



Topological evolution of Multi-Vortex spin textures in amorphous magnetic architectures

Giuseppe Muscas^{a,b,1,*} , M. Venkata Kamalakar^b, Ismael G. Serrano^b, Rimantas Brucas^c, Henry Stopfel^c, Vassilios Kapaklis^{b,3}, Petra E. Jönsson^{b,2,*} 

^a Department of Physics, University of Cagliari, Cittadella Universitaria di Monserrato, S.P. 8 Km 0.700, 09042 Monserrato, CA, Italy

^b Department of Physics and Astronomy, Uppsala University, Box 524, SE-751 20 Uppsala, Sweden

^c Department of Materials Science and Engineering, Box 35, SE-751 03 Uppsala, Sweden

ARTICLE INFO

Keywords:

Magnetic architectures
Magnetic vortex
Multiple vortices
Topological textures
Amorphous materials

ABSTRACT

Advances in understanding exotic magnetic configurations and their complex behavior are paving the way for future technologies based on magnetic nano- and microstructures. In this study, we investigate the evolution of magnetic flux closure configurations in amorphous magnetic architectures using a combination of experimental techniques and advanced micromagnetic simulations. To realize the architectures, an amorphous paramagnetic Fe₈₉Zr₁₁ film is first created by sputtering. Next, boron ion implantation through a mask locally transforms the paramagnetic matrix into embedded ultra-soft ferromagnetic Fe₈₀Zr₁₀B₁₀ disks. With a size of a few micrometers, these disks enable the observation of large-scale flux closure structures by Kerr microscopy. By relating Kerr images and FORC diagrams, we resolve the subtle differences in the nucleation and annihilation fields of the magnetic structures yielding unique signatures for single, double, and multiple vortex configurations. A deeper understanding is provided by a large-scale micromagnetic model, which accurately reproduces the complexity of multi-vortex magnetic textures and enables a comprehensive analysis of their underlying topological properties. Hence, ion-implanted amorphous magnetic architectures can serve as a tunable platform for designing magnetic hardware that leverages topological protection to realize robust, reconfigurable, multi-state magnetic embedded elements for enhanced computational functionality.

1. Introduction

In a magnetic material, the magnetic spins originate from the quantum properties of the material, and the complex interplay between the spins gives rise to size and shape dependent large-scale textures determining the magnetic properties. Advances in the engineering of magnetic materials have resulted in both scientific discoveries and novel technologies [1–3]. It is at the nano- to microscale that the most exotic magnetic phenomena occur and complex topological magnetic configurations, such as vortices, skyrmions, and chiral bubbles, can be stabilized by exploiting the geometrical confinement of engineered mesostructures [4,5]. Among these topological textures, the magnetic vortex represents the simplest yet most versatile configuration [6–14].

The manipulation of magnetic vortices holds great potential in a

wide range of spintronics applications, such as spin-torque oscillators [15,16], for advanced memory components with non-volatile multi-level memory functionality [17,18], and for the integrated memory and logic operations that are needed for neuromorphic computation [17,19,20]. Other applications of magnetic vortices include sensors [21], mechanical actuators [22], and magnetic hyperthermia components [23].

Magnetic vortices are formed in soft magnetic materials shaped as circular disks, if the disks are larger than the critical size for rigid coherent single-domain behavior, but smaller than the size that promotes a multidomain configuration [24]. The size range for vortex formation varies according to the properties of the specific material, and vortices have been observed with a diameter of a few tens of nanometers up to a few micrometers [8,9,25–27]. Typically, topographically

* Corresponding authors at: Department of Physics and Astronomy, Uppsala University, Box 524, SE-751 20 Uppsala, Sweden.

E-mail addresses: g.muscas@unica.it (G. Muscas), petra.jonsson@physics.uu.se (P.E. Jönsson).

¹ <https://orcid.org/0000-0001-7508-0752>.

² <https://orcid.org/0000-0001-9998-0480>.

³ <https://orcid.org/0000-0002-6105-1659>.

patterned disks host a single confined vortex [24,28–30]. The confinement is intrinsically linked to physical patterning, which introduces structural discontinuities such as edges, grain boundaries, and thickness variations. These inhomogeneities are known to influence vortex nucleation, annihilation, and dynamics, often breaking the symmetry of the magnetization configuration [31] and acting as effective pinning sites for vortex cores. Pinning effects can be strongly influenced by local defects and geometric discontinuities [32,33], and this complexity is expected to increase for multi-vortex–antivortex configurations. While a few studies have reported systematic multi-vortex structures [34,35], their reproducible formation in a single element appears to be nontrivial.

An alternative approach to conventional structural patterning is provided by magnetic patterning via high-energy ion irradiation/implantation through a lithographic mask [36]. This approach enables to locally modify the magnetic properties of the material, either by introducing local disorder [36–41] or by modifying the chemical structure of crystalline phases [42–45]. Overcoming the disorder and variability inherent to conventional lithographic patterning, Fe ion implantation enabled high level of structural coherence in an artificial spin ice system [46]. Ion irradiation has been successfully employed in amorphous systems to create patterned magnetic elements, typically through implantation-induced crystallization or stress-mediated anisotropy [47,48]. Recently, magnetically soft and structurally homogeneous amorphous microstructures have been realized by exposing an amorphous $\text{Fe}_{89}\text{Zr}_{11}$ thin film to low energy boron ion implantation through patterned holes in a lithographic mask, creating local regions of $\text{Fe}_{80}\text{Zr}_{10}\text{B}_{10}$ fully embedded in the original matrix. The boron doping slightly increases the atomic Fe-Fe distances [49,50], enhancing the atomic exchange coupling [51] and increasing the Curie temperature (T_C) from 208 K in the original $\text{Fe}_{89}\text{Zr}_{11}$ matrix to 340 K in the implanted parts. Importantly, the implantation process does not introduce any crystallization nor strain [52]; it is thereby possible to avoid structural discontinuities between the matrix and the implanted regions, and the result is a magnetic pattern inside a continuous amorphous film [26]: an *amorphous magnetic architecture*. In contrast to conventional composites, where different phases coexist, or crystalline heterostructures, where interfaces and lattice mismatch dominate the magnetic behavior, this architecture consists of ferromagnetic mesoscale disks patterned directly within an amorphous paramagnetic host without creating structural discontinuities. Moreover, the natural ion straggling induced by the implantation process, produces smooth graded magnetic interfaces [26]. As a result, the magnetic textures are governed primarily by geometrical confinement and exchange-mediated continuity, rather than by extrinsic pinning or interface-driven anisotropies. The key differences between conventional patterning approaches, general ion irradiation/implantation strategies, and the present amorphous magnetic architecture are schematically summarized in Table 1.

In this paper, we investigate the fundamental topological properties of multiple magnetic vortex textures realized by engineering mesoscale

circular disks in $\text{Fe}_{89}\text{Zr}_{11}/\text{Fe}_{80}\text{Zr}_{10}\text{B}_{10}$ artificial magnetic architectures. At room temperature, this amorphous architecture consists of a fully planar structure of ultra-soft ferromagnetic (FM) $\text{Fe}_{80}\text{Zr}_{10}\text{B}_{10}$ disks embedded in the paramagnetic (PM) $\text{Fe}_{89}\text{Zr}_{11}$ matrix [26]. Amorphous disks of different sizes are investigated by combining magnetometry, first-order reversal curves (FORC), magnetic domain imaging via magneto-optic Kerr effect (MOKE), and micromagnetic simulations. A progressive emergence of multiple vortex–antivortex structures with increasing size is observed. Such topologically protected multi-vortex states, where the number and arrangement of vortex–antivortex cores can be tuned by discrete magnetic-field steps, open paths toward emerging magnetic technologies, from high-density, multi-bit magnetic memory [54], to reconfigurable neuromorphic and logic architectures [30,55], or the emerging field of topological-charge-based information processing [56].

2. Experimental section

2.1. Sample preparation

The amorphous series of samples consists of boron-implanted disk elements embedded in a $\text{Fe}_{89}\text{Zr}_{11}$ matrix. A 15 nm thick amorphous $\text{Fe}_{89}\text{Zr}_{11}$ film was deposited by magnetron sputtering on a Si (100) wafer covered by a 5 nm thick amorphous $\text{Al}_{70}\text{Zr}_{30}$ buffer layer to ensure amorphous growth. A final 5 nm $\text{Al}_{70}\text{Zr}_{30}$ capping layer was deposited onto the film to protect it from oxidation. Next, a 200 nm thick Cr mask was deposited, and holes reproducing disks were realized by employing conventional e-beam or photo-lithographic techniques. The sample was doped by scanning the surface with a boron ion flux with an energy of 5 keV and an implantation dose of 2×10^{16} ions/cm², creating implanted regions reproducing the mask, but with smoother edges due to ion straggling [26]. Finally, the mask was removed by chemical etching, leaving a planar sample with $\text{Fe}_{80}\text{Zr}_{10}\text{B}_{10}$ elements embedded in the $\text{Fe}_{89}\text{Zr}_{11}$ matrix. The fabrication method is described in more detail in Ref. [26]. Three samples were prepared, differing in disk diameter: 850 nm, 5 μm , and 20 μm , labelled FZ-850n, FZ-5 m, and FZ-20 m, respectively. The 850 nm disks are arranged in a hexagonal pattern, with a spacing of 1.25 μm between disk edges. The 5 and 20 μm disks are arranged in a square lattice with a lattice parameter equal to twice the disk diameter. More details on the samples are provided in [Supplementary information](#).

As a reference for the magnetic vortex configuration in smaller structures, we report the investigation of soft $\text{Fe}_{13.5}\text{Pd}_{86.5}$ circular disks [57,58]. Each of them has a radius diameter of 450 nm and a mean thickness of 10 nm (Fig. S1). The sample, labelled FP-450n, was grown on $30 \times 30 \text{ mm}^2$ pre-patterned fused silica substrates prepared by surface conformal nano-imprint lithography [58]. The samples were co-sputtered using elemental Fe (99.95 at-%) and Pd (99.95 at-%) targets in an ultra-high vacuum magnetron sputtering system with a base pressure below 2×10^{-7} Pa. Argon was used as the sputtering gas at a

Table 1

Schematic summary comparing conventional lithographically patterned magnetic nanostructures, general ion irradiation/implantation strategies, and the present amorphous magnetic architecture.

Aspect	Conventional patterning	General ion irradiation/implantation patterning	All-amorphous magnetic architecture by ion implantation patterning
Patterning philosophy	Topographic patterning by etching or mask-assisted deposition [8,9,25–27]	High-energy ion irradiation/implantation, causing structural changes (disorder, stress, phase modification) [27,36]	Low-energy ion implantation of small ions causing minimal changes to the amorphous structure yet strongly impacting the magnetic properties [26]
Magnetic inhomogeneity	Dominated by extrinsic defects (edges, grains, stress) [31–33]	Implantation-induced disorder, strain, or compositional variations, mixed with the extrinsic defects of polycrystalline materials [36–45]	Dominated by intrinsic, statistically homogeneous disorder of the amorphous structure [26]
Design implication	Geometry-limited magnetic states [24,28–30]	Non-topographic control via local tuning of magnetic properties. Still, irradiation/implantation-induced inhomogeneities and grain boundaries do influence the magnetic properties [47,48]	Low-energy ion-implantation without conventional structural discontinuities. Magnetic patterning with graded interfaces yielding controlled access to complex and topological magnetic states [26,53][Present work]

pressure of 0.8 Pa. During growth, the sample stage was rotated, and the substrate was kept at room temperature (RT). This resulted in highly uniform polycrystalline disks. The hysteresis loop of this sample exhibits all typical features of vortex formation in the temperature range 100 K to 200 K [58].

2.2. Magnetometry

Magnetization vs field ($M(H)$) measurements of sample FZ-850n were performed in a longitudinal magneto-optical Kerr effect (L-MOKE) setup operating with p-polarized incident light and equipped with an electromagnet. A second setup, equipped with a Helmholtz coil for a precise control of the magnetic field in the range ± 7 mT, and temperature control, was used for all other samples. This setup includes a μ -metal shield reducing the background field to less than 0.002 mT. The laser spot used for the measurements extended over an area of about 7 mm^2 . In all samples, the laser spot illuminated several thousand ferromagnetic elements at the same time. The measurement of each $M(H)$ curve was repeated 100 times and then averaged to improve the signal-to-noise ratio.

