

Magnetic vortex writing and local reversal seeding in artificial spin-vortex ice via all-optical and surface-probe control

Holly Holder^{1,*}, Alexander J. Wright¹, Alex Vanstone¹, Troy Dion^{2,3,5}, Xiaofei Xiao¹, Kilian D. Stenning^{1,4}, Tingjun Zheng¹, Daniel Bromley¹, Tobias Farchy¹, Jack C. Gartside^{1,4,5,†}, Rupert F. Oulton¹, and Will R. Branford^{1,4}

¹Blackett Laboratory, *Imperial College London*, London SW7 2AZ, United Kingdom

²Center for Science and Innovation in Spintronics (CSIS), *Tohoku University*, Sendai, Japan

³Solid State Physics Laboratory, *Kyushu University*, Fukuoka, Japan

⁴London Centre for Nanotechnology, *Imperial College London*, London SW7 2AZ, United Kingdom

⁵Institute for Materials Research, *Tohoku University*, Sendai, Japan



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Artificial spin-vortex ice (ASVI) is a reconfigurable nanomagnetic metamaterial consisting of magnetic nanoislands tailored to support both Ising macrospin and vortex textures. ASVI has recently shown functional applications including reconfigurable magnonics and neuromorphic computing, where the introduction of vortex textures broadens functionality beyond conventional artificial spin ice, which only supports macrospin states. However, local control of writing vortex states in ASVI remains an open challenge. Here, we demonstrate techniques for field-free local magnetic vortex writing. We expand ASVI to support metastable macrospin, single-vortex, and double-vortex states. All-optical writing via focused laser illumination can write double-vortex textures, and surface-probe writing using an MFM tip can write single-vortex states. We leverage this writing to tailor and explore the reconfigurable energy landscape of ASVI, demonstrating programmable local seeding of avalanche-like reversal events. The writing techniques reported here expand the suite of nanomagnetic control techniques, with a host of future applications including fundamental studies of avalanche dynamics, physical memory, and direct writing of nanomagnetic “weights” in physical neuromorphic neural networks.

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I. INTRODUCTION

Artificial spin ices (ASIs), so named because of the ice-rule framework used to investigate their vertex energies [1,2], are systems of closely packed magnetic nanoislands whose competing geometrically frustrated dipolar interactions result in a large number of low-energy microstates [2–4]. The broad design space of nanoisland shape/size and array geometry available in ASI nanofabrication from 2D [3,5] to 2.5D [6,7] and 3D systems [8–11] allows for a highly tunable system, providing a window through which to study fundamental physics, long-range coupling, and emergent many-body behaviors [3,5,12–22]. ASIs also provide a platform to study and realize functional architectures, such as reconfigurable magnonic systems [4,6,7,23–32], and probabilistic and neuromorphic computing schemes [33–39].

Stadia-shaped magnetic nanoislands are traditionally designed with lengths and aspect ratios [40] to preferentially support Ising macrospin textures [2], in which the nanoisland

magnetization is oriented by shape anisotropy to lie parallel along the nanoisland long axis. Magnetic vortex textures, topological defects typically observed in circular and elliptical islands, consist of a magnetic flux-closure pattern centered around a point-defect core (one core in the case of single vortices, two cores for double vortices) [36,41–53]. Vortex textures emit far less stray field than macrospins because of their internal flux closure, and generally exhibit distinct switching fields compared with macrospin textures because of their differing magnetic structure and energetics. Previous studies have explored the local induction of topological magnetic defects via a scanning magnetic force microscopy (MFM) tip [21,52,54–57], and optical manipulation of magnetic topological defects in thin films [58,59] and disks [60,61]. Double vortices possess different resonant magnetic spectra compared to single vortices, or macrospins [36,45]; therefore, a system capable of hosting all three textures could provide access to an enlarged set of magnon spectra, physical memory capabilities, and rich intrasystem interactions.

Recently a version of ASI was demonstrated in which nanoislands were geometrically tailored such that both macrospin and single-vortex textures are metastable, so called “artificial spin-vortex ice” or ASVI [36,37]. In ASVI macrospin and vortex states are engineered to be similar enough in energy that both states can be accessed via uniform global field protocols, resulting in an enlarged microstate space [6,36,37,47]. The geometric tailoring is relatively simple, with the relative energies of macrospin and vortex textures

*Contact author: h.holder20@imperial.ac.uk

†Contact author: j.carter-gartside13@imperial.ac.uk

determined by the nanoisland length to width aspect ratio and thickness [6,36,47]. The bistable textures expand the system beyond the Ising model [62,63] and give rise to a host of emergent properties including enhanced physical memory, formation of separated domain-like regions of clustered vortex and macrospin nanoislands, and enriched magnon spectra. These properties, arising from introducing vortices alongside macrospins, have been leveraged for reconfigurable magnonics [6] and neuromorphic computing schemes [36,37] including experiments demonstrating enhanced computational performance. The ability to further introduce double-vortex textures and local vortex writing to strongly interacting nanomagnetic arrays promises considerable further potential.

A variety of interesting emergent dynamics and functional benefits arise from introducing metastable vortex states to ASI, but so far vortices have been nucleated stochastically via global excitation. Experimental methodologies by which to locally write and control vortex states in nanomagnetic arrays would considerably broaden the range of fundamental and applied studies accessible in these complex many-body systems. Macrospin states have a range of control protocols, including magnetic surface-probe tip-writing [21,64,65], optical switching [66–68], spin-wave control [29,69], in addition to electrical/spin-torque switching approaches [70] which can be challenging to achieve with local precision in dense strongly coupled arrays because of difficulties patterning many nanoscale electrical control lines. Vortex states lack the spatial symmetry breaking and net magnetization of macrospin states, which makes formulating control protocols challenging, with various approaches devised [52,55–61]. In order to fully exploit the benefits of ASVI-style systems combining collinear macrospin and chiral vortex textures, protocols must be developed that can locally and controllably write vortex states to nanoislands. Achieving this will open new possibilities in fundamental and applied studies, including seeding magnetic avalanches and direct programming of neuromorphic physical neural network weights.

Here, we study an expanded ASVI hosting metastable macrospin, single-vortex, and double-vortex states, and experimentally demonstrate two approaches to locally writing vortex textures in nanoislands: Single-vortex writing via a magnetic surface-probe MFM tip, with vortex circulation control provided by where the tip crosses the island, and double-vortex writing via an all-optical approach using a focused laser spot, with selective control over which nanoisland sublattices are written provided by the laser polarization. The surface-probe technique generates a vortex core in the magnetic material below the MFM tip [21,54], with this approach providing convenient *in situ* access to both local write and read operations using MFM as an imaging and writing system. The all-optical technique offers potential for speed, parallel writing, and device integration. Beyond enabling access to multitexture microstates, a key result enabled by local vortex writing is reconfigurable control over locally seeded reversal events where avalanche-like switching pathways nucleate from written vortices, and sequentially propagate through further nanoislands. This programmable control offers an attractive benefit to avalanche studies, which have previously been limited by stochastic reversal nucleation [14,15,71].

Together, these techniques and results highlight the benefits and potential afforded by expanding multistable nanomagnetic arrays to host diverse magnetic states, and developing writing methodologies capable of accessing and controlling the enriched microstate dynamics in these systems.

