High Domain Wall Velocities due to Spin Currents Perpendicular to the Plane

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We consider long and narrow spin valves composed of a first magnetic layer with a single domain wall (DW), a normal metal spacer, and a second magnetic layer that is a planar or a perpendicular polarizer. For these structures, we study numerically DW dynamics taking into account the spin torques due to the perpendicular spin currents. We obtain high DW velocities: 5 m/s for planar polarizer and 80 m/s for perpendicular polarizer for $I = 0.01$ mA. These values are much larger than those predicted and observed for DW motion due to the in-plane spin currents. The ratio of the magnitudes of the torques, which generate the DW motion in the respective cases, is responsible for these large differences.

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The control of the dynamics of a geometrically confined magnetic domain wall (DW) has attracted much attention in the last decade because of the fundamental interest to identify some specific properties of such a nanoscale spin structure and also for the promising applications such as DW-based magnetic memory and logic devices. Recently, field induced DW motion in magnetic nanostripes has been extensively studied [1–3]. However, this solution is hardly transferable for dense arrays of submicronic devices. An alternative to overcome a challenging task of addressing properly a magnetic bit is to use current-induced domain wall motion that has been the subject of many experimental [4–9] and theoretical research [10–14]. The main intrinsic mechanism to bring the DW into motion by the current is the spin transfer torque, resulting from a transfer of a spin momentum from the conduction electrons to the local spin system inside the DW [15].

In most cases, the nanostripe consists of a single magnetic film (e.g., NiFe), and thus the spin polarized current is flowing in the plane of a magnetic layer that contains the DW that is the so-called current-in-plane (CIP) configuration. Our purpose is to study numerically the DW motion for the case of spin currents flowing perpendicular to the plane. Our results show that for this current perpendicular to the plane (CPP) configuration, a DW can be set into a steady-state motion with very high velocities, up to two orders in magnitude larger than those for a CIP stripe with similar applied current densities.

Multidomain states excited by the spin currents in CPP spin-valve nanopillars have been already discussed in literature [16–18]. For example, strongly nonuniform magnetic states were observed in such nanopillars switched by the current [16]. Static two-domain states were observed in CPP nanostructures with strong perpendicular magnetic anisotropy [17]. Current-induced dynamics of a trapped DW in a square nanopillar was numerically studied in Ref. [18]. However, for such small pillars, the motion of a DW is impeded due to the strong interaction of the DW with the edges or with other DWs. In contrast to this previous work, we consider a long and narrow CPP spin-valve structure with a single DW. This original structure allows us to investigate the DW motion subjected only to the CPP-spin transfer torque.

In the simulations, the magnetic stack is the following: a reference magnetic layer, a nonmagnetic spacer, and a free magnetic layer. The free layer has an in-plane magnetization and contains a single DW. The reference layer has a single domain fixed magnetization. We consider two magnetic configurations for the reference layer: a reference layer magnetized in the plane of the film, referred to further as a planar polarizer, and a reference layer magnetized perpendicularly to the plane, a perpendicular polarizer, see the insets of Figs. 1(a) and 2(a). (Spin transfer effect in a CPP spin-valve with a planar free layer and a perpendicular polarizer was recently studied in Ref. [19]). We assume that the current flows perpendicularly to the layers and has a uniform distribution. The magnetization dynamics is described by the Landau-Lifshitz-Gilbert (LLG) equation taking into account the spin transfer effect [20]:

$$\dot{\mathbf{M}} = -\gamma \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} + \mathbf{T}_{\mathrm{STT}} + \frac{\alpha}{M_s}(\mathbf{M} \times \dot{\mathbf{M}}) \qquad (1)$$

where $\mathbf{M}$ is the magnetization vector, γ is the gyromagnetic ratio, M_s is the saturation magnetization, and α is the Gilbert damping. The effective field $\mathbf{H}_{\mathrm{eff}}$ is the sum of the magnetostatic field, the exchange field, and the anisotropy field. The spin transfer torque $\mathbf{T}_{\mathrm{STT}}$ is divided into two components often referred to as a Slonczewski torque $\mathbf{T}_{\mathrm{ST}}$ (ST) and a fieldlike torque $\mathbf{T}_{\mathrm{FLT}}$ (FLT) [21–23]:

$$\mathbf{T}_{\mathrm{ST}} = -\gamma \frac{a_J}{M_s} \mathbf{M} \times [\mathbf{M} \times \mathbf{m}_{\mathrm{ref}}] \qquad (2)$$

$$\mathbf{T}_{\mathrm{FLT}} = -\gamma b_J [\mathbf{M} \times \mathbf{m}_{\mathrm{ref}}] \qquad (3)$$

where $\mathbf{m}_{\mathrm{ref}}$ is a unit vector along the magnetization direction of the reference layer. The ST amplitude is given by