The same setups were used to record the individual FORC curves (Fig. S2) of each sample. In a FORC measurement, the sample is saturated in a positive field, then the applied field is reduced to the value H_r (reversal field) and the FORC magnetization (M) is recorded as a function of the increasing measurement field (H_m). Repeating the FORC measurement for different reversal fields H_r , the FORC distribution is given by the second-order mixed partial derivative of M with respect to H_m and H_r :

$$\rho(H_m, H_r) = \frac{1}{2M_S} \frac{\partial^2 M(H_m, H_r)}{\partial H_m \partial H_r} \quad (1)$$

where M_S is the saturation magnetization. If the magnetization reverses throughout multiple events, the use of different H_r will distinguish such events, producing individual signals in the ρ -diagram. Due to the double derivative, only irreversible contributions to the magnetization reversal between different H_r can be detected in the ρ -diagram, with positive and negative signals [59,60]. The analysis of the diagram offers information about the intrinsic distribution of reversal fields and the eventual interactions among the different magnetic components with an individual reversal. The raw data has been used to calculate the FORC distribution using a Matlab code implementing the FORCinel algorithm, which includes a locally-weighted regression smoothing algorithm [53]. For processing our data, we used a smoothing factor of 10. As a reference, the translated coordinates $H_C = (H_m - H_r)/2$, and $H_U = (H_m + H_r)/2$ are also reported in the FORC diagrams.

To evaluate the absolute value of saturation magnetization of the amorphous samples, the $M(H)$ curve of a reference fully implanted sample was recorded at room temperature with a vibrating sample magnetometer (Lake Shore VSM model 7400) in the range ± 50 mT.

2.3. MOKE microscopy

The magnetization reversal process during an $M(H)$ loop was also investigated by recording real-time images of the magnetic domain structures with a commercial magneto-optical Kerr microscope (Evico magnetics) operating with Carl Zeiss optics with different magnifications (20X and 50X) at room temperature. The system was equipped with a low-noise digital CCD camera and an electromagnet. First, a degauss procedure was applied to bring all rings to the ground state configuration. Then, images of the magnetic domains were recorded during a hysteresis loop. The images were recorded by averaging over 16 frames at each field step to reduce the noise. To maximize the magnetic contrast in the images, a background image of each sample was recorded before the measurements while applying an AC field, and then the images were collected using a real-time background subtraction mode. The

images were processed using the software FIJI [61], normalizing the brightness to equalize the middle grey level for the paramagnetic background (matrix) in each image.

2.4. Micromagnetic simulations

To study the magnetic configurations in amorphous samples, we have created a micromagnetic model using Mumax3 [62], an open-source GPU-accelerated micromagnetic software package, which numerically solves the Landau-Lifshitz-Gilbert (LLG) equation using a finite-difference space discretization. We have developed a micromagnetic model extending the patchy model of Mansuripur et al. [31,63,64], based on the concept of random anisotropy [65]. For an amorphous material the atomic structure exhibits a short-range local order. One can identify structural correlation within a distance d on the order of a few atomic spacings. Each structural unit may exhibit random variations in both the direction of their anisotropy axis and, to some extent, the magnitude of the anisotropy constant. Although no structural correlation is observed over medium to long distances, the magnetic exchange coupling can extend over an effective exchange length $L_{\text{eff}} > d$, grouping several structural units into extended magnetically correlated regions. These correlated regions therefore exhibit an effective average anisotropy, characterized by a common easy-axis direction and a reduced anisotropy-constant magnitude [66,67].

Starting from general consideration on amorphous materials and specific examples of micromagnetic simulations [31,63,65,68–70], we defined a range of values for the simulation parameters and tested their combination to find the common set that reproduced the experimental results (hysteresis loop curves and domain configuration) for all the amorphous samples. The effective exchange length L_{eff} was estimated to be $\approx 17 \text{ }\mu\text{m}$, in agreement with the conclusions of Betancourt et al. [69,70]. However, we selected to discretize the micromagnetic problem with cells of about 7, 9, and 20 nm, for the 850 nm, 5 μm , and 20 μm disks, respectively. This gives the resolution to correctly reproduce the curvature of the samples, the patches, and the subtle features of the magnetic domain configurations in each disk. From the refinement process of the parameters, good agreement with the experimental data has been obtained for patches, defined by Voronoi tessellation [71], with an average size of 100 nm. The direction of the easy axis was random in each patch and the mean value of the uniaxial anisotropy constant K_u set to 50 J/m^3 with a 20% standard deviation. The exchange stiffness A_{ex} was 1.0 pJ/m . The values of both A_{ex} and K_u represent reduced effective room temperature ones. The saturation magnetization of the sample has been fixed to the experimental value recorded at room temperature (330 kA/m, Fig. S3) for a reference $\text{Fe}_{80}\text{Zr}_{10}\text{B}_{10}$ fully implanted film sample. The damping constant used for the simulations was $\alpha = 0.01$. Further details on the parameters' refinement are provided in the dedicated section of [Supplementary information](#).

3. Results and discussion

3.1. Conventional vortex configuration

As a reference for the single vortex configuration, we start by investigating a sample exhibiting all typical features of vortex formation, namely an array of soft FM $\text{Fe}_{13.5}\text{Pd}_{86.5}$ circular disks [57,58], labelled FP-450n. Advanced PEEM-XMCD imaging and MOKE magnetometry have previously elucidated the temperature evolution of the vortex nucleation and annihilation in this system [58]. The disks, arranged in a regular square lattice, have a diameter of 450 nm and thickness of 10 nm (Fig. S1). Within the temperature range 100–200 K, the magnetization vs field $M(H)$ curve of this sample exhibits typical features of vortex formation [57]. Fig. 1a shows the $M(H)$ curve measured at 160 K. Following the descending magnetization branch, decreasing the field from the positive saturation state ($S+$) yields a nucleation step (N), where the magnetization suddenly decreases due to

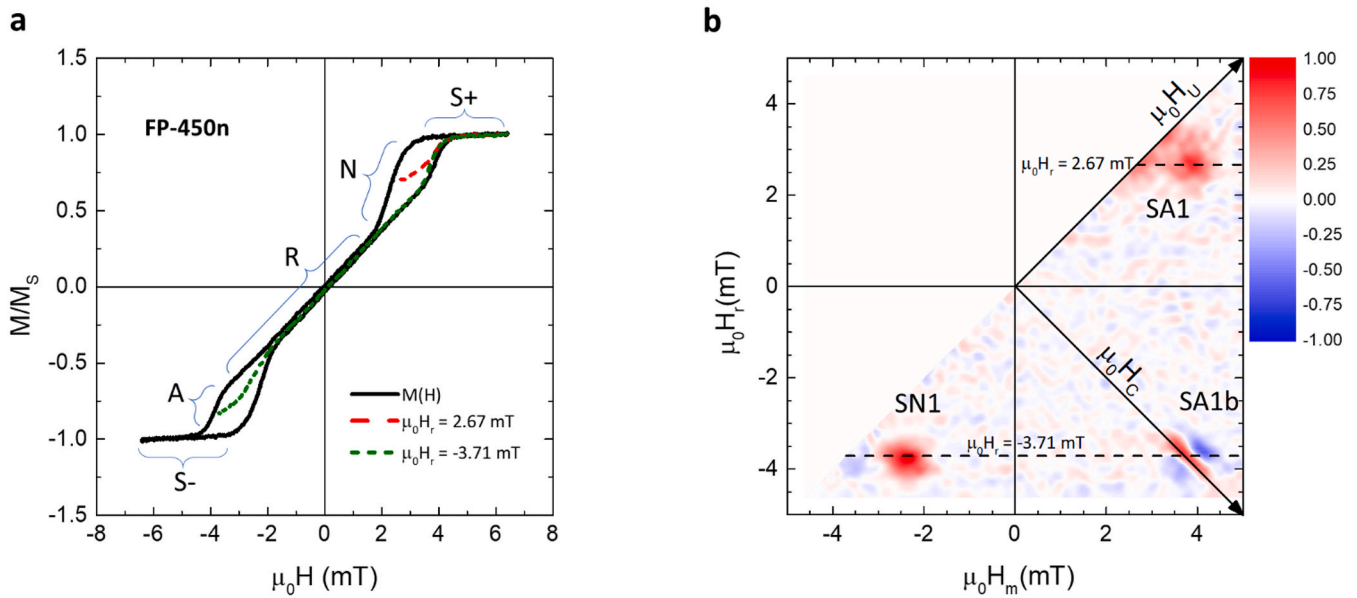


Fig. 1. (a) Magnetization vs field curves $M(H)$ (black continuous line) and selected first-order reversal curves (dashed red and short-dashed green lines) measured with a longitudinal MOKE setup at 160 K for FP-450n. The descending branch is divided into five distinct regions to guide the analysis of consecutive magnetic configurations: from positive saturation (S+) to the nucleation step (N), the vortex core reversible movement (R), and its annihilation (A) which leads to negative saturation (S-). (b) First-order reversal curve diagram for the same sample at 160 K showing the three main signals SA1, SA1b, and SN1, produced by the magnetization reversal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the formation of a flux closure state, i.e., the nucleation of a vortex. Then, the applied field displaces the vortex core in a direction perpendicular to the applied field. The vortex core displacement is a hysteresis-free process that is described by a reversible linear region (R) in the $M(H)$ curve with an almost zero magnetization remanence. The application of negative fields displaces the core in the opposite direction to the point where the vortex configuration is no longer stable and it is annihilated (A), with a corresponding sharp drop of absolute magnetization reaching the negative saturation state (S-).

Fig. 1b shows the corresponding FORC diagram obtained at 160 K for sample FP-450n. The FORC diagram exhibits a so-called “butterfly” pattern, the fingerprint of the presence of the vortex configuration [60,72]. Moving from positive saturation down to a reversal field in the interval $3.5 \text{ mT} > \mu_0 H_r > 2.0 \text{ mT}$, the vortex nucleation is induced. Indeed, sweeping the measurement field H_m back to positive saturation allows observing the vortex annihilation with a positive increment in magnetization represented by signal SA1. A clear example of this phenomenon is visible in the individual first-order reversal curve starting from $\mu_0 H_r = 2.67$ mT, shown as a dashed red line in Fig. 1a, and corresponding to the horizontal scan indicated by the dashed black line in Fig. 1b. SA1 is visible down to a reversal field of $\mu_0 H_r \sim 2.0$ mT, where the nucleation process is completed for all disks and hence no further variation is visible in the corresponding annihilation signal. Further reducing the initial reversal fields in the range $2.0 \text{ mT} > \mu_0 H_r > -3.5$ mT displaces the vortex’s core reversibly, without inducing its annihilation, hence no irreversible signals are visible in the FORC diagram for reversal fields in this range. Reversal fields $-3.5 \text{ mT} > \mu_0 H_r > -4.5$ mT annihilate the vortices into a negative saturation state, therefore, sweeping back the field towards positive saturation induces a (re)nucleation of the vortex, its reversible core displacement, and, finally, its annihilation, as exemplified by the individual FORC starting from $\mu_0 H_r = -3.71$ mT (short-dashed green line in Fig. 1a). The re-nucleation is visible as signal SN1 in the FORC diagram. Note that the sharp increment in magnetization due to the re-nucleation, modifies its slope along successive FORCs, creating a typical small negative signal before SN1 [59,60]. Increasing the measurement field further, the reversible displacement of vortex’s core does not produce any signal in the FORC diagram, until the vortex annihilation creates signal SA1b, characterized by the negative-

positive–negative profile. This originates from the distribution of nucleation fields among different circular elements, and the corresponding distribution of annihilation fields. The distribution results in the shift of the SA1b signal’s peak during subsequent reversal fields H_r , leaving typical negative tails, creating the triple signal structure [59,60,72].

