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Dimensionality cross-over in magnetism: from domain walls (2D) to vortices (1D)

A. Masseboeuf,[1] O. Fruchart,[2,*] J. C. Toussaint,[2,3] F. Cheynis,[2,3] P. Bayle-Guillemaud,[1] and A. Marty[4]

[1] *CEA-Grenoble, DRFMC/SP2M/LEMMA, 17 rue des Martyrs, Grenoble, France*

[2] *Institut NÉEL, CNRS & Université Joseph Fourier – BP166 – F-38042 Grenoble Cedex 9 – France*

[3] *Institut National Polytechnique de Grenoble – France*

[4] *CEA-Grenoble, DRFMC/SP2M/NM, 17 rue des Martyrs, Grenoble, France*

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Dimensionality cross-over is a classical topic in physics. Surprisingly it has not been searched in micromagnetism, which deals with objects such as domain walls (2D) and vortices (1D). We predict by simulation a second-order transition between these two objects, with the wall length as the Landau parameter. This was confirmed experimentally based on micron-sized self-assembled Co(111) dots.

Dimensionality cross-over is a rich topic in theoretical and experimental physics. In magnetism this issue has been widely addressed in the frame of magnetic ordering and critical exponents[1, 2]. Beyond this microscopic level of matter it has been recognized from the early investigations of magnetism that magnetic materials are often not uniformly magnetized on the long range, but rather split in magnetic domains[3]. The study of domains and domain walls (DWs), a field known as micromagnetism, has since been a major topic of magnetism. Micromagnetic objects have tentatively been classified according to their dimensionality. Magnetic domains are 3D, DWs are 2D, Bloch lines (*i.e.* so-called either vortices or anti-vortices) are 1D, Bloch points are 0D[4, 5]. Each entity may serve as a boundary to the object of immediately-greater dimensionality: DWs are found at domain boundaries, Bloch lines inside domain walls to separate areas with opposite winding[3, 5], and Bloch points separate two parts of a vortex with opposite polarities[4, 6]. The study of DWs and vortices as objects that can be moved[7] and even modified[8, 9, 10] in their inner structure is a timely topic, driven by proposals of their use in memory[11] and logic[12] devices. These operations can be achieved using external magnetic fields[7], or the spin-transfer effect[13] which promises a deeper integration in spin-electronic devices. Despite these active and timely studies the possibility of a dimensionality cross-over between a DW and a magnetic vortex has not been addressed. This is surprising as it is now recognized that their structure is greatly modified dynamically during the application of magnetic field or spin-polarized current[14, 15]. Thus, beyond the aesthetics physical issue of dimensionality crossover, the knowledge of how a DW may switch reversibly to a magnetic vortex should have a great importance in understanding and controlling their static and dynamic features.

In this Letter we report the cross-over from a DW to a magnetic vortex. We have considered micron-sized magnetic dots in a flux-closure state. Depending on the dot geometry (size and aspect ratio), the flux may be closed around a vortex[8] or a DW of finite length[16]. It was early discussed that the topology of such DW and vortices should be identical, the former being obtain from the latter by a continuous deformation[16, 17, 18]. Owing to this identical topology an issue arises naturally, that of the possibility of a transition from a DW to a magnetic vortex. We first show by the micromagnetic simulation of dots with variable in-plane aspect ratios that a wall tends to collapse into a vortex at a critical length of a few tens of nanometers. The transition bears the signature of second order, with the wall length as an order parameter. This collapsing effect is then confirmed quantitatively making use of Co(111) self-assembled epitaxial dots as model systems, driven by the dot lateral aspect ratio around a mean hexagonal base.

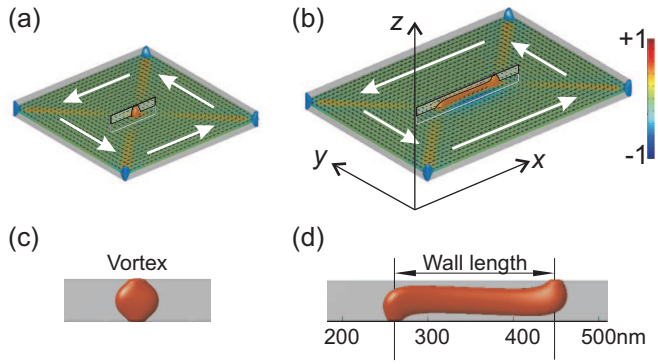

FIG. 1: Simulated magnetization states in flat Fe(110) dots with size (a) 500×500×50 nm: vortex state and (b) 500×750×50 nm: Landau state consisting of a Bloch wall separating two antiparallel domains. The color stands for the direction of magnetization along z, see right scale. In these open views the only parts displayed as volumes are those were m_z is greater than 0.5. This highlights the central vortex or Bloch wall (red) and the magnetization areas close to the vertical edges of the prisms (blue). At all other places the surface displays magnetization in the mid-height plane. (c-d) Views in the xz plane, corresponding to the framed areas in a-b, respectively.

