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# Domain walls dynamics in multisegmented Ni/Co nanowires

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The current induced motion of transverse magnetic domain walls (DWs) in a multisegmented Co/Ni nanowire is investigated numerically. We find that the phase diagram current pulse length – magnitude presents a rare diversity of behaviors depending on the segments length and material parameters. We show that by changing only the pulse shape, in a range of parameters, we obtain the controlled motion of the DW with or without polarity change. The polarity change arises in the simplest case from the birth and propagation of an antivortex along the width of the nanowire. The antivortex can be displaced over long distances depending on the pulse characteristics and boundary conditions. The systematic motion of the DW with polarity flip is found to be stable at room temperature. Moreover, by modifying the material parameters through alloying, the phase diagram can be engineered decreasing the depinning current and paving the way for storage or logic applications.

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## I. INTRODUCTION

An increasing number of magnetic nanostructures are studied nowadays for their storage or logic properties. Functional devices are designed that use the magnetic domains as digital bits which are displaced in controlled manner inside the nanostructure. These devices take advantage of the domain wall (DW) motion induced by a magnetic field or a spin polarized electric current[1, 2] in a flat or cylindrical nanowire. The central ingredient is the proper manipulation of the DWs motion between well-defined positions (pinning centers) in the nanowire in a reproducible manner[3, 4]. Several approaches were used to tailor the domain wall energy landscape like artificial constrictions or protuberances[5–9], bending[10] or local modifications of the magnetic properties like anisotropy or the saturation magnetization[11–13].

Recently, multisegmented nanowires (sometimes referred as multilayered nanowires), which are formed by alternating regions of different composition and structure along the longitudinal axis, were investigated for spintronic applications. Ferromagnetic (FM)/FM[14, 15] or FM/non magnetic (NM)[16] multisegmented nanowires were studied for shift registers[17], magnetic nano-oscillators[18] or flexible spin caloritronic devices[19]. In most cases, cylindrical nanowires were fabricated by electrochemical deposition in alumina templates[20], which allows for readily modifications of geometrical aspect or material properties. Metallic FM/FM multisegmented cylindrical nanowires, composed of Co and Ni segments were shown experimentally to efficiently pin the vortex domain walls at the Co/Ni interface[15]. It was shown that individual Co nanowires can be prepared as single-crystals with *hcp* structure and controlled easy axis orientation [21]. A ferromagnetic nanowire with segments of

different materials and different orientation of the magnetization easy axis can therefore be easily engineered. However, the complex magnetic states (multi-vortex) observed in these wires and the DW dynamics are not completely understood.

In this paper we address this issue, by studying the systematic motion of a magnetic transverse DW in a Co/Ni multisegmented nanostrip (flat nanowire) when submitted to ultrashort spin-polarized current pulses at low and room temperature. When the magnetocrystalline anisotropy easy axis is oriented out-of-plane for the Co segments, a complex periodic pinning potential is created in which an individual transverse DW moves between pinning sites (the Ni regions) for a large range of geometrical characteristics (width/length/number) of segments. The stray field generated at the interfaces between Co and Ni regions deform strongly the DW, which behaves like a string in a tilted washboard potential[22]. When a current pulse is applied, the DW is tilted out-of-plane (tilting angle  $\psi$ ) which is usually suppressed by the effective wall anisotropy  $K_{\perp}$ . A small variation in  $K_{\perp}$  can cause an exponentially large change in  $\psi$  at the segments edges[23], and for certain pulse characteristics and material parameters an antivortex appears[24] that can traverse the nanostrip width switching the transverse DW polarity. More complex structures can appear as a vortex-antivortex pair depending on the exchange energy variation and boundary conditions at the interfaces. We show that by varying only the current pulse shape, in a certain parameter range, the transverse DW can be reliably displaced with or without polarity change with potential applications for storage devices. Our results show that, the systematic DW displacement between pinning regions with polarity switch is stable at room temperature in a Co/Ni multisegmented nanowire. We also determine the impact of the material parameters variation, for example by alloying, on the depinning current and phase diagrams. A 1D model is developed that agrees with the numerical one only in the parameter range where no

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vortex-antivortex structures appear. Our study brings new physical insight into DW motion in multisegmented nanowires and could lead to future theoretical and applied studies.

This article is organized as follows. In Sec. II, we present the numerical simulations and stochastic 1D model used to calculate the DW displacement. In Sec. III, we compute and investigate the phase diagram of the DW dynamics in an infinite nanostrip at T=0K and at room temperature. Discussion and concluding remarks are presented in Sec. IV.

## II. MODEL

The dynamics of the DWs is governed by the Gilbert form of the Landau-Lifschitz equation with adiabatic and non-adiabatic spin-transfer torques[25]:

$$\dot{\mathbf{m}} = -\gamma_0 \mathbf{m} \times \mathbf{H}_{eff} + \alpha (\mathbf{m} \times \dot{\mathbf{m}}) - (\mathbf{u} \cdot \nabla) \mathbf{m} + \beta \mathbf{m} \times (\mathbf{u} \cdot \nabla) \mathbf{m} \quad (1)$$

where  $\mathbf{m}$  is the normalized magnetization,  $\gamma_0$  is the gyromagnetic ratio,  $\mathbf{u} = \mathbf{j}_e P \mu_B / e M_s$  is the spin drift velocity,  $P$  the spin polarization of conduction electrons (taken as 0.7 in numerical simulations),  $\mu_B$  the Bohr magneton and  $\mathbf{j}_e$  the applied current density. The temperature is added to the LLG equation in the form of a thermal field with zero average and uncorrelated in time and space.

We study the dynamics of a transverse DW in a multisegmented nanostrip of Co and Ni regions. The type of DW in confined nanostructures depend on the nanostrip dimensions[26]. The length of the regions/segments (along the longitudinal  $x$  axis) is varied between 20 and 40 nm for Ni and between 50nm and 90 nm for Co. The width (along  $y$  axis) and the thickness of the nanostrip are kept constant at 60nm and respectively at 5nm, while the total strip length is varied around the value of 1300nm to ensure that the end regions are always made of Co (Fig.1(a)). The following parameters are used for Ni: saturation magnetization  $M_s=477$  kA/m, exchange stiffness parameter  $A = 8.6$  pJ/m and damping parameter  $\alpha = 0.05$ , and for Co: saturation magnetization  $M_s=1400$  kA/m, exchange stiffness parameter  $A = 28.1$  pJ/m, damping parameter  $\alpha = 0.005$  and uniaxial magnetocrystalline anisotropy (MCA)  $K_u = 4.5 \times 10^5$  J/m<sup>3</sup>[27] if not specified otherwise. When the Co MCA easy-axis is directed along the perpendicular  $z$ -axis, the transverse DW is pinned in the Ni regions for the geometrical dimensions of the regions chosen (see Fig.1(a)), with the magnetization in-plane. When the Co MCA is directed along the transverse  $y$ -axis a single DW is no longer a stable state and the DWs are pinned in the Co regions as shown in Fig.1(b). As the reliable control of the DW position is a prerequisite for memory applications, only the case with the Co regions having perpendicular  $z$ -axis MCA is studied below.

A series of periodic spin polarized current pulses are applied along the stripe longitudinal axis ( $x$ -direction) to

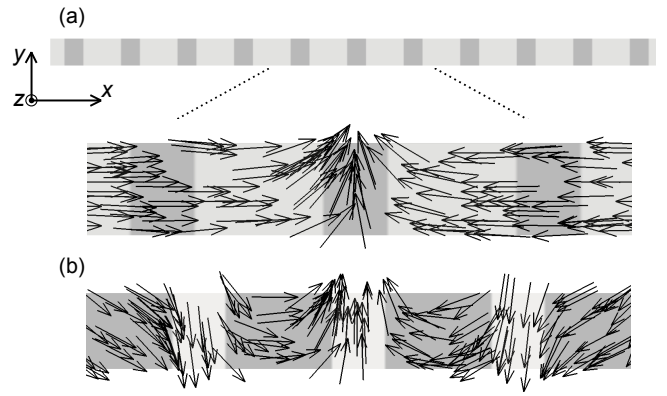


FIG. 1: (Color online) (a) Multisegmented Co/Ni nanowire with an in-plane transverse domain wall. The Ni regions (40 nm length) are shaded and the Co regions (80 nm length) have a magnetocrystalline anisotropy along the  $z$  axis. The arrows indicate the direction of the magnetization. The enlarged section shows the central regions with the transverse domain wall. (b) Expanded part of the multisegmented nanowire when the Co regions have a magnetocrystalline anisotropy along the  $y$  axis. The length of the regions have been inverted: Co regions of 40 nm and Ni regions of 80 nm. The nanowire is 1300 nm long, 60 nm wide and 5 nm thick.

displace the DW, which is initiated in the central Ni region. The current pulse has a trapezoidal geometry with  $t_r$ ,  $t_s$  and  $t_f$  the rise, stable and fall time[3]. The periodic pulses are separated by  $t_z$ , the zero-current time which ensures that the DW reaches its equilibrium position before another pulse is applied. The nonadiabatic parameter is set to  $\beta=2\alpha$ , if not specified otherwise.

The DW dynamics was computed mainly using 3D micromagnetic simulations with the MUMAX3 package [28], some simulations were also conducted with the OOMMF package[29]. The strip was discretized into a mesh with a cell size of  $2 \times 3 \times 2.5$  nm<sup>3</sup>, inferior to the exchange length. A one-dimensional model[30] was also developed to understand the DW displacement in the multisegmented wire. The analytical equations of motion used are based on the 1D model of the DW (collective coordinates: average DW center position  $X$  and azimuthal angle  $\psi$ )[31, 32]:

$$\begin{aligned} (1 + \alpha^2) \dot{X} &= - \frac{\alpha \gamma \Delta}{2 \mu_0 M_s S} \frac{\partial E}{\partial X} + \frac{\gamma \Delta}{\mu_0 M_s} K_{\perp} \sin 2\psi \\ &+ qp \frac{\gamma}{2 \mu_0 M_s S} \frac{\partial E}{\partial \psi} + (1 + \alpha \beta) u + \eta_{\psi} - \alpha \eta_X \\ (1 + \alpha^2) \dot{\psi} &= - qp \frac{\gamma}{2 \mu_0 M_s S} \frac{\partial E}{\partial X} - \frac{\gamma \alpha}{\mu_0 M_s} K_{\perp} \sin 2\psi \\ &- \frac{\alpha \gamma}{2 \Delta \mu_0 M_s S} \frac{\partial E}{\partial \psi} + qp \frac{\beta - \alpha}{\Delta} u + \eta_X + \alpha \eta_{\psi} \end{aligned} \quad (2)$$

with  $\Delta$  the DW width,  $K_{\perp}$  the transverse anisotropy,  $\eta_X$  and  $\eta_{\psi}$  represent stochastic Gaussian noise with zero mean value and correlations  $\langle \eta_i(t)\eta_j(t') \rangle = (2\alpha k_B T)/(\mu_0 M_s \Delta S) \delta_{ij} \delta(t-t')$ .  $E$  is the potential energy of the DW that includes the internal energy and the pinning energy. The azimuthal angle of the DW  $\psi$  represents the conjugate momentum in the Lagrangian formulation.  $q = \frac{1}{\pi} \int dx \partial_x \psi = \pm 1$  represents the chirality or the topological charge of the DW and is related with the direction of rotation of the in-plane magnetization when traversing the DW and  $p = \pm 1$  represents the direction of the magnetization at the DW center along the  $y$ -axis (width). The product  $Q = q \cdot p$  is always equal to +1 for a head-to-head DW and to -1 for a tail-to-tail DW.

