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Domain wall displacement by remote spin-current injection

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We demonstrate numerically the ability to displace a magnetic domain wall (DW) by remote spin current injection. We consider a long and narrow magnetic nanostripe with a single DW. The spin-polarized current is injected perpendicularly to the film plane through a small nanocontact which is located at certain distance from the DW initial position. We show that the DW motion can be initiated not only by conventional spin-transfer torque but also by indirect spin-torque, created by remote spin-current injection and then transferred to the DW by the exchange-spring mechanism. An analytical description of this effect is proposed. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4883740]

The study of domain wall (DW) dynamics in magnetic nanostripes has attracted much attention in the last decade due to both fundamental[1] and applied[2] motivations. On the one hand, complex collective magnetization dynamics can be induced by several means; on the other hand, DW-based nanostructures are very promising for magnetic logic and memory devices.[3–5] Initially, it was proposed to control DW dynamics by magnetic fields.[6–8] However, this approach is hardly suitable for close-packed arrays of nanoscale devices due to significant cross-talk effects. An alternative is to use current-induced DW motion that has been the subject of many experimental[9–13] and theoretical[14–19] studies. The interest in current-induced DW dynamics is encouraged by the development of promising magnetic-based neuromorphic devices,[20] spintronic logic,[5,21] race-track memory,[2] and spintronic memristors.[22–24]

The nanostructures in these devices usually consist of a long and narrow magnetic nanostrip containing the DW. For this geometry, there are two possible current directions: current-in-plane (CIP), when the spin polarized current flows in the plane of the magnetic film, and current perpendicular to the plane (CPP), when it flows perpendicular to the magnetic film. Recent theoretical[25] and experimental[26,27] studies show that in the CPP configuration the DW velocities can be up to two orders of magnitude larger then in the CIP configuration for equal current densities. Thus, the CPP configuration requires relatively low current densities for efficient DW dynamics excitation.[23] The drawback of this configuration, however, is the very high electric current required for efficient DW motion, since a direct current action on the DW is required.[25] Moreover, in the conventional geometry of neuromorphic logic devices,[20] the input current contacts and the DW are separated by a distance $L \gg \Delta$, where Δ is the typical DW width, and the direct current action is simply impossible. The question of a possible non-contact (indirect) interaction between the CPP current, localized in the contact, and the DW remains unresolved.

Recently, an all-magnonic mechanism of DW displacement has been proposed,[28] in which the DW dynamics is induced by spin-waves excited remotely from the DW initial location. To achieve relatively high DW velocities using this mechanism, however, one needs to excite high-amplitude magnons using very high magnetic fields,[29,30] which are hardly achievable in real-life applications.

Here, we propose the study of DW motion induced by a remotely localized CPP spin-current injection that can help to solve these issues. We investigate numerically the DW motion when the spin current is flowing perpendicular to the plane through a small nanocontact (see Fig. 1), which is placed at a certain distance from the initial DW location. We show theoretically that DW displacements of several hundred nanometers can be obtained by a very low remotely injected CPP spin-polarized current (about 50 μA), in contrast to the conventional case when the current flows through the entire DW. In addition to the evident practical interest, this system is of a high fundamental importance too, because the mechanism of interaction between the current and the domain wall is not obvious. We demonstrate here that the perpendicular electric current localized in a small nanocontact generates an in-plane charge-less spin current in the nanowire, and that this spin current may effectively excite DW motion. An analytical description of this effect based on the soliton perturbation theory was proposed.

The magnetization dynamics in the nanostrip is described by the Landau-Lifshitz-Gilbert (LLG) equation with an additional term responsible for the spin transfer[31,32]

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

where $\mathbf{M}$ is the magnetization vector, γ is the gyromagnetic ratio, α is the Gilbert damping constant, M_S is the saturation magnetization, and H_{eff} is the effective field consisting of the magnetostatic field, the exchange field, and the anisotropy field. The spin transfer torque $\mathbf{T}_{STT}$ is represented by two
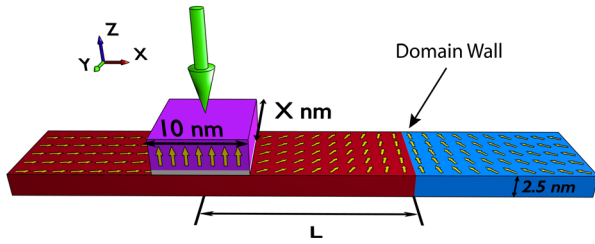
104, 242401-1

