and large Barkhausen jump and related single DW propagation [10-20]. The cylindrical geometry in fact is suitable for realization of the aforementioned unique magnetic properties not only in magnetic wires prepared by any method involving rapid melt quenching, but even in

conventional magnetic wires [14,15] or in nanowires prepared using other techniques (e. g. electrodeposition) [21,22].

It is worth mentioning that recent progress in rapidly quenched technology allows considerable dimensionality reduction of rapidly quenched materials [20,23,24]. Therefore, knowledge obtained in rapidly quenched amorphous materials can be useful for nanotechnology.

As mentioned above, studies of either GMI effect of single DW dynamics in amorphous magnetic wires are essentially important for technical applications. Both, GMI ratio and DW velocity can be further improved by magnetic wires post-processing [25-29].

Recently, we showed that annealing and stress-annealing can considerably improvement the DW dynamics of the Fe-Si-B-C microwires with high and positive magnetostriction coefficient [25,26]. However, magnetic bistability can be observed not only in Fe-based microwires: as-prepared Fe-Ni- based and annealed Co-rich microwires can also present magnetic bistability [27, 30, 31]. Substitution of Fe by Ni and Co allows considerable modification of the magnetostriction coefficient [31,32]. In addition, stress-annealing can also affect magnetic properties of Co-rich microwires [29,30]. Therefore, one can expect that DW dynamics in Fe- Ni- and Co-based microwires can be further improved.

Accordingly, in present paper we provide our experimental results on search of the routes allowing optimization of DW dynamics in Fe- Ni- and Co-based glass-coated microwires.

## 2. Experimental Details

We studied effect of stress-annealing on hysteresis loops and domain walls (DW) dynamics of various glass-coated microwires prepared using Taylor-Ulitovsky technique described elsewhere [13, 18]. The microwires compositions and dimensions are provided in Table 1.

**Table 1.** Compositions and geometry of analysed GMI materials.

Composition	Metallic nucleus diameter, $d$ , ( $\mu\text{m}$ ) for microwires or width (mm) for ribbons	Total diameter, $D$ , ( $\mu\text{m}$ ) for microwires or thickness ( $\mu\text{m}$ ) for ribbons	Ratio $\rho$	Magnetostriction Coefficient, $\lambda_s \times 10^{-6}$
$\text{Co}_{69.2}\text{Fe}_{4.1}\text{B}_{11.8}\text{Si}_{13.8}\text{C}_{1.1}$	25.6	30.2	0.84	-0.4
$\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$	15.2	17.2	0.88	38
$\text{Fe}_{16}\text{Co}_{60}\text{Si}_{13}\text{B}_{11}$	12	29	0.41	20

Fe <sub>62</sub> Ni <sub>15.5</sub> Si <sub>7.5</sub> B <sub>15</sub>	14.35	33.25	0.43	27
Fe <sub>49.6</sub> Ni <sub>27.9</sub> Si <sub>7.5</sub> B <sub>15</sub>	14.2	33.85	0.42	20
Co <sub>56</sub> Fe <sub>8</sub> Ni <sub>10</sub> Si <sub>11</sub> B <sub>16</sub>	22	26.2	0.84	0.1
Fe <sub>8.1</sub> Co <sub>50.7</sub> Ni <sub>17.6</sub> B <sub>13.3</sub> Si <sub>10.3</sub>	11.6	14	0.82	-0.9
Co <sub>65.4</sub> Fe <sub>3.8</sub> Ni <sub>1</sub> B <sub>13.8</sub> Si <sub>13</sub> Mo <sub>1.3</sub> C <sub>1.7</sub>	21.4	23	0.93	-0.1
Co <sub>69.2</sub> Fe <sub>3.6</sub> Ni <sub>1</sub> B <sub>12.5</sub> Si <sub>11</sub> Mo <sub>1.5</sub> C <sub>1.2</sub>	22.8	23.2	0.98	-0.3

Sample annealing has been performed in a conventional furnace at temperature,  $T_{ann}$ , ranging between 200 °C and 400 °C with annealing time,  $t_{ann}$ , up to 60 min.

The stress has been applied during the annealing as well as during the sample cooling with the furnace. This stress value during the annealing within the metallic nucleus and glass shell has been evaluated as described earlier [14, 25,26]:

$$\sigma_m = \frac{K.P}{K S_m + S_{gl}}, \quad \sigma_{gl} = \frac{P}{K S_m + S_{gl}} \quad (1)$$

where  $K = E_2/E_1$ ,  $E_i$  are the Young's moduli of the metal ( $E_2$ ) and the glass ( $E_1$ ) at room temperature,  $P$  is the applied mechanical load, and  $S_m$  and  $S_{gl}$  respectively are the cross sections of the metallic nucleus and glass coating. The value of applied stresses evaluated using eq. (1) was between 118 MPa and 472 MPa.

Structure of as-prepared and annealed samples have been checked by X-ray Diffraction (XRD) employing a BRUKER (D8 Advance) X-ray diffractometer with Cu  $K_\alpha$  ( $\lambda = 1.54 \text{ \AA}$ ) radiation and by DSC measurements using DSC 204 F1 Netzsch calorimeter in Ar atmosphere at a heating rate of 10 K/min. All as-prepared and annealed samples present amorphous structure.

Hysteresis loops have been measured using fluxmetric method previously described elsewhere [30,34]. For better comparison of the samples subjected to different post-processing and of the sample with different chemical composition, we represent the hysteresis loops as dependence of normalized magnetization  $M/M_0$  (where  $M$  is the magnetic moment at a given magnetic field and  $M_0$  is the magnetic moment of the sample at the maximum magnetic field amplitude) versus magnetic field,  $H$ .

The magnetostriction coefficient of studied microwires has been evaluated using the small angle magnetization rotation (SAMR) method described elsewhere [31]. We used the experimental set-up with the improved resolution detailed described in ref. (32).

We measured the magnetic field,  $H$ , dependence of domain wall (DW) velocity,  $v$ , of single DW travelling along the sample by modified Sixtus-Tonks previously described elsewhere [19,33,35]. The principle differences of used method from the classical Sixtus-Tonks [15] set-up are the following:

- i) one sample end is placed outside the magnetization coil in order to ensure a single DW propagation.
- ii) we employed three pick-up coils in order to avoid the multiple DW propagation [33].

When the DW passes through each pick-up coil, it generates the electromotive force (EMF) peaks,  $\varepsilon$ , in it. Consequently, the analysis of the time,  $t$ , dependence of the EMF peaks from 3 pick-up coils allows us to trace the DW travelling along the microwire.

Then, the DW velocity,  $v$ , can be estimated as:

$$v = \frac{l}{\Delta t} \quad (2)$$

where  $l$  is the distance between pick-up coils and  $\Delta t$  is the time difference between the electromotive force (EMF) peaks,  $\varepsilon$ , originated by moving DW in the pick-up coils [33,35].

Use of three pick-up coils allows to study single DW propagation and to discard contribution of nucleation of the new DWs in the other parts of the microwire. As previously shown, DWs can be injected in any part of microwire [33, 36]. However, the local nucleation fields,  $H_n$ , at which new DW can be injected inside the wire is several times higher than the field at which DW depins from the wire ends [33]. Such injection of additional DWs can be detected by modified Sixtus–Tonks method developed by us as the deviation from linear  $v(H)$  dependence [33,36]. The magnetic field, at which the deviation from linear  $v(H)$  is observed, correlates with the minimum nucleation field,  $H_{nmin}$ , within the sample. Accordingly, if applied field  $H \geq H_{nmin}$ , a new domain can be spontaneously nucleated in front of the propagating DW [33,36]. This fact has been previously proved by correlation of  $v(H)$  dependencies measured between different pairs of pick-up coils and the  $H_n$  profiles measured by short movable pick-up coil [33,36].

Below we present comparative studies of  $H_n$  profile,  $v(H)$  dependencies measured between pick-up coils 1-2 and 2-3 and DW propagation evidenced by the EMF peaks sequence in as-prepared  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  sample (see Fig 1 (a)-(c)). To measure the  $H_n$  profile we used the set-up consisting of a short (2.5mm long) magnetizing coil and two pick-up coils wounded around the wire [36]. The sample is previously magnetized by long solenoid. Then local magnetic field of opposite direction is created by short magnetizing coil allows DW injection which detected by the pick-up coils placed close to the short magnetizing coil.



To obtain the  $H_n$  profile, we moved the sample along the pick-up and exiting coils by means of a stepper motor with a step of 1 mm.

Dependence of  $H_n$  on distance along the sample,  $L$ , (see Fig. 1(a)) represents the  $H_n$  profile. The origin of  $H_n$  fluctuations along the sample length has been associated with the sample inhomogeneities [36].

As observed from Fig.1(a),  $H_{nmin}$  -value (about 77 A/m) correlates with the field at which the deviations from linear  $v(H)$  dependencies are observed (see Fig. 1(b)). On the other hand, near the wire ends the  $H_{nmin}$ -values drastically decrease, indicating the presence of the closure end domains which can be depinned by an external field,  $H \leq H_{nmin}$  (see Fig. 1(a)). As discussed elsewhere [33,35], such depinning and hence single DW propagation occurs when the external field becomes higher than the coercivity,  $H_c$ .

Single DW propagation is evidenced by the sequence of the EMF peaks in the set of three pick-up coils (see Fig. 1(c)). The domain wall velocities between pick up coils 1, 2 and 2, 3,  $v_{1-2}$  and  $v_{2-3}$ , evaluated using eq.(2) give almost the same values. Consequently, the extension of linear  $v(H)$  dependencies in the range  $H_c \leq H \leq H_{nmin}$  corresponds to the single DW propagation.

