AIP | Applied Physics Letters

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Citation: Applied Physics Letters **86**, 052504 (2005); doi: 10.1063/1.1855413
View online: http://dx.doi.org/10.1063/1.1855413
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/86/5?ver=pdfcov
Published by the AIP Publishing

Vortex-antivortex assisted magnetization dynamics in a semi-continuous thin-film model system studied by micromagnetic simulations

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(Received 8 July 2004; accepted 2 November 2004; published online 26 January 2005)

We have studied magnetization **M** dynamics in a semicontinuous 33-nm-thick Fe model system, which approaches new equilibrium states under various magnetic fields, $H=0$, −1, −10, and −30 Oe, starting from an initial **M** configuration of complex microstructures experimentally observed in a real continuous Fe film. Simulation results with $H=0$ clearly reveal that small needle-shaped domains and ripple structures found in a frozen state of the demagnetized Fe film continue to grow far into a surrounding 180° domain, and that zigzag folding structures appear through the **M** dynamic evolution assisted by vortex and antivortex. Furthermore, it is found that many domain walls of a cross-tie type exhibit their dynamic developments under $H=-10$ and −30 Oe, caused by interactions between vortex and antivortex states. This vortex–antivortex assisted **M** dynamic evolution offers deeper insights into the comprehensive understanding of the static or dynamic properties of **M** reversal processes as well as additional features or more details of magnetic microstructures in real continuous films.
[DOI: 10.1063/1.1855413]

Recently, we obtained a vector image of static magnetic microstructures associated with a magnetization **M** reversal between oppositely oriented 180° domains in a 33-nm-thick Fe film, using a photon-based scanning transmission x-ray microscope.[1] From this **M** image, we have found that unexpected features of domain and domain-wall structures as well as the well-known 90°, 180° Néel wall segments, and extended ripple structures exist in the continuous film frozen at a certain demagnetized state. The experimental microstructures are quite different from static domain structures observed typically in continuous films.[2] Those additional features include not only vortex–antivortex pairs present at the front of small needle-shaped domains growing into their neighboring 180° domains, but also a rich signature of interactions between vortex and antivortex states.[1]

Meanwhile, magnetic vortex states in confined thin film systems have been much studied both theoretically and experimentally, and their internal structure has been well identified in reduced dimensions such as variously shaped magnetic films.[3–5] We also reported on micromagnetic simulations of the dynamic evolutions of interacting vortex and antivortex pairs in a confined circular disk, revealing that vortex–antivortex pairs play a crucial role in **M** dynamic evolutions.[6] However, detailed features of the interactions between vortex and antivortex, and their role in **M** reversals in *continuous* thin films have not been understood, because micromagnetic modeling studies have been limited to reduced dimension systems, as well as because experimental studies using large-scale continuous films are limited by both temporal and spatial resolutions. Therefore, the experimental features of vortex–antivortex pairs and their interacting signatures at or near domain boundaries observed in a continuous Fe film[1] are fundamentally interesting so as to continue to study how such complex magnetic structures were incorporated in a certain demagnetized state and how they will develop in a realistic model system of *semicontinuous* thin films in further **M** dynamic evolutions under applied magnetic fields, H.

In this letter, we report **M** dynamic evolutions approaching additional equilibrium states starting from an initial **M** state of experimental microstructures under different $H=0$, −1, −10, and −30 Oe, calculated in the framework of a semicontinuous thin-film approximation. It is found from the results of **M** dynamic evolutions that extended ripple and zigzag folding structures, and small needle-shaped domains extending into their surrounding domains continue to grow, and that vortex and antivortex states can play a pivotal role in **M** dynamics through their interactions even in realistic semicontinuous films.