Sample FZ-850n consists of amorphous $\text{Fe}_{80}\text{Zr}_{10}\text{B}_{10}$ disks with a diameter of 850 nm embedded within the amorphous $\text{Fe}_{89}\text{Zr}_{11}$ matrix; at room temperature, the disks are ferromagnetic (FM), while the matrix is paramagnetic (PM). The $M(H)$ curve and FORC diagram measured at room temperature (shown in Fig. 2a–b) are similar to those of FP-450n. Qualitatively, the FORC diagram shows the same three signals related to the nucleation and annihilation processes. Due to the small size of the disks in sample FZ-850, the MOKE microscope setup cannot resolve their magnetic structure. Micromagnetic simulations have instead been used to reproduce the original $M(H)$ curve and representative individual FORC curves (Fig. 2c–d and Fig. S4). Details about the micromagnetic simulations can be found in Supplementary Information, along with an explanation for the small discrepancy between the measured and simulated fields used in Fig. 2.

In Fig. 2c, the simulated spin configurations, which reproduce the main steps of the reversal process corresponding to the formation of signal SA1 in Fig. 2b, are shown. Initially, the disk shows a vortex configuration with a left shifted core, due to the positive applied field. Increasing the field back to positive saturation progressively pushes the core toward the left edge. Simulations reveal that the vortex configuration exhibits large stability and can be substantially distorted and compressed toward the edge before the annihilation takes place at about 15 mT in the simulation, and 11 mT in the real sample. Here the vortex annihilation corresponds to a continuous and almost smooth process, in agreement with the experimental extended weak annihilation signal SA1 in Fig. 2b, which reflects the absence of a sharp annihilation step in the experimental $M(H)$ curve in (Fig. 2a).

Fig. 2d shows the simulated reversal process starting from the reversal field of -15.0 mT. The initial simulated spin structure exhibits some residual curling. Indeed, reversing the field back towards positive saturation induces the formation of a buckling state [57], before the vortex nucleation, which produces the sharp signal SN1 in Fig. 2b.

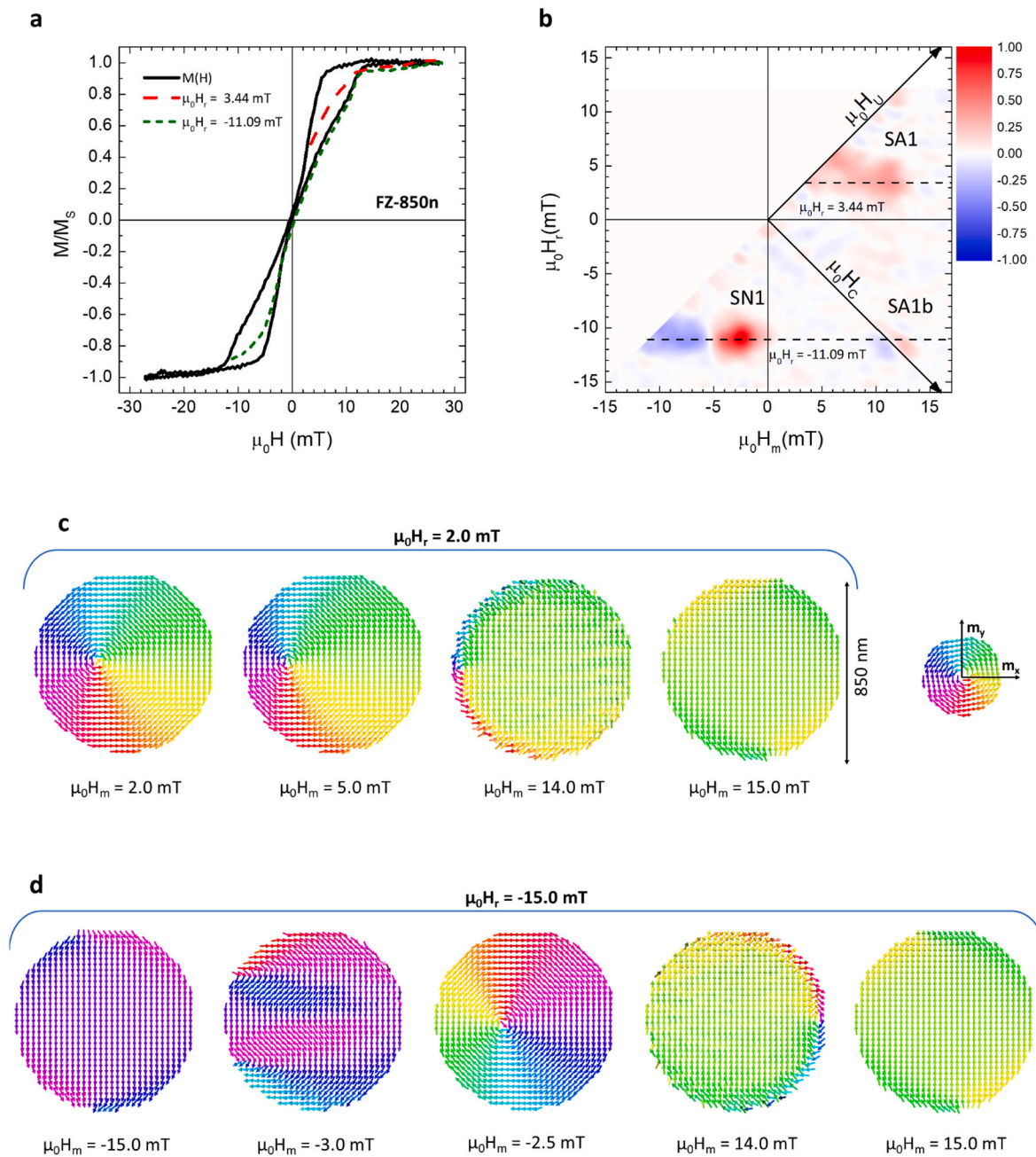


Fig. 2. (a) Magnetization vs field curves $M(H)$ (black continuous line) and selected first-order reversal curves (dashed red and short-dashed green lines) measured with a longitudinal MOKE setup at room temperature for FZ-850n. (b) First-order reversal curve diagram for the same sample showing the three main signals SA1, SA1b, and SN1, produced by the magnetization reversal. Magnetization configurations as a function of measurement field qualitatively reproducing the experimental reversal processes in (b) obtained from micromagnetic simulations obtained with initial reversal fields of 2.0 mT (c) and -15.0 mT (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Increasing the field further, the magnetization configuration evolves with a quite smooth annihilation of the vortex core, resulting in the weaker signal SA1b in Fig. 2b compared to the one for sample FP-450n in Fig. 1b.

The origin of the weaker annihilation signals for the FZ-850n sample compared to the FP-450n sample was investigated by additional micromagnetic simulations. In systems fabricated by ion implantation through a lithographic mask, geometrical imperfections are intrinsically smooth and dominated by ion straggling, which leads to a boundary broadening over a few tens of nanometers rather than to sharp edge irregularities [26]. As a consequence, realistic geometrical variability is mainly captured by small variations in disk size and ellipticity. To

evaluate the possible impact of such effects, additional micromagnetic simulations including controlled distortions of the disk geometry were performed (Supplementary Information and Fig. S5). The results show that the vortex nucleation and annihilation mechanisms remain unchanged across all configurations, with the core being progressively compressed and distorted toward the disk edge prior to annihilation. Only minor quantitative variations are observed, with simulated nucleation fields in the range $+2.0$ to 0.0 mT and simulated annihilation fields between -13.5 and -15.5 mT. These findings indicate that a possible distribution of annihilation fields plays only a secondary role, while the magnetization reversal is primarily governed by the continuous vortex distortion as its core moves close to the edge of the disk.

From this picture, it emerges that the very low concentrations of defects and large homogeneity and ultra-soft ferromagnetic nature of the amorphous architecture structure allow pushing the vortex core very close to the edge of the disk reaching large collinearity not too far from that of the fully saturated state.

3.2. Multiple flux closure configurations

The $M(H)$ curve of larger amorphous disks with a diameter of 5 μm (sample FZ-5 m) is shown in Fig. 3a and exhibits similar features to samples FP-450n and FZ-850n. The bottleneck effect, with almost zero remanent magnetization in the curve, is the typical product of a flux

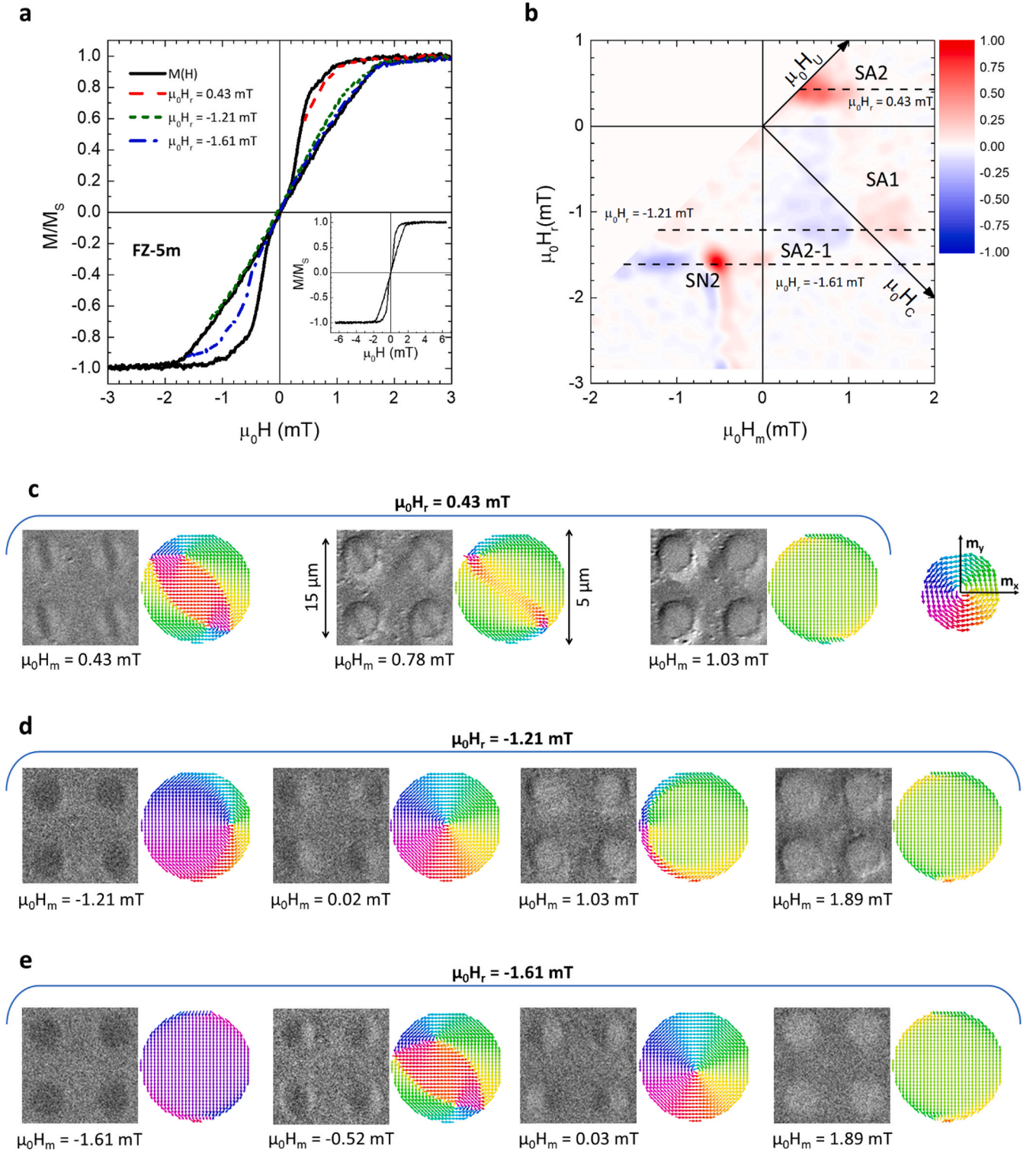


Fig. 3. (a) Magnetization vs field curves $M(H)$ and (b) first-order reversal curve diagram measured with a longitudinal MOKE setup at 300 K for sample FZ-5 m. Magnetization configurations recorded by MOKE microscopy and corresponding micromagnetic simulations as a function of the measurement field after an initial reversal field of 0.43 mT (c), -1.21 mT (d), and -1.61 mT (e) are shown. A greyscale version of the magnetic configurations easier to compare to the Kerr images is presented in Fig. S6.

closure configuration. Also, the FORC diagram (Fig. 3b) exhibits similarities to those of FP-450n and FZ-850n. However, it also displays distinct features, indicating different magnetic configurations and/or magnetization reversal processes in this sample. The large diameter of the disks allows imaging of the magnetic configuration by MOKE microscopy. We have performed equivalent FORC measurements with the MOKE microscope at the three reversal fields corresponding to the appearance of the FORC signals, i.e., $\mu_0 H_r = 0.43$ mT, -1.21 mT, and

-1.61 mT, as indicated by horizontal lines in Fig. 3b.

