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Reversible switching between bidomain states by injection of current pulses in a magnetic wire with out-of-plane magnetization

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The influence of current pulses on the domain structure of a 2 μm wide wire composed of a soft out-of-plane magnetized magnetic material is studied by high spatial resolution nonintrusive magnetic imaging. The injection of current pulses (10^{12} A/m^2) leads to stable magnetic states composed of two domains with opposite magnetization direction separated by a domain wall parallel to the wire. The direction of the magnetization in the domains is reversed back and forth by applying successive current pulses with opposite polarity. The formation and control of the domain states by the current is attributed to the effect of the Oersted field, which is calculated to be large enough to induce the switching.

I. INTRODUCTION

Conventionally magnetic elements in devices are switched by applying external magnetic fields. However, the generation of localized fields entails the fabrication of strip lines or coils that allow one to apply fields at particular positions to achieve selective switching. An alternative approach is to use current injected into the magnetic elements to switch them. For this, different geometries have been proposed and, in particular, two different mechanisms for the switching have been predicted: the Amperian Oersted field generated by the charge currents that is concentric around the current flow and the spin transfer torque arising from the transfer of angular momentum from a spin-polarized current to the magnetization.[1,2] This latter effect can be used in particular to move a domain wall (DW) by current.[3–5] So far, the motion of a DW by current has been mostly investigated in $Ni_{80}Fe_{20}$. Recently the attention has shifted to out-of-plane magnetized metallic materials with narrow domain walls where spin transfer was shown to be more efficient.[6–8] From a fundamental point of view, such materials allow one to study the influence of the hotly debated nonadiabatic spin transfer torque on the DW dynamics that is expected to be higher for narrow DWs due to the higher magnetization gradient.[9]

For using the pure Oersted field effect to switch magnetization, theoretical proposals have been put forward to switch elements reversibly.[10] In particular, ring geometries were proposed, where the concentric field of a current flowing perpendicular to a multilayer stack was shown to switch the ring.[11] More sophisticated geometries based on rings have been used to switch between different magnetic states.[12] Most of these theoretical predictions and experiments make use of a current flow perpendicular to the plane of the layers, so that the Oersted field generates a circular field in the plane. For the case of the widely studied soft magnetic wire in which the current flows in the plane, the Oersted field only plays a minor role: This is due to the geometry of the wire, which is normally much thinner (a few exchange lengths at most) than its width, which, in turn, is much smaller than the wire length. This leads to a magnetization that is oriented along the wire. Thus the concentric Oersted field around the current direction is always perpendicular to the easy magnetization directions and so it cannot change the magnetization easily.

The situation is different in the case of wires magnetized out-of-plane. Here the magnetization points in the same direction as the Oersted field at the edges of the wire, so that more pronounced effects of the Oersted field can be expected. In this paper we investigate the effect of current pulses in soft (CoFeB/Pt) multilayer wires with out-of-plane magnetization configuration using non-intrusive x-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM). We observe the reversible switching of magnetization between well defined magnetic configurations induced by the current injection. We explain our observations by the combined effect of the Oersted field and the dipolar interaction that govern the resulting spin structure.

II. EXPERIMENTAL

The magnetic material used in our study is composed of a Pt(3 nm)/$Co_{60}Fe_{20}B_{20}$(0.6 nm)/Pt(2 nm) multilayer deposited by sputtering. Figure 1(a) shows a hysteresis loop

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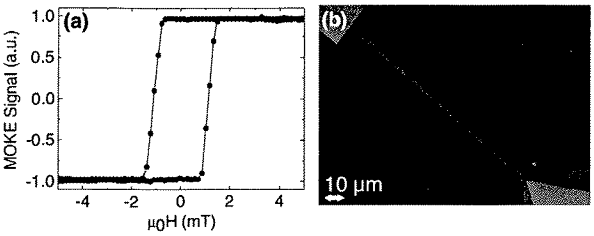

FIG. 1. (a) Kerr rotation loop as a function of the external magnetic field applied perpendicularly to the plane of a Pt(3 nm)/$Co_{60}Fe_{20}B_{20}$(0.6 nm)/Pt(2 nm) multilayer measured at room temperature. (b) Scanning electron microscopy image of 2 μm wide wire connected to gold electrical contacts and a visible injection pad.

