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Magnetic skyrmions in confined geometries: Effect of the magnetic field and the disorder

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ABSTRACT

We report on the effect of the lateral confinement and a perpendicular magnetic field on isolated room-temperature magnetic skyrmions in sputtered Pt/Co/MgO nanotracks and nanodots. We show that the skyrmions size can be easily tuned by playing on the lateral dimensions of the nanostructures and by using external magnetic field amplitudes of a few mT, which allow to reach sub-100 nm diameters. Our XMCD-PEEM observations also highlight the important role of the pinning on the skyrmions size and stability under an out-of-plane magnetic field. Micromagnetic simulations reveal that the effect of local pinning can be well accounted for by considering the thin film grain structure with local anisotropy variations and reproduce well the dependence of the skyrmion diameter on the magnetic field and the geometry.

1. Introduction

Magnetic skyrmions are nanoscale whirling spin configurations [1]. Their small size, topological protection and the fact that they can be manipulated by small in-plane current densities have opened a new paradigm to manipulate the magnetization at the nanoscale. This has led to proposals for novel memory and logic devices in which the magnetic skyrmions are the information carriers [2]. They were first observed in B20 chiral magnets thin films [3,4] within confined geometries [5,6], and in ultrathin epitaxial films [7–9] at low temperature. The recent observation of room-temperature magnetic skyrmions [10–19] and their current-induced manipulation [11,12,16,19–22] in sputtered magnetic films have lifted an important bottleneck toward the practical realization of such devices. However, these experiments have also underlined the sensitivity of the skyrmions dynamics to the defects in the materials as well as the edges which can impede reliable motion. This raises the question of stability - nucleation and annihilation - in these sputtered ultrathin magnetic films. More recently, the influence of the granular structure and the inherent disorder of these films on the skyrmions stability have begun to be addressed [16,19,23].

Here we report on the observation of the effect of the lateral confinement, a perpendicular magnetic field and the local pinning sites on the magnetic texture in sputtered Pt/Co/MgO ultrathin nanostructures with isolated room-temperature magnetic skyrmions. In particular, the evolution of the mean skyrmion diameter in sub-micrometers nanotracks and nanodots is followed by high resolution magnetic imaging. These experimental results are supported by micromagnetic simulations which reproduce well the magnetic field dependence of the skyrmion size in the different geometries. Notably, we show that the granular structure of the sputtered materials leads to local pinning of the skyrmion which can strongly affect its shape and size. Our results underline that the local pinning and the sample geometry play an important role in the field dependence of the skyrmion size and its stability in these films.

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2. Methods

We used X-ray Magnetic Circular Dichroism combined with Photo-Emission Electron Microscopy (XMCD-PEEM) at room temperature to obtain a direct image of the magnetization pattern with a high lateral spatial resolution (down to ~30 nm). The observed contrast is proportional to the projection of the magnetization on the incident X-ray beam direction, which is impinging on the sample under a grazing angle of 16°. As a result, the magnetic contrast is about 3.5 times larger for the magnetization in the sample plane as compared to the magnetization perpendicular to it. As shown in our previous work [13], this allows the direct observation of the internal spin structure of magnetic domain walls (DWs) and magnetic skyrmions. The XMCD-PEEM experiments were carried out with the SPELEEM III microscope (Elmitec GmbH) at the Nanospectroscopy beamline at the Elettra synchrotron in Basovizza, Trieste, Italy, at the CIRCE beamline at the Alba synchrotron, Barcelona, Spain [24,25] and at the I06 beamline at the Diamond synchrotron, Didcot, UK.

The Ta(3)/Pt(3)/Co(0.5-1.1)/Mg(0.9)O_x/Ta(2) (thickness in nm) film was deposited by magnetron sputtering on a 100 mm high-resistivity Si wafer and then annealed for 1.5 h at 250 °C under vacuum and an in-plane magnetic field of 240 mT. The Co layer was deposited as a wedge. The magnetic domains in the thin film are perpendicularly magnetized. All the images presented correspond to a nominal Co thickness of about 1.0 nm, an area close to the reorientation transition and were obtained at room temperature.

The micromagnetic simulations were performed using the Mumax3 code [26]. We used the following micromagnetic parameters extracted from our previous experiments [13]: the Co layer thickness t = 1.06 nm, the exchange constant $A = 2.75 \times 10^{-11}$ J.m^{-1}, the uniaxial anisotropy constant $K_u = 1.45 \times 10^{6}$ J.m^{-3}, the interfacial Dzyaloshinskii-Moriya interaction constant $D = 2.05 \times 10^{-3}$ J.m^{-2}, and the saturation magnetization $M_s = 1.44 \times 10^{6}$ A.m^{-1}. For all the geometries considered hereafter, the cells size is 1 nm × 1 nm × 1.06 nm with only one cell across the film thickness, so that the magnetization is supposed to be uniform along this direction. For convenience, all the simulations were performed at T = 0 K, although temperature should play a significant role on the skyrmion stabilization and interaction with the local disorder [27]. Finally, we define d_s as the mean skyrmion diameter, namely the diameter of a perfectly circular bubble with the same area as the distorted one.