In Fig. 3c, the reversal field $\mu_0 H_r = 0.43$ mT brings the disk to the cat-eye domain configuration observed in the Kerr image. Sweeping the measurement field back annihilates the cat-eye configuration into the positive saturation, producing the sharp signal SA2 in the FORC diagram (Fig. 3b). Micromagnetic simulations reveal the internal details of the cat-eye configuration, which turns out to involve two vortices. Their annihilation, captured by signal SA2, happens symmetrically and

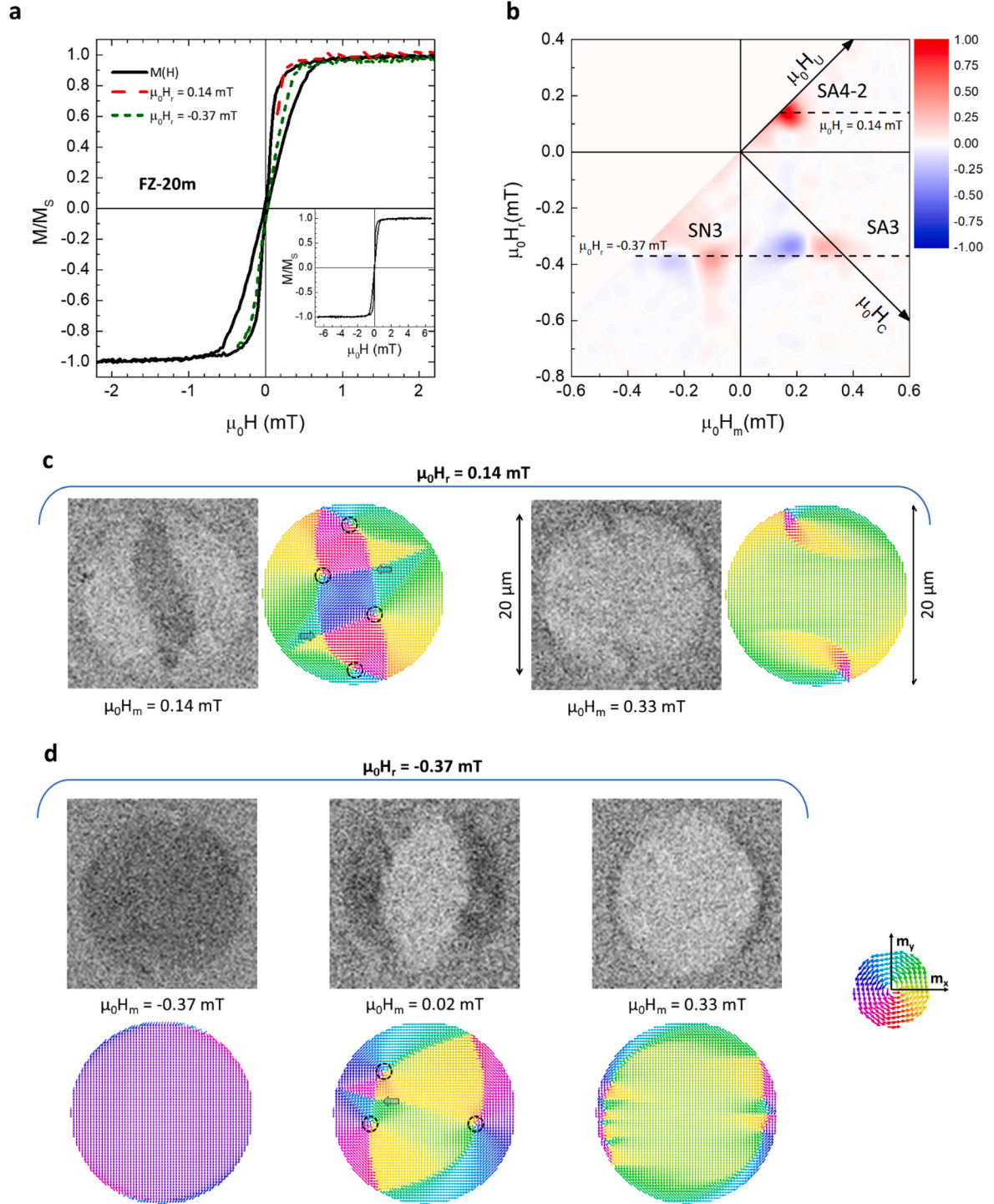


Fig. 4. (a) Magnetization vs field curves $M(H)$ and (b) first-order reversal curve diagram measured with a longitudinal MOKE setup at room temperature for FZ-20 m. Magnetization configurations recorded by MOKE microscopy and corresponding micromagnetic simulations as a function of the measurement field after an initial reversal field of 0.14 mT (c) and -0.37 mT (d) are shown. The presence of multiple vortices and antivortices cores is evidenced with dashed circles and arrows, respectively. See Fig. S7 for the corresponding simulations as greyscale images.

simultaneously.

In Fig. 3d, at the initial reversal field of -1.21 mT, the system consists of negative semi-saturated disks, with small residual positive magnetization regions at the edge. Micromagnetic simulations identify the most stable configuration in such conditions to be a single vortex, with the core largely displaced towards one side of the disk. Hence, one of the two vortices of the cat-eye structure (seen in Fig. 3c at $\mu_0 H_r = \mu_0 H_m = 0.43$ mT) must have been annihilated while decreasing the field to $\mu_0 H_r = -1.21$ mT. Sweeping the field back to positive values, the remanence state is reached (at $\mu_0 H_m = 0.02$ mT in Fig. 3d), where the stable configuration is a symmetric single vortex. Further increasing the measurement field, the vortices annihilate into an almost saturated state. In the FORC diagram (Fig. 3b), this annihilation of the single vortices yields signal SA1.

Progressively decreasing the reversal field from $\mu_0 H_r = 0.43$ mT to $\mu_0 H_r = -1.21$ mT increases the probability of starting the reversal process with one vortex instead of two vortices (corresponding to the cat-eye domain configuration). Hence, during each subsequent sweeping of the measurement field toward positive saturation, the signal SA2, corresponding to the annihilation of the cat-eyes, reduces its magnitude, progressively substituted by the signal SA1 caused by the single vortex annihilation.

In Fig. 3e, the reversal field $\mu_0 H_r = -1.61$ mT induces nearly complete negative saturation in most of the disks, annihilating all vortices, although edge non-collinearities persist. In the FORC diagram, sweeping the measurement field up to about -0.5 mT produces first the intense signal SN2, followed by the weak tail indicated as signal SA2-1 in Fig. 3b. The MOKE images and the micromagnetic simulations show that the SN2 signal corresponds to the nucleation of distorted double vortices, where one of the vortices is already very close to the edge of the disk. The following signal SA2-1 corresponds to the complete expulsion of one of the vortices, leaving only one of the two, which is the stable magnetic configuration at remanence. The degree of distortion and the almost continuous transformation of double vortices into single ones is likely promoted by the continuous sweeping of the field in the same direction. On the other hand, the FORC starting from $\mu_0 H_r = 0.43$ mT, due to the inevitable initial pause and field sweeping reversal, seems to promote more symmetric and regular double vortex cat-eye structures. For $\mu_0 H_r = -1.61$ mT, increasing the measurement field further, the annihilation of the single vortex follows the same process as for $\mu_0 H_r = -1.21$ mT, as no new signal is introduced in the FORC diagram.

It should be noted that observing several Kerr microscope images at remanence, about ~ 90% of the disks exhibit the single vortex configuration, while the remaining disks show a sort of cat-eye configuration (Fig. S8a). Hence, about 10% of the disks do not annihilate one of the two initial vortices to form a single one. We expect the FORC signals from these minority disks to be much weaker than from the majority disks.

The $M(H)$ curve of 20 μm amorphous FM disks (sample FZ-20 m) reported in Fig. 4a suggests a magnetization reversal process in line with that of FZ-5 m, at proportionally lower fields. On the other hand, the FORC diagram (Fig. 4b) shows some clear differences. In Fig. 4c, at the reversal field $\mu_0 H_r = 0.14$ mT, the magnetic domains inside each disk appear as cat-eyes in the Kerr images. The micromagnetic simulation clearly shows four vortices, indicated as circles in the simulated spin structure (Fig. 4c), with the additional presence of two antivortices, identified by small arrows. It is worth noting that the magnetization in the internal area is antiparallel to the direction of the field applied to saturate the sample. Both MOKE microscopy images and simulations show that the annihilation occurs through shrinking and collapsing this internal antiparallel domain. The position of the signal SA4-2 in the FORC diagram (Fig. 4b) suggests that this multiple-vortex structure is annihilated at about $\mu_0 H_m = 0.20$ mT.

In Fig. 4d, at the reversal field $\mu_0 H_r = -0.37$ mT, MOKE microscope images and simulations show that the disks are negatively saturated at this initial reversal field. Signal SN3 indicates the nucleation of a

multiple vortices structure that, at remanence, forms cat-eye shaped domains in the Kerr image. Here, the micromagnetic simulations show a wide central structure with 3 vortices and 1 antivortex. Finally, the annihilation process of the cat-eye configuration occurs through the expansion of the positively magnetized central domain, parallel to the applied field. Hence, the saturation is reached at a larger field compared to the annihilation of the previous 4-vortices structure, as evidenced by the shift of the position of signal SA3 with respect to signal SN4-2 in the FORC diagram. We note that MOKE images taken at remanence (Fig. S8b-c) reveal that some vortex cores have shifted towards the edges and/or collapsed, expanding the internal area into a distorted cat-eye resembling a quasi-single vortex configuration. This distortion is accompanied by magnetization fragmentation near the disk edges due to the presence of multiple domains. Consequently, we expect multi-vortex configurations similar to the cat-eye structure in Fig. 4d. Statistically, cat-eye configurations dominate at remanence, appearing in approximately 75% of the analyzed disks (Fig. S8).

3.3. Topological perspective

Magnetic flux-closure configurations in thin ferromagnetic disks possess a well-defined topological character that originates from the winding of the in-plane magnetization around localized singularities. In these systems, the magnetization lies predominantly in the plane, with local orientation described by the angle θ . Within this framework, vortices and antivortices are characterized by an integer winding number n , defined as:

$$n = \frac{1}{2\pi} \oint \nabla \theta \cdot d\vec{r} = \frac{1}{2\pi} \iint (\partial_x \partial_y \theta - \partial_y \partial_x \theta) dS \quad (2)$$

The winding number counts the number of times the in-plane magnetization rotates along a closed path encircling the defect. This quantity corresponds to the topological charge associated with the first homotopy group of the order-parameter space $\pi_1(S^1)$, and is the appropriate invariant for classifying magnetic vortices, antivortices, and related textures in planar magnetic systems [73,74]. Within this homotopy-based description, vortices and antivortices carry integer winding numbers +1 and -1, respectively, while more complex flux-closure configurations can involve edge defects with fractional winding numbers $\pm 1/2$ [75,76]. Those edge defects can be understood as fractionalized vortices/antivortices. For simply connected geometries, such as the disks investigated here, the net winding number is conserved and fixed to +1, while magnetization reversal and reconfiguration proceed through the creation, annihilation, and rearrangement of vortex-antivortex pairs and fractional edge defects that redistribute this conserved quantity. Bulk topological defects such as the vortex can both be nucleated and annihilated. Therefore, the presence of fractional edge defects is necessary in order to conserve the net winding number in magnetic mesostructures [76–78].