Once  $H \geq H_{nmin}$ , DWs can be injected at sample inhomogeneities observed in Fig.1(a).

Therefore, below we analyze exclusively linear  $v(H)$  dependencies, which correspond to the single DW propagation regimes.

### 3. Results and discussion

We studied two different families of glass-coated microwires, namely microwires (Fe and Fe-Ni based) with positive magnetostriction coefficient,  $\lambda_s$ , presenting spontaneous magnetic bistability and magnetic microwires with vanishing  $\lambda_s$  exhibiting magnetic bistability induced by annealing (Co-based).

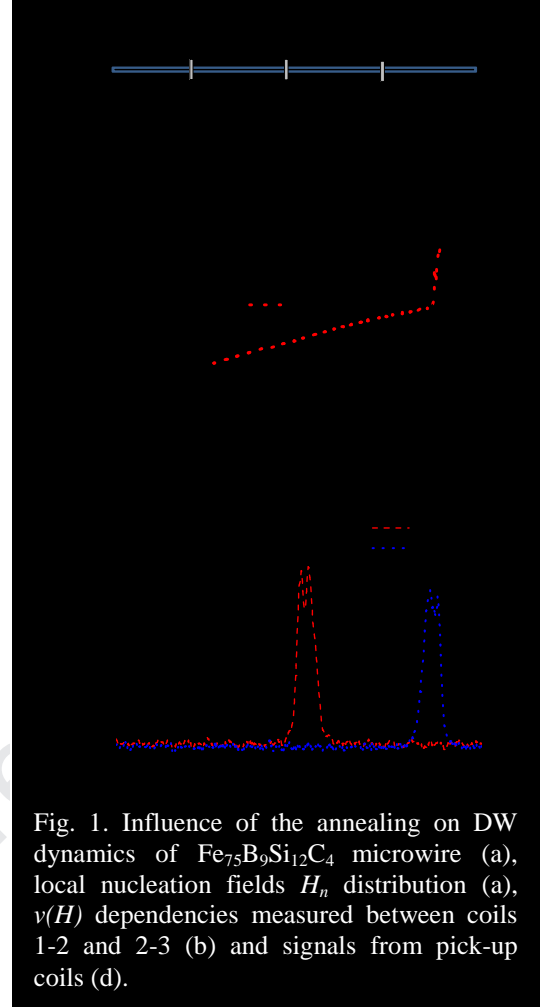


Fig. 1. Influence of the annealing on DW dynamics of  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  microwire (a), local nucleation fields  $H_n$  distribution (a),  $v(H)$  dependencies measured between coils 1-2 and 2-3 (b) and signals from pick-up coils (d).

### 3.1. Tuning of DW dynamics in microwires with spontaneous magnetic bistability.

As mentioned above, amorphous as-prepared Fe-rich microwires generally present spontaneous magnetic bistability characterized by perfectly rectangular hysteresis loop [23, 34].

In the first part of this section, we present experimental results on influence of post-processing on DW dynamics of amorphous  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  microwire ( $d = 15.2 \mu\text{m}$ ;  $D = 17.2 \mu\text{m}$ ) with quite typical composition exhibiting high and positive magnetostriction coefficient ( $\lambda_s \approx 38 \times 10^{-6}$ ) [23, 32].

As shown in Fig.2(a), (b) as-prepared and annealed (without stress)  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  samples present rectangular hysteresis loops, similarly to that reported elsewhere for as-prepared microwires with positive  $\lambda_s$  values [33,34]. Slight magnetic softening ( $H_c$  decrease) can be appreciated upon annealing (see Fig. 2(b) for  $T_{ann} = 300 \text{ }^\circ\text{C}$ ). However, the hysteresis loops of the same but stress-annealed microwire present significant changes: at a sufficiently high stress applied during annealing, transverse magnetic anisotropy can be induced (see Fig.2(c), (d)). Recently a noticeable improvement in magnetic softness and GMI effect has been reported in Fe-rich microwires [25, 29, 37]. Furthermore, if the stress applied during the annealing is not very high, the hysteresis loop can still present rectangular shape (see Fig.2(c)). However, for the sample annealed for a sufficiently high stress, the hysteresis loop becomes almost linear (see Fig. 2(d)).

As reported [37], observed stress-annealing induced magnetic anisotropy depends not only on applied stress, but also on a few more parameters: annealing temperature  $T_{ann}$ , and time,  $t_{ann}$ .

Unlike hysteresis loops, annealing significantly affects the DW dynamics: as can be seen in Fig. 3, a remarkable improvement in DW velocity is achieved upon annealing. The observed magnetic field,  $H$ , dependencies of the velocity DW,  $v$ , can be almost perfectly described by linear dependences.

Fig. 2. Hysteresis loops of as-prepared (a), annealed at  $T_{ann} = 300 \text{ }^\circ\text{C}$  for  $\sigma_m = 0 \text{ MPa}$  (b), stress- annealed at  $T_{ann} = 300 \text{ }^\circ\text{C}$  for  $\sigma_m = 190 \text{ MPa}$  (c) and at  $T_{ann} = 300 \text{ }^\circ\text{C}$  for  $\sigma_m = 380 \text{ MPa}$   $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  sample (d).

Usually, the  $v(H)$  dependencies are described by the following relation [19,23,33,38,39]:

$$v=S(H-H_0) \quad (3)$$

where  $S$  is the DW mobility,  $H_0$  is the critical propagation field.

The influence of the annealing on DW dynamics involves the magnetoelastic anisotropy contribution to the domain wall mobility,  $S$ , given by [23,40, 41]:

$$S = 2\mu_0 M_s / \beta \quad (4)$$

where  $\beta$  is the viscous damping coefficient,  $\mu_0$  is magnetic permeability of vacuum,  $M_s$  - saturation magnetization.

As discussed elsewhere [23,40,41], most of experimental results on influence of annealing on DW dynamics have been explained considering correlation of the magnetic relaxation damping,  $\beta_r$ , and the anisotropy constant,  $K$ , described as [38, 40,41]:

$$\beta_r \approx 2\alpha\pi^{-1}(K/A)^{1/2} \quad (5)$$

where  $A$  is the exchange interaction constant,  $\alpha$  - Gilbert damping parameter.

As discussed elsewhere [18, 23,24, 40, 42], the main origin of magnetic anisotropy in amorphous materials is the magnetoelastic anisotropy,  $K_{me}$ , given by:

$$K_{me} \approx 3/2\lambda_s\sigma \quad (6)$$

where  $\lambda_s$  is the magnetostriction coefficient, and  $\sigma$ —stresses, consisting of the internal stresses,  $\sigma_i$ , and applied stresses,  $\sigma_a$ .

Consequently, the stresses,  $\sigma$ , value (both applied and internal) as well as the magnetostriction coefficient,  $\lambda_s$ , must affect domain wall dynamics and, particularly, mobility,  $S$ .

The easiest way to tune the magnetostriction coefficient,  $\lambda_s$ , value in amorphous alloys is the modification of the chemical composition of the metallic alloy [31,32]. Indeed, Fe-rich compositions present positive  $\lambda_s$  -values (typically  $\lambda_s \approx 20 - 40 \times 10^{-6}$ ), while for the Co-rich alloys,  $\lambda_s$  -values are negative, typically  $\lambda_s \approx -5$  to  $-3 \times 10^{-6}$  [31,32, 43, 44]. Alternatively, the

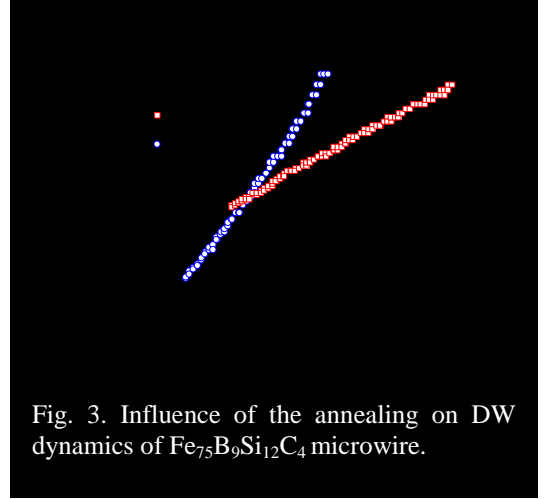


Fig. 3. Influence of the annealing on DW dynamics of  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  microwire.

$\lambda_s$  -values can be modified by doping of Fe-rich alloy by Ni: a decrease of  $\lambda_s$  -values with increasing of Ni-content is reported elsewhere for amorphous alloys [31,43,44].

Nearly-zero  $\lambda_s$  -values can be achieved in the  $\text{Co}_x\text{Fe}_{1-x}$  ( $0 \leq x \leq 1$ ) or  $\text{Co}_x\text{Mn}_{1-x}$  ( $0 \leq x \leq 1$ ) systems at  $x$  about 0,9 – 0,96 [18, 31, 43].

In  $\text{Ni}_x\text{Fe}_{1-x}$  system decrease of  $\lambda_s$  -value with increasing of Ni-content is observed, but it correlates to the simultaneous decreasing of the saturation magnetization. Thus, zero  $\lambda_s$  -values at high Ni-contents correspond to paramagnetic ordering of  $\text{Ni}_x\text{Fe}_{1-x}$  alloys at room temperature [43].

