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Switching a magnetic antivortex core with ultrashort field pulses

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Antivortices are fundamental magnetic structures found alongside vortices in soft magnetic extended films and in patterned elements above a few micrometers in size. While the dynamic behavior of vortices has been the object of numerous studies, the magnetization dynamics of antivortices has not been studied as thoroughly. Using micromagnetic simulations, we investigate the dynamics of a single isolated antivortex in response to subnanosecond external field pulses. We find that these pulses can trigger the reversal of the antivortex core. This reversal mechanism is complementary to the one recently found in the *vortex* core switch. We also investigate the stability of the switching process in the isolated antivortex structure. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2838138]

Owing to dramatic increases in experimental resolution in the past few years, complex magnetization structures in ferromagnetic samples can now be imaged far below the micron scale.[1] In parallel to experimental observations, micromagnetic simulations allow for interpretation of the observed structures and for detailed understanding of their dynamics. Indeed, micromagnetic simulations provide information about quantities which cannot be accessed experimentally such as the energy of the system.[2] Moreover, simulations offer the possibility of studying with high spatial and temporal resolutions the dynamic behavior of elementary magnetic structures, i.e., domain walls, vortices, and antivortices. We focus here on antivortices, which naturally occur in cross-tie domain walls[3] alongside vortices. They distinguish themselves from vortices by an opposite circulation of the in-plane magnetization,[4] which is defined by the topological winding number n. While vortices have a positive winding number ($n=1$) and a circular symmetry of the magnetization, antivortices have a negative winding number ($n=-1$) and only display inversion symmetry about the center [Fig. 1(a)]. Similar to vortices, antivortices possess a core: a region where the magnetization points perpendicular to the sample plane [Fig. 1(b)]. As such, the antivortex core has two possible directions (or polarizations). Only a few studies have been carried out solely on antivortices[5,6] probably because these structures are typically rather unstable in submicrometer samples. So far, antivortex dynamics has been investigated for low-amplitude field excitations[6] and for antivortices coupled to two vortices in a single cross-tie wall.[7] In another experiment, it has recently been found that the number of cross ties can increase when nanosecond field pulses are applied in the plane of a large ferromagnetic thin-film element containing multiple cross-tie walls.[8] Previous studies on the ultrafast dynamics of vortices[9–11] allow to explain the generation of new vortex-antivortex pairs in the sample in response to short external field pulses, which could

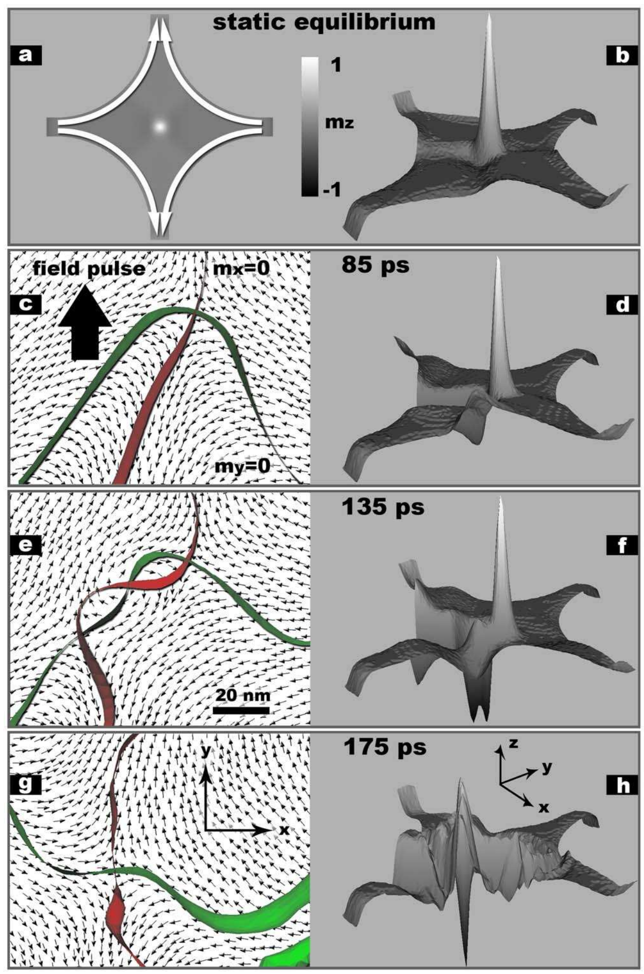

FIG. 1. (Color online) Antivortex core reversal process. In the left column, the magnetic configuration in the antivortex sample is given in (a). The white arrows illustrate the circulation of the magnetization, which aligns with the sample boundaries. Below, the reversal process is shown focusing only on the core region [(c), (e), and (g)]. The arrows indicate the in-plane magnetization while the red and green ribbons show the $m_x=0$ and $m_y=0$ isosurfaces, respectively. The right column shows the evolution of the z component of the magnetization [(b), (d), (f), and (h)]. The indicated times are taken from the moment the external pulse is applied.