FIG. 1. The studied system, composed of a permalloy nanostrip and a nanocontact.
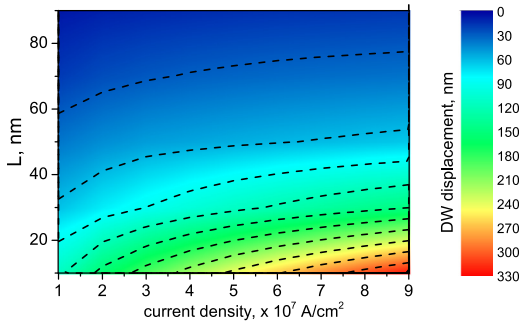

FIG. 2. DW displacement for different initial distances L between the injection contact and the DW and for different current densities in the case of a nanostrip width of $X = 10$ nm.

components:[33,34] a Slonczewski torque (ST) $\mathbf{T}_{ST} = -\gamma \frac{a_j}{M_S} \mathbf{M} \times (\mathbf{M} \times \mathbf{m}_{ref})$ and a field-like torque (FLT) $\mathbf{T}_{FLT} = -\gamma b_j (\mathbf{M} \times \mathbf{m}_{ref})$, where $\mathbf{m}_{ref}$ is a unit vector along the magnetization direction of the reference layer. The ST amplitude is given by $a_j = \hbar J P / 2 d e M_S$, where J is the current density, P is the spin polarization of the current, d is the thickness of the free layer, and $e > 0$ is the charge of the electron. The amplitude of the FLT is given by $b_j = \xi_{CPP} a_j$, where ξ_{CPP} can be larger than 0.4 in case of an asymmetric magnetic tunnel junction.[23]

The system studied here is composed of a permalloy $Ni_{81}Fe_{19}$ (Py[35]) nanostrip magnetized in-plane and containing a head-to-head domain wall, and a reference nanocontact with fixed out-of-plane magnetization (see Fig. 1). Hence, we consider magnetization dynamics in the free layer only, and the nanocontact acts as a static spin polarizer. The size of the nanostrip was $3000 \times X \times 2.5$ nm^3, and the size of the nanocontact was $10 \times X$ nm^2, where $X = 10$–110 nm. The stripe dimensions are large enough in order to have a negligible influence of the edges on the main features of the DW motion. To investigate the remote influence of the CPP spin-polarized current on the domain wall, we have

performed a series of simulations using our micromagnetic finite-difference code SpinPM based on the fourth-order Runge-Kutta method with an adaptive timestep control for the time integration and a mesh size 2×2 nm^2. In order to focus on the spin torque mechanisms of the DW dynamics excitation, both Oersted field and thermal fluctuations have not been taken into account.[36] It should be noted that although here we present the results for the head-to-head DW, the results for a tail-to-tail DW are the same, except the direction of DW motion is reversed.

The displacements of the DW for different distances L and current densities are presented in Fig. 2. The dynamics of the DW is as follows: once the CPP spin-polarized current is switched on in the nanocontact, after some small delay period, the DW starts to accelerate for about 0.5 ns, and decelerates until a complete stop after a few nanoseconds.

To explain these observations, let us consider the magnetization in the current injection region. Since the strip is thin enough (in comparison with its length), at the initial time, the magnetization in the strip beneath the contact is oriented along the strip. The DW width Δ is obtained by fitting of micromagnetic data using a traveling wave ansatz $\theta(\delta x) = 2 \arctan(\exp[\delta x / \Delta])$. In our case, DW width $\Delta \approx 13$–46 nm depending on the nanostripe width (see Fig. 3(a)). It is to be emphasized that Δ must be considerably less than the distance L, by which the nanocontact is separated from the DW. Therefore there is no direct action of the electric current on the DW. However, the presence of the DW even at a considerable distance leads to a small tilt of the magnetization, in other words, to the appearance of a perturbed region ("tail"). The action of the spin-transfer on the DW can be decomposed into two steps. At first, under the influence of the current flowing through the contact, the spins that are beneath the injection contact experience a torque, which leads to a local increase of the Y component of magnetization in the contact region (about 30 emu/cm^3 for our set of parameters). The fact that a local pulse of the spin-polarized current can influence a DW remotely is determined by the presence of exchange stiffness in the magnetic structure of the material (in a soft medium such an effect is obviously absent). Then, through the exchange-spring mechanism, this disturbance is transmitted from the DW "tail" located inside the nanocontact region directly to the domain wall, thereby causing the DW drift.

