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Manipulating the magnetization direction of transverse domain walls in Permalloy/Ir strips using nanosecond current pulses

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Abstract

Using magnetic force microscopy and micromagnetic simulations, we studied the effect of Oersted magnetic fields on transverse magnetic domain walls in Fe₂₀Ni₈₀/Ir bilayer nanostrips. Applying nanosecond current pulses with a current density of around 2×10^{12} A/m², the magnetization direction of a transverse domain wall in the Fe₂₀Ni₈₀-layer could be switched reversibly and reproducibly. This suggests that in bi- and trilayer strips the Oersted field stabilizes the transverse wall magnetization direction during current-induced domain wall motion and prevents domain wall transformations.

Keywords: Domain walls, Oersted field, Current-induced domain wall motion, Micromagnetic simulations

1. Introduction

When a longitudinal electrical current is passing through a nanostrip containing a magnetic domain wall (DW), both the spin and the charge of the conduction electrons act on the DW magnetization. In single ferromagnetic layers, the spin polarization of the current induces a local torque on the domain wall, called the spin-transfer torque (STT) [1, 2]. In multilayered structures containing heavy metals, like Pt or Ta, supplementary torques induced by the spin-orbit coupling also influence the magnetization of the magnetic layer(s) [3, 4]. On the other hand, the charge associated with the current induces an Oersted magnetic field (H_{Oe}), transverse to the current direction. Inside the current flow, this Oersted field increases with the distance from the center of the current, and is proportional to the current density. For strips with a single metallic layer, the in-plane transverse component of the Oersted field can usually be neglected for thin enough strips since the net Oersted field is zero, the maximum fields acting in opposite directions at the bottom and top interfaces of the strip are small and magnetization remains rigidly coupled by exchange along the thickness of the film. In asymmetric strips having different buffer and capping layers, a significant net transverse Oersted field can exist and influence the magnetization configuration of the FM layer(s) during current pulses [5]. In particular, in layers having in-plane magnetization, it may influence the configuration of domain walls that are present in the strip, favoring transverse

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domain walls (TW) with magnetization parallel to the field. The stabilization of one particular TW configuration by a transverse (Oersted) field during current-induced DW motion (CIDM) may delay the onset of domain wall transformations associated to the Walker breakdown [6] up to higher domain wall velocities, as was already shown for field induced motion, both theoretically and experimentally [7, 8, 9, 10, 11, 12].

In this work, we have used Magnetic Force Microscopy (MFM) to study the influence of current pulses on the configuration of magnetic domain walls in Permalloy/Ir (Permalloy : $\text{Fe}_{20}\text{Ni}_{80}$, or Py) bilayer nanostrips with similar Py and Ir thickness. We show that the magnetization direction of the transverse DW can indeed be manipulated using Oersted fields, and we determine the current density needed for switching the transverse domain walls as a function of strip width and Ir thickness. The associated switching fields are compared to the results of micromagnetic simulations. The current densities for which switching takes place are similar to the ones needed for current-induced domain wall motion, indicating that the Oersted field should have an important influence on CIDM in this type of multilayer systems.

2. Materials and Methods

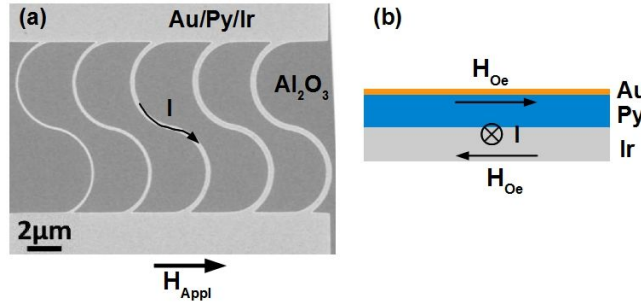


Figure 1: (a) SEM image of 14 μm long and (from left to right) 100, 200, 300 and 400 nm (two times) wide S-shaped nanostrips, together with the current injection pads. The materials, current flow and direction of applied field for nucleating the transverse walls are indicated. (b) Sketch of the layer structure and the geometry of the current and the associated Oersted field (looking along the strip axis).

