Magnetization Dynamics of Vortex-Antivortex Annihilation Processes

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The study of dynamic magnetization processes in nanoscale magnets on the picosecond time scale is currently a very active field of research; important for both fundamental physics and for future applications of nanomagnets in spin-electronic devices. A typical topological object occuring in magnetization structures of thin-film nanomagnets is a vortex, where the magnetization circulates in the film plane around a core region with perpendicular magnetization. The static and dynamic properties of magnetic vortices have been studied intensively by several groups over the last years. The so-called antivortex is the counterpart of a magnetic vortex, which has a similar magnetic structure. A vortex and an antivortex can annihilate when they meet. By means of micromagnetic finite-element simulations we have investigated the dynamics of annihaltion processes of vortex-antivortex pairs in a Permalloy thin-film element of 100 nm size and 10 nm thickness. The results show that the relative orientation of the magnetization in the core of the vortex and the antivortex (being either parallel or antiparallel) has a drastic impact on the dynamics of the annihilation process. In the antiparallel case, the annihilation occurs via a sudden, burst-like emission of spin waves ("exchange explosion"). With this study we obtained a detailed description of a previously unexplored fundamental process in nanomagnetism. The annihilation of vortex-antivortex pairs as studied here has recently been proposed as a sub-process for a new mechanism to switch magnetic vortex cores.

Soft-magnetic thin-film elements tend to form magnetic flux-closure domain patterns, like the well known Landau domain structure [1]. Such flux-closure patterns contain an interesting region of only a few nm in size where the magnetization direction circulates by 360° around one point. These magnetic vortices have attracted much attention over the last years, since they have particular static [2, 3] and dynamic properties [4, 5]. It has been predicted theoretically and demonstrated experimentally [2, 3] that the core region of a magnetic vortex displays a magnetization direction perpendicular to the film plane, known as the vortex polarization. The antivortex is a structure similar to the vortex, in the sense that the magnetization direction in the film plane changes by 360° on a closed loop around one point, however with a different "winding number" (see below). The core of the antivortex is perpendicularly magnetized, as it is the case for a vortex. Fig. 1 schematically shows the structure of a vortex (a) and an antivortex (b). The winding number is defined as the normalized line integral on a closed loop S over the angle α that the magnetization $\vec{M}$ encloses with the x-axis: $W = \oint \alpha(\phi)/2\pi \, \mathrm{d}S$ (cf. Fig. 1c). Antivortices can occur in a certain type of magnetic domain walls, known as cross-tie walls [6].

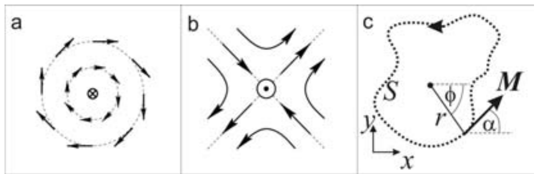

FIG. 1: Schematics of a magnetic vortex (a) and an antivortex (b). In the core of the (anti-)vortex, the magnetization is perpendicular to the plane. (c):Sketch on the definition of the winding number.

We have simulated the annihilation of an antivortex and a vortex in a cross-tie domain wall structure in a Permalloy thin-film element of 100 nm × 100 nm size and 10 nm thickness [7]. A Permalloy platelet of this size is too small to permanently sustain a cross-tie structure. If such a magnetic structure is imposed as an initial magnetic configuration, it decays into a simple vortex state. This domain structure conversion can only occur via a vortex-antivortex annihilation process. At zero field, the conversion into a vortex state occurs within ~ 200 ps. The simulations were performed with the micromagnetic finite-element code based on the Landau-Lifshitz-Gilbert equation already used in previous studies [8]. We used a finite element mesh with about 200.000 tetrahedral elements of about 1.3 nm size. The results show [7] that the vortex-antivortex annihilation process is relatively simple if the vortex and the antivortex have the same polarization. Before the annihilation, the vortex cores approach each other on spiralling orbits and finally meet in the center, where the antivortex is. During this approach, the magnetization between the antivortex and the vortex rotates out of plane, thereby dissolving the complicated ini-

