



Current-driven domain wall motion based memory devices: Application to a ratchet ferromagnetic strip

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Ratchet memories, where perpendicular magnetocrystalline anisotropy is tailored so as to precisely control the magnetic transitions, has been recently proven to be a feasible device to store and manipulate data bits. For such devices, it has been shown that the current-driven regime of domain walls can improve their performances with respect to the field-driven one. However, the relaxing time required by the traveling domain walls constitutes a certain drawback if the former regime is considered, since it results in longer device latencies. In order to speed up the bit shifting procedure, it is demonstrated here that the application of a current of inverse polarity during the DW relaxing time may reduce such latencies. The reverse current must be sufficiently high as to drive the DW to the equilibrium position faster than the anisotropy slope itself, but with an amplitude sufficiently low as to avoid DW backward shifting. Alternatively, it is possible to use such a reverse current to increase the proper range of operation for a given relaxing time, i.e., the pair of values of the current amplitude and pulse time that ensures single DW jumps for a certain latency time. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/1.4993750>

I. INTRODUCTION

Multilayer strips, where high perpendicular magnetocrystalline anisotropy (PMA) appears due to surface effects, have been recurrently proposed as promising data storage devices based on domain walls (DWs) motion.^{1–6} One of the essential requirements to put such devices into practice is the development of a reliable pinning system to precisely control the DWs positions. A ratchet memory device, where PMA is tailored so as to present a sawtooth profile, was proposed elsewhere⁷ to achieve this goal. The field-driven regime of such a ratchet memory was studied, drawing rather interesting features. However, it has been recently shown that a current-driven regime for the DWs can be a more advantageous alternative to the field-driven one.⁸

An unavoidable requisite for such a current-driven regime is the presence in the system of spin-orbit coupling phenomena as the spin Hall effect (SHE), along with the interfacial Dzyaloshinskii-Moriya interaction (iDMI). Multilayer systems with inversion asymmetry, where a ferromagnetic layer (FM) is sandwiched between a heavy metal (HM) and an oxide (Ox) can be then proposed.^{9,10} An anisotropy profile as the one described above make this device suitable for bit storing and shifting in a denser and faster way. The application of adequately estimated current amplitudes, pulse times and duty cycles can permit the synchronous displacement of all DWs along the device.⁸ In this way, every DW performs single jumps over the teeth and always recovers an equilibrium state at any of the valleys of the anisotropy landscape. The latency time of the bit shifting procedure is then given by the sum of the pulse (excitation) time, that makes the DW skip each tooth, and a relaxing time

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required to let the DW move backward to the closest equilibrium position, the latter time depending on the slope of the anisotropy profile. For this device, relaxing times longer than pulse times ensured the proper operation of the device after subsequent pulses.

In order to speed up the bit shifting procedure, two strategies can be proposed. Firstly, the applied current can be increased as to reduce the time needed by the DW to perform one jump. Alternatively, a reduction of the time needed by the DW to reach the equilibrium position must be achieved. The latter strategy is to be applied here by using a reverse current, i.e. a current of inverse polarity to the driving one. The work is then structured as follows. The micromagnetic analysis and the one-dimensional model (1DM) are introduced in section II, while section III describes the system under study. Section IV is divided up into two subsections. Section IV A deals with the variation of the single-jump probability when a reverse current J_r of different relaxing times t_r is applied. Additionally, section IV B focuses on the dependence of the proper range of operation on the reverse current, while maintaining the relaxing time constant. Finally, section V briefly presents the conclusions drawn by this study.

II. MICROMAGNETIC ANALYSIS AND ONE-DIMENSIONAL MODEL

The time evolution of the normalized magnetization \vec{m} is to be considered in order to predict the behavior of the system. Such a time evolution is known to be described by the Landau-Lifshitz-Gilbert (LLG) equations, augmented by the spin-orbit torques (SOT) and thermal fluctuations:^{11,12}

$$\begin{aligned} \frac{d\vec{m}}{dt} = & -\gamma_0 \vec{m} \times (\vec{H}_{eff} + \vec{H}_{th}) - \\ & -\alpha \vec{m} \times \frac{d\vec{m}}{dt} - \gamma_0 \vec{m} \times (\vec{m} \times \vec{H}_{SH}). \end{aligned} \quad (1)$$

where γ_0 and α are the gyromagnetic ratio and the damping parameter, and \vec{H}_{eff} is the effective field, including exchange, anisotropy, and magnetostatic interactions, along with the iDMI. Finally, \vec{H}_{SH} and \vec{H}_{th} are, respectively, the effective field associated to the SHE and the thermal field, the former being proportional to the applied current,¹³ and the latter included as a gaussian-distributed random field.^{11,12,14–16} The complete study of the motion of a DW in such a system requires solving this equation by means of full micromagnetic simulations (μ Mag). These μ Mag simulations have been performed with the help of the Mumax³ package.¹⁷

