

Current-induced magnetization control in dipolar-coupled nanomagnet pairs and artificial spin iceA. Pac^{1,2,*}, G. M. Macauley^{1,2,†}, J. A. Brock^{1,2}, A. Hrabec^{1,2}, A. Kurenkov^{1,2}, V. Raposo^{1,2,3,4}, E. Martinez^{3,4} and L. J. Heyderman^{1,2,‡}¹Laboratory for Mesoscopic Systems, Department of Materials, *ETH Zurich*, 8093 Zurich, Switzerland²*PSI Center for Neutron and Muon Sciences*, 5232 Villigen PSI, Switzerland³Department of Applied Physics, *University of Salamanca*, 37008 Salamanca, Spain⁴Unidad de Excelencia en Luz y Materia Estructuradas (LUMES), *Universidad de Salamanca*, Salamanca, Spain

(Received 23 January 2026; revised 3 August 2026; accepted 10 August 2026; published 13 October 2026)

Exploiting current-induced spin-orbit torques (SOTs) to manipulate the magnetic state of dipolar-coupled nanomagnet systems with in-plane magnetic anisotropy, such as artificial spin ices, provides a route to local, electrically programmable control of the magnetization, with relevance for applications including neuromorphic computing and reconfigurable magnonics. Here, we demonstrate how the orientation of a nanomagnet relative to the direction of an applied electrical current impacts the threshold current density needed for all-electrical field-free magnetization switching, and how dipolar coupling between the nanomagnets influences the switching of interacting pairs and ensembles of nanomagnets. Using a material system designed to generate SOTs in response to electrical currents, we find that the current required to switch the magnetization of isolated nanomagnets varies nonmonotonically as the angle between the nanomagnet long axis and the current increases. This trend in the switching current is also seen in pairs of nanomagnets. These nanomagnet pairs can switch either sequentially or simultaneously, depending on their relative geometry (side-by-side or end-to-end) and the applied current density. In small artificial spin ices, we observe a similar angular dependence of the switching current, which can be used to control the magnetization orientation of specific subsets of nanomagnets. The experimental results are supported by micromagnetic modeling, which illustrates how the various current-induced torques can be exploited to control the magnetization switching. This work thus establishes SOT switching as a practical mechanism for programmable manipulation of dipolar-coupled nanomagnetic systems.

DOI: [10.1103/mmzq-rnjf](https://doi.org/10.1103/mmzq-rnjf)**I. INTRODUCTION**

Artificial spin ices, which are arrays of mesoscopic, single-domain magnets, were first introduced as two-dimensional (2D) analogues of frustrated magnetic systems [1,2]. Since then, they have proven to be a powerful platform for exploring fundamental questions involving phase transitions [3–7] and emergent magnetic monopoles [8,9]. Increasingly, they are also being exploited in schemes for low-power computation, such as reservoir and neuromorphic computing [10–16], as well as reconfigurable magnetic logic [17–19].

Controlling the precise microstate of artificial spin ices, however, remains an outstanding challenge. Applied magnetic fields have provided the most direct means of reconfiguring their magnetic state, with the field orientation enabling specific magnetization reversal processes, including those mediated by emergent domain walls and clocked dynamics

[20,21]. In addition, thermal activation has been used to promote relaxation to low-energy states across a variety of lattices [6,22–24]. More recently, plasmon-assisted photoheating has offered spatial selectivity beyond global heating, enabling targeted reversal of individual nanomagnets within nanomagnetic logic gates [25,26]. Furthermore, there are schemes that use ultrafast lasers [27,28] as well as low-power lasers [29] to achieve specific magnetic states in artificial spin ices. Setting the state of individual nanomagnets can also be achieved using a scanning magnetic tip, though this approach is inherently slow [30,31]. For scalable and energy-efficient applications, it is vital to have local control and read-out of the magnetic state through purely electrical means, i.e., by applying an electric current [32,33].

Current-driven control of the switching of arrays of in-plane nanomagnets opens entirely new vistas for setting magnetic states, which can be exploited to realize neuromorphic computing architectures and reconfigurable magnonics. In particular, spin-orbit torques (SOTs) have emerged as a powerful mechanism to electrically control the magnetization within magnetic thin films, while arrays of magnetic tunnel junctions have been implemented to read the magnetic states [34–38]. SOTs arise when an electrical current passes through a heavy-metal/ferromagnet heterostructure. The electrical current in the heavy metal gives rise to a transverse spin current (of spin polarization σ) that can exert a torque on the magnetic moment $\mathbf{m}$ in the adjacent ferromagnetic layer, and the resulting dynamics depends sensitively on the orientation between

*Contact author: ap4466@princeton.edu

†Present address: Department of Physics, Princeton University, Princeton, New Jersey 08540 USA.

‡Contact author: laura.heyderman@psi.ch

the electric current and the local magnetization [39]. Deterministic switching requires an additional symmetry-breaking mechanism when σ is orthogonal to $\mathbf{m}$, typically achieved by applying a magnetic field orthogonal to both σ and $\mathbf{m}$ [37]. This constraint has hindered the widespread deployment of SOTs in devices based on out-of-plane magnetized films, although the mechanism has been demonstrated in a few individual cases [40]. In contrast, in-plane magnetized systems [32,37] inherently permit the alignment between $\mathbf{m}$ and σ [32], enabling fully deterministic switching in certain scenarios. It has been also shown how the critical current required to switch the nanomagnet magnetization depends on the orientation between magnetization and the current direction in isolated nanomagnets [33]. In our study, we start with non-interacting systems and build on this knowledge when moving on to systems where we deliberately maximize the dipole-dipole coupling between the nanomagnets.

In this work, we demonstrate current-induced switching of isolated and coupled nanomagnets, including pairs of nanomagnets and small artificial spin ice systems consisting of arrays of nanomagnets arranged on a square lattice. We establish how the orientation of the nanomagnets with respect to the electric current impacts the threshold currents required for all-electrical magnetization reversal. Through careful choice of the magnitude and direction of the applied current, we demonstrate control of the magnetic state of the artificial square ice systems, with the ability to tune which sublattices switch.

We begin by quantifying the current-induced switching of isolated nanomagnets, extracting the minimum threshold current density required to switch the magnetization as a function of the angle between the nanomagnet long axis and the current direction. We then examine how dipolar interactions modify the switching behavior of pairs of nanomagnets. Finally, we extend this analysis to artificial square ices composed of orthogonal sublattices of nanomagnets.

Together, these results establish a framework for current-driven control of artificial spin ices and provide a basis for their use in spintronics, for example, for reconfigurable magnonics and in neuromorphic architectures.

II. CURRENT-INDUCED MAGNETIZATION SWITCHING OF ISOLATED NANOMAGNETS

We first examine the SOT switching of isolated nanomagnets as a basis for understanding the collective behavior that emerges in coupled nanostructures. In our experiments, individual stadium-shaped permalloy (Py) nanomagnets are placed on top of a Pt channel, which is schematically shown in Fig. 1(a). Each nanomagnet has a length $l = 450$ nm, width $w = 150$ nm, and thickness $t = 10$ nm. The large in-plane aspect ratio of the nanomagnets, $l/w > 1$, imparts a strong shape anisotropy that, combined with their small dimensions, ensures that the nanomagnets are single domain, with the magnetization $\mathbf{m}$ aligned along the nanomagnet long axis. We neglect any magnetic texture within individual nanomagnets [41,42] and describe their behavior in terms of a single macrospin.

The time evolution of the magnetization $\mathbf{m}$ under the influence of various torques is described by the Landau-

Lifshitz-Gilbert (LLG) equation,

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mu_0 \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \gamma \boldsymbol{\tau}_{\text{SOT}}. \quad (1)$$

where γ is the gyromagnetic ratio and α is the dimensionless Gilbert damping constant. The first term on the right-hand side of Eq. (1) leads to precessional motion of $\mathbf{m}$ around the direction of effective magnetic field $\mathbf{H}_{\text{eff}}$. The second, phenomenological term causes the magnetization to eventually align with the direction of the effective magnetic field. The third term represents the contribution of spin-orbit torques $\boldsymbol{\tau}_{\text{SOT}}$ to the behavior of $\mathbf{m}$.

When an electric current, with current density $\mathbf{J}$, passes through the Pt layer, the spin Hall effect generates a transverse spin current (of spin polarization σ), as indicated in Fig. 1(a) [43–45]. This results in a spin accumulation at the Pt/Py interface that gives rise to torques on the magnetization within the nanomagnets. In general, the resulting spin-orbit torques can be decomposed into two perpendicular components: a fieldlike torque $\boldsymbol{\tau}_{\text{FL}}$, which causes precessional motion of the magnetization, and a dampinglike torque $\boldsymbol{\tau}_{\text{DL}}$, which promotes reversal of $\mathbf{m}$. These torques can be expressed as

$$\boldsymbol{\tau}_{\text{FL}} = \tau_{\text{FL}} \sigma \times \mathbf{m}, \quad \text{and} \quad (2a)$$

$$\boldsymbol{\tau}_{\text{DL}} = \tau_{\text{DL}} (\mathbf{m} \times (\mathbf{m} \times \sigma)), \quad (2b)$$

where τ_{FL} and τ_{DL} are their associated magnitudes [39,46,47]. Equivalently, the torques can be expressed in terms of the cross product of $\mathbf{m}$ with effective fieldlike and dampinglike magnetic fields, defined as $\mu_0 \mathbf{H}_{\text{FL}} \propto -\tau_{\text{FL}} \sigma$ and $\mu_0 \mathbf{H}_{\text{DL}} \propto \tau_{\text{DL}} (\mathbf{m} \times \sigma)$, respectively. In addition to the effective fields resulting from spin-orbit torques, the applied current gives rise to an Oersted field, which acts in the opposite direction to the fieldlike SOT effective field for a Pt layer [48]. The orientations of the SOT effective fields $\mu_0 \mathbf{H}_{\text{FL}}$ and $\mu_0 \mathbf{H}_{\text{DL}}$, and the Oersted field $\mu_0 \mathbf{H}_{\text{Oe}}$, are shown in Fig. 1(a). Typically, the strengths of the associated torques depend on the intrinsic properties of the heavy metal and magnetic material, their respective thicknesses, and the quality of the interface between them [49]. The strength of the dampinglike torque is usually expressed in terms of the spin Hall angle θ_{SH} , for which we assume a value of +0.2 for Pt, according to

$$\tau_{\text{DL}} = \frac{\gamma \theta_{\text{SH}} \hbar}{2e M_{\text{S}} t_{\text{FM}}} J, \quad (3)$$

where M_{S} is the saturation magnetization of the magnetic layer, t_{FM} is its thickness, e is the electron charge, and $\hbar$ is the reduced Planck's constant.