For the simulated spin structures, we identify bulk topological defects by calculating and plotting $(\partial_x \partial_y \theta - \partial_y \partial_x \theta)/2\pi$ over the entire surface and identifying local regions with $n = \pm 1$. Edge defects are related to the presence of a kink in the magnetization at the edge [76]. Both bulk and edge defects can be identified plotting the amplitude of the topological field $|\nabla \theta|$. In Fig. 5, the amplitude of the topological field is plotted together with the simulated spin structure for the FZ-850n sample during a portion of the magnetization reversal of a simulated $M(H)$ curve. In the saturated state, all spins point in the same direction, and topological bulk defects do not exist. Still, the net winding number must be conserved and equal to +1. Therefore, two topological edge defects with $n = +1/2$ exist, one at each pole. For the FZ-850n sample, these topological edge defects approach each other as the applied field is decreased (Fig. 5a) before merging and forming the vortex with $n = +1$ (Fig. 5b), preserving the net winding number. In Fig. 5c, the sample is almost fully saturated in the opposite direction. The vortex retains its

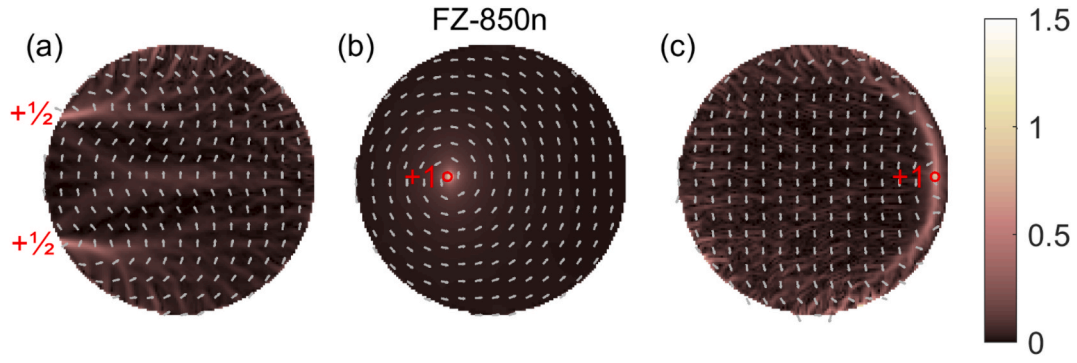


Fig. 5. The amplitude of the topological field $|\nabla\theta|$ for the FZ-850n sample just before (a) and just after (b) the creation of a bulk vortex while decreasing the applied field from saturation. The location of the bulk topological defect is determined from $(\partial_x\partial_y\theta - \partial_y\partial_x\theta)$ and indicated by a red circle for a vortex. (a) $M/M_s = 0.82$; (b) $M/M_s = 0.27$; (c) $M/M_s = 0.87$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

topological winding number, but the vortex itself is strongly distorted as can be seen both from the amplitude of the topological field and the spin structure. The vortex being able to distort and move close to the edge of the disk explains the very weak annihilation signal in the $M(H)$ loop in Fig. 2. Still, the FORC diagram (Fig. 2b) clearly captures 3 signals corresponding to the nucleation of a vortex (SN1) or the annihilation of a vortex (SA1 and SA1b). Hence, the SN1 signal corresponds to transforming two edge topological defects with $n = +1/2$ into a bulk topological defect (a vortex) with $n = +1$, while the SA1 and SA1b signals correspond to the transformation of the vortex ($n = +1$) into two edge topological defects with $n = +1/2$.

For the larger sized disks FZ-5 m, the single vortex formation during the $M(H)$ curve scan follows a different route as illustrated in Fig. 6. Decreasing the applied field from saturation, two topological edge defects with $n = +1/2$ move on opposite sides diagonally from each other (Fig. 6a). Next, each edge defect with $n = +1/2$ is transformed into a

bulk vortex with $n = +1$ inside the disk, each leaving an anti-vortex edge defect with $n = -1/2$, preserving the net winding number $n = +1$ (Fig. 6b).

As the applied magnetic field is further reduced, the cat-eye shaped domain pattern (Fig. 6c) is formed with the domain's walls clearly visible in the amplitude of the topological field. Further reducing the magnetic field, one of the vortex merges with the two edge defects (Fig. 6d) leaving a single vortex (Fig. 6e). Here, two topological edge defects with $n = -1/2$ and a bulk vortex ($n = +1$) could mutually annihilate keeping the topological charge constant.

Finally, reducing the applied field close to negative saturation, the vortex moves very close to the border of the disk. It is still a topological defect with $n = +1$, but highly distorted as can be seen from the spread in the amplitude of the topological field in Fig. 6f. This can explain the absence of a sharp annihilation signal in the $M(H)$ curves in Fig. 3, since the magnetization is very close to the saturated state before the vortex is

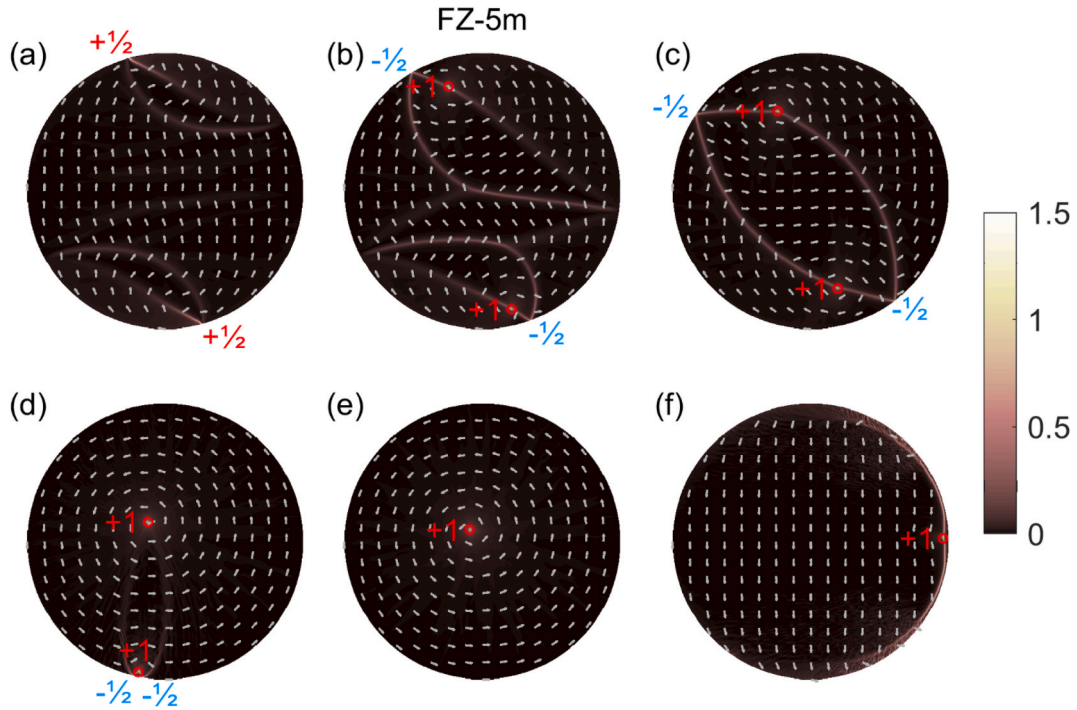


Fig. 6. The amplitude of the topological field $|\nabla\theta|$ for the FZ-5 m sample while decreasing the applied field starting from saturation. The location of each bulk topological defect is determined from $(\partial_x\partial_y\theta - \partial_y\partial_x\theta)$ and indicated by a red circle for a vortex. (a) $M/M_s = 0.91$; (b) $M/M_s = 0.71$; (c) $M/M_s = 0.39$; (d) $M/M_s = 0.10$; (e) $M/M_s = 0.06$; (f) $M/M_s = -0.95$. The color bar indicates the amplitude of the topological field (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

annihilated.

This topological analysis reinforces the observations from the FORC diagram (Fig. 3b). Signal SN2 corresponds to the nucleation of a double vortex structure, occurring while increasing the field from a negative value close to saturation. The topological transformation is from two edge defects with $n = +1/2$, into two bulk vortices along with two edge topological defects with $n = -1/2$. Hence, the net winding number of $+1$ is conserved. The weak signal SA2-1 in the FORC diagram reflects the transition from the topological situation in Fig. 6d to that in Fig. 6e, where 3 topological defects mutually annihilate and only a single bulk vortex survives. Finally, signal SA1 represents the annihilation of the single vortex visible at remanence, while increasing the field to reach (positive) saturation. This process occurs through the transition from a bulk vortex with $n = +1$ to two topological edge defects, each with $n = +1/2$. On the other hand, signal SA2 corresponds to the simultaneous annihilation of two vortices ($n = +1$), by merging each of them with a topological edge defect with $n = -1/2$ into a new topological edge defect with $n = +1/2$.

For the largest disks FZ-20 m, decreasing the applied field from saturation, the two topological edge defects with $n = +1/2$ initially move diagonally, as for the FZ-5 m disks in Fig. 6b, and each splits up into a topological edge defect with $n = -1/2$ and a vortex ($n = +1$) as illustrated in Fig. 7a. However, as the field is further reduced, two more vorticities and two anti-vorticities are created, as shown in Fig. 7b. Next, each anti-vortex moves closer to the original vortex (Fig. 7c-d) leaving a large cat-eye domain in Fig. 7e. Approaching negative saturation, new vortex-antivortex (V-AV) pairs are added to the domain walls. The beginning of this process is illustrated in Fig. 7f. In light of this topological investigation, the SA4-2 signal in the FORC diagram (Fig. 4c) corresponds to the annihilation of two vortices. The SN3 signal represents the nucleation of a three-domain structure with a single vortex domain wall and a V-AV-V domain wall. On increasing the field, such domain wall structure evolves with the formation of multiple V-AV pairs, and their annihilation corresponds to signal SA3.

From a topological perspective, amorphous ferromagnetic disks of different sizes reveal striking differences in their reversal dynamics despite similar features in the $M(H)$ loops. In the smallest sized disks (850 nm in diameter), only a single vortex configuration is nucleated. In the 5 μm disks, either a single vortex or a double-vortex (cat-eye domain configuration) can be stabilized depending on the field-history. However, at remanence, the single vortex is the most favored configuration. Considering the small difference in nucleation field between single- and double-vortex states, and the increased capability of larger disks to host multiple vortices, it is reasonable to expect that for lateral dimensions slightly above 5 μm the double-vortex configuration may become dominant. In the larger 20 μm disks, more complex configurations involving either two vortex (as in the 5 μm disks) or different vortex-antivortex configurations can be stabilized depending on the field history.

From a broader perspective, these results highlight the value of designing deliberately engineered amorphous magnetic architecture. The absence of crystalline interfaces ensures structural continuity, while the spatially confined ferromagnetic regions introduce a functional magnetic patterning that governs the emergence, stability, and interaction of topological defects. This architectural nature, amorphous in structure yet magnetically engineered, provides a degree of control over vortex-antivortex injection and evolution that would be difficult to achieve in conventional patterned crystalline films. It therefore establishes a conceptual and practical framework for designing magnetic systems in which topology, geometry, and amorphous disorder cooperate to produce robust, reconfigurable spin textures.