In the present situation, the DW moves in an effective pinning potential that arises due to the magnetic parameters variation between the segments. The 1D model still give good quantitative results (see Ref.33), if the azimuthal angle  $\psi$  stays well below  $\pi/4$ . The pinning potential can be determined from micromagnetic simulations together with the numerical integration of the DW energy allowing for continuous  $x$ -axis variation of the material parameters ( $K$ ,  $A$ ,  $M_s$ ,  $\alpha$ ,  $\beta$ )[12, 13] contrary to the micromagnetic model where an abrupt transition between segments is considered excepting the exchange energy (the details of the 1D calculation are presented elsewhere). One parameter that varies locally and can introduce numeric artifacts near interfaces is the exchange energy calculation. In its usual implementations, the exchange energy is approximated between nearest or second-nearest neighbors or interpolated between nearest grid points with the Neumann or Dirichlet boundary conditions[34]. The interfaces can lead to singularities in the magnetization due to a jump in the exchange stiffness  $A$  and its effect was studied from some time in connection with grain boundary effects[35, 36]. The effective exchange between adjacent pairs of atoms is usually overestimated particularly in soft magnets when considering the same effective exchange strength over the interface (see Ref.35 and references therein). In micromagnetic packages the effective exchange interaction is usually assumed identical on both sides of the interface and calculated by default as a harmonic mean of the values on each side of the interface. A reduced interface exchange may be closer to reality as a real interface may have impurities or mixing phases or be amorphous and was considered below. The details of the exchange stiffness variation in the interface region are described in the Supplementary Material [33].

### III. RESULTS

In this section we study the impact on the DW dynamics of the segments length and material parameters variation at zero and room temperature. The phase diagram (stable time  $t_s$  - current amplitude  $j_e$ ) obtained

when periodic current pulses are applied shows a rich variety of stable states including systematic displacement with or without DW polarity change.

#### A. Influence of the segments length on the phase diagrams at $T = 0K$

To describe the DW dynamics in a Co/Ni multisegmented nanowire (Fig. 1(a)), we use the analysis previous used for the DW dynamics in a notched nanowire[3, 4]. A transverse DW pinned in a Ni region in the center of the nanowire is submitted to a series of periodic trapezoidal spin-polarized current pulses. The Ni regions represent the pinning sites for DW displacement. For a reliable control of DW propagation, the DW should move forward and backward to the same position after a periodic current pulse. The current pulses are varied in length, amplitude or shape and the DW motion is extracted after several periodic current pulses. The relative DW position, after the series of periodic pulses, is represented in a phase diagram (stable time  $t_s$  - current amplitude  $j_e$ ). The regular DW displacements were shown to form bands depending on the pulse characteristics in notched nanowires[3, 4].

In Fig. 2, the influence of the segments length variation on the phase diagram is shown at  $T=0K$ . The Ni segments were varied between 20 and 40 nm (top row to bottom row), while the Co segments were varied between 50 and 90 nm (left column to right column). The bands were indexed as follows: band 0 if the DW stays pinned in the initial Ni segment, band +1 if the DW was displaced periodically to the nearest neighbor Ni segment in the direction of the spin transfer torque (STT) and band -1 if the DW was displaced to the nearest neighbor Ni segment in the opposite direction of the STT. The superior bands ( $\pm 2$  etc.) correspond to the DW displacement between the initial pinning site and the second neighboring site and so on. The 'u' state represents an unintended state where the DW does not move periodically back and forth to the initial pinning site or depins completely.

The pinning potential varies strongly with the segments length[33]. For a small length, the pinning barrier is small and the DW can move easily between the pinning sites as shown in panel (a). In this case the DW depins easily and the bands are thin and a reliable control cannot be achieved. Increasing the Ni or Co segments length by 10 nm, increases strongly the stability and the band width (panels (b) and (f)). The pinning potential of the Ni segments becomes important as soon as the segment width increases above the domain wall width (25nm in Ni). Increasing the Ni width even more, diminishes the slope of the pinning potential without a clear modification of the pinning barrier height (details in Ref.33). Increasing the Co length, increases the barrier height but not the pinning potential slope. The depinning current has a complex dependence on the Ni and Co segments length. It increases with increasing Co or Ni length as

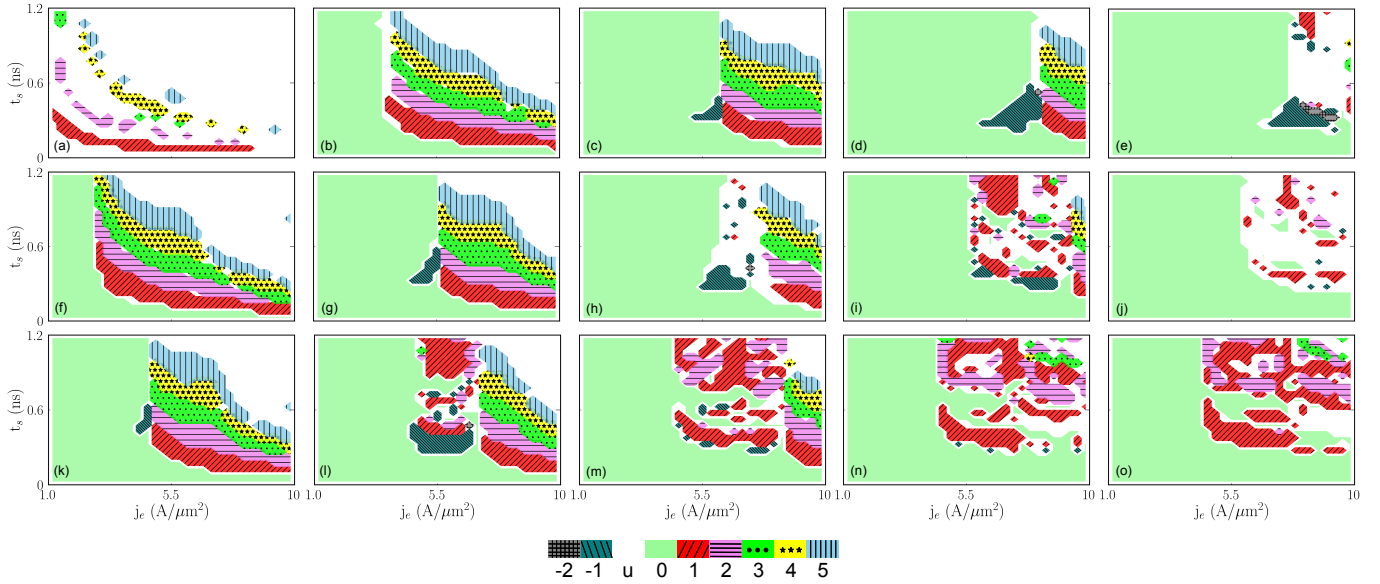


FIG. 2: (Color online). Micromagnetic phase diagrams (pulse stable time – pulse amplitude) of DW motion under a periodic current pulse in a multisegmented Ni/Co nanowire at  $T=0\text{K}$ . The periodic pulse is formed by two identical current pulses of opposite amplitude (forward-backward motion) separated by a waiting time of 5ns. The length of the Ni and Co regions is varied as: from the top row to the bottom row the Ni regions length increases from 20 nm (top row) to 40 nm (bottom row) in steps of 10nm, while the Co regions length increases from left column to right column from 50 nm (left column) to 90 nm (right column) in steps of 10 nm. The thickness of the nanowire is 5 nm and its total length is around 1300 nm (varies slightly to always have Co regions at the ends). The observed DW motion is classified in bands numbered as follows: positive bands correspond to the DW moving in the direction of the electron flow, negative numbers to the DW moving contrary to the electron flow, zero state correspond to the DW staying pinned at initial position and 'u' to the unintended states in which the DW does not come back to the initial state after the periodic pulse.

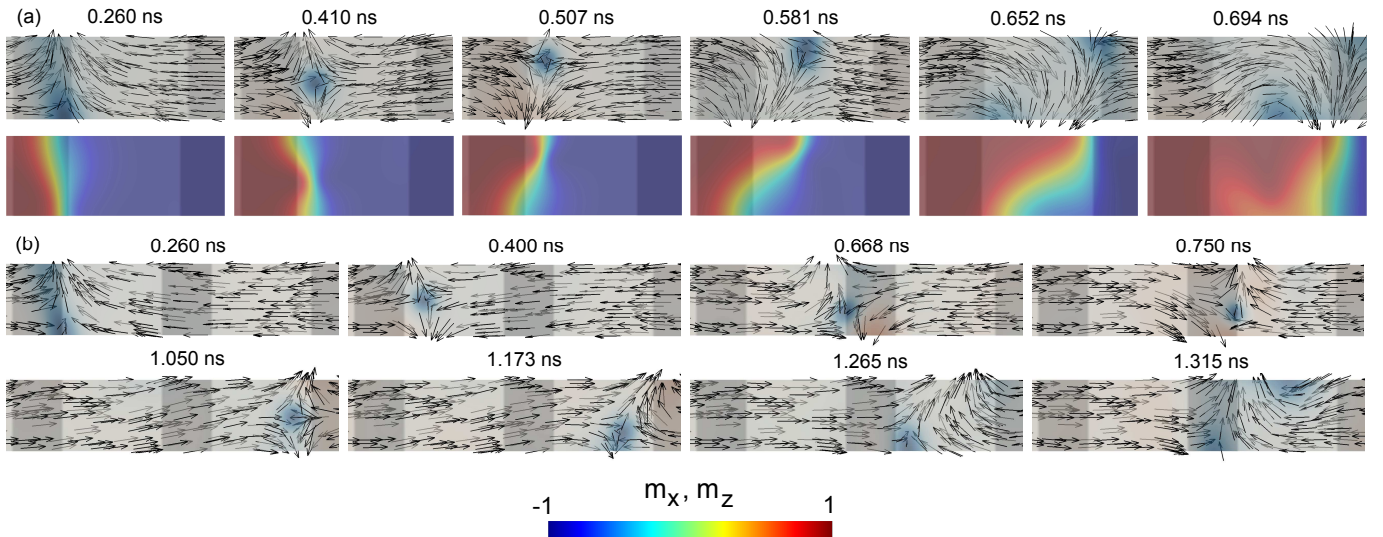


FIG. 3: (Color online) DW displacement in a 40nm Ni/ 80 nm Co segmented nanowire under a current pulse with  $t_s = 400\text{ps}$ ,  $j_e=5.5 \text{ A}/\mu\text{m}^2$  (a) or  $t_s = 1050\text{ps}$ ,  $j_e=6.4 \text{ A}/\mu\text{m}^2$  (b) was applied. Both cases correspond to a state +1. The Ni regions are indicated by darker colors. In panel (a), an antivortex is observed crossing the nanowire width (first row, blue circle) while the TDW changes polarity when moving to the nearest Ni region. In panel (b) the antivortex does not cross the nanowire width and is expelled on the same edge it entered. The TDW does not change its polarity when moving to the nearest Ni region. The second row in panel (a) shows the  $m_x$  component of magnetization, illustrating the DW deformation in the process.

long as the DW motion forms regular bands in the phase diagram. Starting from (20 nm Ni)/(90 nm Co) (panel (e)), (30 nm Ni)/(70 nm Co) (panel (h)) and (40 nm Ni)/(60 nm Co) (panel (l)), the depinning does not start with regular DW bands but with non regular (chaotic like) pockets/branches of the bands that appear in the phase diagrams. In these cases, the depinning current decreases with increasing segments length.