II. RESULTS AND DISCUSSION

A. Artificial spin-vortex ice arrays

We study NiFe ASVI arrays that are “width-modified” [30,36,37], consisting of alternating rows of wide and narrow stadia nanoislands as can be seen in the SEM image in Fig. 1(a). Wide nanoislands are metastable and host single-vortex, double-vortex, and macrospin states. Narrow nanoislands almost exclusively host macrospin states. Breaking the array into these two nanoisland types affords us additional global control of array microstates as narrow nanoislands have significantly higher switching fields, and allows the possibility of studying reduced-dimensionality (1D) avalanches [14]. A range of arrays were fabricated with differing nanoisland dimensions to study whether small geometrical changes have significant effects on system behavior, as nanomagnetic textures are sensitive to island size and aspect ratio [47,72]. Arrays 1–4 are $14\ \mu\text{m} \times 14\ \mu\text{m}$ and comprise 676 nanoislands arranged in 26 rows (13 wide and 13 narrow) of nanoislands, with 26 nanoislands per row. Array 5 is $95\ \mu\text{m} \times 95\ \mu\text{m}$ and comprises $\sim 31\text{ k}$ nanoislands. The dimensions of each array are listed in Table I (see Figs. S1–S4 within the Supplemental Material [73] for island geometry analysis via SEM images). Nanoislands are 20-nm-thick Permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) with a 5-nm Al_2O_3 cap.

Figure 1(b) schematically illustrates the two vortex writing techniques used in this work: scanning probe (Tip-writing) control via dipolar interaction between nanoislands and an MFM Tip, and all-optical (Laser-writing) via scanning of a continuous-wave, linearly polarized focused laser spot. Examples of wide nanoisland macrospin, single-vortex, and double-vortex textures are shown in Figs. 1(c)–1(e), respectively, with columns left-to-right showing MuMax3 [74] simulated magnetization states, MuMax3 simulated MFM images, and experimental MFM images.

B. Surface-probe vortex writing

Here, we demonstrate surface-probe writing of vortices with a magnetic MFM tip. Previous work has shown that the tightly spatially focused divergent monopole-like dipolar field at the apex of a high-moment MFM tip can inject a vortex-core topological defect into magnetization textures of thin films and nanoislands, localized directly under the tip [21,54,56,57]. As the strong magnetic field emanates from the tip, it promotes the alignment of proximal magnetic moments in the nanoisland below it towards the direction of the local field to reduce their Zeeman energy [21,54]. Figure 2 shows that for the wide islands in our width-modified arrays that support vortex textures, the magnetic vortex core injected by the tip can remain stable inside the nanoisland after the tip has passed, resulting in locally written vortex textures. Additionally, we demonstrate access to both clockwise and anticlockwise single-vortex circulation textures, with the

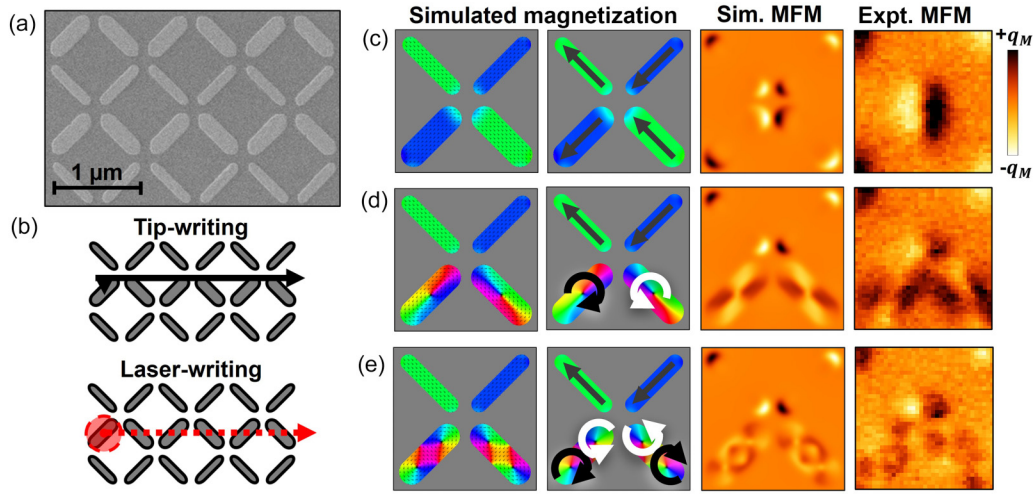


FIG. 1. Introduction to artificial spin-vortex ice hosting macrospin, single-vortex, and double-vortex states. (a) SEM image of a NiFe ASVI Array. The array is “width-modified” with alternating rows of wide and narrow nanoislands. (b) Schematic illustrating scanning MFM tip (Tip-writing), and all-optical (Laser-writing) technique protocols with respect to nanoisland geometries. (c)–(e) Simulated (MuMax3) micromagnetic textures, simulated MFM (60 nm lift height), and experimental MFM images of (c) nanoisland macrospins, (d) single-vortex states, and (e) double-vortex states. All narrow nanoislands are in macrospin states. Arrows and colors represent the direction of magnetization within each nanoisland. Simulated nanoislands have vertex gaps of 100 nm, lengths of 600 nm, and thicknesses of 20 nm, with widths of 200 nm, and 125 nm for wide and narrow nanoislands.

circulation of the resultant vortices defined by the point in the nanoisland where the MFM tip crosses.

Figure 2(a) shows a magnetic force micrograph of ASVI Array 2 in an initial global-field saturated state (negative x direction, termed the “type 2” ASI state [3]), with Fig. 2(b) showing the same array section after a tip-writing operation has been performed in a line in the bottom wide-bar row. A chain of six nanoislands are written into single-vortex states by the MFM tip. Figure 2(c) shows the magnetic state of the same region after a second tip-write along the third-from-bottom row. A chain of nanoislands are written into primarily single-vortex states, with two double vortices written at the middle and right side of the chain.

Figure 2(d) shows a section of Array 5 after a tip-writing line is performed scanning from left-to-right with many vortices written and macrospin flips. The two lower images are duplicates of the top, with added annotations showing: middle row, the approximate deduced tip-trajectory (gray dashed arrow); bottom row, the resultant written states of vortices (anticlockwise circulation in white, clockwise in black), and

the magnetization direction of tip-written macrospin states (-45° nanoislands with south-east macrospins in pink, $+45^\circ$ nanoislands with north-east macrospins in yellow). The tip trajectory moves through the array at a slight angle, crossing the lower end of the nanoislands at the left-hand side of the array, with the point at which the tip crosses the nanoisland moving gradually upwards until it crosses the top end of the nanoisland at the right-hand side of the array. A transition in the resultant tip-written magnetic states is observed across the scan line, going from writing anticlockwise single vortices (white) on the left, to a mix of anticlockwise and clockwise single vortices in the middle, to the possible start of a clockwise vortex (black) regime on the right. This suggests that the position at which the tip crosses the nanoisland has an impact on the circulation of the resultant written vortex state. Additionally, a change is observed in which nanoislands are written into oppositely magnetized macrospin states, with macrospin reversals occurring only in nanoislands oriented at -45° to the horizontal (pink, with south-east pointing macrospins) on the left, and subsequent macrospin reversals

TABLE I. Sample dimensions. Average lengths (L), widths (W), aspect ratios (R), and vertex gaps (V , from a nanoisland end to a vertex center) of wide and narrow nanoislands in the arrays used within this work, measured with a scanning electron microscope. The values reported for Arrays 1–4 are reasonably representative of the full arrays owing to their overall size, but the larger size of Array 5 makes reporting representative errors difficult. The values stated for the Array 5 are therefore ideal, but fabrication-based quenched disorder will affect the behavior of the array.

