



Magnetization reversal of the transverse domain wall confined between two clusters of magnetic impurities in a ferromagnetic planar nanowire

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ARTICLE INFO

Article history:

Received 2 February 2016

Received in revised form

31 March 2016

Accepted 31 May 2016

Available online 9 June 2016

Keywords:

Rectangular nanowire

Transverse domain wall

Polarity switching

Magnetic impurities

Micromagnetic simulation

Magnetization dynamics

ABSTRACT

Numerical simulations have been used to investigate the polarity reversal of the transverse domain wall in rectangular magnetic nanowires and the stabilization of the domain wall position after occurring the polarity reversal. In order to control the wall position we have considered two clusters of magnetic impurities, identical and equidistant from the nanowire width axis. Traps of pinning and blocking for the transverse domain wall can be originated from magnetic impurities, consisting of a local variation of the exchange constant. Under suitable excitation amplitudes it is possible to switch the polarity of the transverse domain wall by applying a nanosecond axial magnetic field pulse in a fast and controllable way.

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1. Introduction

During the last decades the magnetization dynamics in nanostructured systems has become a subject of relevance from fundamental micromagnetism as well as for their new potential technological applications. Nanoscaled magnetic thin films are interesting objects to study exotic magnetic structures like vortices, skyrmions and domain walls. The detailed understanding of the static and dynamic properties of these nanoscale spin configurations is a crucial requirement for the realization of future spintronic devices [1–5]. Under suitable conditions, a single domain wall can be experimentally injected into a magnetic nanowire [6–9]. Vortex and transverse are two topologies of the domain wall that can exist in a planar nanowire made of a soft magnetic material [11,12]. The transverse domain wall can occur in four different profiles, once it is characterized by two mutually independent structural properties: charge and polarity. The wall charge (head-to-head or tail-to-tail) specifies the wall structure in relation to the magnetization orientation of the antiparallel

domains. The wall polarity (upward or downward) specifies the wall structure in relation to its magnetization, that is, the direction of magnetic moments in relation to the wire width axis. It is important to point out that several works refer to this structural property of the transverse domain wall as a chirality instead of polarity [13–15]. Multiple domain walls can coexist in the same magnetic nanowire, but it is necessary that adjacent domain walls alternate between head-to-head and tail-to-tail configurations. Although in a magnetic nanowire the domains walls are restricted to the unidirectional movement, the system response is very sensitive under the action of an external agent. When an external magnetic field is applied along the wire's long axis to move a transverse domain wall, the domain with magnetization oriented in the direction of the field expands to minimize the Zeeman energy. As a result, the motion direction of the wall depends only on its charge: a head-to-head domain wall is shifted in the direction of the field, whereas a tail-to-tail domain wall is shifted in the opposite direction. On the other hand, when a spin-polarized current is used to shift a transverse domain wall, it is observed that its motion direction is independent of both wall properties, charge and polarity. Thus, either wall profile will be shifted in the direction of the electron flow [3,10].

For the control of the domain wall motion it is very important to impose certain positions along the wire where the wall can stop. This is a crucial requirement for the racetrack memory [3], in

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which an entire encoded domain wall pattern moves coherently along a nanowire. In contrast with the racetrack memory, a new concept for a multibit memory cell employing the structural properties of a single transverse domain wall trapped around the notches in a planar nanowire has been proposed by Atkinson et al. [16]. In Ref. [15] it was reported that the polarity of the transverse domain wall can be not only detected but also reset by using a cross-shaped trap, moreover the authors introduced an important parameter associated with the transverse domain wall, the so-called domain wall fidelity length: a characteristic distance in which the domain wall maintains its structural integrity before undergoing Walker breakdown [17]. The polarity reversal of the transverse domain wall was also observed by applying an appropriated spin-polarized current in Fe/Permalloy double layer nanowires [18]. Recently a hourglass-shaped nanowire with a transverse domain wall trapped in the middle has been proposed to store information in the wall polarity [19]. As has been reported previously [18,20], the polarity reversal of the transverse domain wall is mediated by nucleation and annihilation of an antivortex and the basic physics behind the mechanism of the polarity reversal was widely discussed in Refs. [21–24]. It is worth mentioning that another mechanism has been reported in very narrower nanowires, i.e., the structure of the transverse domain wall can rotate about the wire long axis as a whole [19]. On the other hand, vortex domain walls can be present in wider and thicker nanowires. In this case, numerical simulations indicated that polarity of the vortex domain wall can be reversed when the vortex reaches one of the edges of the wire, where occurs its absorption and reemission with the opposite polarity [25].