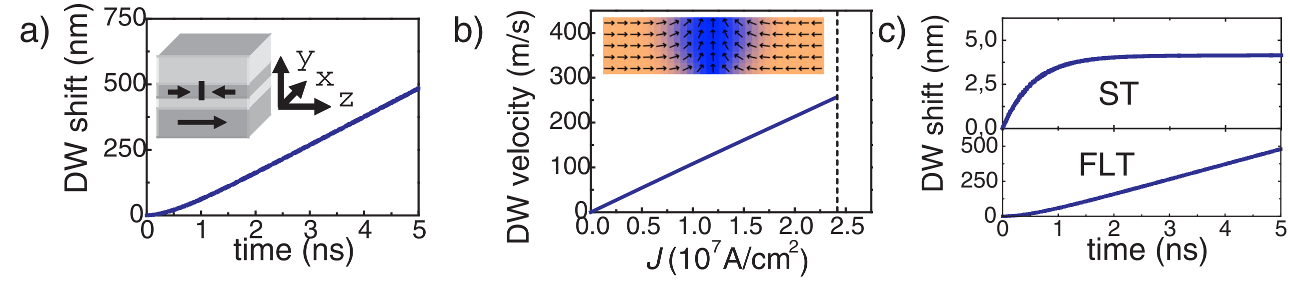

FIG. 1 (color online). (a) DW displacement for $J = 1 \times 10^7\ \mathrm{A/cm^2}$ for a CPP spin valve with the planar polarizer. Inset: sketch of the device. (b) Velocity of the steady-state DW motion as a function of the current density J. The dashed line shows a threshold for the domain excitation. Inset: shape of the DW during its steady-state motion for $J = 1 \times 10^7\ \mathrm{A/cm^2}$; the color code (grayscale) represents the x-component of magnetization ranging from 0 to $+M_s$. (c) DW displacement taking into account only the ST (top panel) or only the FLT (bottom panel).

$a_J = \hbar JP/2deM_s$, where d is the thickness of the free layer, J is the current density, $e > 0$ is the charge of the electron, and P is the spin polarization of the current. The amplitude of the FLT is $b_J = \xi_{\mathrm{CPP}} a_J$, where ξ_{CPP} is typically about 0.1 [22,24]. In the following, we will also consider the two effective fields related to the two torques $\mathbf{T}_{\mathrm{ST}}$ and $\mathbf{T}_{\mathrm{FLT}}$: $H_{\mathrm{ST}} = \frac{a_J}{M_s}[\mathbf{M} \times \mathbf{m}_{\mathrm{ref}}]$ and $H_{\mathrm{FLT}} = b_J \mathbf{m}_{\mathrm{ref}}$.

For the calculations, we consider that the reference layer is a fixed spin polarizer, and therefore we study the dynamics only in the free layer. The initial magnetic configuration in the free layer is a transverse head-to-head DW wall located in the middle of the stripe. The current is switched on at time $t = 0$ with a zero rise time. The magnetic parameters used in the simulations are for Co: $M_s = 1400\ \mathrm{emu/cm^3}$, the exchange constant $A = 1.3 \times 10^{-6}\ \mathrm{erg/cm^3}$, $\alpha = 0.007$, and we neglect the bulk anisotropy. We assume that the free layer has perfect edges and is $50 \times 3 \times 8000\ \mathrm{nm^3}$ in size. For both studied structures that is the planar or perpendicular polarizer, we have used a spin polarization $P = 0.32$ (corresponding to $a_J = 25$ Oe at $J = 10^7\ \mathrm{A/cm^2}$) and $\xi_{\mathrm{CPP}} = 0.1$. To compare the efficiency of each torque in the current-induced DW motion, we perform some additional simulations, in which only one torque, the ST or the FLT, is taken into account.

