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Polarity reversal of a magnetic vortex core by a unipolar, nonresonant in-plane pulsed magnetic field

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We report the polarity reversal of a magnetic vortex core using a nonresonant in-plane pulsed magnetic field of arbitrary waveform studied using time-resolved x-ray photoemission electron microscopy and micromagnetic simulations. The imaging and simulations show that a 5 mT pulse, higher than the critical field for nonlinear effects, effectively leads to the randomization of the vortex core polarity. The micromagnetic simulations further show that the onset of stochastic core polarity randomization does not necessarily coincide with the critical reversal field, leading to a field window for predictable core reversal. © *2009 American Institute of Physics*.
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The rich and fascinating dynamics of magnetic vortices in micron- and submicron-sized ferromagnetic disks have been of great interest because they not only offer insights into fundamental magnetization processes but also have potential applications in nonvolatile data storage.[1] A magnetic vortex is a three-dimensional spin structure that consists of a circulating in-plane magnetization and an out-of-plane vortex core. The vortex can have two chiralities, clockwise or counterclockwise, and the vortex core can have two polarities, up ($p=1$) or down ($p=-1$), making it attractive for information storage. To reverse the core polarity directly with a field applied along the core polarization direction (perpendicular to the disk plane) would require prohibitively large fields of up to 0.3 T. However, the vortex state has a fundamental excitation mode corresponding to the in-plane gyrotropic motion of the vortex structure about its equilibrium position that provides a lower-field route to core reversal via *in-plane* field excitation.

This mode is manifested in the resonantly excited motion of the vortex core, as well as its free motion after a perturbation from its equilibrium position. The gyrotropic motion of the core is therefore connected to its polarity through nonlinear dynamical effects that are evident when the core is displaced far from the disk center. Van Waeyenberge *et al.*[2] recently showed that the core in 1.5 μm Permalloy ($Ni_{80}Fe_{20}$) squares can be reversed with an in-plane field of only 1.5 mT. Later, Yamada *et al.*[3] demonstrated current-induced core reversal in 1-μm-diameter Permalloy disks using a spin polarized ac. In these two cases, reversal was observed for rf excitation close to the translational-mode eigenfrequency. However, theoretical work[4–6] and experiments[7,8] suggest that nonresonant pulsed excitations also promote core reversal.

In this letter, we report the polarity reversal of a magnetic vortex core by a unipolar in-plane magnetic field pulse train with the pulse frequency well below the resonance frequency. Using time-resolved x-ray photoemission electron microscopy (TR-PEEM), we determined the vortex core polarity by imaging the sense of the free vortex core gyration in 6-μm-diameter Permalloy disks after a 1 mT field pulse. We demonstrate that the core polarity can be switched back and forth by pulsing at 5 mT. We also performed both TR-PEEM imaging and micromagnetic simulations on the vortex dynamics in Permalloy disks pulsed at 5 mT to explore the vortex core reversal mechanism. This work confirms that core polarity reversals linked with nonlinear magnetization dynamics can be achieved using arbitrary waveforms, that resonant excitation is not necessary, and that stochastic effects play a non-negligible role for high excitation fields.

The TR-PEEM imaging of Permalloy disks of diameter $2R=6$ μm and 30 nm thickness, patterned on top of a gold coplanar waveguide, was performed at the soft x-ray circularly polarized beamline (4-ID-C) in sector 4 of the Advanced Photon Source. The TR-PEEM images were obtained at the Ni L_3 resonance (852.7 eV) by an Omicron-Focus PEEM in a pump-probe arrangement with ~100 ps temporal resolution. More details about the sample fabrication and TR-PEEM experiments can be found in previous publications.[9,10]

The vortex core polarity of the magnetic disk was determined by watching the sense of the undriven gyrotropic core motion from the TR-PEEM images after the removal of an in-plane field below the critical amplitude for core reversal. Previously we determined the critical field for the onset of nonlinear effects to be ~2.5 mT, therefore we chose the magnitude of the detecting field to be 1 mT.[11] The initial core polarity was determined to be *up* from the TR-PEEM images taken right before or shortly after the falling edge of the field pulse, as shown in Fig. 1(a). We then pulsed the disk with a pulse train of magnitude $h_x=5$ mT (pulse duration=75 ns, fall time=185 ps, and repeat rate=6.53 MHz) for 2 s and checked the core polarity by taking the TR-PEEM images with 1 mT pulses. The core polarity remained in the up direction. Subsequent tests with a 5 mT pulse train resulted in *down* [as shown in Fig. 1(b)], down, and up [Fig. 1(c)] polarities. Thus, we have demonstrated that the core polarity can be switched back and forth by pulsing at 5 mT.

