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We have used time-resolved x-ray photoemission electron microscopy to investigate the magnetization dynamics induced by nanosecond current pulses in NiFe/Cu/Co nanowires. The Oersted magnetic field present during the current pulses induces a large tilt of the NiFe magnetization, transverse to the wires. Spin-wave-like oscillations of the NiFe magnetization are also observed and attributed to precessional motion about the effective field. Our results clearly show that both the quasi-static and dynamic effects of the Oersted field have to be taken into account when interpreting current-induced domain wall motion in multilayered nanowires. This internal, transverse magnetic field may contribute to the increased efficiency of current-induced domain wall motion observed in NiFe/Cu/Co nanowires.

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The possibility to manipulate the magnetic configuration of nanowires by using electrical currents is a recent, exciting development in spintronics. Electrical currents can affect the magnetization of magnetic nanowires both through the charge and the spin of the conduction electrons. The Oersted magnetic field (H_{Oe}) generated by an electrical current has been known for a long time, and more recently the effects of Spin-Transfer Torque (STT) [1, 2] and Rashba spin-orbit torque [3] on nanowire magnetization have been observed. In general, several of these effects are present at the same time. For instance, it was shown that a combination of Oersted fields and STT is needed to explain the magnetization reversal in trilayered pillars induced by a current flowing perpendicular to the plane of the layers [4, 5]. For in-plane systems, H_{Oe} has been invoked to explain the oscillating behavior of constricted domain walls (DWs) in NiFe nanostructures [6] and the magnetization reversal in mesoscopic NiFe/Cu/Co/Au bars [7]. Although the effect of transverse Oersted fields on long-distance current-induced domain wall motion (CIDM) has not been observed until now, it has been shown that a transverse magnetic field can modify the DW shape and velocity for magnetic field induced DW motion [8, 9].

In general, the effect of current on the nanowire magnetization or on the position and shape of magnetic domain walls is studied by quasistatic measurements before and after a current pulse [10, 11]. However, the effect of the Oersted field on the magnetization can only be investigated by direct observations *during* the current pulses. In this paper we have achieved these observations for the first time using time-resolved x-ray magnetic circular dichroism combined with photoemission electron microscopy (XMCD-PEEM) [12, 13]. Our measurements were performed on NiFe/Cu/Co nanowires, for which high current-induced DW velocities (> 180 m/s) have been previously demonstrated for relatively low current densities ($< 5 \times 10^{11}$ A/m^2) [14, 15]. These properties make such nanowires promising for applications, for instance in so-called race-track memories [16]. Our results show that the Oersted field induces both quasi-static and precessional effects on the NiFe magnetization. These effects may contribute to the increased efficiency of current-induced domain wall motion observed in such trilayers.

Spin-valve nanowires with widths of 300 nm and 400 nm were patterned in zigzag shapes, with angles of 90° and 13 μm long straight sections, combining electron beam lithography and ion-beam etching on Cu(2nm)/$Ni_{80}Fe_{20}$(5nm)/Cu(5nm)/Co(5nm)/CoO(6nm) stacks on highly resistive Si(100) ($\rho = 300\ \Omega$.cm). Contact electrodes made of Ti/Au were subsequently deposited using evaporation and a lift-off technique. XMCD-PEEM measurements were performed at the TEMPO beamline at the synchrotron SOLEIL, France, using a Focus IS-PEEM. Prior to the measurements, the sample surface was cleaned using in-situ Ar-bombardment, removing part of the 2 nm Cu protective layer. In order to avoid electrical discharges, the voltage between the sample and the object lens of the PEEM was set to 5.4 keV instead of the nominal 12 keV, limiting the spatial resolution to about 0.6 μm. The local XMCD intensity in the NiFe layer was imaged by tuning the x-ray energy to the Ni L_3 absorption edge (852.8 eV). This XMCD intensity is determined by the projection of the local magnetization on the x-ray incidence direction. To optimise the magnetic contrast, the difference between two consecutive images obtained with 100% left- and right-circularly polarised x-rays was computed.