We chose to study Py/Ir bilayers since the epitaxial growth of Ir(111) on sapphire(0001) is well controlled [13] and Py(111) can be grown epitaxially on Ir(111) [14]. The initial goal was to obtain high quality samples with few defects for current-induced domain wall motion. Samples with two different Ir thicknesses were studied, Py(10 nm)/Ir(10 nm) and Py(10 nm)/Ir(15 nm), capped by 2 nm of Au. Nanostrips with a length of 14 μm and 100 to 400 nm wide were patterned using electron-beam lithography and ion-beam etching. Fig. 1 shows the scanning electron microscope (SEM) image of the S-shaped nanostrips, which are connected in parallel to Au contacts through the injection pads. A 50 mT quasi-static magnetic field pulse was applied along the radius of the bends (horizontal direction in Fig. 1) to nucleate TWs at the bends of these nanostrips. Measurements were then performed without magnetic field applied. The applied current pulses had a duration of 3 ns, with rise and fall times of 0.8 ns. This pulse length was chosen to be longer than typical precession times and short enough to limit the influence of thermal effects on the DW configuration. The current flowing through the strips was deduced from the voltage measured across the 50 Ohm input of a 6 GHz LeCroy oscilloscope in series

with the sample, supposing that the resistivity is the same for all strips and the current in each strip is thus proportional to its width. We applied current densities, averaged over the sample cross-section, between 1.5 and 3×10^{12} A/m². For estimating the amplitude of the Oersted field induced by the current pulses, we measured the DC conductivity of continuous layers with different Py and Ir thickness in the Van der Pauw geometry [15] : Au(2nm)/Py(10nm)/Ir(10nm), Au(2nm)/Py(15nm)/Ir(10nm) and Au(2nm)/Py(10nm)/Ir(15nm). These measurements indicate that the resistivity of the Py layer is about a factor 5 larger than the one of Ir : 15 ± 5 $\mu\Omega\cdot\text{cm}$ (Py) vs. 3 ± 0.5 $\mu\Omega\cdot\text{cm}$ (Ir). These values are lower than literature values for Py (≈ 30 $\mu\Omega\cdot\text{cm}$ [16]) and Ir (≈ 4.7 $\mu\Omega\cdot\text{cm}$ for bulk Ir), which may be related to the crystalline quality of epitaxially grown layers.

The effective Oersted field acting on the Py layer is given by the sum of the fields generated by the currents in the Ir and Au layers, with the Oersted field from the Au layer opposite to the one of the Ir layer. For its calculation, we suppose that the current densities in the Ir and Au layers are the same, five times larger than the current density in the Py layer. At the center of the Py layer, the Oersted field is then given by Ampère's law : $H_{\text{Oe}} = (\mu_0 J_{\text{Ir}} t_{\text{Ir}} - \mu_0 J_{\text{Ir}} t_{\text{Au}})/2$. We thus neglect the contribution of the current flowing inside the Py layer, which does not give a net contribution to the Oersted field.

