Indirect Control of Antiferromagnetic Domain Walls with Spin Current

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The indirect controlled displacement of an antiferromagnetic domain wall by a spin current is studied by Landau-Lifshitz-Gilbert spin dynamics. The antiferromagnetic domain wall can be shifted both by a spin-polarized tunnel current of a scanning tunneling microscope or by a current driven ferromagnetic domain wall in an exchange coupled antiferromagnetic-ferromagnetic layer system. The indirect control of antiferromagnetic domain walls opens up a new and promising direction for future spin device applications based on antiferromagnetic materials.

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Current induced domain wall motion is an important aspect in magnetism due to its potential applications in magnetic memory [1,2] and logic devices [3]. The motion of domain walls directly influenced by spin current exhibiting a spin transfer torque has been studied experimentally [4–6] and theoretically [7–9]. The investigations of current driven antiferromagnetic domain walls is very limited [10]. Antiferromagnetic domain wall motion driven by the spin current by indirect means has not been described so far. In this Letter we propose two promising directions for experiments on the indirect control of an antiferromagnetic (AFM) domain wall guided by of a theoretical description of the spin dynamics in antiferromagnetic film structures.

Yamaoka *et al.* [11] have shown that it is possible to manipulate domain walls with the strayfield of a magnetic force microscope tip. Recent experiments [12] have demonstrated magnetization switching of nanoislands due to the spin current of a spin-polarized scanning tunneling microscope (SP-STM). These experiments allow us to address the domain wall individually and therefore provide a platform for potential applications of STM-based devices for information storage and logic devices. Based on these results, we propose to use the spin current of the SP-STM tip to shift antiferromagnetic domain walls. Another possibility is to drive the antiferromagnetic domain wall with the aid of a ferromagnetic (FM) domain wall. While the manipulation using an SP-STM tip is restricted to the atomic length scale, the controlled interaction between domain walls is important for the development of new devices in the field of antiferromagnetic metal based spintronics [13,14]. Furthermore, the results contribute to an improved understanding of the exchange bias effect [15–17] and provide new insight into the domain wall dynamics of filled nanotubes [18]. For the sake of simplicity, the present investigation is concentrated on idealized model systems. However, with regards to recent experiments [12,19] the realization of our proposal seems to be within reach.

We consider a 2D antiferromagnetic wire with a width up to $L_x = 41a$, where a is the lattice constant, consisting of classical Heisenberg spins. The long axis of the wire is the x axis which contains two domains (A and B) separated by a 180° transverse domain wall. The domains can be distinguished by their AFM sublattices. In domain A sublattice 1: $\mathbf{S}_i = +\hat{\mathbf{x}}$ is localized on even ($x_i + y_i = 2l$, $l \in \mathbb{Z}$)) and sublattice 2: $\mathbf{S}_i = -\hat{\mathbf{x}}$ on odd ($x_i + y_i = 2l + 1$)) lattice sites, vice versa in domain B.

The magnetic properties of the system are well described by the model Hamiltonian:

$$\mathcal{H} = J\sum_{\langle ij\rangle}\mathbf{S}_i \cdot \mathbf{S}_j - D_x\sum_i (S_i^x)^2 + D_z\sum_i (S_i^z)^2, \quad (1)$$

where $\mathbf{S}_i = \boldsymbol{\mu}_i/\mu_S$ is a three dimensional magnetic moment of unit length. The first sum in Eq. (1) is the exchange interaction between nearest neighbors with $J = 1$ for an antiferromagnetically coupled system. The second sum represents a uniaxial anisotropy, with the x axis as the easy axis of the system ($D_x/J = 0.125$). The last sum describes a hard z-axis anisotropy ($D_z/J = 0.05$).