In order to explore the mechanism of the vortex core reversal, we examined the behavior of the magnetic vortex in the first several nanoseconds after removal of the 5 mT field

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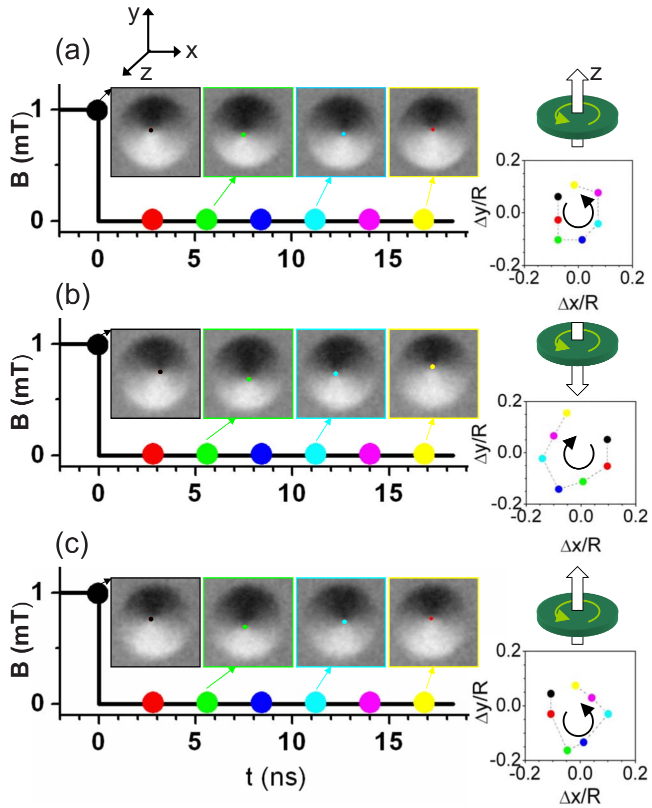

FIG. 1. (Color online) Experimental results of magnetic vortex core polarity reversal. The initial core polarity was up, determined from the sense of the vortex gyration revealed by the TR-PEEM images taken with 1 mT field pulses [panel (a)]. The core polarity was reversed to down polarization after pulsing at 5 mT for 2 s for the second time [panel (b)]. The core polarity was switched back to up polarization after the fourth pulse train.

pulse in more detail. The experimental data were compared with micromagnetic simulations where the Permalloy disks were represented using the following material parameters: saturation magnetization $M_s=8.0\times10^5$ A/m, exchange stiffness constant $A=1.3\times10^{-11}$ J/m, and the magnetocrystalline anisotropy was neglected. The damping parameter of $\alpha=0.01$ and a gyromagnetic ratio of $\gamma=1.76\times10^2$ GHz/T were used for simulations after removing $h_x=5$ mT. The top row of Fig. 2 shows the PEEM images and the second row shows the corresponding simulated images of spin distribution calculated for a disk of the same size using cells of 6×6 nm^2. In both sets of images the gray level represents the magnitude of the x component of magnetization M_x. The simulated cross-sectional plots of the out-of-plane component of magnetization M_z along the y direction are shown in the bottom row of Fig. 2.