Micromagnetic simulations were carried out using the object-oriented micromagnetic framework code.[7] In the micromagnetic modeling, the dimension of individual cells used is 100 nm × 100 nm × 33 nm[8] and the physical parameters relevant to a polycrystalline Fe film are given as follows: an exchange constant of $A=4.2\times10^{-11}$ (J/m), a saturation magnetization of $M_s=1.7\times10^{6}$ (A/m), an anisotropy constant of $K=0$.[9] Several damping values are also considered.[10]

To carry out computer simulations on temporal dynamic evolutions in large-scale areas such as a real continuous film, an initial **M** configuration shown in Fig. 1 is used. The spa-

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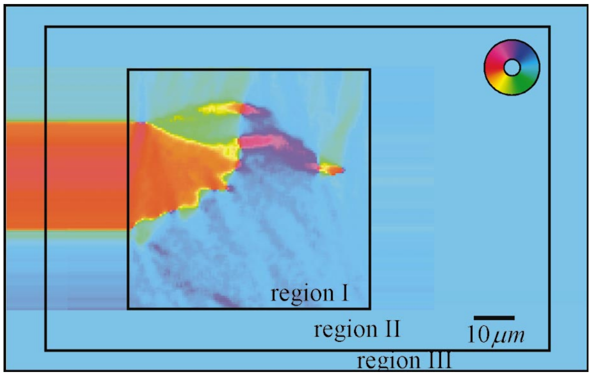

FIG. 1. (Color) An **M** configuration as a starting state for dynamic evolutions displayed by colors representing the in-plane components of local **M**. The innermost region of a $60 \times 60\ \mu m^2$ field (region I) is experimental data observed at a frozen state of a demagnetized Fe film. The regions II and III show possible orientations of local **M** in areas surrounding the $60 \times 60\ \mu m^2$ field. The local **M** in regions I and II are allowed to be relaxed, while those in region III are kept to be fixed during the **M** dynamic evolutions in micromagnetic simulations.

tial variations of local **M** in Fig. 1 are classified into three different areas: (1) The inner $60 \times 60\ \mu m^2$ area (region I) displays experimental data of the spatial variations of local **M** obtained in parts of a real Fe film. Details on the complex microstructures were reported elsewhere.[1] In order to study how these complex microstructures (in region I) evolve in further **M** dynamics in continuous films, possible **M** orientations in large areas surrounding the $60 \times 60\ \mu m^2$ field are assumed as shown in regions II and III. The starting **M** configuration in the inner area (regions I and II) is allowed to relax toward equilibrium ground states under given strengths of H, while the **M** orientations in the outermost area (region III) intentionally remain fixed as they were at the initial state. Such a semicontinuous thin-film approximation allows to reduce or at least minimize shape and boundary effects caused by a nonlocal magnetostatic interaction, as well as allows to save computation time for an enormous number of interacting cells suitable for a realistic continuous film model.

Starting from the initial **M** configuration shown in Fig. 1, relaxation dynamic evolutions proceed toward final equilibrium states under the environmental conditions as mentioned earlier. Figures 2(a) and 2(b) show the resultant in-plane **M** vector images of those dynamic evolutions calculated with $H=0$ and -10 Oe, respectively.[11] In both cases, the initial ripple structures extending into surrounding 180° domains continue to grow into the dominant 180° domains and then overlap each other. Also, smaller needle-shaped domains continue to grow into large ones. The features of vortex and antivortex states at domain boundaries and their pairs at the front of the tips of needle-shaped domains seem to stimulate the creation of tiny offspring domains to be extended into the surrounding domains in further **M** evolutions. For the case of $H=0$ Oe, a single large needle-shaped domain with the zigzag folding structure of local **M** orientations continues to extend much far into its surrounding domain as the evolutions proceed further. As displayed by the streamline representation, the extending needle-shaped domain is differentiated from the surrounding domains by two cross-tie walls facing each other, along which vortex and antivortex pairs are alternatively arranged. In fact, their arrangement is a segment of the well-known cross-tie wall structure typically observed in thin films.[2] As the dy-

