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Dynamic switching of the spin circulation in tapered magnetic nanodisks

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Magnetic vortices are characterized by the chirality of the curl of the magnetization and the polarity of the vortex core. This leads to four possible stable magnetization configurations that can be utilized in a multi-bit memory cell. Ultrafast control of vortex core polarity has been shown using both alternating and pulsed magnetic fields and currents. Here we demonstrate ultrafast switching of vortex chirality using nanosecond field pulses by imaging the process with full-field x-ray transmission microscopy. The dynamic reversal process is controlled by far-from-equilibrium gyrotropic precession of the vortex core and the reversal is achieved at significantly reduced field amplitudes when compared to quasi-static switching. We further show that both the field pulse amplitude and duration required for efficient chirality reversal can be controlled by selection of the disk geometry.

Magnetic vortices are curling magnetization structures which represent the lowest energy state in sub-micron size magnetic disks or polygons [Hub98]. The flux closure character is exchange-compensated by a singularity in the disk center, the vortex core [Shi00, Wac02]. The vortex state is characterized by the chirality of the magnetization curl, either clockwise or counterclockwise (c=+1 or -1), and the polarity of the core, which points either up or down (p=+1 or -1) perpendicular to the film surface. These two characteristics determine the response of a vortex to the application of magnetic field or electric current [Cho04].

When excited by a fast-rising magnetic field or spin-polarized current, vortices exhibit a rich variety of fundamental dynamic behaviors inherent in chiral structures [Gus02, Nov02a, Par05, Buc07, Ant09, Ish06, Pri07, Ruo09]. In general terms, the vortex magnetization distribution represents a magnetic topological soliton [Kos90] and features low-frequency precessional modes [Gus02, Buc07], associated with the translational motion of the core. The precessional mode has been a subject of a considerable interest, with applications in oscillators [Pri07, Ruo09] and resonant amplification of gyrotropic precession at low-field [Wae06] or low-current [Yam07] excitation.

Due to their multiple stable ground states, vortices have been studied as potential multi-bit memory cells [Boh08, Nak11, Got11]. This application requires independent control of both the chirality and polarity. The polarity can be reversed by applying a quasi-static out-of-plane magnetic field, although its magnitude is quite large, on the order of 0.5 – 1.0 T [Kik01]. However, fast stimuli can lead to much more efficient core polarity switching. Using magnetic field [Wae06, Her07] or current [Yam07], the vortex core can be driven into precession and the core polarity reversed as soon as the core reaches a critical velocity [Yam07, Gus08]. The polarity reversal involves the creation and annihilation of a vortex-antivortex pair, followed by formation of a core with the opposite polarity. The switching occurs in less than 100 ps [Her07, Xia06].

Unlike switching core polarity, controlled switching of vortex chirality with magnetic fields requires displacing the vortex core out of the disk and then reforming the vortex with the opposite chirality. The former can be done by using a quasi-static magnetic field B_{an} which annihilates the vortex by expelling the core out of the disk. The latter can be done either by exploiting an asymmetry in the structure shape [Sch01, Yak10, Jaa10] or in the spatial distribution of the magnetic field [Gai08, Kon08, Yak11] to control the chirality of the vortex that forms as the field is removed. Symmetry breaking in vortex creation can also be achieved by interfacial effects, such as exchange biasing [Tan09] or the Dzyaloshinskii-Moriya interaction [Im12]. Other approaches have been proposed based on spin-transfer torque [Cho07] or dynamic evolution of the C-shaped magnetization states after expelling the vortex core [Ant09]. Until now, control of vortex chirality has only been experimentally demonstrated under static conditions.

The ultrafast character of vortex polarity switching suggests the possibility of switching vortex chirality on similar timescales and selective control of both polarity and chirality. In this paper we show that far-from-equilibrium gyrotropic precession enables dynamic switching of vortex chirality and substantially decreases B_{an} compared to static conditions. This annihilation field reduction resembles the reduction of switching fields in Stoner-Wohlfarth particles [Sto49] by precessional reversal using fast-rising magnetic field pulses [He94]. In the present case, the lower bound of the time required for chirality switching is determined by the gyrotropic eigenfrequency of the vortex core motion which is determined by the disk geometry [Gus02].

