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High domain wall velocity at zero magnetic field induced by low current densities in spin valve nanostripes

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Current-induced magnetic domain wall motion at zero magnetic field is observed in the permalloy layer of a spin-valve-based nanostripe using photoemission electron microscopy. High domain wall velocities (exceeding 150 m/s) are obtained for current densities well below 10^{12} A/m². These values are beyond the expectations of conventional models describing the interaction between spin-polarized currents and domain walls, suggesting a contribution from vertical spin currents in these trilayer structures.

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Moving magnetic domain walls using electric currents via spin-torque effects rather than using a magnetic field is one of the recent exciting developments in spintronics [1]. Since the prediction of spin-torque effects [2], many experimental [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] and theoretical [16, 17, 18] works have been dedicated to the study of current-induced domain wall motion (CIDM). Besides fundamental investigations, the use of domain walls in logic [19] and memory [20] devices has already been proposed. Low current densities and high domain wall (DW) velocities at zero magnetic field are required for future applications.

Direct evidence of CIDM at zero field has been reported for several nanostripe systems, including permalloy (FeNi) [7, 12], magnetic semiconductors [10] and systems with perpendicular magnetization [8, 13, 15]. For the commonly used FeNi system, the critical current densities are not much below 10^{12} A/m² at zero magnetic field [9, 12], associated with DW velocities going from some m/s up to about 100 m/s [12]. Much lower critical currents are found for magnetic semiconductors like GaMnAs (about 1×10^9 A/m²) because of the low magnetic moments, but the observed DW velocities are small

(< 1 m/s) [10]. Moreover, these materials are not ferromagnetic at room temperature. Low current density values are also found in spin-valve-based nanostripes with either in-plane [3, 11] or perpendicular anisotropy [8]. Additionally, transport measurements in FeNi/Cu/Co trilayers show CIDM induced by subnanosecond current pulses [6], indirectly indicating high DW velocities in such spin-valve-based systems.

In this work we show direct evidence of CIDM at zero magnetic field, with high DW velocities (exceeding 150 m/s) at current densities well below 10^{12} A/m². Currents perpendicular to the plane in the vicinity of the DW are probably partly responsible for this increase in efficiency, which makes the trilayer systems possible candidates for spintronic applications based on CIDM.

We observed domain wall motion in the FeNi layer of 400 nm wide FeNi (5 nm)/Cu (8 nm)/Co (7 nm)/CoO (3 nm) nanostripes, by using Photoemission Electron Microscopy (PEEM) combined with X-ray Magnetic Circular Dichroism (XMCD) [21]. The nanostripes were processed from film stacks grown by sputtering on high resistivity Si substrates, combining electron beam lithography and lift-off technique. They were patterned in zigzag shapes with angles of 90° and 120° (see Fig. 1a). Contact electrodes made of Ti/Au were subsequently deposited using evaporation and lift-off technique.

The samples were mounted on a sample holder that allows both magnetic field pulses and current pulses to be applied. For field pulses, we used a combination of double stripline-like microcoils and a home-made pulsed current supply [22]. Nanosecond magnetic field pulses could be

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applied in the plane of the stripes, perpendicular to the long axis of the zigzag, as indicated in Fig 1. Current pulses were injected into the nanostripes using a standard pulse generator providing voltage pulses with 4 ns risetime and tunable length. The current flowing through the stripes was deduced from the voltage measured over the 50Ω entrance of a 6 GHz oscilloscope connected in series with the stripes.

In order to avoid discharges from the objective lens of our Focus IS-PEEM, which is at a distance of 2 mm from the sample, the voltage on the objective lens was kept low (up to 4.2 keV), therefore limiting the spatial resolution to about $0.7 \mu\text{m}$. The measurements were performed at the ESRF beamline ID08. In order to image the domain structure in the FeNi layer of the trilayer system, the x-ray energy was tuned to the Ni L_3 absorption edge (852.8 eV). To optimize the magnetic contrast and minimize the topographic contrast, the difference between two consecutive images obtained with 100% left- and right-circularly polarized x-rays was computed. An attempt to image the buried reference layer by tuning the x-ray energy to the Co L_3 -edge failed due to the limited escape depth of the secondary electrons.

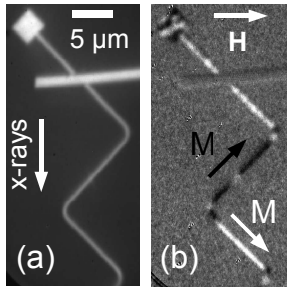


FIG. 1: Topographic (a) and magnetic (b) PEEM images of a 400 nm wide spin-valve-like nanostripe with a zigzag angle of 90° , taken at the Ni L_3 -edge. A static in-plane magnetic field of 400 mT was applied perpendicular to the incoming x-ray beam before the measurements, as indicated by the arrow at the top of (b). In (b), white (black) contrast corresponds to domains having a magnetization component parallel (antiparallel) to the incoming x-ray direction, as indicated by the black and white arrows. The horizontal bar in the upper part of the images is one of the gold contacts for current injection.

In order to prepare the initial magnetic domain configuration of the nanostripes, we applied an in-plane external field, perpendicularly to the zigzag long axis. The remanent magnetic state obtained for a 400 nm wide, 90° angle zigzag nanostripe is shown in Fig. 1b. It consists of several magnetic domains (white or black) separated by domain walls. The contrast is given by the projection of the magnetization on the beam direction, i.e., white (black) domains have their magnetization pointing downwards (upwards), along the stripes. The magnetization is nearly saturated in the straight sections, but a black-white-black-white contrast is visible at the bends. The magnetization in the straight sections of the buried Co layer is expected to be parallel to the FeNi magnetiza-

tion, leading to domain walls at the bends. These head-to-head or tail-to-tail domain walls lead to strong magnetostatic effects that induce a local antiparallel alignment between Co and FeNi layers in the vicinity of the Co DW [23]. These magnetostatic interactions prevent domain wall motion across the bends, but should not hinder DW motion away from the bends.