It is conventional to distinguish between two geometries for SOT-induced switching of in-plane magnetized nanomagnets, which are defined by the orientation of the initial magnetization relative to the direction of the current density. In both of these geometries, the magnetization—here the macrospin associated with the net moment of the single-domain nanomagnet—lies in the plane. Based on the coordinate system in Fig. 1(a), in which the current density $\mathbf{J}$ flows along the x axis, these two geometries are:

(1) Type x , in which the long axis of the nanomagnet, and therefore the initial magnetization, is collinear with, and either parallel or antiparallel to, the applied current [32]; and

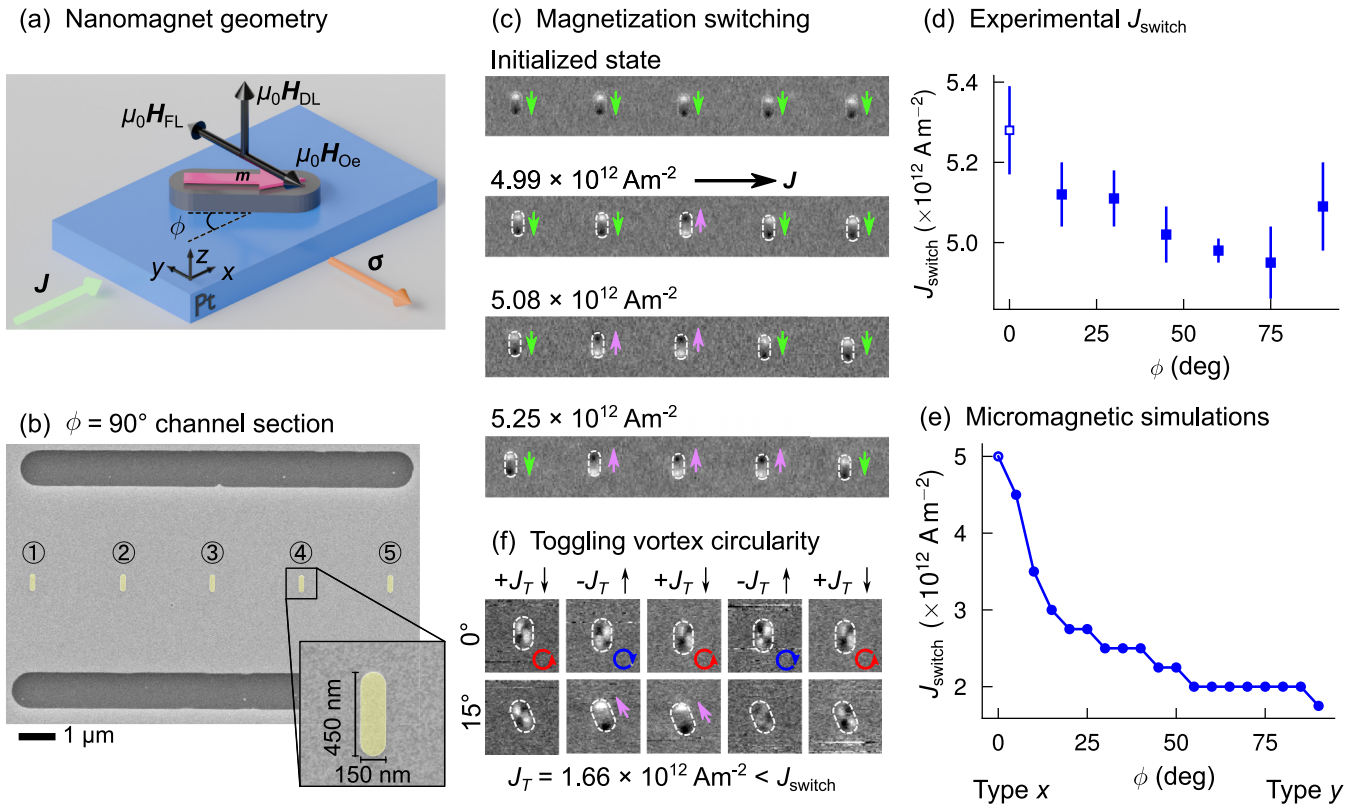


FIG. 1. Current-induced switching of isolated nanomagnets. (a) Schematic of an isolated stadium-shaped nanomagnet, shown in gray and with magnetization $\mathbf{m}$ (pink arrow), on top of a heavy metal channel, shown in blue. An applied current density $\mathbf{J}$ (green arrow) gives rise to the injection of spins with spin polarization σ pointing along the negative y axis (orange arrow). This polarized spin current gives rise to fieldlike and dampinglike SOT effective magnetic fields ($\mu_0 \mathbf{H}_{FL}$ and $\mu_0 \mathbf{H}_{DL}$). The Oersted field $\mu_0 \mathbf{H}_{Oe}$ generated by the charge current passing through the heavy metal layer opposes $\mu_0 \mathbf{H}_{FL}$. (b) SEM image of a row of five nanomagnets with their long axis orthogonal to the current direction, $\phi = 90^\circ$. (c) MFM images showing current-induced switching following the application of 1- μs current pulses. The nanomagnets were initialized in a uniform magnetic state (green arrows), and switched nanomagnets are indicated by purple arrows. (d) Experimentally obtained dependence of J_{switch} on ϕ . The data were obtained by averaging the current density at which the middle three nanomagnets switch for each angle, with the error bars corresponding to the standard deviation. The data point at $\phi = 0^\circ$ is located at the current density at which reversal was first observed, since a deterministic J_{switch} cannot be defined in this geometry. (e) Simulated angular dependence of J_{switch} from micromagnetic simulations. (f) MFM images demonstrating the ability to control the sense of magnetization circulation in vortex states found in larger nanomagnets in the Type-x geometry where $\phi = 0^\circ$. These vortex states are not well controlled when the angle is changed to 15° where several different magnetic states can be seen following application of the current pulse. Nanomagnet states going from left to right: anticlockwise vortex, two single-domain, multidomain and anticlockwise vortex.

(2) Type y, in which the long axis of the nanomagnet, and therefore the initial magnetization, is orthogonal to the applied current [37].

In Fig. 1(a), the initial magnetic configuration of the nanomagnet is represented by the macrospin $\mathbf{m}$, which is oriented at an angle $\phi \leq 90^\circ$ with respect to the negative x -axis. In what follows, we correspondingly define $\phi \in [0^\circ, 90^\circ]$ as the angle between the long axis of the nanomagnet and the channel. In each figure, the current direction will be indicated explicitly to uniquely specify the magnetic configuration with respect to the current flow.

We patterned isolated Py nanomagnets with various orientations ϕ on top of Pt channels using electron-beam lithography in combination with ion-beam milling of a Ta(3 nm)/Pt(6 nm)/Py(10 nm)/Ru(2 nm) sputter-deposited multilayer stack. The thickness of the Py layer was chosen to be large enough to provide sufficient magnetic contrast when imaging the nanomagnets using magnetic force microscopy (MFM). The Pt channels are connected to

Cr(5 nm)/Au(100 nm) bond pads patterned on top of the sputtered magnetic stack and deposited by thermal evaporation. Further details of the fabrication process for these devices can be found in Appendix A. Scanning electron microscopy (SEM) images of the entire device layout are provided in Sec. 1 of Supplemental Material [50] (see also references [51,52] therein).

To determine the impact of the orientation of the applied current on the threshold current J_{switch} required to switch the magnetization, we fabricated nanomagnets with ϕ increasing from 0° to 90° in 15° increments. For each orientation, five nanomagnets were patterned on a channel. Each nanomagnet on a given channel is separated from its immediate neighbors by $2.5 \mu\text{m}$ to minimize the dipolar coupling between the nanomagnets. An SEM image of a channel with nanomagnets oriented at $\phi = 90^\circ$ to the current direction is shown in Fig. 1(b). We label the five nanomagnets ① to ⑤ going from left to right. Also visible are horizontal slits, which separate adjacent channels where nanomagnets of different

orientations are patterned. A detailed rationale of the chosen sample design is provided in Sec. 1 of Ref. [50].

The nanomagnets were first initialized by applying an in-plane magnetic field to set them all in the same magnetic configuration. This was confirmed using MFM [first row of Fig. 1(c)], where the identical orientation of bright-dark contrast for every nanomagnet confirms that all the macrospins point in the same direction as indicated by the green arrows.