In the areas of the phase diagrams where the non regular branching of the bands appear, the DW starts to depin due to the apparition of an antivortex at the boundary between the Ni and Co regions similar to the depinning from a notch[24, 37]. This depinning mechanism is detailed in Fig. 3 for (40 nm Ni)/(80 nm Co) multisegmented nanowire (phase diagram in Fig. 2(m)). The DW behaves like a string in an tilted washboard potential[22] and cannot be treated as 1D any longer. The position and azimuthal angle depend on the  $y$  coordinate. It was shown in Ref.23 that the azimuthal angle  $\psi$  of a 2D DW segment varies as a solution of a Schrodinger type equation, with the DW anisotropy  $K_{\perp}$  playing the part of the difference between the potential barrier energy and the particle energy. The exponential like solutions of the Schrodinger equation apply to the azimuthal angle, and a small change in the DW anisotropy at the lower and upper edges induces an exponential increase of  $\psi$  at the boundaries. The DW anisotropy changes drastically at the boundary between the Ni and Co regions, therefore a tilting of the azimuthal angle out of the plane is favored. The antivortex appears at the lower edge where the DW center touches first the segments boundary. The antivortex may be followed by other complex structures (vortex-antivortex pair, half antivortices) depending on the effective exchange strength over the interface[33].

The nucleation and dynamics of the antivortex are more complex here than in the case of a transverse DW movement above the Walker breakdown in an homogeneous strip. As detailed in Fig. 3 and Fig. 4 (see movie in Ref.33), the DW first pinned in the Ni region starts to move after the application of a current pulse without deformation. After just 20ps, the DW begins to deform, the lower edge moving faster than the upper edge (contrary to the motion in a homogeneous strip) as shown in the position of the DW center on the top and bottom edges in the first row of Fig. 4. The lower part of the DW center reaches first the Ni/Co boundary, passing slightly in the Co region and being pulled back (also the upper edge moves back in the same time). The magnetization angle starts turning out of plane in the  $-z$  direction at the lower and upper DW edges and along all the DW center line (nanostrip width) as seen in Fig. 3(a). An antivortex is formed at the lower edge with its core polarity along  $-z$  direction (not to be confounded with the transverse DW polarity which is along  $\pm y$  direction), while the magnetization of the upper edge turns gradually in-plane direction (after reaching an angle of  $-24^{\circ}$  for  $t_s = 400ps$ ,  $j_e = 5.5 A/\mu m^2$  or  $-32^{\circ}$  for  $t_s = 1050ps$ ,  $j_e = 6.4 A/\mu m^2$ ). For currents above  $7.9 A/\mu m^2$ , an antivortex can also

form at the upper edge, but these cases are fewer and form smaller pocket bands than the ones found below this current value that are discussed here. In the case of a total pulse duration of 0.41ns for a current amplitude of  $5.5 A/\mu m^2$  (Fig. 3(a) and Fig. 4 first column), the antivortex moves slowly to the right and up across the strip width with the lower and upper parts of the DW still pinned on the Ni/Co boundary. At the pulse end, the upper edge of the DW moves continuously to the right while the lower edge is pushed in the other direction deforming strongly the DW. The DW center line has a wave like dynamical deformation. The antivortex at the center of the wall stays pinned and moves for a short time only in the  $+y$  direction. The lower DW edge becomes much larger (still being in the Ni region) and at the same time the upper edge shrinks (being in the Co region). The antivortex begins to move to the right and up (see the trajectory in the bottom row of the Fig. 4), following the upper edge, and being attracted to it and the lower DW edge moves to the right displacing the DW now with opposite polarity to the next Ni region. Bursts of spin waves are ejected along the edges as the antivortex comes out of the nanowire. If the current pulse is applied in the opposite direction, the antivortex will form at the upper edge (image not shown) with a polarity along the  $+z$  direction and the DW will travel to the next Ni region to the left changing its polarity. As discussed below (section III C), the DW displacement with polarity switching is stable at room temperature.

A particularity of the DW motion in the Ni/Co multisegmented nanowire is the possibility of systematic displacement *with or without* polarity switching by changing the pulse characteristics (magnitude and length) for all types of interfaces considered. As observed from the phase diagrams in Fig. 2, when the length of the segments is increased, the homogeneous bands are displaced to the right until they disappear and on the left the chaotic-like pockets of bands appear. In the different pockets corresponding to the  $+1$  state, the antivortex always appear, but it only traverses the nanowire width for low pulse duration. This constitutes a *unique* case, where the motion of a transverse DW between pinning sites takes places with or without polarity switching depending on the pulse length. Fig. 3(b) and the second column of Fig. 4 (movie in Ref.33) display the case when the pulse length is long enough ( $t_s = 1050ps$ ,  $j_e = 6.4 A/\mu m^2$  but same behavior for  $j_e = 5.5 A/\mu m^2$ ) for the antivortex to traverse the next nearest Ni region completely and come close to the second to the right Ni region before the pulse ends. The antivortex comes out at the lower edge where it entered and the DW is displaced one pinning region without polarity switching, contrary to the shorter pulse case. The antivortex deforms strongly when passing the Co/Ni and Ni/Co boundaries with spin wave emissions (or half-antivortices) along the edges. The antivortex moves almost linearly in the Ni and in the middle of the Co regions and shows an inertial displacement after the pulse end continuing in the  $\pm y$  direction depending on

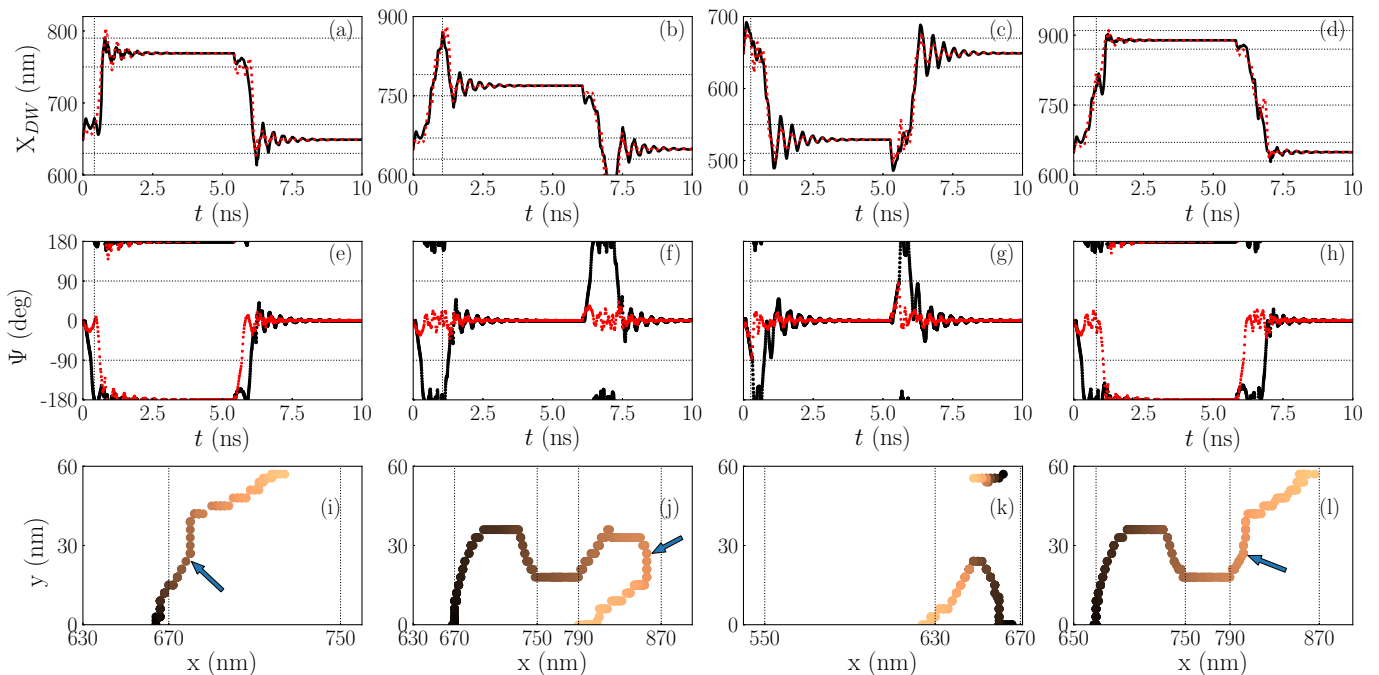


FIG. 4: (Color online) Time variation of the DW upper (dotted line) and lower (full line) center position (first row) and azimuthal angle (second row) in a 40nm Ni/ 80 nm Co multisegmented nanowire. The first column correspond to a forward followed by a backward pulse with characteristics  $t_s = 400\text{ps}$ ,  $j_e = 5.5 \text{ A}/\mu\text{m}^2$  separated by  $t_z = 5 \text{ ns}$ , the second column to forward-backward pulses with characteristics  $t_s = 1050\text{ps}$ ,  $j_e = 6.4 \text{ A}/\mu\text{m}^2$ ,  $t_z = 5 \text{ ns}$ , the third column to forward-backward pulses with characteristics  $t_s = 250\text{ps}$ ,  $j_e = 8.5 \text{ A}/\mu\text{m}^2$ ,  $t_z = 5 \text{ ns}$ , and the last column to forward-backward pulses with characteristics  $t_s = 800\text{ps}$ ,  $j_e = 6.4 \text{ A}/\mu\text{m}^2$ ,  $t_z = 5 \text{ ns}$ . The last row shows the temporal antivortex trajectory (time variation from dark to lighter colors) with the arrows indicating the current pulse end. The horizontal dotted lines in the first row and the vertical dotted lines in the last row illustrate the Ni regions edges. The vertical dotted lines in the first row pinpoint the current pulse end.

its previous displacement. Therefore, timing the pulse length just right when the antivortex goes up or down in the Co regions (close to the Ni boundaries) will make the antivortex traverse or not the nanowire width and variate the DW polarity. The last column of Fig. 4 shows another possibility of DW polarity switching due to the antivortex traversing the nanowire, where the DW travels to the second pinning Ni region to the right (+2 state). As the pulse ends when the antivortex moves upward, it continues to move until goes out at the upper edge switching the DW polarity.

As shown elsewhere[3, 4, 38–40], the DW shows automotion (inertial transient displacement) due to the current pulse shape. Here, the automotion appears in some phase diagrams (negative bands) with an example being shown in the third column of Fig. 4. For a pulse width  $t_s = 250\text{ps}$  and  $j_e = 8.5 \text{ A}/\mu\text{m}^2$ , the DW is first pushed to the right (in the direction of the STT), and afterwards is pulled back by the potential well. An antivortex is created at the upper edge and a second one at the lower edge, joining across the nanowire width and both moving to the left at the pulse end. The antivortices separate and the upper one is ejected while the lower one enters the nanowire, oscillate in size emitting spin waves and

comes out of the nanowire. Both antivortices come out on the same edge they entered, while the DW moves to the next Ni region to the left keeping its polarity.