[nm]	L_{Wide}	W_{Wide}	R_{Wide}	L_{Narrow}	W_{Narrow}	R_{Narrow}	V
Array 1	546 ± 11	182 ± 6	3	546 ± 15	122 ± 11	4.5	91 ± 9
Array 2	593 ± 9	203 ± 6	2.9	588 ± 10	132 ± 6	4.5	95 ± 5
Array 3	569 ± 12	199 ± 7	2.9	569 ± 14	135 ± 11	4.2	86 ± 9
Array 4	595 ± 10	213 ± 4	2.8	596 ± 11	145 ± 13	4.1	86 ± 9
Array 5	600	200	3	600	125	4.8	100

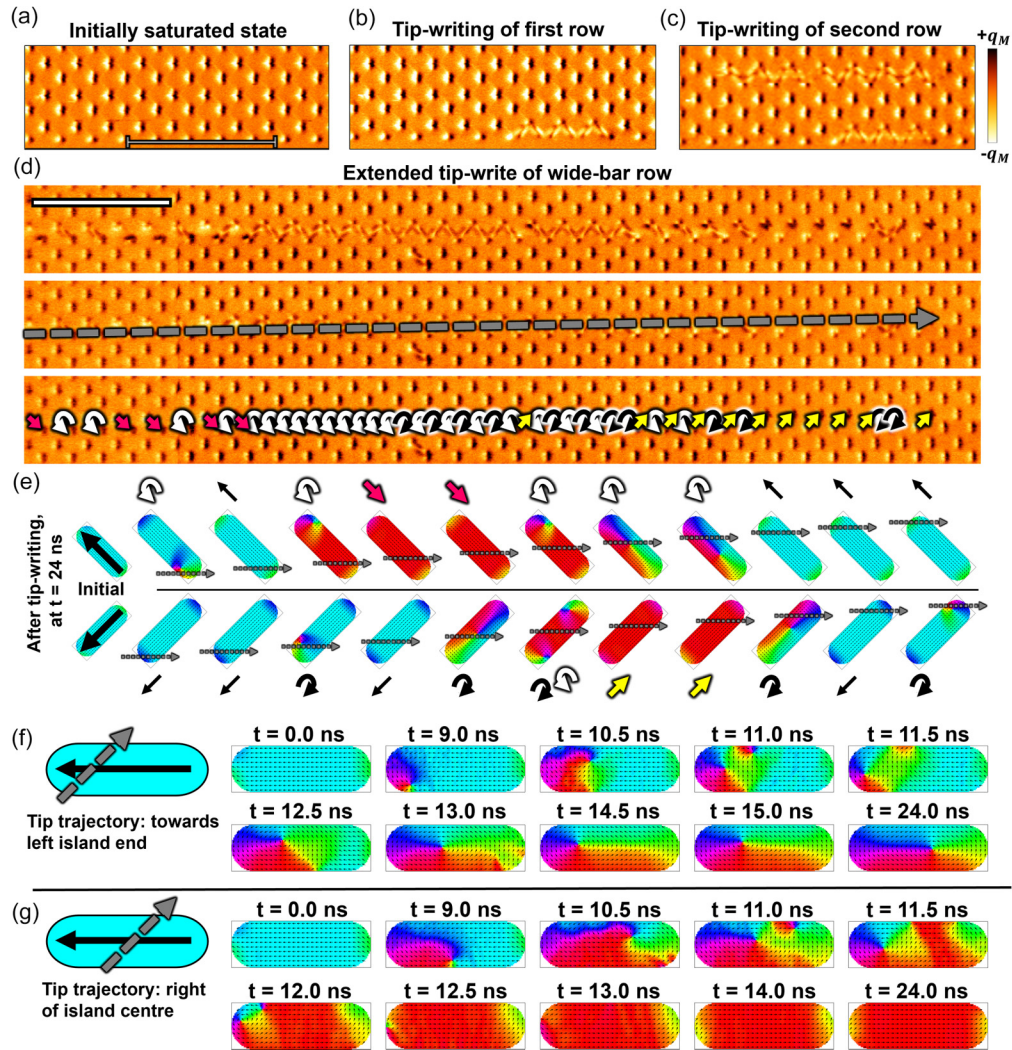


FIG. 2. MFM tip writing of single-vortex states. (a) MFM image showing section of Array 2 after initial global field saturation in the negative x direction. Scale bar = $5\ \mu\text{m}$. (b) MFM image after tip-writing the bottom wide nanoisland row. A chain of single vortices is induced. (c) MFM image after a second tip-write along the third wide nanoisland row. A long chain of primarily single vortices is induced, with a double vortex in the middle of the chain and on the right end of the chain. (d) MFM image showing section of Array 5 after tip-writing, with the approximate deduced tip motion path highlighted (middle row), and annotated vortex circulation chiralities and macrospin-to-macrospin reversals (bottom row). A crossover in vortex writing behavior is observed as the tip crosses the nanoislands at different regions along the island length, going from purely anticlockwise circulation on the left of the write-line, to mixed circulation. Scale bar = $5\ \mu\text{m}$. (e) Simulated micromagnetic states of nanoislands after being tip-written at different tip-island crossing points. Tip-writing positions are shown by dashed gray arrows over nanoislands. Final-state labels correspond to those in (d), with black arrows denoting nanoislands that are not written. Nanoislands have dimensions of Array 5 wide bars. Note that here the color wheel is defined relative to the initial nanoisland magnetization for ease of reading. (f) Time series of the tip-writing process, showing magnetic texture evolution as the MFM tip crosses close to the island edge. Schematic at the left shows the approximate location of tip trajectory. The initially $-x$ saturated macrospin is written into an anticlockwise single-vortex state by the tip. (g) Tip-writing time series in which an initially $-x$ saturated macrospin is written into a reversed $+x$ macrospin state by a tip crossing at island center.

on the right only in $+45^\circ$ nanoislands (yellow, with north-east pointing macrospins). Further examples showing evidence of the impact of the tip-nanoisland crossing point on the resultant written state, with some deviations from the trend, are shown in Figs. S5 and S6 within the Supplemental Material [73].

To investigate the physical mechanism of the observed writing, we perform micromagnetic simulations of tip-writing on a single isolated nanoisland at a range of tip-nanoisland crossing points corresponding to different regions along the angled tip-trajectory scan performed in Fig. 2(d), with island

dimensions corresponding to a wide bar of Array 5. The results are shown in Figs. 2(e)–2(g).

Figure 2(e) shows the final nanoisland states after simulated MFM tip scans at different tip-island crossing points, from the island-bottom to island-top. Nanoislands were oriented at $\pm 45^\circ$, and a “tip”, modeled here as a monopole moment, scans horizontally across the nanoisland at different offsets along the long axis of the bar (details in Methods). The top row shows resultant post-tip-scan states of nanoislands oriented at -45° , and the bottom row $+45^\circ$. Approximate tip

locations are shown by gray dashed arrows, and annotation arrows above/below each nanoisland denote the resultant written states, corresponding to those used in Fig. 2(d). Note that here the color wheel is defined locally to the initial nanoisland magnetization for ease of reading. The simulations generally reproduce experimental observations of different writing regimes at different tip-island crossing points. These are: primarily anticlockwise circulation in single vortices induced in nanoislands by a tip crossing close to the bottom narrow edge of the bar, a mix of anticlockwise and clockwise single vortices being induced by a more central tip crossing, and primarily anticlockwise circulation of single vortices induced by a tip crossing close to the top narrow edge of the bar. However, there is uniform vortex circulation selectivity by nanoisland orientation, with -45° hosting anticlockwise single vortices, and $+45^\circ$ clockwise single vortices.