Many devices based on domain walls require traps to stabilize the wall at predefined positions along the nanowire. These traps correspond to critical points, which can act either as pinning sites (potential wells) or blocking sites (potential barriers). The incorporation of artificial defects into the nanowire has been realized by local variations either of geometry [14,26–29] or of the magnetic properties [30–34]. Non-magnetic defects like notches patterned as part of the nanowire have been widely used as traps for domain walls. As an alternative method is to use ion irradiation to modify the magnetic properties in a selected area of the nanowire [35]. Magnetic defects (local variations of the exchange stiffness constant, saturation magnetization, anisotropy constant, damping parameter, and so on) are more interesting because they do not distort the wire geometry besides providing more parameters to control the strength of the pinning or blocking sites. In a previous study, we have introduced a Hamiltonian model being able to describe two types of point like magnetic impurities, which can behave as pinning or blocking traps for the transverse domain wall in magnetic nanowires [36].

Following the idea of using a magnetic nanowire as a multibit memory cell previously proposed by Atkinson et al. [16], let us consider two clusters of magnetic impurities, identical and equidistant from the nanowire width axis, as shown in Fig. 1.

A small axial magnetic field can be used to drive the domain wall up to one of these traps. As the transverse domain wall can occur in two different polarities, we have a four-fold degenerate state. Fig. 2 shows four possible states for a head-to-head

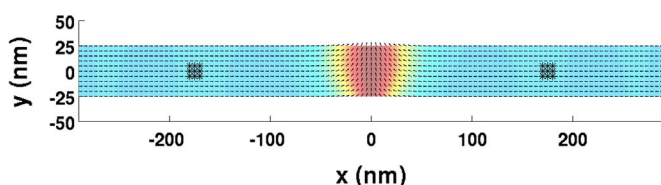


Fig. 1. Schematic view of the modified nanowires. The black spots represent two small clusters containing magnetic impurities located on the wire long axis.

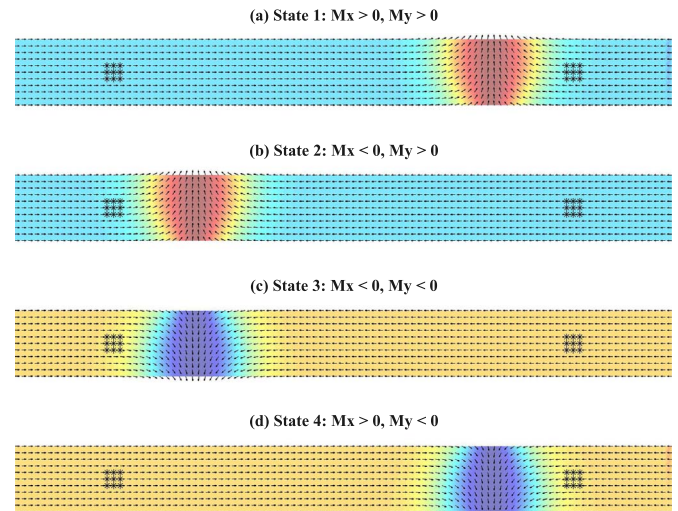


Fig. 2. Schematic view of possible states for a planar magnetic nanowire which contains only one transverse domain wall confined between two identical clusters of magnetic impurities. Considering the initial condition of the system with the wall in the state 1 and under appropriated influence of an external agent (magnetic field or spin-polarized current) the wall can reach another state, in this case, the final state can be 2 or 3 or 4. The transition from state 1 to state 2 characterizes a position switching, the transition from state 1 to state 3 indicates two switches, the polarity switching as well as the position switching.