After initializing the magnetic state, 1- μ s-long current pulses of increasing amplitude were applied using a pulse generator, with no reinitialization of the magnetic state between pulses. For this, the current density was increased from 4.86×10^{12} to 5.38×10^{12} A m $^{-2}$, in steps of $\sim 0.05 \times 10^{12}$ A m $^{-2}$. The resulting magnetic configuration after each pulse was imaged using MFM. For the $\phi = 90^\circ$ nanomagnets shown in Fig. 1(c), nanomagnet ③ was the first to switch, followed by nanomagnet ②, and then nanomagnet ④. No switching was observed for nanomagnets ① and ⑤, even at higher current densities, because of reduced current density near the channel edges caused by fringing (Sec. 1 of Ref. [50]). The threshold switching current density, J_{switch} , shown in Fig. 1(d), was therefore defined as the average minimum current density required to switch the three central nanomagnets (②–④). We find that J_{switch} is largest near $\phi = 0^\circ$, where geometry is predominantly Type *x*, and decreases to a minimum at $\phi \sim 75^\circ$ before it increases again at $\phi = 90^\circ$, where switching is predominantly Type *y*. The increase in J_{switch} for $\phi = 90^\circ$ results in a trend that is somewhat different to the previous experimental observation of a monotonic dependence of J_{switch} on ϕ [32].

Assigning a precise value for the threshold current density is difficult for a pure Type-*x* geometry. In this geometry, with $\phi = 0^\circ$, the long axis of the nanomagnet is aligned with the current direction. For sufficiently high current densities, the effective field associated with the SOT drives the magnetization to point along the short axis of the nanomagnet. When the current is removed, and in the absence of any intrinsic disorder that may break the symmetry, the macrospin has an equal probability of relaxing into either of the two minimum energy states with the macrospin oriented along the long axis of the nanomagnet [53]. This means that the macrospin may relax back to its initial state. To differentiate this type of behavior from deterministic switching observed at other angles, the point at $\phi = 0^\circ$ is represented by an unfilled marker. This corresponds to the current density at which the magnetization first switches—from its initial magnetization direction to an opposite direction—after a current pulse. The current-induced reversal has been verified with two further experimental geometries for switching the magnetization of isolated nanomagnets; (i) reversing the current direction or (ii) reversing both the initial magnetization direction and the current direction (see Sec. 5 of Ref. [50]).

To better understand and complement our experimental data, we analyzed the dependence of J_{switch} on ϕ using micromagnetic simulations, the details of which are provided in Sec. 6 of Ref. [50]. In the simulations, the fieldlike torque is assumed to be proportional to the dampinglike torque, expressed as $H_{\text{FL}} = k H_{\text{DL}}$. We can then compare the experimental results from Fig. 1(d) with the simulations in Fig. 1(e) that include both the Oersted field and a ratio of the fieldlike

component to the dampinglike component of $k = 0.5$. The estimated strength of the Oersted field was obtained using COMSOL simulations, with more details provided in Sec. 2 of Ref. [50]. The micromagnetic simulations reproduce reasonably well the overall reduction in J_{switch} with increasing ϕ , leveling off between 50° and 90° , while experimentally, J_{switch} reaches a minimum at $\phi \sim 75^\circ$ before it subsequently increases, with a higher value at 90° .

To further examine the influence of the different contributions to switching, we also performed simulations with $k = 0$ (Sec. 6 of Ref. [50]) that corresponds to a purely dampinglike torque. This is because it is the dampinglike torque that is commonly considered the primary driver of magnetization switching by stabilizing the reversed state and minimizing the total energy [32,54]. When the Oersted field is included, the simulated minimum shifts to 80° – 90° when going from $k = 0.5$ to $k = 0$, while the minimum shifts to larger values when the Oersted field is not considered (Sec. 6 of Ref. [50]). Taken together, the simulation results demonstrate that the angular dependence of J_{switch} is governed by the interplay between the dampinglike and fieldlike SOT effective fields, and Oersted field.

We also carried out micromagnetic simulations of magnetic-field-driven switching in a single nanomagnet, as well as calculations of the energy barriers for isolated nanomagnet reversal through coherent rotation (Sec. 3 of Ref. [50]). From the micromagnetic simulations, we observe a minimum in the switching field at an angle of $\sim 22^\circ$, which is given by the nanomagnet lateral dimensions [55]. The position of the minimum differs from that found for the SOT-driven magnetization reversal, which can be explained by the fact that the SOT-driven magnetization reversal is driven by the combined effect of multiple fields (dampinglike, fieldlike, and Oersted).

Lastly, we have found that slightly larger nanomagnets ($l = 470$ nm, $w = 170$ nm) are capable of supporting either a single-domain state or a vortex state [56,57]. Interestingly, for such nanomagnets at $\phi = 0^\circ$, the circulation of the magnetization in the vortex state [10]—clockwise or anticlockwise—can be deterministically controlled, providing a means to toggle between them. This is illustrated in the upper row of images in Fig. 1(f). Following initialization in a magnetic field, the larger magnets were in a single-domain state. On application of a current pulse of density 1.66×10^{12} A m $^{-2}$, this transformed into a vortex state. It was then possible to toggle between clockwise and anticlockwise vortices with a threshold current density of $J_{\text{T}} = 1.66 \times 10^{12}$ A m $^{-2}$. This is below the current density required to switch the smaller nanomagnets at $\phi = 0^\circ$, which is around 5.1×10^{12} A m $^{-2}$. However, for nanomagnets oriented at $\phi = 15^\circ$, the switching between vortices with opposite sense of magnetization circulation becomes less deterministic, with current pulses leading to a mixture of vortex, multidomain, and single-domain states [see lower row of images in Fig. 1(f)].

III. SWITCHING OF PAIRS OF NANOMAGNETS ON CURRENT INJECTION

Now that we have established the current-induced switching behavior of isolated nanomagnets, we examine the

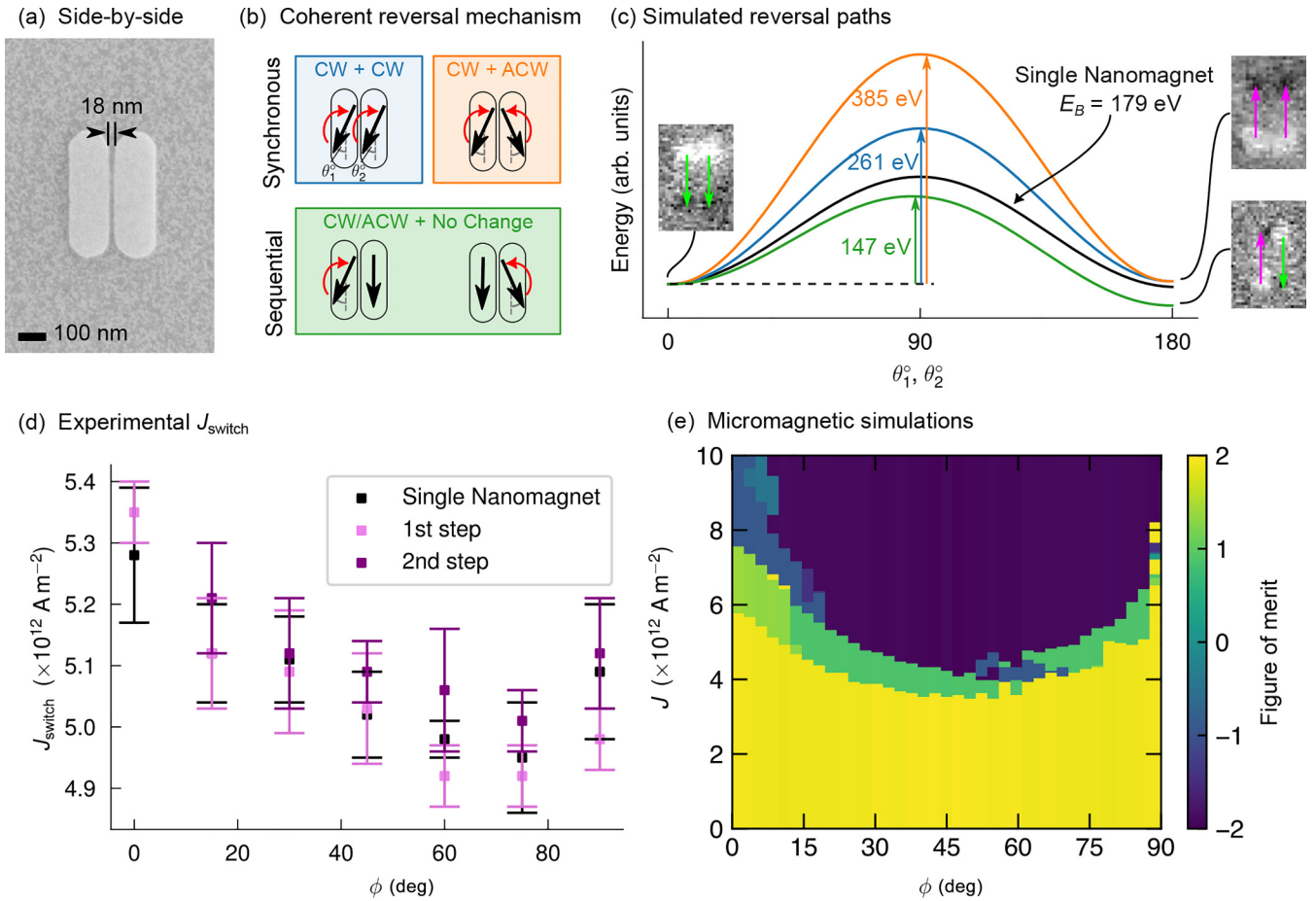


FIG. 2. Current-induced switching of side-by-side pairs of nanomagnets. (a) SEM image of a side-by-side nanomagnet pair. (b) Schematic of the different mechanisms for coherent magnetization reversal in the nanomagnet pair. For synchronous switching, both nanomagnets reverse simultaneously, rotating either in the same sense (in blue) or opposite senses (in orange). For sequential switching, one nanomagnet reverses before the other. (c) Reversal paths and energy barriers determined from micromagnetic simulations for the switching processes shown in (b) with the same color scheme. MFM images of the experimentally observed magnetic states are shown on either side of the energy barriers. (d) Experimental dependence of J_{switch} on ϕ for sequential switching of side-by-side nanomagnetic pairs. Data for the case of an isolated nanomagnet are included for comparison. (e) Simulated switching scenarios following current-pulse injection. The figure of merit, $m_{\text{start}}^1 \cdot m_{\text{end}}^1 + m_{\text{start}}^2 \cdot m_{\text{end}}^2$, identifies the switching threshold as a function of ϕ , where +2 (yellow) corresponds to the initial parallel configuration, -2 (dark blue) to the reversed parallel state, and 0 (green) to an antiparallel configuration.

simplest example of a coupled system, namely a pair of dipolar-coupled nanomagnets. We fabricated devices with two different arrangements of pairs: either (i) side-by-side [shown in Fig. 2(a)] or (ii) end-to-end (shown in Fig. S1.1(c), Ref. [50]). The edge-to-edge separation of the two nanomagnets arranged side-by-side (end-to-end) is 18 nm (22 nm). In both cases, this was the minimum spacing—and hence largest dipolar coupling—we could achieve with our fabrication process.