This exclusive bar orientation single-vortex circulation selectivity is not observed in our experimental tip-writing results. This is likely caused by two factors: In simulation, the island geometry and dimensions are perfectly geometrically uniform with smooth edges. In experiment, islands have stochastic patterning imperfections that will locally vary magnetic reversal dynamics (often termed “quenched disorder” [3]). Another key difference between the simulated and experimental conditions is the absence of neighboring nanoislands in our simulations, which add a local background dipolar field contribution that can impact reversal dynamics.

Macrospin-to-macrospin switching is only observed for more central tip-crossings in simulation. These macrospin reversals follow the same pattern seen in experiment, with macrospin reversals occurring only in nanoislands orientated at -45° to the horizontal (pink, with south-east pointing macrospins) for tip-writing in the lower half of the nanoisland, and subsequent macrospin reversals only in $+45^\circ$ nanoislands (yellow, with north-east pointing macrospins) for tip-writing in the upper half of the nanoisland.

Largely, the key features observed in experimental writing are captured by the simulations, highlighting that control of the tip-nanoisland crossing point can afford additional control of the resultant written states, including control over whether vortices or macrospins are written, and the circulation of written vortices.

To investigate the dynamic reversal pathways of the observed writing, we study the temporal trajectories of the magnetization texture during the tip writing process. Figures 2(f) and 2(g) show time series of isolated Array 5 wide nanoislands throughout the tip-writing process, with the approximate location of the tip trajectory shown in the schematics to the left of the time series. Figure 2(f) shows the time evolution of the magnetic texture as tip-writing is performed with a tip-island crossing point towards the end of the nanoisland, where an initially $-x$ saturated macrospin is written into an anticlockwise single-vortex state. Here, a converging magnetization region localized under the MFM tip moves across the island, driving the formation of an anticlockwise magnetization region to the left of the tip ($t = 9.0\text{--}10.5$ ns), which stabilizes into a magnetic vortex with its own core at $t = 11$ ns. As the tip leaves the nanoisland ($t = 11.5$ ns), the vortex core migrates to a low-energy state towards the island bulk ($12.0\text{--}24.0$ ns), resulting in a stable written vortex state.

Figure 2(g) shows the time evolution for tip-writing with a tip-island crossing point towards the nanoisland center. Here, because of the central initial crossing point of the tip, the “red” region of the nanoisland, which is oriented in the $+x$ direction opposing the initial macrospin orientation, rapidly grows larger from $t = 9.0\text{--}10.5$ ns, dominating the nanoisland by 10.5 ns. This results in a more contorted texture of rotating regions of the magnetization texture that are not aligned along $+x$ and associated high exchange energy penalty for those regions, causing them to collapse as the tip leaves the nanoisland and resulting in a final magnetization state corresponding to a $+x$ oriented macrospin, and observed macrospin-to-macrospin reversal process, corresponding to experimental observations in Fig. 2(d) and previously reported MFM tip macrospin-to-macrospin switching by some of the coauthors [21]. Further time-series simulation results can be provided upon reasonable request. These time-series simulations describe the varying micromagnetic reversal pathways that can be selectively driven by the tip-island crossing point, elucidating the underlying physics and confirming the degree of writing selectivity afforded by controlling the tip-island crossing point.

The control over single-vortex circulation provided by the tip crossing point are broadly well correlated with previously reported micromagnetic simulation work investigating the writing of nanomagnetic disks (although differences in tip motion are noted) [52], highlighting that the experimental results obtained here have potential applicability to a broader range of nanomagnetic geometries beyond islands and stadia.

The success rate and fidelity of the tip-writing technique has room for improvement. Often attempted tip-writes give no writing (an “unsuccessful” write), and when writing does successfully occur, some islands along a write-line may not be written at all, or a reversed macrospin is written instead of a vortex (a “low fidelity” write). We have observed examples of writing events that inject vortices into many successive nanoislands, such as the written states shown in Figs. 2(b) and 2(c). Our experimental results and simulations suggest that while tip-crossing points afford control, unless this control is exercised the varying reversal dynamics at different crossing points will result in different writing behavior, highlighting the need for high accuracy in the spatial control of the tip trajectory. The amplitude of the tip field was found to have substantial effect in simulations, with simulated tip strength and polarity chosen because of correspondence with experimental observations (see Figs. S7 and S8 within the Supplemental Material [73]). Experimentally we observed that different batches of tips or different manufacturers appeared to have different magnetic strengths, leading to variations in writing fidelity. As better control is gained over the spatial control and tip quality and strength, the fidelity and success of tip-writing protocols will likely improve.

C. All-optical vortex writing

Here, we consider all-optical linearly polarized laser writing of double-vortex textures. The speed and potential for future device integration make all-optical writing an attractive magnetic microstate control approach [75–78]. In addition to

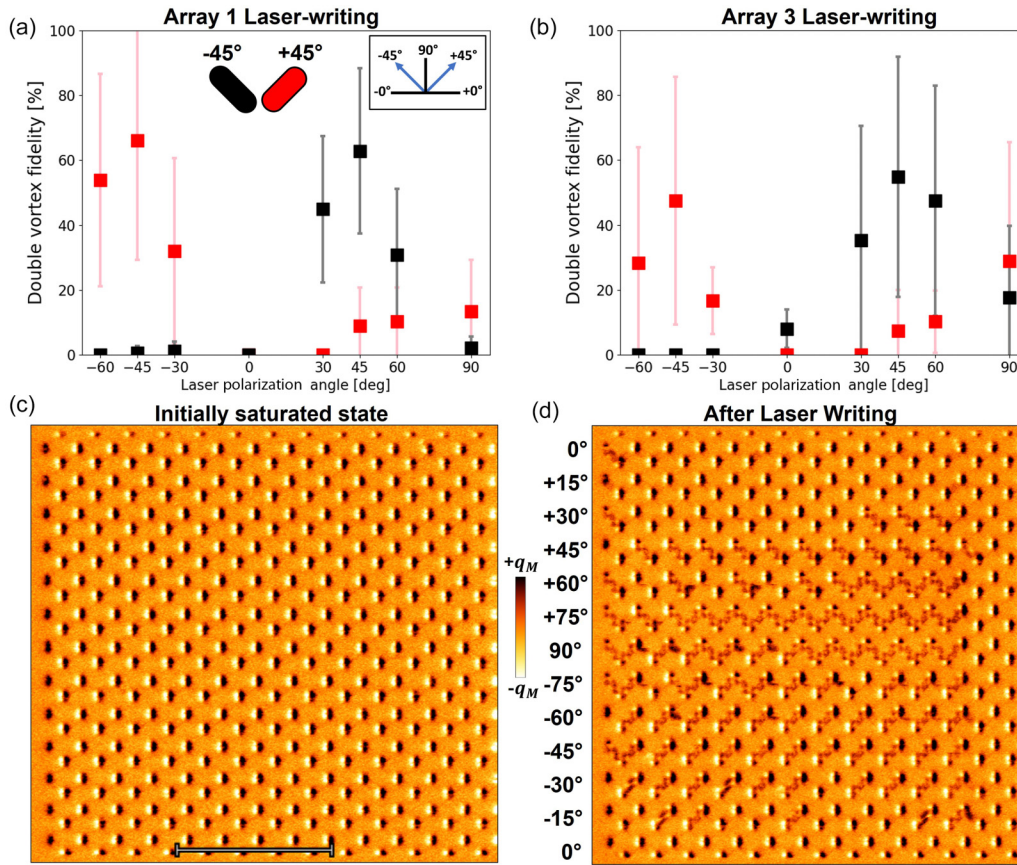


FIG. 3. All-optical laser writing of double vortices. (a) and (b) Experimental fidelity of double vortices induced by laser writing as a function of laser polarization, for wide nanoislands from Arrays 1 and 3, with $P = 4.8$ mW. Statistics for nanoislands oriented at $+45^\circ$ are shown in red, while nanoislands oriented at -45° are shown in black. Error bars show the standard deviation. Insets show a schematic of two wide nanoislands showing orientation nomenclature and corresponding colors, and axes showing nomenclature of laser polarization respectively. (c) MFM image showing the initially saturated state of Array 4. Scale bar = $5 \mu\text{m}$. (d) MFM image showing the same array after laser writing of all wide nanoisland rows ($P = 5.0$ mW). The laser polarization is labeled on the left-hand side of each row.