Temporal resolution was obtained using the time structure of the x-ray beam at the SOLEIL synchrotron in 8-bunch mode, with a 50-60 ps long photon bunch impinging on the sample surface at a repetition rate of 6.77 MHz. Current pulses with variable lengths (2-12 ns) and amplitudes (0-10 mA) were applied to the nanowires at the same repetition rate. The temporal evolution of the magnetic configuration in the nanowires upon application of the current pulses was obtained by recording images for different delays between the current and photon pulses [12, 17, 18]. The total acquisition time for each XMCD-image was about 1 minute (30 s for each circular polarisation), meaning that sequences of about 4×10^8 current (pump) and photon (probe) pulses were averaged.

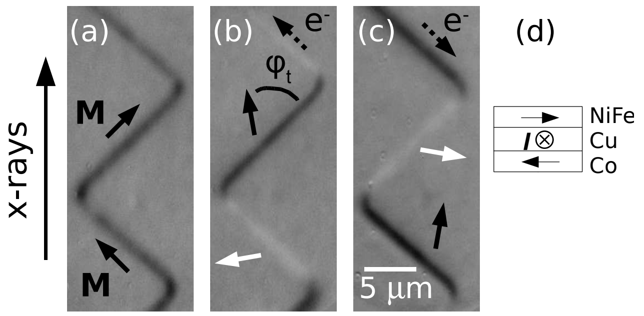

FIG. 1: Time-resolved XMCD-PEEM images of the NiFe layer of a 300 nm wide nanowire before **(a)** and during +4 mA **(b)** and -4 mA current pulses **(c)**. The arrows give the approximate magnetization direction in the wire, while their color indicates the sign of the projection of the magnetization on the incoming x-ray direction, positive (black) or negative (white). The tilt angle φ_t, the angle between the magnetization direction and the nanowire axis, is indicated in **(b)**. The directions of H_{Oe} acting on the NiFe and Co magnetization for one current direction are schematically shown in **(d)**

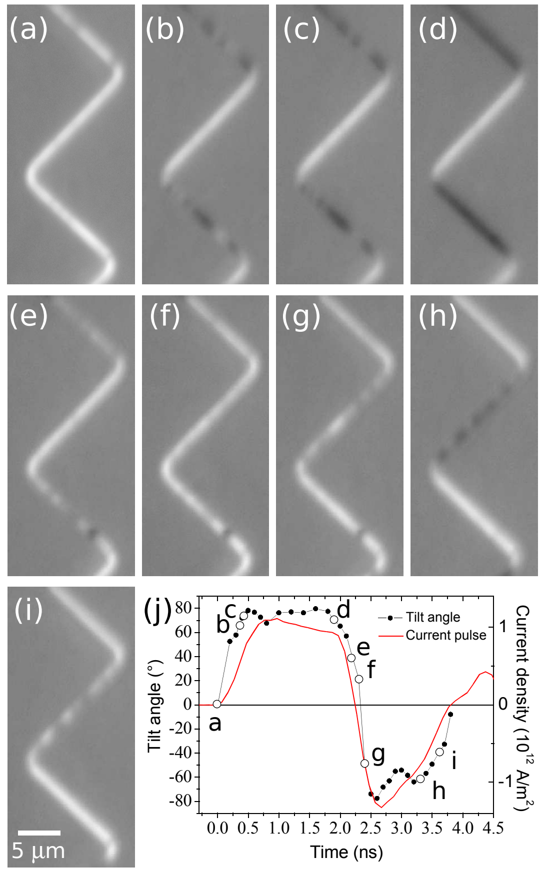

FIG. 2: (color online) Time-resolved XMCD-PEEM images of the NiFe layer of a 400 nm wide nanowire at time delays of (a) 0 ns, (b) 0.35 ns, (c) 0.45 ns, (d) 1.9 ns, (e) 2.2 ns, (f) 2.3 ns, (g) 2.4 ns, (h) 3.3 and (i) 3.6 ns with respect to the beginning of the positive part of the bipolar current pulse. These delays are indicated on the bipolar pulse plotted in (j), together with the magnetization tilt angle φ_t. The oscillations in φ_t at the beginning of the positive and negative parts of the pulse indicate magnetization precession about H_{Oe}.