To gain insight into the effect of the dipolar interaction on the switching characteristics, we first performed micromagnetic simulations to estimate the intrinsic energy barrier to magnetization reversal (Sec. 3 of Ref. [50]). For simplicity, we adopted the Stoner-Wohlfarth model [58], in which the macrospin associated with a nanomagnet rotates in a coherent fashion between two bistable configurations separated by an energy barrier. In reality, we expect that, due to the size of the nanomagnet, the magnetization reverses via domain nucleation and domain wall propagation rather than coherent rotation [59,60]. Nevertheless, this simplified model

is sufficient to capture the trend in the energy barriers for the various nanomagnet pair configurations that are observed experimentally. The macrospin rotation is parameterized by an angle θ (relative to the nanomagnet long axis). In this picture, the energy minima for each individual nanomagnet correspond to the situation in which the macrospin is aligned in one of two directions along the long axis of the nanomagnet, while the energy maximum—corresponding to the energy barrier with respect to the energy of the initial configuration—occurs when the macrospin points along the nanomagnet short axis.

We show schematics for the possible switching processes for the side-by-side pair in Fig. 2(b), with the rotation angles for the macrospins in two nanomagnets, θ_1 and θ_2 , indicated. For two side-by-side nanomagnets, the lowest-energy state is the one in which the macrospins are antiparallel. When both macrospins are aligned parallel—as occurs when an external magnetic field is used to initialize them—the state is energetically metastable once the magnetic field is removed. We

identify several pathways for reversing the macrospins from one parallel state to the other with two possible switching types:

Synchronous switching, in which both nanomagnets reverse in a single step. In a simplified model, we assume that both nanomagnets reverse at the same rate, and they can either reverse both in the same sense [blue panel, Fig. 2(b)] or in opposite senses [orange panel, Fig. 2(b)].

Sequential switching, in which one nanomagnet reverses [left and right schematics in green panel, Fig. 2(b)], with the second nanomagnet reversing at a later time. Again, the two nanomagnets can reverse in opposite senses or in the same sense.

In Fig. 2(c), we show the energy as a function of the macrospin angle for different scenarios. For a single, isolated nanomagnet, the energy barrier to switching is found to be ~ 179 eV [black curve, Fig. 2(c)]. In the case of *sequential switching* shown in the green panel of Fig. 2(b), the reversal of the first nanomagnet happens via clockwise or anticlockwise rotation of the magnetization, while the magnetization in the second nanomagnet remains unchanged, and this corresponds to the green curve in Fig. 2(c) with an energy barrier of 147 eV. The reversal of the second nanomagnet then follows the same green curve shown in Fig. 2(c), but this time in reverse, so that the energy barrier is increased to 182.5 eV since the energy associated with the initial antiparallel state of the system is lower than that of the parallel configuration.

We now consider the situation in which both nanomagnets switch in a single step, which we refer to as *synchronous switching*. For simplicity, we will assume that both macrospins rotate at the same rate, so that $\theta = |\theta_1| = |\theta_2|$, and we find that the energy barrier is significantly higher than for sequential switching. When the macrospins rotate in the same direction (both clockwise or both anticlockwise), the energy barrier is 261 eV [blue panel and curve in Figs. 2(b) and 2(c), respectively]. When they rotate in opposite directions, this energy barrier increases to 385 eV [orange panel and curve in Figs. 2(b) and 2(c), respectively]. In both of these scenarios for synchronous switching, the initial and final states have the same energy, as evidenced by the symmetry of the blue and orange curves. Due to the much larger energy barrier for the synchronous switching, we would expect to observe sequential switching experimentally.

For an end-to-end pair of nanomagnets, the initial parallel configuration after applying a magnetic field is the system's low-energy state, and the antiparallel configuration is energetically unfavorable, making synchronous switching of the end-to-end nanomagnet pair more likely. The simulation results for the end-to-end pair of nanomagnets are discussed in detail in Sec. 3 of Ref. [50].

Now that we have established the expected behavior for nanomagnetic pairs, we turn to the experimental results. The procedure used was the same as for the isolated nanomagnets. We began by initializing the nanomagnets into a parallel configuration using a magnetic field and then applied current pulses of increasing amplitude. As predicted, for the side-by-side nanomagnet pair, the reversal process is sequential and, in Fig. 2(d), we show the experimental results for J_{switch} versus ϕ for the first and second steps, which are shown in light and dark purple, respectively. We see in Fig. 2(d)

that the behavior for the side-by-side pairs of nanomagnets is qualitatively the same as that for isolated nanomagnets, which is displayed with black points in Fig. 2(d). In particular, J_{switch} has a minimum at around $\phi = 75^\circ$, with a gradual increase in J_{switch} with the increase or decrease of the angle. This trend in J_{switch} versus ϕ is also seen for end-to-end pairs of nanomagnets (see Sec. 4 of Ref. [50]).

Assuming that the two nanomagnets are identical, for the first step, going from a parallel to antiparallel configuration, there should be no preference for which nanomagnet switches first and, therefore, J_{switch} corresponds to the current required to switch either nanomagnet in the pair. Nevertheless, any difference between the nanomagnets that give differences in the energy barriers to switching could lead to a more deterministic switching sequence within the nanomagnet pair. In accordance with the micromagnetic simulations, where the energy barrier associated with switching the first nanomagnet is lower than the energy barrier to switching of an isolated nanomagnet, it can be seen in Fig. 2(d) that, in general, the threshold current densities for the first step are lower than those required to switch the isolated nanomagnets, and are also lower than those required for the second step. This is particularly evident at higher angles.

Another notable feature is that, at 0° (Type x), the system switches to the antiparallel state but does not subsequently switch to the parallel configuration. As for the case of isolated nanomagnets, for sufficiently high current densities, the SOT drives the magnetization to point along the short axis of the nanomagnets. For pairs of nanomagnets, after the current pulse, the macrospins relax into an antiparallel alignment to minimize the energy and reach an energy well.

We verify our experimental observations with micromagnetic simulations of SOT switching for side-by-side pairs of nanomagnets for different J_{switch} and ϕ , with the results shown in Fig. 2(e). The figure of merit reflects whether switching occurs in one or both nanomagnets, and is given by the dot product of the initial and final magnetization states for each nanomagnet in the pair summed together ($m_{\text{end}}^1 \cdot m_{\text{start}}^1 + m_{\text{end}}^2 \cdot m_{\text{start}}^2$), where $m = +1$ and -1 corresponds to the nanomagnet magnetization before and after switching. At current densities insufficient to switch the nanomagnets, the figure of merit is $+2$ and corresponds to the yellow region in Fig. 2(e). At sufficiently high current densities, both nanomagnets switch, and the figure of merit is -2 , represented by the dark blue region. Between these two regions lies a narrow green region, corresponding to the situation in which only one of the nanomagnets has switched. It can be seen in Fig. 2(e) that, for most angles, as J increases, the system transitions from no switching (yellow) to one nanomagnet switching (green), and then to both nanomagnets switching (dark blue). This is consistent with the experimental results and our estimates of the energy barriers; namely, that, for nearly all ϕ , on increasing J , the green region in Fig. 2(e) is reached before the dark blue region, and magnetization reversal proceeds by sequential switching of the nanomagnets. Therefore, with careful choice of the current amplitude, one can control the final magnetic configuration of a pair of dipolar-coupled nanomagnets. Additional details on the switching behavior of the individual nanomagnets within each pair are provided in Sec. 7 of Ref. [50].

From the angular dependence of J_{switch} for end-to-end pairs of nanomagnets, we find that sequential switching is rarely observed experimentally and that simultaneous switching of both nanomagnets via a single step is more common. As mentioned above, this is because, starting from the initial parallel configuration, the system is more likely to switch directly to the opposite parallel configuration, than to the energetically unfavorable antiparallel configuration. Both the simulation and experimental results for the end-to-end pairs are discussed in Secs. 3 and 4 of Ref. [50], respectively.

IV. SWITCHING OF ARTIFICIAL SPIN ICE STRUCTURES

Having demonstrated deterministic switching in pairs of dipolar-coupled nanomagnets, we now extend our approach to small artificial spin ices, which consist of nanomagnets with the same dimensions as those used in our previous experiments, but this time the nanomagnets are arranged on a square lattice as shown in Fig. 3(a). Here, the edge-to-edge separation between the nanomagnets is 25 nm. Artificial square ices are among the most thoroughly explored artificial spin systems, with the magnetic behavior investigated on applying magnetic fields [1,61,62] and in thermally active systems [22,63]. With its two orthogonal sublattices of nanomagnets and well-defined hierarchy of interactions, the artificial square ice is an ideal testbed for probing how SOTs can be exploited to control the magnetic configuration. Using the same channel design employed for the single-nanomagnet measurements, the largest artificial square ice that can be accommodated between the slits in each region comprises a 4×4 array of square plaquettes decorated with nanomagnets.