Below experimental results on DW dynamics of Fe-Ni based microwires with similar  $d$ ,  $D$  and  $\rho$ -values, i.e.,  $\text{Fe}_{62}\text{Ni}_{15.5}\text{Si}_{7.5}\text{B}_{15}$  ( $d=14.35 \mu\text{m}$ ;  $D=33.25$ ;  $\rho=0,43$ ) and  $\text{Fe}_{49.6}\text{Ni}_{27.9}\text{Si}_{7.5}\text{B}_{15}$  ( $d=14.2 \mu\text{m}$ ;  $D=33.85$ ;  $\rho=0.42$ ) are compared (see Fig.4). From previous knowledge on origin of internal stresses in glass-coated microwires it is expected that these samples must present quite similar internal stresses values and distribution [18,42, 45].

Similarly to Fe-rich microwires, Fe-Ni- rich ( $\text{Fe}_{62}\text{Ni}_{15.5}\text{Si}_{7.5}\text{B}_{15}$  and  $\text{Fe}_{49.6}\text{Ni}_{27.9}\text{Si}_{7.5}\text{B}_{15}$ ) microwires present rectangular hysteresis loops (see Figs. 4(a),(b)). According to previously published results on compositional dependence of magnetostriction coefficient [31],  $\text{Fe}_{62}\text{Ni}_{15.5}\text{Si}_{7.5}\text{B}_{15}$  and  $\text{Fe}_{49.6}\text{Ni}_{27.9}\text{Si}_{7.5}\text{B}_{15}$  microwires present magnetostriction coefficient values of about  $27 \times 10^{-6}$  and  $20 \times 10^{-6}$ , respectively. Similarly to  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  microwires, both Fe-Ni -rich microwires present linear  $v(H)$  dependencies.

Higher coercivity,  $H_c$ , and lower DW mobility of  $\text{Fe}_{62}\text{Ni}_{15.5}\text{Si}_{7.5}\text{B}_{15}$  microwire can be related to higher  $\lambda_s$  -values of  $\text{Fe}_{62}\text{Ni}_{15.5}\text{Si}_{7.5}\text{B}_{15}$  microwires. On the other hand, considerable decrease of DW mobility and DW velocity under applied tensile stress is observed i.e.  $\text{Fe}_{49.6}\text{Ni}_{27.9}\text{Si}_{7.5}\text{B}_{15}$  in microwire (see

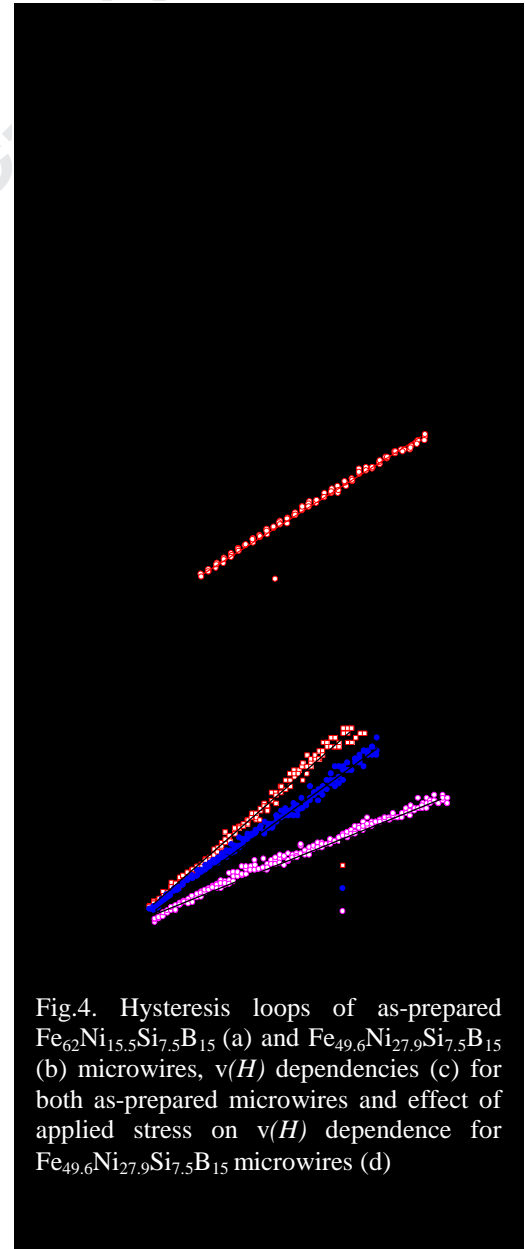


Fig.4. Hysteresis loops of as-prepared  $\text{Fe}_{62}\text{Ni}_{15.5}\text{Si}_{7.5}\text{B}_{15}$  (a) and  $\text{Fe}_{49.6}\text{Ni}_{27.9}\text{Si}_{7.5}\text{B}_{15}$  (b) microwires,  $v(H)$  dependencies (c) for both as-prepared microwires and effect of applied stress on  $v(H)$  dependence for  $\text{Fe}_{49.6}\text{Ni}_{27.9}\text{Si}_{7.5}\text{B}_{15}$  microwires (d)

Fig.4(d)). Similar influence of applied stresses on DW dynamics is previously reported by us in various microwires with positive magnetostriction coefficient [23, 33, 40].

For comparison, influence of applied stresses on  $v(H)$  dependence of  $\text{Fe}_{16}\text{Co}_{60}\text{Si}_{13}\text{B}_{11}$  ( $d \approx 12 \mu\text{m}$ ,  $D \approx 29 \mu\text{m}$ ) with  $\lambda_s \approx 20 \times 10^{-6}$  is depicted in Fig.5. Similarly to Fe- and Fe-Ni based microwires,  $\text{Fe}_{16}\text{Co}_{60}\text{Si}_{13}\text{B}_{11}$  microwire exhibits rectangular hysteresis loop (Fig. 5(a)). A decrease in  $v$  and  $S$ -values is observed in  $\text{Fe}_{16}\text{Co}_{60}\text{Si}_{13}\text{B}_{11}$  microwire upon applied tensile stress (Fig. 5(b)).

From provided experimental results, it is clear that magnetoelastic anisotropy plays a decisive role in DW dynamics optimization in magnetic microwires with positive magnetostriction (i.e., exhibiting spontaneous magnetic bistability). Therefore, one of the highest  $S$ -values is reported for low-magnetostrictive Co-rich microwire [23]. Indeed, high  $v$ - and  $S$ - values are observed in  $\text{Co}_{56}\text{Fe}_8\text{Ni}_{10}\text{Si}_{11}\text{B}_{16}$  microwires with low and positive magnetostriction constant ( $d = 22 \mu\text{m}$ ;  $D = 26.2 \mu\text{m}$ ,  $\lambda_s \approx 10^{-7}$ ) (Fig. 6(a)).

The  $\text{Co}_{56}\text{Fe}_8\text{Ni}_{10}\text{Si}_{11}\text{B}_{16}$  microwire presents more than one order of magnitude higher  $S$ -values than the other samples (Fig. 6(b)). However, in both  $\text{Co}_{56}\text{Fe}_8\text{Ni}_{10}\text{Si}_{11}\text{B}_{16}$  and  $\text{Fe}_{49.6}\text{Ni}_{27.9}\text{Si}_{7.5}\text{B}_{15}$  microwires  $S$  -value rapidly drops upon applied stresses (see Fig. 6(b)).

Accordingly, as can be seen from Figs. 2-5, minimizing magnetoelastic anisotropy either by heat treatment or by selection a chemical composition with a low magnetostriction coefficient is a route for DW dynamics optimization in magnetic microwires.

However, an alternative possibility is related to the design of the magnetic anisotropy distribution, which is more favorable for the DW dynamics improvement [25, 26].

In fact, both cylindrical geometry and the specific domain structure of magnetic microwires with positive magnetostriction coefficient consisting of a single axially magnetized inner domain surrounded by the outer domain shell with transverse magnetic anisotropy are the unique condition for realization of ultra-fast magnetization switching. In

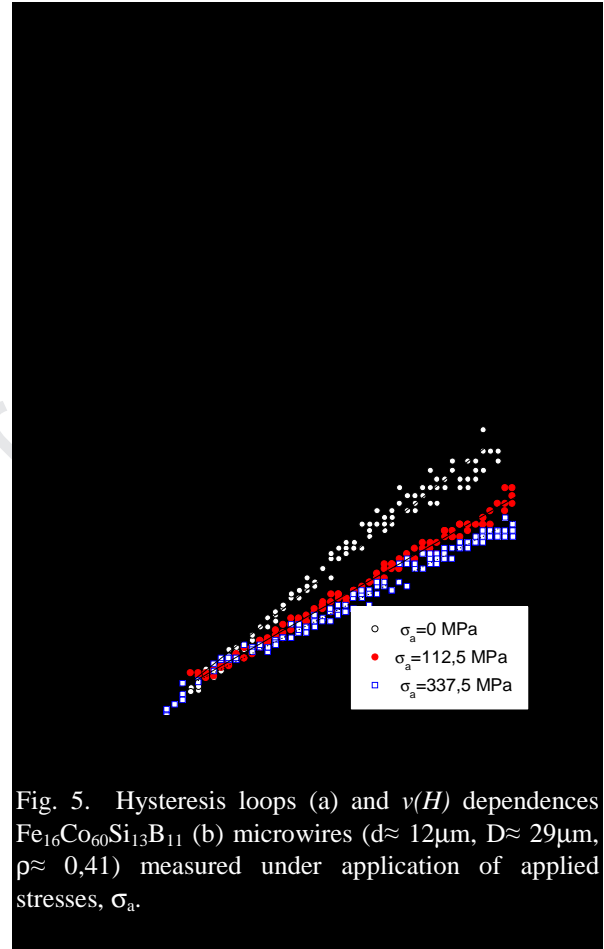


Fig. 5. Hysteresis loops (a) and  $v(H)$  dependences  $\text{Fe}_{16}\text{Co}_{60}\text{Si}_{13}\text{B}_{11}$  (b) microwires ( $d \approx 12 \mu\text{m}$ ,  $D \approx 29 \mu\text{m}$ ,  $\rho \approx 0.41$ ) measured under application of applied stresses,  $\sigma_a$ .