Additionally, the one-dimensional model has also been specifically tailored to obtain a more simple approach to the DW dynamics in this system.⁸ Two mutually dependent equations can be derived for such a dynamics:

$$\begin{aligned} \dot{q} = & \frac{\gamma_0 \Delta}{1 + \alpha^2} [(H_D - H_k \cos \Phi) \sin \Phi] + \\ & + \frac{\gamma_0 \Delta}{1 + \alpha^2} [\alpha (H_{SH} \cos \Phi + H_{th} + H_r r(q))], \end{aligned} \quad (2a)$$

$$\begin{aligned} \dot{\Phi} = & \frac{\gamma_0}{1 + \alpha^2} [\alpha (H_k \cos \Phi - H_D) \sin \Phi] + \\ & + \frac{\gamma_0}{1 + \alpha^2} [H_{SH} \cos \Phi + H_{th} + H_r r(q)]. \end{aligned} \quad (2b)$$

The terms H_D , H_k , stand for the iDMI and the magnetostatic interaction, respectively, and their definition can be found elsewhere.^{18,19} The other terms, H_{SH} and H_{th} , are straightforwardly derived from their counterparts in the LLG equations. Finally, the sawtooth anisotropy profile, given by a function $K_u(x)$ of the longitudinal coordinate x (see the central column of Figure 1), introduces the terms $H_r = \frac{K_u^+ - K_u^-}{2\mu_0 M_s}$, and

$$\begin{aligned} r(q) = & \frac{1}{\cosh^2 \left[\left(1 - \left\{ \frac{q}{d} \right\} \right) \frac{d}{\Delta} \right]} + \frac{1}{\cosh^2 \left(\left\{ \frac{q}{d} \right\} \frac{d}{\Delta} \right)} - \\ & - \frac{\frac{\Delta}{d} \sinh \left(\frac{q}{\Delta} \right)}{\cosh \left(\left\{ \frac{q}{d} \right\} \frac{d}{\Delta} \right) \cosh \left[\frac{\left(1 - \left\{ \frac{q}{d} \right\} \right) d}{\Delta} \right]}, \end{aligned} \quad (3)$$

where the braces stand for the fractional part function.