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account for the observed increase in the number of cross ties. However, little is known about the dynamics of antivortices in this case. We present here the magnetization dynamics of an isolated antivortex in response to in-plane external field pulses of subnanosecond duration. We have found that such ultrashort pulses can lead to the reversal of the antivortex core. This reversal process is complementary to the one recently found in vortices.[9,11] We have also investigated the stability of the antivortex structure following the reversal of its core.

For this study, a single antivortex has been artificially stabilized in a sample whose shape anisotropy can sustain this particular magnetization structure [Fig. 1(a)]. The sample, similar to the ones used in Refs. 5 and 6, is built from four circular segments with a radius of 200 nm. Its branches are 40 nm wide and 20 nm thick. The simulations are performed with a fully three-dimensional micromagnetic code based on the finite-element method, as used in Ref. 9, which allows to accurately compute the magnetization in samples with curved boundaries. The antivortex configuration was obtained by initially saturating the sample perpendicularly to the plane and then by minimizing the total energy of the system using the conjugate gradient method.[12] The material parameters of Permalloy have been used for the simulation: $A=1.3\times10^{-11}$ J/m (exchange constant), $\mu_0 M_s=1.0$ T (M_s is the saturation magnetization), $K=0$ (anisotropy constant) and $K_s=10^{-4}$ J/m^2 (surface anisotropy).[13] The sample was discretized using around 180 000 tetrahedral elements. This is equivalent to a cell size of approximately 4 nm^3. The external excitation was provided by a short in-plane Gaussian-shaped pulse field applied in the y direction, as indicated in Fig. 1(c). The maximum intensity of the pulse was 60 mT and its duration was 60 ps. The dynamic response of the magnetization was calculated using the Landau–Lifshitz–Gilbert equation with a damping parameter of $\alpha=0.01$. For the interpretation of the results, we have used the isosurface representation introduced in Ref. 4 to highlight the location of the antivortex core, i.e., the region where the magnetization is perpendicular to the sample plane ($m_z=\pm1$). This can be located by visualizing the intersection of the $m_x=0$ and $m_y=0$ isosurfaces (**m** is the normalized magnetization $\mathbf{m}=\mathbf{M}/M_s$).

The magnetization dynamics following the application of the external field is shown in Figs. 1(c)–1(h). In the left-hand column, the arrows represent the in-plane magnetic structure and the ribbons denote the $m_x=0$ and $m_y=0$ isosurfaces. In the right-hand column, the topography of the z component of the magnetization is given, showing the orientation and spatial distribution of the core. In response to the external field pulse, the antivortex core is initially displaced from its equilibrium position. As the field strength increases, the in-plane magnetization is distorted and a region develops where the the in-plane magnetization rotates by 90° over a few nanometers [Fig. 1(c)]. The resulting high local exchange energy density is reduced by the rotation of the magnetization out of the sample plane. This leads to the formation of a dip in the profile of the z component of the magnetization, shown in Fig. 1(d). Such a perpendicular distortion of the magnetization is equally found when a vortex is displaced from its equilibrium position[14,15] and is the starting point of the vortex core reversal process as well.[9] The orientation of the dip is determined by the stray field of the antivortex core and, thus, invariably forms in the opposite direction of the core.[9,16] The further distortion of the in-plane magnetization causes the dip to develop until $|m_z|$ reaches a maximum value (here, $m_z=-1$). This results in the formation of a new antivortex 135 ps after the application of the pulse. Simultaneously, a vortex is also produced, insuring the conservation of the winding number.[17] The additional intersections of the isosurfaces shown in Fig. 1(e) mark the location of the new antivortex-vortex pair [also shown in Fig. 1(f)]. Finally, the newly created vortex and the original antivortex, which have opposite polarizations, annihilate[4] within approximately 10 ps, leaving only the newly formed antivortex in the sample [Figs. 1(g) and 1(h)], shown about 25 ps after the annihilation process.

