



# Controlling of the single domain wall propagation in magnetic microwires by magnetostatic interaction

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## ABSTRACT

Ultrafast magnetization switching through the single domain wall (DW) propagation has been reported in amorphous micrometric and submicrometric wires. However the performance of prospective devices utilizing DW propagation is determined by the degree to which DW propagation can be controlled. In this article, we propose a novel method for effectively controlling the single DW propagation in a specially designed array consisting of two magnetic microwires by the stray field from magnetically softer microwires. We have experimentally demonstrated that the DW velocity of magnetically harder Fe-rich microwire in such a linear array is affected by the stray field of magnetically softer Co-rich microwire. Additionally, the domain wall can be trapped in the Fe-rich microwire by the stray field produced by the Co-rich microwire in such a linear array. The observed effect of magnetostatic interaction depends on the position of the Co-rich microwire in such a linear array. Controllable domain wall propagation observed in such a linear array can be a useful tool for simple and more flexible ways of controllable trapping and braking of single DWs in Fe-rich microwires showing spontaneous magnetic bistability.

## 1. Introduction

Magnetic wires have attracted considerable attention due to their rather attractive magnetic properties, such as magnetic bistability or giant magneto-impedance (GMI) effect [1–5], potentially suitable for several prospective applications (magnetic and magnetoelastic sensors, magnetic memory and logic, electronic surveillance, etc.) [2,3,6–9].

Among different families of magnetic wires, amorphous magnetic wires produced by rapid quenching from the melt present clear advantages, such as superior magnetic softness as well as excellent mechanical properties [10–13]. Therefore, the studies of amorphous magnetic wires have become the subject of intensive research over the past 4 decades.

There are several preparation techniques allowing the fabrication of amorphous magnetic wires [5,10–12]. The so-called Taylor-Ulitovsky technique allows the preparation of magnetic wires with the most

extended diameters range (within 4 orders of magnitude): from submicrometric (0.1  $\mu\text{m}$ ) [14] to 100  $\mu\text{m}$  diameters [15]. The fabrication method is fast (up to 100 m per minute) and low cost [16–18]. Additionally, such magnetic wires are covered with flexible and insulating glass coating and have cylindrical metallic nuclei [13,14,16–18]. Accordingly, in addition to the excellent magnetic softness and superior mechanical properties, such glass-coated microwires present enhanced corrosion resistance and biocompatibility [12,16,19]. Therefore, studies of glass coated magnetic microwires generated huge interest due to emerging prospective applications [9,19–23].

As mentioned above, amorphous magnetic wires can present magnetic bistability associated with fast magnetization switching through large and single Barkhausen jump [16,23–25]. The hysteresis loop of such magnetic wires presents perfectly rectangular shape. The origin of magnetic bistability is the remagnetization process of single domain

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with axial magnetization orientation through the fast domain wall (DW) propagation [23–25]. Such peculiar feature of magnetic wires is considered among the most promising phenomena, from the viewpoint of applications [16,23–27].

Among the most promising applications involving either controllable DW propagation or perfectly rectangular hysteresis loops observed in amorphous nano- and microwires are racetrack memory, magnetic logics, magnetic and magnetoelastic sensors or electronic surveillance [6–9,23,24,27,28].

As regarding the single DW propagation, the principal advantage of amorphous wires is unusually high DW velocity,  $v$ :  $v \geq 1$  km/s are commonly reported for various families of amorphous wires [23,26,27]. Such  $v$  – values can be further improved by appropriate processing of amorphous microwires, such as annealing or application of a transverse magnetic field [23,26,27].

On the other hand, the degree of control over DW propagation in ferromagnets is another issue for implementing the above-mentioned DW propagation applications [27–29]. However, only a few successful attempts involving controlled DWs injection, propagation, or pinning in amorphous microwires have been reported [30–34]. At the same time, the influence of various factors (applied stresses, annealing, applied transverse field, induced magnetic anisotropy or graded magnetic anisotropy, distribution of defects along the wire) on the DW dynamics in amorphous microwires was previously reported [27].

Accordingly, in this paper, we provide recent experimental results on the manipulation of single DW propagation in amorphous Fe-rich glass-coated microwires by magnetostatic interaction with other Co-rich glass-coated microwires.

## 2. Experimental

The DW dynamics was studied in as-prepared 12 cm long Fe<sub>69</sub>B<sub>12</sub>Si<sub>14</sub>C<sub>5</sub> microwire (metallic nucleus diameter  $d = 19.8 \mu\text{m}$ , total diameter  $D = 28.6 \mu\text{m}$ ) with positive magnetostriction coefficient,  $\lambda_s$ , ( $38 \times 10^{-6}$ ) [27] as well as in a linear array consisting of the same 12 cm long Fe<sub>75</sub>B<sub>9</sub>Si<sub>12</sub>C<sub>4</sub> microwire and 1 cm long Co-rich microwire (Co<sub>64.6</sub>Fe<sub>5.8</sub>B<sub>16.8</sub>Si<sub>11</sub>Cr<sub>3.4</sub>,  $d = 80 \mu\text{m}$ ,  $D = 92.3 \mu\text{m}$ ) placed near Fe-rich microwire (see Fig. 1). In all the cases, the samples have been inserted

inside a thin capillary. A capillary with pick-up coils was placed coaxially inside a magnetizing 140 mm long solenoid in the region with a homogeneous magnetic field. While the position of Fe-rich microwire was fixed, the measurements of DW propagation have been performed at different positions of Co-rich microwire along the Fe-rich microwire (see Fig. 1).