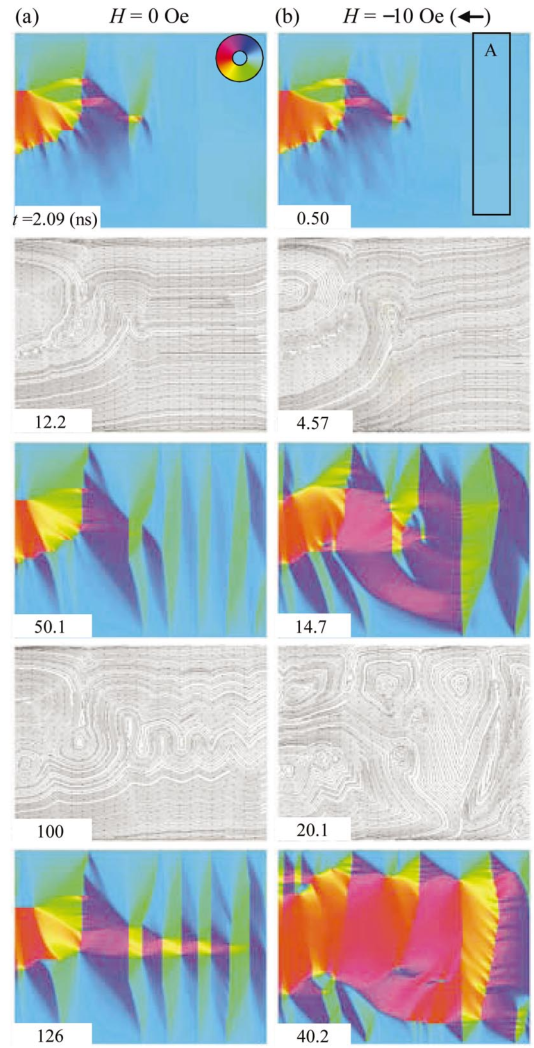

FIG. 2. (Color) Images of the temporal evolution of magnetic microstructures in regions I and II taken at each time as noted for **M** dynamic processes under $H=0$ Oe in (a) and $H=-10$ Oe in (b), starting from the initial **M** configuration shown in Fig. 1. The in-plane orientations of local **M** are represented by either way of colors or streamlines for the clear presentation of both the weak variations of local **M** and fine vortex structures.

namic evolution proceeds further, the two cross-tie walls become far away through the propagation of the vortex–antivortex arrays along an axis perpendicular to the direction of H, thus the large needle-shaped domain with an opposite direction relative to the dominant **M** orientation becomes larger. Such interacting cross-tie walls were also found in results obtained from a similar dynamic evolution with $H=-30$ Oe (not shown here), as well as in 180° domains formed in an Fe film onto a surface-roughness modulated Si substrate.[12] The zigzag folding structures of local **M** orientations shown outside as well as inside the two cross-tie walls are a consequence of the alternating arrangement of vortex and antivortex, as shown in Fig. 2(a). It is evident that the formation and development of the cross-tie walls are associated closely with the dynamic evolutions driven by vortex–antivortex pairs through their creation and propagation.

For the case of $H=-10$ Oe shown in Fig. 2(b), the areas of local **M** oriented along the direction of H become broader, and then more complex domain features appear. Next, we stress the dynamic evolution of the vortex–antivortex pairs originally present at the initial state and cross-tie walls at domain boundaries. The domain and/or domain–wall structures are associated with the evolution of vortex and antivortex pairs driven by their interactions. These subtle features are somewhat affected by the shape effect of a finite dimension as well as the fixed **M** configuration that were inevitably introduced in such micromagnetic modeling as mentioned earlier. From the image taken at $t=84.4$ ns in Fig. 2(b), it is also found that many subtle domain structures near the edge of the finite dimension are caused by the pinning as well as the creation of a number of vortices near the edge, which are influenced by the fixed **M** in the outermost region III. However it is certain that the existing vortex and antivortex, and their propagation, annihilation, and creation can dominate the aspect of **M** dynamic evolutions, and hence affect the resultant **M** reversals and static domain and domain–wall structures.

Also, the evolution features of clearly defined cross-tie walls are quite interesting, as displayed in Fig. 3(a). These images definitely show how the cross-tie wall is formed and developed in series at the boundary between two different dominant domains in a continuous thin-film system, through the formation, propagation, and annihilation of many vortex–antivortex pairs. As shown in Fig. 3(b), the periodic arrangement of the alternating vortex and antivortex evolves with time. Some of those vortex–antivortex pairs disappear faster than others through the annihilation of each pair. Near the end of the evolution, all the pairs disappear, yielding that local **M** are all changed to be aligned along the direction of H (i.e., a saturated state). We also notice that the cores of some vortices remain fixed at certain positions where they are initially formed, which are likely to be pinned until they disappear. This seems to be influenced by the subtle features of surrounding magnetic microstructures.