In Fig. 3(b), we illustrate in a simplified schematic the mechanism for the switching of two of the nanomagnets in one of the square rings with a current applied in the horizontal direction as indicated. The initial magnetic state is set with an applied magnetic field $\mu_0 \mathbf{H}_{\text{ext}}$, and we indicate the macrospin directions with green arrows when the field is removed. Type-y nanomagnets (indicated with an orange border) will switch for a sufficiently large current density due to a combination of $\mu_0 \mathbf{H}_{\text{FL}}$, $\mu_0 \mathbf{H}_{\text{DL}}$, and the Oersted field, with the fieldlike SOT effective field indicated with purple arrows, while the current density is not large enough to switch the magnetization in the Type-x nanomagnets (indicated with blue border). However, it should be mentioned that, when the current density is sufficiently large so that the magnetization in the Type-x nanomagnets points along the short axis, the nanomagnets can reverse with a certain probability.

We know from the experimental results for isolated nanomagnets shown in Fig. 1(d) that J_{switch} for the Type-y ($\phi = 90^\circ$) nanomagnets is lower than J_{switch} for Type-x ($\phi = 0^\circ$) nanomagnets. Therefore, even after arranging the nanomagnets in a square array, we expect that nanomagnets with their long axis orthogonal to the current will switch at a lower current density than the nanomagnets with their long axis parallel to the current. This is confirmed by our experimental measurements where the Type-y nanomagnets switch first when negative-polarity current is applied [see Fig. 3(c)]. Looking at the experiment in more detail, in the initialized state, the magnetization of the Type-y (Type-x) nanomagnets points down (to the right), as indicated by the green arrows overlaid on the

first MFM image in Fig. 3(c). A series of negative-polarity current pulses was then applied, with the pulse polarity and amplitude indicated above the corresponding MFM images. Six current pulses of 1 μs duration were applied, with amplitudes increasing from 4.95×10^{12} to 5.38×10^{12} A m $^{-2}$. The magnetic state was measured after each pulse using MFM, without reinitializing the nanomagnet array between the successive pulses. The magnetization directions after switching are indicated by the purple arrows.

Because the negative current is applied along the horizontal direction, the Type-y nanomagnets reverse first, with switching originating at the right-hand edge of the array. As the current density increases, more Type-y nanomagnets progressively reverse their magnetization. Interestingly, it can be seen in Fig. 3(c) that the switching does not occur uniformly across the array of nanomagnets but rather starts at the right-hand border at a current density of 4.95×10^{12} A m $^{-2}$, and propagates from right to left. This may be a result of variations in geometry [17], dipolar interactions between the nanomagnets [64], or current density (see Fig. S1.2 in Ref. [50]). The Type-x nanomagnets, all with their long axes parallel to the current direction, also reverse once a sufficiently large current density is applied. Indeed, we find that, at a current density greater than 5.21×10^{12} A m $^{-2}$, Type-x nanomagnets begin to switch. As seen for the Type-y nanomagnets, the number of switched Type-x nanomagnets increases as the current density is increased. This evolution is displayed quantitatively in Fig. 3(e) where the cumulative number of switches for Type-x and Type-y nanomagnets is shown. A clear separation between the threshold current densities required to switch the two nanomagnet types is evident. Interestingly, Type-x nanomagnets start switching at lower current densities (5.21×10^{12} A m $^{-2}$) than those required to switch isolated nanomagnets (5.28×10^{12} A m $^{-2}$) and side-by-side pairs (5.35×10^{12} A m $^{-2}$). This reduction in the switching current may be related to the modified local magnetic field environment. In summary, from these experiments, we can infer that both sublattices will switch simultaneously provided a large enough current pulse is applied.

When a current of positive polarity is applied, no switching is observed in the Type-y nanomagnets [see Fig. 3(d)], as the direction of the fieldlike SOT effective field is aligned with their initial magnetization. Consistent with their higher switching threshold, Type-x nanomagnets remain unchanged until higher current densities are reached ($+5.38 \times 10^{12}$ A m $^{-2}$). Even then, the number of switched Type-x nanomagnets is significantly smaller than that observed for negative current polarity. Since the current-induced fieldlike SOT effective field in the Type-x nanomagnets is directed along their short axis, one would expect the onset of switching to occur at comparable current densities for both polarities. This observed asymmetry may be a result of slight differences in the pulse shapes associated with the positive and negative current pulses, but also the different local magnetic field environment. In particular, it can be seen in Fig. 3(c), that Type-x nanomagnets only begin to switch after the majority of the Type-y nanomagnets have reversed, thus modifying the dipolar field landscape within the array. In contrast, in Fig. 3(d), there is no modification of the dipolar field landscape because the Type-y nanomagnets do not switch.

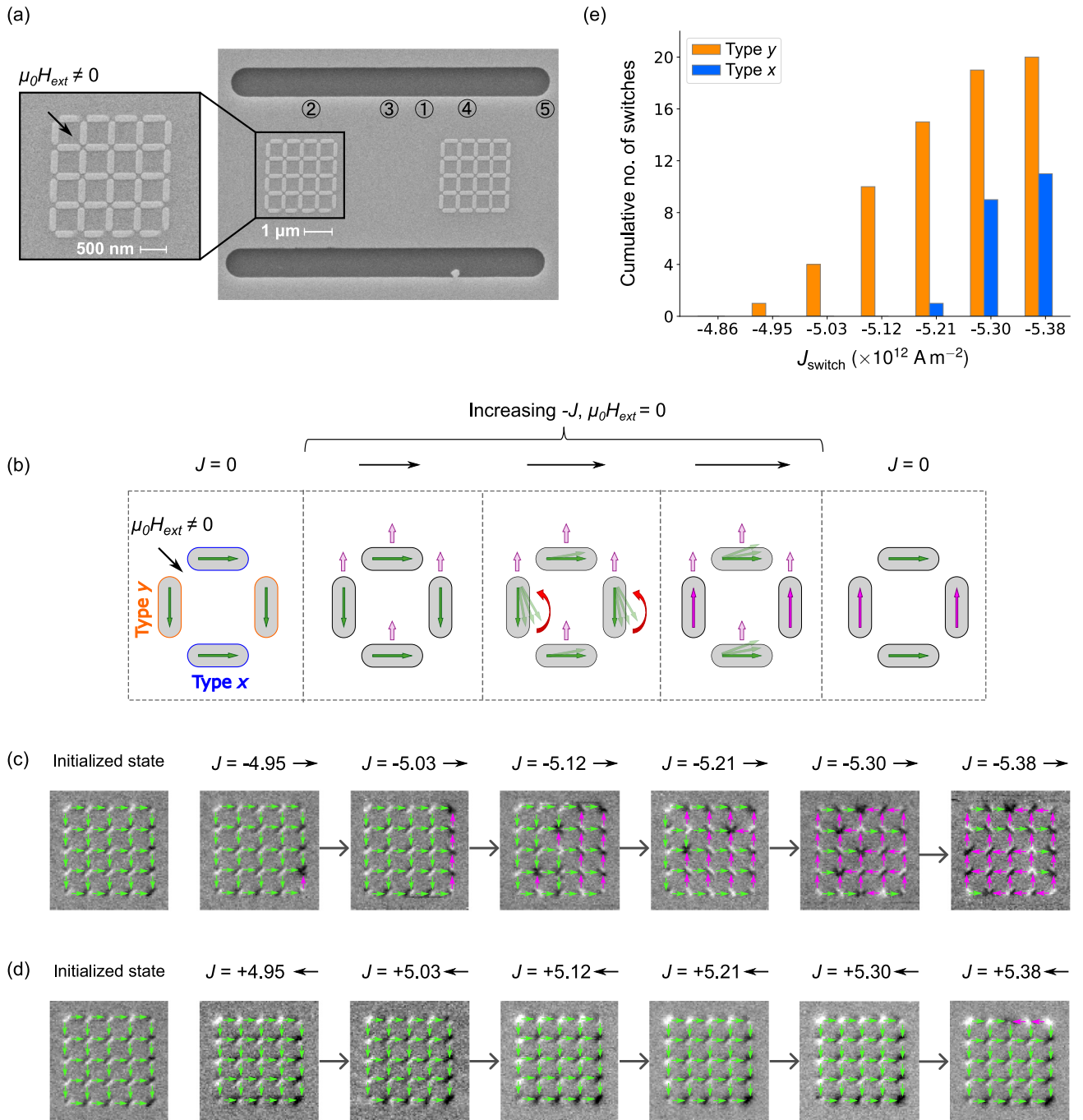


FIG. 3. Current-induced switching of an artificial square ice with an array of nanomagnets on orthogonal sublattices. (a) SEM image of two artificial square ices with 4×4 square plaquettes (position ② with zoomed-in image and position ④ on the channel). The applied initializing magnetic field, $\mu_0 H_{\text{ext}}$, is indicated by a black arrow. (b) Schematic of the expected switching behavior in a single square ring of nanomagnets, where the nanomagnets with blue (orange) borders indicate Type- x (Type- y) nanomagnets. After initialization, a horizontally applied negative-polarity current generates a fieldlike SOT effective field (purple arrows) and dampinglike effective field (out-of-plane, not shown) that drives reversal of the Type- y nanomagnets, but is insufficient to reverse the Type- x nanomagnets. [(c) and (d)] MFM images showing the magnetic state in the artificial spin ice at position ② after successive current pulses of increasing magnitude for negative (c) and positive (d) polarities. Unswitched (switched) nanomagnets are indicated by green (purple) arrows. (e) Cumulative number of switched nanomagnets for increasing current density for the same artificial square ice.