Beyond the specific results of the samples investigated, the approach and materials proposed here open new avenues for engineering intricate magnetic architectures previously limited by conventional topographic patterning techniques. This advancement has profound implications for the development of unconventional magnetologic devices, particularly in the quest for developing artificial magnetic synapses. The all-amorphous design allows for the precise arrangement and

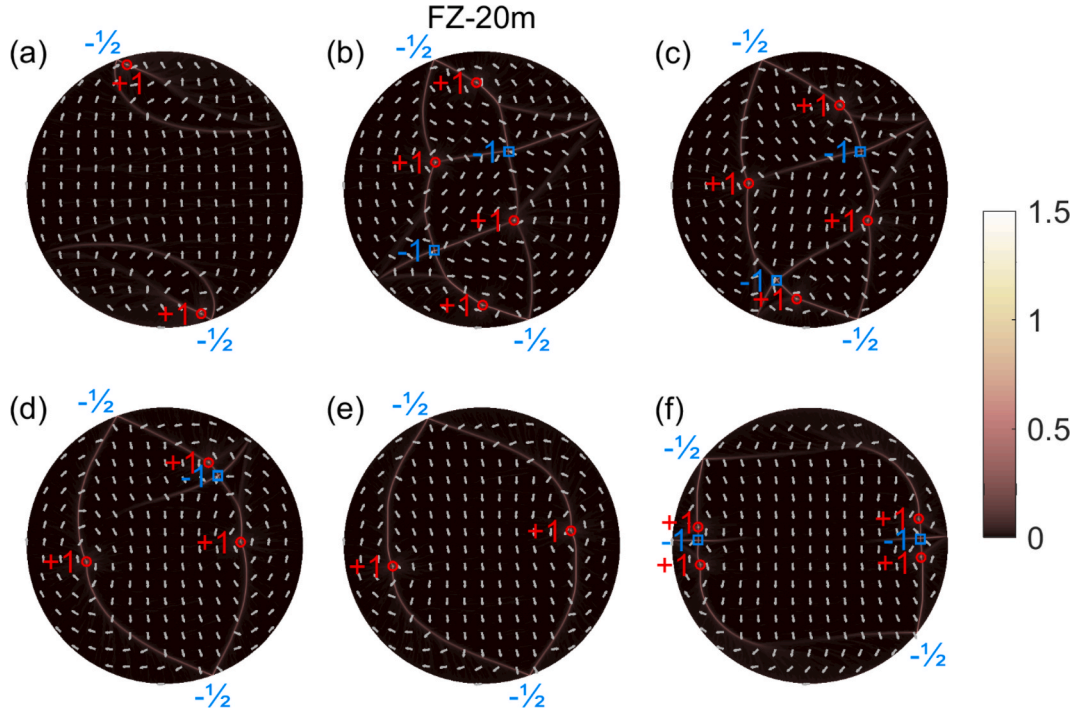


Fig. 7. The amplitude of the topological field $|\vec{\nabla}\theta|$ for the FZ-20 m sample while decreasing the applied field starting from saturation. The location of the bulk topological defect is determined from $n_{\text{local}} = \frac{1}{2\pi} \oint (\partial_x \partial_y \theta - \partial_y \partial_x \theta)$ and indicated by a red circle for surrounding the local area yielding $n_{\text{local}} = 1$ (vortex), and a blue square for the local area yielding $n_{\text{local}} = -1$ (anti-vortex). (a) $M/M_s = 0.90$; (b) $M/M_s = 0.33$; (c) $M/M_s = 0.05$; (d) $M/M_s = -0.22$; (e) $M/M_s = -0.39$; (f) $M/M_s = -0.69$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

manipulation of magnetic textures, which is essential for achieving high-performance, energy-efficient neuromorphic elements [79]. The topological properties of vortex-based structures provide inherent stability, making them robust against external perturbations and ensuring reliable storage of information, a critical aspect for the long-term memory functions of artificial synapses [80]. This stability is coupled with the ability to create and manipulate multiple vortices within a magnetic element, enabling the encoding of multiple states. This capability is essential for achieving multi-level synaptic weights, which are crucial for complex neuromorphic computing [81,82]. For instance, by controlling the number and configuration of vortices, one could modulate synaptic weights to mimic the dynamic behavior of biological synapses. Moreover, the interactions between multiple vortices can be tuned to create diverse synaptic behaviors, such as potentiation and depression, by adjusting the magnetic fields or currents applied to the system. This tunability allows for the simulation of synaptic plasticity phenomena [82], which are fundamental for learning and memory in artificial neural networks. More broadly, the ability to engineer topological magnetic architectures within fully amorphous patterned materials establishes a versatile platform for the design of next-generation functional magnetic systems, from artificial synapses to reconfigurable spin-based computing. Future research should focus on assembling these architectures into complete devices while maintaining stability and functionality, as well as exploring their integration with existing neuromorphic technologies to enhance computational capabilities.

4. Conclusions

We have reported the evolution of magnetic flux closure configurations achievable in amorphous architectures where embedded ferromagnetic disks are prepared by boron ion implantation into a parent paramagnetic FeZr amorphous matrix. This study has been carried out using a combination of conventional $M(H)$ curves, FORC diagrams, Kerr microscopy, and advanced micromagnetic simulations. Conventional $M(H)$ curves can only provide general information on the formation of flux closure for disks with diameters of 850 nm, 5 μm , and 20 μm . However, by applying for the first time FORC diagrams together with Kerr microscopy to the study of mesoscale disks we demonstrated that the FORC technique has the benefit of resolving even subtle differences in the nucleation and annihilation fields of similar but distinct magnetic flux closure structures. We have also developed a micromagnetic model of amorphous mesoscale ferromagnetic structures with a single set of parameters tuned through direct comparison with the $M(H)$ curves and Kerr images. The simulations allow us to resolve the underlying spin configurations and identify their topological fingerprints, including the nucleation and annihilation of single vortices, double vortices, and more complex multi-vortex states accompanied by anti-vortices. The ability to deterministically control the number and arrangement of vortex–antivortex cores in microscale disks using tailored magnetic-field protocols establishes this system as a promising platform for high-density magnetic memory, reconfigurable logic, and topologically encoded information processing.

This study was made possible by the exceptional magnetic softness of the amorphous magnetic structures, combined with the absence of conventional crystalline defects, creating an environment where flux closure structures can emerge on a large scale and be observed by Kerr microscopy. The structural continuity across the full amorphous architecture enables an unprecedented level of control over the injection and dynamics of topological defects, a process typically constrained by extrinsic structural defects in conventional topographically patterned systems.

Beyond the specific system studied, these insights provide a framework for exploring spin textures and emergent topological phenomena across a broader range of geometries and length scales. These findings also open new perspectives for designing unconventional magnetic micro- and nanostructures, pushing the boundaries of topological

magnetism toward novel functional architectures. In particular, the ability to integrate within a single element multiple magnetic states with intrinsic topological stability suggests that similar multi-state magnetic textures could serve as fundamental building blocks for neuromorphic computing hardware, paving the way for innovative approaches in artificial intelligence hardware design.

CRediT authorship contribution statement

Giuseppe Muscas: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Venkata Kamalakara:** Resources, Investigation, Writing – Review & Editing, Funding acquisition. **Ismael G. Serrano:** Writing – review & editing, Investigation, Formal analysis. **Rimantas Brucas:** Writing – review & editing, Investigation, Formal analysis. **Henry Stopfel:** Writing – review & editing, Investigation, Formal analysis. **Vassilios Kapaklis:** Writing – review & editing, Validation, Methodology, Conceptualization. **Petra E. Jönsson:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Open access funding is provided by Uppsala University. We acknowledge financial support from the Swedish Research Council (VR) and the Carl Trygger Foundation. *MVK acknowledges support from the European Research Council (ERC) Project SPINNER (Grant No. 101002772), Stiftelsen Olle Engkvist Byggmästare (Grant No. 200-0602), Formas (Grant No. 2023-01607), and the Knut and Alice Wallenberg Foundation (Grant No. 2022.0079).* Ion implantations were performed at the Uppsala Tandem Laboratory. The authors are thankful for an infrastructure grant by VR-RFI (Grant No. 2019-00191) supporting the accelerator operation. We acknowledge Myfab Uppsala for providing facilities and experimental support. Myfab is funded by the Swedish Research Council (No. 2020-00207) as a national research infrastructure.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.matdes.2026.117171>.

Data availability

Data will be made available on request.

References

- [1] A. Thapa, B. Sharma, A Review on Novel Low-Dimensional Materials based magnetic Tunnel Junctions: Opportunities, Challenges, and Applications, *Advanced Materials Technologies* 10 (2025) e00133, <https://doi.org/10.1002/admt.202500133>.
- [2] G. Gubbiotti, A. Barman, S. Ladak, C. Bran, D. Grundler, M. Huth, H. Plank, G. Schmidt, S. van Dijken, R. Streubel, O. Dobrovolskiy, V. Scagnoli, L. Heyderman, C. Donnelly, O. Hellwig, L. Fallarino, M.B. Jungfleisch, A. Farhan, N. Maccaferri, P. Vavassori, P. Fischer, R. Tomasello, G. Finocchio, R. Clérac, R. Sessoli, D. Makarov, D.D. Sheka, M. Krawczyk, R. Gallardo, P. Landeros, M. d'Aquino, R. Hertel, P. Pirro, F. Ciubotaru, M. Becherer, J. Gartside, T. Ono, P. Bortolotti, A. Fernández-Pacheco, *J. Phys. Condens. Matter* 37 (2025) 143502, <https://doi.org/10.1088/1361-648X/ad9655>, 2025 roadmap on 3D nanomagnetism.