the creation of topological defects in (out-of-plane anisotropy) ferrimagnetic [58] and (in-plane anisotropy) ferromagnetic [59] thin films via ultrafast laser illumination, optical switching of single-vortex cores in Permalloy nanodisks via a circularly polarized ultrafast laser-induced inverse Faraday effect has previously been theorized [60], and complex topological defects created from single-vortex states via ultrafast laser quenching in a variety of Permalloy nanodisk shapes experimentally demonstrated [61] (both in-plane anisotropy). Here, a linearly polarized continuous-wave focused laser spot is scanned across rows of wide nanoislands to primarily write double-vortex states. The all-optical writing of double vortices offers polarization-based selectivity of which $\pm 45^\circ$ nanoisland orientations are written, with single nanoisland-level spatial control.

Multiple repeated laser writing processes were performed, in order to collect write-fidelity statistics on which $\pm 45^\circ$ island subsets were written at which laser polarizations. Arrays 1 and 3 were both studied, to investigate effects of nanoisland geometry and aspect ratio on the laser-writing procedure. Figures 3(a) and 3(b) show the double-vortex writing fidelities in these two arrays as a function of polarization angle for a laser power of 4.8 mW, with the inset schematic in Fig. 3(a) illustrating the nomenclature for

nanoisland orientation and laser polarization. Nanoisland orientations $\pm 45^\circ$ are denoted by red ($+45^\circ$) and black (-45°) squares. Only laser polarizations with at least four repeated illuminated rows are included. The all-optical writing preferentially writes double vortices into nanoislands where the laser polarization is aligned closely to the short axis (width) of the nanoisland—potentially because of asymmetric optical absorption in the nanoislands, discussed further below. Laser writing can also induce nanoislands into single-vortex states, though these are observed more rarely. Nanoislands showing signs of magnetic damage after illumination (determined by reduced MFM image contrast) are not included in these switching statistics, nor are nanoislands that are induced into single-vortex/indeterminate multidomain textures (see Tables S1 and S2 within the Supplemental Material [73] for full statistics, including rare occurrences of laser-induced damage).

While the general trend of preferential laser-induced double vortex writing when the linear laser polarization is aligned along the nanoisland width/short axis holds for both Array 1 and 3, the total double-vortex writing fidelity shows some variation between the two array geometries with Array 1 exhibiting overall higher fidelity. Further investigations can determine if these fidelity discrepancies are caused by the

differences in nanoisland dimensions between Arrays 1 and 3, with the possibility of optimizing nanoisland dimensions for enhanced fidelity.

To demonstrate more granular variations of the laser polarization on all-optical double-vortex writing, we perform a study where adjacent rows of an ASVI array (Array 4) are written with incremental 15° steps of the laser polarization between rows. Figure 3(c) shows an MFM image of Array 4 in an initial global-field saturated state ($-x$ direction). Figure 3(d) shows the same array after laser writing all wide-bar rows, with the laser polarization shown at the left-hand side of each written row. The effect of the laser polarization on the all-optical double vortex writing can be clearly observed— $\pm 45^\circ$ polarization gives high-fidelity writing in the angled nanoisland subset where the nanoisland width is parallel to the laser polarization, $75\text{--}90^\circ$ shows good fidelity writing in both nanoisland subsets, while 0° polarization results in almost no writing events. This difference in fidelity between 90° rotated laser polarizations is intriguing, and one potential mechanism for this could be the predicted reversal in laser-induced IFE B_z -field polarity when linear polarization is rotated by 90° [79]. Simulations suggest that inverting the B_z -field polarity may result in an inversion of the resultant written vortex state, and because of the local dipolar field of the array, only one vortex circulation is favored by the background dipolar field emanating from neighboring islands. The laser-write illumination scans shown in Figs. 3(c) and 3(d) were not scanned to the very right-hand side of the array, explaining the lack of write events in that region, and the resulting longer exposure of the final illuminated column from a longer laser spot dwell-time results in two damaged nanoislands (see Fig. S9 within the Supplemental Material [73] for MFM images of the resaturated array state showing this).

The strong polarization dependence of which nanoisland orientation is written may be caused by polarization-dependent optical absorption within the nanoislands. To test this, simulations using the Lumerical FDTD package [80] were performed to calculate the total optical absorption within the nanoislands. The absorption is found to be uniformly higher when the laser polarization is oriented along the short axis (width) of the nanoisland, across Arrays 1–3, although the increase in absorption is relatively small ($1.125 - 1.167\times$ higher when the laser polarization lies along the nanoisland width vs length). Array 1 wide nanoisland absorptions are calculated to be 5.4% (perpendicular) and 4.8% (parallel), and 9.1% and 7.8% for Array 3 (see Fig. S10 within the Supplemental Material [73]). Further investigation of the differences in the all-optical writing behavior between these polarizations provide fertile ground for future work, including studying well-separated nanoislands that are not influenced by the magnetic state/stray field of neighboring bars. As the laser absorption will also induce local heating of the nanoislands [67,68], thermal effects will likely induce a degree of stochasticity to the writing process.

The differences in optical absorption at different polarizations appear to be relatively small, and although geometrical imperfections will alter experimental absorption it is speculated that the polarization selectivity may also be influenced by an additional physical mechanism,

such as a magneto-optical effect. A single optically induced macrospin-to-macrospin reversal is also observed. The physical mechanism(s) underpinning the optical writing of double vortices is an area of ongoing research. In addition to the local plasmonic heating induced by the laser spot [67,68], the possibility of additional influences, such as the inverse Faraday effect, which traditionally has been considered to result from circularly polarized incident light, but can be induced by linearly polarized light at a polarization angle offset from the long axis of a nanoisland [79], are under investigation.

D. Local seeding of avalanche-like reversal via double-vortex writing

Vortex textures in strongly interacting nanomagnetic arrays have been previously shown to influence the reversal dynamics of neighboring islands, leading to emergent growth of vortex-state domains in large arrays [36]. Previously, vortex nucleation studies in such arrays have been purely stochastic. Here, we investigate the ability of locally laser-written double-vortex textures to influence the switching dynamics of neighboring bars and controllably nucleate avalanche-like reversal events that propagate through multiple islands.

Double-vortex states have very low stray dipolar field and a significantly lower coercive switching field than macrospin or single-vortex states, allowing them to locally modify both the dipolar field landscape and reversal dynamics of the array. Interestingly, while double vortices have a significantly lower coercive field than macrospins, single vortices have a higher coercive field than macrospins, demonstrated experimentally previously [36]. This allows for multilevel coercive field programming in these tristable multitexture ASVIs, discussed further in Fig. 5 below.