The motion of a vortex or antivortex in a nanowire can be described by the Thiele equation[30, 41]:

$$-\mathbf{G} \times \frac{d\mathbf{X}}{dt} - \hat{\mathbf{D}} \frac{d\mathbf{X}}{dt} + \frac{\partial E}{\partial \mathbf{X}} = 0 \quad (3)$$

where  $\mathbf{X} = (X, Y)$  is the antivortex core position,  $E(\mathbf{X})$  is the potential energy of the antivortex,  $\mathbf{G}$  is the gyrovector and  $\hat{\mathbf{D}}$  is the damping tensor. The first term of the Eq.(3) suggests a Magnus-type force that acts in a perpendicular direction to the antivortex velocity (gyration) pushing it to the edges. The gyrovector is along the  $z$ -axis and is expressed as  $\mathbf{G} = -\frac{2\pi\mu_0 M_s q p t \hat{z}}{\gamma}$ , with  $q$  the topological charge ( $=-1$  for an antivortex),  $p$  the polarization of the antivortex core ( $\pm 1$  along the  $z$ -axis) and  $t$  the sample thickness. Knowing the potential energy of the antivortex, its motion can be calculated analytically[42, 43] and shows a gyrotropic motion under applied magnetic field or current.

In the multisegmented Ni/Co nanowire, the gyrovector is oriented in the  $-z$  direction for the initial antivortex. To

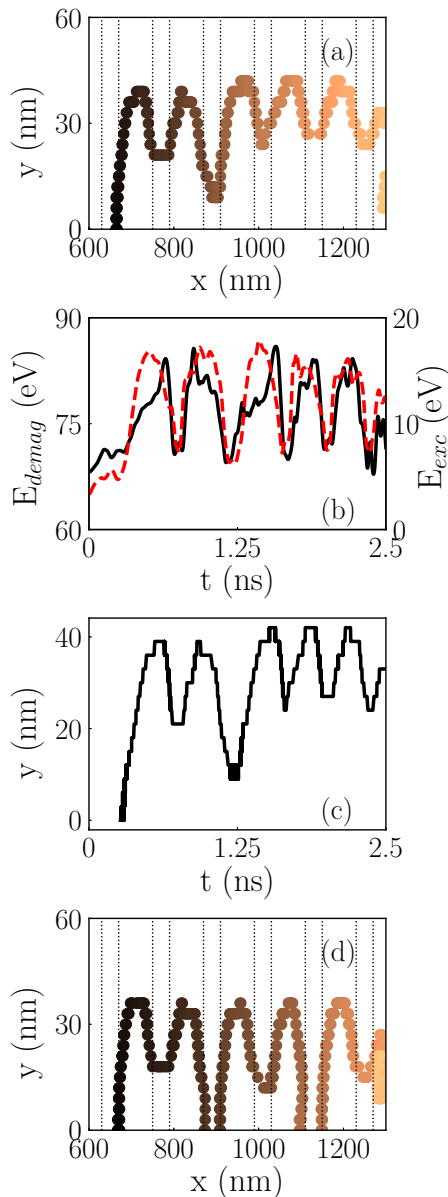


FIG. 5: (Color online) Temporal antivortex trajectory (time variation from dark to lighter colors) in a 40nm Ni/ 80 nm Co multisegmented nanowire for a 5 ns current pulse with magnitude  $j_e$  of  $5.5 \text{ A}/\mu\text{m}^2$  in (a) and  $6.4 \text{ A}/\mu\text{m}^2$  in (d). The temporal evolution of the demagnetizing (full line) and exchange (dashed line) energies and the antivortex  $y$  position corresponding to panel (a) are shown in (b) and (c) respectively. The vertical dotted lines in (a) and (d) illustrate the Ni regions edges. The nanowire is 1300 nm long.

understand better the motion of the antivortex, a longer current pulse with  $t_s=5$  ns is applied (Fig. 5). The Oersted field created by the current pulse is not taken into account although it may become important for longer pulses, influencing the antivortex motion[42]. The displacement of the antivortex along the nanowire follows

a clockwise gyrotropic motion in each Co region crossed. The gyration appears to stop in the Ni regions and to restart again when the antivortex reenters the Co region. The average velocity of the antivortex (not shown) increases to around 400 m/s when approaching a Ni region (on the downward  $y$  motion) and decreases to around 250 m/s when the antivortex leaves the Ni region (on the upper  $y$  motion). As seen in the Fig. 5(b), the demagnetizing energy and the exchange energy have a similar oscillatory behavior each time the antivortex moves across the Co/Ni region correlating with its motion (compare panels (b) and (c)). The antivortex pursues the potential energy shape implying that due to the demagnetizing and exchange energy variation the gyrotropic motion is lessened whenever the antivortex come close to a Co/Ni boundary (the demagnetizing field changes sign at each Ni/Co boundary). If the magnitude of the current pulse is too high (see Fig. 5(d)), the gyroforce (which depends on the  $M_s$  through the gyrovector and on velocity) is strong enough to push the antivortex out of the wire each second Co region before the antivortex could reach the Ni region. The antivortex is recreated again (comes back into the wire) at the next Ni/Co boundary and this periodic motion continues until it reaches the end of the wire. It should be pointed out that the antivortex does not change its core polarization during its motion in the multisegmented nanowire (for the pulse characteristics used).

## B. Influence of material parameters

In order to control and understand the depinning current in the Ni/Co multisegmented nanowire, we altered the potential energy landscape in which the DW moves by modifying the magnetization, the exchange stiffness or the anisotropy of the Co regions (along with the damping constant  $\alpha$  and the nonadiabatic parameter  $\beta$ ) and the effective exchange at the Ni/Co interfaces. While the magnetization of a thin film is measured by magnetometry, the exchange constant is estimated indirectly assuming particular models[27, 44] leading to a higher uncertainty. Therefore, we varied the exchange constant  $A$  on a larger range from 15 to 50 pJ/m (higher values suggested recently[45, 46]) and the magnetization  $M_s$  between 1300 and 1500 kA/m for the Co regions (details in Ref.33). We observed that the depinning current varies oppositely to the depinning field when varying  $A$  or  $M_s$ , the depinning current decreasing with increasing both  $A$  or  $M_s$  up to a threshold value. Lowering the magnetization has a higher impact on the potential barrier height for the DW, while the variation of the exchange constant influences more the form of the potential well. In Fig. 6 we present the consequences of the exchange stiffness constant variation (exchange length and domain wall width scale with  $\sqrt{A}$ ) on the phase diagrams for a multisegmented 40 nm Ni/80 nm Co nanowire. For the lowest exchange constant value (panel (a)), the regular



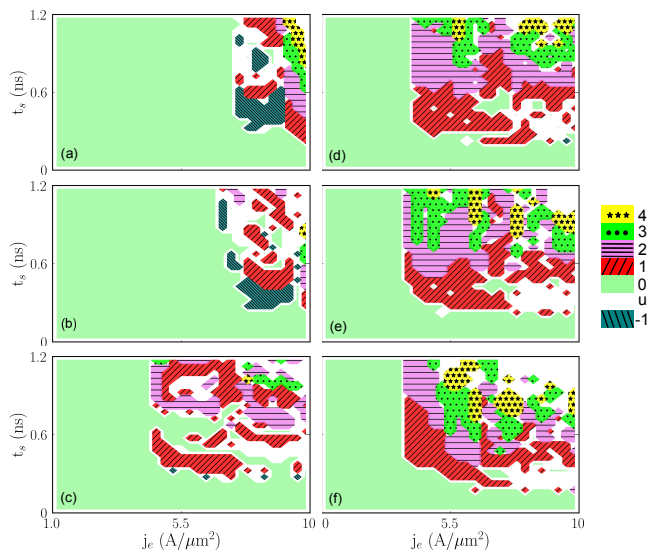


FIG. 6: (Color online) Micromagnetic phase diagrams of DW motion under a periodic current pulse in a multisegmented 40 nm Ni/80 nm Co nanowire at  $T=0K$ . Only exchange stiffness constant  $A$  is varied for the Co regions from 15 pJ/m (a) to 20 pJ/m (b), 28.1 pJ/m (c), 35 pJ/m (d), 40 pJ/m (e) and 50 pJ/m (f).

The observed DW motion is classified in bands numbered as follows: positive bands correspond to the DW moving in the direction of the electron flow, negative numbers to the DW moving contrary to the electron flow, zero state correspond to the DW staying pinned at initial position and 'u' to the unintended states in which the DW does not come back to the initial state after the periodic pulse.

bands are still visible to the right of the phase diagram but large pockets of disordered bands appear to the left with a large -1 pocket band. Increasing further on the exchange stiffness constant, the regular bands shift to the right of the phase diagram and disappear, leaving only the branching pocket bands that correspond to the antivortex presence. For the largest  $A$  value, the pocket bands seem to become more regular for lower current values as the +1 band is observed continuously up to a pulse length  $t_s = 850$ ps, followed by superior bands (still a +1 band branches to higher currents). The dynamics of the DW and the antivortex also changes compared with the case presented above (shown in panel (c), identical with Fig. 2(n)). In this case, the branch of the +1 band appearing at lower currents (to the left of the phase diagram) does not correspond anymore to the DW movement with polarity change. Inside this branch the DW moves to the next (+1) Ni region with or without polarity change, as the two different branches seen in panel (c) (for  $A = 28.1$  pJ/m) coalesce. For a current of  $j_e = 4.0$  A/ $\mu\text{m}^2$ , the DW moves with polarity change up to a pulse length of  $t_s = 750$  ps from which the motion takes place without DW polarity change[33]. The antivortex

with core polarity in the  $-z$  direction that is created at the lower edge traverses faster the nanowire width and disappears at the upper edge in the +1 Ni region, while the DW moves to the +1 Ni region and remains pinned. Above  $t_s = 700$  ps, another antivortex with core polarity in the  $+z$  direction is formed at the upper edge in the +1 Ni region and for pulses between 750 ps and 850 ps traverses the nanowire width almost vertically in the Ni region (with the DW staying pinned) changing the DW polarity to the initial one ( $+y$  direction). For longer pulses, the second antivortex moves towards the +2 Ni region before going out of the sample, displacing the DW to the +2 Ni region. The DW motion with polarity change is still stable at room temperature (see next section) even for the increased stiffness constant.

When the effective exchange energy is lowered, the DW motion with polarity change still arises, with the antivortex moving along the Ni/Co interface and reversing the polarity of the DW. The band like states become larger and more ordered and the systematic DW motion is more stable[33]. When the effective inter-region exchange is increased (considering the same value on both sides of the interface), the antivortex traverses faster the nanowire width and other complex structures appear, as vortex-antivortex pairs or half-antivortices along the edges. The state bands are intermixed and less regular, but the DW motion with polarity changing still occurs depending on the pulse characteristics.

When varying the magnitude of the magnetocrystalline anisotropy constant  $K_u$  for the Co segments, the phase diagram is modified greatly[33]. For a 40 nm Ni/80 nm Co wire, when the anisotropy constant is lowered to a value of  $5 \times 10^4$  J/ $\text{m}^3$ , from  $4.5 \times 10^5$  J/ $\text{m}^3$ , the regular bands are still visible with small band pockets to the left, almost identical to the case of shorter Co segments (of 60 nm, shown in Fig. 2(l)). The states/bands are displaced to the left (lower currents) in the phase diagram. Even when the the anisotropy constant of the Co regions is turned off (equal to zero as in the Ni regions), the phase diagram is similar to the one of the reduced anisotropy constant with band pockets between 3.1 and 8.2 A/ $\mu\text{m}^2$  and regular bands above. However, in the band pockets, the DW motion with polarity switching does not happen for all the points in the same band pocket and pairs of vortex-antivortex can enter the nanowire even for low currents making the DW motion with or without polarity switching unstable. When the anisotropy constant is increased to a value of  $1 \times 10^6$  J/ $\text{m}^3$ , the regular bands and the pocket bands almost disappear, as the DW is highly distorted being pinned at the boundary of the Ni/Co regions and transforming in several perpendicular DWs when moving across the Co regions (uniaxial anisotropy higher than demagnetizing energy). The systematic DW displacement is no longer stable in this case.