- [3] J. Puebla, J. Kim, K. Kondou, Y. Otani, Spintronic devices for energy-efficient data storage and energy harvesting, *Commun Mater* 1 (2020) 24, <https://doi.org/10.1038/s43246-020-0022-5>.
- [4] D. Makarov, O.M. Volkov, A. Kákay, O.V. Pylypovskiy, B. Budinská, O. V. Dobrovolskiy, New Dimension in Magnetism and Superconductivity: 3D and Curvilinear Nanoarchitectures, *Adv. Mater.* 34 (2022) 2101758, <https://doi.org/10.1002/adma.202101758>.
- [5] P. Fischer, D. Sanz-Hernández, R. Streubel, A. Fernández-Pacheco, Launching a new dimension with 3D magnetic nanostructures, *APL Mater.* 8 (2020) 010701, <https://doi.org/10.1063/1.5134474>.
- [6] R. Antos, Y. Otani, J. Shibata, Magnetic vortex dynamics, *J. Phys. Soc. Jpn.* 77 (2008) 1–8, <https://doi.org/10.1143/JPSJ.77.031004>.
- [7] K.Y. Guslienko, Magnetic Vortex State Stability, Reversal and Dynamics in Restricted Geometries, *J. Nanosci. Nanotechnol.* 8 (2008) 2745–2760, <https://doi.org/10.1166/jnn.2008.003>.
- [8] M. Vanatka, M. Urbánek, R. Jíra, L. Flajšman, M. Dhankhar, M.-Y.-Y. Im, J. Michalická, V. Uhlíř, T. Sikola, Magnetic vortex nucleation modes in static magnetic fields, *AIP Adv.* 7 (2017) 105103, <https://doi.org/10.1063/1.5006235>.
- [9] M. Goiriena-Goikoetxea, K.Y. Guslienko, M. Rouco, I. Orue, E. Berganza, M. Jaafar, A. Asenjo, M.L. Fernández-Gubieda, L. Fernández Barquín, A. García-Arribas, Magnetization reversal in circular vortex dots of small radius, *Nanoscale* 9 (2017) 11269–11278, <https://doi.org/10.1039/C7NR02389H>.
- [10] R.P. Beardsley, S. Bowe, D.E. Parkes, C. Reardon, K.W. Edmonds, B.L. Gallagher, S. A. Cavill, A.W. Rushforth, Deterministic control of magnetic vortex wall chirality by electric field, *Sci. Rep.* 7 (2017) 7613, <https://doi.org/10.1038/s41598-017-07944-9>.
- [11] X. Fu, S.D. Pollard, B. Chen, B.K. Yoo, H. Yang, Y. Zhu, Optical manipulation of magnetic vortices visualized in situ by Lorentz electron microscopy, *Sci. Adv.* 4 (2018) 1–12, <https://doi.org/10.1126/sciadv.aat3077>.
- [12] R.V. Verba, D. Navas, A. Hierro-Rodríguez, S.A. Bunyayev, B.A. Ivanov, K. Y. Guslienko, G.N. Kakazei, Overcoming the Limits of Vortex Formation in magnetic Nanodots by Coupling to Antidot Matrix, *Phys. Rev. Appl* 10 (2018) 1, <https://doi.org/10.1103/PhysRevApplied.10.031002>.
- [13] A. Ehrmann, T. Blachowicz, Vortex and double-vortex nucleation during magnetization reversal in Fe nanodots of different dimensions, *J. Magn. Magn. Mater.* 475 (2019) 727–733, <https://doi.org/10.1016/j.jmmm.2018.12.031>.
- [14] L. Ramasubramanian, A. Kákay, C. Fowley, O. Yildirim, P. Matthes, S. Sorokin, A. Titova, D. Hilliard, R. Böttger, R. Hübner, S. Gemming, S.E. Schulz, F. Kronast, D. Makarov, J. Fassbender, A. Deac, Tunable magnetic Vortex Dynamics in Ion-Implanted Permalloy Disks, *ACS Appl. Mater. Interfaces* 12 (2020) 27812–27818, <https://doi.org/10.1021/acsami.0c08024>.
- [15] P. Bhattacharjee, S. Barman, Spin-torque vortex-oscillator with modified saturation magnetization in ferromagnetic nanodots, *Phys. B Condens. Matter* 695 (2024) 416579, <https://doi.org/10.1016/j.physb.2024.416579>.
- [16] M. Romera, P. Talatchian, S. Witrocz, L. Lebrun, K.J. Merazzo, P. Bortolotti, L. Vila, R. Ferreira, M.C. Cyrille, U. Ebels, V. Cros, J. Grollier, Tuning the Mutual Synchronization of Electrically coupled Spin-Torque Oscillators by Selecting the Vortex Dynamic Regime, *Adv. Electron. Mater.* 11 (2025) 2400808, <https://doi.org/10.1002/aeml.202400808>.
- [17] J.C. Gartside, K.D. Stenning, A. Vanstone, H.H. Holder, D.M. Arroo, T. Dion, F. Caravelli, H. Kurebayashi, W.R. Branford, Reconfigurable training and reservoir computing in an artificial spin-vortex ice via spin-wave fingerprinting, *Nat. Nanotechnol.* 17 (2022) 460–469, <https://doi.org/10.1038/s41565-022-01091-7>.
- [18] V. Sluka, A. Kákay, A.M. Deac, D.E. Bürgler, C.M. Schneider, R. Hertel, Spin-torque-induced dynamics at fine-split frequencies in nano-oscillators with two stacked vortices, *Nat. Commun.* 6 (2015) 6409, <https://doi.org/10.1038/ncomms7409>.
- [19] A. Khosla, A.K. Gupta, S.K. Maharana, D. Mittal, M.S. Sabir, R. Medwal, Spin current driven self-reliant magnetic vortex synapses, *Phys. Rev. B* 111 (2025) 014423, <https://doi.org/10.1103/PhysRevB.111.014423>.
- [20] T. Böhnert, Y. Rezaeiyan, M.S. Claro, L. Benetti, A.S. Jenkins, H. Farkhani, F. Moradi, R. Ferreira, Weighted spin torque nano-oscillator system for neuromorphic computing, *Commun Eng* 2 (2023) 1–8, <https://doi.org/10.1038/s44172-023-00117-9>.
- [21] T. Mühl, J. Körner, S. Philipp, C.F. Reiche, A. Leonhardt, B. Büchner, Magnetic force microscopy sensors providing in-plane and perpendicular sensitivity, *Appl. Phys. Lett.* 101 (2012) 112401, <https://doi.org/10.1063/1.4750058>.
- [22] P. Vavassori, M. Pancaldi, M.J. Perez-Roldan, A. Chuvilin, A. Berger, Remote Magnetomechanical Nanoactuation, *Small* 12 (2016) 1013–1023, <https://doi.org/10.1002/smll.201503351>.
- [23] X.L. Liu, Y. Yang, C.T. Ng, L.Y. Zhao, Y. Zhang, B.H. Bay, H.M. Fan, J. Ding, Magnetic Vortex Nanorings: a New Class of Hyperthermia Agent for Highly Efficient In Vivo Regression of Tumors, *Adv. Mater.* 27 (2015) 1939–1944, <https://doi.org/10.1002/adma.201405036>.
- [24] J.K. Ha, R. Hertel, J. Kirschner, Configurational stability and magnetization processes in submicron permalloy disks, *Phys. Rev. B* 67 (2003) 064418, <https://doi.org/10.1103/PhysRevB.67.064418>.
- [25] R.P. Cowburn, D.K. Koltsov, A.O. Adeyeye, M.E. Welland, Single-Domain Circular Nanomagnets, *Phys. Rev. Lett.* 83 (1999) 1042–1045, <https://doi.org/10.1103/PhysRevLett.83.1042>.
- [26] G. Muscas, R. Brucas, P.E. Jönsson, Bringing nanomagnetism to the mesoscale with artificial amorphous structures, *Phys. Rev. B* 97 (2018) 174409, <https://doi.org/10.1103/PhysRevB.97.174409>.
- [27] J.I. Martín, J. Nogués, K. Liu, J.L. Vicent, I.K. Schuller, Ordered magnetic nanostructures: fabrication and properties, *Journal of Magnetism and Magnetic Materials* 256 (2003) 449–501, [https://doi.org/10.1016/S0304-8853\(02\)00898-3](https://doi.org/10.1016/S0304-8853(02)00898-3).
- [28] K.Y. Guslienko, X.F. Han, D.J. Keavney, R. Divan, S.D. Bader, Magnetic Vortex Core Dynamics in Cylindrical Ferromagnetic Dots, *Phys. Rev. Lett.* 96 (2006) 067205, <https://doi.org/10.1103/PhysRevLett.96.067205>.
- [29] M.-Y. Im, P. Fischer, K. Yamada, T. Sato, S. Kasai, Y. Nakatani, T. Ono, Symmetry breaking in the formation of magnetic vortex states in a permalloy nanodisk, *Nat. Commun.* 3 (2012) 983, <https://doi.org/10.1038/ncomms1978>.
- [30] O.M. Volkov, D. Wolf, O.V. Pylypovskiy, A. Kákay, D.D. Sheka, B. Büchner, J. Fassbender, A. Lubk, D. Makarov, Chirality coupling in topological magnetic textures with multiple magnetochiral parameters, *Nat. Commun.* 14 (2023) 1491, <https://doi.org/10.1038/s41467-023-37081-z>.
- [31] H. Oezelt, E. Kirk, P. Wohllhüter, E. Müller, L.J. Heyderman, A. Kovacs, T. Schrefl, Vortex motion in amorphous ferrimagnetic thin film elements, *AIP Adv.* 7 (2017) 056001, <https://doi.org/10.1063/1.4973295>.
- [32] M. Möller, J.H. Gaida, C. Ropers, Pinning and gyration dynamics of magnetic vortices revealed by correlative Lorentz and bright-field imaging, *Phys. Rev. Res.* 4 (2022) 013027, <https://doi.org/10.1103/PhysRevResearch.4.013027>.
- [33] C. Holl, M. Knol, M. Pratzner, J. Chico, I.L. Fernandes, S. Lounis, M. Morgenstern, Probing the pinning strength of magnetic vortex cores with sub-nanometer resolution, *Nat. Commun.* 11 (2020) 2833, <https://doi.org/10.1038/s41467-020-16701-y>.
- [34] W.L. Gan, M. Chandra Sekhar, D.W. Wong, I. Purnama, S.Y. Chiam, L.M. Wong, W. S. Lew, Multi-vortex states in magnetic nanoparticles, *Appl. Phys. Lett.* 105 (2014) 152405, <https://doi.org/10.1063/1.4898349>.
- [35] K. Shen, L. Li, F. Tan, C.C. Ian Ang, T. Jin, Z. Xue, S. Wu, M. Yin Chee, Y. Yan, W. Siang Lew, NIR and magnetism dual-response multi-core magnetic vortex nanoflowers for boosting magneto-photothermal cancer therapy, *Nanoscale* 16 (2024) 10428–10440, <https://doi.org/10.1039/D4NR00104D>.
- [36] C. Chappert, H. Bernas, J. Ferré, V. Kottler, J.-P. Jamet, Y. Chen, E. Cambril, T. Devolder, F. Rousseaux, V. Mathet, H. Launois, Planar Patterned Magnetic Media Obtained by Ion Irradiation, *Science* 280 (1998) 1919–1922, <https://doi.org/10.1126/science.280.5371.1919>.
- [37] J. Fassbender, J. McCord, Magnetic patterning by means of ion irradiation and implantation, *J. Magn. Magn. Mater.* 320 (2008) 579–596, <https://doi.org/10.1016/j.jmmm.2007.07.032>.
- [38] M. Jaafar, R. Sanz, J. McCord, J. Jensen, R. Schäfer, M. Vázquez, A. Asenjo, Pattern-induced magnetic anisotropy in FePt thin films by ion irradiation, *Phys. Rev. B* 83 (2011) 094422, <https://doi.org/10.1103/PhysRevB.83.094422>.
- [39] A. Varea, E. Menéndez, J. Montserrat, E. Lora-Tamayo, A. Weber, L.J. Heyderman, S.C. Deevi, K.V. Rao, S. Suriñach, M.D. Baró, K.S. Buchanan, J. Nogués, J. Sort, Tuneable magnetic patterning of paramagnetic Fe₆₀Al₄₀ (at. %) by consecutive ion irradiation through pre-lithographed shadow masks, *J. Appl. Phys.* 109 (2011) 093918, <https://doi.org/10.1063/1.3590158>.
- [40] T. Mewes, R. Lopusnik, J. Fassbender, B. Hillebrands, M. Jung, D. Engel, A. Ehresmann, H. Schmoranz, Suppression of exchange bias by ion irradiation, *Appl. Phys. Lett.* 76 (2000) 1057–1059, <https://doi.org/10.1063/1.125937>.
- [41] D. McGrouther, J.N. Chapman, Nanopatterning of a thin ferromagnetic CoFe film by focused-ion-beam irradiation, *Appl. Phys. Lett.* 87 (2005) 022507, <https://doi.org/10.1063/1.1992661>.
- [42] C. Sürgers, K. Potzger, T. Strache, W. Möller, G. Fischer, N. Joshi, H. v. Löhneysen, Magnetic order by C-ion implantation into Mn₅Si₃ and Mn₅Ge₃ and its lateral modification, *Applied Physics Letters* 93 (2008) 062503, <https://doi.org/10.1063/1.2969403>.
- [43] E. Menéndez, M.O. Liedke, J. Fassbender, T. Gemming, A. Weber, L.J. Heyderman, K.V. Rao, S.C. Deevi, S. Suriñach, M.D. Baró, J. Sort, J. Nogués, Direct magnetic Patterning due to the Generation of Ferromagnetism by Selective Ion Irradiation of Paramagnetic FeAl Alloys, *Small* 5 (2009) 229–234, <https://doi.org/10.1002/smll.200800783>.
- [44] S. Kim, S. Lee, J. Ko, J. Son, M. Kim, S. Kang, J. Hong, Nanoscale patterning of complex magnetic nanostructures by reduction with low-energy protons, *Nat. Nanotechnol.* 7 (2012) 567–571, <https://doi.org/10.1038/nnano.2012.125>.
- [45] S. Kim, S. Lee, J. Hong, An array of ferromagnetic nanoislands nondestructively patterned via a local phase transformation by low-energy proton irradiation, *ACS Nano* 8 (2014) 4698–4704, <https://doi.org/10.1021/nn500683b>.
- [46] C. Vantaraki, O. Bikondoa, M.P. Grassi, B. Ojha, A. Stamatelatos, N. Kiwiatek-Maroszek, M.A.N. Orti, M. Foerster, T. Saerbeck, D. Primetzhöfer, M. Wolff, N. Jaouen, T.P.A. Hase, V. Kapaklis, Long-range structural and magnetic coherence in embedded mesospin metamaterials, *Sci. Rep.* 16 (2026) 12178, <https://doi.org/10.1038/s41598-026-48207-w>.
- [47] T. Devolder, I. Barisic, S. Eimer, K. Garcia, J.-P. Adam, B. Ockert, D. Ravelosona, Irradiation-induced tailoring of the magnetism of CoFeB/MgO ultrathin films, *J. Appl. Phys.* 113 (2013) 203912, <https://doi.org/10.1063/1.4808102>.
- [48] N. Martin, J. McCord, A. Gerber, T. Strache, T. Gemming, I. Mönch, N. Farag, R. Schäfer, J. Fassbender, E. Quandt, L. Schultz, Local stress engineering of magnetic anisotropy in soft magnetic thin films, *Appl. Phys. Lett.* 94 (2009) 062506, <https://doi.org/10.1063/1.3079664>.
- [49] R. Moubah, A. Zamani, A. Olsson, S. Shi, A. Hallén, S. Carlson, D. Arvanitis, P. Nordblad, B. Hjörvarsson, P. Jönsson, Soft Room-Temperature Ferromagnetism of Carbon-Implanted Amorphous Fe₉₃Zr₇ Films, *Appl. Phys. Express* 6 (2013) 053001, <https://doi.org/10.7567/APEX.6.053001>.
- [50] J.M. Barandiaran, P. Gorria, J.C. Gomez Sal, L. Fernandez Barquin, S.N. Kaul, Influence of boron on the magnetic and transport properties of FeZr amorphous and nanocrystalline alloys, *IEEE Trans. Magn.* 30 (1994) 4776–4778, <https://doi.org/10.1109/20.334218>.
- [51] K.A. Gallagher, M.A. Willard, V.N. Zabenkin, D.E. Laughlin, M.E. McHenry, Distributed exchange interactions and temperature dependent magnetization in