We study the ability of laser-written double-vortex states to drive avalanche-like nucleation in a two-step process: First, we prepare a negative x direction saturated array state (Array 1) and scan a 4.8 mW, $+45^\circ$ polarization laser spot across a single row of the array to induce double vortices. Figure 4(a) shows an MFM image of the resultant array microstate with multiple double-vortex states written.

We then apply a global magnetic field of $H_{\text{app}} = 18.2$ mT, below the saturated-state macrospin coercive field of 20 mT {coercive field measured via magneto-optical Kerr effect $M(H)$ loops, data in Fig. S12 within the Supplemental Material [73]}, with the resultant array microstate shown via MFM image in Fig. 4(b). This allows us to isolate switching to nanoislands that have had their effective coercive fields lowered by the distortions applied to the local dipolar field landscape via the presence of flux-closing vortex textures. Here, we observe two key results: Double vortices have been converted primarily to macrospins oriented in the $+x$ direction as 18.2 mT is above the mean double-vortex breakdown field [see Fig. 5(b)] for relative texture switching fields, one double vortex remains at left edge of array, likely owing to patterning imperfections, one double-vortex has switched to a single-vortex towards the left-edge). In addition, multiple nanoislands that were not written into double-vortex states have also been reversed to point in the $+x$ direction, including a five-island chain of consecutive macrospin reversals where the laser-written double vortices have served to nucleate an

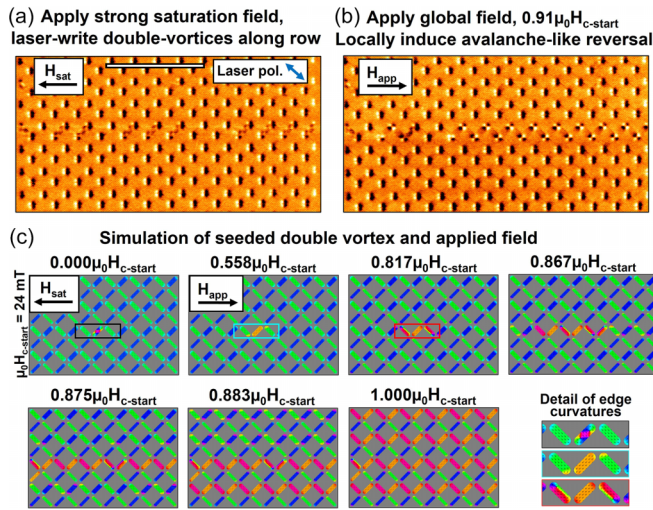


FIG. 4. Locally seeded avalanche-like reversal via optical double vortex writing. (a) Experimental MFM image showing nine laser-written double vortices along a row in Array 1, following application of an initial global saturating field ($-x$ direction). Scale bar is $5 \mu\text{m}$, laser polarization shown inset. (b) Subsequent field-activated microstate evolution of same array section. A $+x$ direction global magnetic field is applied at 91% of $\mu_0 H_{c\text{-start}}$. Around the double vortices local modification of the stray-field landscape leads to an avalanche-like chain of reversals occurring leading to a one-dimensional row of type-1 ASI vertices. Two isolated switches occurred in regions of the array away from double vortices. (c) Simulated reduced Array 1, initially saturated in the $-x$ direction with a seeded double vortex, with a global field applied in $+x$ at 0.2 mT steps. Snapshots of changed macrostates are shown, with $\mu_0 H_{c\text{-start}}$ corresponding to first switch of initially globally saturated simulated array.

avalanche-like reversal event. The resultant state is a one-dimensional chain of “Type-1” ASI state [3], which is the ground state of square ASI, leading to “chequerboard”-like MFM vertex contrast. The resultant Type-1 domain chain is 17 nanoislands long, with only seven of the nanoislands originally laser-written into a double-vortex state. This has formed an effective one-dimensional avalanche [14]. Reduced dimensionality avalanches in strongly interacting systems are intriguing phenomena that have been previously studied [14], though without the ability for controlled local nucleation, which the vortex writing introduces. Throughout the rest of the array, all other macrospin nanoislands away from the written vortex line did not reverse (338 nanoislands) save for a single island at the array edge where the effective switching fields are reduced. These results demonstrate the ability of vortex writing to reconfigurably locally seed avalanche-like switching, where manually written nanoisland states nucleate longer-range switching behaviors. The local vortex writing provides a way to controllably define the nucleation sites for reversal, introducing reconfigurable spatial control to avalanche switching studies [14,15,71], which are typically limited by stochastic dynamics, opening inviting routes for future research into many-body avalanche dynamics in strongly interacting systems. Further tests of laser-writing double vortices and subsequent reversal activation by global field are shown in Figs. S13–S15 within the Supplemental Material [73].

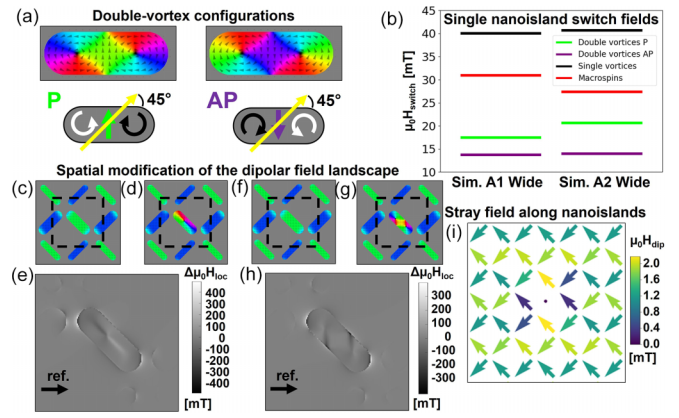


FIG. 5. Simulated switching fields of different nanoisland textures and modification of the stray field landscape. (a) Micromagnetic simulations (above) and corresponding schematics (below) showing texture of the two double-vortex nanoisland configurations used to calculate switching fields. Configurations are labeled as P (parallel) or AP (antiparallel) depending on direction of the central component of the double-vortex texture with respect to the applied magnetic field at $+46^\circ$ (yellow arrow). N.B. simulated fields are applied at $\pm 45^\circ$ (to break symmetry) and then averaged, corresponding to the experimental sample geometry in which nanoislands lie at $\pm 45^\circ$ and fields are applied parallel to the x axis. (b) Plot showing the simulated magnetic switching field of a single-vortex (black), parallel double-vortex (lime), antiparallel double-vortex (purple), and macrospin state (red) of a single wide nanoisland, for dimensions corresponding to “wide” nanoislands from Array 1 (left column) and Array 2 (right column). (c)(d) Cropped array section of micromagnetic simulations in an all-macrospin state, and with a clockwise single vortex, corresponding to dimensions of Array 5. (e) Plot of matching array section to that shown by dotted boxes in (c) and (d), with grayscale intensity representing the decrease in local demagnetizing field along the $-x$ direction when the all-macrospin state is subtracted from the vortex state, i.e., a relative increase along $+x$. (f)(g) Cropped-array section of micromagnetic simulations in an all-macrospin state, and with a double vortex, corresponding to dimensions of Array 5. (h) Plot of matching array section to that shown by dotted boxes in (f) and (g), with grayscale intensity representing the difference as in (e). (i) Plot showing section of ASVI Array 5 model used to calculate reduction in stray magnetic field in nanoislands neighboring a vortex texture (shown here as a small dot). $\mu_0 H_{\text{dip}}$ is the magnitude of the stray field along the direction of magnetization of each bar.

