Flipping Magnetic Vortex Cores on the Picosecond Time Scale

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IFF-9: Electronic Properties

The study of dynamic magnetization processes and the search for increasingly faster switching times is one of the strongest driving forces in magnetism research. A fundamental understanding of these processes is paramount and can naturally lead to technological applications. An ultrafast magnetic reversal process induced by an external field is the precessional switching. In this case, the magnetization rotates homogeneously within about 300 ps. The high speed of this process is achieved by exploiting the dipolar field of the ferromagnet. This was until recently believed to represent the fundamental speed limit of field-induced magnetic switching. A novel type of magnetization reversal consists in the switching of the core of a magnetic vortex. Using advanced micromagnetic simulations we have resolved the microscopic details of this process which unfolds on a length scale of only a few nanometers, and we discovered an ultrafast route to switching of a magnetic vortex core within a few tens of picoseconds. This constitutes the fastest field-induced magnetic switching mechanism ever reported and opens new possibilities for future data storage applications with ultimate speeds.

Ferromagnetic materials in confined geometries typically form domain structures that close the magnetic flux. In the center of such flux-closure structures there is a region of only a few nanometers in size known as a magnetic vortex, where the magnetization circulates around a core. In the vortex core, the magnetization points out of the vortex plane, thereby preventing a singularity of the exchange energy density. The strength of the exchange interaction (which is of the order of 10 Tesla) confers the vortex core a very high structural stability. The very small size of the vortex core, in combination with the fact that it can have two stable orientations: "up" or "down" with respect to the sample plane naturally makes it a good candidate for data storage, given a mechanism allowing to easily switch it. The experimental demonstration that vortex cores can be switched by low in-plane magnetic fields has been provided only very recently [1]. In the experiment of Ref. [1], short oscillating magnetic field pulses of low amplitude were used, tuned to the gyrotropic resonance frequency of the system [2]. This frequency depends on the particle size and shape and is typically in the order of a few 100 MHz. By exploiting this resonance, it was demonstrated that the vortex core reversal can be triggered with sinusoidal field pulses a few ns in duration.

We have studied the dynamics of vortex core reversal with micromagnetic simulations using a fully three-dimensional finite-element algorithm based on the Landau-Lifshitz-Gilbert equation [3]. Our simulations show that the time scale required for a vortex core reversal is not limited by the relatively slow gyrotropic resonance frequency: A vortex core reversal process can also be triggered by a non-resonant, unipolar, and very short field pulse (below 100 ps) of moderate strength ($\sim$80 mT) applied parallel to the film plane of, *e.g.*, a sub-micron sized $Ni_{81}Fe_{19}$ (Permalloy, Py) disk (Fig.1). We found that the core reversal occurs through a sequence consisting of a vortex-antivortex pair creation, followed by an annihilation process, resulting in a final magnetic structure of a single vortex with opposite polarization. The time required for the core reversal is of the order of 40 ps. These results are reported in detail in Ref. [4].

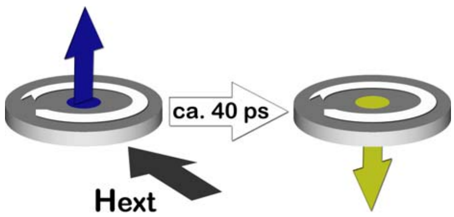

FIG. 1: Schematics of a field-pulse driven vortex core switching. The vortex core magnetization can be switched by a short magnetic field pulse applied in the film plane. This switching process requires only about 40 ps.

A typical example of the vortex-antivortex pair creation mediated core switch process is shown in Fig. 2 for a disk-shaped Py sample (radius of 100 nm and thickness of 20 nm). An 80 mT Gaussian-shaped field pulse of a duration of 60 ps is applied in the plane of the Py disk, which is initially in a symmetric vortex state. To clearly identify the microscopic processes leading to the core reversal, we have highlighted the $m_x = 0$ and $m_y = 0$ isosurfaces [3], the