Altering the pulse shape, by varying the rise time or the fall time has the same impact on the phase diagrams as for a notched nanowire[3], displacing the states at higher currents and do not improve the dynamics dis-

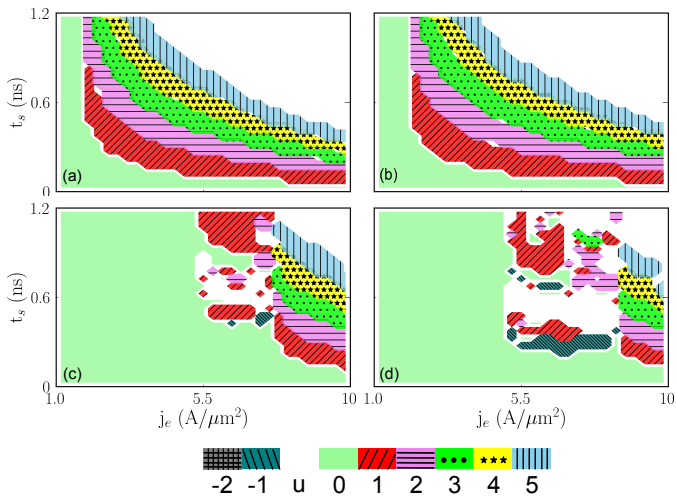


FIG. 7: (Color online) Micromagnetic phase diagrams of DW motion under a periodic current pulse in a multisegmented Ni/Co<sub>50</sub>Ni<sub>50</sub> nanowire at T=0K. The length of the regions varies as : (a) 30 nm Ni/50 nm Co<sub>50</sub>Ni<sub>50</sub>, (b) 20 nm Ni/60 nm Co<sub>50</sub>Ni<sub>50</sub>, (c) and (d) 40 nm Ni/80 nm Co<sub>50</sub>Ni<sub>50</sub>. From (a) to (c)  $\alpha=0.05$  and  $\beta=2\alpha$  for both region's type, while in (d)  $\alpha_{Co_{50}Ni_{50}}=0.005$ . The observed DW motion is classified in bands numbered as follows: positive bands correspond to the DW moving in the direction of the electron flow, negative numbers to the DW moving contrary to the electron flow, zero state correspond to the DW staying pinned at initial position and 'u' to the unintended states in which the DW does not come back to the initial state after the periodic pulse.

cussed here.

To be able to compare to other real materials, whose parameters were already measured, we replace the Co regions with a Co<sub>50</sub>Ni<sub>50</sub> alloy with the following parameters:  $M_s = 1070$  kA/m,  $A = 22.7$  pJ/m and  $K_u = 7.5 \times 10^4$  J/m<sup>3</sup>[44]. The damping constant  $\alpha$  is varied between the values of Ni and Co[47, 48]. Alloying the Co regions with Ni decreases the DW potential barrier between the regions and thus it should lower the depinning current. The results are presented in Fig. 7. For a 30 nm Ni/50 nm Co<sub>50</sub>Ni<sub>50</sub> multisegmented nanowire (panel (a)), the depinning current decreases to  $1.9$  A/ $\mu\text{m}^2$  from  $2.8$  A/ $\mu\text{m}^2$  for the case of pure Co regions (Fig. 2(f)), while the bands become larger and more regular. The same situation is observed for the 20 nm Ni/60 nm Co<sub>50</sub>Ni<sub>50</sub> multisegmented nanowire, with the depinning current being  $2.2$  A/ $\mu\text{m}^2$  (as compared to  $3.4$  A/ $\mu\text{m}^2$  for pure Co). Varying the segments length, we observe that the pocket-like bands due to the presence of the antivortex appear for longer segments length. The regular bands are still visible for the 40 nm Ni/80 nm Co<sub>50</sub>Ni<sub>50</sub> multisegmented nanowire (panel (c)), even when a lower damping parameter (equal to the one of Co) is used for Co<sub>50</sub>Ni<sub>50</sub> segments (panel (d)). In this case, for both damping pa-

rameters, the same behavior is observed in the pocket bands as for the Ni/Co multisegmented wire: for the lower  $t_s$  pockets of +1 band, the DW changes polarity when moving to the +1 pinning site while for larger  $t_s$  pockets of +1 band, the DW does not change its polarity when moving to the next pinning site (the antivortex enters and comes out of the nanowire on the lower edge).

### C. Temperature dependence

The temperature is taken into account by introducing a stochastic thermal field in the effective field term of the LLG equation in both the precession and damping term[49]. The effect of temperature was computed micromagnetically mainly for the +1 band on 100 realizations per point. A symmetric current pulse ( $t_r=t_f=5$ ps) was applied, after an initial relaxation time of 5 ns, followed by another relaxation time of 5ns. These results are valid at low temperature compared to the Curie temperature of materials, as the saturation magnetization is considered constant. At larger temperature the alternatives are the Landau-Lifschitz-Bloch equation or an atomistic model[50, 51].

In Fig. 8, the probability distributions at T = 293 K for positioning the DW to the nearest notch (+1 band) for different Co/Ni or Co<sub>50</sub>Ni<sub>50</sub>/Ni multisegmented nanowires are shown. The probability distribution for a regular +1 band (no antivortex present) is shown in the first two columns, while in the last column the probability distribution when the antivortex appears and traverses the nanowire. In panel (a), for a Ni 30 nm/Co 50nm nanowire, the maximum of the probability distribution is of 87% obtained for a pulse with  $t_s = 150$  ps and  $j_e = 6.1$  A/ $\mu\text{m}^2$ . The maximum of the probability distribution increases to 96% for the multisegmented Ni 20 nm/ Co 60nm nanowire (panel (b)), obtained for the pulse characteristics  $j_e = 9.1$  A/ $\mu\text{m}^2$  and  $t_s = 100$  ps. The maximum probability increases to 100% for the multisegmented Ni 40 nm/ Co 50nm nanowire (image not shown) at the same pulse characteristics. In the case of a Ni/Co<sub>50</sub>Ni<sub>50</sub> wire, the maximum of the distribution probability is of 96% for  $j_e = 8.2$  A/ $\mu\text{m}^2$  and  $t_s = 100$  ps for 30 nm Ni/50 nm Co<sub>50</sub>Ni<sub>50</sub> segmented wire (panel(d)), and of 97% for  $j_e = 6.1$  A/ $\mu\text{m}^2$  and  $t_s = 150$  ps for 20 nm Ni/60 nm Co<sub>50</sub>Ni<sub>50</sub> segmented wire (panel(e)).

In the case of DW displacement with polarity change, the maximum of the probability distribution is of 100% for Ni 40 nm/ Co 80nm multisegmented nanowires (panel (c)) for several points centered on  $j_e = 5.5-6.1$  A/ $\mu\text{m}^2$  and  $t_s = 350-400$  ps (also obtained for other values of effective exchange). This indicates that the systematic DW motion with polarity change is stable at room temperature in a reasonable parameter range and can lead to practical applications. For the regular DW displacement without polarity change, the maximum of the probability distribution is reached for  $j_e = 6.4$  A/ $\mu\text{m}^2$  and  $t_s = 1050$  ps and is of 82% in the same multisegmented nanowire.

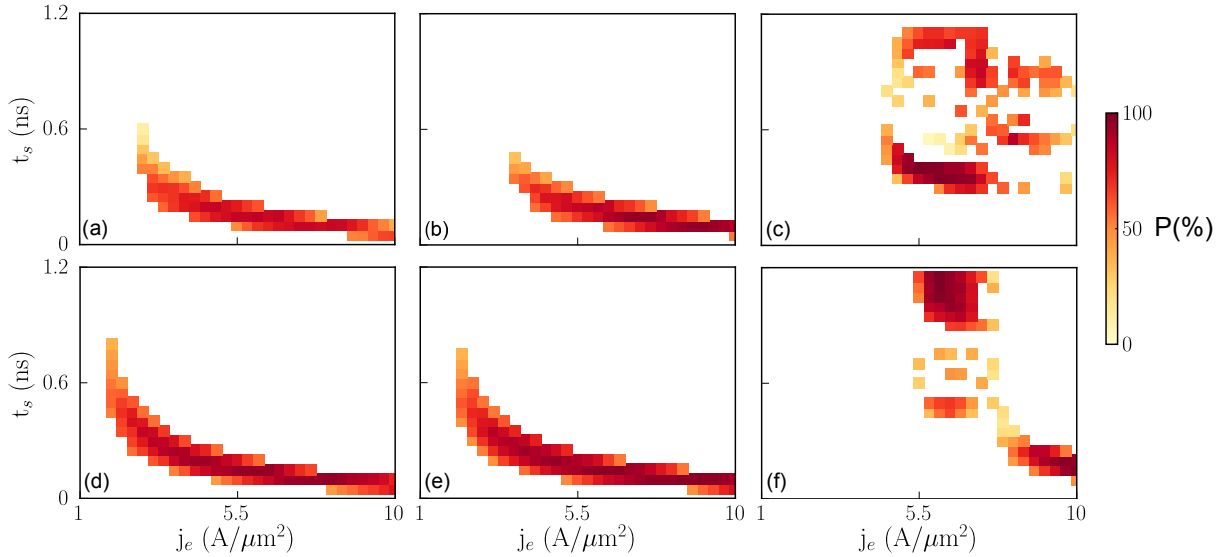


FIG. 8: (Color online) Probability of DW motion in +1 bands at  $T=293\text{K}$  for a multisegmented nanowire of Ni and Co or  $\text{Co}_{50}\text{Ni}_{50}$  regions : (a) Ni 30 nm/ Co 50nm, (b) Ni 20 nm/ Co 60nm, (c) Ni 40 nm/ Co 80nm, (d) 30 nm Ni/50 nm  $\text{Co}_{50}\text{Ni}_{50}$ , (e) 20 nm Ni/60 nm  $\text{Co}_{50}\text{Ni}_{50}$  and (f) 40 nm Ni/80 nm  $\text{Co}_{50}\text{Ni}_{50}$

The motion with polarity change is more stable at room temperature than the motion without, for the chosen parameters. The maximum probability diminishes to 75% in the second band and to 28% for the -1 band (not shown). The 100% maximum probability for DW motion with probability change is also realized for the same multisegmented wire with an increased stiffness constant  $A$  of 50 pJ/m for the Co regions, for slightly lower pulse values ( $j_e = 5.2\text{-}5.5 \text{ A}/\mu\text{m}^2$  and  $t_s = 350\text{-}400$  ps). A high probability of DW displacement (96%) is also obtained for a Ni 40 nm/ Co 70nm wire at  $j_e = 5.5 \text{ A}/\mu\text{m}^2$  and  $t_s = 400$  ps for the +1 band, corresponding to polarity changing DW motion, similarly as above. On the contrary, for the 40 nm Ni/80 nm  $\text{Co}_{50}\text{Ni}_{50}$  segmented wire (panel(f)), the maximum rate of success of 100% is realized for the DW motion without polarity change around  $j_e = 6.1 \text{ A}/\mu\text{m}^2$  and  $t_s$  between 1100-1150 ps, while the success rate decreases to 68% for the polarity changing motion ( $j_e = 6.4 \text{ A}/\mu\text{m}^2$  and  $t_s = 500$  ps). This behavior can be understood by the larger pocket of +1 band (at lower  $t_s$ ), corresponding to polarity changing motion, for the Co/Ni wire than for the Ni/ $\text{Co}_{50}\text{Ni}_{50}$  wire.