To investigate the time-resolved reversal pathways throughout the avalanche-like reversal, we perform micromagnetic MuMax3 simulations of the process, initializing a single double vortex within the array and gradually increasing the applied global magnetic field to study the locally nucleated long-range avalanche-like switching. Figure 4(c) shows the results of these simulations. A negative ($-x$) direction saturated macrospin array (dimensions following Array 1) is initialized with a single double vortex at the center. A global field is then applied in the positive x direction, and increased up to 24 mT that is the macrospin reversal field in these simulations when no vortices are present. The simulations reveal details of the reversal pathway. First, the double vortex is switched to a $+x$ direction magnetized macrospin (second

panel). This serves to induce local rotation of the edge curvature in the neighboring macrospins (see inset), which lower their effective coercive fields and cause them to switch into single-vortex states (third panel). This in turn reduces the effective switching field of their nearest neighbors, and the reversed chain grows in length (fourth panel), with a row of reversed macrospins and single-vortex states propagating out from the initial double vortex location at the array center. By the fifth panel, the reversed chain has spanned the array width, with no other nanoislands in other rows switching. This qualitatively reproduces the observed experimental results, and shows that the ability of written vortex states to locally reduce the effective switching fields of neighboring islands is of substantial magnitude to nucleate and drive long-range avalanche-like switching at global fields that are below the switching thresholds of nanoislands not adjacent to the written vortex states. This result is substantial, and motivates local writing of vortex textures as a tool to locally seed and manipulate long-range many-body switching dynamics that are often challenging to control.

The determination of the simulated array coercive field, and a simulation of an extended array section with initial microstate matching that in Fig. 4(a), with reversals occurring at applied fields far below those required to induce reversals in nanoislands far from vortices, are provided in Figs. S17–S19 within the Supplemental Material [73].

E. Multilevel switching fields of macrospin, single-vortex, and double-vortex states

Here, we explore the different relative coercive switching fields for the three macrospin, single-vortex, double-vortex textures hosted by the ASVI. The switching fields required to reverse the three possible initial nanoisland magnetic textures (double-vortex, single-vortex, macrospin) into a macrospin aligned with the applied field H_{app} are calculated via micromagnetic simulation and shown in Fig. 5(b). We show that the relative switching fields of the three textures are well distributed from low (double-vortex), medium (macrospin), to high (single-vortex). The ability to locally write and control these three tristable textures provides a rich, multilevel system in which even globally uniform magnetic fields can provide tailored switching activation to islands in the three different texture states, broadening the potential microstate control and switching studies relative to arrays comprising just macrospin or macrospin/single-vortex textures.

The simulations shown here in Fig. 5 correspond to the experimental setup of the system, with nanoislands at $\pm 45^\circ$ and applied fields along the x direction (all fields had 1° symmetry breaking in the x - y plane). For clarity and to highlight their dissimilar switching dynamics, we separate double-vortex states into two configurations “Parallel” (P) and “Antiparallel” (AP) shown in Fig. 5(a), with accompanying magnetic schematics. The parallel state “P” is so-called because of the central region of the double-vortex texture containing a component aligned parallel to the applied magnetic field H_{app} along $+45^\circ$. The antiparallel state “AP” is named for the reverse. For laser writes performed on x direction saturated arrays, the configuration of the written double-vortex states depends only on the initial saturation direction of the array,

regardless of laser polarization or laser scanning direction. The resulting configurations are such that laser writing of an array induces double vortices with central components opposite to the saturation direction, likely owing to this configuration having lower energy than the other because of the Zeeman energy being influenced by the local background dipolar field emanating from neighboring macrospin nanoislands.

Figure 5(b) shows the resulting simulated switching fields of isolated wide nanoislands in initially macrospin, single-vortex, parallel double-vortex, and antiparallel double-vortex states, for dimensions corresponding to Arrays 1 and 2. For both arrays, there is a clear trend in switching field amplitude going from the double-vortex, to macrospin, to single-vortex states, with broadly separated switching fields that are spaced far enough to overcome the effects of quenched disorder from patterning imperfections, allowing different sets of textures to be targeted for switching via different amplitude global magnetic fields. Further details are provided in Figs. S20–S22 within the Supplemental Material [73] including simulated magnetization maps of different textures at different field strengths, showing the various reversal pathways.

In Figs. 5(c)–5(i), we investigate via simulations the reduction in local dipolar field landscape at the neighboring bars around a written vortex state, corresponding with the Fig. 4 investigations on double-vortex-driven avalanche-like switching. Figure 5(c) shows a simulated region of Array 5 with all wide nanoislands in macrospin states, and Fig. 5(d) the same state with the addition of a clockwise single vortex. Simulations were performed with further columns to both the left-hand and right-hand sides, all in macrospin states, to negate any edge effects. Figure 5(e) shows a plot of the local difference in the demagnetizing field (along the x axis) between the vortex state, and the all-macrospin state, of the region highlighted by dotted boxes in Figs. 5(c) and 5(d), where $\Delta\mu_0 H_{\text{loc}} > 0$ represents a decrease in demagnetizing field for the vortex state in the initial saturation direction ($-x$) (i.e., a relative increase along the reference direction). Further information, including y -field plots, can be found in Figs. S23 and S24 within the Supplemental Material [73]. Similarly, Figs. 5(f) and 5(g) show the macrospin and double-vortex states, with Fig. 5(h) showing the difference in demagnetizing field between the two states as before.

In addition to the detailed micromagnetic simulations, Fig. 5(i) shows a simplified dipolar-field macrospin model of the reduction in dipolar field landscape caused by the presence of a vortex. Here, we simply model the vortex by the absence of a macrospin, as the substantial internal flux closure of vortex textures means they emit far less dipolar field than macrospins. This leads to modification of the effective switching fields of nanoislands that neighbor vortex textures, since the effective switching field $\mu_0 H_{\text{c-eff}}$ is a combination of the intrinsic nanoisland switching field $\mu_0 H_{\text{c-int}}$ (the field it would reverse at if it was an isolated nanoisland) and the effect of the stray dipolar field emanating from neighboring nanoislands $\mu_0 H_{\text{dip}}$, giving $\mu_0 H_{\text{c-eff}} = \mu_0 H_{\text{c-int}} + \mu_0 H_{\text{dip}}$. In a saturated macrospin state in which all nanoislands have been polarized by a global magnetic field (the so-called “Type-2” artificial spin ice state), the stray field of neighboring nanoislands increases the effective switching field $\mu_0 H_{\text{c-eff}}$, as an applied

field oriented against the nanosland magnetization would have to overcome both the intrinsic nanosland switching field $\mu_0 H_{c-int}$ and the additional stray dipolar field from neighboring magnets $\mu_0 H_{dip}$. The simulations in Fig. 5 show both the switching selectivity afforded by the three-tier well-separated coercive reversal fields of the three textures, and elucidate the substantial effect that vortex states impose on the local dipolar field landscape and hence array switching dynamics, enabling the long-range avalanche-like control demonstrated here. The denser and more strongly interacting the array, the greater the control over array switching dynamics that locally written vortices are able to introduce.

III. CONCLUSIONS

In this work, we have presented two methods for reconfigurable local control of vortex states in nanoslands, and demonstrated that written vortex states can significantly modify the switching dynamics of strongly interacting arrays—leading to avalanche-like switching. The methods introduced here expand the range of controllably accessible nanosland textures and microstates in nanomagnetic arrays, and expand artificial spin-vortex ice to host three distinct states beyond the two previously demonstrated—granting six states per nanosland and a large 6^N microstate space in an N -island array (core polarity is not considered here). We have characterized the fidelity and polarization-dependent selectivity of all-optical double-vortex writing, and shown evidence that surface-probe writing can offer single-vortex circulation and macrospin reversal subset control via the point at which the magnetic tip crosses the nanosland.