Permalloy disks of different widths and thicknesses were excited either by applying in-plane magnetic field pulses created by current pulses in a waveguide or by externally applied static magnetic fields. The details of the sample and waveguide are shown in Fig. 1. Magnetization states were imaged with full-field magnetic soft x-ray transmission microscopy (MTXM) at the Advanced Light Source, BL 6.1.2 (see Methods). The images in Figs. 1 and 2 were taken in remanence, before and after field application.

Figures 2a-c show the response of 510-nm-wide and 20-nm-thick disks (subsequently referred to as "510/20 disks") to a static magnetic field at increasing amplitudes. Before applying the magnetic fields, the vortex chiralities were random (not shown). Figure 2a illustrates the situation after applying a negative field of 90 mT. Upon increasing the field amplitude in the positive direction, there is a threshold above which the vortex chirality of the individual disks is successively switched (Fig. 2b), indicating a distribution in static vortex annihilation field, $B_{an\text{-}stat}$. Prior to reaching $B_{an\text{-}stat}$, the vortex core moves to the side of the disk and finally annihilates when $B_{an\text{-}stat}$ is reached [Gus01a], see also Fig. 3c. Finally, a positive field of 34 mT results in switching of all the chiralities in the opposite direction (Fig. 2c). Similar images for 250/20 disks are shown in Figs. 2d and 2e which have $B_{an\text{-}stat}$=51 mT. The measured values of $B_{an\text{-}stat}$ for different disk geometries are listed in Table 1 and are taken as the field at which 50% of the vortex chiralities have switched.

Figure 2g shows the magnetic states of the 250/20 disks after applying a 1000-ps pulsed field to initiate dynamic switching. The dynamic annihilation threshold field ($B_{an\text{-}dyn}$) was only 26 mT (Fig. 2g) which is roughly half $B_{an\text{-}stat}$. This significant decrease of the field amplitude was observed for different disk geometries (see Table 1) with ratios $B_{an\text{-}dyn}/B_{an\text{-}stat}$ varying from 0.44 to 0.59.

While we see a significant reduction in the switching field with pulsed current, there is a lower limit to the pulse duration where switching is not observed or requires higher fields. In 250/20 disks, the switching was only observed for pulses of 1000 ps (Fig. 2g) or longer (Fig. 2h). The minimum pulse durations required for the chirality switching are summarized in Table 1 (column $t_{s,}$ switching time) and plotted in Fig. 3a (blue triangles) for the different 20-nm-thick disks.

Using opposite field pulse polarity, the magnetization in the disks relaxes with opposite chirality (see Supplementary Fig. 1). Moreover, all the disks relax to the same chirality for sufficient vortex annihilation fields and pulse durations. As identical results with respect to the field polarity were obtained for both static and pulsed fields, purely dynamic effects can be ruled out. Edge roughness and lithography defects breaking the circular symmetry of the disks would be a natural explanation for the symmetry breaking, but the final chirality was the same in all the disks of the chain even in samples with different disk geometries.

Our observation can be explained by a slight variation in the disk thickness at the disk boundary. As the disks were sputtered by directional ion-beam sputtering over a resist pattern (see Methods), such an asymmetry arises due to a shadowing effect and is reproduced in all the disks on the waveguide. Note that a small induced uniaxial anisotropy might also be present, but this cannot explain the symmetry breaking in the chirality creation. While magnetic dipolar interaction between the disks can be neglected when the disks are in a vortex state, it can become significant when the disks reach the monodomain state after vortex annihilation [Cow99, Nat02]. However, this effect cannot provide an explanation for the formation of the same vortex chirality in the long chain of disks we are studying.

The trends we observe can be explained by analytical models describing vortex dynamics. The magnitude of the static annihilation field can be determined using the rigid-core model [Gus01a, Nov01]. It satisfactorily predicts the annihilation fields for a wide range of L/R, where L is the disk thickness and R its radius. A static magnetic field moves the vortex core to a new equilibrium point (Fig. 3c) which is at a distance s from the disk center: $s=R*\chi*H/M_S$ [Gus01a, Gus02] where χ is the static susceptibility of a vortex, H the magnetic field intensity and M_S the spontaneous magnetization of the material. Due to a flux-closing magnetization configuration in vortices, their annihilation requires expelling the vortex core out of the disk, i.e. when $s=R$.