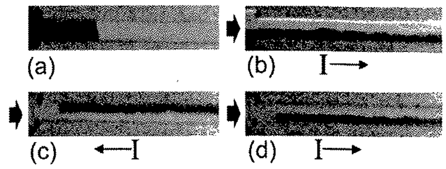

FIG. 2. XMCD-PEEM magnetic images of a 2 μm wide CoFeB/Pt wire. A white contrast corresponds to the magnetization pointed up and a black contrast to the magnetization pointing down. (a) A DW is shown in the wire. (b) After the injection of a current pulse (1.0×10^{12} A/m^2 for 25 μs, direction indicated by the arrow) in the wire, the original DW structure completely disappears and a long DW parallel to the wire is created. When the current direction is reversed, the magnetization in the domain also reverses [(c) and (d)].

measured using the magneto-optical Kerr effect with the field oriented perpendicularly to the plane of the sample. A square loop with a very low coercive field of around 1 mT is found that shows that the magnetization is oriented out-of-plane with a remanence of 1 and indicates a reversal with very low pinning. Comparison to conventional Pt/Co(0.6 nm)/Pt with a coercivity of 35 mT makes the special low coercivity of the multilayer with CoFeB very conspicuous. Such a low pinning and nucleation field in CoFeB based multilayer may arise from the lower pinning at grain boundaries due to the amorphous nature of CoFeB.

To study the influence of current pulses in this material, we fabricated 100 μm long and 2 μm wide lines by e-beam lithography and lift-off connected to gold electrodes for current injection [see Fig. 1(b)]. The width of the samples was kept large to allow for magnetization configurations with a spin structure that can vary across the wire. A large pad was patterned on one side of the wire to nucleate reverse domains. So far giant magnetoresistance or the extraordinary Hall effect were mostly used to characterize the influence of the current on the magnetization of out-of-plane magnetized metallic wires[6–8] but these measurements become hard to interpret as soon as complicated spin structures occur. We therefore directly image the magnetization using XMCD-PEEM with the energy set to the Co-L_3 absorption edge.[13] Since the incoming photon beam arrives at the sample at an angle of 16°, the XMCD signal is sensitive to the out-of-plane component of the magnetization, which allows us to image the domains in this material. This technique is particularly well suited, since it allows for fast nonintrusive high resolution imaging in contrast to, e.g., magnetic force microscopy, where the magnetic tip interacts with the sample and might even change the magnetic configuration.

To initialize the magnetic state of the wire, a coil integrated to the sample holder was used that allows the generation of magnetic field pulses perpendicular to the sample plane with varying amplitude and polarity. For current injection, a current pulse of variable length ranging between 12.5 and 100 μs with a long rise time was used that is part of a specially designed setup that is compatible with the PEEM end station.[14]

III. RESULTS AND DISCUSSION

To study the influence of the current injection on magnetization, we first generate a DW in the wire by preparing a monodomain state with a strong magnetic field pulse and then applying a small magnetic field in the opposite direction. Figure 2(a) shows a magnetic image of a DW in a 2 μm wide wire. We see that the magnetic contrast is strong, even though we only have 0.6 nm magnetic material in the sample. This points to the high sensitivity of XMCD-PEEM and shows that we can accurately detect the position of the DW and determine the complete magnetization configuration of the wire. Starting from this initial configuration, we inject 25 μs long current pulses with increasing amplitude starting from a current density of about 10^{10} A/m^2. No change in the magnetization structure is observed up to a current density of about 1×10^{12} A/m^2 where the DW vanishes and a new bidomain structure with a DW in the center parallel to the wire is created [Fig. 2(b)]. Starting from this configuration, the injection of a current pulse with an opposite polarity [Fig. 2(c)] leads to the equivalent bidomain structure with reversed magnetization directions. By reversing again the current polarity, the magnetization in the domain can be switched back [Fig. 2(d)]. The magnetization direction in the bidomain structure can thus be switched back and forth by current using alternative injection of current pulses with opposite polarities. Interestingly, a bidomain structure with a DW parallel to the wire could also sometimes be created from a monodomain state by the sole effect of an out-of-plane magnetic field pulse. This indicates that this state is close in energy to the monodomain state and that it is favored by the reduction of the stray field energy.