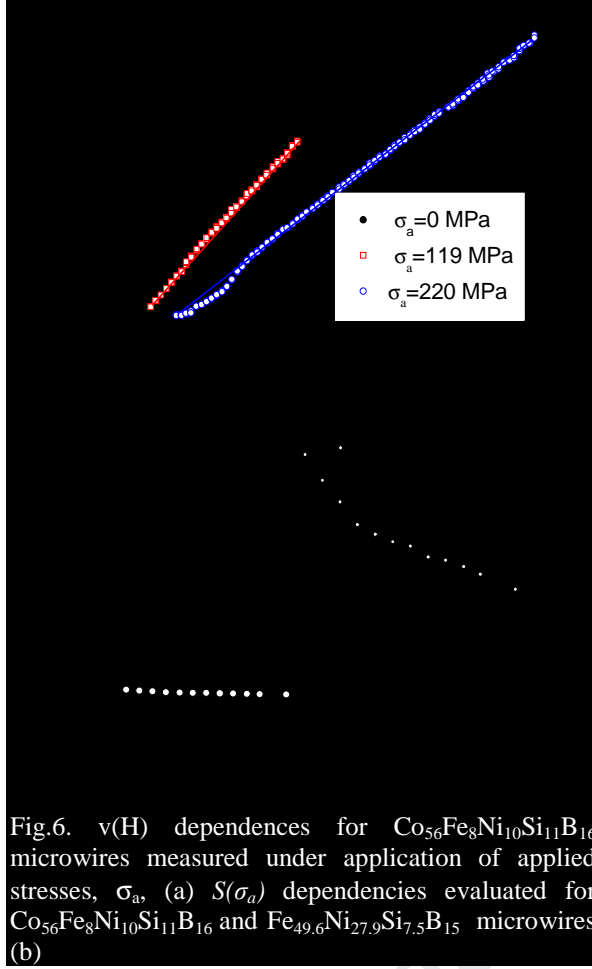


Fig.6.  $v(H)$  dependences for  $\text{Co}_{56}\text{Fe}_8\text{Ni}_{10}\text{Si}_{11}\text{B}_{16}$  microwires measured under application of applied stresses,  $\sigma_a$ . (a)  $S(\sigma_a)$  dependencies evaluated for  $\text{Co}_{56}\text{Fe}_8\text{Ni}_{10}\text{Si}_{11}\text{B}_{16}$  and  $\text{Fe}_{49.6}\text{Ni}_{27.9}\text{Si}_{7.5}\text{B}_{15}$  microwires (b)

magnetic microwires with such domain structure the magnetization reversal is attributed to the depinning and fast DW propagation within an inner single domain upon application of external magnetic field.

However, it has been theoretically and experimentally shown that the DW velocity of magnetic wires can be further improved by applying a transverse bias magnetic field [46-50]. The reported beneficial influence of the transversal magnetic field on the DW dynamics is attributed to the influence of the transverse field on the spin precession as well as on the DW shape [46-48].

As can be observed from Figs. 2(c),(d), stress-annealing allows one to

induce transverse magnetic anisotropy in magnetic microwires with a positive magnetostriction coefficient. The stress-annealing induced transverse magnetic anisotropy and its radial distribution depend on the stress-annealing conditions, that is the annealing temperature,  $T_{ann}$ , the stress applied during the annealing,  $\sigma_m$ , and the annealing time,  $t_{ann}$  [25,35,50]. As can be appreciated from Fig. 2(c), at certain stress-annealing conditions (low enough  $T_{ann}$  or  $\sigma_m$  -values) the hysteresis loops remain rectangular in shape, although they present a lower coercivity,  $H_c$ , and remanent magnetization,  $M_r/M_o$ .

The influence of stress-annealing conditions on the hysteresis loops and DW dynamics of  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  microwire is shown in Fig.7. Similarly as it was recently reported [26,30], after stress-annealing, a rectangular hysteresis loop is observed in the  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  sample, but with lower  $H_c$  and  $M_r/M_o$  – values (Fig. 7(a)). Thus, it is possible to observe a single DW propagation in stress-annealed  $\text{Fe}_{75}\text{B}_9\text{Si}_{12}\text{C}_4$  samples.

As-compared to as-prepared sample, stress-annealing allows remarkable improvement of DW velocity (Fig.7(b)). Comparison of the S-values obtained by stress-annealing gives values of the order of  $27 \text{ m}^2/\text{As}$  (see Fig. 7(c)). At the same time, the coercivity decrease upon stress-annealing is more significant (see Fig. 7(c)).

As can be observed from Fig. 2(c),(d), further decrease of  $H_c$ - and  $M_r/M_o$  - values is observed rising  $\sigma_m$ ,  $T_{ann}$  and  $t_{ann}$ . Reduced  $H_c$  and  $M_r/M_o$  - values after stress-annealing have been explained in terms of core-shell model of magnetic wires as an increase of the outer domain shell volume with transverse magnetization orientation in expense of a decreasing in the inner axially magnetized core volume [25, 35, 50]. Such modification of the spatial distribution of magnetic anisotropy is also evidenced by remarkable improvement of Giant magnetoimpedance, GMI, ratio,  $\Delta Z/Z$ , and modification of magnetic field dependence of  $\Delta Z/Z$  [35, 51].

Observed remarkable improvement of the DW dynamics (S and v-values) is attributed to the transverse magnetic anisotropy of the outer domain shell that affects the travelling DW in a similar way as the application of transversal bias magnetic field that allows the DW velocity enhancement [26, 35]. Recently, S-values improvement up to 45 m<sup>2</sup>/As by stress-annealing is reported [26].

Accordingly, the DW dynamics magnetic microwires with positive magnetostriction coefficient exhibiting spontaneous magnetic bistability can be considerably improved either by minimization of the magnetoelastic anisotropy or by stress-annealing induced transverse magnetic anisotropy.

### 3.2. Domain wall dynamics in microwires with induced magnetic bistability

As reported in a few recent publications, considerable magnetic hardening and transformation of linear hysteresis loop to rectangular is observed in a number of Co-rich microwires with low and negative magnetostriction coefficient [27-29]. These modifications

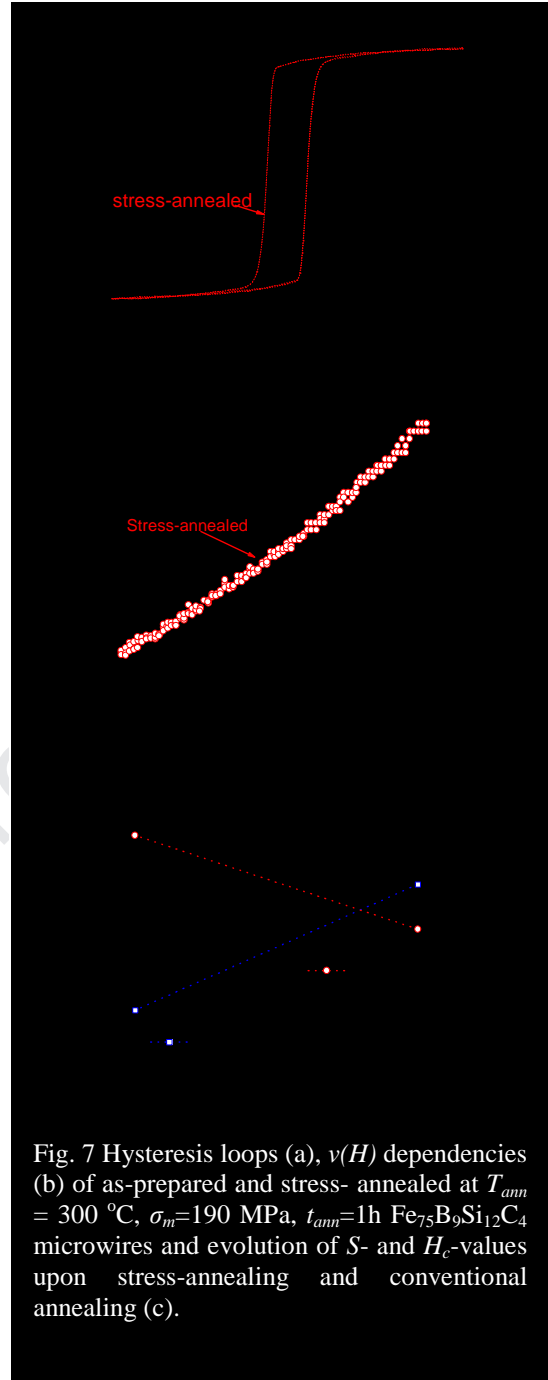
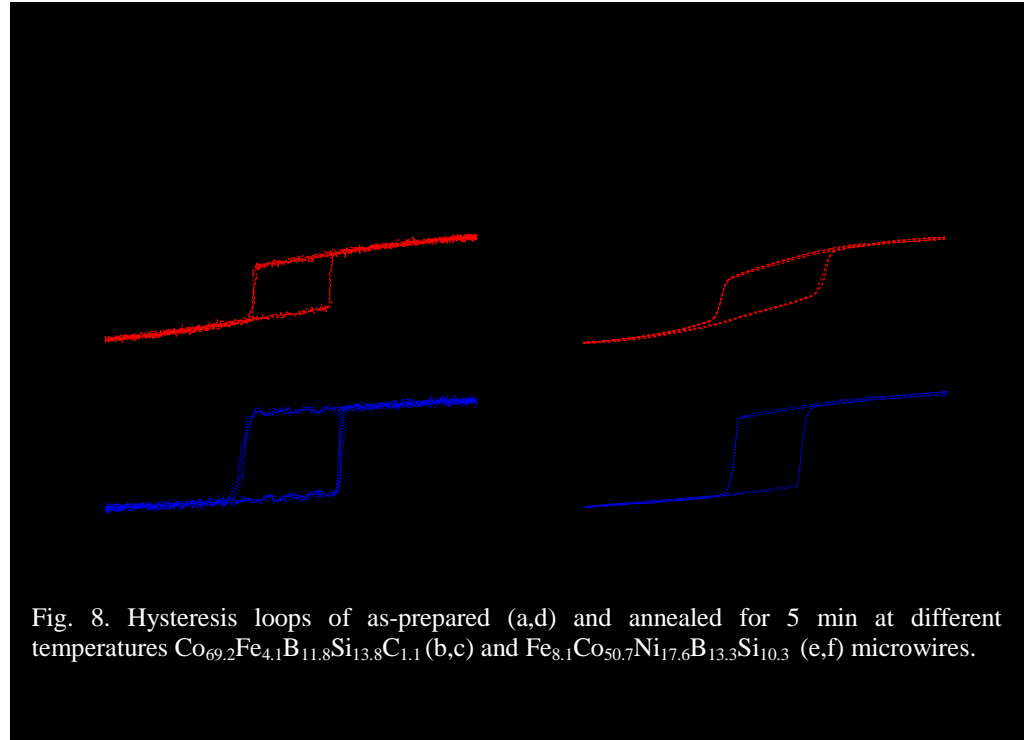