The various static features of a cross-tie type wall have been observed experimentally in magnetic films of intermediate thickness regimes and well predicted in reduced dimensions using micromagnetic modeling.[2,13] Also, **M** reversals are believed to be dominated simply by coherent/incoherent rotations of **M** or by the movements of domain walls in continuous thin films, according to theoretical and experimental studies. On the contrary, we have found not only unexpected features of vortex and antivortex pairs present at the front of growing needle-shaped domains, but also vortex–antivortex assisted dynamic **M** reversals in continuous films. The interactions of two cross-tie walls facing each other and their dynamic developments are clearly found in light of the creation, propagation, and annihilation of vortices and antivortices in a semicontinuous thin-film model system. To conclude, from the present micromagnetic simulations as well as the previous experimental observation of a vector image of vortex and antivortex pairs it is manifested that vortex–antivortex pairs can play a crucial role in **M** dynamic evolutions in continuous thin-film systems. This work provides deeper insights into the microscopic understanding of **M** reversals, and additional features as well as more details of magnetic microstructures typically observed in real continuous films.

This work was supported by the KOSEF through the q-Psi at Hanyang University.

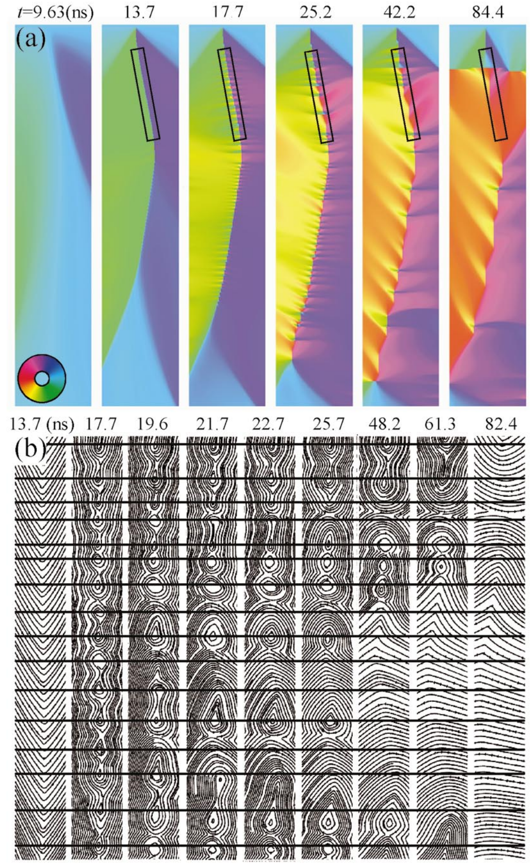

FIG. 3. (Color) (a) Enlarged images for the area marked by "A" in Fig. 2(b), showing the dynamic evolution of cross-tie walls at domain boundary. (b) A streamline representation of the dynamical evolution of the cross-tie wall shown in the area marked by a rectangle in (a). The horizontal straight lines are shown to compare the positions of the cores of dynamically evolving vortices and antivortices.

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[8]The large cell size was used in the model simulations for several following reasons: (1) The fine feature of vortex and antivortex states and their interacting signature were observed in experiments even with a spatial resolution (approximately 200 nm) much greater than the typical exchange length of 4.8 nm. (2) The number of cells used for such a large-scale thin-film model system reaches a limit of the computing power so that simulations with a smaller cell size are likely to be impossible. (3) If the cell size were reduced more with holding the cell number, the results of this simulation would be influenced by the size effect of a finite dimension associated with a nonlocal magnetostatic interaction.

[9]The negligible anisotropy constant has been typically used in model systems such as a polycrystalline thin film having a large exchange interaction and a random distribution of magnetic anisotropy.

[10]The major structures obtained with $\alpha=0.5$ are not much different from those with $\alpha=0.01$, but with the smaller α we also obtained different time scales and fine structures being associated with spin waves.

[11]We also carried out similar micromagnetic simulations with $H=-1$ and -30 Oe, but the results are not shown here due to the limitation of this journal length.

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