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# Controlled switching of Néel caps in Bloch magnetic domain walls

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While magnetic hysteresis usually considers magnetic domains, the switching of the core of magnetic vortices has recently become an active topic. We considered Bloch domain walls, which are known to display at the surface of thin films flux-closure features called Néel caps. We demonstrated the controlled switching of these caps under magnetic field, occurring via the propagation of a surface vortex. For this we considered flux-closure states in elongated micron-sized dots, so that only the central domain wall can be addressed, while domains remain unaffected.

Data storage relies on the handling of two states, called bits. In magnetoelectronic devices bits are stored using the two directions of magnetization in nanoscale bistable domains. In hard-disk drives these are written in granular continuous thin films, while in solid-state Magnetic Random Access Memories (MRAMs) bits rely on dots patterned with lithography[1]. While miniaturisation is the conventional way to fuel the continuous increase of device density, disruptive solutions are also sought. To these belong in recent years many fundamental studies investigating no more the domains, but the manipulation of domain walls and magnetic vortices as objects in themselves. The degree of freedom associated with these may be their location, *e.g.* for a domain wall moved along a stripe[2], or their internal structure, *e.g.* the up-or-down polarity of a vortex in a circular dot[3, 4, 5]. In the latter case the chirality of the flux-closure around the vortex might also be exploited as a second degree of freedom[6, 7, 8]. In this context it is of fundamental interest to revisit all existing internal degrees of freedom in classical domain walls, and determine whether or not they might be switched independently of their environment.

In this Letter we consider an already known internal degree of freedom in Bloch domain walls, the so-called Néel caps (NCs), and report the controlled magnetic switching of these NCs. Bloch walls in thin films have been extensively addressed[9, 10]. In contrast to the simplest text-book case where a translational invariance is assumed within the DW plane, Bloch walls in thin films with in-plane magnetization are known to display an extra degree of freedom beyond the up-or-down polarity of its core: the direction of magnetization in the NCs, occurring at both surfaces of the wall to decrease the magnetostatic energy (Fig. 1a). The name NC was given only later[11], as the arrangement of magnetiza-

tion in NCs mimics that of a Néel wall, a type of DW with solely in-plane magnetization[12]. At remanence the two NCs are antiparallel to each other and thus in principle two degenerate ground states exist, which we named after the direction of magnetization of the bottom and top NCs, *i.e.*  $(-, +)$  and  $(+, -)$  (Fig. 2a). This overall arrangement was named an asymmetric Bloch wall[10]. So far nobody demonstrated that the remanent state of antiparallel NCs could be selected reliably. This mainly stems from the fact that in thin films, where such processes had been sought, the magnetization in the domains rotates easily under applied fields, often affecting the location and even the existence of domain walls[13]. To lift this limitation we considered elongated dots displaying a flux-closure state, where a finite-size Bloch domain wall is stabilized by the internal dipolar fields (Fig. 1b-c). The structure of these flux-closure states has long since been described, and is now called a Landau state[15, 16, 17, 18, 19, 20]. Here we demonstrate numerically and experimentally that NCs can be switched controllably under the application of a magnetic field without affecting the other two degrees of freedom found in the dot: the core with perpendicular magnetization of the Bloch wall, nor the chirality of the in-plane flux-closure.

The sample consists of epitaxial micron-sized self-assembled elongated Fe(110) dots with atomically-smooth facets. These were fabricated using UHV pulsed-laser deposition on  $\text{Al}_2\text{O}_3(11\bar{2}0)$  wafers buffered with a layer of W(110). The dots grow spontaneously as a result of a dewetting process named Stranski-Krastanov growth mode, driven by the large lattice mismatch between Fe and W ( $\approx 10\%$ ). The facets arise spontaneously and reproducibly with well-defined directions in relation with the single-crystallinity of the dot[21]. The growth temperature ( $530^\circ\text{C}$ ) and nominal thickness (5 nm) were chosen so that the average length, width and height of the dots are  $1\text{ }\mu\text{m}$ ,  $0.5\text{ }\mu\text{m}$  and  $0.1\text{ }\mu\text{m}$ , respectively. The dots were capped *in situ* with 0.7 nm-thick Mo followed by a 2.5 nm-thick Au layer to prevent oxidation during the transfer in

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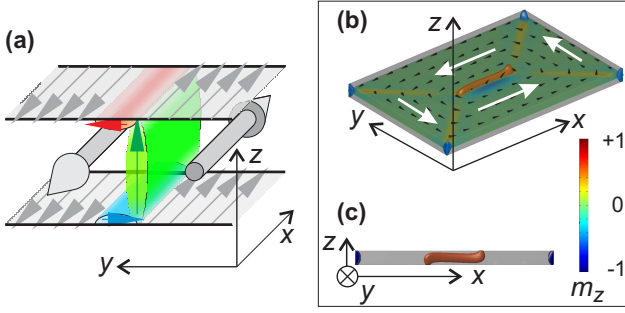