transverse domain wall trapped around the one of two traps present in the nanowire. Each of these magnetic configurations can represent a different memory state. Once the pair of traps are located on opposite sides of the nanowire these magnetic configurations are energetically equivalent. These states can be obtained, for example, starting from a monodomain configuration. In this case, a transverse domain wall can be nucleated at one of the nanowire ends by applying a combination of magnetic fields: an axial field configures the wall charge whereas a transverse field configures the wall polarity. Very recently, we have performed numerical simulations to demonstrate that the position of the transverse domain wall can be controlled from a trap to another [37]. Thus, applying an appropriated axial magnetic field it is possible to displace the wall without changing its polarity. By increasing the excitation amplitude, the wall polarity can be randomly reversed during the Walker breakdown.

In this work, we have used micromagnetic simulations to investigate the position stabilization of a domain wall after occurring a single reversal of its polarity. The use of this arrangement of magnetic impurities showed that the strength of the pinning (or blocking) was independent of both charge and polarity of the transverse domain wall and it allowed us to stabilize the wall position with emerges from nucleation and annihilation of an antivortex. In other words, the wall with reversed polarity remains trapped around one of two clusters of magnetic impurities and the found results indicated that it is possible to switch the polarity of the transverse domain wall in a fast and controllable way. Thus, we can manipulate the properties of the existing wall without the need to inject a new transverse domain wall with a specific profile [16].

2. Model and simulation details

We have considered a simplified magnetic impurity model, which is based on the local variation of the exchange constant. Fig. 3 shows a schematic representation of a cluster of magnetic material into the sample, where both the host and the guest

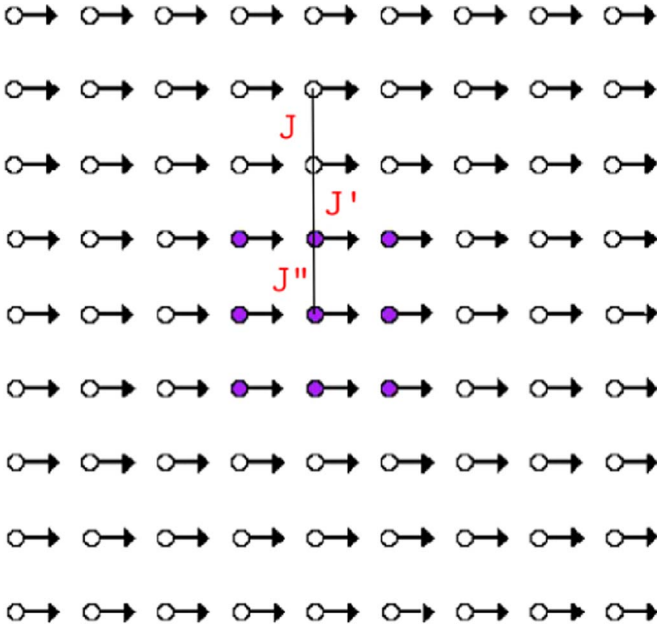


Fig. 3. Schematic view of a magnetic cluster incorporated into a nanomagnet. For simplicity, the magnetic moments are displayed in a square lattice. The purple sites represent magnetic impurities. J characterizes the strength of the exchange constant between host material sites. J' describes the exchange constant of mixed type interactions, which couple one site of the host material and other of the guest material. J'' measures the exchange constant strength of the interactions coupling two sites of the guest material. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

materials are soft ferromagnetic. Taking into account only the exchange interactions between the nearest-neighbor sites, one can identify three possible values for the strength of the exchange constant, see Fig. 3.