3. Results and discussion

3.1. Observation of room-temperature magnetic skyrmions in nanotracks

At remanence or in the presence of a small magnetic field (<2 mT), worm-like domains are observed in the tracks (Fig. 1.a), a configuration which minimizes the dipolar energy. These worms tend to align with the tracks, while they are randomly oriented in the largest areas of the nanostructures. Moreover, they seem to be repelled from the edges, which is reproduced well by the simulations. Interestingly, a strong white (black) contrast is observed on the upper (bottom) DWs delimiting the worm-like domains (see inset of Fig. 1.a). Since the contrast is proportional to the projection of the magnetization along the X-ray propagation direction, and the DWs are perpendicular to this direction, the contrast is consistent with DWs having a left-handed homochiral Néel structure [13]. When applying a larger magnetic field (typically $B_z > 2$ mT) the initial worm-like domains shrink and lead to the formation of isolated skyrmions (Fig. 1.b-c). Again, the white/black contrast at the top/bottom edge of the skyrmion demonstrates that the homochiral Néel structure is preserved (see inset of Fig. 1.b).

The average skyrmion diameter is plotted as a function of B_z in Fig. 2 for tracks of two different widths (300 nm and 500 nm) along with the results of the simulations. For both wire widths, a large decrease of the skyrmions size is observed when small fields (~5 mT) are applied. In the 300 nm tracks, the average diameter changes from 140 nm down to 80 nm, showing a large susceptibility of the skyrmions size to B_z. In addition, we observe that the track width affects the skyrmions size, especially at low magnetic field: the narrower the track the smaller the skyrmions, as suggested by previous numerical studies [28]. This geometrical confinement effect can be explained by the dipolar interactions of the DWs delimiting the skyrmion with the magnetic charges on the tracks edges. These results thus show that the skyrmion size

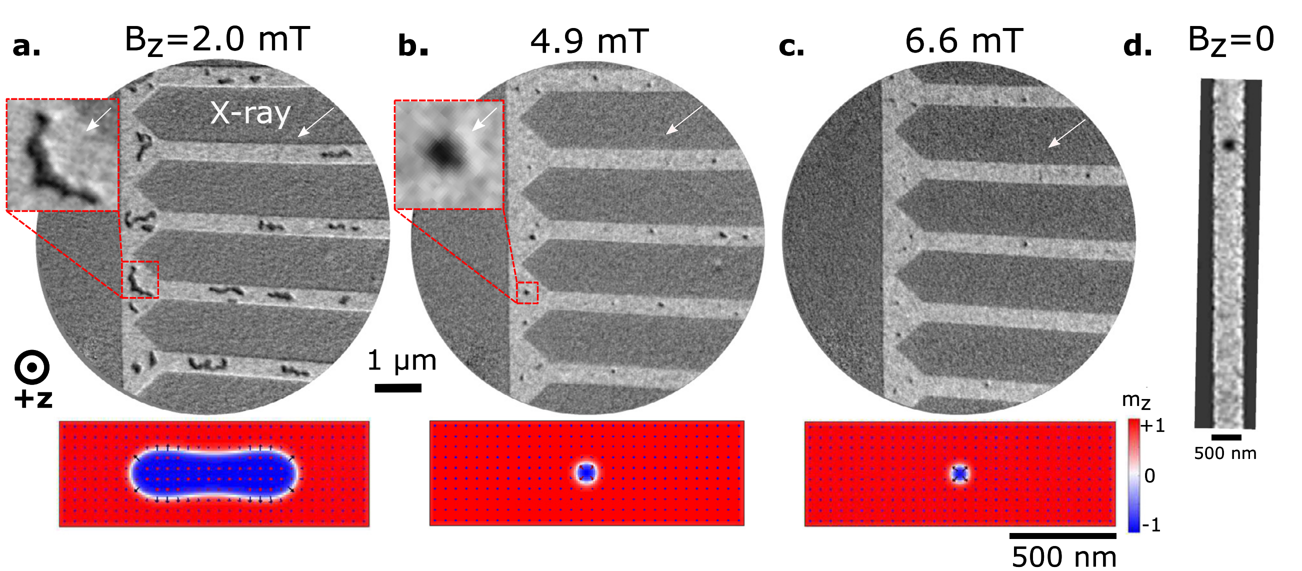

Fig. 1. a-c. XMCD-PEEM images of the magnetic texture in 500 nm-wide tracks during the application of a magnetic field perpendicular to the film plane. The insets show a zoom in the region delimited by the dashed red boxes of dimensions a. 800 nm × 800 nm and b. 500 nm × 500 nm. Below each image is represented the simulated distribution of the magnetization in 1500 nm × 500 nm tracks, for the same applied magnetic field and in the case of a disorder-free film. The white arrows indicate the X-ray beam direction. d. XMCD-PEEM image of a magnetic skyrmion in a 540 nm-wide track at zero external magnetic field.

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