The experimental results obtained for the artificial square ice demonstrate that the switching behavior can be effectively defined by the orientation of the nanomagnets with respect to the current—Type x or Type y —and the polarity of the applied

current. In terms of the geometry, for negative current, a notable difference is observed in the onset of the first switching events between Type y ($J = -4.95 \times 10^{12} \text{ A m}^{-2}$) and Type x ($J = -5.21 \times 10^{12} \text{ A m}^{-2}$). As a further example, data on the

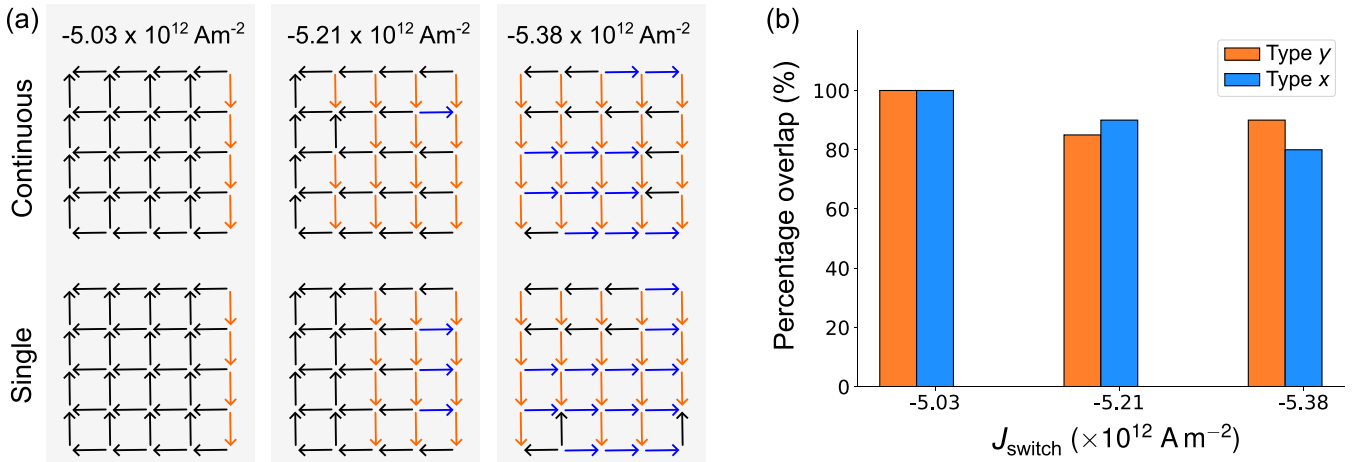


FIG. 4. Comparing a pulse series with single pulse switching in an artificial square ice. (a) Magnetic configurations obtained using two current-pulse schemes. (Top) States measured after applying a series of current pulses of increasing current density without reinitialization in a magnetic field. (Bottom) States obtained after reinitializing the sample before applying a single pulse of the indicated current density. (b) Percentage overlap between the magnetic states produced by the two protocols for three different current densities, shown separately for Type-y and Type-x nanomagnets. The overlap is defined as the percentage of nanomagnets with the same magnetization direction for both protocols.

switching behavior of large square arrays oriented at 45° to the current direction indicate that the two sublattices switch at the same current densities (see Sec. 8 of Ref. [50]). This indicates that sublattice control can be achieved by applying a global input in the form of electric currents. Such control introduces new possibilities for manipulating magnetization reversal in artificial spin systems composed of in-plane stadium-shaped nanomagnets.

Finally, we investigate whether specific magnetic states in small arrays can be achieved with a single current pulse or if a gradual increase in pulse amplitude is required to progressively modify the magnetic configuration. To address this, we compare (i) the magnetic configurations obtained on *continuously* increasing the current density [Fig. 4(a), top panel], based on the experimental configuration shown in Fig. 3(a), with (ii) the magnetic configurations achieved by injecting a *single* pulse of the same amplitude, but this time initializing the system with an applied magnetic field between each current pulse [Fig. 4(a), bottom panel]. We then determine the percentage overlap, which is the percentage of nanomagnets that have the same orientation of the magnetization at a given current for the two different procedures. This is shown for Type-y and Type-x nanomagnets in Fig. 4(b). Across all current densities, the overlap remains above 80% for both nanomagnet types, demonstrating that the magnetic states produced by the two approaches are very similar. These results indicate that a single current pulse is sufficient to reliably access a given magnetic state and that gradual evolution through intermediate states is not required.

V. CONCLUSION

We have demonstrated deterministic, field-free magnetization reversal in single-domain Py nanomagnets driven by SOTs. By systematically studying isolated nanomagnets, dipolar-coupled pairs of nanomagnets, and small artificial

square ices consisting of arrays of dipolar-coupled nanomagnets on two orthogonal sublattices, we have established how geometry and interactions govern the threshold current density required for switching.

For isolated nanomagnets with dimensions $450 \text{ nm} \times 150 \text{ nm} \times 10 \text{ nm}$, oriented at various angles with respect to the current direction, the minimum threshold current density occurred near 75° , with successful switching observed for angles between 15° and 90° at current densities in the range $4.9\text{--}5.4 \times 10^{12} \text{ A m}^{-2}$. For nanomagnet pairs in the side-by-side configuration, switching occurred in two steps: starting from a metastable parallel alignment of the two macrospins, one nanomagnet reversed first to give an antiparallel configuration, stabilizing the system in a global energy minimum. This was followed by a second step at a slightly higher current density as the pair of nanomagnets transitioned from an antiparallel configuration back to the opposite metastable parallel configuration. In contrast, for end-to-end pairs of nanomagnets, magnetization reversal occurred in a single switching step with both nanomagnets reversing synchronously rather than sequentially.

For the artificial square ice, we showed that the two orthogonal nanomagnet sublattices—one with the nanomagnet long axis perpendicular to the current, and the other with the nanomagnet long axis parallel to the current—exhibit distinct reversal thresholds. This enables selective, current-driven switching of one nanomagnet sublattice while leaving the orthogonal sublattice unaffected.

Together, these results introduce SOTs as a practical route for controlling artificial spin ices through purely electrical means, offering a straightforward approach that is compatible with existing CMOS architectures. This is an important step towards using artificial spin ice arrays as platforms for programmable magnetic logic and neuromorphic architectures.

ACKNOWLEDGMENTS

We thank Anja Weber for her help with sample fabrication, Thomas Jung for access to the MFM tool, and Simone Finizio for his help with preparing the PCB for electrical setup. We are grateful for financial support from the Swiss National Science Foundation (Project No. 200020_200332). We would also like to acknowledge the support from the EU FET-Open RIA project SpinENGINE (Grant No. 861618). J.A.B. acknowledges support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant No. 884104 (PSI-FELLOW-III-3i). The work by V.R. and E.M. was partially supported by Project No. PID2023-150853NB-C31 funded by MICIU/AEI/10.13039/501100011033 and by FEDER, UE. Financial support of the Department of Education of the Junta de Castilla y León and FEDER Funds is gratefully acknowledged (Escalera de Excelencia CLU-2023-1-02).

DATA AVAILABILITY

The dataset supporting this study is available in an online repository [65].

APPENDIX A: FABRICATION

All devices investigated in this work, with isolated nanomagnets, nanomagnet pairs, and square arrays, were fabricated on a single chip to minimize device-to-device variations arising from the fabrication process.

The multilayer stack Ta(4 nm)/Pt(6 nm)/Py(10 nm)/Ru(2 nm) where Py corresponds to Ni₈₀Fe₂₀, was deposited on a high-resistivity Si/SiO₂ substrate by DC magnetron sputtering at a base pressure of 5.3×10^{-8} mbar. This was followed by the first step of electron-beam lithography (EBL) to obtain alignment markers. For this, we used a positive-tone resist of polymethyl methacrylate (PMMA, 4% EL), spun at 4000 rpm for 60 s to obtain a resist thickness of approximately 270 nm. After electron beam exposure using an electron beam writer (EBPG5000Plus) and development, a Cr(5 nm)/Au(100 nm) bilayer was deposited by thermal evaporation at a base pressure of 5.3×10^{-6} mbar, followed by a lift-off process to give the alignment markers.

The sample was then cleaned in acetone and isopropanol, and dehydrated at 125° for 5 mins to improve the subsequent resist adhesion to the film. Once the sample had cooled down, a negative-tone resist of hydrogen silsesquioxane (HSQ, XR-1541 2%) was spin-coated at 4000 rpm for 60 s, resulting in a resist thickness of ~ 50 nm. The nanomagnet patterns were exposed in the electron beam writer and developed to form a hard mask. Pattern transfer was achieved by Ar ion milling

with a beam voltage of 400 V and an Ar flow of 8 sccm, which removed the magnetic film down to the Pt layer. During milling, the sample was rotated at 20 rpm and tilted at 15° with respect to the ion beam. After milling, the residual HSQ mask was removed using buffered hydrofluoric acid solution.

The heavy-metal current-carrying channels were fabricated in a subsequent EBL step using a negative-tone resist N2401, spin-coated at 4000 rpm for 30 s to obtain a resist thickness of ~ 80 nm. After EBL exposure and development, the exposed regions of the resist remained, which acted as a hard mask for subsequent ion milling down to the substrate to create the channels, while the nanomagnets remained protected by the resist mask. The remaining resist was removed by placing the chip in dimethylsulfoxide (DMSO) at 60 °C for 2 h with gentle ultrasonication.

Electrical contact pads were fabricated in the final lithography step using the same process employed for the alignment markers, consisting of exposure of the pattern in PMMA with the electron beam writer, Cr(5 nm)/Au(100 nm) evaporation, and lift-off. Lastly, the quality of the sample was checked using scanning electron microscopy and magnetic force microscopy prior to wire bonding of the sample to a printed circuit board for electrical measurements.