The classical ferromagnet model has been modified to describe the nanowire containing a distribution of magnetic impurities, which consists in the following Hamiltonian

$$H = J \left\{ -\frac{1}{2} \sum_{\langle i,j \rangle} \hat{m}_i \cdot \hat{m}_j + \right. \\ \left. -\frac{J'}{2J} \sum_{\langle i,j' \rangle} \hat{m}_i \cdot \hat{m}_{j'} - \frac{J''}{2J} \sum_{\langle i',j' \rangle} \hat{m}_{i'} \cdot \hat{m}_{j'} + \right. \\ \left. + \frac{D}{2J} \sum_{ij} \left[\frac{\hat{m}_i \cdot \hat{m}_j - 3(\hat{m}_i \cdot \hat{r}_{ij})(\hat{m}_j \cdot \hat{r}_{ij})}{(r_{ij}/a)^3} \right] + \right. \\ \left. -\frac{Z}{J} \sum_i \hat{m}_i \cdot \vec{b}_i^{ext} \right\} \quad (1)$$

where $\hat{m}_k \equiv (m_k^x, m_k^y, m_k^z)$ is a dimensionless vector with $|\hat{m}_k| = 1$ representing the magnetic moment located at the site k of the lattice. The first three terms in Eq. (1) describe the ferromagnetic coupling, taking into the local variation of the exchange constant account. The first and the third terms describe only the interactions among magnetic moments located in the host and the guest materials, respectively. In the second term, the exchange interactions at the interface between the two ferromagnetic materials have been modeled by ferromagnetic coupling. Furthermore, we assumed the following constraint among the strength of exchange constants: $J' = \sqrt{J \cdot J''}$. Consequently, the exchange constant strength at the interface J' always keeps between the values J and J'' . For the case $J' < J \Rightarrow J'' < J' < J$, the cluster of magnetic

impurities tends to pin the transverse domain wall and for the case $J'' > J \Rightarrow J < J' < J''$, the cluster of magnetic impurities tends to block the transverse domain wall [37]. The last two terms in Eq. (1) are dimensionless versions of dipolar and Zeeman interactions respectively. The Hamiltonian can be rewritten as $H = J \mathcal{H}$, where $\mathcal{H}$ is the dimensionless term in curly brackets. The system energy is measured in unities of J .

In the micromagnetic approach the interaction constants depend on the material parameters and also the manner in which the system is partitioned into cells. Following the methodology developed by Wysin in the Ref. [38], each cell contains an effective magnetic moment $\vec{m}_i = (M_S V_{cel}) \hat{m}_i$, where V_{cel} is the volume of the work cell. To ensure that all microscopic magnetic moments in each cell are aligned due to exchange interaction, the cell size was chosen based on the exchange length $\lambda = \sqrt{\frac{2A}{\mu_0 M_S^2}}$, which depends

on material parameters: the exchange stiffness constant A and the saturation magnetization M_S . The magnetic nanowires were discretized into a simple cubic lattice $V_{cel} = a^3$. In this case, the interaction constants among the cells are given by $J = 2Aa$ and $\frac{D}{J} = \frac{1}{4\pi} \left(\frac{a}{\lambda} \right)^2$. In the presence of an applied magnetic field, the

coefficient of Zeeman interaction is $\frac{Z}{J} = \left(\frac{a}{\lambda} \right)^2$. The connection between applied magnetic field and its dimensionless corresponding is given by $\vec{b}_i^{ext} = \frac{1}{\mu_0 M_S} \vec{B}$.

The dynamics of the system is followed by solving numerically the discrete version of the Landau-Lifshitz-Gilbert equation given by

$$\frac{d\hat{m}_i}{d\tau} = -\frac{1}{1+\alpha^2} \left[\hat{m}_i \times \vec{b}_i + \alpha \hat{m}_i \times (\hat{m}_i \times \vec{b}_i) \right] \quad (2)$$

where $\vec{b}_i = -\frac{\partial H}{\partial \hat{m}_i}$ is the dimensionless effective field at site i containing individual contributions from the exchange, dipolar and Zeeman fields. The connection between time and its dimensionless corresponding is given by $\Delta t = \frac{1}{\omega_0} \Delta \tau$, where

$\omega_0 = \left(\frac{\lambda}{a} \right)^2 \gamma \mu_0 M_S$, being γ the gyromagnetic ratio. As in references [39–41], the typical parameters for Permalloy-79 ($\text{Ni}_{79}\text{Fe}_{21}$): $A = 1.3 \times 10^{-11} \text{ J/m}$, $M_S = 8.6 \times 10^5 \text{ A/m}$ and $\alpha = 0.01$ were used to estimate the exchange length as $\lambda_{\text{Py-79}} \approx 5.3 \text{ nm}$ and the work cell volume was chosen as $V_{cel} = 5 \times 5 \times 5 \text{ nm}^3$.