Fig. 7 Hysteresis loops (a),  $v(H)$  dependencies (b) of as-prepared and stress-annealed at  $T_{ann} = 300$  °C,  $\sigma_m=190$  MPa,  $t_{ann}=1h$  Fe<sub>75</sub>B<sub>9</sub>Si<sub>12</sub>C<sub>4</sub> microwires and evolution of S- and  $H_c$ -values upon stress-annealing and conventional annealing (c).

of the hysteresis loops strongly depend on annealing conditions, i.e. on  $T_{ann}$  and  $t_{ann}$  (see Fig.8).

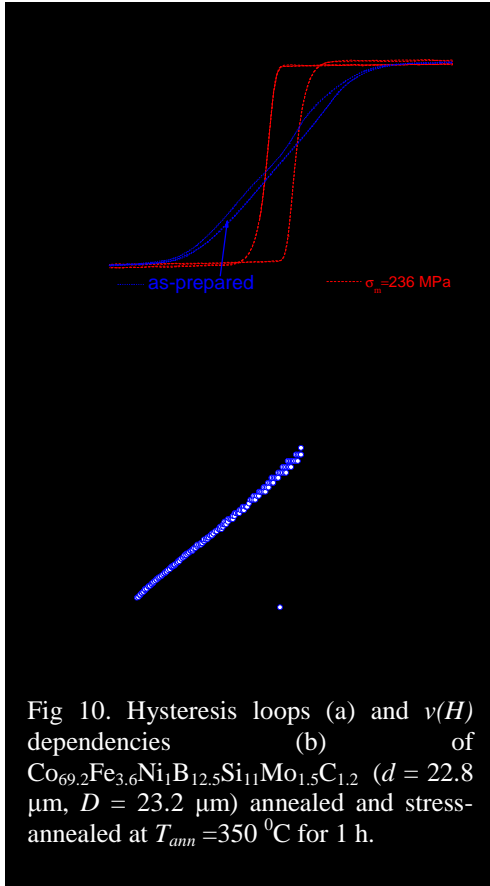
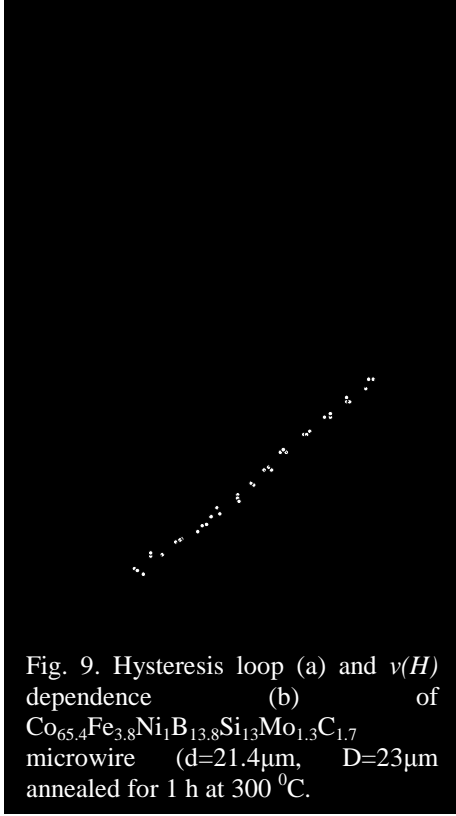


The origin of these changes is explained considering either the influence of internal stresses relaxation on the magnetostriction coefficient of Co-rich microwires, or competition between the magnetoelastic and shape magnetic anisotropy. In any case, annealed Co-rich present magnetic bistability [27-29]. The consequence of such evolution of hysteresis loops upon annealing is that annealed Co-rich microwires with annealing induced magnetic bistability can also present DW propagation [27,28].

One of the examples obtained for  $\text{Co}_{65.4}\text{Fe}_{3.8}\text{Ni}_{13.8}\text{Si}_{13}\text{Mo}_{1.3}\text{C}_{1.7}$  microwire ( $d=21.4\mu\text{m}$ ,  $D=23\mu\text{m}$ ) annealed for 1 h at  $300^\circ\text{C}$  is provided below (see Fig. 9). This microwire after annealing has perfectly rectangular hysteresis loop (see Fig.9(a)). Generally, DW dynamics in annealed Co-rich microwires presents similar features: almost linear  $v(H)$  dependence and rather high DW velocity values (typically above 1 km/s) (see Fig 9(b)).

The linear hysteresis loop transforms into a rectangular one upon annealing and stress-annealing in  $\text{Co}_{69.2}\text{Fe}_{3.6}\text{Ni}_{12.5}\text{Si}_{11}\text{Mo}_{1.5}\text{C}_{1.2}$  microwires (see Fig.10(a)). As-compared to the annealed sample, stress-annealing allows the coercivity,  $H_c$ , reduction (see Fig.10(a)). Generally, higher DW velocity values (up to 3 km/s) have observed in  $\text{Co}_{69.2}\text{Fe}_{3.6}\text{Ni}_{12.5}\text{Si}_{11}\text{Mo}_{1.5}\text{C}_{1.2}$  ( $d = 22.8 \mu\text{m}$ ,  $D = 23.2 \mu\text{m}$ ) microwires (Fig. 10(b)). Similarly to Fe-rich microwires, stress annealing allows DW velocity improvement (see Fig.





10(b)). However, the extension of the linear  $v(H)$  dependence is also considerably affected by the stress-annealing (see Fig. 10).

As discussed elsewhere [25, 33, 52], the extension of the linear  $v(H)$  dependence is determined in weak fields by the switching field and in the high fields, by the threshold between single and multiple domain wall propagation regimes.

Therefore, the modification in the low field region of  $v(H)$  dependence must be related to lower coercivity values of stress-annealed samples (see Fig. 10(a)). However, shorter extension of linear  $v(H)$  dependence in the high field region must be attributed to the effect of stress annealing on minimum nucleation field within the sample at which a new domain can be spontaneously nucleated in front of the propagating head-to-head closure domain. In any case an increase of the  $S$ -value from  $27\text{ m}^2/\text{As}$  up to  $29\text{ m}^2/\text{As}$  can be appreciated from Fig. 10(b).

As discussed above, transformation of linear hysteresis loops to rectangular is a common feature of Co-rich microwires with vanishing magnetostriction coefficient. One more example is shown in Fig. 11(a), where the hysteresis loop of  $\text{Co}_{69.2}\text{Fe}_{4.1}\text{B}_{11.8}\text{Si}_{13.8}\text{C}_{1.1}$  glass-coated microwires ( $d=25.6\mu\text{m}$ ,  $D=30.2\mu\text{m}$ ) annealed at  $300^\circ\text{C}$  is provided.

Perhaps the main difference between the DW dynamics of magnetic microwires with spontaneous magnetic bistability ( $\lambda_s$ -values) and Co-rich microwires with annealing induced

magnetic bistability lies in the stress dependence of the DW dynamics.