Fig. 1: (a) Schematic view of a domain wall of Bloch type, terminated by a Néel cap at each surface. The magnetization is opposite in the top and bottom Néel caps, and points along the  $\pm y$  axes *i.e.* across the plane of the wall. (b-c) 3D and cross section views of a so-called *Landau* state in a rectangular magnetic dot ( $700 \times 500 \times 50$  nm). In (b) only volumes with normalized perpendicular magnetization  $|m_z| > 0.5$  are displayed, which highlights the vortex and the domain wall. The map of  $m_z$  at mid-height is also shown, and the in-plane curling of magnetization is indicated by white arrows.

air between the growth chamber and the magnetic imaging setups.

Two high-resolution imaging instruments were used, bringing complementary informations. The first instrument is an Elmitec GmbH LEEM/PEEM microscope (LEEM V), based at the nanospectroscopy beamline of ELETTRA synchrotron (Trieste, Italy). In the Low Energy Electron Microscopy (LEEM) mode[22], topographical features are revealed with a lateral resolution below 10 nm. In the X-ray Photo-Emission Electron Microscope mode (XPEEM) the X-rays energy was tuned at the Fe  $L_3$  edge,  $h\nu = 707$  eV. The magnetic contrast is obtained using XMCD-PEEM (X-Ray Magnetic Circular Dichroism)[23]. The spatial resolution is here 25 nm, with a probing depth of 10 nm. Maps of the in-plane component of surface magnetization parallel to the X-ray beam are thus achieved. As a second instrument we used a FEI Titan transmission electron microscope in the Fresnel contrast mode[24]. The microscope is equipped with a Gatan Imaging Filter for zero-loss filtering and a dedicated Lorentz lens, and was operated at 300 kV. We tilted the sample by  $20^\circ$  so that the field produced by the Lorentz exhibits an in-plane component, which we used in our experiments to switch the NCs. The Fresnel images highlight the location of vortices and domain walls separating the in-plane domains, with a bright or dark contrast revealing the chirality of the domains around them, not the magnetization of their core. The Sapphire substrate was mechanically polished and then ion-milled to permit transmission of the electrons.

The micromagnetic simulations were performed using GL\_FFT, a custom-developed code[25, 26] based on a finite-differences scheme. The prism cell dimensions are  $\Delta_x = \Delta_y = 3.9$  nm and  $\Delta_z = 3.1$  nm. Due to the large thickness of the dots bulk magnetic properties of Fe at

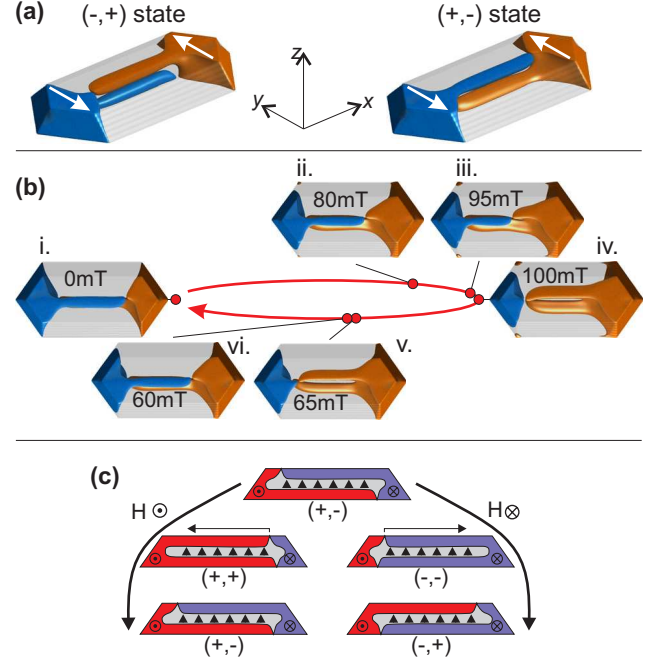


Fig. 2: (a) Simulation in an elongated dot of the  $(-, +)$  and  $(+, -)$  states. Only volumes with  $|m_y| > 0.5$  are displayed, while positive and negative values appear red and blue, respectively. (b) A magnetization process of Néel caps under  $H_t > 0$  (c) Schematic cross-sectional view of the switching of NCs: the final state is  $(-, +)$  or  $(+, -)$  depending on the sign of the applied field.