The equations of motion (2) were integrated numerically using the fourth-order predictor-corrector scheme with time step $\Delta \tau = 0.01$. Simulations were performed assuming the Permalloy-79 as the host material in nanowires with length $L = 1 \mu\text{m}$, width $d = 50 \text{ nm}$ and thickness $t = 5 \text{ nm}$, differing in the magnetic impurities arrangement parameters: the local variation of the exchange constant and the relative distance between the clusters. The adopted coordinate system is shown in Fig. 1 and we have investigated four different values to the relative distance between the clusters D_c as 200, 250, 300 and 350 nm. We have considered a variety of possible candidates for the guest material (clusters of impurities), being attributed seven different values to the ratio of exchange constants J''/J . For a local reduction of the exchange constant we assumed for the J''/J the following values: 0.25, 0.50 and 0.75, whereas for a local increase of the exchange constant we used 1.25, 1.50, 1.75 and 2.0. Let us note that the pinning and blocking effects become weaker when $J''/J \rightarrow 1^-$ and $J''/J \rightarrow 1^+$ respectively. In a previous study [41] we have suggested two possible candidates for the guest material, a cluster of Ni or Fe in Permalloy nanowires should act as a local trap for pinning or blocking the wall respectively.

3. Results and discussion

The mechanism of polarity reversal is mainly governed by the parameters of an external agent, in our case, the amplitude and duration of the magnetic field pulse. The typical switching time is a few nanoseconds, thus pulses of this duration are needed to switch the wall polarity [42]. Therefore we have considered a nanosecond pulse in our simulations. We have chosen as initial condition the system with a single transverse domain wall placed near the trap on the right and the wall polarity was configured to point upward (see, for example, Fig. 2 (a)). The methodology used to obtain this equilibrium configuration is described in the Ref. [37]. Over a wide range of the excitation amplitudes B and exchange constant ratio J''/J , we numerically calculated the dynamic response of the wall under the influence of a homogeneous magnetic field pulse applied along the nanowire long axis, given by $\vec{B}_i^{ext} = B \hat{x}$. The duration of the pulse was always the same $\Delta t = 1.0$ ns and the direction of the magnetic field has always been configured to point from the cluster where the wall was trapped to the other one. At low excitation amplitudes, we have observed that the domain wall propagates without changing its polarity. For the system with stated dimensions and for a nanosecond magnetic field pulse we have noted that there was a critical excitation amplitude, about 7.5 mT, which was the minimum value of the required field for the nucleation of an antivortex. For excitation amplitudes range from 7.5 up to 17.0 mT the antivortex is nucleated close to one wire ends and the wall with reversed polarity is expelled by the one other; after the antivortex annihilation

finishes, the newborn wall moves in the opposite direction to that one provided by the pulse and due to its large momentum, the wall overcomes the two traps and the system becomes a monodomain. We have found a critical range, around 18.0 mT, where the polarity reversal occurred abruptly, being the antivortex nucleated inside the region delimited by the two traps. In these situations, the newborn wall emerged with a very low momentum and it could be stabilized around one of two traps (clusters of magnetic impurities).

Fig. 4 shows event diagrams for the final state of the whole sample set, one can note that the control of the wall position after occurring a single reversal of its polarity occurs in a very well defined range of parameters. From (a) to (d) the relative distance between the clusters increases of 50 in 50 nm. The spots on any horizontal line represent the same nanowire with the same initial condition (transverse domain wall with upward polarity and trapped by the cluster on the right), but submitted to different excitation amplitudes. In response to the applied field pulse, the transverse domain wall moves in the negative x direction and undergoes a Walker breakdown [17]. It is very difficult to stabilize the wall which emerges from nucleation and subsequent annihilation of an antivortex.