Previously exchange-springs were studied in heterophase systems,[37,38] but similar effects can be observed in homogeneous systems as well. Indeed, in our case, each subsequent magnetic moment of the DW "tail" is deflected at a slight
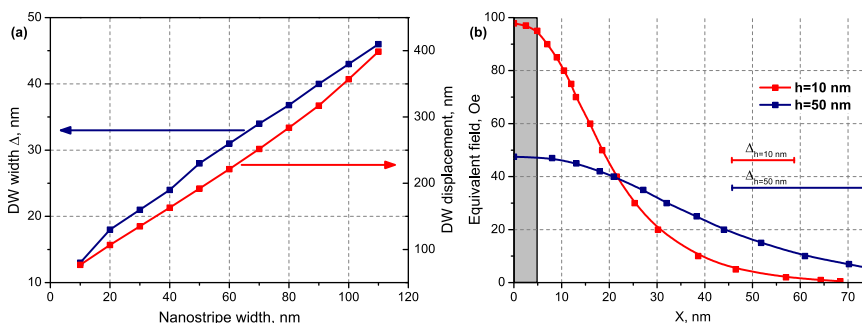

FIG. 3. (a) Dependence of DW width Δ and DW displacement on the nanostripe width. Initial distance is $L = 40$ nm, current density is $J = 5 \times 10^7$ A/cm^2. The blue and red arrows indicate to which axis the curves belong. (b) Dependence of the equivalent magnetic field on X position for two nanostripe thicknesses. The grey region represents the current nanocontact. The blue and red segments show the width of the DW for the cases of $h = 10$ nm and $h = 50$ nm.

angle from the direction of the previous one. If the external action (CPP local current in our case) deflects one or more of the magnetic moments slightly (edge of the spring is deformed), then due to the strong exchange interaction the subsequent magnetic moments are also deflected one by one. As a result, the exchange-spring is straightened, pushing the DW. After the complete straightening of the exchange-spring, the DW stops accelerating and starts to slow down due to damping and after some time finally stops. Hence, the effect is defined by the static exchange-spring tension. The numerical simulations demonstrate a delay in the onset of the DW motion with respect to the time of the current switching, corresponding to the propagation time of the spring excitation (static tension). It is worth stressing that in this case of indirect action of the spin transfer, the angular momentum is transferred to the DW not by conduction electrons but by a charge-less spin current, due to the exchange-spring interaction. Moreover, when the nanostrip width is increased, the domain wall becomes wider, therefore, the "tail" of the DW also becomes longer, the DW is affected by the current for a longer time, and consequently the DW should be displaced over larger distances. This effect is confirmed by the simulations (see Fig. 3(a)).

To estimate the magnitude of the exchange-spring interaction, we obtained the dependence of the equivalent field (i.e. the magnetic field with direction opposite to the DW motion direction which has to be applied to counterbalance the action of the exchange-spring static tension) on the X coordinates (see Fig. 3(b)). We see that, even at a distance of several times greater than the DW width Δ the equivalent field is still large enough to displace the DW significantly. It also shows that at large thicknesses of the nanostrips, the equivalent field decays more slowly. Despite the fact that for large thicknesses, the equivalent field near the nanocontact is smaller, the effectiveness of the exchange-spring will still be higher for large thicknesses than for smaller ones, as follows from the results of the DW displacement (see Fig. 3(a)). The reason for this is that with increasing thickness of the nanostrip, the efficiency of the magnetic field is growing faster than the efficiency of the local current contact. As a result, although the actual magnetic field required to balance the action of the exchange-spring proves to be smaller, the force acting on the DW will be larger for larger thicknesses.