Core annihilation is qualitatively different when using pulsed magnetic fields with a rise time much shorter than the period of the translational vortex eigen-oscillation [Gus02]. Applying such a pulse causes the vortex core to gyrate about an equilibrium point determined by the amplitude of the pulse. The trajectory of the vortex core is approximately circular (Fig. 3d, solid line), if the nonlinearity of χ for $s/R \rightarrow 1$ is neglected. The speed of chirality switching is determined by the time needed to expel the vortex core from the disk. The switching is most efficient when the core is annihilated during the first half-period of the oscillation. In this regime the influence of damping on the core trajectory can also be neglected [Gus02] and the threshold $B_{an\text{-}dyn}$ corresponds to $s=R/2$. In this case, the model predicts $B_{an\text{-}dyn}=B_{an\text{-}stat}/2$ which is close to our experimental observations. Note that the measured $B_{an\text{-}stat}$ values listed in Table 1 include any possible deviations from the expected values due to sample imperfections.

The gyration eigenfrequency ω_0 can be used to estimate the lower limit of the switching time (see Fig. 3a, solid line) and is well described by the pole-free model in the linear vortex susceptibility regime [Gus02]. We observe experimental values that are larger by an offset roughly decreasing with the disk radius. This offset is a result of our finite pulse rise time (~500 ps, see Methods). The experimental core frequency was also found to be lower than predicted for high-aspect-ratio disks [Par03]. The model's neglect of core annihilation at the disk boundary has a small effect on the actual switching time.

We have not yet considered the stability of core polarity which can limit efficient expelling of the vortex core. Polarity reversal inverses the sense of core gyration [Cho04] and can prevent it from reaching the disk boundary. This effect is similar to Walker breakdown in domain wall motion in nanowires [Hub98]. A moving vortex core loses its rigid character [Doe48] as the kinetic energy is accumulated in the core deformation and the corresponding effective field might eventually flip the polarity [Yam07, Gus08]. Polarity switching occurs when the core velocity v_c reaches a critical value v_{crit} which depends only on intrinsic parameters of the disk [Gus08]. Simulations show this becomes an issue for relatively thick and large disks. In the first approximation, assuming $B=B_{an\text{-}stat}/2$, a circular core trajectory (linear regime) and constant ω_0, the corresponding core velocity is $\omega_0 R/2$. Since ω_0 is proportional to L/R in the pole-free model [Gus02], v_c depends only on the disk thickness L. Assuming the material parameters of our disks (see Methods), L=20 nm yields v_c=320 m/s which is below the calculated value v_{crit}=347 m/s [Gus08].

A more quantitative understanding requires going beyond the rigid-core model. As the core approaches the disk boundary, the vortex susceptibility falls into the nonlinear regime and a realistic dependence of the vortex core displacement *s* on the applied field *B* should be taken into account. Figure 3b shows *s/R* vs. *B* curves illustrating vortex annihilation for 20-nm-thick disks calculated using micromagnetic simulations and the rigid-core model. The simulated initial susceptibility is larger than that one predicted by the rigid-core linear model (dotted lines). The linear regime ends approximately at $s=0.25*R$ which is consistent with the experimental observations [Che09].

When comparing the $B_{an\text{-}stat}$ predicted by the rigid-core model and the simulated one, the model overestimates $B_{an\text{-}stat}$ for small *R* and underestimates $B_{an\text{-}stat}$ for large *R* (see also Supplementary Fig. 2). In the limit of a rigid core, where the exchange energy contribution is neglected [Gus01a], the model satisfactorily describes the core displacement for $s/R \ll 1$ in disks with large *R*. However, larger magnetic poles emerging at the disk edges effectively prevent core annihilation when $s/R \rightarrow 1$. Therefore, nonlinearity in χ becomes significant and $B_{an\text{-}stat}$ is higher than the value predicted by the model. In case of small *R*, vortex annihilation is exchange-dominated due to large magnetization gradients and the structure tends to be single-domain. Hence, $B_{an\text{-}stat}$ is lower than the value predicted by the analytical model.