The rapid emission and annihilation of an antivortex-vortex pair out of an antivortex clearly is a novel process in micromagnetism. In spite of the very different in-plane magnetization structure of vortices and antivortices, the used isosurface representation enables us to identify and highlight

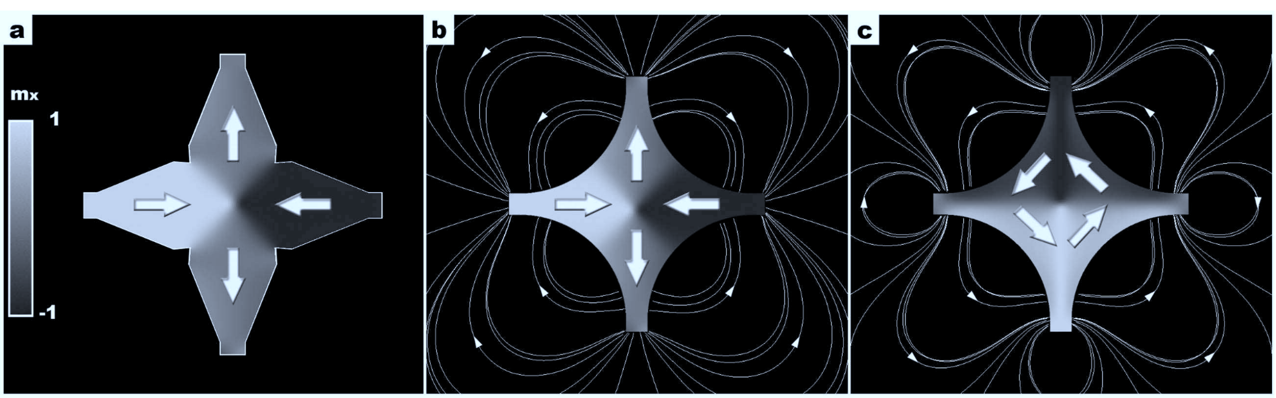

FIG. 2. Modified sample with four notches (a). The thick arrows show the magnetization direction in the sample. The scale only applies to the interior of the sample and represents the value of the x component of the magnetization. Stray field due to the magnetic charges present in the antivortex structure (b). The flux does not circulate in the same direction in each loop, forming four virtual vortices around the structure. Stray field generated by a vortex structure in the sample (c). The flux circulates around the vortex.

the remarkable analogy between the core reversal processes found in antivortices and vortices (see, e.g., Fig. 2 in Ref. 9). In the example given above, the system eventually relaxes back into an antivortex state. However, if the pulse strength is above 100 mT (while keeping the duration at 60 ps), a vortex nucleates at the sample edges. The antivortex is subsequently expelled from the sample and the system relaxes into a vortex state. For pulses stronger than 120 mT, additional pairs are created, emitted by both the antivortex and the nucleated vortex. The annihilation processes which follow leave a pair of head-to-head and tail-to-tail domain walls in the sample. A complete description of the possible final states is given in Ref. 18. The strong dependence of the final magnetization state in the sample on the excitation parameters underlines the metastable character of the antivortex structure. In an attempt to avoid vortex nucleation and, thus, increase its stability, we have cut notches in the sample, as shown in Fig. 2(a). Such notches have indeed been shown to repel vortex walls in thin-film elements.[19] We have noticed that in this case, however, the notches facilitated the nucleation of a vortex in the sample. The weak stability of the antivortex can be explained by the presence of areas in the sample where the magnetization diverges, creating a volume charge density $\rho = -\nabla \cdot \mathbf{m}$. At the branch extremities, where the magnetization is perpendicular to the sample boundary, surface charge densities $\sigma = \mathbf{n} \cdot \mathbf{m}$ also arise. The magnetic flux in the sample is thus not closed, which gives rise to the stray field shown in Fig. 2(b). In each one of the loops, the magnetic flux circulates in a different direction. These flux-closure loops can be seen as *virtual* vortices, i.e., whose center is located *outside* the sample. Because they are close to the sample boundary, these virtual vortices can easily enter the sample and nucleate a vortex if the magnetic configuration is sufficiently excited. In contrast to this situation, Fig. 2(c) shows the demagnetizing field in a sample containing a magnetic vortex. Here, the external flux lines loop around the single vortex structure present inside the sample.

In conclusion, we have investigated the ultrafast dynamics of an isolated antivortex core through micromagnetic simulations. The simulations have shown that the core of an antivortex can be switched and that this process is mediated by the production of a new antivortex and the annihilation of the original one with a short-lived vortex. The static topological complementarity of vortices and antivortices is thus also exhibited in this ultrafast process. These results imply that the dynamic transformation of cross-tie walls and the creation of new magnetization patterns results from pair creation and annihilation processes equally triggered by vortices and antivortices. While antivortices are a suitable playground for the study of the dynamics of fundamental magnetization structures, the limits on the stability of isolated antivortices require an excellent control of the applied external field parameters.

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