For the final test of the proposed mechanism, simulations were performed for the case of $\alpha = 1$. Such a large damping eliminates the effect of spin waves, as they fade out before reaching the DW. Also in this case, there is practically no movement by inertia (as soon as the external forces stop acting, the DW should immediately stop its free motion). However, the result of our simulations shows that the DW is still displaced by a distance of about 60 nm (with a width of the DW $\Delta = 13$ nm), which corresponds to the distance at which the equivalent field almost becomes zero. From this, we can conclude that the spin waves do not determine the effect, which is caused only by the exchange-spring static tension. Another important result is that the considered mechanism of DW dynamics excitation (via static tension of the exchange-spring) does not require an alternating current or magnetic field in contrast to the case in which the DW is excited by spin waves.[29,30] This makes it promising for

practical applications like racetrack memory, magnetic logic, and neuromorphic devices.

For an analytical insight into this mechanism, let us consider Eq. (1) in spherical coordinates with the energy represented by $E = A((\nabla\theta)^2 + \sin^2\theta(\nabla\phi)^2) + 2\pi M_S^2 \cos^2\theta - K_\perp \sin^2\theta \cos^2\phi$, where A is the exchange constant, $K_\perp$ is the anisotropy constant, ϕ is the polar angle, and θ is the azimuth angle. Due to the shape anisotropy, the magnetization lies almost entirely in the plane. The simulation shows that the deviation of the magnetization from the plane is not more than 3% of M_S. With this in mind, we consider a small deviation in θ: $\theta = \pi/2 + \theta_1$ ($\theta_1 \ll 1$). In this case, Eq. (1) takes the following form:

$$-\dot\theta_1 - \alpha\dot\phi = \frac{\omega_\perp}{2}\sin 2\phi - \frac{2\gamma A}{M_S}\phi'' + \gamma a_j(x,t), \quad (2)$$

$$\dot\phi - \alpha\dot\theta_1 = -\frac{2\gamma A}{M_S}\theta_1'' - \theta_1\left(\frac{2\gamma A}{M_S}(\phi')^2 - \omega_\parallel - \omega_\perp\cos^2\phi\right), \quad (3)$$

where $\omega_\perp = 2\gamma K_\perp/M_S$, $\omega_\parallel = 4\pi\gamma M_S$ and $a_j(x,t)$ is not equal to zero only in the contact region. Taking into account that $\omega_\perp/\omega_\parallel \ll 1$ and $2\gamma A/M_S l^2 \ll \omega_\parallel$, where l is the typical spatial scale, and neglecting small quantities, we can rewrite Eq. (3) in following form: $\theta_1 = \dot\phi/\omega_\parallel$. Substituting this result into Eq. (2), we obtain

$$\ddot\phi - c^2\frac{\partial^2\phi}{\partial x^2} + \omega_0^2\sin\phi\cos\phi = -\alpha\omega_\parallel\dot\phi - \gamma\omega_\parallel a_j(x,t), \quad (4)$$

where $c^2 = 8\pi\gamma^2 A$ and $\omega_0^2 = \omega_\parallel\omega_\perp$. Equation (4) is the modified version of the sine-Gordon equation. Study of the applicability of this equation was carried out recently.[39–41] The solution of this equation with zero right-hand side is represented by a kink soliton propagating with constant velocity $\tan(\tilde\phi_0/2) = \exp\{\pm(x - vt - x_0)/\Delta\}$, where v is the velocity of the domain wall, x_0 is the initial distance between the DW and nanocontact center, $\Delta = \Delta_0\sqrt{1 - v^2/c^2}$ and $\Delta_0 = c/\omega_0$. Since the maximum velocity in modelling is about 250 m/s and $c \approx 1000$ m/s, we can estimate $1 \geq \sqrt{1 - v^2/c^2} \geq 0.96$, and therefore $\Delta \approx \Delta_0$.