APPENDIX B: MICROMAGNETIC SIMULATIONS FOR PAIRS OF NANOMAGNETS

The simulations that were used to obtain Fig. 2(e) involved a pair of side-by-side stadium-shaped nanomagnets with length $l = 450$ nm, width $w = 150$ nm and thickness $t = 10$ nm, with edge-to-edge separation of 30 nm. We assumed standard material parameters for permalloy: a saturation magnetization of $M_S = 860 \times 10^3$ A m⁻¹ and an exchange constant of $A_{ex} = 13 \times 10^{-12}$ J m⁻¹. A low interfacial DMI parameter, $D = 1$ mJ m⁻², was used, reflecting the fact that the nanomagnets sit on top of a heavy-metal Pt layer. The Gilbert damping α was set to 0.2. The Oersted field coefficient based on COMSOL simulations was $b = 3.8$ (1 mT/10¹² A m⁻²), while the ratio between the fieldlike and dampinglike torques was $k = 0.5$. The current density was increased from 0 to 10¹³ A/m² in steps of 0.05×10^{12} A m⁻², while the angle ϕ was increased from 0° to 90° in steps of 5°.

For each point in the switching map in Fig. 2(e), the simulation was run for 5 ns comprising 2.5 ns with the current applied, followed by a further 2.5 ns without current where the system relaxes. The end state of the nanomagnetic pair was then examined and compared with the initial state to construct the figure of merit, which is a measure of whether both, one, or neither of the two nanomagnets switched.

[1] R. F. Wang, C. Nisoli, R. S. Freitas, J. Li, W. McConville, B. J. Cooley, M. S. Lund, N. Samarth, C. Leighton, V. H. Crespi, *et al.*, Artificial ‘spin ice’ in a geometrically frustrated lattice of nanoscale ferromagnetic islands, *Nature (London)* **439**, 303 (2006).

[2] S. H. Skjærvø, C. H. Marrows, R. L. Stamps, and L. J. Heyderman, Advances in artificial spin ice, *Nat. Rev. Phys.* **2**, 13 (2020).

[3] L. Anghinolfi, H. Luetkens, J. Perron, M. G. Flokstra, O. Sendetskyi, A. Suter, T. Prokscha, P. M. Derlet, S. L. Lee, and

- L. J. Heyderman, Thermodynamic phase transitions in a frustrated magnetic metamaterial, *Nat. Commun.* **6**, 8278 (2015).
- [4] O. Sendetskyi, L. Anghinolfi, V. Scagnoli, G. Möller, N. Leo, A. Alberca, J. Kohlbrecher, J. Lüning, U. Staub, and L. J. Heyderman, Magnetic diffuse scattering in artificial kagome spin ice, *Phys. Rev. B* **93**, 224413 (2016).
- [5] O. Sendetskyi, V. Scagnoli, N. Leo, L. Anghinolfi, A. Alberca, J. Lüning, U. Staub, P. M. Derlet, and L. J. Heyderman, Continuous magnetic phase transition in artificial square ice, *Phys. Rev. B* **99**, 214430 (2019).
- [6] K. Hofhuis, S. H. Skjærvø, S. Parchenko, H. Arava, Z. Luo, A. Kleibert, P. M. Derlet, and L. J. Heyderman, Real-space imaging of phase transitions in bridged artificial kagome spin ice, *Nat. Phys.* **18**, 699 (2022).
- [7] L. Berchialla, G. M. Macauley, F. Musser, T. Wang, A. Kleibert, P. M. Derlet, and L. J. Heyderman, Realizing blumcapel degrees of freedom with toroidal moments in a ruby artificial spin ice, *ACS Nano* **20**, 3423 (2026).
- [8] E. Mengotti, L. J. Heyderman, A. F. Rodríguez, F. Nolting, R. V. Hügli, and H.-B. Braun, Real-space observation of emergent magnetic monopoles and associated Dirac strings in artificial kagome spin ice, *Nat. Phys.* **7**, 68 (2011).
- [9] S. Ladak, D. E. Read, G. K. Perkins, L. F. Cohen, and W. R. Branford, Direct observation of magnetic monopole defects in an artificial spin-ice system, *Nat. Phys.* **6**, 359 (2010).
- [10] J. C. Gartside, K. D. Stenning, A. Vanstone, H. H. Holder, D. M. Arroo, T. Dion, F. Caravelli, H. Kurebayashi, and W. R. Branford, Reconfigurable training and reservoir computing in an artificial spin-vortex ice via spin-wave fingerprinting, *Nat. Nanotechnol.* **17**, 460 (2022).
- [11] K. D. Stenning, J. C. Gartside, L. Manneschi, C. T. S. Cheung, T. Chen, A. Vanstone, J. Love, H. Holder, F. Caravelli, H. Kurebayashi, *et al.*, Neuromorphic overparameterisation and few-shot learning in multilayer physical neural networks, *Nat. Commun.* **15**, 7377 (2024).
- [12] A. Kurenkov, J. Maes, A. Pac, G. M. Macauley, B. Van Waeyenberge, A. Hrabec, and L. J. Heyderman, Perpendicular-anisotropy artificial spin ice with spontaneous ordering: A platform for reservoir computing with flexible timescales, *Commun. Eng.* **4**, 183 (2025).
- [13] H. Li, L. Li, R. Xiang, W. Liu, C. Yan, Z. Tao, L. Zhang, and R. Liu, Physical reservoir computing and deep neural networks using artificial and natural noncollinear spin textures, *Phys. Rev. Appl.* **22**, 014027 (2024).
- [14] K. Hon, Y. Kuwabiraki, M. Goto, R. Nakatani, Y. Suzuki, and H. Nomura, Numerical simulation of artificial spin ice for reservoir computing, *Appl. Phys. Express* **14**, 033001 (2021).
- [15] J. H. Jensen, E. Folven, and G. Tufte, Computation in artificial spin ice, in *The 2018 Conference on Artificial Life* (MIT Press, Tokyo, Japan, 2018), pp. 15–22.
- [16] T. Taniguchi, Echo state property and memory capacity of artificial spin ice, *Sci. Rep.* **15**, 9073 (2025).
- [17] H. Arava, N. Leo, D. Schildknecht, J. Cui, J. Vijayakumar, P. M. Derlet, A. Kleibert, and L. J. Heyderman, Engineering relaxation pathways in building blocks of artificial spin ice for computation, *Phys. Rev. Appl.* **11**, 054086 (2019).
- [18] P. Gypens, J. Leliaert, and B. Van Waeyenberge, Balanced magnetic logic gates in a kagome spin ice, *Phys. Rev. Appl.* **9**, 034004 (2018).
- [19] F. Caravelli and C. Nisoli, Logical gates embedding in artificial spin ice, *New J. Phys.* **22**, 103052 (2020).
- [20] Y. Li, G. W. Paterson, G. M. Macauley, F. S. Nascimento, C. Ferguson, S. A. Morley, M. C. Rosamond, E. H. Linfield, D. A. MacLaren, R. Macêdo, *et al.*, Superferromagnetism and domain-wall topologies in artificial “Pinwheel” spin ice, *ACS Nano* **13**, 2213 (2019).
- [21] J. H. Jensen, A. Strømberg, I. Breivik, A. Penty, M. A. Niño, M. W. Khaliq, M. Foerster, G. Tufte, and E. Folven, Clocked dynamics in artificial spin ice *Nat. Commun.* **15**, 964 (2024).
- [22] A. Farhan, P. M. Derlet, A. Kleibert, A. Balan, R. V. Chopdekar, M. Wyss, J. Perron, A. Scholl, F. Nolting, and L. J. Heyderman, Direct observation of thermal relaxation in artificial spin ice, *Phys. Rev. Lett.* **111**, 057204 (2013).
- [23] I. Gilbert, G.-W. Chern, S. Zhang, L. O’Brien, B. Fore, C. Nisoli, and P. Schiffer, Emergent ice rule and magnetic charge screening from vertex frustration in artificial spin ice, *Nat. Phys.* **10**, 670 (2014).
- [24] S. Zhang, I. Gilbert, C. Nisoli, G.-W. Chern, M. J. Erickson, L. O’Brien, C. Leighton, P. E. Lammert, V. H. Crespi, and P. Schiffer, Crystallites of magnetic charges in artificial spin ice, *Nature (London)* **500**, 553 (2013).
- [25] M. Pancaldi, N. Leo, and P. Vavassori, Selective and fast plasmon-assisted photo-heating of nanomagnets, *Nanoscale* **11**, 7656 (2019).
- [26] P. Gypens, N. Leo, M. Menniti, P. Vavassori, and J. Leliaert, Thermoplasmonic nanomagnetic logic gates, *Phys. Rev. Appl.* **18**, 024014 (2022).
- [27] D. Pecchio, S. Sahoo, O. Chubykalo-Fesenko, S. Koraltan, G. M. Macauley, T. Thomson, D. Suess, V. Scagnoli, and L. J. Heyderman, Ultrafast laser-induced magnetic relaxation in artificial spin ice driven by dipolar interactions, *Phys. Rev. B* **113**, 064404 (2026).
- [28] D. Pecchio, S. Sahoo, V. Scagnoli, and L. J. Heyderman, Attaining the ground state of kagome artificial spin ice via ultrafast site-specific laser annealing, *Phys. Rev. B* **113**, 054434 (2026).
- [29] K. D. Stenning, X. Xiao, H. H. Holder, J. C. Gartside, A. Vanstone, O. W. Kennedy, R. F. Oulton, and W. R. Branford, Low-power continuous-wave all-optical magnetic switching in ferromagnetic nanoarrays, *Cell Rep. Phys. Sci.* **4**, 101291 (2023).
- [30] J. C. Gartside, D. M. Arroo, D. M. Burn, V. L. Bemmer, A. Moskalenko, L. F. Cohen, and W. R. Branford, Realization of ground state in artificial kagome spin ice via topological defect-driven magnetic writing, *Nat. Nanotechnol.* **13**, 53 (2018).
- [31] H. Holder, A. J. Wright, A. Vanstone, T. Dion, X. Xiao, K. D. Stenning, T. Zheng, D. Bromley, T. Farchy, J. C. Gartside, *et al.*, Magnetic vortex writing and local reversal seeding in artificial spin-vortex ice via all-optical and surface-probe control, *Phys. Rev. B* **113**, 184426 (2026).
- [32] S. Fukami, T. Anekawa, C. Zhang, and H. Ohno, A spin-orbit torque switching scheme with collinear magnetic easy axis and current configuration, *Nat. Nanotechnol.* **11**, 621 (2016).
- [33] Y. Takahashi, Y. Takeuchi, C. Zhang, B. Jinnai, S. Fukami, and H. Ohno, Spin-orbit torque-induced switching of in-plane magnetized elliptic nanodot arrays with various easy-axis directions measured by differential planar Hall resistance, *Appl. Phys. Lett.* **114**, 012410 (2019).

