

Magnetic Nonreciprocity in a Hybrid Device of Asymmetric Artificial Spin-Ice-Superconductors

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Controlling the size and distribution of potential barriers within a medium of interacting particles can unveil unique collective behaviors and innovative functionalities. We introduce a unique superconducting hybrid device using a novel artificial spin ice structure composed of asymmetric nanomagnets. This structure forms a distinctive superconducting pinning potential that steers unconventional motion of superconducting vortices, thereby inducing a magnetic nonreciprocal effect, in contrast to the electric nonreciprocal effect commonly observed in superconducting diodes. Furthermore, the polarity of the magnetic nonreciprocity is *in situ* reversible through the tunable magnetic patterns of artificial spin ice. Our findings demonstrate that artificial spin ice not only precisely modulates superconducting characteristics but also opens the door to novel functionalities, offering a groundbreaking paradigm for superconducting electronics.

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In type-II superconductors, magnetic fluxes penetrating into materials are quantized and referred to as vortices; each vortex has a quantized flux of $\Phi_0 = h/2e = 2.068 \times 10^{-15}$ Wb and consists of supercurrents encircling non-superconducting cores. The vortices are propelled by the Lorentz force when an external current is applied, and their motion generates resistance and dissipates energy. Consequently, the electromagnetic properties of superconducting materials are dominated by the motion behavior of these vortices. Controlling vortex motion is crucial for the development of innovative electronic devices, such as vortex pumps, diodes, and rectifiers.^[1,2] Vortex dynamics has become an active research area, both in fundamental studies of vortex matter and in applications in electronics.^[3] Researchers have demonstrated that vortices can be trapped by nanoscale defects, including those created by irradiation,^[4,5] grain boundaries,^[6–8] doping^[9] and nanostructures fabricated using nanofabrication techniques.^[10–17] However, once the samples are prepared using these methods, the spatial distribution of the vortices' pinning potential landscape is fixed. To introduce flexibility in tailoring superconducting vortices, earlier studies have indicated that superconducting vortices can interact with magnetic nanostructures.^[18–28] By applying an external magnetic field, the magnetization of these structures can be controlled *in situ*, which alters the pinning potential distribution and enables reconfigurability of superconductivity.^[26–28]

Recently, a magnetic structure known as artificial spin ice (ASI) has been utilized as a reconfigurable pinning potential to control vortices in superconducting heterostructures.^[29–31] ASI, an array of nanomagnets, allows for the alteration of the magnetization direction of these nanomagnets through an in-plane external magnetic field. This enables ASI to create a variety of magnetic charge structures, offering diverse regulatory effects on the vortices and thus allowing for flexible customization of superconducting properties and functionalities. Examples include switchable geometric vortex frustration,^[30] reversible vortex Hall effect,^[31] and programmable vortex diodes.^[29,30] However, prior research on vortex control using ASI all relied on symmetrical nanomagnets. In this Letter, we introduce a novel square ASI structure made of asymmetric nanomagnets. The unique shape of these nanomagnets induces a unique magnetic non-reciprocal effect, which can be reconfigured *in situ* by altering the magnetization states of the ASI. Analogous to the electric nonreciprocal effect in superconducting diodes, the magnetic nonreciprocity acts like a magnetic-field-driven superconducting 'diode', wherein zero resistance is observed only when the magnetic field is applied in one specific direction. Our findings underscore the pivotal role of locally asymmetric magnetic potential in unlocking distinctive superconducting properties, setting the stage for a new paradigm in superconducting electronics.

Our experiment was conducted using a

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superconductor-ASI heterogeneous structure. An optical image of the sample is presented in Fig. 1(a). The device comprises a 50-nm-thick $\text{Mo}_{79}\text{Ge}_{21}$ (MoGe) film microbridge, which was deposited on a silicon wafer employing standard photolithography and magnetron sputtering techniques. The ASI structure was subsequently fabricated on top of the MoGe film using e-beam lithography and e-beam evaporation. Detailed methodologies of the sample fabrication are documented elsewhere.^[30,31] As depicted in Fig. 1(a), the sample is segmented into three sections, i.e., S1–S3, each featuring a unique ASI structure, alongside a section (REF) that retains a bare

MoGe film serving as a reference. Figures 1(b)–1(d) showcase scanning electron microscopy images of three distinct ASI structures. Section S1 in Fig. 1(a) consists of an array of symmetrical nanomagnets, with dimensions of 300 nm (length) $\times$ 80 nm (width) $\times$ 25 nm (thickness). The ASI array in section S2 comprises asymmetrically trapezoidal nanomagnets, each sized at 300 nm (altitude) $\times$ 40 nm (base1) $\times$ 120 nm (base2) $\times$ 25 nm (thickness). Conversely, the ASI array in section S3 features geometrically inverted nanomagnets relative to those in section S2.