We first show the effect of relatively long, 10 ns current pulses on the NiFe magnetization of a 300 nm wide nanowire. Figure 1 shows XMCD-PEEM images for the nanowire taken before (a) and during the application of current pulses with amplitudes of +4 mA (b) and -4 mA (c), with the electron flow directions indicated in the Figure. Before and after the current pulses, the magnetization is aligned along the wire and no domain walls are present, leading to an almost homogeneous XMCD intensity (Fig. 1(a)). During the current pulses, the NiFe magnetization tilts away from the wire axis, with a tilt angle φ_t. This tilt is anti-clockwise for a positive and clockwise for a negative current direction, as can be inferred from the magnetic contrast in the differently oriented sections of the nanowire. This is expected since the Oersted field acts in opposite directions transverse to the wire for opposite current directions.

To quantify the effect of the Oersted field on the NiFe magnetization, we acquired, for a 400 nm wide nanowire, a series of XMCD-PEEM images during the application of bipolar current pulses (Fig. 2). The positive/negative part of the pulse is about 2 ns/1 ns long, with a maximum amplitude of +7 mA/−9 mA. The latter value corresponds to a current density of 1.5×10^{12} A/m^2 assuming a homogeneous current distribution in the stack.

Fig. 2 shows a selected series of images, confirming the opposite magnetization tilt for both current directions, as in Fig. 1. The magnetization tilt angle φ_t is given in Fig. 2(j). We extracted φ_t from the time-dependent XMCD intensity in the nanowire bends, where the magnetization is parallel to the x-ray beam direction before the current pulse.

The transverse Oersted field leads to a surprisingly large tilt, around 75°, of the NiFe magnetization. For a soft magnetic material such as NiFe the magnetization direction in a nanowire is mainly determined by magnetostatic effects, which favor magnetization along the wire axis. For a 5 nm thick, 400 nm wide wire the transverse demagnetization factor is about 0.023 [19], meaning that to obtain $\varphi_t = 75°$ a transverse (Oersted) field of $0.023 \times \mu_0 M_S \times \sin 75° = 22$ mT would be required (with $\mu_0 M_S = 1$ T for permalloy).

The Oersted field inside a wire with rectangular cross-section is given by $B_x = \mu_0 J z$, where J is the current density and z is the distance from centre of the wire. A current of +7 mA in the 400 nm wire, corresponding to an average current density of 1.17×10^{12} A/m^2, results in H_{Oe}= 7.3 mT for a homogeneous current distribution over the NiFe/Cu/Co trilayer structure, and a maximum of 11 mT for a current flowing entirely through the Cu and Co layers. This maximum value of 11 mT should lead to a magnetization tilt φ_t of only 28° instead of the observed 75°.

An overestimation of demagnetizing effect is most likely at the origin of the discrepancy between the observed and expected tilt angles. First, the transverse demagnetizing factor can be smaller than the nominal value of 0.023, by several tens of percents, because of edge roughness [20], because of a decrease of effective thickness due to surface oxidation or because of intermixing at the NiFe/Cu interface. Second, the magnetostatic interaction between the NiFe and Co layers can significantly decrease the transverse demagnetizing effects with respect to single NiFe wires. Part of the magnetic charges on the edges of the NiFe layer are compensated by mirroring effects on the edges of the Co layer, as has been shown by micromagnetic simulations [21]. Moreover, if the current is centered in the Cu layer the Co magnetization tilt induced by H_{Oe} will be opposite to the one induced in the NiFe layer, further increasing the compensating effect of the Co magnetic charges. Unfortunately, the weak magnetic signal obtained for the Co L_3-edge images did not allow observing the magnetization tilt in the Co layer during the current pulse. Finally, a larger tilt of the magnetization at the center of the wire than at its edges is expected if one takes into account the real, non-homogeneous profile of the demagnetizing field, which results from highly non-homogeneous dipolar fields in thin flat wires. The combined effect of non-uniform magnetization in the wire, edge roughness and dipolar interactions between NiFe and Co layers can explain the large observed magnetization tilt.

