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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 (10¹² A/m²) 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. © 2009 American Institute of Physics [DOI: 10.1063/1.3058618]

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 Ni₈₀Fe₂₀. 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 more pronounced effects of the Oersted field 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)/Co₈₀Fe₂₀B₂₀(0.6 nm)/Pt(2 nm) multilayer deposited by sputtering. Figure 1(a) shows a hysteresis loop
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 wires5–8 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-edge 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 especially 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/m². No change in the magnetization structure is observed up to a current density of about $10^{12}$ A/m² 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/m² 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.
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 effect could be an alternative to spin-torque induced switching in micrometer size structures for certain well defined geometries.

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