In Fig. 2, we show an example of current-induced DW motion in a 400 nm wide stripe with zigzag angles of 120° . The initial domain structure was again induced by a static magnetic field applied perpendicular to the long axis of the zigzag, at an angle of 60° with respect to the straight sections. This large angle prevented a complete saturation of the magnetization in all the branches. The domain structure in Fig. 2a could be obtained reproducibly by applying 50 ns long magnetic field pulses with an amplitude of 50 mT. Starting from this initial state, we applied current pulses with different amplitudes and lengths, in order to determine the DW velocity and the threshold current. Fig. 2b shows the domain structure obtained after applying one 15 ns long current pulse with an amplitude of +5 mA. This current pulse causes a displacement of the domain wall from position A to position B in the images. A current pulse with the same amplitude and a length of 20 ns induced a movement of the same domain wall from A to C (Fig. 2c). Note that in these images only one DW moves for all the applied current amplitudes, showing that the pinning strengths can strongly differ at different positions in the nanostripe. This pinning is most likely due to the presence of domain walls in the Co layer. The free motion of the FeNi DW over section A-C in Fig. 2 indicates that no Co DW is present in this section. The much higher coercivity of Co in these trilayer systems also makes current-induced DW motion in Co very unlikely for the current densities used here.

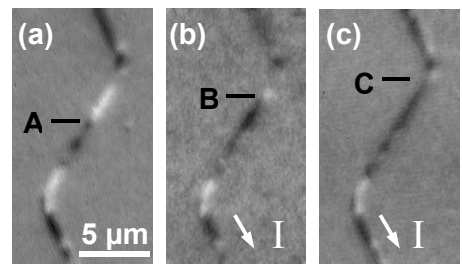


FIG. 2: XMCD-PEEM images of the FeNi layer of a 400 nm wide spin-valve-like nanostripe with a zigzag angle of 120° , (a): after applying an in-plane 50 mT magnetic field pulse perpendicular to the long direction of the stripe; after application of (b) 15 ns and (c) 20 ns long current pulses of +5 mA, starting from the same initial position given in (a). The DW positions before the current pulses (A), after the 15 ns pulse (B) and after the 20 ns pulse (C) are indicated.

The 15 ns pulse caused a CIDM of $(2.7 \pm 0.2) \mu\text{m}$, the 20 ns pulse $(3.4 \pm 0.2) \mu\text{m}$, resulting in domain wall velocities of $(180 \pm 10) \text{ m/s}$ and $(170 \pm 10) \text{ m/s}$, respectively.

The current density in the FeNi layer corresponding to the +5 mA pulse is 5×10^{11} A/m² if we consider a uniform current distribution through the trilayer stack and 1×10^{11} A/m² if we suppose that the current density is proportional to the conductivity in each layer [11]. The value of 5×10^{11} A/m² gives thus an upper bound for the current density in the FeNi layer. Our experimental setup did not allow current pulses with an amplitude larger than 5 mA to be applied, but this result clearly shows that for this trilayer system the current-induced domain wall velocities are well above literature values for single FeNi layers [12], for current densities that are at least a factor two smaller.

Measurements using 50–200 ns current pulses with an amplitude of 2 mA, a value below which no CIDM was detected in our wires, showed DW velocities of (18 ± 2) m/s. For a uniform current distribution, this corresponds to a current density of 2×10^{11} A/m².

In general, experimental results of current-induced DW dynamics are described (at least qualitatively) using a phenomenological model with two components for the spin transfer torque, i.e. the adiabatic and the non-adiabatic torque. In the simplest approach of a 1D domain wall model [18], the DW velocity is expressed as $v_{DW} = \frac{\beta}{\alpha}u$ where u is the rate of spin angular momentum transfer from the conduction electrons to the local moments in the domain wall ($u = JPg\mu_B/(2eM_S)$) where J is the current density and P its polarization rate [18]). Several experiments indicate a value of the non-adiabaticity parameter β close to α , the damping term [24, 25]. However, recently Hayashi *et al.* [12] observed a maximum DW velocity of 110 m/s (for $J = 1.5 \times 10^{12}$ A/m²) at zero magnetic field in 300 nm FeNi nanostripes. This velocity is larger than the spin angular

momentum transfer rate u for any $P < 1$ (for $P = 0.7$, u is about 75 m/s and $\frac{\beta}{\alpha} \approx 1.5$). Using the same parameters, our current density $J \approx 5 \times 10^{11}$ A/m² would lead to a spin transfer rate u of about 25 m/s. Our measured velocity of 175 m/s would then correspond to a very large $\frac{\beta}{\alpha}$ of about 7. Such a large nonadiabaticity seems unlikely and other spin transfer mechanisms must be considered to explain our high DW velocities.

A specificity of our spin-valve structures is that part of the incident spin flux in the FeNi layer is transformed, in the region around the DW, into spin accumulation in the Cu and Co layers. This spin accumulation in the Cu spacer layer below the DW induces a vertical (Current Perpendicular to the Plane or CPP) spin current that flows into the DW and exerts an additional torque on the DW. This situation is somewhat similar to that of spin transfer in the CPP geometry of magnetic pillars. Our results suggest that the yield of this additional vertical spin transfer channel is much higher than the yield of the in-plane spin transfer channel, as predicted recently by micromagnetic simulations on similar nanostructures containing a single DW [26]. Our direct observation of high velocity current-induced DW motion confirms the potential of these trilayer systems for applications in DW-based magnetic memories and logic devices.

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