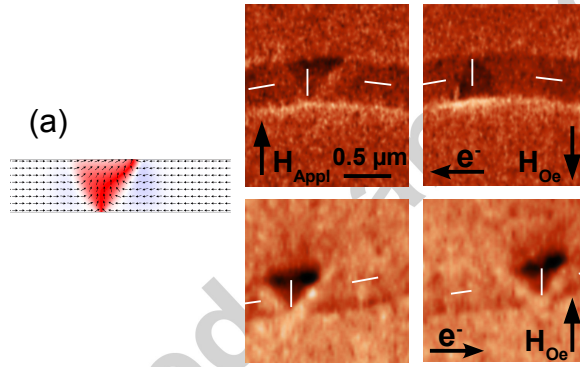


Figure 2: (a) Micromagnetic simulation of a head-to-head TW in a 300 nm wide, 10 nm thick Py strip. (b,c) Transverse domain walls in a 14 μm long and 400 nm wide S-shaped Au(2nm)/Py(10nm)/Ir(15nm)/Al₂O₃(0001) nanostrip. MFM images of (b) the initial configuration of a head-to-head TW and (c) after applying a $J_{\text{Ir}} = 2.3 \times 10^{12}$ A/m², 3 ns current pulse. (d) and (e) Displacement of a TW in a 400 nm wide Au(2nm)/Py(10nm)/Ir(10nm)/Al₂O₃(0001) nanostrip induced by a 3 ns current pulse with a current density $J_{\text{Ir}} = 3.4 \times 10^{12}$ A/m² ($J_{\text{Py}} = 6.8 \times 10^{11}$ A/m²). Both the initial and final magnetization direction of the TW are parallel to the Oersted field direction. The dotted white arrows indicate the magnetization direction in the strip and the domain walls, while the black arrows give the direction of electron flow and the directions of applied and Oersted magnetic fields.

MFM images were taken in air and at 300K, using a NT-MDT microscope NTegra-Aura with custom-made low moment magnetic tips, obtained by depositing 3-5 nm of Co₈₀Cr₂₀ on commercial AC240TS probes from Olympus. No influence of the tip moment on the TW shape or position was detected. According to the DW phase diagram [17, 18], the energetically most favorable DW structure for a Py thickness of 10 nm and strip widths larger than 150 nm is the vortex wall. However, the strong quasistatic field pulse applied to nucleate the DWs imposes the formation of a TW with its magnetization parallel to this field as the initial state. For the strip dimensions used here, such a metastable TW is asymmetric, as seen in the simulation and the MFM images of Fig. 2. Fig. 2(b,c) shows an example of the TW switching, for a 400 nm

wide Py(10nm)/Ir(15nm) nanostrip. In the initial state the TW has its magnetization pointing up (Fig. 2(b)). After a pulse of duration 3 ns and current density J_{Ir} of 2.3×10^{12} A/m², corresponding to an H_{Oe} of about 19 mT pointing down in the image, the TW magnetization has switched (Fig. 2(c)).

3. Results and Discussion

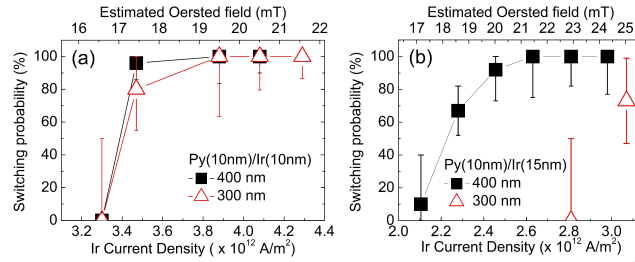


Figure 3: TW switching probability as a function of current density and corresponding Oersted field in 300 and 400 nm wide Au(2nm)/Py(10nm)/Ir/Al₂O₃(0001) nanostrips for Ir thickness of (a) 10 nm and (b) 15 nm.

The probability of TW magnetization switching was measured for different current pulses. Fig. 3(a) shows the TW switching probability as a function of the current density in the Ir layer and the corresponding Oersted field for Py(10 nm)/Ir(10 nm) bilayers. The Py thickness of 10nm is sufficient to guarantee that the influence on the DW configuration of effects due to the large spin-orbit interaction in the Ir and Au layers, like the Rashba effect [3], spin Hall effect [4] or Dzyaloshinskii-Moriya interaction [19], is negligible. The TW switching probability increases with increasing current density. From Fig. 3(a) we can deduce approximate switching fields (fields required to switch the DW magnetization direction with 100% probability) of 18 ± 3 mT for 400 nm and 19 ± 3 mT for 300 nm wide strips. The corresponding current densities J_{Ir} are between 3.5 and 3.8×10^{12} A/m². The 300 nm wide TWs require a higher transverse field to reach a deterministic switching, as expected from the higher transverse demagnetizing field for narrower nanostrips of a given thickness. The error bars on the determined experimental switching fields are rather large, since the switching fields are extrapolated from a limited number of events (a maximum of ten per current density value) and the uncertainty in the current densities in the different layers is large.

It is expected that the switching field depends only on the strip width and Py thickness. For larger Ir thickness a smaller current density is needed to obtain the same Oersted field, and the current density for switching should thus be lower. This is indeed the case, as can be seen in Fig. 3(b) where the switching probability of the DW magnetization as a function of Ir current density is plotted for 15 nm of Ir. The current densities J_{Ir} for switching are between 2.4 and 3.1×10^{12} A/m². However, the associated estimated Oersted fields for switching are slightly higher than for 10 nm of Ir : 21 ± 3 mT for 400 nm and > 25 mT for 300 nm wide strips. We will come back to this discrepancy later.