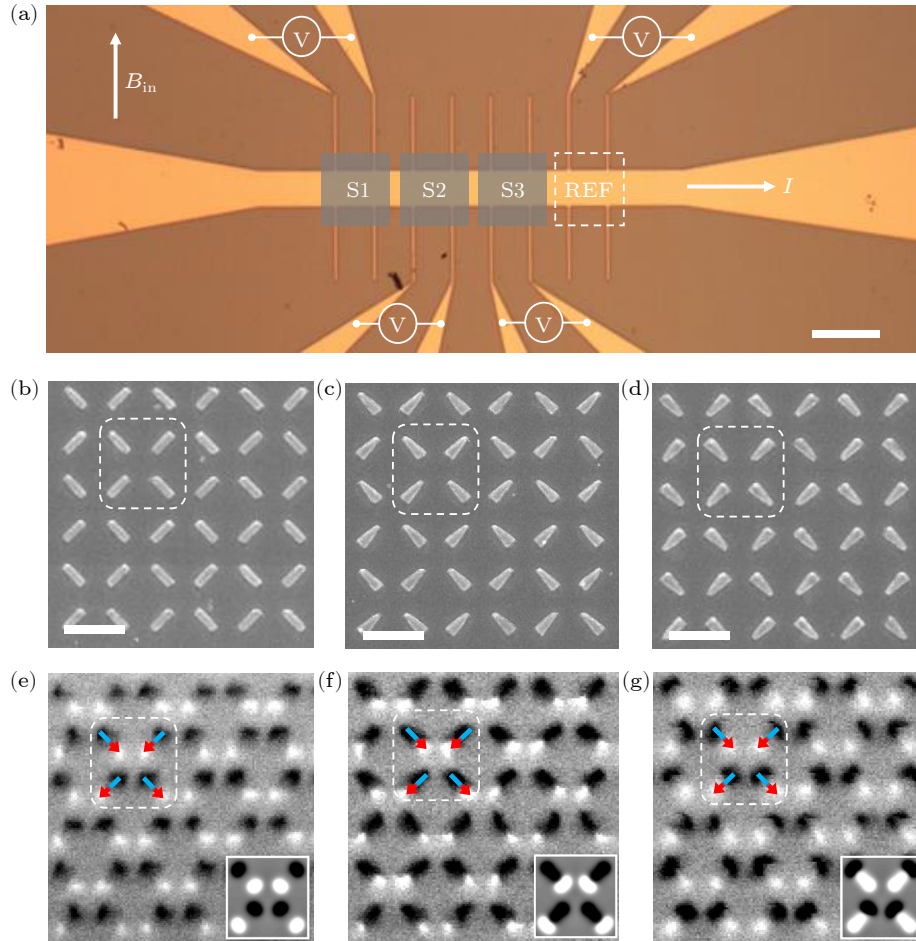


Fig. 1. Device and sample structure. (a) Optical image of a superconducting MoGe microbridge with four sections. Scale bar, 100 μm . (b)–(d) Scanning electron microscopy (SEM) images showing square-ASIs structures in sections S1–S3, respectively. Scale bar: 700 nm. The dashed boxes highlight a magnetic vertex containing four nanobars. (e)–(g) Magnetic force microscopy (MFM) images of the square-ASI structures in (b)–(d), respectively. The white/black spots reveal positive/negative magnetic charges, while the arrows indicate the magnetizations of single-domain nanomagnets.

The interaction between the ASI and the superconducting film is dominated by the magnetic charges of ASI's nanomagnets and superconducting vortices. Each nanomagnet can be considered as a dumbbell consisting of a pair of positive and negative magnetic charges, which respectively repel (attract) and attract (repel) vortices depending on the directions of magnetic fields.^[30,31] Therefore, the distribution of the magnetic charge patterns is

crucial for controlling vortex dynamics in superconductors. The magnetic charge patterns of ASIs can be directly revealed from magnetic force microscopy (MFM). Figures 1(e)–1(g) show MFM images of the ASI magnetized using an in-plane magnetic field pointing to the bottom. The magnetization directions of nanomagnets are indicated by arrows in Figs. 1(e)–1(g). The white and black spots display the positive and negative magnetic charges,

respectively. The positive and negative magnetic charges in section S1 are equal in size and strength [Fig. 1(e)], while section S2 displays smaller positive charges and larger negative charges [Fig. 1(f)], and section S3 reveals inversed geometries (as compared to section S2) of positive and negative charges [Fig. 1(g)]. The geometric structures of the magnetic charge patterns can be revealed more clearly from micromagnetic simulations in the insets of Figs. 1(e)–1(g).

To investigate the impact of the magnetic charge potentials on the motion of superconducting vortices, we conducted magnetotransport experiments in a three-axis su-

perconducting vector magnet. This apparatus can generate a magnetic field in any desired 3D orientation, enabling *in situ* control over the magnetic charge potentials and the density of superconducting vortices. The in-plane magnetic field is utilized solely to magnetize the ASI, establishing specific magnetic charge potentials, and is removed during transport measurements. An out-of-plane magnetic field B is applied to adjust the density and polarities of vortices within the MoGe film. The superconducting transition temperature for the MoGe film is identified at 6.6 K (see Fig. S3 in the Supplementary Material), with the transport experiments conducted at 5.7 K.