The micromagnetic modelling demonstrates acceleration and deceleration of the DW. To take this into account, let us assume that the right-hand side of the equation only slightly modifies the DW's profile but changes the velocity. This assumption was confirmed by simulations. In this case, we can use the soliton perturbation theory. We represent the solution of Eq. (4) as $\phi = \phi_0 + \phi_1$, where $\phi_1 \ll 1$ and ϕ_0 is the modified kink $\tan(\phi_0/2) = \exp\{\pm(x - x_c(t) - x_0)/\Delta_0\}$ with $x_c(t)$ is treated as the DW's position. Then after linearisation and neglecting small values Eq. (4) assumes the form

$$\left(\frac{\partial^2}{\partial t^2} - c^2\frac{\partial^2}{\partial x^2} + \omega_0^2\cos 2\phi_0\right)\phi_1 = -\alpha\omega_\parallel\dot\phi_0 - \gamma\omega_\parallel a_j(x,t)$$
$$+ \frac{\ddot x_c}{\Delta_0}\sin\phi_0. \quad (5)$$

Let us define the operator $\hat L = \partial^2/\partial t^2 - c^2\partial^2/\partial x^2 + \omega_0^2\cos 2\phi_0$ and function $f(\phi_0) = -\alpha\omega_\parallel\dot\phi_0 - \gamma\omega_\parallel a_j(x,t) + (\ddot x_c/\Delta_0)\sin\phi_0$. Using this notation, Eq. (5) can be written as $\hat L\phi_1 = f(\phi_0)$. According to the Fredholm alternative,[42]

this equation has a solution if and only if the right-hand side $f(\phi_0)$ of the equation is orthogonal to the eigenfunction of operator $\hat{L}$ with zero eigenvalue, which can be found from the equation $\hat{L}\phi_1^{(0)} = 0$. For the present problem, the required eigenfunction takes the form $\phi_1^{(0)} = \partial\phi_0/\partial x$. Then, considering that $\dot{\phi}_0 = \mp(\dot{x}_c/\Delta_0)\sin\phi_0$ and $\partial\phi_0/\partial x = \pm\sin\phi_0/\Delta_0$, the solubility condition is

$$\left(\alpha\omega_\parallel \frac{\dot{x}_c}{\Delta_0^2} + \frac{\ddot{x}_c}{\Delta_0^2}\right)\langle\sin^2\phi_0\rangle - \frac{\gamma\omega_\parallel}{\Delta_0}\langle a_j(x,t)\sin\phi_0\rangle = 0, \quad (6)$$

where $\langle...\rangle$ means integration over x. After integration, taking into account that $a_j(x,t)$ is not equal to zero only inside the contact region, we obtain a Newton-like equation of motion

$$m\ddot{x}_c = -\alpha\omega_\parallel m\dot{x}_c + F(x_c), \quad (7)$$

where $m = 1/(\pi\gamma^2\Delta_0)$ is the effective mass of the DW, $F(x_c) = (a_j\omega_\parallel/\pi\gamma)\cdot\arctan\left[\exp\left\{(d/2-L-x_c)/\Delta_0\right\}\right] - \arctan\left[\exp\left\{(-d/2-L-x_c)/\Delta_0\right\}\right]$ is the force created by the current, and d is the size of the contact along the X axis.

Time dependence of the velocity of the domain wall for different L, obtained from Eq. (7), in comparison with the micromagnetic modelling results is shown in Fig. 4. The proposed analytical model demonstrates a good agreement with the results of micromagnetic simulation. It should be noted that although for small L values theory predicts an absolutely correct final DW displacement, with increasing L the difference between simulations and theoretical predictions slightly increases, up to 10 nm for $L = 100$ nm (see inset in Fig. 4). The reason for this discrepancy lies in the fact that the analytical 1D model is based on the rigid soliton model. Under this assumption, we neglect DW deformation and consider that the action of the current contact propagates instantaneously. But in the case of large L values, the exchange-spring needs some time, corresponding to the propagation time of the spring excitation, to start pushing the DW. During this time, the effective in-plane spin current slightly attenuates.
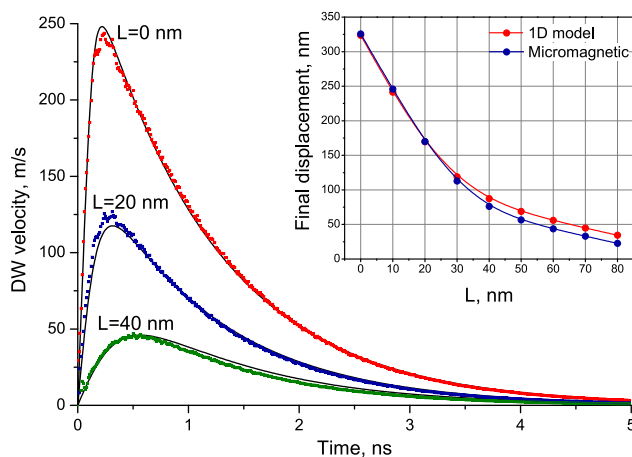
Because of this, the 1D model slightly overestimates the final displacement of the DW for larger L values.