Let us describe our methods. Micromagnetic simula-

*Olivier.Fruchart@grenoble.cnrs.fr

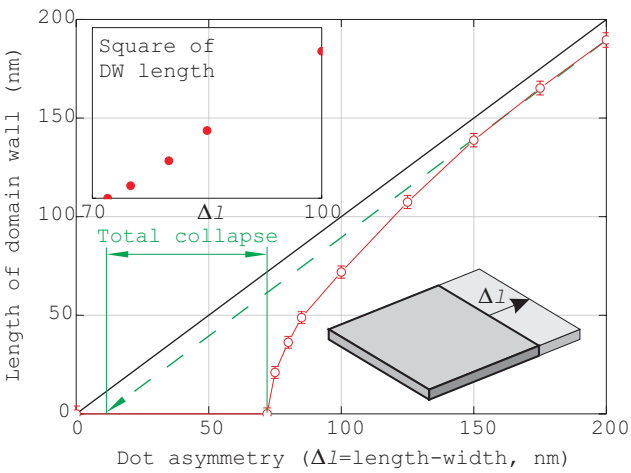

FIG. 2: Open symbols: length of the Bloch wall in the Landau state for dot thickness 50 nm, plotted versus the dot lateral asymmetry Δl (length minus width, see inset sketch). Linear line with slope +1: wall length in the simple geometrical Van den Berg model (black line). Dotted line: asymptotic extrapolation from long dot, whose intercept with the x axis defines the total collapsed. Inset: squared length of Bloch wall, same x axis.

tions were performed using GL_FFT, a custom-developed finite-differences code based on the temporal integration of the Landau-Lifshitz-Gilbert equation[19]. The cell size was $3.91 \times 3.91 \times 3.13$ nm or lower and the parameters for bulk Fe at room temperature were used to fit an well-characterized experimental case of self-assembled dots displaying DWs[10]. The experimental systems consist of self-assembled micron-size Co(111) dots[20], epitaxially-grown under ultra-high vacuum using pulsed-laser deposition[21]. These were grown on a single-crystalline 10 nm-thick W buffer layer deposited on sapphire $(11\bar{2}0)$ wafers, and capped with a 5 nm-thick Au layer to prevent oxidation. The wafer was then thinned with mechanical polishing and ion milling. Lorentz microscopy was performed in the Fresnel mode using a JEOL 3010 microscope equipped with a GATAN imaging filter. In this mode DWs (resp. vortices) are highlighted as dark or bright lines (resp. dots) depending on the chirality of magnetization curling around the DW/vortex[22]. The image are formed with a dedicated mini-lens, while an axial magnetic field can be added using the conventional objective lens. The samples were prepared by applying a saturating 3 T magnetic field, and then imaged at remanence.

We first present the results of micromagnetic simulation. As a simple textbook case we considered flat prismatic Fe(110) dots[10] with fixed height-over-width ratio 0.2 and thickness 50 nm and above. The length, taken along the in-plane Fe[001] direction, was varied from 1 to 1.5 with respect to the width. As expected for elongated dots of such thickness[16, 17, 18] a Landau state occurs, displaying two main longitudinal domains separated by a Bloch wall (FIG. 1b,d). The DW displays perpendicular magnetization in its core, while it is terminated at each surface by an area with in-plane magnetization, the *Néel caps*[23]. At each end of the DW the magnetic flux escapes through a surface vortex. We define the length of the DW as the distance between the projections into the film plane of the locii of these two vortices (FIG. 1d). From this definition a vortex is a DW with zero length, such as found *e.g.* for a dot with a square base (FIG. 1a,c). Series of simulations of the equilibrium state for variable dot length were performed the following way. At each stage the magnetization map is stretched or compressed along the length to serve as a crude input for the map of the next value of length, for which the equilibrium state is again calculated. The series was performed once with rising length, then again with decreasing length back to the square base. This yielded identical results, ruling out the possibility of metastable configurations. To avoid discretization artifacts the number of cells was kept constant for all simulations of a dot of given height. Instead the length of each cell was varied progressively to fit the dot length. The dependence of the DW length with the dot length is shown for thickness 50 nm on FIG. 2. For significantly-elongated dots the wall length increases linearly with slope 1. In this regime the two surface vortices are sufficiently apart one from another to have a negligible interaction. Their position is essentially determined by the minimization of the energy of the triangular closure domain along the two short sides of the dot. By a view of mind upon increasing the dot length the new configuration may be constructed by adding an x-independent (y, z) slab of DW at mid-length of the dot. On the reverse in the low-length regime the DW length decreases faster than slope 1, so that a vortex state is reached before the dot has a square base. We define the *collapsed* length as the difference between the length of dot upon the collapse and the asymptotic linear variation of wall length for an elongated dots (FIG. 2). Plotting the square of the DW length versus the dot length reveals a linear variation. The cross-over is therefore Landau-like, *i.e.* of second order. Such transitions are always associated with a breaking of symmetry, which in the present case is whether the top surface vortex shifts towards $+x$ or $-x$. The results are qualitatively similar for other thicknesses.