The fundamental equation of motion for magnetic moments is the Landau-Lifshitz-Gilbert (LLG) equation with additional spin torque terms to describe the influence of the electric current which is written as:

$$\frac{\partial \mathbf{S}_i}{\partial t} = -\frac{\gamma}{(1+\alpha^2)\mu_S}\mathbf{S}_i \times [\mathbf{H}_i + \alpha(\mathbf{S}_i \times \mathbf{H}_i)] + \mathcal{C}\mathbf{S}_i \times \mathbf{T}_i + \mathcal{D}\mathbf{S}_i \times (\mathbf{S}_i \times \mathbf{T}_i), \quad (2)$$

where γ is the gyromagnetic ratio, $\alpha = 0.025$ is the Gilbert damping constant and the internal field is $\mathbf{H}_i = -\partial\mathcal{H}/\partial\mathbf{S}_i$. The last two terms are the contributions (precession and relaxation) of the spin torque [20].

In order to examine the manipulation of an antiferromagnetic transverse domain wall with an SP-STM tip, we consider a tip moving at a constant height h along the long axis (x axis) of the stripe with constant velocity $v_{\text{tip}} = 0.02\frac{a\mu_S}{\gamma t J}$. To describe the influence of the electric current we have used a similar description as in the case of a spin valve [21–23] $\mathcal{C} = 0$ and $\mathcal{D} = 1$. To describe the local strength and orientation of the current we used the description given by Tersoff and Hamann [24]:

$$\mathbf{T}_i = -I_0 e^{-2\kappa\sqrt{(x_i - x_{\rm tip})^2 + (y_i - y_{\rm tip})^2 + h^2}}\mathbf{P}, \tag{3}$$

where $\kappa = 3.7128/a$ is the work function, $\mathbf{r}_{\rm tip} = (x_{\rm tip}, y_{\rm tip}, h)$ the time dependent tip position, $\mathbf{r}_i = (x_i, y_i, 1)$ the position of the spin $\mathbf{S}_i$, $\mathbf{P}$ the tip polarization, and $I_0 = 1.0 \times 10^7 \frac{\mu_S}{\gamma t J}$.

Within this framework we can examine different tip polarization scenarios. The simplest cases are for tip polarizations along the cardinal axis of the stripe as shown in Fig. 1: In case I the tip polarization is (anti-)parallel to the magnetization inside the domains $\mathbf{P} = \pm\hat{\mathbf{x}}$; case II, (anti-) parallel to the magnetization inside the domain wall $\mathbf{P} = \pm\hat{\mathbf{y}}$; or case III, perpendicular to the magnetization inside both the domains and the domain wall $\mathbf{P} = \pm\hat{\mathbf{z}}$ (see Fig. 1).

Our simulations show that cases I and II ($\mathbf{P} = \pm\hat{\mathbf{x}}$ and $\mathbf{P} = \pm\hat{\mathbf{y}}$)) as well as the domain wall $\mathbf{P} = \pm\hat{\mathbf{y}}$ lead to the situation of a blocked domain wall, with no change of the domain wall position for any current. However, a tip polarization perpendicular to the magnetization ($\mathbf{P} = \pm\hat{\mathbf{z}}$) leads to a controlled motion of the domain wall as it is shown in Fig. 2. This is opposite to a ferromagnetic domain wall where all three cases (I–III) lead to a wall displacement [25].

Figure 2 shows the displacement of the antiferromagnetic domain wall and tip as a function of time. The simulation starts with an SP-STM tip one lattice position behind the center of the antiferromagnetic domain wall as the current is switched on. Depending on the orientation of the tip magnetization [up (down)] and the domain type underneath $[A\ (B)]$ the tip either shifts the domain wall ahead or in the opposite direction. In the latter case the tip loses the domain wall. In the former case the domain wall will be shifted through the whole stripe. The velocity of the domain wall is equal to the tip velocity $v = +v_{\rm tip}$ in this case.

A change in either the tip polarization or the sample domain type would reverse direction of the domain wall motion. This is similar to the case of a ferromagnetic domain wall, where the change of the domain types corresponds with the change from a head-to-head to a tail-to-tail domain wall. If the domain wall width becomes comparable with the lattice constant (Ising limit) the straight motion in Fig. 2 becomes steplike. In this case the domain wall moves a distance of one lattice constant, pauses, then moves another lattice constant. This process is periodic and looks like a staircase in the domain wall displacement. Without additional hard-axis (z-axis) anisotropy ($D_z/J = 0$) the tip will always pull the domain wall.