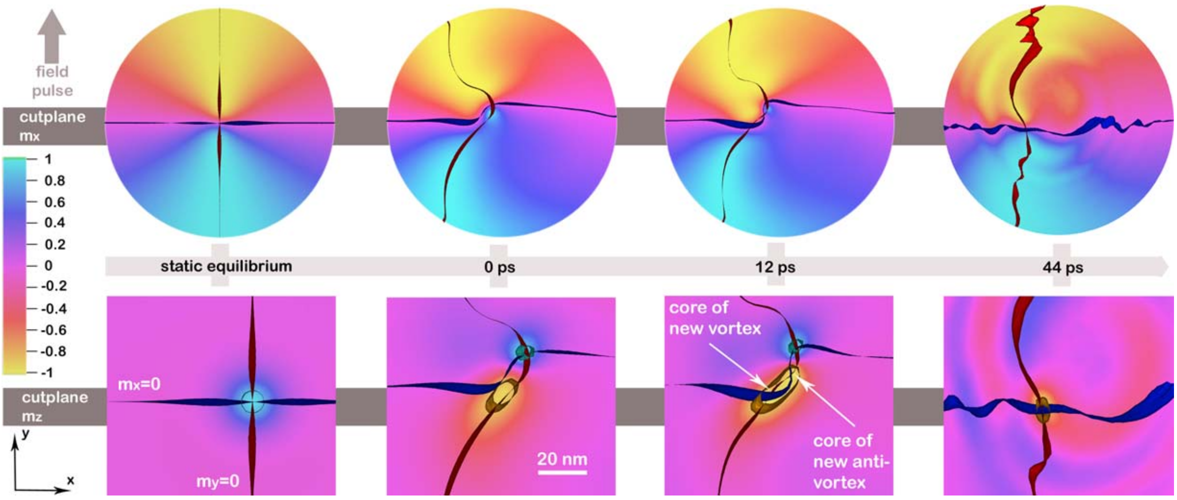

FIG. 2: Pair-creation mediated vortex core reversal in a Py disk of 100 nm radius and 20 nm thickness. A Gaussian field pulse is applied in the disk plane, parallel to the y axis. The top row shows the x component of the magnetization m_x in the initial state, followed by the state of the sample at the pulse maximum ("0 ps") and then at two different times after the pulse maximum has been reached. The blue and red ribbons represent the $m_x = 0$ and $m_y = 0$ isosurfaces, respectively. The bottom row shows a magnification of the region where these ribbons intersect, marking the cores of the original vortex, then at 12 ps after the pulse maximum, of the newly created vortex-antivortex pair, and finally of the remaining vortex core. This core has opposite polarization with respect to the initial vortex core, indicated by the yellow color on the underlying cut plane representing the z component of the magnetization m_z . The green and orange cylindrical ribbons are the isosurfaces where $m_z = 0.8$ and $m_z = -0.8$, respectively.

intersection of which determines the exact position of the vortex core. Before an external field is applied, these $m_x = M_x/M_\mathrm{s} = 0$ and $m_y = M_y/M_\mathrm{s} = 0$ isosurfaces appear as straight ribbons (oriented parallel to the x and y axis, respectively) crossing each other perpendicularly at the center of the vortex core. As the field pulse perturbs the system, the vortex shifts away from its original position and the formerly circular arrangement of the magnetization around the core is stretched, resulting in bent isosurfaces. As the isosurfaces approach each other, the distance over which the magnetization rotates by 90° in the plane shrinks to a few nanometers. The magnetization thus rotates out of the sample plane in order to locally reduce the exchange energy. This rotation occurs in the direction opposite direction to the original vortex orientation owing to the strong dipolar field of the vortex core. A few picoseconds after the peak value of the pulse is reached, the isosurfaces are bent strongly enough to form two additional intersections. These intersections mark the creation of a vortex-antivortex pair. Once a pair is created, the antivortex quickly moves towards the original vortex and, through a rapid process, they annihilate each other. We have reported the micromagnetic details of the annihilation process in Ref. [3], showing that it is connected with a sudden generation of spin waves. After the sequence of pair creation and annihilation processes, the magnetic structure is again in a vortex state, but with opposite polarization with respect to the original vortex.

Additionnally, we conducted a systematic study on the influence of the applied pulse's duration and strength on the core switch. We found that it occurred in our disk-shaped sample for well-defined combinations of the applied pulse's duration and strength. In particular, we observed that by increasing the applied field strength to 120 mT, it was possible to trigger a core switch with field pulses only 5 ps long.

In conclusion, we presented a novel ultrafast process in nanomagnetism for switching the core of magnetic vortices. Although this reversal mode involves a series of complex processes on the nanometer scale – the creation of a vortex-antivortex pair, a subsequent annihilation process – the chain of events only requires a very short field pulse of suitable shape to be initiated. A further advantage of the vortex core reversal mechanism lies in the simplicity of the required sample and magnetic structure: all that is needed is a magnetic vortex, which is a structure that forms naturally in sub-micron sized magnetic disks. The high speed of this switching mechanism is due to the fact that it is driven by the exchange field and represents a promising advance in the search for the ultimate speed limit of magnetic switching.

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