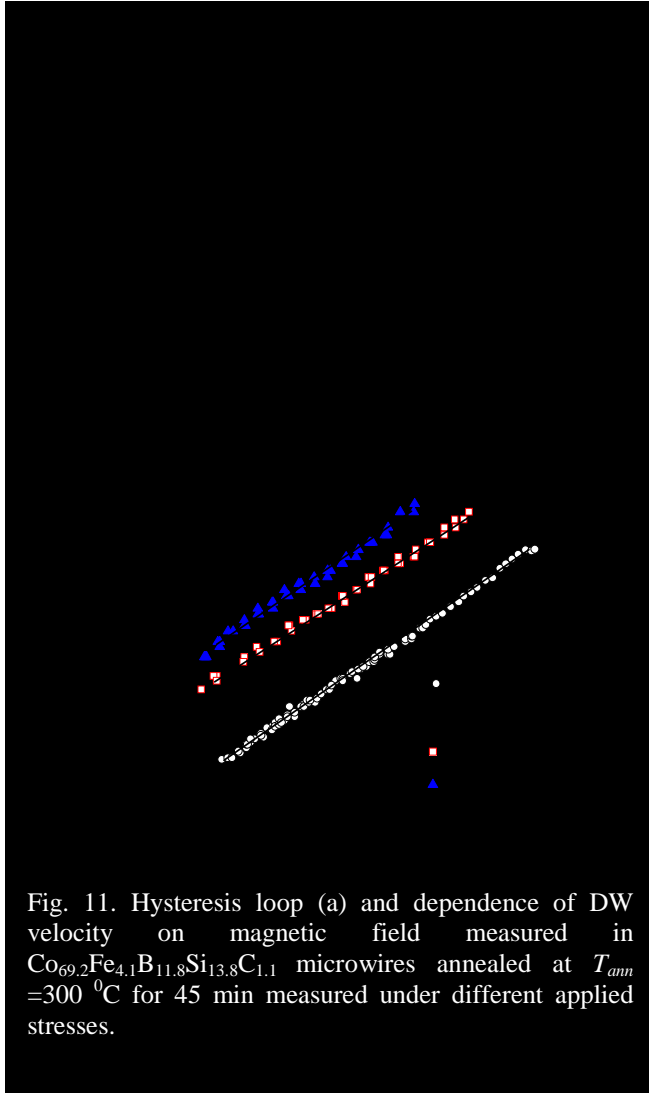


Fig. 11. Hysteresis loop (a) and dependence of DW velocity on magnetic field measured in  $\text{Co}_{69.2}\text{Fe}_{4.1}\text{B}_{11.8}\text{Si}_{13.8}\text{C}_{1.1}$  microwires annealed at  $T_{\text{ann}}=300\text{ }^{\circ}\text{C}$  for 45 min measured under different applied stresses.

effect of the applied stress [25, 35,51].

The rectangular character of hysteresis loops in Co-rich microwires maintains at certain conditions even after stress-annealing (moderate stresses values and annealing temperatures). As-compared to annealed samples, stress-annealed Co-rich samples present lower  $H_c$  –values (Fig. 12(a)) and the same features when the DW dynamics is measured upon applied stress: increase of DW velocity can be observed upon influence of applied stress (see Fig. 12(b)). However, similarly to Fe-rich microwires (see Fig 2(d)), the hysteresis loop of the same sample stress-

As can be appreciated from Fig. 11(b), the  $v(H)$  dependences of  $\text{Co}_{69.2}\text{Fe}_{4.1}\text{B}_{11.8}\text{Si}_{13.8}\text{C}_{1.1}$  glass-coated microwires ( $d=25.6\text{ }\mu\text{m}$ ,  $D=30.2\text{ }\mu\text{m}$ ) present a considerable enhancement in the DW velocity at given  $H$ -values upon applied tensile stress. This behavior is exactly the opposite to that observed for magnetic microwires with spontaneous magnetic bistability (see Figs. 4-6).

Observed increase in DW velocity has been explained considering the stress dependence of the magnetostriction coefficient, i.e., the decrease in  $\lambda_s$  under

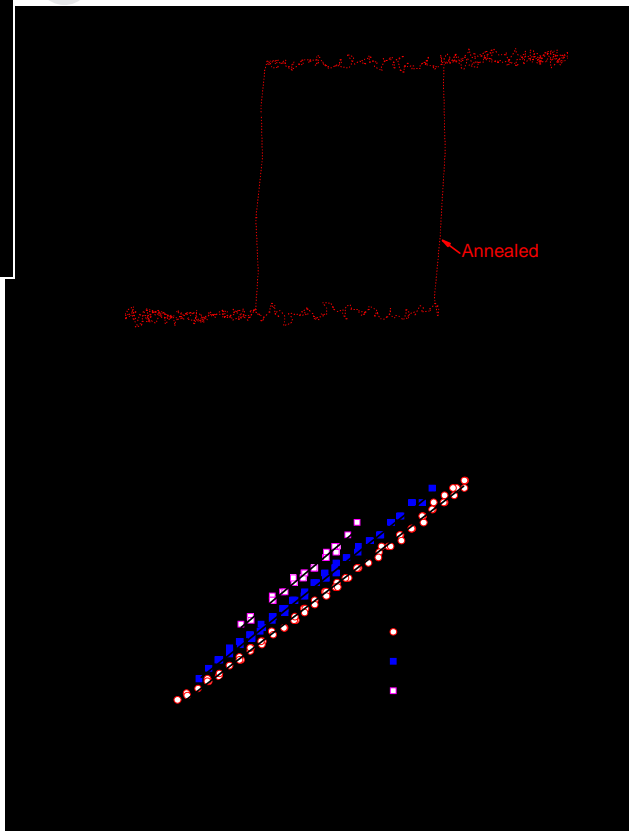


Fig. 12 Hysteresis loops of  $\text{Co}_{69.2}\text{Fe}_{4.1}\text{B}_{11.8}\text{Si}_{13.8}\text{C}_{1.1}$  glass-coated microwires annealed and stress annealed at  $300^{\circ}\text{C}$   $\sigma=80\text{ MPa}$  for 45 min (a) and  $v(H)$  dependencies of the same microwire measured under different tensile stresses.

annealed at a sufficiently high  $T_{ann}$  and/or  $\sigma_a$  does not present a rectangular hysteresis loop, as shown in Fig. 13 for stress-annealed (at  $T_{ann}=400$  °C for  $\sigma_a = 118$  MPa)  $\text{Co}_{69.2}\text{Fe}_{3.6}\text{Ni}_1\text{B}_{12.5}\text{Si}_{11}\text{Mo}_{1.5}\text{C}_{1.2}$  microwires.

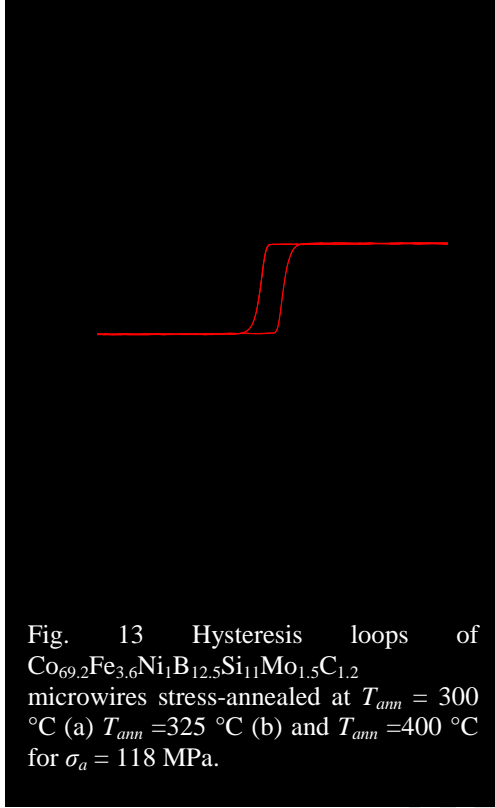


Fig. 13 Hysteresis loops of  $\text{Co}_{69.2}\text{Fe}_{3.6}\text{Ni}_1\text{B}_{12.5}\text{Si}_{11}\text{Mo}_{1.5}\text{C}_{1.2}$  microwires stress-annealed at  $T_{ann} = 300$  °C (a)  $T_{ann} = 325$  °C (b) and  $T_{ann} = 400$  °C for  $\sigma_a = 118$  MPa.

Therefore, considering the evolution of hysteresis loops annealed under stress at different  $T_{ann}$  we can deduce that stress-annealing of Co-rich microwires allows induction of transverse magnetic anisotropy.

From comparison of DW dynamics of annealed without stress and stress-annealed microwires we can appreciate that the DW dynamics is affected by the stress-annealing (Fig. 14): the most remarkable influence of stress-annealing is that the magnetic field range at which the single DW propagation can be observed is shifted to low -field region (see Fig. 14) as compared to annealed (for  $\sigma_m = 0$  MPa) samples. This must be attributed to lower coercivity (and hence lower switching field) of stress-annealed

samples.

However, for certain stress-annealing conditions a remarkable increase of DW mobility can be obtained. In the present case (Fig. 14) the annealed  $\text{Co}_{69.2}\text{Fe}_{3.6}\text{Ni}_1\text{B}_{12.5}\text{Si}_{11}\text{Mo}_{1.5}\text{C}_{1.2}$  microwire presents DW mobility  $S \approx 34$   $\text{m}^2/\text{As}$ , while stress-annealed (at  $\sigma_m = 354$  MPa) -  $S \approx 35.5$   $\text{m}^2/\text{As}$ .

Even more remarkable DW mobility improvement has been recently observed by us: when  $S \approx 40$   $\text{m}^2/\text{A}\cdot\text{s}$  have been achieved at appropriate stress-annealing conditions [29].

The origin of induced magnetic bistability in the case of Co-rich microwires has been attributed to the internal stresses relaxation upon conventional furnace annealing that allows modification of the domain structure and appearance of inner axially magnetized core responsible for the magnetization switching by DW propagation [25, 29, 37].