- [34] L. Liu, O. J. Lee, T. J. Gudmundsen, D. C. Ralph, and R. A. Buhrman, Current-induced switching of perpendicularly magnetized magnetic layers using spin torque from the spin hall effect, *Phys. Rev. Lett.* **109**, 096602 (2012).
- [35] M. Cubukcu, O. Boulle, M. Drouard, K. Garello, C. Onur Avci, I. Mihai Miron, J. Langer, B. Ocker, P. Gambardella, and G. Gaudin, Spin-orbit torque magnetization switching of a three-terminal perpendicular magnetic tunnel junction, *Appl. Phys. Lett.* **104**, 042406 (2014).
- [36] I. M. Miron, K. Garello, G. Gaudin, P.-J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella, Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection, *Nature (London)* **476**, 189 (2011).
- [37] L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman, Spin-torque switching with the giant spin hall effect of tantalum, *Science* **336**, 555 (2012).
- [38] H. Kubota, S. Tsunegi, S. Tamaru, T. Taniguchi, T. Yamamoto, A. Sugihara, K. Yakushiji, R. Matsuura, T. Wakabayashi, T. Isokawa, *et al.*, Electrical detection of emergent magnetization dynamics in artificial spin ice, *APL Mater.* **13**, 091110 (2025).
- [39] K. Garello, I. M. Miron, C. O. Avci, F. Freimuth, Y. Mokrousov, S. Blügel, S. Auffret, O. Boulle, G. Gaudin, and P. Gambardella, Symmetry and magnitude of spin-orbit torques in ferromagnetic heterostructures, *Nat. Nanotechnol.* **8**, 587 (2013).
- [40] L. Wei, X. Yin, P. Liu, P. Zhang, W. Niu, P. Liu, J. Yang, J. Peng, F. Huang, R. Liu, *et al.*, Field-free spin-orbit torque-induced switching of perpendicular magnetization at room temperature in WTe₂/ferromagnet heterostructures, *Appl. Phys. Lett.* **123**, 252404 (2023).
- [41] N. Strandqvist, G. Fitez, O. Heinonen, and P. Schiffer, Nanomagnet shape effects on magnetic reversal in artificial spin ice, *Phys. Rev. B* **111**, 184420 (2025).
- [42] S. Gliga, A. Kákay, L. J. Heyderman, R. Hertel, and O. G. Heinonen, Broken vertex symmetry and finite zero-point entropy in the artificial square ice ground state, *Phys. Rev. B* **92**, 060413 (2015).
- [43] M. I. Dyakonov and V. I. Perel, Current-induced spin orientation of electrons in semiconductors, *Phys. Lett. A* **35**, 459 (1971).
- [44] A. Hoffmann, Spin Hall effects in metals, *IEEE Trans. Magn.* **49**, 5172 (2013).
- [45] J. Sinova, S. O. Valenzuela, J. Wunderlich, C. H. Back, and T. Jungwirth, Spin Hall effects, *Rev. Mod. Phys.* **87**, 1213 (2015).
- [46] A. Manchon, J. Železný, I. M. Miron, T. Jungwirth, J. Sinova, A. Thiaville, K. Garello, and P. Gambardella, Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems, *Rev. Mod. Phys.* **91**, 035004 (2019).
- [47] J. Kim, J. Sinha, M. Hayashi, M. Yamanouchi, S. Fukami, T. Suzuki, S. Mitani, and H. Ohno, Layer thickness dependence of the current-induced effective field vector in Ta[CoFeB]/MgO, *Nat. Mater.* **12**, 240 (2013).
- [48] T. D. Skinner, M. Wang, A. T. Hindmarch, A. W. Rushforth, A. C. Irvine, D. Heiss, H. Kurebayashi, and A. J. Ferguson, Spin-orbit torque opposing the Oersted torque in ultrathin Co/Pt bilayers, *Appl. Phys. Lett.* **104**, 062401 (2014).
- [49] B. Han, B. Zhang, S. Sun, B. Wang, Y. Guo, and J. Cao, The thickness dependence of the field-like spin-orbit torque in heavy metal/CoFeB/MgO heterostructures, *J. Appl. Phys.* **130**, 213902 (2021).
- [50] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/mmzq-rnjf> for a summary of the channel design and current density distribution; estimate of the Oersted field generated by the current passing through the heavy metal layer; estimates of the switching fields and energy barrier to switching of isolated and coupled nanomagnets; experimental results for end-to-end pairs of nanomagnets; isolated nanomagnet switching; micromagnetic simulations for isolated nanomagnet switching; micromagnetic simulations for the side-by-side pairs; and the SOT switching of an extended square artificial spin ice, which also contains Refs. [51,52].
- [51] A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, F. Garcia-Sanchez, and B. Van Waeyenberge, The design and verification of MuMax3, *AIP Adv.* **4**, 107133 (2014).
- [52] A. Pac, Artificial spin systems: Magnetic frustration of out-of-plane Archimedean lattices and towards control of the magnetic state with spin-orbit torques, Ph.D. Thesis, ETH Zurich, 2025.
- [53] Y.-T. Liu, C.-C. Huang, K.-H. Chen, Y.-H. Huang, C.-C. Tsai, T.-Y. Chang, and C.-F. Pai, Anatomy of type-x spin-orbit-torque switching, *Phys. Rev. Appl.* **16**, 024021 (2021).
- [54] F. Hellman, A. Hoffmann, Y. Tserkovnyak, G. S. D. Beach, E. E. Fullerton, C. Leighton, A. H. MacDonald, D. C. Ralph, D. A. Arena, H. A. Dürr, *et al.*, Interface-induced phenomena in magnetism, *Rev. Mod. Phys.* **89**, 025006 (2017).
- [55] G. W. Paterson, G. M. Macaulay, Y. Li, R. Macêdo, C. Ferguson, S. A. Morley, M. C. Rosamond, E. H. Linfield, C. H. Marrows, R. L. Stamps, *et al.*, Heisenberg pseudo-exchange and emergent anisotropies in field-driven pinwheel artificial spin ice, *Phys. Rev. B* **100**, 174410 (2019).
- [56] K. L. Metlov and K. Y. Guslienko, Stability of magnetic vortex in soft magnetic nano-sized circular cylinder, *J. Magn. Magn. Mater.* **242-245**, 1015 (2002).
- [57] T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto, and T. Ono, Magnetic vortex core observation in circular dots of permalloy, *Science* **289**, 930 (2000).
- [58] E. C. Stoner and E. P. Wohlfarth, A mechanism of magnetic hysteresis in heterogeneous alloys, *Philos. Trans. R. Soc. Lond. Ser. A* **240**, 599 (1948).
- [59] M. Ferreira Velo, B. Malvezzi Cecchi, and K. R. Pirota, Micromagnetic simulations of magnetization reversal in kagome artificial spin ice, *Phys. Rev. B* **102**, 224420 (2020).
- [60] N. S. Bingham, X. Zhang, J. Ramberger, O. Heinonen, C. Leighton, and P. Schiffer, Collective ferromagnetism of artificial square spin ice, *Phys. Rev. Lett.* **129**, 067201 (2022).
- [61] C. Phatak, A. K. Petford-Long, O. Heinonen, M. Tanase, and M. De Graef, Nanoscale structure of the magnetic induction at monopole defects in artificial spin-ice lattices, *Phys. Rev. B* **83**, 174431 (2011).
- [62] H. Arava, E. Y. Vedmedenko, J. Cui, J. Vijayakumar, A. Kleibert, and L. J. Heyderman, Control of emergent magnetic monopole currents in artificial spin ice, *Phys. Rev. B* **102**, 144413 (2020).
- [63] J. P. Morgan, A. Stein, S. Langridge, and C. H. Marrows, Thermal ground-state ordering and elementary excitations in artificial magnetic square ice, *Nat. Phys.* **7**, 75 (2011).
- [64] R. V. Hügeli, G. Duff, B. O'Conchuir, E. Mengotti, A. F. Rodríguez, F. Nolting, L. J. Heyderman, and H. B.

Braun, Artificial kagome spin ice: Dimensional reduction, avalanche control and emergent magnetic monopoles, *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **370**, 5767 (2012).

[65] A. Pac, A. Hrabec, and V. Scagnoli, Current-induced magnetization control in dipolar-coupled nanomagnet pairs and artificial spin ice [Data set], Zenodo, 2026, <https://doi.org/10.5281/zenodo.18857646>.