The simulations consist of a numerical integration of Eq. (1) on a two-dimensional mesh using our micromagnetic code based on the forth order Runge-Kutta method with an adaptive time-step control for time integration. The mesh size is 2.5 nm. The DW position and velocity are extracted from the averaged magnetization of the whole element. The Oersted field and the thermal fluctuations are not taken into account. The injected current densities are always below the threshold values corresponding to the reversal or excitation of the magnetization inside the domains adjacent to the DW.

In Fig. 1, we present the results for the planar polarizer. In Fig. 1(a), we show the calculated DW displacement for $J = 1 \times 10^7\ \mathrm{A/cm^2}$. The DW moves immediately after applying the current and then reaches a regime of steady motion after about 2 ns. In this latter regime, the DW velocity is 105 m/s. We find that the DW velocity increases linearly with the current density J as shown in Fig. 1(b). At current densities larger than a threshold value $J = 2.4 \times 10^7\ \mathrm{A/cm^2}$, we observe domain excitation due to the spin transfer, and as the DW disappears, its velocity cannot be defined anymore. Note that during the steady motion, the shape of the DW, displayed in the inset to Fig. 1(b), remains virtually unchanged. Looking at the separate treat-

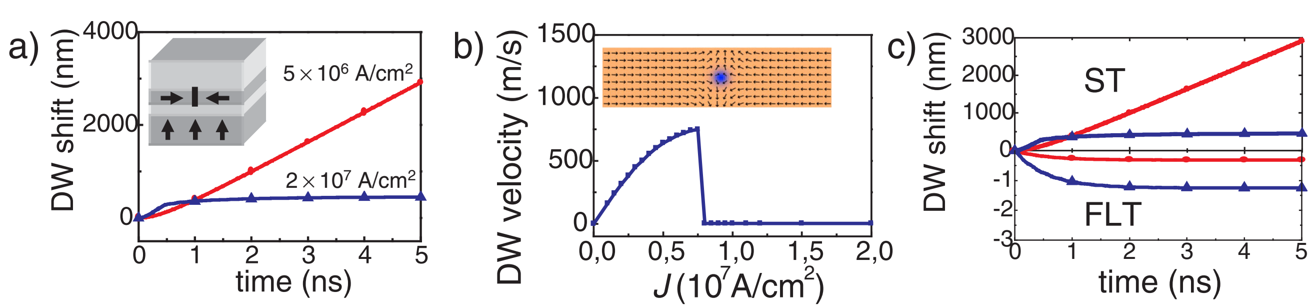

FIG. 2 (color online). (a) Current-induced DW displacement for $J = 0.5 \times 10^7\ \mathrm{A/cm^2}$ (circles) and for $J = 2 \times 10^7\ \mathrm{A/cm^2}$ (triangles) for a CPP spin valve with the perpendicular polarizer. Inset: sketch of the device. (b) Velocity of the steady-state DW motion as a function of the current density J. Inset: snapshot of the transformed and eventually stopped DW; the color code (grayscale) represents the out-of-plane component of magnetization ranging from 0 to $+M_s$. (c) DW displacement taking into account only the ST (top panel) or only the FLT (bottom panel), for $J = 0.5 \times 10^7\ \mathrm{A/cm^2}$ and for $J = 2 \times 10^7\ \mathrm{A/cm^2}$.

ment of the torques $\mathbf{T}_{\rm ST}$ and $\mathbf{T}_{\rm FLT}$ in Fig. 1(c), we find that it is the FLT that is responsible for the steady DW motion. Indeed, the effect of the ST is only to shift the DW at a small distance of about 4 nm. This displacement is almost negligible compared to the hundreds nanometers on which the DW travels during the first few nanoseconds due to the FLT. Furthermore, the simulation, which take into account either both torques or only the FLT, yields equal velocities of the DW in the steady motion regime.