The simulated results agree well with the PEEM images. Just before the falling edge of the 5mT field pulse (Fig. 2, 0 ns), the vortex core is displaced far from the disk center with a core of positive polarity. At $t=0.4$ ns (Fig. 2, 0.4 ns), the simple vortex structure breaks down and is replaced by a complicated domain state in which there are two central gray regions symmetric with respect to the y-axis and a narrowed dark triangular area at the lower part of the disk. The cross-sectional plot reveals that the vortex core is replaced by a series of cores of both positive and negative polarities. At 0.6 ns (Fig. 2, 0.6 ns), the top vertex of the lower dark triangular area moves downward, forming an elongated cross-tie domain wall along the y-axis. At 0.8 ns (Fig. 2, 0.8 ns), the wall shrinks and the top vertex of the lower dark triangle moves upward. Finally, a new vortex of a negative polarity is reformed at 4.8 ns (Fig. 2, 4.8 ns). Figure 3 shows the simulated vortex core evolution in more detail, confirming the appearance of the elongated domain wall (>1 μm long) within ~0.5 ns of removing the pulse. This transient domain state results from the large distortion of the core region when the core is displaced beyond $0.25R$.[11] It should also be noted that the polarity of the new vortex appears to be effectively *uncorrelated* with the original polarity. Therefore, the observed polarity of the new vortex can be either be

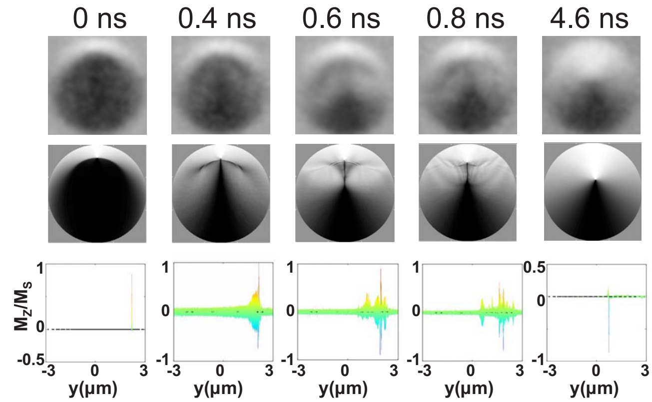

FIG. 2. (Color online) Transient domain states observed both in experiment and simulation shortly after the falling edge of a 5 mT excitation pulse (removed at time $t=0$ ns). The experimental PEEM images (top row) agree well with the micromagnetic simulations (second row). The cross-sectional plots of M_z along the y direction (bottom row) reveal that the vortex core is replaced by a complex cross-tie domain wall consisting of a series of cores of both positive and negative polarities.

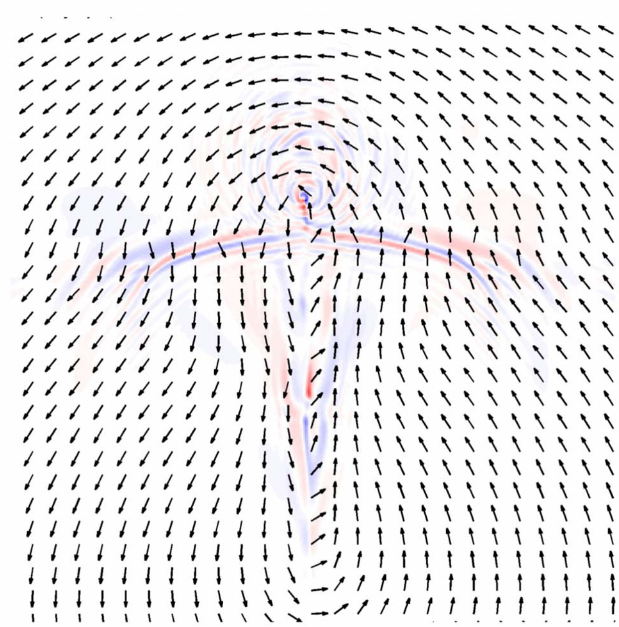

FIG. 3. (Color online) Simulated domain wall evolution in a 6 μm disk. Sequence shows the detailed evolution of the central domain wall region for the first 6.6 ns. This simulation is for a 6-μm-diameter disk excited by a 5 MT pulse amplitude with 200 ps fall time and other simulation parameters are the same as described in the manuscript. The movie is zoomed into a 2.5×2.5 μm^2 area centered along the x direction, shifted up by 1.5 μm in the y direction. The red and blue represent the magnitude of the magnetic moment along + and $-z$, respectively. (Enhanced online.) [URL: http://dx.doi.org/10.1063/1.3111430.1]