Our observation of locally seeded avalanche-like reversal events presents rich future opportunities to study intriguing avalanche reversal dynamics in ASVI and related strongly coupled systems without relying on stochastic nucleation of switching, which limited previous studies, with magnetic vortex textures acting as programmable defects in the stray dipolar field landscape, which can trigger long-range avalanche-like reversal events.

The customization of the local dipolar field landscape and array switching pathways offers routes forward for applied studies, including data input and “weight” programming of future ASVI-based neuromorphic and probabilistic computation schemes via microstate writing. Gaining local, reconfigurable control over the nucleation of magnetic vortex textures in nanomagnetic arrays enables direct exploitation of the enriched microstate dynamics and avalanche physics on offer in strongly interacting nanomagnetic arrays. We anticipate future work using the methods described here for programming computational states, both local writing of nanoslands to implement physical neuromorphic network weights, and preparation of switching pathways to implement Ising/Boltzmann machine-like optimization computing and probabilistic computing schemes.

IV. METHODS

A. Fabrication

ASVI arrays were fabricated via an electron beam lithography (Raith eLine) lift-off process using PMMA

resist. Sample measurements were determined via scanning electron microscopy, on the same Raith system, with average values reported for Arrays 1–3, where stated uncertainties are the standard deviation from this average in a sampled nanosland distribution.

B. Laser writing

Laser writing was performed with a $\lambda = 633$ nm continuous-wave (CW) HeNe laser via a Witec Alpha 300R Microscopy System, focused through a 100x (0.9 N.A.) Zeiss objective, with a final Gaussian spot $\frac{1}{e^2}$ diameter of 580 nm. Transmission through the lens is stated to be 91%. As such, powers reported in this work have been multiplied by 0.91 after power measurement without the objective lens present (some further optical losses may be present in the system). A maximum 2% difference was found between the power at different polarizations after the lens. Line scanning was performed by a piezo stage moving at 20 $\mu\text{m/s}$, with the center of the laser spot visually aligned with the center of the nanosland row [Fig. 1(b)]. For the statistics gathered in Figs. 3(a) and 3(b), nanoslands that were induced into a single-vortex state, or unidentifiable spin textures, were not counted towards double-vortex fidelities. All nanoslands were subsequently resaturated with a permanent magnet and measured via MFM to verify that no clear damage to the nanoslands had occurred from the laser illumination process. Nanoslands displaying signs of moderate damage were excluded from the total statistics. Laser polarizations of $\pm 36^\circ$ and $\pm 54^\circ$ were only performed on Array 1 in limited number and are not shown in the figure (full data is available in Tables S1 and S2 within the Supplemental Material [73]). Laser writing for these statistics was performed in both the $+x$ and $-x$ directions. Arrays were initially saturated in both the positive and negative x directions, with resulting statistics combined regardless of scan direction or initial saturation direction. Each illuminated row is recorded as a single data point for each $\pm 45^\circ$ nanosland orientation. Average fidelities and standard deviations are reported.

C. Tip writing

Magnetic tip writing was performed on a Veeco Dimension 3100 Magnetic Force Microscope in tapping mode, using a commercially available high-moment tip (Bruker MESP-HM), at a low scanning speed (≈ 1 to 2 $\mu\text{m/s}$), in an orientation shown by Fig. 1(b). The exact location of the tip with respect to the nanoslands is manually controlled to $\approx \pm 500$ nm, more precise tip location can be discerned from resulting vortex locations. Measurements were analyzed with Gwyddion [81].

D. MFM imaging

Samples were magnetically imaged on the same system, using a low (Bruker MESP-LM-V2) or normal moment (Bruker MESP-V2) tip. Magnetic fields were applied to the sample via an electromagnet with saturation performed with a strong permanent magnet. Coercive and saturation field values were determined using a commercial Durham Magneto Optics

nanoMOKE2 system to measure the longitudinal Magneto-Optical Kerr Effect (MOKE) signal.

E. Simulations and plotting

Absorption simulations were performed with the Lumerical Inc. FDTD solver [80]. Micromagnetic simulations were performed with MuMax3 [74,82]. Saturation magnetization was set to $M_{\text{sat}} = 750 \times 10^3$ A/m, exchange stiffness $A_{\text{ex}} = 13 \times 10^{-12}$, and dM/dt with a stopping condition of 1×10^{-6} . Hysteresis simulations were performed statically, with energy minimization at each field step, with field applied at an angle of $\pm 1^\circ$ to the 45° direction (to break symmetry) and then calculated switching fields averaged. The applied magnetic field was incremented by $+0.1$ mT between each energy minimization step until reversal was observed. Single-vortex switching fields were averaged across both angular nanoisland orientations and both circulations. The averaging was performed on multiple initial random seeds. The magnetic simulation used to calculate the local stray dipolar field reduction in Fig. 5(i) was implemented with $M_{\text{sat}} = 800 \times 10^3$ A/m, matching the geometry of Array 5, and with no stray dipolar field from the vortex texture. The stray field was calculated at the locations of the centers of each nanoisland, using a dumbbell-like model [83] where the poles of the surrounding nanoislands were considered as point magnetic charges. Hysteresis simulations were discretized into cells of $2 \text{ nm} \times 2 \text{ nm} \times 5 \text{ nm}$, with other simulations discretized into $2 \text{ nm} \times 2 \text{ nm} \times 20 \text{ nm}$. Dimensions were chosen to match the measured array geometries as closely as possible while maintaining an even number of cells, and with highest prime factors of 7 or less where possible, for optimal performance [74]. Tip-writing simulations were created with OOMF [84], with the “tip” modeled as a monopole moment, and were performed with a 1° offset, with $T = 0$ K. Nanoislands had dimensions of wide bars from Array 5, with $\alpha = 0.01$, saturation magnetization $M_{\text{sat}} = 750 \times 10^3$ A/m, tip speed $v = 100$ nm/s, time steps $= 100$ ps. Avalanche simulations modeled Array 1, with $\alpha = 0.006$, $A_{\text{ex}} = 13 \times 10^{-12}$, $M_{\text{sat}} = 750 \times 10^3$ A/m, $T = 300$ K, and were performed with a 1° offset. Figures 5(e) and 5(h) were created with MATLAB [85]. All other analysis and plotting was performed with python [86], numpy [87] and matplotlib [88].

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H.H. and J.C.G. conceived the work. H.H. drafted the manuscript, with contributions from all authors. J.C.G. fabricated the ASVI. H.H. performed laser writing of horizontally saturated arrays and applied magnetic field protocols. A.J.W. performed micromagnetic simulations of tip writing and avalanching. T.Z., H.H., T.F., and D.B. performed preliminary laser writing tests of vertically saturated and demagnetized arrays. J.C.G. and H.H. performed MFM tip-writing experiments. H.H., J.C.G., T.Z., T.F., and D.B. performed MFM measurements. A.V. performed simulations for the calculation and analysis of the stray dipolar field in Fig. 5(i). T.D. created programs for the calculation and analysis of the spatial demagnetizing field landscape in Figs. 5(c)–5(g) and Figs. S17–S18. H.H. performed all other simulations, with contributions from K.D.S. and T.D. T.Z., J.C.G., A.V., and H.H. performed MOKE measurements of the coercive field. X.X. performed absorption simulations and measurements of the laser spot diameter. A.V. and T.Z. performed SEM measurements and analysis of nanoisland dimensions; Figs. S1–S4 were created by A.V. [73,89]

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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