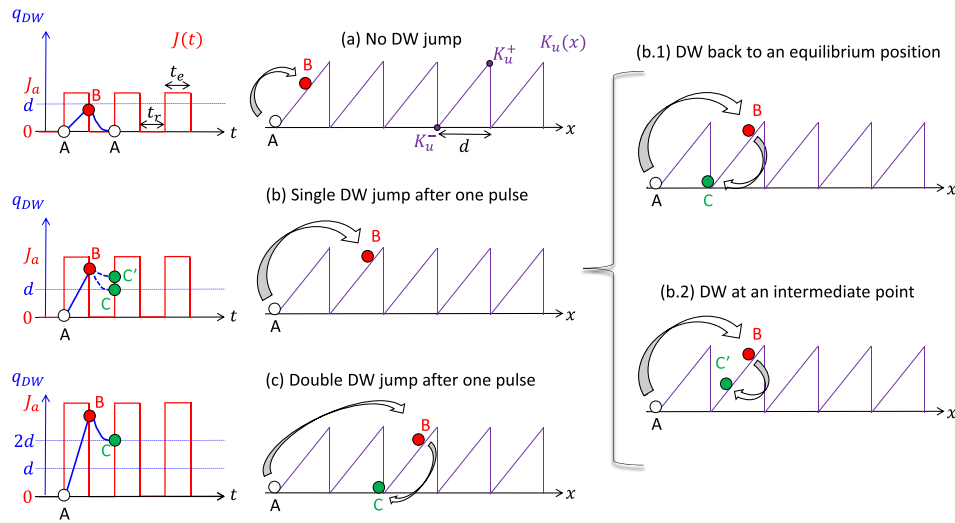


FIG. 1. Likely behaviors of the DW motion under the application of pulsed currents in a FM ratchet. The sawtooth anisotropy energy profile, as represented in the central column of images, is meant to drive the DW to well defined positions. The periodicity of this profile is given by a characteristic length d . (a) For low currents, the DW is not able to jump over any profile tooth, i.e., the DW maximal run distance is less than d for the excitation time t_e . (c) For high currents, multiple teeth can be overcome at once after each pulse, that is, the DW runs distances over $2d$. (b) For intermediate currents, the DW final position after the excitation and relaxing (t_r) times is located between the two subsequent teeth. However, if this final position does not match the anisotropy minimum position, as the figure (b.2) depicts, further pulses may promote multiple jumps rather than single ones. The proper performance of the device is obtained when the DW overcome one single tooth at each pulse, matching the DW final position the minimum of the anisotropy energy profile, as in (b.1).

III. DESCRIPTION OF THE FM RATCHET SYSTEM

A FM strip with high PMA sandwiched between a HM and an oxide is considered within this work. Material parameters commonly found in the literature¹⁸ have been used for the present study: saturation magnetization M_s of $1.1 \frac{\text{MA}}{\text{m}}$, exchange constant A of $16 \frac{\text{pJ}}{\text{m}}$ and a Gilbert damping parameter $\alpha = 0.5$. An interfacial DMI with a DMI parameter $D = 1 \frac{\text{mJ}}{\text{m}^2}$ has also been considered (a brief discussion on the convenience of using a constant DMI parameter is included in our previous work⁸). This value is sufficiently high as to induce Néel DWs and, thus, to efficiently drive the DW by means of the SHE. An electric current is then applied through the HM, giving rise to a spin Hall current with a spin Hall angle of a typical value $\theta_{SH} = 0.1$. A cross section $L_y \times L_z$ of $128\text{nm} \times 0.6\text{nm}$ has been taken for the FM strip.

The ratchet anisotropy profile is obtained by tuning the out-of-plane anisotropy as described elsewhere.⁷ Five periods of the sawtooth anisotropy profile are depicted in the central column of Figure 1. The highest and lowest anisotropy values, $K_u^+ = 1.27 \frac{\text{MJ}}{\text{m}^3}$ and $K_u^- = 1 \frac{\text{MJ}}{\text{m}^3}$, respectively, are indicated. A ratchet period $d = 128\text{nm}$ has been taken, as represented in the figure. Figure 1 summarizes the results obtained in our previous work.⁸ A sufficiently high pulsed current as to promote single DW jumps over the teeth of the sawtooth profile, but sufficiently low not to give rise to multiple DW jumps is considered in this work, i.e., the intermediate current range described in the caption of Figure 1. Within this current range, the DW might not be able to reach the equilibrium position at the anisotropy energy minimum by the time the current is switch on again, as depicted in the bottom-right case of Figure 1. In that case, a double jump may occur after subsequent pulses. This possibility was avoided in our previous study by prolonging the relaxing time.⁸

IV. RESULTS

As it has been already stated, the proper performance of the device is obtained when the DW overcome only one tooth at each current pulse, and its final position matches the equilibrium position at the energy minimum of the anisotropy profile. Such an equilibrium position must be

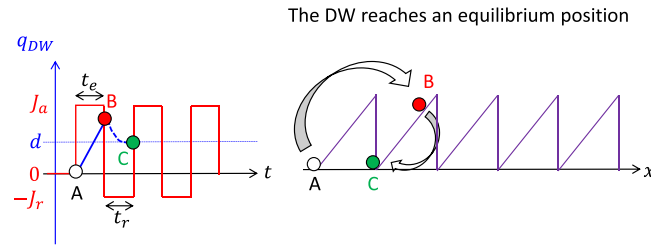


FIG. 2. Use of a current of inverse polarity J_r to ensure the proper operation of the ratchet system. After the application of a driving pulse current of amplitude J_a and width t_e , DWs slide backwards to an equilibrium position within the relaxing time t_r due to the combined effect of the slope of the anisotropy profile together with the reverse current J_r .

reached in a time less than t_r after the driving pulse of amplitude J_a and width t_e is switched off. Since the DW is located at any arbitrary position between subsequent teeth by the time the driving current is switched off, the time t_r might not be sufficiently long as to let the DW slide backwards to the equilibrium position by the effect of the slope of the anisotropy profile. As an alternative, instead of switching off the driving current, a current of amplitude J_r and opposite polarity to J_a can be injected so as to drive the DW to the equilibrium state in a faster way, as Figure 2 depicts. This can be of use whether a reduction of the time t_r is sought or, for a fixed t_r , the range of driving currents J_a of successful operation is to be broadened, as the following sections detail.