Concerning the current injection experiment, the dependence of the direction of the magnetization in the domain on the current polarity is clearly consistent with the effect of the Oersted field that points in opposite directions on the different sides of the wire. To further understand our results, we calculated the two dimensional spatial distribution of the Oersted field in the cross section of the wire by solving analytically the Biot–Savart law.[15] The spatial distribution of the Oersted field in the $x-y$ plane for a current flowing in the $-z$ direction with a density of 10^{12} A/m^2 is plotted on Fig. 3(a) and the variation of its out-of-plane component (y-direction) with x at the level of the CoFeB layer is shown on Fig. 3(b). As expected, the Oersted field is antisymmetric with respect to the wire center and increases rapidly as one approaches the wire edges with a maximum value of about 8 mT at the edges. This high field is enough to nucleate a reverse domain on the edge of the wire and switch to the bidomain structure

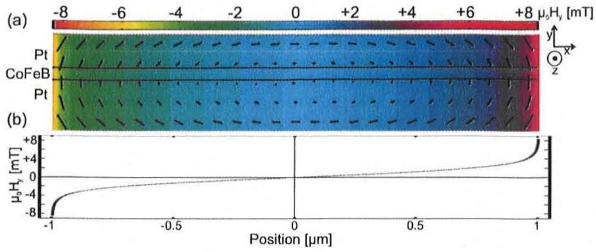

FIG. 3. (Color online) (a) Cross-section of a wire with the calculated distribution of the Oersted field. The current (10^{12} A/m^2) flows homogeneously in the wire in the $-z$ direction. The wire dimensions are 5.6 nm $\times 2$ μm (x and y are plotted at different scales). The out-of-plane component of the Oersted field H_y is plotted in color. (b) H_y as a function of the lateral position x in the wire.

with a DW parallel to the wire. This configuration is clearly favored by the magnetic stray field energy and the symmetry of the Oersted field. The direction of the magnetization in the domains can then be switched back and forth by the Oersted field whose symmetry fits with the one of the bidomain structure. We point out that the Oersted field needed to nucleate a reversed domain on the wire edges is high compared to the 1 mT coercivity measured by Kerr rotation in the continuous film on a macroscopic sample. A possible reason stems from the fact that in the continuous film the defects with the lowest coercivity will initiate the switching by nucleating a reverse domain. In the structured elements, there is a lower probability of the presence of such nucleation sites with low coercivity at the edges of the wire.[16]

As already mentioned, we were not able to observe the current-induced DW motion expected for a spin transfer mechanism. As high current density is associated with a high current in these wide wires, this can be explained by the fact that the bidomain state induced by the Oersted field is obtained at a current density lower than the one required for the spin torque induced DW motion. As the bidomain state becomes energetically more unfavorable for narrower wires, we expect the observed behavior to be superseded by spin-torque effects for narrower wires. So our observations yield an upper limit for wire dimensions that can be used for current-induced DW motion studies in soft magnetic out-of-plane magnetized materials. Nevertheless the observed behavior could be useful in itself, with reproducible switching between two distinct magnetization configurations that does not rely on the spin torque effect and is thus present in all soft magnetic out-of-plane magnetized materials where a current flows along the wire.

To conclude, the influence of current injection on the domain structure of a 2 μm wide wire patterned in a soft out-of-plane magnetized magnetic materials was studied by XMCD-PEEM. The injection of a current pulse with a current density of 10^{12} A/m^2 leads to the formation of a stable bidomain magnetic state composed of two domains with opposite magnetization direction separated by a DW parallel to the wire. The direction of the magnetization in the domains can be reversed back and forth by applying successive current pulses of alternative current polarity. The formation and control of this domain state by the current is explained by the effect of the Oersted field that points in opposite directions at the two edges of the wire. This ability to control the domain structure and to switch magnetization back and forth between two well defined magnetic states using the Oersted field opens an interesting way to manipulate magnetization that could be an alternative to spin-torque induced switching in micrometer size structures for certain well defined geometries.

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