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The authors report on a method to tune the orientation of in-plane magnetic domains and domain walls in thin ferromagnetic strips by manipulating the magnetic anisotropy of the system. Uniaxial in-plane anisotropy is induced in a controlled way by oblique evaporation of magnetic thin strips. A direct correlation between the magnetization direction and the domain wall orientation is found experimentally and confirmed by micromagnetic simulations. The domain walls in the strips are always oriented along the oblique evaporation-induced easy axis, irrespective of the shape anisotropy. The controlled manipulation of domain wall orientations could provide promising possibilities for recently proposed devices based on domain wall propagation. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2778466]

In soft-magnetic thin strips, the magnetization naturally aligns with the strip axis to minimize the magnetostatic energy. If the strips are sufficiently long, the magnetic structure may split up into domains with opposite magnetization. The boundary regions between ferromagnetic domains of opposite direction are known as domain walls (DWs). Recently, DWs in thin strips have been proposed as carriers of information, which can be transmitted either by external magnetic fields[1] or electric current pulses.[2] This kind of DW displacement is used in recently presented concepts of devices with a magnetic logic architecture referred to as "domain wall logic"[3,4] and in a "racetrack" design based on current-induced domain wall propagation.[5] In these devices, the information is transported and processed as the DWs propagate along a complex network of magnetic thin strips. Domain walls are thus presently considered to hold promising technological potential.

Typical DWs occurring in magnetic strips are *head-to-head* domain walls, which have been thoroughly studied in the last years.[6–9] Most of these studies focused on establishing a phase diagram of the possible DW structures, namely, the "vortex" and the "transverse" walls, as a function of the magnetic film thickness and the nanostructure width. Other extrinsic parameters such as topographic defects and edge roughness were found to influence the propagation velocity of DWs.[10] Additionally, parameters linked to the intrinsic properties of the material have an influence on DW characteristics. Such intrinsic properties include saturation magnetization and spin polarization of the conduction electrons[11] or magnetic anisotropy and magnetization direction. Only little is known about the effect of these intrinsic properties on the DW spin structure and on the spin torque effect that can be used for DW propagation. The control of such internal parameters represents a promising approach to optimizing DW propagation velocities and the use of DWs in the previously mentioned applications.

We report on a method allowing to tune the orientation of in-plane magnetic domains and domain walls in thin magnetic strips. This is achieved by controlling the magnetic anisotropy. In particular, we show that uniaxial magnetic anisotropy has a direct influence on the DW orientation in thin Co strips. The direction of the in-plane uniaxial anisotropy is controlled by oblique evaporation (OE) along different azimuthal angles. The oblique incident deposition is known to induce, via the so-called self-shadowing effect,[12] anisotropic film growth that shows crystallographic texture. This anisotropic film texture is directly connected to the magnetocrystalline anisotropy. In obliquely evaporated films, both the shape anisotropy (morphology) and the magnetocrystalline anisotropy (texture) contribute to the uniaxial magnetic anisotropy. The easy magnetization axis is oriented in the film plane and can be either parallel or perpendicular to the evaporation direction, depending on the evaporation angle. When the evaporation angle is below 75° (with respect to the surface normal), the in-plane easy magnetization axis is oriented perpendicular to the evaporation direction, while it is parallel for angles above 75°.[13] While OE has long been

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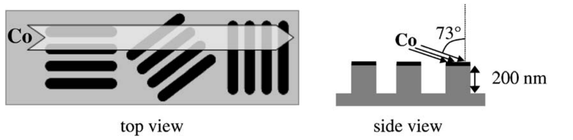

FIG. 1. Schematics of the sample geometry where the Co flux is evaporated at oblique incidence on a prepatterned substrate.

known to generate a uniaxial magnetic anisotropy,[14] the effect of the anisotropy on the domain wall orientation and its spin structure has not yet been reported.

In this experiment, 5–8 nm thick polycrystalline Co films are evaporated at grazing incidence on prepatterned Si substrates (Fig. 1). The patterning consists of submicron strips which have been structured by electron-beam lithography. A polar evaporation angle of 73° ensures that the in-plane magnetization axis is perpendicular to the evaporation direction. The effect of the OE-induced in-plane magnetic anisotropy on the DW spin structure in thin magnetic strips is investigated using x-ray magnetic imaging with high lateral resolution in combination with micromagnetic simulations performed with a finite element algorithm.[15]

High-resolution photoemission electron microscopy in combination with x-ray magnetic circular dichroism (XMCD-PEEM) has been carried out at the Elettra Synchrotron (Trieste, Italy) using a commercial version of the Spectroscopic-LEEM microscope.[16] The samples have been grown *in situ*, and the virgin state magnetic domain configurations (as-grown state) have been analyzed by tuning the energy of circularly polarized x rays to the Co L_3 edge at two opposite elliptical helicities.[17] The maximum contrast is obtained when the easy magnetization axis is oriented parallel or antiparallel to the direction of the incident photons. Therefore, the cobalt evaporator (flux direction) has been oriented perpendicular to the direction of the incoming x rays. In order to compare different configurations, strips with three different azimuth orientations have been patterned on the same Si substrate, as shown in Fig. 1.