At lower or higher excitation amplitudes, the system becomes a monodomain (black squares in Fig. 4). Although the wall polarity is reversed, it is not possible to control its position, thus the wall polarity can not be flipped in a controllable way. However, there were appropriated amplitudes in which the wall polarity was reversed and the system conserved its configuration with two

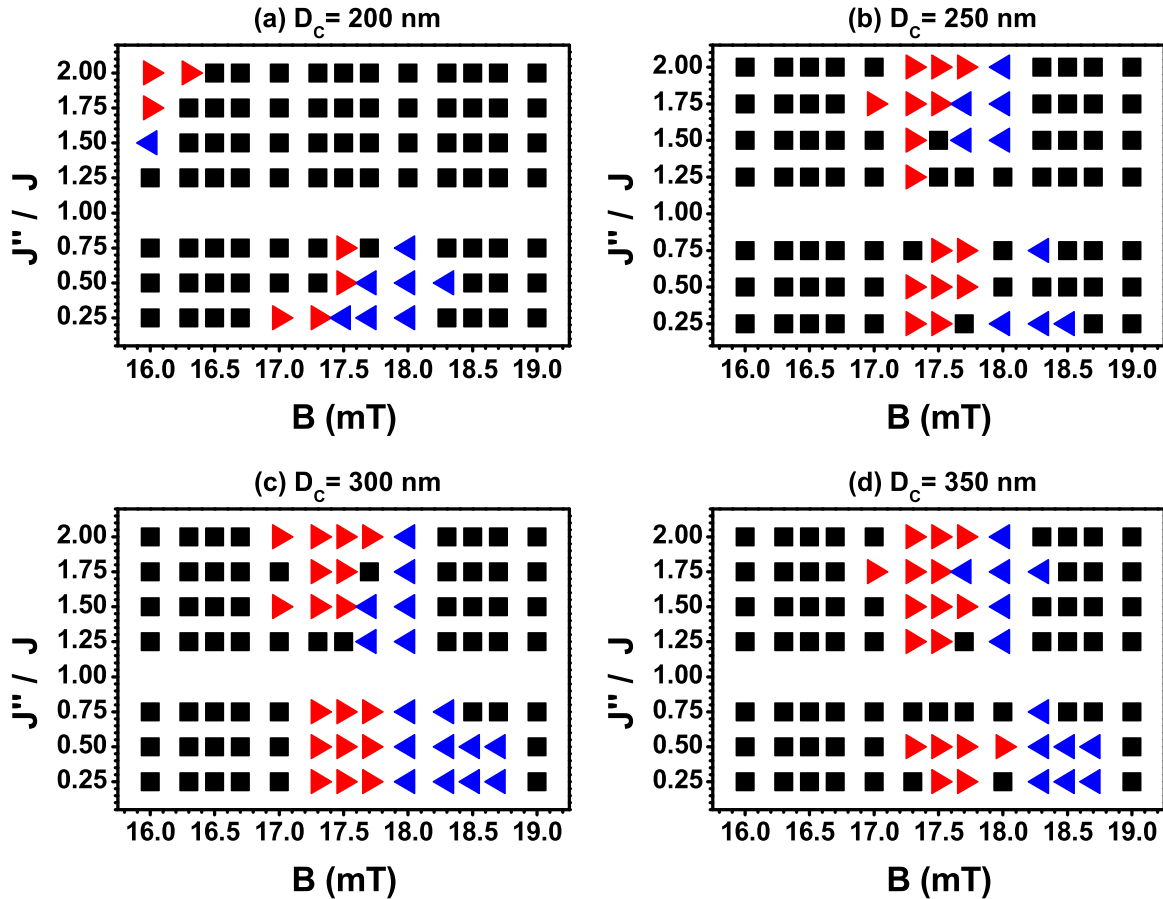


Fig. 4. Position controllability diagram after occurring a single reversal of the transverse domain wall polarity in Permalloy nanowires with two identical clusters of magnetic impurities. Black squares include events in which occurred the polarity switching, but the wall was immediately expelled by one of the wire ends. Triangles correspond to a combination of parameters for which the domain wall position could be controlled after the occurrence of a single polarity switching. Red triangles represent the event in which only the polarity switching happened. Blue triangles indicate the event in which not only the polarity switching happened but also the position switching. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