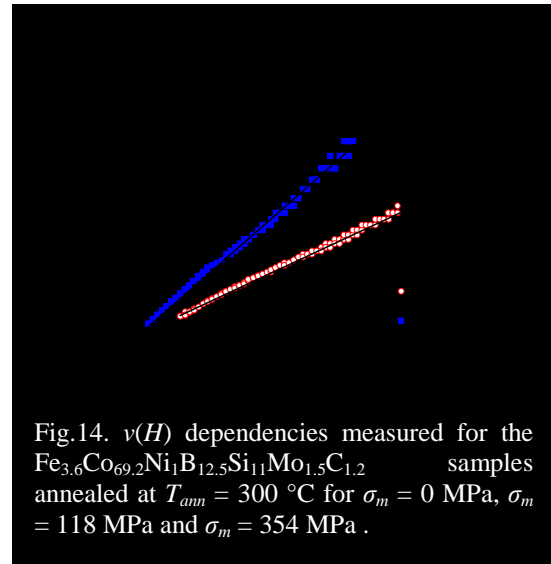


Fig.14.  $v(H)$  dependencies measured for the  $\text{Fe}_{3.6}\text{Co}_{69.2}\text{Ni}_1\text{B}_{12.5}\text{Si}_{11}\text{Mo}_{1.5}\text{C}_{1.2}$  samples annealed at  $T_{ann} = 300$  °C for  $\sigma_m = 0$  MPa,  $\sigma_m = 118$  MPa and  $\sigma_m = 354$  MPa .

Beneficial influence of the stress-annealing on DW dynamics has been explained considering that it allows increasing of the volume of outer domain shell with transverse magnetization orientation in expense of decreasing of the radius of inner axially magnetized core. Such transverse magnetic anisotropy can affect the DW dynamics in similar way as the applied transverse magnetic field and hence is beneficial for the DW dynamics optimization.

In any case the origin of high DW velocity observed in magnetic microwires must be attributed to low magnetic anisotropy of amorphous microwires, essentially non-abrupt DW shape with the characteristic width,  $\delta$ , of a head-to-head DW a few time larger than the metallic nucleus diameter,  $d$ , of microwire (i.e.  $10 \leq \delta/d \leq 50$ ) [54]. It is also worth mentioning that in the case of essentially non-abrupt DW, the DW mobility normal to the wall surface is reduced by the domain aspect ratio and the elongated DW can move quite fast [55].

As can be deduced from experimental results on DW dynamics presented above in magnetic microwires with either positive (i.e. presenting spontaneous magnetic bistability) or negative (with induced magnetic anisotropy) careful selection of microwire composition or conditions of post-processing allows achievement of extremely fast DW dynamics. Furthermore, furnace annealing and especially stress-annealing are promising methods allowing optimization of DW dynamics in magnetic microwires.

## Conclusions

We showed that minimizing magnetoelastic anisotropy either by selection a chemical composition with a low magnetostriction coefficient or by heat treatment is an appropriate route for domain wall dynamics optimization in magnetic microwires. As-prepared Co-based microwires with low and negative magnetostriction present linear hysteresis loops. Stress-annealing allows further improvement of domain wall velocity and hence is promising methods allowing optimization of DW dynamics in Fe-, Ni and Co-based magnetic microwires.

In magnetic microwires with induced magnetic bistability an increase of DW velocity can be observed upon applied tensile stress. This behavior is exactly the opposite to that observed for magnetic microwires with spontaneous magnetic bistability

Beneficial influence of the stress-annealing on DW dynamics has been explained considering that it provides the magnetic anisotropy distribution more favorable for faster domain wall dynamics.

It is assumed that stress-annealing allows increasing of the volume of outer domain shell with transverse magnetization orientation in expense of decreasing of the radius of inner axially magnetized core. Such transverse magnetic anisotropy can affect the DW dynamics in similar way as the applied transverse magnetic field and hence is beneficial for the DW dynamics optimization.

### Acknowledgements

This work was supported by Spanish MCIU under PGC2018-099530-B-C31 (MCIU/AEI/FEDER, UE), by the Government of the Basque Country under PIBA 2018-44 projects, by the University of Basque Country under the scheme of “Ayuda a Grupos Consolidados” (Ref.: GIU18/192) and by Act 211 of Government of the Russian Federation, contract # 02.A03.21.0011.. The authors thank for technical and human support provided by SGIker of UPV/EHU (Medidas Magnéticas Gipuzkoa) and European funding (ERDF and ESF).

### References

- [1] J. Lenz and A. S. Edelstein, Magnetic sensors and their applications, *IEEE Sensors Journal*, 6 (3) ( 2006) 631-649
- [2] M. Díaz-Michelena, Small Magnetic Sensors for Space Applications, *Sensors* 9 (2009) 2271-2283
- [3] P. Ripka, G. VeHrtesy, Sensors based on soft magnetic materials Panel discussion, *J. Magn. Magn. Mater.* 215- 216 (2000) 795-799
- [4] F. Fiorillo, G. Bertotti, C. Appino, M. Pasquale, Soft Magnetic Materials, J. Webster (ed.), Wiley Encyclopedia of Electrical and Electronics Engineering 1999, John Wiley & Sons, Inc., p.42. DOI: 10.1002/047134608X.W4504.pub2.
- [5] D. C. Jiles, Recent advances and future directions in magnetic materials, *Acta Mater.* 51 (2003) 5907-5939.
- [6] High Performance Soft Magnetic Materials (Editor A. Zhukov), Springer Series in Materials Science, vol. 252, Springer International Publishing, 2017, p.216. ISBN: 0933-033X, DOI: 10.1007/978-3-319-49707-5.

- [7] K. Mohri, F.B. Humphrey, K. Kawashima, K. Kimura and M. Muzutani, Large Barkhausen and Matteucci Effects in FeCoSiB, FeCrSiB, and FeNiSiB Amorphous Wires, *IEEE Trans.Magn.*, Mag-26 (1990) 1789-1781.
- [8] I. Ogasawara and S. Ueno, Preparation and properties of amorphous wires, *IEEE Trans. Magn.* 31. No 2, (1995) 1219-1223, DOI: 10.1109/20.364811
- [9] M. Vázquez and D.-X. Chen, The magnetization reversal process in amorphous wires, *IEEE Trans. Magn.*, 31, No. 2 (1995) 1229-1239. DOI: [10.1109/20.364813](https://doi.org/10.1109/20.364813)
- [10] L.V. Panina and K. Mohri, Magneto-impedance effect in amorphous wires, *Appl Phys Lett.*, 65(1994) 1189-1191.
- [11] R. Beach and A. Berkowitz, Giant magnetic field dependent impedance of amorphous FeCoSiB wire, *Appl. Phys. Lett.* 64 (1994) 3652-3654.
- [12] A. Zhukov, M. Ipatov and V. Zhukova, Advances in Giant Magnetoimpedance of Materials, Handbook of Magnetic Materials, ed. K.H.J. Buschow, Volume 24 chapter2, 139, 2015
- [13] M. Knobel, M. Vazquez, L. Kraus, Giant magnetoimpedance, Handbook of magnetic materials ed. E. Bruck vol. 15 (2003) 497-563.
- [14] E.P. Harrison, G. L. Turney and H. Rowe, Electrical Properties of Wires of High Permeability, *Nature*, 135 (1935) 961.
- [15] K.J. Sixtus and L. Tonks, "Propagation of large Barkhausen discontinuities II", *Physical Review*, 42 (1932) 419-435 DOI: 10.1103/PhysRev.42.419.
- [16] A.P. Zhukov, The remagnetization process of bistable amorphous alloys, *Mater. Design*, 14(5) (1993) 299-305
- [17] M.-H. Phan, H.-X. Peng, S.-C. Yu, M. Vázquez, Optimized giant magnetoimpedance effect in amorphous and nanocrystalline materials, *J. Appl. Phys.*, 99 (2006) 08C505
- [18] A. Zhukov, V. Zhukova, J.M. Blanco and J. Gonzalez, Recent research on magnetic properties of glass-coated microwires, *J. Magn. Magn. Mater.*, 294 (2005) 182-192
- [19] R. Varga, K. Richter, A. Zhukov, and V. Larin, Domain Wall Propagation in Thin Magnetic Wires, *IEEE Trans. Magn.*, 44, 11, Part 2 (2008) 3925-3930.
- [20] S Corodeanu, H Chiriac, T-A Óvári, Accurate measurement of domain wall velocity in amorphous microwires, submicron wires, and nanowires, *Review of Scientific Instruments*, 82 (9) (2011) 094701
- [21] N.Biziere, Ch. Gatel, R. Lassalle-Balier, M. C.Clochard, J. E. Wegrowe, and E. Snoeck, Imaging the Fine Structure of a Magnetic Domain Wall in a Ni Nanocylinder, *Nano Lett.*, 13 (2013) 2053–2057, [dx.doi.org/10.1021/nl400317](https://doi.org/10.1021/nl400317)