A. Probability dependence on the reverse current and the relaxing time

The results that are to be presented here have been obtained by means of the tailored 1DM described in section II, which has been proven to draw rather accurate results for these ratchet systems,⁸ and to be rather less time consuming for the determination of the reduction of the bit shifting latencies. Along this study, a driving current $J_a = 1.6 \frac{\text{TA}}{\text{m}^2}$ and an excitation time $t_e = 1\text{ns}$ have been considered. Figure 3 represents the probability of proper operation of the device, i.e, single jumps as those depicted in Figure 2 as a function of the relaxing time t_r and the reverse current J_r , the values of the latter magnitude given in absolute terms. The probability has been statistically calculated after forty stochastic realizations at a temperature of 300K. It can be noticed that, in the absence of the reverse current, a rather low probability of DW single jumps is obtained, even for relaxing times t_r as long as 1ns. However, a relaxing current of $J_r = 80 \frac{\text{GA}}{\text{m}^2}$ is sufficiently high as to drive the DW to the equilibrium position after the 1-ns long relaxing time for every realization. Additionally, it can be checked that the use of a reverse current with a modulus of 10% of the driving current J_a allows a reduction of the relaxing time to $t_r = 0.6\text{ns}$, but keeping the system within the proper operation regime. Latencies, calculated as the sum of the pulse width $t_e = 1\text{ns}$ and the relaxing time t_r , are then reduced in this case from a total time much longer than 2ns to an interval of 1.6ns.

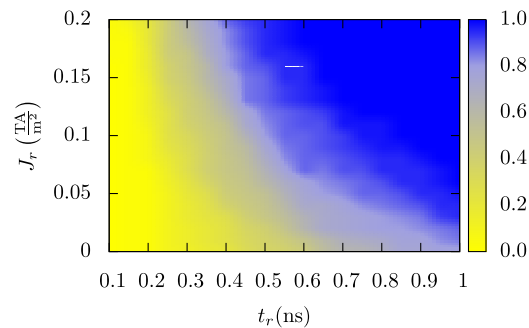


FIG. 3. Probability of single jumps of one DW after the application of one driving pulse of amplitude $J_a = 1.6 \frac{\text{TA}}{\text{m}^2}$ and width $t_e = 1\text{ns}$ as a function of the relaxing time t_r and reverse current J_r . The results are obtained by means of the 1DM. The probability has been statistically computed by evaluating forty different stochastic realizations for each relaxing time and current at a temperature of 300K.

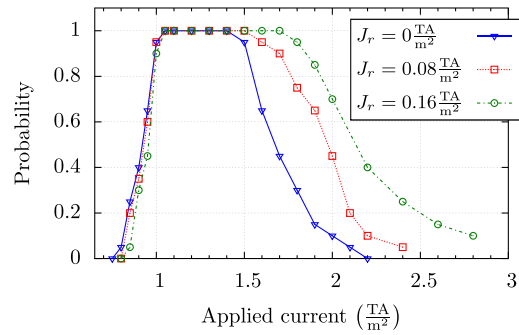


FIG. 4. Probability of single jumps of one DW after the application of one driving pulse of current with a width $t_e = 1$ ns. A relaxing time $t_r = 1$ ns is considered for three different amplitudes of the reverse current J_r . Results are computed from full μ Mag simulations (dots) and the IDM (lines). The probability has been statistically obtained by evaluating twenty different realizations for each pair of driving and reverse currents, at a temperature of 300K.

B. Broadening of the range of operation

Alternatively to the considerations made in the previous section, a broadening of the range of operation, that is, the range of driving currents J_a leading to DW single jumps, can be achieved. This might be of particular interest in order to reduce as much as possible bit shifting error rates. Figure 4 depicts the probability of proper operation of the device after the application of one current pulse 1-ns long, as a function of the current amplitude J_a for three different reverse currents J_r of values $0 \frac{\text{TA}}{\text{m}^2}$, $0.08 \frac{\text{TA}}{\text{m}^2}$ and $0.16 \frac{\text{TA}}{\text{m}^2}$. Reverse currents are also applied for 1ns. Dots in these plots correspond to the results obtained by means of full μ -Mag simulations, while lines correspond to the results obtained from the use of the IDM. Prior to any consideration, it is timely again to insist on the rather good agreement between both the μ -Mag and the IDM approaches.