A second indirect manipulation method is manipulation by a second (ferromagnetic) domain wall. In this case the antiferromagnetic stripe is placed on top of a ferromagnetic stripe (see Fig. 3). This situation requires an altered Hamiltonian. The new one is given by the Hamiltonian of the antiferromagnetic layer [Eq. (1)] plus additional contributions from the ferromagnetic layer ($\mathcal{H}_{\rm FM}$) and the coupling between the antiferromagnet and ferromagnet ($\mathcal{H}_C$):

$$\mathcal{H} = \mathcal{H}_{\rm AFM} + \mathcal{H}_{\rm FM} + \mathcal{H}_C, \tag{4}$$

where

$$\mathcal{H}_{\rm FM} = -J_{\rm FM}\sum_{\langle nm\rangle}\mathbf{S}_n \cdot \mathbf{S}_m - d_x\sum_n (S_n^x)^2 + d_z\sum_n (S_n^z)^2,$$

$$\mathcal{H}_C = J_C\sum_{\langle {\rm in}\rangle}\mathbf{S}_i \cdot \mathbf{S}_n.$$

The contributions of $\mathcal{H}_{\rm FM}$ to the total Hamiltonian are similar to $\mathcal{H}_{\rm AFM}$ where the ferromagnetic exchange constant $J_{\rm FM} = J$ and the easy axis is $d_x/J = 0.075$, and the hard axis is $d_z/J = 4$. Further, we assume an antiferromagnetic interlayer coupling with the coupling constant $J_C = 0.5J$ and the Gilbert damping $\alpha_{\rm FM} = 0.02$ of the ferromagnet.

The LLG Eq. (2) must also be modified such that $\mathcal{C} = -\frac{\alpha-\beta}{(1+\alpha^2)}$, $\mathcal{D} = \frac{1+\alpha\beta}{(1+\alpha^2)}$ (with nonadiabaticity parameter β), $\mathbf{T}_i = u_x\frac{d\mathbf{S}_n}{dx}$ and $u_x = 0.2\frac{\mu_S}{\gamma t J}$ [20]. It is important to note that the current flows only through the ferromagnetic layer.

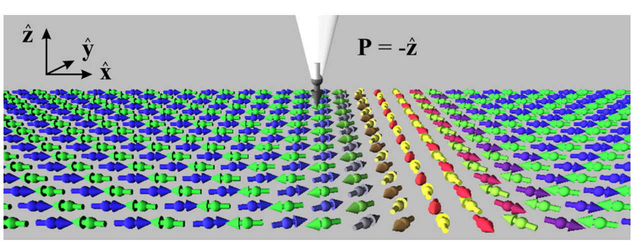

FIG. 1 (color online). Manipulation of an antiferromagnetic domain wall with an SP-STM tip.

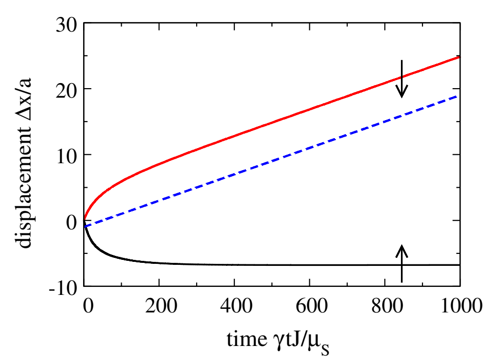

FIG. 2 (color online). Domain wall displacement of an antiferromagnetic domain wall with a moving SP-STM tip. The tip is moving with a constant velocity marked by the dashed line. Depending on the orientation of the tip polarization $\mathbf{P} = \pm\hat{\mathbf{z}}$ the domain wall will be shifted ahead of the tip (↓) or pushed away in the opposite direction (↑).