Let us stress that at the beginning of the pulse the magnetization tilt angle is not constant, but that H_{Oe} induces precessional effects on the NiFe magnetization. Figure 3 shows contrast-enhanced XMCD-PEEM images of the bottom section of the nanowire of Fig. 2, taken with delay steps of 100 ps at the beginning of the positive part of the pulse. The oscillations of the magnetization tilt, also visible in the curve of φ_t versus time of Fig. 2(j), indicate precessional motion of the magnetization about the effective field. Since the images are averaged over 10^8 current pulses, the large contrast means that the phase of the excited oscillations with respect to the current pulses is well defined. The spatiotemporal variations in the magnetic contrast may be due to local

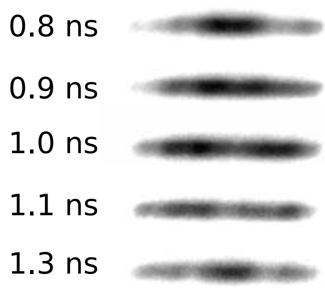

FIG. 3: Time-resolved XMCD-PEEM images of the lower, 13 μm long section of the 400 nm wide nanowire, taken at the indicated delays after the beginning of the positive part of the current pulse. The oscillation frequency of the spatiotemporal variations of the XMCD contrast, resembling spin-waves, is about 2 GHz.

inhomogeneities in the magnetization of the permalloy layer itself or to anisotropy fluctuations in the Co layer that can be transmitted to the NiFe layer through magnetostatic interactions. On the other hand, these spatiotemporal variations of the tilt angle strongly resemble spin-waves. The excitation of spin-waves by the Oersted field in spin-valve trilayers was predicted by Kim et al. [22] and spin-wave-like features were observed using Lorentz microscopy on 30 nm thick NiFe nanowires upon current injection [23]. Our results show that time-resolved XMCD-PEEM is a very suitable technique to observe such magnetization oscillations.

The period of the observed oscillations is about 500 ps, corresponding to a frequency of 2 GHz. Taking the theoretical demagnetizing factors of our wire ($N_x = 0$, $N_y = 0.023$ and $N_z = 0.977$), Kittel's formula for homogeneous magnetization precession transverse to the wire gives an oscillation frequency of 2 GHz for a transverse magnetic field of about 28 mT. This value is expected to be only approximate since in our case the precession takes place about an axis that is not transverse to the wire but tilted by about 15° and the precession is far from homogeneous (Fig. 3). However, the calculated field is of the same order of magnitude as the calculated Oersted field. Measurements with different current densities are needed to study the magnetization precession frequency as a function of tranverse field and tilt angle.

In quasi-static measurements performed on similar nanowires we have observed that current pulses with a density above $1.5 - 2 \times 10^{12}$ A/m^2 can induce nucleation of reversed domains in initially saturated nanowire sections. The precession of the magnetization about a large enough H_{Oe} is expected to favor local magnetization reversal, similar to the reversal of magnetization in magnetic nanostructures [24] induced by transverse magnetic field pulses.

In order to explain the increased efficiency of domain wall motion induced by spin-polarized currents in such trilayers [14, 15], spin-currents perpendicular to the film plane have been invoked [25]. Our measurements show that the effect of H_{Oe} on the domain walls should be taken into account as well. The presence of H_{Oe} during CIDM should stabilise transverse domain walls having their magnetization parallel to H_{Oe}, while transverse walls with opposite magnetization direction or vortex walls will have much higher energies. The stabilisation of one type of transverse domain walls during the CIDM should inhibit domain wall transformations during propagation (the so-called Walker Breakdown [26]), which are known to significantly slow down the domain wall motion [27, 28]. An important increase in domain wall velocity and suppression of the Walker breakdown by applying a transverse magnetic field was indeed observed in field-induced domain wall motion in similar trilayered nanowires [8, 9].

In conclusion, in this paper we provide the first direct microscopic evidence of the effect of Oersted fields on the magnetic configuration when applying current pulses to magnetic nanowires. In general, our experiments show the potential of time-resolved XMCD-PEEM for the study of dynamic effects, like domain wall motion and spin-waves, induced in magnetic nanowires by current pulses. We show that the Oersted-field induced magnetization tilt in magnetic nanowires with several metallic layers such as spin-valve nanowires can be very large for relatively modest current densities. In many cases reported in the literature domain wall motion is studied in single permalloy wires that comprise metallic buffer layers or protecting layers. Our measurements clearly indicate that also in these cases the quasi-static and precessional effects of the Oersted field should be carefully considered. On the other hand, the effect of the Oersted field on magnetization reversal or magnetic domain wall motion could be tailored by tuning the thickness of the different metallic layers to further improve the efficiency in future spintronic devices.

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