In conclusion, we have demonstrated theoretically the possibility of spin current induced domain wall motion in the CPP geometry, when the DW is initially located outside the nanocontact region. Although velocities in this case are lower than in the usual CPP case (about 500 m/s),[27] they are still higher than the velocities in the CIP geometry; the required currents are very low (about 50 μA), in contrast to the case when the current flows through the entire sample.[23,25,27] We have shown that the DW dynamics in this case is induced by indirect spin-torque, created by a remote spin-current injection, which is transferred then to the DW by the exchange-spring mechanism. The analytical description of this effect based on soliton perturbation theory was proposed. Although this mechanism of DW dynamics excitation can be used by itself, it can also be effectively used to depin a DW, when magnetization dynamics is driven by less effective methods (e.g., in-plane current injection). On this basis, the remotely localized contact injection of CPP spin-polarized current becomes a very promising option for practical applications such as racetrack memory, magnetic logic, and neuromorphic devices.

FIG. 4. Time dependence of the DW velocity obtained analytically (continuous black line) for different distances L in comparison with the micromagnetic modelling results (points). In the inset: comparison of the final DW displacements obtained using the 1D analytic model and by micromagnetic simulations as a function of L.

[1]E. Saitoh, H. Miyajima, T. Yamaoka, and G. Tatara, Nature **432**, 203 (2004).
[2]S. S. P. Parkin, M. Hayashi, and L. Thomas, Science **320**, 190 (2008).
[3]D. Allwood, G. Xiong, C. Faulkner, D. Atkinson, D. Petit, and R. Cowburn, Science **309**, 1688 (2005).
[4]M. Hayashi, L. Thomas, R. Moriya, C. Rettner, and S. S. Parkin, Science **320**, 209 (2008).
[5]B. Behin-Aein, D. Datta, S. Salahuddin, and S. Datta, Nat. Nanotechnol. **5**, 266 (2010).
[6]T. Ono, H. Miyajima, K. Shigeto, K. Mibu, N. Hosoito, and T. Shinjo, Science **284**, 468 (1999).
[7]D. Atkinson, D. A. Allwood, G. Xiong, M. D. Cooke, C. C. Faulkner, and R. P. Cowburn, Nature Mater. **2**, 85 (2003).
[8]G. S. D. Beach, C. Nistor, C. Knutson, M. Tsoi, and J. L. Erskine, Nature Mater. **4**, 741 (2005).
[9]J. Grollier, P. Boulenc, V. Cros, A. Hamzić, A. Vaurès, A. Fert, and G. Faini, Appl. Phys. Lett. **83**, 509 (2003).
[10]A. Yamaguchi, T. Ono, S. Nasu, K. Miyake, K. Mibu, and T. Shinjo, Phys. Rev. Lett. **92**, 077205 (2004).
[11]M. Kläui, P.-O. Jubert, R. Allenspach, A. Bischof, J. A. C. Bland, G. Faini, U. Rüdiger, C. A. F. Vaz, L. Vila, and C. Vouille, Phys. Rev. Lett. **95**, 026601 (2005).
[12]M. Hayashi, L. Thomas, C. Rettner, R. Moriya, Y. B. Bazaliy, and S. S. P. Parkin, Phys. Rev. Lett. **98**, 037204 (2007).
[13]D. Ravelosona, S. Mangin, J. A. Katine, E. E. Fullerton, and B. D. Terris, Appl. Phys. Lett. **90**, 072508 (2007).
[14]Y. B. Bazaliy, B. A. Jones, and S.-C. Zhang, Phys. Rev. B **57**, R3213 (1998).
[15]G. Tatara and H. Kohno, Phys. Rev. Lett. **92**, 086601 (2004).
[16]Z. Li and S. Zhang, Phys. Rev. Lett. **92**, 207203 (2004).
[17]S. Zhang and Z. Li, Phys. Rev. Lett. **93**, 127204 (2004).
[18]A. Thiaville, Y. Nakatani, J. Miltat, and Y. Suzuki, Europhys. Lett. **69**, 990 (2005).
[19]A. V. Khvalkovskiy, V. Cros, D. Apalkov, V. Nikitin, M. Krounbi, K. A. Zvezdin, A. Anane, J. Grollier, and A. Fert, Phys. Rev. B **87**, 020402 (2013).
[20]M. Sharad, C. Augustine, G. Panagopoulos, and K. Roy, IEEE Trans. Nanotechnol. **11**, 843 (2012).
[21]J. A. Currivan, Y. Jang, M. D. Mascaro, M. A. Baldo, and C. A. Ross, IEEE Magn. Lett. **3**, 3000104 (2012).