The predictions of the simulations have been confirmed experimentally. Self-assembled dots have been used for this study because they display sharp and well-defined edges, so that the dot length and aspect ratio can be measured with accuracy and confidence. We could not make use of the well-characterized case of Fe(110) dots as these dots are elongated by their crystallographic nature[21] and thus always display DWs[24], not vortices. Instead we developed self-assembled face-centered cubic Co(111) dots. These display a trigonal symmetry reflecting their crystalline structure, however with a base close to a regular hexagon (FIG. 3b). Contrary to previous studies

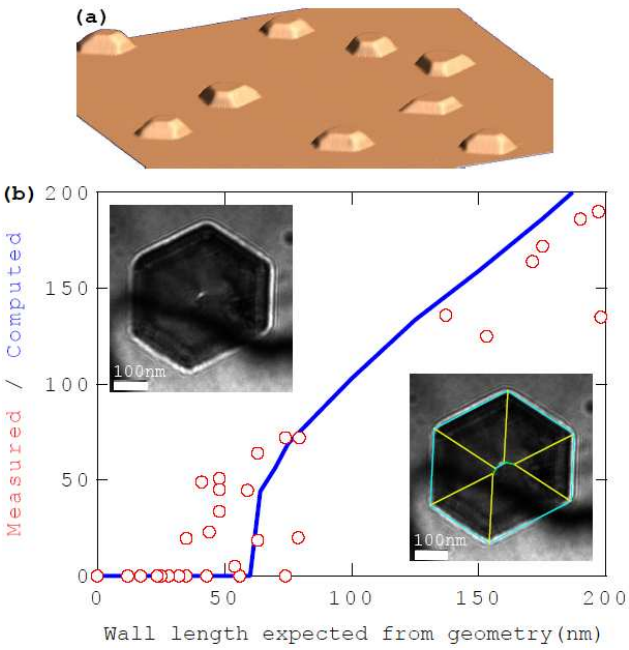

FIG. 3: (a) True Z-scale 3D view of a $6 \times 6\,\mu$m AFM image of self-assembled Co(111) dots (b) Open symbols: DW length measured in Co(111) dots plotted versus the length expected from the geometrical Van den Berg construction. The predictions from simulations for the estimated thickness of the dot 100 nm are superimposed without adjustment, as guide to the eye. Insets: typical Co dot displaying a vortex (upper left) along with the associated construction predicting a DW (lower right, central blue line).

dealing with very thin dots thus found in a nearly single-domain state[25], the thickness of our dots is in the range $100 - 200$ nm inducing flux-closure states around a DW or vortex. Owing to the natural spread of shape occurring in epitaxial self-assembly we could study the length of DWs as a function of the dot aspect ratio, by a statistical investigation of an assembly of dots over the same sample. For each dot we measured the experimental DW length, and computed the expected DW length predicted by the simple Van den Berg geometrical construction. This construction is relevant for vanishing thickness and infinite variable dimensions[26], and equals the dot asymmetry used in the simulations so that a direct comparison with the data of FIG. 2 is possible. FIG. 3b summarizes this analysis, performed over more than 30 dots. Despite the spread of thickness, lateral size and shape of the experimental dots, the collected results are quantitatively consistent with the simulation predictions. The experimental spread of points may be attributed first to errors in the measurement of both the DW length and dot dimensions, second to the spread of dot thickness as the collapsing length slightly depends on the thickness. Despite this spread, it shall be noticed that only vortices are observed when the expected length lies below 40 nm. This cannot be attributed to an experimental limitation to identify short DWs, as many DWs with length below 40 nm have been measured. These however all lie for expected wall length above 40 nm. These correlations lie above statistical fluctuations, which unambiguously demonstrates the collapse of DWs towards vortices in a quantitative agreement with simulations.

To conclude we have addressed a dimensionality crossover in micromagnetism, that of a magnetic domain wall (DW, 2D) into a magnetic vortex (1D). Simulations and experiments agree quantitatively that DWs collapse into vortices at a critical length of a few tens of nanometers, *i.e.* revealing a short-ranged attractive force between the two extremities of a DW. Beyond physics aesthetics and increasing fundamental knowledge, our investigation should prove useful when analyzing the increasing number of experiments dealing with the behavior of domain walls and vortices under the effect of pulsed magnetic fields or spin-polarized currents, which undergo complex variations of shape and length during their dynamics. This includes the case of *e.g.* the vortex state, where a domain wall dynamically replaces the vortex[27], or the multiplication of vortices or transformation of the type of domain wall in magnetic stripes[14, 28].

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