- amorphous Fe88–xCoxZr7B4Cu1 alloys, *J. Appl. Phys.* 85 (1999) 5130–5132, <https://doi.org/10.1063/1.369100>.
- [52] A. Zamani, R. Moubah, M. Ahlberg, H. Stopfel, U.B. Arnalds, A. Hallén, B. Hjörvarsson, G. Andersson, P.E. Jönsson, Magnetic properties of amorphous Fe93Zr7 films: effect of light ion implantation, *J. Appl. Phys.* 117 (2015) 143903, <https://doi.org/10.1063/1.4917212>.
- [53] G. Muscas, M. Menniti, R. Brucas, P.E. Jönsson, Mesoscale magnetic rings: complex magnetization reversal uncovered by FORC, *J. Magn. Magn. Mater.* 502 (2020) 166559, <https://doi.org/10.1016/j.jmmm.2020.166559>.
- [54] R. Sbiaa, R. Law, S.Y.H. Lua, E.L. Tan, T. Tahmasebi, C.C. Wang, S. N. Piramanayagam, Spin transfer torque switching for multi-bit per cell magnetic memory with perpendicular anisotropy, *Appl. Phys. Lett.* 99 (2011) 092506, <https://doi.org/10.1063/1.3632075>.
- [55] J. Torrejon, M. Riou, F.A. Araujo, S. Tsunegi, G. Khalsa, D. Querlioz, P. Bortolotti, V. Cros, K. Yakushiji, A. Fukushima, H. Kubota, S. Yuasa, M.D. Stiles, J. Grollier, Neuromorphic computing with nanoscale spintronic oscillators, *Nature* 547 (2017) 428–431, <https://doi.org/10.1038/nature23011>.
- [56] E. Isufi, G. Leus, B. Beferull-Lozano, S. Barbarossa, P. Di Lorenzo, Topological signal processing and learning: recent advances and future challenges, *Signal Process.* 233 (2025) 109930, <https://doi.org/10.1016/j.sigpro.2025.109930>.
- [57] K.Y. Guslienko, V. Novosad, Y. Otani, H. Shima, K. Fukamichi, Magnetization reversal due to vortex nucleation, displacement, and annihilation in submicron ferromagnetic dot arrays, *Phys. Rev. B* 65 (2001) 024414, <https://doi.org/10.1103/PhysRevB.65.024414>.
- [58] E. Östman, U.B. Arnalds, E. Melander, V. Kapaklis, G.K. Pálsson, A.Y. Saw, M. A. Verschuuren, F. Kronast, E.T. Papaioannou, C.S. Fadley, B. Hjörvarsson, Hysteresis-free switching between vortex and collinear magnetic states, *New J. Phys.* 16 (2014) 053002, <https://doi.org/10.1088/1367-2630/16/5/053002>.
- [59] D.A. Gilbert, G.T. Zimanyi, R.K. Dumas, M. Winklhofer, A. Gomez, N. Eibagi, J. L. Vicent, K. Liu, Quantitative Decoding of Interactions in Tunable Nanomagnet Arrays using first Order Reversal Curves, *Sci. Rep.* 4 (2014) 4204, <https://doi.org/10.1038/srep04204>.
- [60] D.A. Gilbert, L. Ye, A. Varea, S. Agramunt-Puig, N. del Valle, C. Navau, J.F. López-Barbera, K.S. Buchanan, A. Hoffmann, A. Sánchez, J. Sort, K. Liu, J. Nogués, A new reversal mode in exchange coupled antiferromagnetic/ferromagnetic disks: distorted viscous vortex, *Nanoscale* 7 (2015) 9878–9885, <https://doi.org/10.1039/C5NR01856K>.
- [61] J. Schindelin, I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, T. Pietzsch, S. Preibisch, C. Rueden, S. Saalfeld, B. Schmid, J.-Y. Tinevez, D.J. White, V. Hartenstein, K. Eliceiri, P. Tomancak, A. Cardona, Fiji: an open-source platform for biological-image analysis, *Nat. Methods* 9 (2012) 676–682, <https://doi.org/10.1038/nmeth.2019>.
- [62] A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, F. Garcia-Sanchez, B. Van Waeyenberge, The design and verification of Mumax3, *AIP Adv.* 4 (2014) 107133, <https://doi.org/10.1063/1.4899186>.
- [63] M. Mansuripur, R. Giles, G. Patterson, Coercivity of domain-wall motion in thin films of amorphous rare-earth-transition-metal alloys, *J. Appl. Phys.* 69 (1991) 4844–4846, <https://doi.org/10.1063/1.348250>.
- [64] H. Oezelt, A. Kovacs, F. Reichel, J. Fischbacher, S. Bance, M. Gusenbauer, C. Schubert, M. Albrecht, T. Schrefl, Micromagnetic simulation of exchange coupled ferri-/ferromagnetic heterostructures, *J. Magn. Magn. Mater.* 381 (2015) 28–33, <https://doi.org/10.1016/j.jmmm.2014.12.045>.
- [65] R. Alben, J.J. Becker, M.C. Chi, Random anisotropy in amorphous ferromagnets, *J. Appl. Phys.* 49 (1978) 1653, <https://doi.org/10.1063/1.324881>.
- [66] G. Herzer, The Random Anisotropy Model, in: B. Idzikowski, P. Švec, M. Miglierini (Eds.), *Properties and Applications of Nanocrystalline Alloys from Amorphous Precursors*, Springer-Verlag, Berlin/Heidelberg, 2005: pp. 15–34. https://doi.org/10.1007/1-4020-2965-9_2.
- [67] G. Herzer, Modern soft magnets: Amorphous and nanocrystalline materials, *Acta Mater.* 61 (2013) 718–734, <https://doi.org/10.1016/j.actamat.2012.10.040>.
- [68] H. Fu, R. Giles, M. Mansuripur, Coercivity mechanisms in magneto-optical recording media, *Comput. Phys.* 8 (1994) 80, <https://doi.org/10.1063/1.168516>.
- [69] I. Betancourt, G. Hrkac, T. Schrefl, Micromagnetic study of magnetic domain structure and magnetization reversal in amorphous wires with circular anisotropy, *J. Magn. Magn. Mater.* 323 (2011) 1134–1139, <https://doi.org/10.1016/j.jmmm.2010.11.089>.
- [70] I. Betancourt, G. Hrkac, T. Schrefl, Magnetic domain structure and magnetization reversal in amorphous microwires with circular anisotropy: a micromagnetic approach, *J. Appl. Phys.* 109 (2011) 013902, <https://doi.org/10.1063/1.3525564>.
- [71] J. Leliaert, B. Van de Wiele, A. Vansteenkiste, L. Laurson, G. Durin, L. Dupré, B. Van Waeyenberge, Current-driven domain wall mobility in polycrystalline Permalloy nanowires: a numerical study, *J. Appl. Phys.* 115 (2014) 233903, <https://doi.org/10.1063/1.4883297>.
- [72] R.K. Dumas, C.-P. Li, I.V. Roshchin, I.K. Schuller, K. Liu, Magnetic fingerprints of sub-100 nm Fe dots, *Phys. Rev. B* 75 (2007) 134405, <https://doi.org/10.1103/PhysRevB.75.134405>.
- [73] N.D. Mermin, The topological theory of defects in ordered media, *Rev. Mod. Phys.* 51 (1979) 591–648, <https://doi.org/10.1103/RevModPhys.51.591>.
- [74] O. Bezsmertna, R. Xu, O. Pylypovskiy, D. Raftrey, A. Sorrentino, J.A. Fernandez-Roldan, I. Soldatov, D. Wolf, A. Lubk, R. Schäfer, P. Fischer, D. Makarov, Magnetic Solitons in Hierarchical 3D magnetic Nanoarchitectures of Nanoflower Shape, *Nano Lett.* 24 (2024) 15774–15780, <https://doi.org/10.1021/acs.nanolett.4c04584>.
- [75] F.G. Mertens, A.R. Bishop, Dynamics of Vortices in Two-Dimensional Magnets, in: P.L. Christiansen, M.P. Sørensen, A.C. Scott (Eds.), *Nonlinear Science at the Dawn of the 21st Century*, Springer, Berlin, Heidelberg, 2000: pp. 137–170. https://doi.org/10.1007/3-540-46629-0_7.
- [76] O. Tchernyshyov, G.-W. Chern, Fractional Vortices and Composite Domain Walls in Flat Nanomagnets, *Phys. Rev. Lett.* 95 (2005) 197204, <https://doi.org/10.1103/PhysRevLett.95.197204>.
- [77] H. Youk, G.-W. Chern, K. Merit, B. Oppenheimer, O. Tchernyshyov, Composite domain walls in flat nanomagnets: the magnetostatic limit, *J. Appl. Phys.* 99 (2006) 08B101, <https://doi.org/10.1063/1.2167049>.
- [78] G.-W. Chern, D. Clarke, H. Youk, O. Tchernyshyov, Halfvortices in Flat Nanomagnets, in: B. Barbara, Y. Imry, G. Sawatzky, P.C.E. Stamp (Eds.), *Quantum Magnetism*, Springer Netherlands, Dordrecht, 2008: pp. 35–48. https://doi.org/10.1007/978-1-4020-8512-3_3.
- [79] T. Leonard, S. Liu, M. Alamdar, H. Jin, C. Cui, O.G. Akinola, L. Xue, T.P. Xiao, J. S. Friedman, M.J. Marinella, C.H. Bennett, J.A.C. Incorvia, Shape-Dependent Multi-Weight magnetic Artificial Synapses for Neuromorphic Computing, *Adv. Electron. Mater.* 8 (2022) 2200563, <https://doi.org/10.1002/aem.202200563>.
- [80] K.M. Song, J.-S. Jeong, B. Pan, X. Zhang, J. Xia, S. Cha, T.-E. Park, K. Kim, S. Finizio, J. Raabe, J. Chang, Y. Zhou, W. Zhao, W. Kang, H. Ju, S. Woo, Skyrmion-based artificial synapses for neuromorphic computing, *Nat. Electron.* 3 (2020) 148–155, <https://doi.org/10.1038/s41928-020-0385-0>.
- [81] H. Mou, Z. Luo, X. Zhang, Tunable magnetic synapse for reliable neuromorphic computing, *Appl. Phys. Lett.* 125 (2024) 044103, <https://doi.org/10.1063/5.0210317>.
- [82] S. Lequeux, J. Sampaio, V. Cros, K. Yakushiji, A. Fukushima, R. Matsumoto, H. Kubota, S. Yuasa, J. Grollier, A magnetic synapse: multilevel spin-torque memristor with perpendicular anisotropy, *Sci. Rep.* 6 (2016) 31510, <https://doi.org/10.1038/srep31510>.