- [22] S. Da Col, S. Jamet, M. Stano, B. Trapp, S. Le Denmat, L. Cagnon, J. C. Toussaint, and O. Fruchart, Nucleation, imaging, and motion of magnetic domain walls in cylindrical nanowires, *Appl. Phys. Lett.*, 109 (2016) 062406 (2016)
- [23] J. M. Blanco, V. Zhukova, M. Ipatov, A. Zhukov, Magnetic properties and domain wall propagation in micrometric amorphous microwires, *Sensor Letters* 11 (1) (2013) 187-190
- [24] T.-A. Óvári, S. Corodeanu, H. Chiriac, Domain wall velocity in submicron amorphous wires, *J. Appl. Phys.* 109 (7) (2011) 07D502
- [25] V. Zhukova, J. M. Blanco, P. Corte-Leon, M. Ipatov, M. Churyukanova, S. Taskaev, A. Zhukov, Grading the magnetic anisotropy and engineering the domain wall dynamics in Fe-rich microwires by stress-annealing, *Acta Mater.*, 155 (2018) 279-285. DOI: [10.1016/j.actamat.2018.05.068](https://doi.org/10.1016/j.actamat.2018.05.068)
- [26] P. Corte-León, J. M. Blanco, V. Zhukova, M. Ipatov, J. Gonzalez, M. Churyukanova, S. Taskaev, A. Zhukov, Engineering of Magnetic Softness and Domain Wall Dynamics of Fe-rich Amorphous Microwires by Stress- induced Magnetic Anisotropy, *Sci. Reports*, 9 (2019) 12427 DOI: <https://doi.org/10.1038/s41598-019-48755-4>
- [27] A. Zhukov, A. Talaat, M. Ipatov, J.M. Blanco, V. Zhukova, Tailoring of magnetic properties and GMI effect of Co-rich amorphous microwires by heat treatment, *J. Alloys Compound.* 615 (2014) 610–615, DOI: <http://dx.doi.org/10.1016/j.jallcom.2014.07.079>
- [28] A. Zhukov, K. Chichay, A. Talaat, V. Rodionova, J.M. Blanco, M. Ipatov, V. Zhukova, Manipulation of magnetic properties of glass-coated microwires by annealing, *J. Magn. Magn. Mater.*, 383 (2015) 232–236 <http://dx.doi.org/10.1016/j.jmmm.2014.10.003>
- [29]. A. Zhukov, M. Ipatov, M. Churyukanova, A. Talaat, J.M. Blanco and V. Zhukova, Trends in optimization of giant magnetoimpedance effect in amorphous and nanocrystalline materials, *J. Alloys Compound.* 727 (2017) 887-901 DOI: [10.1016/j.jallcom.2017.08.119](https://doi.org/10.1016/j.jallcom.2017.08.119)
- [30] V. Zhukova, P. Corte-Leon, M. Ipatov, J. M. Blanco, L. Gonzalez-Legarreta and A. Zhukov, Development of Magnetic Microwires for Magnetic Sensor Applications, *Sensors*, 19 (2019) 4767
- [31] A. Zhukov, M. Churyukanova, S. Kaloshkin, V. Sudarchikova, S. Gudoshnikov, M. Ipatov, A. Talaat, J.M. Blanco and V. Zhukova, Magnetostriction of Co-Fe-based amorphous soft magnetic microwires, *J. Electr. Mater.* 45 (1) (2016) 226-234.
- [32] M. Churyukanova, V. Semenkova, S. Kaloshkin, E. Shuvaeva, S. Gudoshnikov, V. Zhukova, I. Shchetinin, and A. Zhukov, Magnetostriction investigation of soft magnetic microwires, *Phys. Status Solidi A*, 213(2) (2016) 363–367.



- [33] V. Zhukova, J. M. Blanco, V. Rodionova, M. Ipatov, and A. Zhukov, Domain wall propagation in micrometric wires: Limits of single domain wall regime, *J. Appl. Phys.* 111 (2012) 07E311.
- [34] V Zhukova, A. Zhukov, J.M. Blanco, J. Gonzalez and B. K. Ponomarev, Switching field fluctuations in a glass coated Fe-rich amorphous microwire, *J. Magn. Magn. Mater.* 249/1-2 (2002)131-135
- [35] M. Ipatov, V. Zhukova, A. K. Zvezdin and A. Zhukov, Mechanisms of the ultrafast magnetization switching in bistable amorphous microwires, *J. Appl. Phys.*, 106 (2009) 103902.
- [36] M. Ipatov, N.A. Usov, A. Zhukov, J. Gonzalez, Local nucleation fields of Fe-rich microwires and their dependence on applied stresses, *Physica B*, 403 (2008) 379–381
- [37] 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. Rep.*, 8 (2018) 3202. DOI: [10.1038/s41598-018-21356-3](https://doi.org/10.1038/s41598-018-21356-3)
- [38] R. Varga, A. Zhukov, V. Zhukova, J. M. Blanco and J. Gonzalez, Supersonic domain wall in magnetic microwires, *Phys. Rev. B*, 76, (2007,)132406, doi: <https://doi.org/10.1103/PhysRevB.76.132406>
- [39] N. L. Schryer and L. R. Walker, The motion of  $180^\circ$  domain walls in uniform dc magnetic fields, *J. Appl. Phys.* **45** (12), 5406-5421 (1974)
- [40] V. Zhukova, J.M. Blanco, M. Ipatov, A. Zhukov, Magnetoelastic contribution in domain wall dynamics of amorphous microwires, *Physica B*, 407 (2012) 1450–1454
- [41] K. Richter, R. Varga, J. Kováč, and A. Zhukov, Controlling the Domain Wall Dynamics by Induced Anisotropies, *IEEE Trans. Magn.*, 48 ( 4) (2012) 1266-1228
- [42] H Chiriac, TA Óvári, Amorphous glass-covered magnetic wires: preparation, properties, applications, *Progr. Mater. Sci.*, 40 (5) (1996) 333-407
- [43] G. Herzer, Amorphous and nanocrystalline soft magnets, in Proceedings of the NATO Advanced Study Institute on Magnetic Hysteresis in Novel Materials, Mykonos, Greece, 1-12 July 1996 ed. George C. Hadjipanayis, NATO ASI Series (Series E: Applied Sciences) vol. 338, pp. 711-730. Kluwer Academic Publishers (Dordrecht/Boston/London) 1997.
- [44] Y. Konno, K. Mohri, Magnetostriction measurements for amorphous wires, *IEEE Trans Magn.*, 25 (1989) 3623-3625.



- [45] A. Zhukov, J. Gonzalez, A. Torcunov, E. Pina, M.J. Prieto, A.F. Cobeño, J.M. Blanco, V. Larin and S. Baranov, Ferromagnetic resonance and Structure of Fe-based Glass-coated Microwires, *J. Magn. Magn. Mater.*, 203 (1999) 238-240.
- [46] A. Kunz, and S.C. Reiff, Enhancing domain wall speed in nanowires with transverse magnetic fields, *J. Appl. Phys.*, 103 (2008) 07D903, DOI: [10.1063/1.2829032](https://doi.org/10.1063/1.2829032).
- [47] J. Yang, G. S. D. Beach, C. Knutson, C. and J. L. Erskine, Magnetic domain-wall velocity enhancement induced by a transverse magnetic field, *J. Magn. Magn. Mater.*, 397 (2016) 325–332.
- [48] M.T. Bryan, Th. Schrefl, D. Atkinson, D. and D.A. Allwood, Magnetic domain wall propagation in nanowires under transverse magnetic fields, *J. Appl. Phys.* 103 (2008) 073906; doi: [10.1063/1.2887918](https://doi.org/10.1063/1.2887918).
- [49] V. Zhukova, J. M. Blanco, M. Ipatov and A. Zhukov, Effect of transverse magnetic field on domain wall propagation in magnetically bistable glass-coated amorphous microwires, *J. Appl. Phys.*, 106 (2009) 113914.
- [50] 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.*, 498 (2020) 166180, Doi: [10.1016/j.jmmm.2019.166180](https://doi.org/10.1016/j.jmmm.2019.166180)
- [51] 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. Alloys Compound.* 814 (2020) 152225
- [52] V. Zhukova, O.A. Korchuganova, A.A. Aleev, V.V. Tcherdyntsev, M. Churyukanova, E.V. Medvedeva, S. Seils, J. Wagner, M. Ipatov, J.M. Blanco, S.D. Kaloshkin, A. Aronin, G. Abrosimova, N. Orlova and A. Zhukov, Effect of annealing on magnetic properties and structure of Fe-Ni based magnetic microwires, *J. Magn. Magn Mater.*, 433 (2017) 278–284 DOI:[10.1016/j.jmmm.2017.03.028](https://doi.org/10.1016/j.jmmm.2017.03.028)
- [53] M. Barandiaran, A. Hernando, V. Madurga, O.V. Nielsen, M. Vazquez and M. Vazquez-Lopez, Temperature, stress, and structural relaxation dependence of the magnetostriction in metallic glasses, *Phys. Rev.B*, 35, (1987) 5066-5071
- [54] S. A. Gudoshnikov, Yu. B. Grebenshchikov, B. Ya. Ljubimov, P. S. Palvanov, N. A. Usov, M. Ipatov, A. Zhukov, and J. Gonzalez, Ground state magnetization distribution and characteristic width of head to head domain wall in Fe-rich amorphous microwire, *Phys. Status Solidi A*, 206( 4) (2009) 613–617

- [55] L.V. Panina , M.Ipatov , V.Zhukova , A.Zhukov, Domain wall propagation in Fe-rich amorphous microwires, *Physica B*, 407 (2012) 1442–1445

Journal Pre-proof

Rectangular hysteresis loops of annealed Co-rich microwires

Tuning of hysteresis loops varying stress-annealing conditions

Enhancement of domain wall velocity after annealing and stress-annealing

Enhancement of domain wall velocity by applied stress in Co-rich microwires

Modification of the magnetic anisotropy distribution by stress-annealing

Journal Pre-proof



**DEPARTAMENTO DE  
FISICA DE MATERIALES**  
**UNIVERSIDAD DEL PAIS VASCO**  
**EUSKAL HERRIKO UNIBERTSITATEA**

FACULTAD DE QUIMICA  
Pº Manuel de Lardizabal, 3  
Apartado 1072  
20080 SAN SEBASTIAN (SPAIN)  
Tel.: (+ 34 943) 0186 11  
Telefax: (+ 34 43) 017130

San Sebastian, February 18 -th, 2020

Dear Editor,

The authors of the manuscript “Controlling the domain wall dynamics in magnetic microwires” declare no competing financial or/and non-financial interests.

On behalf of the authors

Dr. A. Zhukov

E-mail: [arkadi.joukov@ehu.es](mailto:arkadi.joukov@ehu.es)  
Tel: 34-943-018611  
Fax: 34-943-017130