A simple explanation of these results can be given by analyzing the symmetry of the different torques [3,12,14,19]. The magnetization dynamics according to Eq. (1) is a gyration around the effective field and a motion towards the effective field due to the damping. For the ST, $\mathbf{H}_{\rm ST}$ is directed perpendicular to the plane. The gyration around $\mathbf{H}_{\rm ST}$ leads to the DW displacement. Because of the damping, the magnetization tilts towards $\mathbf{H}_{\rm ST}$. As a result, magnetic charges appear at the opposite sides of the free layer. They generate a magnetostatic field which balances $\mathbf{H}_{\rm ST}$; thus, the DW stops. $\mathbf{H}_{\rm FLT}$ is a uniform field directed along $\mathbf{m}_{\rm ref}$; thus, the DW moves due to the FLT as it is expected for a uniform magnetic field. It is possible to write an analytical equation for the DW motion in a one-dimensional approximation (e.g., similarly to Ref. [12]):

$$\begin{array}{c} \frac{u}{\Delta} - \alpha\dot{\Phi} - \gamma a_J = \frac{\gamma}{M_s} K_x \sin(2\Phi) \\ -\alpha\frac{u}{\Delta} - \dot{\Phi} + \gamma b_J = 0 \end{array}. \tag{4}$$

Here, the collective coordinates (u, Φ) define the magnetization in the DW using a traveling wave ansatz $\theta(z, t) = 2\tan^{-1}\exp(\frac{z-ut}{\Delta})$, $\phi(z, t) = \Phi(t)$, where θ, ϕ are the spherical angles, Δ is the parameter of the domain wall width, and K_x is the shape anisotropy constant for the x-axis. The steady-state solution of Eq. (4) is $\dot{\Phi} = 0$, with the DW velocity given by $u = \gamma b_J \Delta/\alpha$. This analytical result is in a good agreement with our numerical findings. It shows that the final DW velocity does not depend on a_J and gives $\Delta = 17$ nm by fitting the data in Fig. 1(b) vs $\Delta = 19$ nm yielded from the fit of the magnetization profiles to the traveling wave ansatz.

The results for the case of the perpendicular polarizer are presented in Fig. 2. We clearly identify two behaviors for the DW motion for the current densities below or above the critical value $J_c = 0.8 \times 10^7$ A/cm^2. For $J < J_c$, the DW motion is similar to the previous planar case; i.e., after a short transient phase, the DW moves steadily. It is illustrated in Fig. 2(a) for $J = 0.5 \times 10^7$ A/cm^2; $u = 640$ m/s for this example. The DW velocity increases with J as shown in Fig. 2(b). Noteworthy, at a given current density, the DW velocity is much higher than in the case of a planar polarizer. We find that the ratio of the DW velocities ranges from 15 for $J \ll J_c$ to 9.4 for $J = J_c$. For the large-current regime ($J \geq J_c$), the DW undergoes a structure transformation from a transverse DW to an antivortex DW, which strongly influences the DW motion [see the simulation results for $J = 2 \times 10^7$ A/cm^2 in Fig. 2(a)]. An antivortex is formed at the narrower part of the DW at the edge of the stripe, similarly to Ref. [14]. It then shifts towards the middle of the stripe. Whereas the antivortex approaches the middle, the DW velocity diminishes until it eventually vanishes [see the resulting magnetization distribution in the inset to Fig. 2(b)]. Contrary to the planar case, the DW steady motion is generated by the ST, as we conclude by analyzing the simulation results for a separate treatment of the two torques, see Fig. 2(c). The action of the FLT is to shift the DW at a very small distance (0.3 nm for $J = 0.5 \times 10^7$ S/cm^2) in the opposite direction. The simulations, which take into account only the ST, yield the same DW velocities and the value of the critical current J_c as those shown in Fig. 2(b).

For the perpendicular polarizer, $\mathbf{H}_{\rm ST}$ is parallel to the magnetization direction of one of the domains. That induces a steady DW motion. $\mathbf{H}_{\rm FLT}$ is directed perpendicularly to the plane; thus, the FLT results only in a finite displacement of the DW. The magnetization gyration around $\mathbf{H}_{\rm ST}$ is a rotation towards the perpendicular direction. This rotation is balanced by the demagnetization field for $J < J_c$; however, for the large currents ($J \geq J_c$), it results in the formation of the antivortex. Once the antivortex reaches the middle line of the stripe, the total torque acting on the DW vanishes and the DW stops [25]. The large difference for the DW velocities between the perpendicular and planar polarizers, found at low currents, is related to the multiplication factor $\xi_{\rm CPP}$ between the torques.