When we selected Co-rich microwire, we considered several factors:

- The magnetization of Co-rich microwire is lower than that of Fe-rich microwire [16,17,24].
- The macroscopic demagnetizing factor,  $D_{Co}$ , of Co-rich microwires. Although, generally the correct evaluation of  $D_{Co}$  tensor of cylinder is rather complex [35], for relatively long wire (for  $\Delta = l/d \gg 1$ ),  $D_{Co}$  can be expressed as [36]:

$$D_{Co} = 4\pi[\ln(2\Delta) - 1] / \Delta^2 \quad (1)$$

being  $l$  is the sample length,  $d$ -metallic nucleus diameter.

Accordingly, for relatively short and thick microwire the  $D_{Co}$  -value is relatively high.

The DW propagation has been studied using modified Sixtus-Tonks-like technique based on use of three pick-up coils placed on the capillary at a distance of 27 mm from each other along the studied Fe-rich microwire [27,37]. Three pick-up coils (2 mm long and 1 mm inner diameter) have been placed inside the solenoid coaxially, surrounding the studied sample and separated by the same distance. The pick-up coils are connected to corresponding digital oscilloscope inputs. Resistors have been connected in parallel to the pick-up coils to suppress the oscillations. A homogeneous magnetic field,  $H$ , along the microwire is created by the aforementioned long (140 mm long, 10 mm in diameter) solenoid using a square waveform with a frequency of 10 Hz. A single-layer magnetizing solenoid with a reduced number of turns was used to avoid a situation where the DW could start to propagate while  $H$  is still rising. The transient time of the coil is mainly determined by the inductance, which is proportional to the square of the number of turns,  $N$ . Therefore, by reducing  $N$ , we decrease the transient time and increase the sweep rate,  $dH/dt$ . The distance between the end of the microwire and the first pick-up coil is about 40 mm, so the transient process ends when the DW reaches the first pick-up coil.

The DW velocity,  $v$ , has been evaluated from the time difference,  $\Delta t$ , in the electromotive force,  $EMF$ , peaks induced by the travelling DW in the pick-up coils, separated by the distance,  $l$ , as [27,37]:

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

Such setup has been previously successfully used for studies of the DW propagation in magnetic microwires [27,28].

Similarly to previous studies, one end of Fe-rich microwire is placed outside the magnetizing solenoid to ensure the DW propagation from the opposite wire end [27,28].

Both samples were prepared by the Taylor-Ulitovsky method, described in details elsewhere [16–18].

The fluxmetric method, developed for precision measurements of magnetically soft microwires at room temperature [38], has been used to measure the axial hysteresis loops of the studied microwires, as well as of the microwires array. For better comparison of microwires with different chemical compositions (and hence different saturation magnetization) and diameters we use the normalized magnetization  $M/M_0$  versus magnetic field  $H$ , being  $M$  - the magnetic moment at a given magnetic field and  $M_0$  - the magnetic moment of the sample at the maximum magnetic field amplitude  $H_{max}$ .

As expected from previous knowledge on magnetic properties of glass-coated microwires Fe-rich microwire with  $\lambda_s > 0$  presents perfectly rectangular axial hysteresis loops (see Fig. 2a), while inclined axial hysteresis loop with much lower coercivity,  $H_c$ , ( $H_c \approx 15$  A/m) is observed in Co-rich microwire with vanishing  $\lambda_s$  (see Fig. 2b). Such

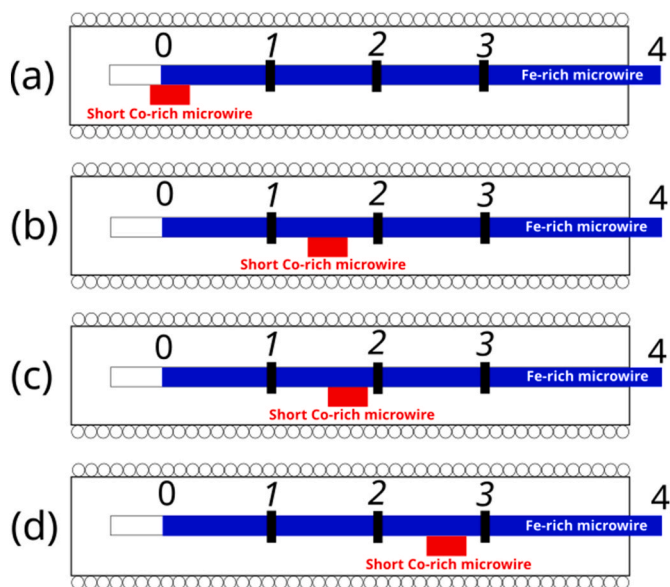


Fig. 1. The schematic sketch of the experimental set-up (1,2,3- pick-up coils, 0- sample end inside the solenoid, 4- sample end outside the solenoid) and the position of Fe-rich and Co-rich microwires with respect to magnetizing solenoid and pick-up coils during the  $EMF$  peaks measurements 0.5 cm (a); 4.5 cm (b); 5 cm (c) and 7.5 cm (d) from 0- Fe-rich sample end inside the solenoid.