As a reference system, continuous cobalt films have been deposited under identical conditions and various azimuthal angles on flat (unpatterned) Si(111) surfaces. Figure 2(a) shows hysteresis loops measured on an 8 nm thick polycrystalline Co film by longitudinal magneto-optical Kerr magnetometry. The external magnetic field is applied in the plane, along three different azimuth angles with respect to the evaporation direction [cf. inset of Fig. 2(a)]. The easy magnetization axis is always found to be in the surface plane and perpendicular to the evaporation direction, independent

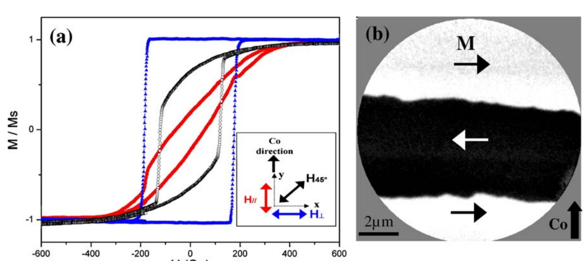

FIG. 2. (Color online) Hysteresis loops measured longitudinally in an 8 nm thick Co/Si(111) continuous film evaporated at oblique incidence show an easy magnetization axis oriented perpendicular to the Co flux direction (image inset). (b) The corresponding XMCD-PEEM image measured in the virgin state shows large magnetic domains along the easy magnetization axis.

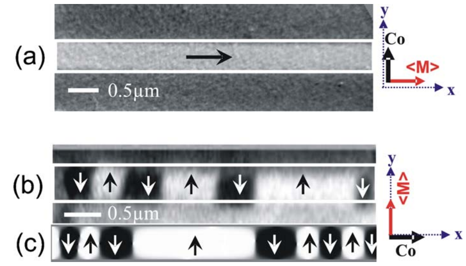

FIG. 3. (Color online) Magnetic domain configurations observed by XMCD-PEEM in 5 nm thick Co nanostrips where the easy magnetization axis is (a) parallel to the strips' axis and (b) perpendicular to the strips' axis. The magnetic domain configuration is confirmed by micromagnetic simulations (c).

of the in-plane crystallographic orientation of the substrate. The measured in-plane coercive field is approximately 200 Oe, which is around ten times larger than the expected value for a film deposited at normal incidence (13–26 Oe).[18] The saturation field along the hard axis is about 500 Oe. The polar representation (not shown) of the magnetization intensity along different azimuth angles proves the uniaxial character of the OE-induced anisotropy and confirms that the easy magnetization axis is perpendicular to the Co flux. Elongated magnetic domains of alternating opposite magnetization perpendicular to the evaporation flux direction are observed by XMCD-PEEM, as shown in Fig. 2(b). These 3–4 μm wide magnetic domains are separated by 180° Néel walls and are aligned along the OE-induced easy magnetization axis.

In the case of Co strips, different micromagnetic configurations are expected because of the competition between the OE-induced anisotropy and the shape anisotropy. Therefore, we investigated three different geometries where the OE-induced easy magnetization axis is oriented parallel, perpendicular, and at 45° with respect to the axis of the strips.

When the OE-induced easy axis is parallel to the axis of the strips [Fig. 3(a)], 0.5 μm wide Co strips are found to be in a single-domain magnetic configuration. In this case, the magnetization is oriented along the strips, as imposed by both shape and OE-induced anisotropies. Our micromagnetic simulations confirm this observation and show that if a domain wall is present, it is aligned along the strips.

Figure 3(b) shows the magnetic domain structure obtained when the easy magnetization axis is oriented perpendicular to the strips. A multidomain configuration is observed, with 180° DWs oriented along the strip width separating domains with opposite magnetization. In this case, the induced anisotropy is stronger than the shape anisotropy, since the latter tends to align the magnetization along the strips. This result is observed for different strip widths ranging from 0.5 to 2 μm, and is in agreement with micromagnetic simulations, which yield 180° DWs oriented perpendicular to the strips, cf. Fig. 3(c).