Under these conditions, the proper operation of the device requires the use of a driving current J_a above a certain threshold, given in this case by the value $1.1 \frac{\text{TA}}{\text{m}^2}$. The DW run distance then exceeds the value d defining the periodicity of the anisotropy profile, almost independently of whether or not a subsequent reverse current is applied. If no reverse current is applied (red line/dots), and the driving current J_a exceeds a value of $1.4 \frac{\text{TA}}{\text{m}^2}$, the relaxing time t_r is not sufficiently long to let the DW backward slide down to the closest equilibrium position at the anisotropy energy minima. Further increase of the driving current J_a above $2.2 \frac{\text{TA}}{\text{m}^2}$ would give rise to DW run distances greater than $2d$. Consequently, the range of proper operation, defined as the driving currents leading to DW single jumps with a probability closest to one, is estimated to be of only $0.3 \frac{\text{TA}}{\text{m}^2}$.

However, the use of the reverse current J_r contributes to extend the range of proper operation up to $0.4 \frac{\text{TA}}{\text{m}^2}$ for $J_r = 0.08 \frac{\text{TA}}{\text{m}^2}$ and $0.6 \frac{\text{TA}}{\text{m}^2}$ for $J_r = 0.16 \frac{\text{TA}}{\text{m}^2}$. In these cases, the reverse current promotes

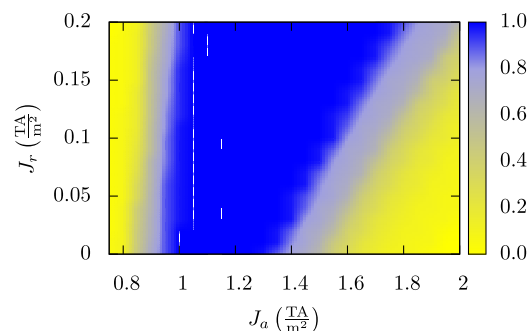


FIG. 5. Probability of single jumps of one DW after the application of one driving pulse. A pulse rise time of 250ps has been considered, so that the current varies either from J_a to $-J_r$ or from $-J_r$ to J_a within this interval, and then hold for 750ps, i.e., $t_e = t_r = 1$ ns. The results are obtained by means of the IDM. The probability has been statistically computed by evaluating forty different stochastic realizations for each relaxing time and current at a temperature of 300K.

the DW movement from the position reached over the corresponding slope of the anisotropy profile after the driving pulse current down to the anisotropy energy minimum.

As a final consideration, it must be noted that the current pulses used for this study has been taken with a negligible rise time. This might not seem sufficiently realistic. However, with the help of the described IDM, estimations of the probability of single jumps of one DW after the application of one driving pulse can be easily calculated in a straightforward way under more practical conditions. As an example, a pulse rise time of 250ps can be defined, so that the current varies from J_a to $-J_r$ and vice versa within this interval. Each current then holds for 750ps, so that pulse and relaxing times are both equal to 1ns. The dependence of the probability on the driving and reverse currents is presented as a color map in Figure 5. A net, but small reduction of the proper range of operation is obtained when no reverse current is applied, if compared with the corresponding curve ($J_r = 0$) plotted in Figure 4. However, this reduction is compensated as the density of the reverse current is increased, with an approximately linear increase of the range of operation.

V. CONCLUSIONS

The current-driven DW motion of a ratchet FM strip previously reported⁸ has been considered and improved along this work. It is demonstrated that the application during the DW relaxing time of a current of inverse polarity to that applied during the DW driving procedure reduces device latencies by reducing that relaxing time. That reverse current must be sufficiently intense as to drive the DW to the equilibrium position faster than the anisotropy slope itself, but with an amplitude rather low, so that DW backward shifting is not promoted. Alternatively, it is possible to use such a reverse current to increase the proper range of operation of the device for a given relaxing time, i.e., the pair of values of the driving current amplitude and pulse time that ensures single DW jumps for a certain latency time.

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