#### IV. DISCUSSION AND CONCLUSIONS

A multisegmented Ni/Co nanowire constitutes an particular case in which a transverse magnetic DW can be displaced systematically, between well-defined pinning sites (Ni segments), with or without polarity switching between initial and final positions. This system brings an additional degree of freedom (the DW polarity) to the DW motion compared to the homogeneous nanowire

with artificial constrictions studied extensively[3]. Depending on the particular geometric dimensions of the segments and material parameters as discussed below, the DW can be displaced with polarity flip controlled by the current pulse characteristics. The DW polarity flip is primary due to the birth and propagation of an antivortex along the DW width similar with the DW motion above the Walker breakdown in homogeneous nanostrips. The antivortex is created at the boundary between the Ni/Co regions and has in part the expected gyrotropic motion governed by the complex potential along the wire. The polarity switch is determined by the current pulse length (and magnitude), the antivortex keeping its previous motion direction after the pulse end. The antivortex can be displaced long distances along the multisegmented nanowire having a sinusoidal motion depending on the boundary conditions and effective exchange.

Several parameters play an important role in the emergence of complex textures in the Ni/Co multisegmented nanowire. The total energy of the system comprises the exchange energy, the anisotropy energy which for Co segments is given by the effective anisotropy constant  $K_{\text{eff}} = K_u - N_z \mu_0 M_s^2 / 2$ , the effective DW transverse anisotropy  $K_{\perp} \sin^2 \psi$ [52] where  $K_{\perp} = K_y - K_x$  for the Co regions with perpendicular anisotropy and  $K_{\perp} = K_z - K_y$  for the Ni regions with in-plane anisotropy ( $K_i$  - effective anisotropy constants), and the pinning energy. It was shown previously that a step in the anisotropy ( $K_{\text{eff}}$ )[12] pins the DW and that the depinning field depends on the anisotropy step. Under an applied polarized current, the stable Neel wall in the Ni region will start to move and tilts (increasing  $\psi$ ). The rotation anisotropy barrier to the transition to a Bloch wall depends on the rotation

anisotropy constant  $K_{\perp}$ , the DW width  $\Delta$  and the azimuthal angle  $\psi$ [13]. This rotation anisotropy barrier suppresses the tilting of the DW when  $K_{\perp}$  is large[22, 23]. In the studied case, at the Ni/Co boundary there is a large fluctuation in  $K_{\perp}$  due to the large variation in the saturation magnetization and the suppression of the tilting no longer applies. The DW transverse anisotropy constant  $K_{\perp}$  fluctuation is a main ingredient that leads to the birth of an antivortex and to the DW motion with polarity switching. We also observed that, for the segments length studied, the antivortex starts to emerge when the transverse anisotropy  $K_{\perp}$  changes sign for the Co regions. In the opposite case, when the rotation anisotropy barrier is too low (increasing  $K_u$  in Co) the DW starts to rotate and transforms from Neel to Bloch wall when moving, leading to a non-reliable systematic movement between pinning regions. Even though the antivortex emerges without a perpendicular magneto-crystalline anisotropy (PMA) present ( $K_u = 0$  in Co), the presence of a moderate PMA favors the emergence and stability of a singular antivortex at lower currents and supports the large +1 band pockets with or without a homogeneous DW polarity switching. Another principal ingredient is the exchange energy variation between segments, as detailed in part in the Fig. 6: a moderate exchange constant  $A$  preserves the different +1 band pockets while an increase barrier will collapse the different pockets and reduce the possibility of DW motion with or without polarity switching. A low effective exchange stiffness at the Ni/Co interfaces stabilizes the DW motion and diminishes the apparition of other complex textures leading to larger state bands[33].

In the case of only an adiabatic spin-transfer torque (non adiabatic parameter  $\beta = 0$  in all segments), an antivortex still forms (see figure in Ref. 33), but for a Ni 40 nm/ Co 80nm segments the lower and upper +1 band pockets collapse and form only one band with very few states without DW polarity motion reducing the applications.

The DW motion with polarity switching between neighboring pinning segments (+1 band) is room temperature compatible as the success rate is 100% in a reasonable current range depending on the segments length.

For 40 nm long Ni segments, the success rate is only 76% for DW motion with polarity flip and 71% without polarity flip for 60 nm Co segments. The maximum probability increases systematically with the Co segment length, being of 96% and 88% with and without polarity switch for 70 nm Co segments and up to 100% and 92% for 90 nm Co segments. The room temperature stability paves the way for possible memory applications.

Our results predict that the best possible implementation for memory devices (like the racetrack memory) is obtained for Ni segments with widths comparable with the DW width having neighboring segments with materials parameters not very different of those of Ni having a lower variation at the interfaces. In this respect, a Co-Ni alloy with a magnetization, exchange stiffness and anisotropy closer to the Ni values (and a lowered effective exchange at the interface), reduce the apparition of complex textures (like antivortices or vortices) and stabilize the DW motion leading to lower depinning currents and larger bands, increasing the range of reliable systematic DW displacement. This could be the case in real structures, where the grain boundaries are far from perfect.

In summary, transverse DW motion with or without polarity switching was shown to occur in multisegmented Ni/Co nanowires depending only on the current pulse shape. The polarity switching is mainly due to the emergence of complex textures that traverse the nanowire width. The motion is room temperature compatible and can be engineered by alloying. The additional degree of freedom in the DW motion can open the way for logical or memory devices based on the information encoding into the magnetization direction of a domain wall.

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**Domain walls dynamics in multisegmented Ni/Co nanowires –  
Supplemental Material**

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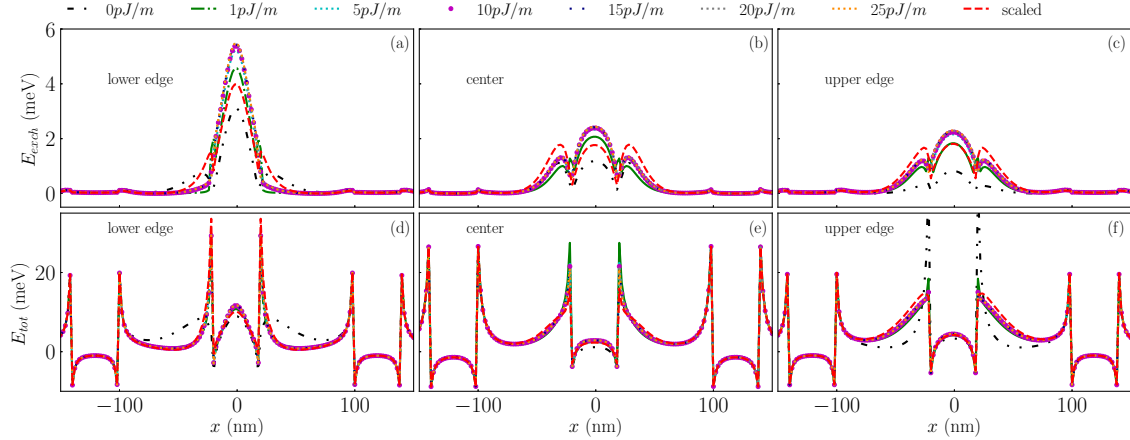


FIG. S1. (Color online) Exchange (upper row) and total (lower row) energy variation along a line on the lower edge, center or upper edge of the nanowire when a DW is pinned in the central region ( $x = 0$  nm for different values of the inter-region exchange constant. A 1300 nm long nanowire was considered with 40 nm Ni/80 nm Co segments.

## I. INFLUENCE OF THE EXCHANGE INTERACTION ON THE DW MOTION

The exchange energy calculation is dependent on the formulation used (6 neighbors, 12 neighbors, 26 neighbors)<sup>1</sup> and the boundary conditions. The exchange stiffness  $A$  has a local character and its variation produces a slope change in magnetization at the interface<sup>2,3</sup> or a discontinuity if the effective exchange is reduced. The standard implementation is based on an equal effective exchange on both sides of the interface (calculated as a harmonic mean of the values of each side), overestimating it particularly in soft magnets. In several numerical packages, the effective exchange can be scaled to desired values.

Fig.S1 details the change in the exchange energy density (panels (a)-(c)) along a line in the longitudinal  $x$  direction at the bottom edge, in the middle and at the upper edge when a DW is pinned in the central region (center of the nanowire at  $x=0$ ). Only the central part of the 1300 nm long nanowire is shown. The effective exchange stiffness was varied between zero and the value of the Co region, having the same value for adjacent cells on the interface (curves corresponding to numerical values), or having different values on adjacent cells with a reduced value on the Ni side to approach real structures (curve denoted 'scaled'). This last choice was made for the figures shown in the main paper (considering the interfaces as grain boundaries), but changing to a conventional numerical calculation (see Figs.S2 and

S3) does not influence the conclusions as detailed below. The effective exchange variation at the interfaces shows a small jump (quasi-discontinuity) for lower values and an abrupt slope change for larger values as expected. When the effective exchange is zero (which could correspond to a dead atomic layer at the interface) the DW is pinned strongly and higher currents are needed to depin it. The larger discontinuity for lower values creates a local potential well along the interface that pins the antivortex and can stabilize it leading to longer displacement inside the nanowire (panels (b) and (c)). Numerical simulations were also performed with buffer regions (of 4 nm width) between each of the Ni/Co regions (not shown), using a Co-Ni alloy with intermediate parameters, but the results stayed similar with the ones with the reduced effective exchange.

The total energy density (here just multiplied by the total volume) on the same three longitudinal lines is shown on panels (d) to (f). Excepting the case of zero effective exchange, the curves are almost identical. Even though the variation of the effective exchange is not visible on the total energy, its impact is important on the phase diagrams as detailed in Fig.S2 and S3. Fig.S2 shows the same segment length variation as the Fig.2 on the main paper, now calculated with an effective exchange around 13pJ/m (default value calculated as the harmonic mean of values on each side) on both sides on the interfaces. Several periodic pulses were applied, which put a more stringent condition on the realization of the states (if one pulse is used the bands will be much larger with less unwanted states) as our nanowire is finite and the pinning potential tilts when approaching the ends (Fig.S5). In this case, the antivortex appears much faster and traverses the nanowire width at lower currents and for smaller segments leading to other textures entering the nanowire as vortices, vortex-antivortex pairs or half antivortices around the edges (see Movie section) before the DW stabilization. The increase effective exchange brings a higher slope change in the exchange energy at the bottom edge where the initial textures enter the nanowire, causing a more complex deformation of the DW. The DW displacement with polarity change is still obtained (starting from shorter current pulses) on an important number of states (see the Movies) in the +1 band, which becomes even larger in some cases.