300 K have been used: magneto-crystalline fourth-order anisotropy constant  $K_1 = 4.8 \times 10^4$  J/m<sup>3</sup>, exchange energy  $A = 2 \times 10^{-11}$  J/m and spontaneous magnetization  $M_s = 1.73 \times 10^6$  A/m.

We first report simulations. First notice on Fig. 1b-c, as already known[15, 27], that a vortex and a Bloch wall in a dot are topology equivalent. Conceptually the asymmetric Bloch wall can be derived from a vortex by shearing apart its top and bottom extremities. This leads to the prototypical Landau structure[20]. In the following we call these extremities *surface vortices*. We now focus on faceted dots (Fig. 2), whose shape and size are those investigated experimentally. For a given chirality and polarity of the DW the set of NCs gives rise to two degenerate ground states at zero external field, *i.e.*  $(-, +)$  and  $(+, -)$  (Fig. 2a). Starting from a  $(+, -)$  state, a transverse magnetic field  $H_t$  is applied (*i.e.* along  $y$ ). Upon applying a positive  $H_t$  no significant change occurs up to 95 mT (Fig. 2b). At  $H_t = 100$  mT the top surface vortex propagates through the top NC to the other end of the DW, and settles atop the bottom vortex surface. The two NCs are then parallel and aligned along the field direction  $[(+, +)$  state]. This arrangement is known as an *asymmetric Néel wall*, consistent with the finding in thin films that asymmetric Néel walls are favored against asymmetric Bloch walls under a transverse field[13, 14].

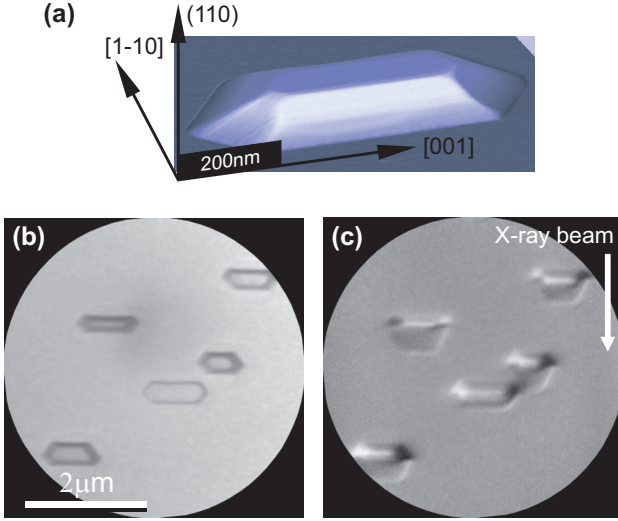


Fig. 3: (a) 3D view of a typical self-assembled epitaxial Fe(110) dot (Atomic force microscopy, true aspect ratios). (b) LEEM (topography) and (c) XMCD-PEEM (magnetism) typical view of an ensemble of dots. After magnetization at  $-130$  mT the dots are in the  $(-, +)$  state at remanence whatever their size, height or aspect ratio. The white arrow indicates the direction of the X-rays, thus the component of in-plane surface magnetization imaged.

Upon decreasing  $H_t$  back to zero no significant change occurs down to 60 mT, where suddenly the surface vortex travels back to its initial position  $[(+, -)$  state]. Under now decreasing negative fields the top NC remains unaffected, while it is the bottom NC that switches still around  $H_t = -100$  mT (Fig. 2c)  $[(-, -)$  state]. Interestingly, when  $H_t$  is reduced back to zero it is again the top NC that switches back. This leaves a  $(-, +)$  state at remanence, *i.e.* opposite to the initial state. The fact that it is always the top NC that switches back when the field magnitude is reduced might be related to the tilted facets (Fig. 3a-b), which break the symmetry between the top and bottom surfaces. Thus owing to this breaking of symmetry and according to micromagnetic simulations, one should be able to switch the set of NCs by applying a magnetic field transverse to the dot. At remanence the top NC should be antiparallel to the applied field (Fig. 2c).

The micromagnetic predictions were confirmed experimentally. As no significant magnetic field can be applied while imaging with XMCD-PEEM, the state of the NCs was checked at remanence after *ex situ* application of a transverse magnetic field  $H_t$  with a given sign and magnitude. For each field several tens of dots were imaged (20 to 40). NCs are revealed as a thin stripe of dark or light contrast along the length of the dots (Fig. 3c). In principle this contrast could be mistaken as arising from a Néel wall. This is however ruled out as the magnetic force microscopy signature of these walls is monopolar, while Néel walls would induce bipolar contrasts[18]. We