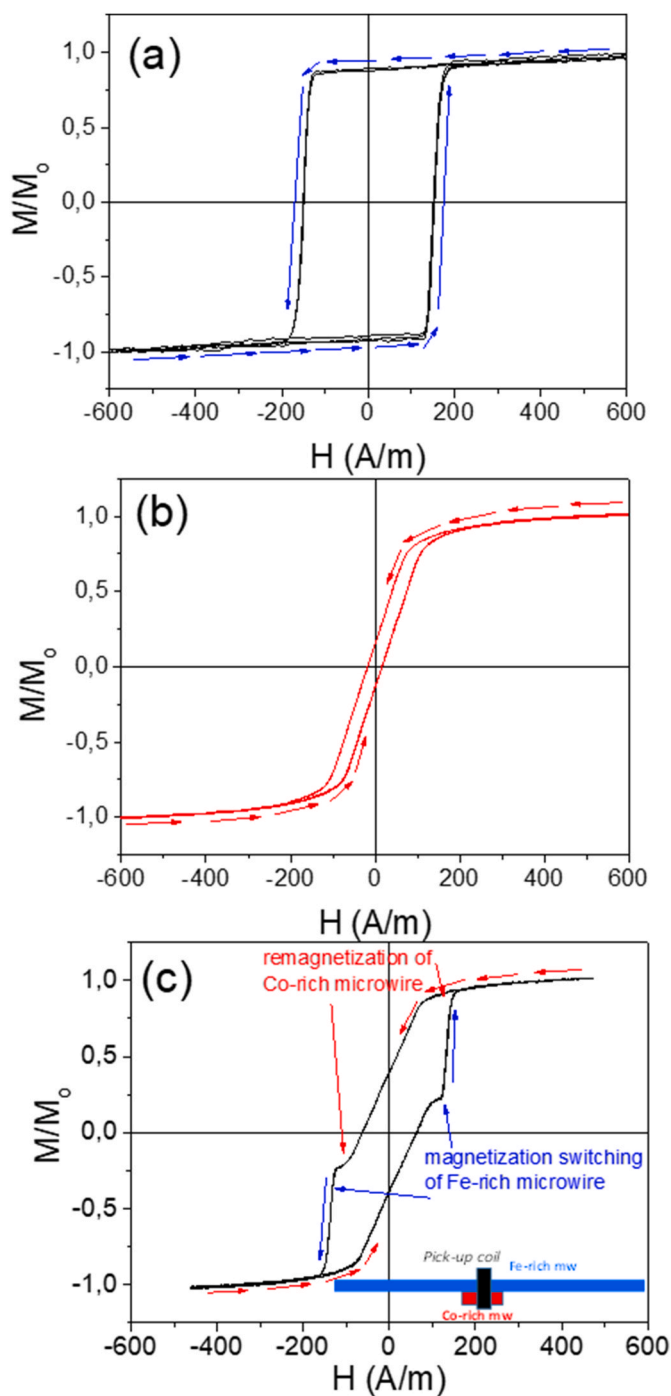


Fig. 2. Hysteresis loops of studied Fe-rich (a) and Co-rich (b) samples and linear array consisting of Fe-rich and Co-rich microwires (c).

character of axial hysteresis loops is commonly explained by the domain structure of studied microwires: the domain structure of magnetic microwires is commonly described as consisting of a single axially magnetized domain, surrounded by outer domain shell. The core-shell domain structure is commonly reported both experimentally (using Magneto-optical Kerr effect, MOKE, or magneto-optical indicator films, MOIF methods) [39–43] and theoretically [44] in magnetic wires. Bamboo-like domain structure is typically observed in the outer shell of Co-rich magnetic wires with vanishing magnetostriction [39–41]. While, radially oriented domains are reported in the outer shell for Fe-rich microwires [39,42–44]. The schematic picture of domain structures of Fe-rich and Co-rich microwires is provided in Fig. 3.

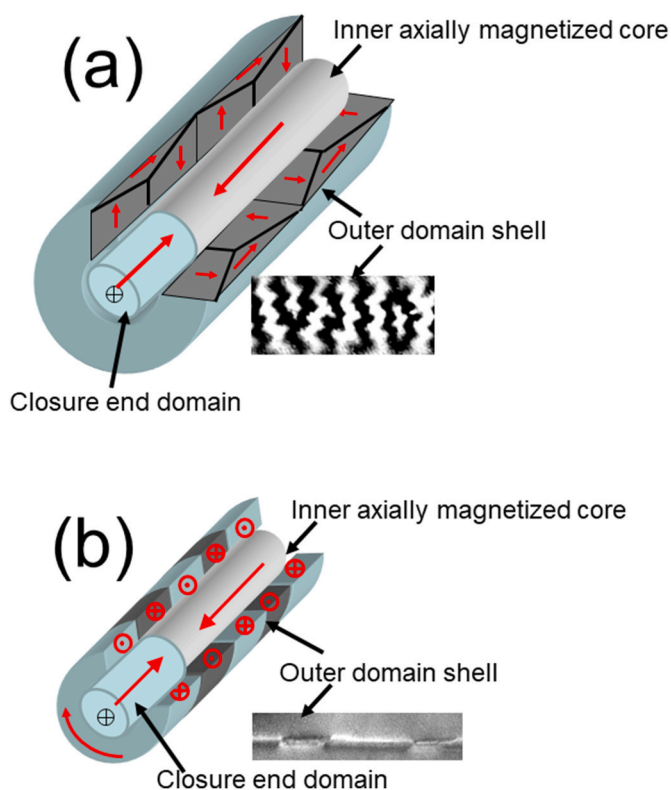


Fig. 3. Schematic pictures of domain structure of Fe-rich (a) and Co-rich (b) microwires.