The impact of the reduction in the effective exchange at the interface is detailed in Fig.S3 (compare to Fig.7 in the main paper). When the effective exchange is reduced (to around 10%), the complex textures (vortex-antivortex) that appear at the interfaces are greatly reduced or absent and in the case of a  $\text{Co}_{50}\text{Ni}_{50}$  alloy (in place of pure Co),



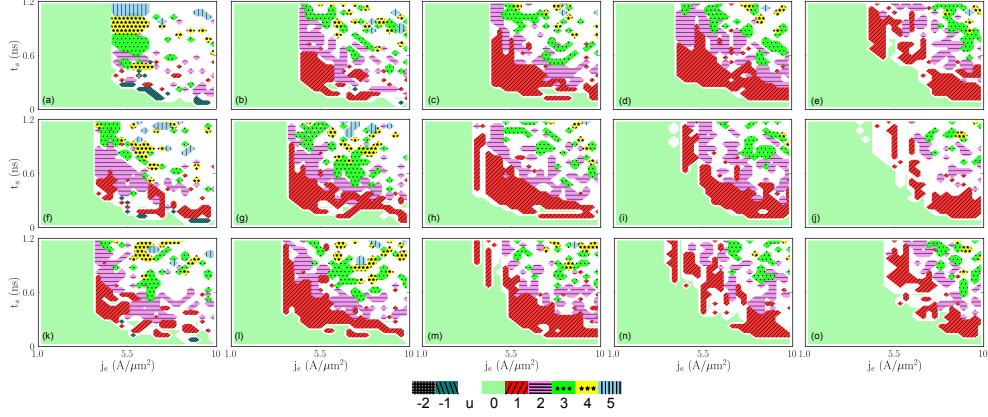


FIG. S2. (Color online) Micromagnetic phase diagrams (same as Fig.2 in the main paper) of DW motion under a periodic current pulse in a multisegmented Ni/Co nanowire at  $T=0\text{K}$  for a periodic pulse with a waiting time of 5ns between pulses. The effective exchange stiffness is calculated as the harmonic mean of the exchange constant of each neighboring region (default value). The length of the Ni and Co regions is varied as: from the top row to the bottom row the Ni regions length increases from 20 nm (top row) to 40 nm (bottom row) in steps of 10nm, while the Co regions length increases from left column to right column from 50 nm (left column) to 90 nm (right column) in steps of 10 nm. The thickness of the nanowire is 5 nm and its total length is around 1300 nm (varies slightly to always have Co regions at the ends). The observed DW motion is classified in bands numbered as follows: positive bands correspond to the DW moving in the direction of the electron flow, negative numbers to the DW moving contrary to the electron flow, zero state correspond to the DW staying pinned at initial position and 'u' to the unintended states in which the DW does not come back to the initial state after the periodic pulse.

regular bands are obtained as for the artificial constrictions (notches). For systematic DW displacement the regular bands are desired as complex textures may reduce the reliable and reproducible DW motion between Ni regions although 100% probabilities are obtained at room temperature in some cases. For the 40 nm Ni/80 nm Co multisegmented nanowire, the reduced effective exchange increases the +1 band which becomes larger and continuous, but still the antivortex appears and traverses the nanowire leading to some states with polarity change. For applications the lower effective exchange should be aimed (and probably realized in real structures) as the bands become more continuous and larger producing more reliable DW motion.

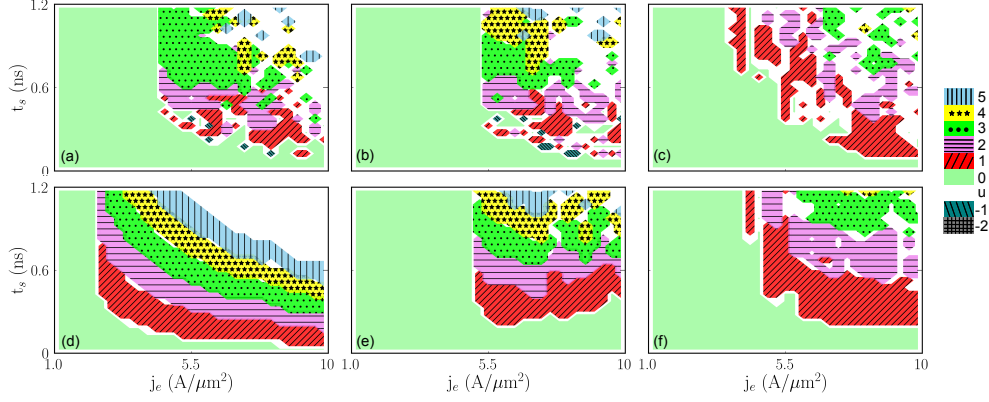


FIG. S3. (Color online) Influence of the effective exchange interaction at the Ni/Co interface on the phase diagram for a 30 nm Ni/50 nm  $\text{Co}_{50}\text{Ni}_{50}$  in (a) and (d), 20 nm Ni/60 nm  $\text{Co}_{50}\text{Ni}_{50}$  in (b) and (e), and 40 nm Ni/80 nm Co multisegmented nanowire, in (c) and (f). In the upper row, the effective exchange stiffness is calculated as the harmonic mean of the exchange constant of each neighboring region, while in the bottom row the effective exchange stiffness is reduced to 0.8 pJ/m (considering the same value on adjacent cells).

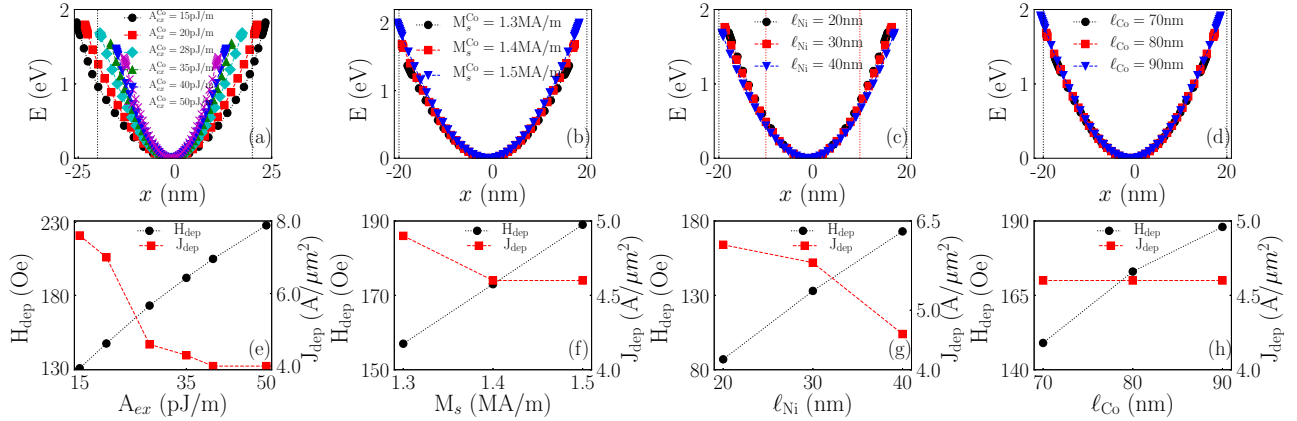


FIG. S4. (Color online) Variation of the DW pinning potential with the exchange constant (a) and saturation magnetization (b) of the Co regions for a 40 nm Ni/80 nm Co multisegmented nanowire, and with the Ni segments lengths for 80 nm Co segments (c) or with the Co segments length for 40 nm Ni segments (d). The depinning field and current are shown from (e) to (h) for the same parameters as the superior panels.

## II. INFLUENCE OF THE SEGMENTS LENGTH AND OF MATERIAL PARAMETERS ON THE DW PINNING

A transverse DW is pinned in a Ni region in a multisegmented Ni/Co nanowire as shown in the main article for a large range of segments length. To determine the pinning energy, a quasistatic approach can be used as in the case of artificial notches, applying a constant magnetic field to the DW and extracting the total energy and DW position. The DW potential energy is shown in Fig. S4, for a DW pinned in a central well (same values as in the main paper). In panel (a) et (b), the variation of the potential energy on the material parameters (exchange constant  $A$  and saturation magnetization  $M_s$ ) of Co regions is shown, while panels (e) and (f) display the pinning field and current dependence on the same parameters for a 40 nm Ni/80 nm Co multisegmented nanowire. Potential energy, depinning field and depinning current are shown in panels (c), (d) and (g), (h) when one type of the segment length is varied : in (c) and (g) the Ni segments length is varied while the Co segments are kept constant at 80 nm, while in (d) and (h) the Co segments length is varied while the Ni segments length is kept constant at 40 nm. As can be observed, the exchange constant influences the potential slope and barrier, while the saturation magnetization impacts mostly the potential barrier magnitude. The depinning field varies oppositely to the depining current when the material parameters are varied or the segments length. This is due to the different actions on the DW of the field and current (push or rotate).

When using the pinning potential presented in Fig. S4 in an analytical 1D model, the barrier and the form of the DW potential seem not to give pertinent results. We therefore extracted the demagnetizing, exchange and total energy along a line passing through the middle of the nanowire (in the longitudinal  $x$  direction) without applied external magnetic field or spin-polarized current. The details of the energetic landscape are presented on the Fig. S5, when a transverse DW is pinned in the central Ni region for a 40 nm Ni/80 nm Co multisegmented nanowire of 1300 nm length. As can be observed, the total energy is dominated by the demagnetizing energy and has a complex form, different from the parabolic shape displayed in Fig. S4. There is an important potential barrier associated with each Ni/Co boundary due to the opposite demagnetizing field on each side of the boundaries. The pinning Ni region do not have an energy minimum in the middle, but rather a more or less flat saddle point depending on the Ni regions length. For 20 nm length Ni segments,

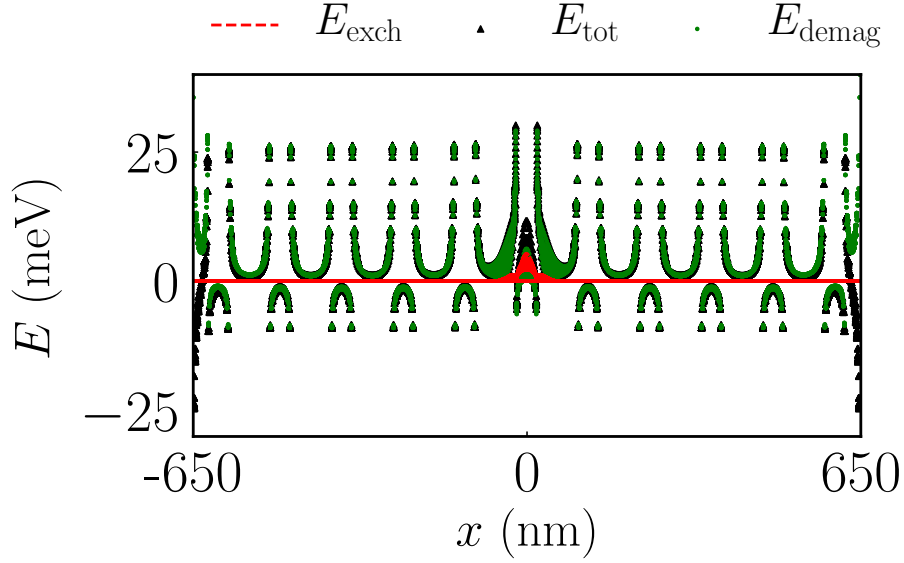


FIG. S5. (Color online) Demagnetizing, exchange and total energy variation along a 40 nm Ni/80 nm Co multisegmented nanowire when a transverse DW is pinned in the central Ni region. No magnetic field or spin-polarized current is applied.

the saddle point becomes a local maximum and the DW pins at the boundaries. For 40 nm Ni segments, the DW is stably pinned in the middle of the Ni regions.