Small DW displacements were sometimes observed upon switching the TW magnetization direction. Such a displacement can be induced by STT, by inertial auto-motion [20] or by a combination of both [21]. In our case, where the transformation is imposed by the transverse field, such a displacement has to take place during the 3ns current pulse. In our micromagnetic

simulations, a small displacement (in the order of the domain wall width) indeed occurs during the transformation. The systematic observation of such displacements in the experiment may be hampered by the important pinning of the DWs in our samples. No switching of the TW magnetization was observed in 100 and 200 nm wide strips up to the highest available current density (J_{Ir} about 4.4×10^{12} A/m² for Py(10nm)/Ir(15nm) and 3.3×10^{12} A/m² for Py(10nm)/Ir(15nm)).

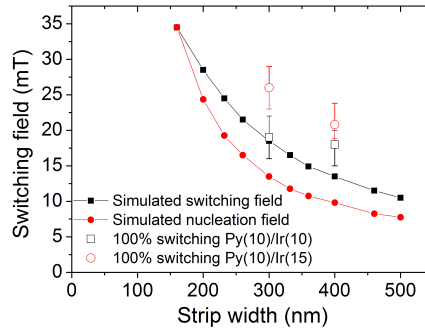


Figure 4: Simulated vortex nucleation fields (filled red dots) and switching fields (filled black squares) for a TW in 10 nm thick Py nanostrips with different widths. The experimental switching fields for 10 nm (open black squares) and 15 nm (open red dots) of Ir are also given. The continuous lines are guides to the eye.

In order to compare the experimental values found for the TW switching fields with a model case, we performed micromagnetic simulations using the finite differences OOMMF code from NIST [22]. In these simulations, typical values for Py [17, 18] were used for spontaneous magnetization ($\mu_0 M_{Py} = 1.0053$ T) and exchange stiffness ($A_{Py} = 10$ pJ/m). Magnetocrystalline anisotropy was zero, while the cell size was set to $4 \times 4 \times 10$ nm³ and the damping parameter to 0.01. The thickness of the Py layer was fixed to 10 nm and the strip width was varied from 160 to 600 nm. To minimize size effects, the strip length was chosen to be at least 20 times its width, and magnetic moments at the extremities of the nanostrips were fixed to avoid non-uniform magnetization profiles at the edges. Initial conditions were such that a relaxed TW is located at the center of the nanostrips. An instantaneous, homogeneous magnetic field pulse of 3 ns duration was then applied from remanence, with only a component transverse to the nanostrip, and the system was let free to evolve. If DW transformation did not occur, the amplitude of the magnetic field was increased by 0.25 mT each time (starting again from remanence). In Fig. 4, the red dots give the fields for which a vortex core is nucleated at the border of the strip, and the transverse wall transforms into a vortex wall. This is called the nucleation field. The black squares give the field for which the vortex core is annihilated at the opposite edge, resulting in a transverse wall with its magnetization opposite to its initial direction. This switching field is larger than the nucleation field, since a VW is more stable than a TW for strip widths larger than 160 nm. The switching field is found to scale with the inverse of the nanostrip width. What is measured in the experiment corresponds to this switching field, since the final state contains a TW with switched magnetization direction.

Also experimentally the nucleation field was observed to be lower than the switching field. In fact, vortex walls were observed in the 300 and 400 nm wide strips after applying pulses with a current density corresponding to a switching probability lower than 100% in Fig. 3. No systematic study of the nucleation fields was performed, but an upper bound is given by

the Oersted fields corresponding to the lowest current densities in Fig. 3, i.e. 17.5 ± 3 mT for Py(10nm)/Ir(10nm) and 18.5 ± 3 mT for Py(10nm)/Ir(15nm). No spontaneous transformation of TWs into VWs was observed in the absence of current, indicating that the energy barrier for the transformation of this metastable state to a VW can not be overcome at room temperature.