Due to the nonlinearity in static χ for disks with large *R*, the equilibrium points corresponding to B_{andyn} fields (Fig. 3b, open circles) are further than $0.5*R$ for disk diameters of 500 nm ($\approx 0.65*R$) and 1000 nm ($\approx 0.75*R$), assuming a field amplitude of $B_{andyn}=B_{anstat}/2$ in all cases. Therefore, the nonlinearity leads to core trajectories that are close to elliptical (Fig. 3d, dashed lines), as has been observed experimentally [Che09]. Although ω_0 can be considered constant during the initial core motion in the linear region [Dus12], v_c increases with the distance between the core and the equilibrium point and might reach v_{crit} in large disks. This possibility is confirmed by simulations. For the 500/20 and 1000/20 disks, the core reached a velocity above 400 m/s within the first 30 ps of motion, leading to the polarity switching. In 250/20 disks the polarity was conserved and the core was expelled.

In the experiment the chirality was switched by pulses in disks up to 30-nm thick and 1.1-μm in diameter. This is not expected based on the analytical model or simulations and can be explained by the positive effect of finite rise time. Figure 3e schematically shows the core gyrating about a moving equilibrium point, when the rise time is comparable to the period of the core eigen-oscillation. The core follows a cycloidal trajectory and the instantaneous distance between the core and the equilibrium point is decreased. Consequently, the amplitude of the pulse has to be increased above $B_{anstat}/2$ to expel the core.

To gain further insight into vortex annihilation and subsequent chirality switching, pump-probe stroboscopic imaging was performed. A unipolar field pulse was applied to the sample containing 1040/20 disks at a repetition rate of 3.05 MHz. It was verified that the magnitude of the pulse was sufficient to switch the vortex chirality in the disk. However, in the experiment the same final chirality was maintained in each imaging cycle. Figure 4a shows stroboscopic images of the vortex annihilation (images 1-4, left column) during application of a field pulse plotted in Fig. 4b. The images in the right column of Fig. 4a were produced by micromagnetic simulation to qualitatively explain the observed magnetic contrast.

The vortex cores follow part of a cycloidal trajectory since the rise time (4 ns) is comparable to the eigenoscillation period (5.1 ns for 1040/20 disks). The symmetric magnetic contrast of two vortex core trajectories apparent in the images 2-4 correspond to two opposite polarities of the vortex core (red and green dots), since the core polarity defines the sense of the core precession [Cho04]. The acquired images represent an average of a multitude of cycles. We conclude that core polarity is not on average conserved during the annihilation-nucleation process. If vortex core polarity was conserved, only one trajectory would be observed. The images also directly confirm that the core is expelled during the field pulse. The two core trajectories are schematically illustrated in Fig. 4c. Stroboscopic images of the precession of a vortex core with constant polarity are shown in Supplementary Fig. 3.

In summary, we have demonstrated controllable vortex chirality switching with nanosecond field pulses. The results are explained by analytical models and micromagnetic simulations, highlighting the underlying phenomena controlling both the time and field scales for switching. Efficient reversal of vortex chirality is controlled by the nanodisk geometry. Importantly, scaling down the disks accelerates vortex chirality switching. Following predictions of the analytical model, the switching time can be shortened to 250 ps for 100/20 disks. The limit is set by the transition of a vortex to a monodomain for NiFe disks smaller than 100 nm [Chu10]. In the presented experiment we observed random core polarity nucleation upon chirality switching. The core polarity could be controlled by an out-of-plane field bias [Jaa10] or even directly using a pulse with an out-of-plane field component. Alternatively, the core polarity can be subsequently adjusted using a feedback loop, as choosing the right geometry of the disks along with the field pulse parameters enables selective polarity switching. Our results indicate a path to the independent control of all four vortex states on sub-nanosecond timescales.

Methods

Sample preparation and experimental set-up. Gold-capped permalloy ($Ni_{80}Fe_{20}$) nanodisks with diameters in the range of 250-1100 nm and thicknesses of 20 and 30 nm were patterned into linear arrays (see Fig. 1a), by electron beam lithography and lift-off processing. The Au capping layer was 2 nm thick. Deposition of the NiFe thin film on a 500-nm-thick polymethyl methacrylate (PMMA) mask was done by directional ion beam sputtering with the sputtered particles incident at 15° from the film normal. Shadowing by the PMMA mask led to a slight thickness asymmetry at one side of the disks (see Fig. 1b). The variation of the disk thickness was the same in all the disks within the sample. Magnetic field pulses were applied by passing a current through a gold waveguide carrying the disks, made by lift-off and subsequent trimming to a desired width (0.8-2.2 μm) by a focused ion beam. The entire structure was fabricated on a 200-nm-thick SiN membrane to ensure transparency for soft x-rays.