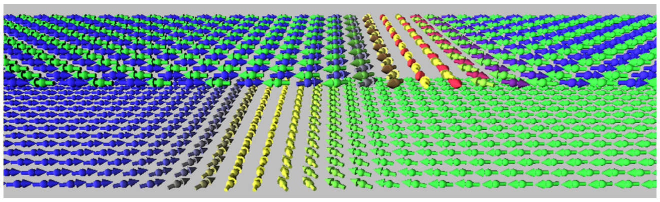

FIG. 3 (color online). Ferromagnetic-antiferromagnetic double layer with ferromagnetic and antiferromagnetic domain walls. The antiferromagnetic layer is somewhat lifted to improve the view on the ferromagnetic layer.

This means $\mathbf{T}_i$ acts solely in the ferromagnet, while $\mathbf{T}_i$ of the antiferromagnet is zero.

The starting conditions of this simulation are two relaxed domain walls, one in the antiferromagnetic layer at $x_i = 100a$, and one in the ferromagnetic layer at $x_n = 30a$ (see Fig. 4). Figure 4(b) shows that both domain walls induce a magnetization in the y direction in the opposite layer due to the interlayer coupling.

After switching on the current the ferromagnetic domain wall starts to move. A detailed description of the motion and corresponding velocities is given elsewhere [20]. When the ferromagnetic wall approaches the antiferromagnetic domain wall the ferromagnetic domain wall shifts the antiferromagnetic one, reducing the velocity of the ferromagnetic domain wall. The wall linking and reduction of the domain wall velocity can be clearly seen in Fig. 5(a). The velocity reduction can be explained by the fact that a domain wall can be seen as a quasiparticle of certain mass and the connection process as an inelastic collision of two quasiparticles. In such a collision, if $D_z/J = 0$ the velocity of the ferromagnetic domain wall remains constant [see Fig. 5(b)]. In this case the velocity of the ferromagnetic domain wall is small (lower velocity limit see [20]) and the antiferromagnetic domain wall has enough time to react. However, regardless of the value of D_z/J, the speed of the antiferromagnetic and ferromagnetic domain wall is identical and the distance between both domain walls stays the same, as is apparent in Figs. 5(a) and 5(b).

Figure 5(c) shows the y component of the magnetization in both layers during the domain wall motion. It can be seen that the ferromagnetic domain wall is just behind the antiferromagnetic domain wall. It is remarkable that the center of the ferromagnetic domain wall is at the same place as the zero-crossing of the induced signal in the antiferromagnetic layer. The same is true for the signal of the antiferromagnetic domain wall in the ferromagnet. As can be seen in Fig. 5(a), after collision there is no change in the distance between the two domain walls, meaning the coupling is stable. However, if the ferromagnetic domain wall is faster than the highest possible velocity of the antiferromagnetic domain wall, the linking does not take place and the antiferromagnetic domain wall will not move.

Another interesting fact for this system is that an antiferromagnetic domain wall without an additional hard-axis anisotropy ($D_z/J = 0$) follows a precessional motion only if the driving ferromagnetic domain wall also precesses during motion; i.e., the ferromagnet also has no hard-axis anisotropy ($d_z/J = 0$). This behavior is explained by the coupling between the antiferromagnet and the ferromagnet. There are no external forces acting on the antiferromagnetic domain wall. Because of the interlayer exchange coupling the collinear orientation of the transverse components of the ferro- and antiferromagnetic domain walls is energetically favorable. Therefore, if the ferromagnetic domain wall precesses the antiferromagnetic domain wall must also follow the precessional motion. Anyhow, the antiferromagnetic domain wall precesses only if the ferromagnetic domain wall is precessing. This is independent of whether the antiferromagnetic domain wall would normally precess or not.

In a biaxial ferromagnet ($d_z/J \neq 0$) with currents higher than some critical current the domain wall starts to oscillate. This behavior is called Walker breakdown [26]. In this regime the ferromagnetic domain wall starts to move periodically forward and backward. Because of the interlayer

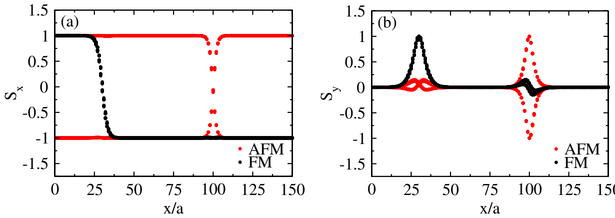

FIG. 4 (color online). Domain wall profiles (a) easy axis direction and (b) transverse component of the ferromagnetic and antiferromagnetic domain wall before coupling.