The remagnetization process of Fe-rich microwires runs by the depinning of single DW from one of the closure end domains and subsequent DW propagation along the entire inner core [25–27,30]. Instead, the remagnetization process of Co-rich microwires usually present low coercivity and high magnetic permeability [21,38].

The axial hysteresis loops of the array consisting of one  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  and one  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwires is shown in Fig. 2c. The unusual hysteresis loop of such linear array has been previously explained as the superposition of those of Fe-rich and Co-rich microwires with rather different remagnetization processes [45]. Briefly, from Fig. 2b we can see that the magnetization of Co-rich microwire essentially depends on applied magnetic field in low magnetic field amplitude,  $H_0$ , region. Indeed, when the magnetic field changes from  $H = -600$  A/m to  $H = +600$  A/m the magnetization of Co-rich microwire starts to change from about  $H = -200$  A/m (slow and reversible change) followed by more substantial change from  $H \geq -120$  A/m (see Fig. 2b). The coercivity,  $H_c$ , of Fe-rich microwire is about 130 A/m (see Fig. 2a). When magnetic field changes from  $-130$  A/m to  $130$  A/m, the  $M/M_0$  of Co-rich changes from  $M/M_0 \approx -0.85$  to  $M/M_0 \approx +0.85$ . At the same time, the magnetization of the magnetically bistable Fe-rich microwire remains almost the same (about  $M/M_0 \approx -0.9$ ) up to  $H \pm 130$  A/m. At this  $H$ -value Co-rich microwire is already magnetized in the opposite direction ( $M/M_0 \approx +0.85$ ). Accordingly, the unusual hysteresis loop of the array consisting of Fe and Co-rich microwires (see Fig. 2c) must be explained as the superposition of magnetization processes of magnetically bistable Fe-rich microwire and magnetically soft Co-rich microwire.

We assume that at this magnetic field region the domain wall tears off from one end of the Fe-based microwire but does not have time to propagate through the whole wire because of the effect of stray field coming from Co-rich microwire. Further decreasing of  $H_0$  below switching field of individual Fe-based sample leads to the disappearance of the influence Fe-based microwire and we observe the hysteresis loops

typical for Co-based microwire.

### 3. Results and discussion

As expected from the perfectly rectangular hysteresis loop of studied  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire and similarly to the previously reported experimental results on the DW dynamics in Fe-rich microwires, a linear  $v(H)$  dependence is observed in studied  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  sample (see Fig. 4a). Such DW dynamics is characterized by a sequence of the  $EMF$  signals,  $\varepsilon$ , induced in the pick-up coils by the travelling DW, as reported elsewhere [34,46,47]. It is essential to note that in the  $v(H)$  dependence show in Fig. 4, the  $H$ -values are represented for the magnetic field generated by the magnetizing coil.

As previously discussed [47], the  $EMF$ ,  $\varepsilon$ , generated in the turn of the pick-up coil due to the change in magnetic flux is given as:

$$\varepsilon(t) = \frac{\Delta\phi}{\Delta t} \quad (3)$$

being  $\Phi = BS$  is the magnetic flux,  $S$  is the area of the surface,  $B = M + H$  is the magnetic induction, and  $M$  is the magnetization. Accordingly, the  $EMF$  amplitude and width is determined by  $\frac{\partial M}{\partial t}$ .

The  $\varepsilon(t)$  dependencies observed for Fe-rich microwire with almost the same  $EMF$ -signals amplitude and width are typical for DW propagation with a uniform velocity, when a propagating DW passes sequentially through the first, second and third pick-up coils (see Fig. 4b).

As shown below, the remagnetization in the linear array consisting of 12 cm long  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire and 1 cm long  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  sample is rather different. In Fig. 5 the  $EMF$  signals,  $\varepsilon$ , induced in the pick-up coils by the remagnetization process in the array consisting of 12 cm long  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire and 1 cm long  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  sample as a function of position of Co-rich microwire measured at. In the case when a piece of Co-rich microwire is placed far from the position of any pick-up coil, the peaks sequence is rather similar to that of a single Fe-rich microwire (see Fig. 5a). However, the picture changes when the 1 cm long Co-rich sample moves through the 12 cm long Fe-rich microwire. Thus, approaching Co-rich sample to the position of 1-st pick-up coil, the  $EMF$  signal in the 1-st pick-up coil becomes smaller (see Fig. 5b). Then, at certain position of Co-rich microwire (in the proximity of the 2-nd pick-up coil between 1-st and 2-nd coils), only the  $EMF$  signals in the pick-up coils 2 and 3 are observed (Fig. 5c). If we move further the 1 cm long Co-microwire along the Fe-rich microwire and when the Co-rich microwire reaches the position between 2-nd and 3-rd pick-up coils, only the  $EMF$  signal in the pick-up coil 3 is observed. Such influence of Co-rich microwires on the DW dynamics in studied linear array must be attributed to the magnetostatic interaction of 12 cm long  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire and 1 cm long  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwires. Particularly, we must assume that stray field produced by a short Co-rich microwire allows to trap DW

propagating from the wire end placed inside the magnetizing coil. However, as reported previously [30], a new DW can be injected under effect of magnetic field in the Fe-rich microwire section after the Co-rich microwire. Therefore, at some positions of Co-rich microwires, at a given  $H$ -values  $EMF$  signals can be observed only at 2-nd and or 3-rd pick-up coils.