A very important issue is the maximum value of the DW velocity that can be induced by a given current I in a CPP spin valve. For a uniform current flow assumed above, this parameter should be tiny. However, for a uniform flow, most of the current does not contribute to the DW excitation as it goes through the bulk of the domains where the spin transfer torque vanishes. To gain more insight into this issue, we perform simulations for a current I flowing locally through a rectangular region that is centered at the DW at each instant of time. The region of the current localization has the same width as the free layer stripe w and a length $L_{\rm local}$. Only linear regime is considered. For both planar and perpendicular polarizers, we find that for $L_{\rm local} = 3\Delta$, the DW velocity u reaches about $0.95u_{\rm unif}$, where $u_{\rm unif}$ is the DW velocity calculated for a uniform current flow with $J = I/wL_{\rm local}$. For $L_{\rm local} \leq \Delta$, we find $u \approx \frac{1}{2}u_{\rm unif}L_{\rm local}/\Delta$. Thus, the maximum DW velocity induced by a vertical current I equals to $\frac{1}{2}u_{\rm unif}$, where $u_{\rm unif}$ is determined for $J = I/w\Delta$.

It is interesting to compare our simulation results to those obtained for the spin transfer induced DW motion in the CIP nanostripes made of a single magnetic material [4,6–8]. A steady-state DW motion for such systems is due to the so-called nonadiabatic spin torque that accounts for the spin transfer effect for the spins of the conduction electrons mistracking from a nonuniform magnetization

[13,14]. The steady-state DW velocity is given in our notations by $u = \xi_{\rm CIP}\gamma a_J d/\alpha$ [13], where d is the thickness of the magnetic layer, a_J is calculated for $J = I/wd$, and the nonadiabaticity parameter $\xi_{\rm CIP}$ is typically 0.01 [8]. We find that the ratio of the predicted DW velocities for the CPP structure with the planar polarizer and the CIP magnetic stripe, at a given current value, is up to $\xi_{\rm CPP}/2\xi_{\rm CIP}$ [26]; that is a factor of about 5 considering existing experimental data for $\xi_{\rm CPP}$ and $\xi_{\rm CIP}$ [8,24]. The same ratio for the CPP structure with the perpendicular polarizer and the CIP stripe can be estimated as $1/\xi_{\rm CIP}$; that is a factor of about 50. Indeed, for a CIP nanostripe with the same sizes as our free layer and $\xi_{\rm CIP} = 0.01$, we find that the DW velocity is $u = 1$ m/s $I = 0.01$ mA. For the CPP structures, the simulations with $L_{\rm local} = \Delta$ give us for the same current $u = 5$ m/s for the planar polarizer and $u = 80$ m/s for the perpendicular polarizer. This clearly evidences the usefulness of vertical spin current to move a DW with a high efficiency in a nanostripe. Similar results are obtained for other materials, such as NiFe and CoNiPt (with large perpendicular anisotropy); details will be given elsewhere. We note that the effect of the ST on a trapped DW was also discussed in Ref. [18] for a CPP nanopillar, but a large-scale DW motion was not studied.

In practice, a flow of vertical spin current localized on a DW could happen in a spin-valve stripe with the current injected inplane [5,27]. In these CIP spin-valve devices, the critical current densities for DW motion at zero field has been found to be a few 10^6 A/cm^2, compared to about a few 10^7 A/cm^2 in standard NiFe CIP stripes [6,8]. A quantitative explanation of these significant differences is beyond the scope of this Letter; however, our results evidence that if there is a vertical spin flow through a DW, it can play a very important role in the reduction of the critical currents.

Our main findings may be summarized in comparing the predicted DW velocities for three different magnetic structures: a CIP nanostripe and long spin valves with vertical spin current with a planar polarizer or with a perpendicular polarizer. Different torques are responsible for the steady-state DW motion in these structures: the nonadiabatic torque, the FLT, and the ST, respectively. The ratio of the magnitudes of the torques is the cause of the large difference in the DW velocities for these structures. The very effective DW motion due to the vertical spin currents we predict could potentially be an original solution to achieve the necessary breakthrough in reducing the power consumption for the writing processes in spintronic devices.

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