Current pulses in the waveguide were generated using a fast pulse generator (Picosecond Pulse Labs 10,050A) with a nominal risetime of 45 ps. The pulses were passed through the sample and recorded on a 4-GHz oscilloscope (LeCroy WaveMaster 804Zi-A). The recorded rise time was approximately 500 ps, longer than the nominal value due to pulse distortion in the waveguide. Time-resolved experiments were carried out using a different pulser (Agilent 81150A), providing a rise time of 2 ns, but allowing a repetition rate of 3.05 MHz required for pump-probe imaging. The recorded pulse shape is shown in Fig. 4b.

Magnetic imaging. Magnetic full-field transmission soft x-ray microscopy (MTXM) experiments were performed at beamline 6.1.2 at the Advanced Light Source (ALS), Berkeley, USA [Fis06]. The spatial resolution of 25 nm is determined by the Fresnel-zone plates. Magnetic contrast was obtained using X-ray magnetic circular dichroism (XMCD), giving absorption coefficients proportional to the projection of the magnetization on the direction of the incoming x-rays. The sample was oriented at 60° with respect to the x-ray beam to measure the in-plane magnetization component. Each image was acquired for one circular polarization at the Fe L_3 edge (707 eV). The contrast was further enhanced by dividing the image by a reference image containing all vortices with the same chirality or a reference at saturation (indicated in the Figure labels). The presented images were processed by band-pass filtering using the ImageJ program to remove spatial frequencies higher than 0.5 px^{-1} (resolution limit) and smaller than 0.017 px^{-1} (background removal).

The time-resolved experiments were based on a pump-probe technique enabling stroboscopic imaging of reproducible events [Kas08]. The time structure of the ALS in 2-bunch mode operation allows synchronizing field pulses (pump) with the x-ray photon flashes (probe) and recording the temporal evolution of the magnetization in the nanodisks for different delays between the field pulses and photon flashes. The temporal resolution is given by the length of the photon flashes (70 ps), arriving to the sample separated by 328 ns. The total acquisition time for each image is 120 s (480 s – Suppl. Fig. 3), i.e. about $3.7x10^8$ ($1.5x10^9$ – Suppl. Fig. 3) events are averaged.

Micromagnetic simulations were carried out using the OOMMF code [Don99]. The nanodisks were discretized with a cell size of 4x4x4 nm^3. Zero magnetocrystalline anisotropy and an exchange constant of A_{ex}=10 pJ/m typical for NiFe were used. The damping parameter α, spontaneous magnetization M_S and gyromagnetic ratio γ were determined experimentally using ferromagnetic resonance on blanket film samples, with values: α=0.0072, M_S=690 kA/m and γ=2.09x10^{11} rad*Hz/T. The M_S value was verified by vibrating sample magnetometry.

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Author contributions
V.U. and M.U. designed and planned the experiment, M.U. and L.H. fabricated the samples. V.U., M.U., J.S. and T.Š. performed the experiments with help from M.-Y.I., P.F., N.E. and J.J.K. V.U. and M.U. carried out the micromagnetic simulations, analyzed the data and prepared the figures. E.E.F. was involved in experimental planning and analysis of the results. V.U. wrote the manuscript which was commented on by all the authors.

Competing financial interests
The authors declare no competing financial interests.

Size (nm) *(diameter/thickness)*	$B_{\text{an-stat}}$ (mT) *(simulated)*	$B_{\text{an-stat}}$ (mT)	$B_{\text{an-dyn}}$ (mT)	$B_{\text{an-dyn}}/B_{\text{an-stat}}$	t_s (ns)
250/20	67	51	26	0.51	1
510/20	53	32	14	0.44	1.5
960/20	39	27	13	0.48	2.5
1000/20	38	29	17	0.59	2.5
1040/20	37	23	11	0.48	2.8
560/30	66	48	22	0.46	2.8
1100/30	46	37	20	0.54	3.5

Table 1 – Static and dynamic annihilation fields for different disk geometries.
$B_{\text{an-stat}}$, $B_{\text{an-dyn}}$ and switching time t_s, indicating the minimum pulse duration where switching was observed, listed for different disk geometries. The average value of $B_{\text{an-dyn}}/B_{\text{an-stat}}$ is (0.50±0.02) mT.

DISCLAIMER

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