As previously discussed [47], the  $\varepsilon$ -signal, generated by moving DW in the pick-up coil turn can be expressed as:

$$\varepsilon(t) = -\frac{2\pi Qv}{c} \frac{R^2}{(z + R^2)^{3/2}} \quad (4)$$

where  $c$  is the speed of light,  $R$  is the radius of the coil turn,  $v = -dz/dt$ -DW velocity and  $Q$ -magnetic charge. The eq. (4) is obtained for the case if the characteristic DW width,  $\delta$ , is small as-compared with the distance,  $z$ , between the pick-up coil turn and the DW.

The difference in  $EMF$  signals must be attributed to the change in  $Qv$  product. Accordingly, the  $EMF$  modification observed in Fig. 5b and 5c must be attributed to the different DW velocity,  $v$ , values [47].

Observed changes in  $\varepsilon(t)$  dependencies must be attributed to the influence of the stray field from Co-rich microwire on DW dynamics of Fe-rich microwire.

From Fig. 2 it is important to note, that the magnetic anisotropy field,  $H_k$ , of employed  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwire (about 110 A/m) is below the coercivity,  $H_c$ , of  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire (about 130 A/m). Therefore, when the magnetization switching of 12 cm long  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire takes place, the  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwire is already magnetized by external field in the direction opposite to the  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire.

Such magnetized in opposite direction  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwire produces a stray field,  $H_d$ . The  $H_d$ -value is determined by the macroscopic demagnetizing factor,  $D_{co}$  [35,48–50].

We must consider that the DW propagation in  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire takes place under the effect of a homogeneous magnetic field,  $H$ , produced by the long solenoid and the stray field,  $H_d$ , produced by  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwire magnetized in the opposite direction (since its coercivity,  $H_c \approx 15$  A/m). As discussed elsewhere,  $H_d$  can be expressed as:

$$H_d = D_{co} M \quad (5)$$

being  $M$ -magnetization of  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwire. As mentioned above, correct evaluation of  $D_{co}$  tensor of the microwire is rather complex [35,48].

As previously experimentally shown [49–51],  $H_d$ -value and spatial distribution of magnetic microwires are affected by applied magnetic field,  $H$ , microwire length as well as by the domain structure of magnetic microwires. Thus,  $H_d$ -spatial distributions of Fe-rich and Co-rich magnetic microwires are rather different at low magnetic field [50]. Such difference has been attributed to the rather different domain structure of Fe-rich and Co-rich microwires [50]. However, the two-pole

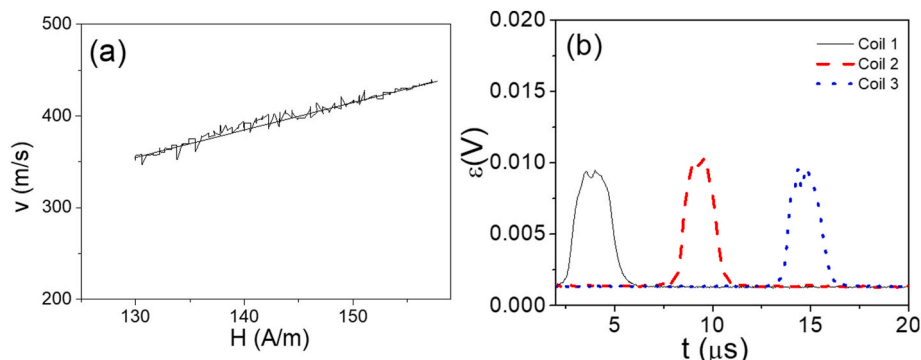


Fig. 4.  $v(H)$  dependence (a) and the  $EMF$  peaks induced by the travelling DW in the pick-up coils (b) in  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire measured at  $H = 135$  A/m.



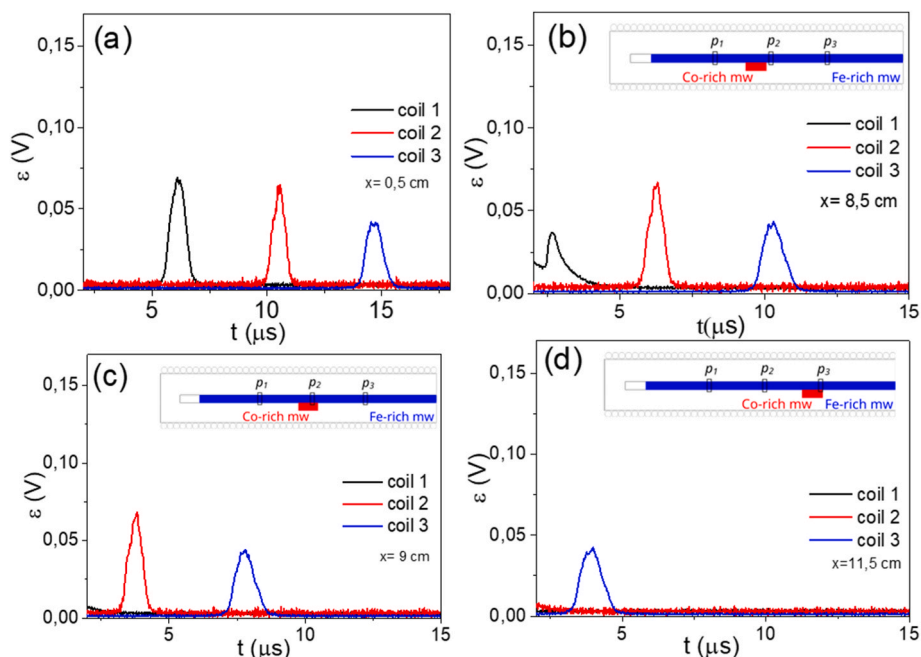


Fig. 5. The EMF peaks induced by the magnetization change in the pick-up coils in linear array consisting of 12 cm long Fe-rich and 1 cm long Co-rich microwire with different positions along the Fe-rich microwire: 0.5 cm (a); 4.5 cm (b); 5 cm (c) and 7.5 cm (d) recorded at  $H = 130$  A/m.