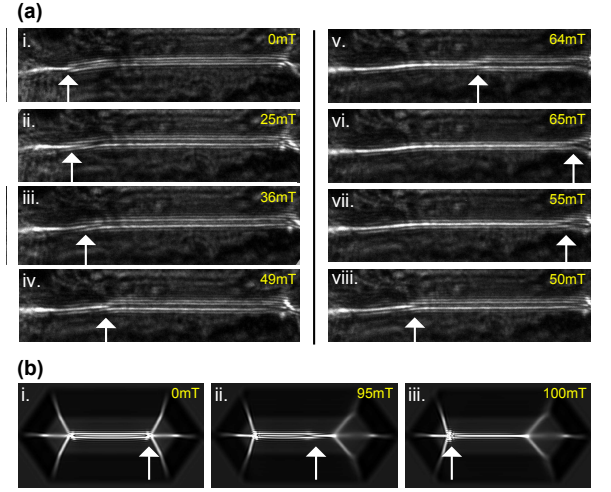


Fig. 4: (a) Fresnel-mode Lorentz microscopy of one single dot of thickness  $t = 60 \pm 20$  nm as a function of rising (i.-vi.) and then decreasing (vi.-viii.) field. (field of view  $1100 \times 300$  nm). The in-plane component of the applied field is indicated on each image. The location of the surface vortex associated with the switching of a Néel cap is indicated with an arrow. (b) Simulation of Fresnel mode images of the switch of Néel cap, based on the micromagnetic configurations of Fig. 2b i., iii. and iv. The defocusing is  $500 \mu\text{m}$

now describe the results. In the as-grown state the  $(-, +)$  and  $(+, -)$  states were found in equal ratios within statistical fluctuations. In contrast the occurrence of the  $(+, -)$  state  $[(-, +)$ , resp] reaches 95 % after application of  $H_t = +150$  mT ( $H_t = -150$  mT, resp.). The mean switching field is  $H_{sw} = 120$  mT with a  $\pm 10$  mT distribution. This value is in close agreement with the numerical simulations presented above ( $H_{sw} = 100$  mT). The remaining 5 % of dots are still found in the  $(-, +)$  [resp.  $(+, -)$ ] state. This lack of switching could result from subtle changes in the arrow-shape of the dots such as an asymmetry, which may induce the departure of the bottom surface vortex at decreasing field, instead of the top one. This remains to be studied.

The dots were then investigated under an *in situ* magnetic field by Lorentz microscopy. In the Fresnel mode the domain wall is revealed by fringes arising from interferences of electrons having gone through the two longitudinal domains (Fig. 4a). Computed Fresnel contrasts based on simulated micromagnetic configurations show that domain walls with parallel NCs give rise to a narrower pattern of fringes (Fig. 4b), allowing us to follow in the experiments the location of the propagating surface vortex responsible for the switching of a NC. All features predicted by the simulations (Fig. 2b) are thus confirmed: the hysteresis (see *e.g.* iv. versus viii.); the translational susceptibility of the surface vortex that is negligible for low field and increases dramatically close to the vicinity of the switching field upon increasing the field (i.-v., compare with Fig. 2b i.-iii.); the negligible or even zero



susceptibility before the switching back when the field is decreased (vi.-vii., compare with Fig. 2b iv.-v.). Besides as opposite chiralities induce dark or light fringes respectively, the experimental images (i.-viii.) taken through the hysteresis demonstrate that the chirality is not affected by the switching of the NCs, neither at rising nor at decreasing field. This is consistent with XMCD-PEEM experiments where the occurrence of clockwise and anti-clockwise chiralities remained similar for all applied magnetic fields and no cross-correlation between the chirality and the state of the NCs could be evidenced either, within the statistical error bars[28]. Concerning the polarity of the DW core, which is detectable neither by XMCD-PEEM nor by Lorentz microscopy, we must rely only on the simulations to infer that the core of the DW remains unaffected by the switch of NCs.

To conclude we have demonstrated numerically and experimentally that the direction of magnetization of the Néel caps, an internal surface feature of Bloch walls, can be switched controllably using a transverse magnetic field. This was achieved in elongated ferromagnetic dots displaying a flux-closure state, so that the domain wall can be manipulated while the domains remain unaf-

fected owing to the internal demagnetizing field[29]. The switching occurs through the propagation of surface vortices through the NCs. The selection of the state of the NCs at remanence is made possible by the tilted facets of the dots, which lift the degeneracy between the top and bottom surfaces. The switching affects neither the chirality of the in-plane domains nor the polarity of the core of the DW. These results show that at least three degrees of freedom may be addressed independently and reliably in a single magnetic dot, whereas only two had been manipulated so far in the now widely-studied vortex state found in high-symmetry dots. This fundamental knowledge of the possibility of an internal switching in Bloch walls may also be of use for studies of field- or current-driven movement of domain walls, were it is well known that domain walls can undergo topological transformations during their movement[30].

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