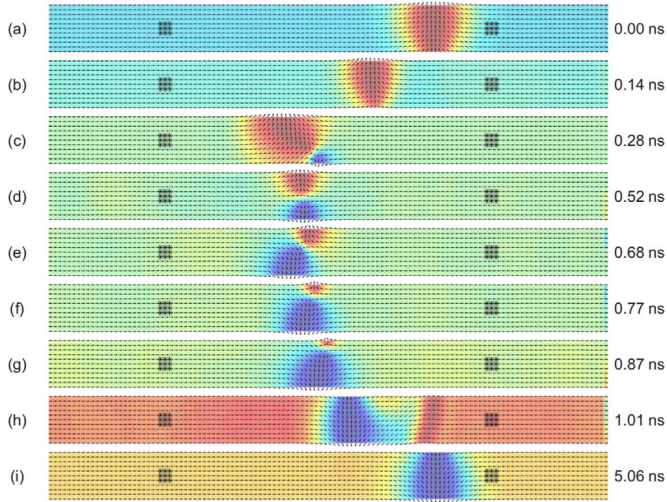


Fig. 5. Snapshots images of the controllable switching of transverse domain wall polarity in Permalloy planar nanowires presenting two clusters of magnetic impurities characterized by $D_c = 300$ nm and $J^*/J = 2.0$. The polarity switching was excited under the influence of a nanosecond magnetic field pulse of 17.5 mT. From the top to the bottom, equilibrium initial configuration of the system at $t = 0$ and configurations after 0.14, 0.28, 0.52, 0.68, 0.77, 0.87, 1.01, 5.06 ns. The simulation for later times shows that the wall position at 5.06 ns is an equilibrium configuration. These snapshots images demonstrate that the wall returned to its initial position with the reversed polarity. This event is represented by red triangles in Fig. 4. In order to observe that it is a reversible process, see videos in the Supplementary material [43] labeled as S1 and S2 where the external agent is applied once again. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

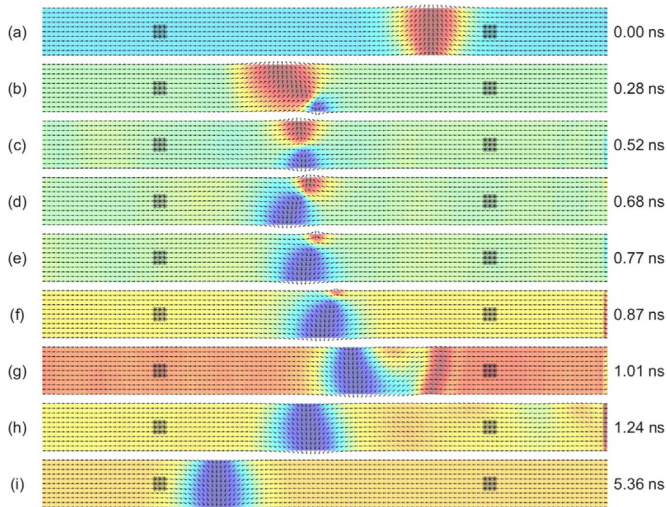


Fig. 6. Snapshots images of the controllable switching of transverse domain wall polarity in Permalloy planar nanowires presenting two clusters of magnetic impurities characterized by $D_c = 300$ nm and $J^*/J = 2.0$. The polarity switching was excited under the influence of a nanosecond magnetic field pulse of 18.0 mT. From the top to the bottom, equilibrium initial configuration of the system at $t = 0$ and configurations after 0.28, 0.52, 0.68, 0.77, 0.87, 1.01, 1.24, 5.36 ns. The simulation for later times shows that the wall position at 5.36 ns is an equilibrium configuration. These snapshots images demonstrate that the wall stayed in the opposite position to its initial position with the reversed polarity. This event is represented by blue triangles in Fig. 4. In order to observe that it is a reversible process, see videos in the Supplementary material [43] labeled as S3 and S4 where the external agent is applied once again.

domains, so that, the domain wall position can be controlled after a single reversal of the wall polarity. Since there are two possibilities for the final state of the wall position, the polarity switching can be or not accompanied by the position switching (see, for examples, Figs. 5 and 6). Red triangles represent the event in

which the wall returned to its initial position with the reversed polarity, (For examples, see videos in the Supplementary material [43] labeled as S1 and S2). On the other hand, blue triangles indicate the event in which the wall stayed in the opposite position to its initial position with the reversed polarity (For examples, see videos in the Supplementary material [43] labeled as S3 and S4).