magnetic structure has been observed at high enough external magnetic field [49]. Additionally, even at  $H > H_k$ ,  $H_d$  -value and spatial distribution (axial and vertical components) are affected by the distance along the microwire and the distance to the microwire center [49,50]. Close to the magnetized microwire ends the magnetic field component normal to the microwire axis is experimentally observed [50,51]. The amplitude of stray magnetic fields oriented normally to the microwire axis at the wire ends reached maximum values and reduces to zero, moving further from the wire end [50,51]. On the other hand, when the magnetostatic interaction of magnetically bistable microwires was discussed, it was roughly assumed that  $H_d$  is directed against the applied magnetic field,  $H$  [45]. Accordingly, if the stray field produced by a short Co-rich microwire is opposite to the magnetic field produced by the solenoid, the DW can be braked or even pinned. However, under the effect of stray field directed transverse to the applied magnetic field,  $H$  or even with  $H_d$  component directed in the same direction as the applied magnetic field,  $H$ , new DW can be injected. Such influence of transverse magnetic field on DW injection is previously reported [52]. In this case, at a given  $H$ -values EMF signals can be observed only at 2-nd and/or 3-rd pick-up coils as observed in Fig. 5c and 5d.

In the present case, Co-rich microwire with  $H_c \approx 15$  A/m is remagnetized even by low reversal magnetic field, while the DW propagation within the Fe-rich microwire takes place. The schematic sketch of the remagnetization process in a linear array consisting of long Fe-rich microwire and short Co-rich microwire is shown in Fig. 6.

The shape of travelling DW can be critical for the detailed consideration of the effect of stray field on DW dynamics. Studies of the shape

of the propagating DW in magnetic microwires is a topic of many previous papers [27,53–59]. Briefly, from the rigorous analysis of the EMF peaks induced by the propagating DW in the pick-up coils it was reported that such DW is rather extended. Thus, in contrast to nanowires where the characteristic DW width,  $\delta_w$ , is of the order of the wire diameter ( $\delta_w/d \sim 1-2$ ), in amorphous glass-coated Fe-rich microwires the EMF peak shape fits better to  $\delta_w/d \sim 35-75$  [53]. Accordingly, the DW extension in studied Fe-rich microwires must be of the order of 1 mm.

Several attempts to evaluate the DW shape from the EMF peaks or from the MOKE studies have been made [54–58]. Most of the experimental data (obtained using the EMF peak shape analysis and/or magneto-optical Kerr effect, MOKE) have been interpreted considering either conical, planar, narrow tail at one end close to cylindrical at the other end and even deformed conical-like DW shapes.

It is worth noting, that the direct experimental confirmation of the DW shape is unlikely possible, since even MOKE studies can be performed only in the microwire surface, while magnetization switching in amorphous microwires takes place within the whole microwire diameter. Extremely large  $\delta_w/d$ -values observed in amorphous glass-coated microwires must be attributed to rather complex DW shape.

In the present case there are the following general features that must be considered:

- The propagating DW separates two domains with the opposite magnetization inside the inner core of microwire with axially oriented magnetization.
- The DW extension in studied Fe-rich microwires is about 1 mm, being an order of magnitude lower than the length of Co-rich microwire with the opposite magnetization at the moment of the DW propagation (see Fig. 6).

From aforementioned description it looks clear that the stray field produced by shorter Co-rich microwire can affect the DW dynamics of neighboring Fe-rich microwire. Previously, a modification of DW dynamics in a linear array consisting of two magnetically bistable microwires is already reported [32]. The influence of the position of Co-rich microwire on DW dynamics in  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire is shown in