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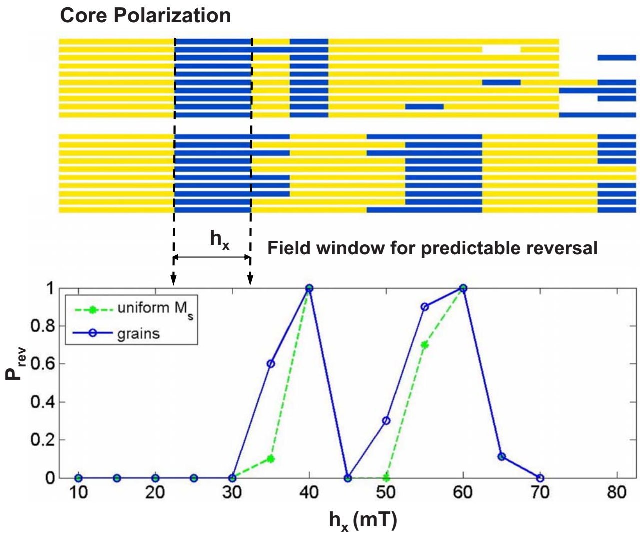

FIG. 4. (Color online) Micromagnetic simulations of core reversal probability for a 500-nm-diameter, 30-nm-thick $Ni_{80}Fe_{20}$ disk at $T=300$ K using ten different random seeds. The top panel shows whether the core polarity changed (yellow/light) or stayed the same (blue/dark) on the rising and falling edges of the pulse. White indicates an undetermined (multivortex or expelled vortex) state. The lower panel summarizes the overall probability of core reversal P_{rev} as a function of the field pulse amplitude h_x excluding undetermined states.

up or down after applying the 5 mT field pulse train, which agrees well with our experimental core reversal result.

Since our experimental results and simulation with $h_x = 5$ mT suggest that there is a stochastic component to the core reversal, we investigated the statistical probability of core reversal by running simulations with thermal effects included ($T=300$ K) using ten different random seeds. To achieve reasonable computing times, the simulations were done for a 500-nm-diameter disk and 30-nm-thick (2×2 nm^2 cells) disk. Grains of 17 ± 5 nm in size were incorporated into the simulations, where M_s was allowed to vary by 5% between grains, as was the uniaxial anisotropy with magnitude of 1000 $erg/cm^3 \pm 10\%$ and random in-plane orientation. Figure 4 summarizes the simulation results, where the core polarity state after the rising and falling edges of the pulse are shown in the top panel and the reversal probability averaged from the ten seeds is plotted in the lower panel as a function of the pulse field. Based on the relative critical radii and fields, h_x in Fig. 4 should be scaled by ~ 0.1 for direct comparison with the experiment. The simulations indicate that there is a narrow h_x window over which the vortex core reversal is predictable, as indicated in Fig. 4. However, for the computed fields there is one core reversal on the rising edge and another reversal on the falling edge, so there is no net change in polarity. At higher h_x (30 mT), randomization of the core polarity is observed although instead of a steady reversal probability P_{rev} of 0.5, P_{rev} is quasiperiodic in h_x over a wide field range. This may be due to the fact that core reversal is actually the result of a series of reversal events as it travels the length of the domain wall (see Fig. 3) leading to a preferred polarity for a given h_x and step edge. Stochastic effects are less pronounced when grains are omitted. With a careful design of the excitation pulse magnitude, it should be possible to achieve controlled polarity reversal by a nonresonant in-plane magnetic pulse field experimentally.

In conclusion, by using TR-PEEM we have studied the polarity reversal of a magnetic vortex core in a 6 μm Permalloy disk excited by a nonresonant in-plane magnetic field pulse train of 5 mT. For large pulse amplitudes, there is a stochastic component to the reversal and the achieved polarity is quasirandom, a process that is related to the distortions of the core region that occur when the core is displaced beyond 25% of the disk radius. These results show that the core polarity may be controlled via an in-plane field of moderate strength and arbitrary time profile although careful choice of h_x is necessary to minimize stochastic randomization, which will have significant implications for the use of the vortex state in magnetic devices.

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