4. Conclusion

In summary, we have performed numerical simulations to investigate the magnetization dynamics of a single transverse domain wall present in a Permalloy planar nanowire with thickness $t = 5$ nm and width $d = 50$ nm. A nanosecond axial magnetic field pulse was used to induce domain wall motion. We have observed that the polarity reversal of the transverse domain wall can occur during its propagation when the field amplitude was larger than a certain value (about 7.5 mT for the considered nanowire). The polarity reversals observed in our simulations were mediated by nucleation and annihilation of an antivortex. This mechanism of polarity reversal is very well discussed in Ref. [24]. Once Permalloy nanowires are weakly damping systems, during the wall propagation its polarity can flip randomly. Thus, one of the fundamental issues for the realization of spintronic devices is how to switch the polarity from one state to another in a fast and controllable way. The main goal in this paper was to study of the polarity reversal of the transverse domain wall under the condition that the wall with reversed polarity was stabilized at predefined positions. For this purpose, we have considered the usage of a distribution of magnetic impurities consisting of two clusters, which work as traps for pinning or blocking the wall. The control of the wall position using a pair of magnetic impurities was addressed in a previous work [37] and requires smaller excitation amplitudes than the polarity control does, about one order of magnitude. In the present work we had to increase the size of the magnetic impurity clusters, in order that the pinning and blocking effects become stronger. Thus, it was possible to stabilize the newborn wall which emerges from nucleation and subsequent annihilation of a antivortex. As a result, we can switch the polarity of the wall in a fast and reversible way. For an axial magnetic field pulse with duration of 1 ns, the required amplitude to reverse the wall polarity and control its position is about 17.5 mT. Thus, we have found that typical time interval from the pulse application to stabilization of the wall position is about 5 ns. Our result for switching time is of the same order of magnitude than the obtained in a previous work by Vanhaverbeke et al. [18]. In contrast to previous studies on the polarity control, we showed that the polarity switching can be managed in a Permalloy nanowire with two traps, in our nanowire no local modification of system geometry is required [19] or even an additional ferromagnetic layer [18]. The polarity switching mechanism in a fast and controllable way must involve an external agent strong enough to provide the required energy in order that the nucleation and annihilation of the antivortex occurs inside the region delimited by the two traps; it can be achieved by tuning the parameters of the external agent and the relative distance between the traps. It is worth mentioning that the polarity switching mechanism is not result of the wall-impurities interaction, the traps are only necessary to provide stability for the wall and control the Walker breakdown in order to obtain a single polarity reversal of the transverse domain wall. Once the position and polarity of the wall can be controlled independently, the modified magnetic nanowire is attractive from a data storage perspective, because it would enable the realization of ultrafast and high-density nonvolatile memory devices. Although the results presented here are for a very simple distribution of magnetic impurities, we believe their consequences can be planned and

extended for the design and realization of future spintronic devices based on domain walls.

Acknowledgments

This work was partially supported by CNPq, CAPES and FAPEMIG (Brazilian Agencies). Numerical works were done at the Laboratório de Simulação Computacional do Departamento de Física da UFJF.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.jmmm.2016.05.107>.

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- [43] See the Supplemental material at [URL will be inserted by J.M.M.M.] for videos of the following: videos S1 ($J''/J = 0.25$ and $B = 17.5$ mT) and S2 ($J''/J = 2.00$ and $B = 17.5$ mT) show respectively the reversible change of the transverse domain wall polarity using a pair of traps acting as pinning and blocking sites. Videos S3 ($J''/J = 0.25$ and $B = 18.5$ mT) and S4 ($J''/J = 2.00$ and $B = 18.0$ mT) show respectively the reversible change of the transverse domain wall polarity and its position using a pair of traps acting as pinning and blocking sites.