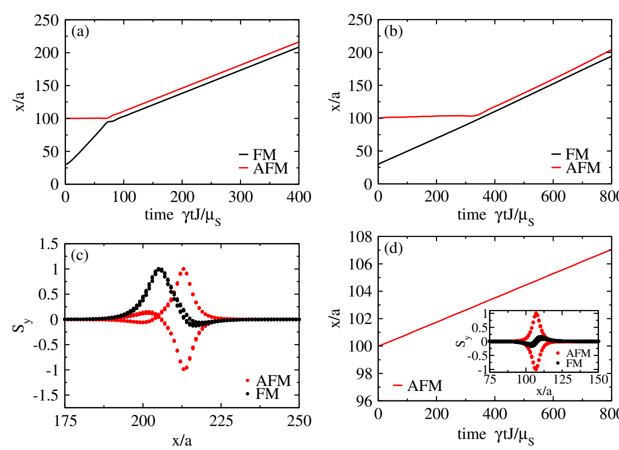

FIG. 5 (color online). Domain wall displacement in a FM-AFM double layer: (a) with and (b) without hard-axis anisotropy in the ferromagnetic layer. (c) Transverse S_y components of the domain walls corresponding with Fig. 5(a) during coupled motion. (d) Antiferromagnetic domain wall displacement without a ferromagnetic domain wall.

coupling the antiferromagnetic domain wall periodically moves forward and stops, depending on the distance between the two domain walls.

Thus far we have described the interaction between a ferromagnetic and an antiferromagnetic domain wall. However, in principle there is no need of a ferromagnetic domain wall to drive the antiferromagnetic domain wall. Figure 5(d) shows the wall displacement of an antiferromagnetic domain wall driven by a current in the ferromagnetic layer. The domain wall is driven solely by the current acting on the magnetization component in the ferromagnet induced by the antiferromagnetic domain wall (see inset). The velocity in this case is very small but the motion is still present.

In summary we have demonstrated that it is possible to shift an antiferromagnetic domain wall by the SP-STM tip with the aid of the spin-polarized tunneling current. For this purpose the tip polarization **P** has to be perpendicular to the magnetization inside the domains and domain wall. The direction of the domain wall motion is identical for $\mathbf{P} = \pm\hat{\mathbf{z}}$. To change the direction of the domain wall motion one has to change the orientation of the tip polarization **P**. During motion the velocity of the antiferromagnetic domain is equal to the velocity of the SP-STM tip.

An alternative method to indirectly control an antiferromagnetic domain wall is the usage of the interplay between antiferromagnetic and ferromagnetic domain walls in exchange coupled ferromagnetic-antiferromagnetic double layers. We have shown that it is possible to drive an antiferromagnetic domain wall with the aid of a ferromagnetic domain wall, when the ferromagnetic domain wall itself is driven by a spin current. The coupling between the ferromagnetic and antiferromagnetic layer leads to induced magnetization changes in the opposite layer due to the domain walls. During the motion both domain walls couple via these induced signals. We have further shown that the coupling with the antiferromagnetic domain wall reduces the velocity of the ferromagnetic domain wall. Only if the ferromagnet has no additional hard-axis anisotropy ($d_z/J = 0$) does the velocity remain constant. A surprising result was that the antiferromagnetic domain wall without hard-axis anisotropy ($D_z/J = 0$) does not show a precessional motion if the ferromagnetic domain wall does not precess. A precessional motion occurs only if both layers do not possess any hard-axis anisotropy. Finally, we have shown that the ferromagnetic domain wall makes the manipulation of domain walls much easier; however, a ferromagnetic domain wall is not necessary. The induced signal of the antiferromagnetic domain wall in the ferromagnetic layer can also be used to drive the antiferromagnetic domain wall. Here, the velocity is very small but the motion is measurable.

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