### III. COMPARISON BETWEEN THE ANALYTIC AND MICROMAGNETIC PHASE DIAGRAMS AT T=0K

The energy functional without external magnetic field or spin polarized current for a magnetic nanowire (1D model) is:

$$E[\theta, \psi] = \int_V \{A[(\nabla\theta)^2 + \sin^2\theta(\nabla\psi)^2] + K_{\perp} \sin^2\theta \sin^2\psi + K_{eff} \sin^2\theta\} d\mathbf{r} \quad (1)$$

where  $K_{\perp}$  is the effective DW transverse anisotropy and  $K_{eff} = K_u - N_z\mu_0 M_s^2/2$  the effective anisotropy constant. For the multisegmented nanowire, all the material parameters depend on the position. The usual DW ansatz is introduced ( $\theta(x) = 2 \arctan\left(e^{-Q\frac{x-X}{\Delta}}\right)$ ) and the energy is integrated along the longitudinal axis  $x$  across a Ni/Co boundary<sup>4,5</sup>. The material parameters ( $A, K_i, M_s$ ) are varied linearly across the Ni pinning regions in the effective form  $P_{eff} = P_{Co} - (P_{Co} - P_{Ni})\delta(x)$  up to a distance equal to the DW width on each side of the

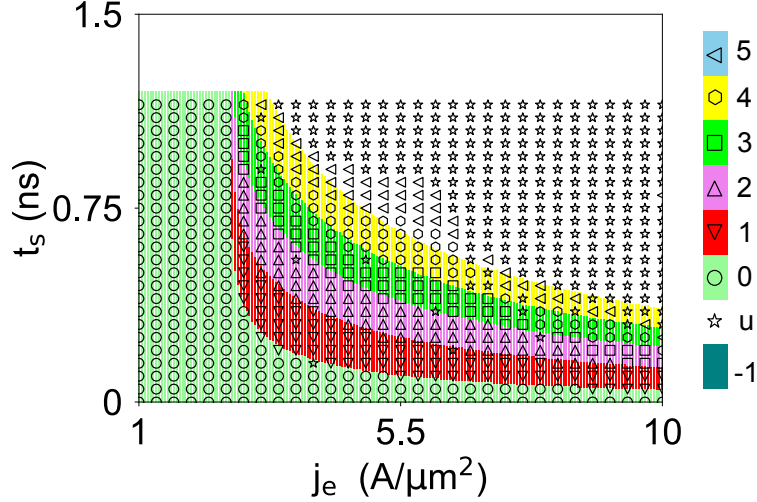


FIG. S6. (Color online) Analytic (vertical colored lines) and micromagnetic (symbols) phase diagram for a 30 nm Ni/50 nm Co multisegmented nanowire. The analytical calculation is superposed on the micromagnetic calculations (symbols). The observed DW motion is classified in bands numbered as follows: positive bands correspond to the DW moving in the direction of the electron flow to the corresponding neighboring Ni segment, negative numbers to the DW moving contrary to the electron flow, zero state correspond to the DW staying pinned at initial position and 'u' to the unintended states in which the DW does not come back to the initial state after the periodic pulse.

Ni region. Here  $\delta$  is a normalized parameter ( $\leq 1$ ) calculated from the DW profile. The damping and nonadiabatic parameters ( $\alpha$  and  $\beta$ ) are also varied but in a sinusoidal manner (and not as a step function as in the micromagnetic simulations) across the segments. Lastly, to compensate for the effective DW anisotropy in the energy integration an effective pinning potential was added to the total energy with a parabolic dependence in the center of the Ni regions (see Fig. S4 and Fig. S5) as for the notched nanowires<sup>6</sup>. Complete details of the models would be given elsewhere. The magnitude and width of the pinning potential were determined from the micromagnetic simulations. Even though the actual variation of the demagnetizing energy is more complex as shown in Fig. S5, this still gives good qualitative results when the distortion of the DW and the azimuthal angle are small.

The comparison between the phase diagram obtained by analytic calculations (colors) and the one obtained by micromagnetic simulations (symbols) is shown in Fig. S6. The phase diagram was computed for a symmetric current pulse with  $t_r = t_f = 5$  ps. The analytical

phase diagram was calculated up to the fourth band, and the unintended states in the upper right quarter of the micromagnetic phase diagram are due to the DW reaching the end of the calculated zone (only the first five bands are calculated). We observe a good agreement between the two diagrams, the depinning current line is well reproduced analytically as well as the form of the first band. Starting from the second band, the differences are more obvious and the analytical model gives only a qualitative description.

#### IV. INFLUENCE OF THE MAGNETO-CRYSTALLINE ANISOTROPY

In Fig. S7, the impact of the magneto-crystalline anisotropy constant of the Co regions is detailed for a 40 nm Ni/80 nm Co multisegmented nanowire. We observe that even for  $K_u = 0$  in both Co and Ni regions, the out-of-plane tilting of the DW still arises at the Ni/Co boundary, but as discussed in the main text in the +1 band pocket at lowest current and pulse length, both DW motion with and without polarity flip are found. In the larger +1 band pocket situated at higher currents (above  $t_s = 600$  ps and  $j_e = 5.5$  A/ $\mu\text{m}^2$ ), pairs of vortex-antivortex enter from both upper and lower edges of the nanowire (with opposite core polarity), some of them coalesce (exchange explosions) and DW moves switching polarity (see Video). The DW motion becomes more complex and stable separate regions of pulse characteristics that lead to DW motion with or without switching cannot be found. The perpendicular anisotropy plays a role in the stability of magnetic textures at lower current and pulse length. On the other limit, when the perpendicular anisotropy is too high, the rotational anisotropy barrier diminishes in the Co region and the DW starts to rotate when moving across the Co regions and other DW appear (see panel (d)).

#### V. INFLUENCE OF THE NON-ADIABATIC SPIN-TORQUE

If the non-adiabatic torque is turned off in the LLG equation ( $\beta = 0$ ), the phase diagram changes as presented in Fig. S8 for a 40 nm Ni/80 nm Co multisegmented nanowire (compare with the case with the adiabatic torque displayed in Fig. S7(c)). In this case, the large +1 band pockets at lower and higher (longer) currents (pulse length) coalesce and the large +1 band pocket at lowest current and pulse length contains both states with or without DW polarity switch. The number of states without polarity switch is greatly reduced as the

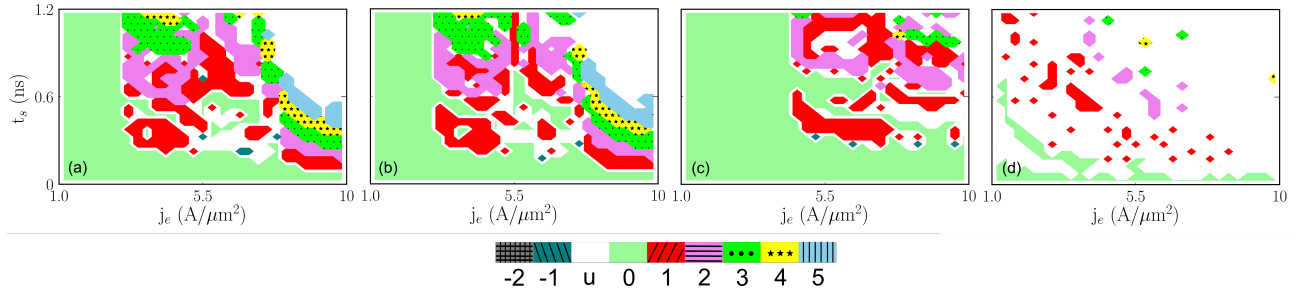


FIG. S7. (Color online) Influence of the magneto-crystalline anisotropy ( $K_u$ ) of the Co regions on the phase diagram of a 40 nm Ni/80 nm Co multisegmented nanowire: (a)  $0 \text{ J/m}^3$ , (b)  $5 \times 10^4 \text{ J/m}^3$ , (c)  $4.5 \times 10^5 \text{ J/m}^3$  and (d)  $1 \times 10^6 \text{ J/m}^3$ .

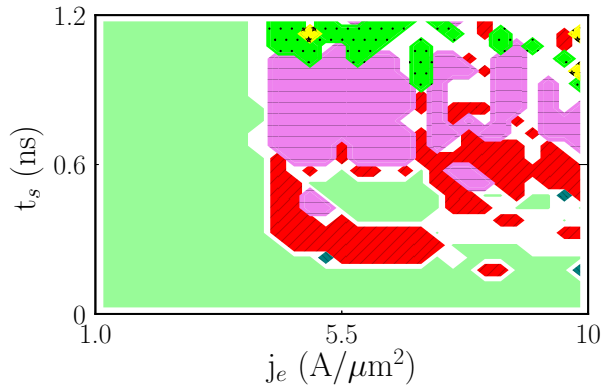


FIG. S8. (Color online) Phase diagram for a 40 nm Ni/80 nm Co multisegmented nanowire when the non-adiabatic parameter  $\beta = 0$  in all segments.

antivortex traverses more rapidly the nanowire (analytical solutions in Ref. 7 determine the dependence on the non-adiabatic parameter).

## VI. TEMPERATURE STABILITY

The DW motion with polarity switching is stable at room temperature having a 100% success rate for a reasonable range of current parameters when the Co segments have a length superior to 70 nm (for 40 nm Ni segments length). The temporal variation of the DW position and angle is shown in Fig. S9 for the upper edge DW center and lower edge DW center. As can be observed, aside for the first oscillation, the DW central line stays well in the Ni region after the current pulse implying temperature stability.

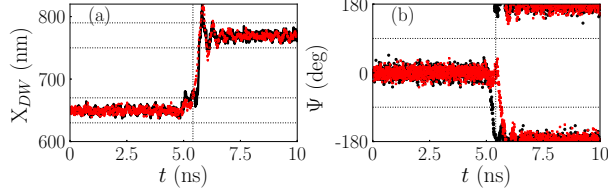


FIG. S9. (Color online) Time variation of the DW upper (dotted line) and lower (full line) center position (first row) and azimuthal angle (second row) in a 40nm Ni/ 80 nm Co multisegmented nanowire when a current pulse with  $t_s = 400\text{ps}$ ,  $j_e = 5.5 \text{ A}/\mu\text{m}^2$  was applied after an initial relaxation time of 5 ns.

## VII. MICROMAGNETIC SIMULATIONS – VIDEOS

Four videos showing the  $x - y$  projection of the central segments in a 40nm Ni/ 80 nm Co multisegmented nanowire are presented with their names self-explanatory. The Ni regions are shaded (darker) than Co regions. Each video contains a split screen, the upper part is color coded by the  $x$  component of the normalized magnetization, while the lower part by the  $z$  (out-of-plane) component of the normalized magnetization. In each video, only the one forward symmetric pulse with  $t_r = t_f = 5\text{ps}$  is shown (electrons moving to the right). The total simulation time is indicated.

- One video that presents the +1 state with polarity switching corresponding to the case shown in the Fig.3 of the main paper(scaled effective exchange). The antivortex traverses the nanowire from the bottom to the top edge. The pulse parameters are  $t_s = 400 \text{ ps}$  and  $j_e = 5.5 \text{ A}/\mu\text{m}^2$ .
- One video that presents the +1 state with polarity switching corresponding to the case of effective exchange of 13pJ/m (default value). After the initial antivortex traverses the nanowire from the bottom to the top edge, more magnetic textures enter the nanowire and traverse it. The pulse parameters are  $t_s = 400 \text{ ps}$  and  $j_e = 5.5 \text{ A}/\mu\text{m}^2$ .
- One video that presents the +1 state without polarity switching corresponding to the case of effective exchange of 1pJ/m. After the initial antivortex traverses the nanowire from the bottom to the top edge along the interface, several magnetic textures appear along the edges. The pulse parameters are  $t_s = 400 \text{ ps}$  and  $j_e = 5.5 \text{ A}/\mu\text{m}^2$ .



- One video that presents the +1 state with polarity switching when the magnetocrystalline anisotropy of Co segments is turned off. Several antivortices enter the nanowire from the top and bottom edges. The pulse parameters are  $t_s = 700$  ps and  $j_e = 5.8$  A/ $\mu\text{m}^2$ .

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