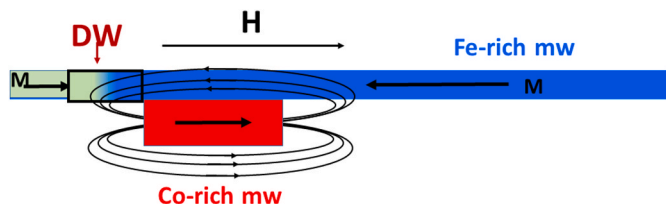
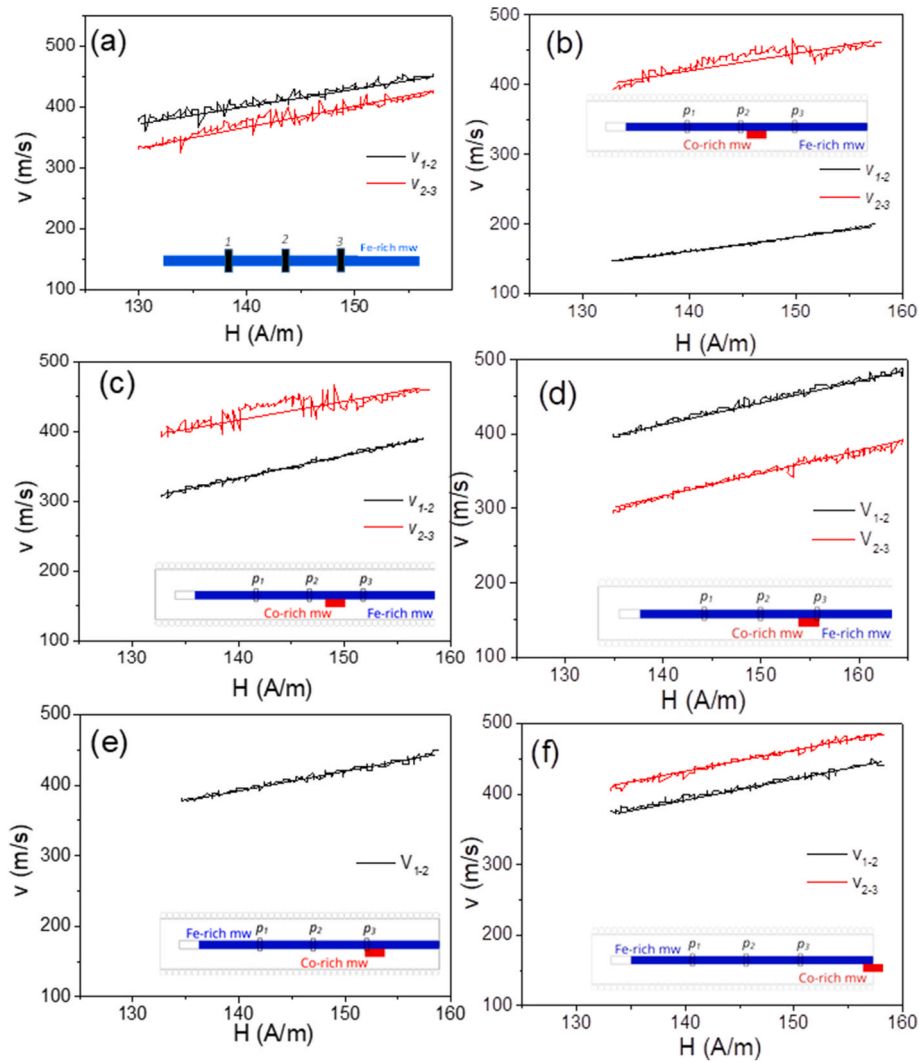


Fig. 6. Schematic sketch of the remagnetization process in a linear array consisting of long Fe-rich microwire and short Co-rich microwire.



**Fig. 7.**  $v(H)$  dependencies of single  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire (a) and linear array consisting of 12 cm long Fe-rich and 1 cm long Co-rich microwire with different positions along the Fe-rich microwire: 6 cm(b), 6.5 cm (c), 8.5 cm (d), 9.3 cm (e) and 11.5 cm (f).

**Fig. 7.** As shown in Fig. 7a, in the single  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire (without Co-rich microwire) the DW wall travels with almost constant velocity: DW velocities between 1-st and 2-nd and 2-nd and 3-rd pick-up coils,  $v_{1-2}$  and  $v_{2-3}$ , respectively, are almost identical. However, the DW dynamics in the presence of Co-rich microwire can be rather different. When the Co-rich microwire moves towards the pick-up coil 1, the  $v_{1-2}$  - values become substantially lower than  $v_{2-3}$  - values (see Fig. 7b). With further movement of the Co-rich microwire behind the pick-up coil 1, the  $v_{1-2}$  - values become higher (see Fig. 7c). Interesting, that while the position of Co-rich microwire is far from the coils 2 and 3 the  $v_{2-3}$  - values are almost unchanged (see Fig. 7b and c). However, moving Co-rich microwire towards pick-up coils 2 and 3 the  $v_{1-2}$  - values become higher, while the  $v_{2-3}$  - values become lower (see Fig. 7d). At certain position of Co-rich microwire along the Fe-rich microwire (when the Co-rich is moved behind pick-up coil 2 and closer to the pick-up 3) only the signals on pick-up coils 1 and 2 are observed (see Fig. 7e). At such Co-rich microwire position the  $v_{1-2}$  - values become similar to the case shown in Fig. 7 b,c, (when Co-rich microwire is far from any pick-up coils), while  $v_{2-3}$  value cannot be detected. At this Co-rich microwire position the moving DW is trapped between the pick-up coils 2 and 3. Finally, when the Co-rich microwire is placed far from the pick-up coils 1, 2, 3, the DW dynamics is still rather similar to the case of single Fe-rich microwire, (see Fig. 7f).

As mentioned above, the DW velocity is a function of the magnetic

field. The magnetic field acting on the DW is influenced by the superposition of the magnetic field created by the magnetizing solenoid and the stray field from the Co-rich microwire magnetized in the opposite direction. This is the reason why the DW dynamics is affected by the position of the Co-rich microwire: when the Co-rich microwire is located close to the travelling DW, the stray field generated by the Co-rich microwire affects the DW dynamics. Since the direction of the stray field roughly has the opposite direction to the magnetic field generated by the solenoid, a stronger external magnetic field is required for DW propagation. Therefore, the DW velocity and magnetic field at which DW dynamics is observed are affected by the position of the Co-rich microwire.