Fig. 4 also shows the experimental values of the switching fields, determined for Py(10nm)/Ir(10nm) (open black squares) and Py(10nm)/Ir(15nm) (open red dots). For each strip width, the experimentally determined switching field is higher for the Py(10nm)/Ir(15nm) strips than for the Py(10nm)/Ir(10nm) strips, which is unexpected. To calculate the current density in the different layers, we supposed that it does not vary with layer thickness, which is not necessarily correct. Counil *et al.* [16], for example, reported a change in resistivity of a factor 3 for a Py layer upon changing the thickness from 20 to 3 nm. In our case, the resistivities of 10 and 15 nm of Ir may be different due to different crystalline quality or different interface contributions.

A possible overestimation of the Oersted field may also be at the origin of the difference between the experimental and simulated switching fields. On the other hand, the experimental switching field can be influenced by sample imperfections leading to DW pinning and thus to a higher switching field.

Current-induced switching of the TW magnetization not related to Oersted fields has been reported in literature [23, 24, 25]. In order to ascertain that the TW magnetization is imposed by the Oersted field, we applied current pulses giving rise to fields parallel to the TW magnetization. DW transformations were not observed in that case, but sometimes DW displacements took place (Fig. 2(d,e)). This behavior confirms that the Oe field can tune and stabilize the TW magnetization.

Our measurements show that in Py(10nm)/Ir(10nm,15nm) bilayer nanostrips the current density needed to impose a TW magnetization direction is of the order of 2 to 3×10^{12} A/m² in the Ir layer, corresponding to only 4 to 6×10^{11} A/m² in the Py layer. These current density values are of the same order of magnitude as those reported in the literature for domain wall propagation in single layer Py nanostrips. We therefore expect the Oe field to have an influence on DW motion through the stabilization of the DW magnetization. In fact, it has been shown by Eastwood *et al.* [26] that for Py nanostrips with similar width (390 nm) and thickness (10 nm) the TW magnetization can already be stabilized with a transverse field of the order of 5 mT. In previous measurements on trilayer Py/Cu/Co nanostrips, we observed high current-induced DW velocities for current densities corresponding to transverse Oersted fields of about 3-4 mT [27]. In that case, the Py layer thickness was smaller (5nm), leading to a higher stability of the TW configuration according to the DW phase diagram [17, 18], a stability that is further increased by the magnetostatic interaction with the Co layer [28]. The stabilization of a given TW configuration and the consequent shift of the Walker breakdown to higher current densities may contribute to the high maximum domain wall velocities observed in these trilayer nanostrips [27, 29].

Fixing the magnetization of a transverse domain wall by an Oersted field can also be of interest in other types of bilayer strips. It was shown in a recent theoretical work that in Py/Pt bilayer strips TWs can move through a combination of STT and vertical spin currents associated to the spin Hall effect in the Pt layers [30]. The direction of motion of the TW depends on its magnetization with respect to the polarity of the spin Hall current. Very high domain wall velocities against the electron flow direction are expected, for current densities just below the threshold current for spin Hall current induced TW switching. If the current density for TW switching can be increased by adding an Oersted field, higher maximum domain wall velocities may be reached. Engineering hybrid systems with in-plane magnetization that lead to a combination of current-induced torques acting on the domain wall magnetization, like STT, spin Hall current

and Oersted fields, may lead to much higher current-induced domain wall velocities, as it was already shown for perpendicular magnetic systems [31, 32, 33].

4. Conclusions

We have used Magnetic Force Microscopy to study the switching of the magnetization of transverse magnetic domain walls in epitaxial Py/Ir bilayers with 10 nm of Py, induced by Oersted fields. The estimated switching fields are 20-25 mT for 300 nm wide strips, and 18-22 mT for 400 nm wide strips. These values are slightly higher than the ones deduced from micromagnetic simulations for perfect strips. The associated current densities are of the order of 10^{12} A/m², comparable to the current densities used for current-induced domain wall motion in single Py strips. The influence of the Oersted field on the domain wall configuration should thus be taken into account when studying current-induced domain wall motion in bilayer systems or other systems where part of the current can flow inside buffer or cover layers.

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