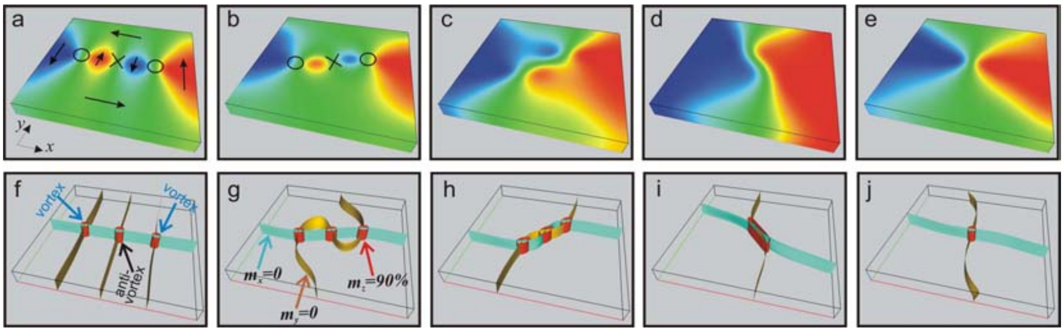

FIG. 2: Dynamics of a vortex-antivortex annihilation process with opposite polarization. In the panels a-e, a visualization with isosurfaces has been used, as described in the text. The configurations are shown at 5 ps (a,f), 110 ps (b,g), 135 ps (c,h), 138 ps (d,i) and 141 ps (e,j). In the bottom row, the panels f-j, show magnified top views on the region of interest. In addition, the isosurfaces $m_z = 0$ are displayed as green ribbons.

tial magnetic structure. In this case, the annihilation is a smooth, continuous rearrangement of the magnetization. The situation is very different if the antivortex has opposite polarization with respect to the neighboring vortices. To study this case, an unstable cross-tie structure is chosen as initial configuration, similar to the previous case, but now the polarization of the antivortex is negative, while the vortices have positive polarization. Using an isosurface representation of the magnetic structure [7], the dynamics of the annihilation process is shown in Fig. 2. The extended isosurfaces display the areas where $m_x = 0$ and $m_y = 0$, respectively. These isosurfaces allow for a precise localization of the cores: The (anti-)vortex cores are the only points in the sample where the z-component of the magnetization reaches 100%. Both the x and y-component are zero in the core center, hence the cores are at the intersections of the $m_x = 0$ and $m_y = 0$ isosurfaces. The cores are encircled by cylindrical isosurfaces displaying the regions where $m_z = 90\%$. The blue cylinder around the antivortex is the isosurface of $m_z = -90\%$. In this antiparallel case, the annihilation process begins with a relatively slow approach of the antivortex towards one of the vortices (here: on the left). This proceeds until the cores of the vortex and the antivortex meet in one point, leading to a dramatic and sudden annihilation, accomplished by a propagating micromagnetic singularity [9] (Bloch point, BP).

Isosurfaces and their intersections are not only helpful for locating vortex cores. They can also help identifying and locating BPs. In the panels f-j of Fig. 2, the $m_z = 0$ isosurface is displayed in addition to the $m_x = 0$ and $m_y = 0$ ribbons. A singularity occurs when these three isosurfaces intersect in one point: There –and only there– $|\boldsymbol{M}|$ is equal to zero inside the sample. In panel i of Fig. 2, the intersection of the cyan colored $m_x = 0$, the green $m_y = 0$, and the yellow $m_z = 0$ ribbon marks the point where a BP is formed. As the BP leaves the sample on the surface, the vortex-antivortex structure is dissolved and a large amount of exchange energy is released. The energy is converted into spin waves, recognizable as wave fronts emitted from the region where the BP was formed.

In conclusion, high-resolution micromagnetic simulations have been used to unveil the complicated magnetization dynamics of vortex-antivortex annihilation processes. When vortex and antivortex are polarized oppositely, the annihilation involves a sudden, burst-like emission of spin waves (exchange explosion). In that case, the annihilation is mediated by a propagating BP. The vortex-antivortex annihilation is considered to be an important sub-process of a complicated, recently observed vortex core reversal mechanism triggered by field pulses [5]. Our simulations provide detailed insight into crucial aspects of this process, and we have thus made the first step towards a theoretical understanding of a new micromagnetic mechanism [10], which opens the possibility of using magnetic vortex cores for data storage purposes [5, 11].

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