Thus, in the linear array consisting of 12 cm long  $\text{Fe}_{69}\text{B}_{12}\text{Si}_{14}\text{C}_5$  microwire and 1 cm long  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwire the  $v_{1-2}$  - and  $v_{2-3}$  - values are tunable by the position of the Co-rich microwire. In this way, travelling DW can be braked and even trapped by the magnetostatic interaction with magnetically softer short microwire in the linear array.

Such difference must be attributed to the superposition of the applied magnetic field and stray field from the 1 cm long  $\text{Co}_{64.6}\text{Fe}_{5.8}\text{B}_{16.8}\text{Si}_{11}\text{Cr}_{3.4}$  microwire.

As discussed elsewhere [35,36,48,49], the stray field of a magnetic material is determined by the shape of the sample as well as by its magnetization. Accordingly, the magnetostatic interaction in the linear

array must be affected by the length, composition and diameter of magnetically softer microwires. Consequently, above described experimental results can be a useful tool for simple, and more flexible way of controllable trapping and braking of single DWs in Fe-rich microwires showing spontaneous magnetic bistability.

As discussed above, clear advantage of amorphous microwires is ultrafast DW propagation with DW velocities up to several km/s [26,27,31].

The magnetic logic elements operation (AND, NOT, OR) is determined by the degree of DW control propagation monitoring, i.e., their controllable injection, propagation, trapping or interaction. Previously, was reported that single DW propagation can be effectively pinned either by local magnetic field or by creation of artificial defects [60–62].

The stray field produced by Co-rich microwire magnetized in the opposite direction depends on its length and/or diameter. As discussed above, the magnetic field acting on travelling DW is determined by the superposition of external magnetic field and stray field produced by Co-rich microwire magnetized in the opposite direction. Accordingly, there are several parameters, such as the length and diameter of the Co-rich soft magnetic microwire or the magnitude of the external magnetic field, that can either trap or decelerate the DW travelling along the Fe-rich long microwire in determined places (see scheme in Fig. 8).

Although the experimental results provided in Figs. 4 and 6 are obtained when the length of Fe-rich microwire is about 12 cm, the magnetic bistability in Fe-rich microwire with diameter about 10  $\mu\text{m}$  can be observed for the microwire of about 2 mm [36]. Therefore, the size of such magnetic logic shown in Fig. 8 can be much smaller.

It must be noted, that switching of the local magnetization of a Co microwire was previously reported through the internal stray field originated by a ferromagnetic gate electrode [63]. The similarity of observed by us effect of stray field on the DW propagation in linear microwires array and the effect of the stray field of a ferromagnetic gate on the local domain reversal lies in the controllability of the magnetic state. However, the fundamental difference between these two cases is that the DW propagation due to the stray field created by the ferromagnetic gate electrode was not achieved, while in the present case a significant change in the DW dynamics (braking and even trapping of the travelling DW) is demonstrated. Additionally, the effect of the dipolar stray fields from nearest neighbor nanowires on a ground state configuration consisting of alternating up and down magnetization in adjacent wires was observed in [Co/Pd]<sub>15</sub> and L1<sub>0</sub>-FePt nanowire arrays [64]. In the latter case the influence of dipolar stray field on the magnetization reversal process was observed at magnetic field above 100 kA/m, i.e., 4 orders of magnitude higher  $H$ -values.

#### 4. Conclusion

We report on the effect of magnetostatic interaction in the linear array consisting of Fe-rich magnetically bistable microwire and Co-rich microwire with soft magnetic properties. Both the hysteresis loop and the DW dynamics in such linear array are remarkably affected by the presence and position of short Co-rich microwire. The travelling DW can be either trapped or braked by the short Co-rich microwires. The origin of such magnetostatic interaction is discussed considering the superposition of the external magnetic field and the stray field produced by short Co-rich microwire already magnetized by the external field in the moment of DW propagation in the Fe-rich microwire. Such magnetostatic interaction can be a useful tool for simple, and more flexible way of controllable trapping and braking of single DWs in Fe-rich microwires showing spontaneous magnetic bistability.

#### Data availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

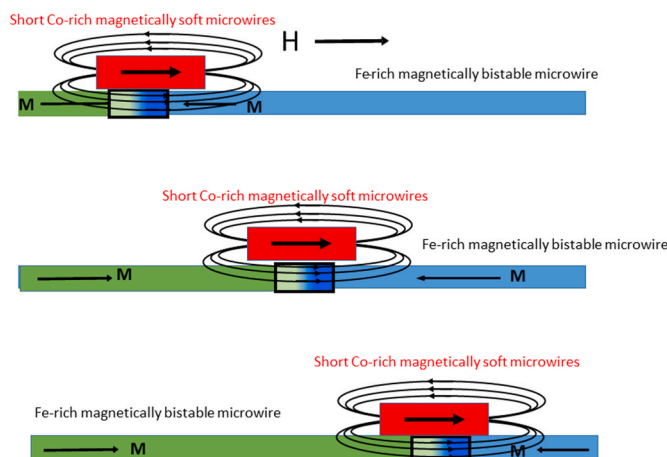


Fig. 8. Schematic picture of the engineering of DW propagation based on magnetostatic interaction in the system of linear arrays of two microwires.

#### Declaration of competing interest

The authors of the manuscript “Controlling of the single domain wall propagation in magnetic microwires by magnetostatic interaction” by Paula Corte-Leon, Alvaro Gonzalez, Juan Maria Blanco, Valentina Zhukova, Mihail Ipatov, Julian Gonzalez and Arcady Zhukov declare no competing financial or/and non-financial interests.

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