[22]X. Wang, Y. Chen, H. Xi, H. Li, and D. Dimitrov, IEEE Electron Device Lett. **30**, 294 (2009).

[23]R. Chanthbouala, A. Matsumoto, J. Grollier, V. Cros, A. Anane, A. Fert, A. V. Khvalkovskiy, K. A. Zvezdin, K. Nishimura, Y. Nagamine, H. Maehara, K. Tsunekawa, A. Fukushima, and S. Yuasa, Nat. Phys. **7**, 626–630 (2011).

[24]N. Locatelli, V. Cros, and J. Grollier, Nature Mater. **13**, 11 (2014).

[25]A. V. Khvalkovskiy, K. A. Zvezdin, Y. V. Gorbunov, V. Cros, J. Grollier, A. Fert, and A. K. Zvezdin, Phys. Rev. Lett. **102**, 067206 (2009).

[26]C. T. Boone, J. A. Katine, M. Carey, J. R. Childress, X. Cheng, and I. N. Krivorotov, Phys. Rev. Lett. **104**, 097203 (2010).

[27]P. J. Metaxas, J. Sampaio, A. Chanthbouala, R. Matsumoto, A. Anane, A. Fert, K. A. Zvezdin, K. Yakushiji, H. Kubota, A. Fukushima, S. Yuasa, K. Nishimura, Y. Nagamine, H. Maehara, K. Tsunekawa, V. Cros, and J. Grollier, Sci. Rep. **3**, 1829 (2013).

[28]P. Yan, X. S. Wang, and X. R. Wang, Phys. Rev. Lett. **107**, 177207 (2011).

[29]D.-S. Han, S.-K. Kim, J.-Y. Lee, S. J. Hermsdoerfer, H. Schultheiss, B. Leven, and B. Hillebrands, Appl. Phys. Lett. **94**, 112502 (2009).

[30]M. Jamali, H. Yang, and K.-J. Lee, Appl. Phys. Lett. **96**, 242501 (2010).

[31]J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).

[32]L. Berger, Phys. Rev. B **54**, 9353 (1996).

[33]S. Zhang, P. M. Levy, and A. Fert, Phys. Rev. Lett. **88**, 236601 (2002).

[34]K. Xia, P. J. Kelly, G. E. W. Bauer, A. Brataas, and I. Turek, Phys. Rev. B **65**, 220401 (2002).

[35]The Py magnetic parameters used in the modelling are: $M_S = 800$ emu/cm^3, the exchange constant $A = 1.3 \times 10^{-6}$ erg/cm, $\alpha = 0.01$, spin polarization $P = 0.31$, and the bulk anisotropy is neglected.

[36]It is worth noting that for the studied geometry the amplitude of the Oersted field even under the contact is not more than 15 Oe, and at a distance of about 10–15 nm it almost completely disappears. Hence, it leads only to a change of the DW initial position by 10–15 nm.

[37]E. Kneller and R. Hawig, IEEE Trans. Magn. **27**, 3588 (1991).

[38]H. Zeng, J. Li, J. Liu, Z. L. Wang, and S. Sun, Nature **420**, 395 (2002).

[39]Y. B. Bazaliy, Phys. Rev. B **76**, 140402 (2007).

[40]Y. B. Bazaliy, Appl. Phys. Lett. **91**, 262510 (2007).

[41]Y. B. Bazaliy, Phys. Rev. B **85**, 014431 (2012).

[42]A. Scott, *Nonlinear Science: Emergence and Dynamics of Coherent Structures* (Oxford University Press, 2003).