A multidomain magnetic configuration is also observed in submicron strips when the OE-induced magnetization axis is at an intermediate angle [Fig. 4(a)]. In this case, the magnetic domains are separated by inclined 180° DWs. The orientation of these DWs mostly coincides with the OE-induced magnetic easy axis. The micromagnetic simulations show that the DWs contain a vortex spin structure. Inclined domain walls in ultrathin epitaxial Fe strips have also been reported by Vedmedenko *et al.*[19] In that study, it was found

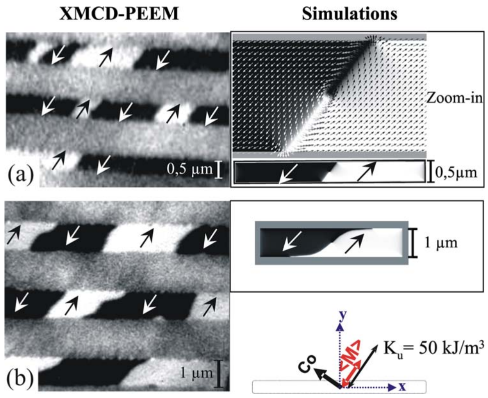

FIG. 4. (Color online) XMCD-PEEM images (left) and the corresponding micromagnetic simulations (right) showing inclined domain walls in 5 nm thick Co (a) nanostrips and (b) microstrips where a uniaxial magnetic anisotropy is induced at 45° with respect to the strips' axis, as indicated by arrows in the sketch.

that the orientation of the DW follows crystallographic directions despite the shape anisotropy. This effect has been attributed to the presence of an anisotropic exchange interaction. Here, we show the presence of a clear correlation between magnetic anisotropy and domain wall orientation.

The inclined orientation of the DWs in thin strips may be surprising, as it would seem more advantageous for the DWs to be oriented perpendicular to the strip. Since the magnetization always changes by 180° between two adjacent domains, irrespective of the DW direction, the exchange energy *density* does not depend on the DW orientation. Therefore, an alignment of the DW perpendicular to the strip would minimize the DW length and thereby reduce the total exchange energy. However, such a perpendicular orientation is neither observed in the experiment nor in the simulations. We thus attribute the inclined alignment of the DWs with the easy axis to magnetostatic effects. An equal amount of positive and negative magnetic volume charges $\rho=-\nabla M$ is created on either side of the DW only if the DW is parallel to the magnetization direction in the domains. These charges compensate each other and this DW orientation is therefore magnetostatically optimal. Any other DW orientation would lead to charged domain walls, thereby increasing the dipolar energy. This explains the observed tendency of 180° DWs in thin film strips to align along the direction of the magnetization in the adjacent domains.

When an intermediate anisotropy angle (about 45°) is induced in wider strips of 1–2.5 μm, a more complex DW structure is observed, as shown in Fig. 4(b). A gradual rotation of the DWs from 45° (in the centre of the microstructure) to parallel to the strips (close to the borders), leading to an S-like shape, is observed both experimentally on XMCD-PEEM images and in the micromagnetic simulations. We attribute the occurrence of these S-shaped domain walls to a nonuniform balance between OE-induced anisotropy and shape anisotropy. The latter is stronger at the borders and tends to rotate the magnetization along the axis of the strips, while the OE-induced anisotropy dominates in the center of wide strips. The gradually changing orientation of the magnetization from the center of the strip to the boundary and the observed S-shaped DWs are consistent with the previous argument concerning the correlation between the DW orientation and the magnetization direction in the domains. As shown in Figs. 4(a) and 4(b), different strips of the same geometry display very similar features in the virgin state concerning DW density, profile, and orientation.

We have also performed the same set of measurements on Fe instead of Co using substrates with either (001) or (111) orientation (not shown here). Our results indicate that the effect of the anisotropy on the DW orientation is not specific to Co strips or to the orientation of the substrate, and that it can be generalized to other materials and substrates. We thus conclude that oblique evaporation is a suitable method for controlling the domain wall orientation in thin magnetic strips. Its use in other materials such as magnetic alloys and diluted magnetic semiconductors could provide a better understanding of the interaction between DWs and electrical currents, particularly in the case of inclined DWs.[20]

In conclusion, we have demonstrated a simple way to control the magnetic anisotropy and DW orientation in thin magnetic strips. We have induced a uniaxial in-plane magnetic anisotropy by oblique evaporation. This anisotropy is found to dominate in thin nanostructures, and it has been exploited for controlling DW orientations. The control of the DW orientation in thin strips demonstrates the possibility of altering the static and likely also the dynamic properties of DWs. This is expected to extend the possibilities within the ongoing research which aims at using DWs as rapid and versatile carriers of information.

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