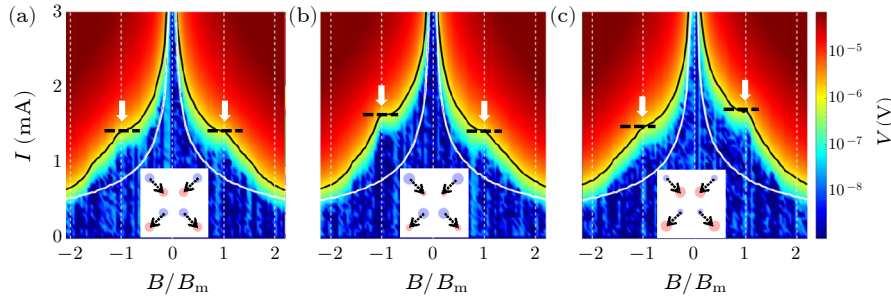


Fig. 2. Magnetic nonreciprocal effect. (a)–(c) Dissipation voltage induced by vortices/antivortices motion, dependent on both current and magnetic field. The three maps correspond to the results obtained under magnetic charge states of Figs. 1(e)–1(g), respectively. The magnetic field unit is normalized by the matching field $B_m = 78.9$ Gs. Black lines denote critical current curves extracted with a voltage criterion of $1 \mu\text{V}$, and white lines represent critical current curves in the REF section. The red/blue spots reveal positive/negative magnetic charges in insets, while the arrows indicate the magnetizations of single-domain nanomagnets.

Figures 2(a)–2(c) illustrate the magnetic field and current dependences of the dissipation voltages measured under the magnetic charge patterns in Figs. 1(e)–1(g), respectively. The magnetic field values are normalized by the first matching field $B_m = 78.9$ Gs, at which the vortex density equals the nanomagnet density. The insets in Figs. 2(a)–2(c) depict schematic diagrams of the magnetic charge patterns, correlating with Figs. 1(e)–1(g), respectively. The black solid lines in Figs. 2(a)–2(c) represent the critical current (I_c) curves, determined using a voltage criterion of $1 \mu\text{V}$. The white solid line in each figure corresponds to the I_c curve of section REF for the bare MoGe film. These results indicate that the ASI structures significantly enhance I_c , presenting a strong vortex pinning effect from the magnetic charges. Additionally, the I_c curves of sections S1–S3 with ASIs exhibit clear peaks/kinks at $B = \pm B_m$ [Figs. 2(a)–2(c)], which is a typical feature of the vortex matching effect.^[30,31] The I_c curve of section S1, employing symmetric nanomagnets, shows a symmetric response with respect to magnetic field B [Fig. 2(a)], similar to the symmetrical effects observed in hybrid devices of square-ASI/superconductor^[30] and pinwheel-ASI/superconductor.^[31] Figure 2(b) highlights a significant finding that the I_c curve is asymmetrical relative to $B = 0$. Specifically, the critical currents under negative fields surpass those under positive fields, implying that vortices move more easily at positive fields than at negative fields. This phenomenon leads to a magnetic non-reciprocal effect triggered by asymmetric nanomagnets.

Interestingly, Fig. 2(c) demonstrates that the polarity of the magnetic nonreciprocity can be reversed by inverting the asymmetric geometry of the nanomagnets. These magnetic nonreciprocal effects can also be repeated in another device (see Fig. S1 in the Supplementary Material).

To elucidate the microscopic mechanism behind the magnetic nonreciprocal effect and its association with the asymmetry of ASI's nanomagnets, we performed molecular dynamic (MD) simulations on our devices. The detailed MD simulation methodology is described elsewhere.^[30,31] Figures 3(a)–3(c) display the simulated I_c curves corresponding to Figs. 2(a)–2(c), respectively. They show a nice consistency between the experimental outcomes and simulations in terms of symmetric and/or asymmetric responses across all sample structures. Except for clear matching effects at $B = \pm B_m$, Figs. 3(a)–3(c) also show matching peaks at $B = \pm 1.5 B_m$, which is due to collective motion of interstitial vortices (see Fig. S2 in the Supplementary Material). Very weak kinks at $B = \pm 1.5 B_m$ can also be observed in experiments [Figs. 2(a)–2(c)]. To further unveil the microscopic nature of magnetic symmetry/asymmetry, we simulated the vortex motion behavior under positive and negative fields, which are presented in Videos 1–3. Screenshots depicting the vortices' trajectories are shown in Figs. 3(d)–3(i). Given that the driving force on a vortex from the applied current is opposite to that on an antivortex (which possesses inverted magnetic flux polarity and reversed circulating supercurrent) from the same current, vortices (under a positive magnetic field) and antivortices

(under a negative magnetic field) move in opposite directions. For section S1 with symmetric nanomagnets, the size and field strength of the positive and negative magnetic charges are identical, except for their polarity. Con-

sequently, vortices/antivortices exhibit equivalent motion [Video 1, Figs. 3(d) and 3(g)] under positive and negative fields, though in reversed directions, leading to a symmetric transport response [Fig. 3(a)].

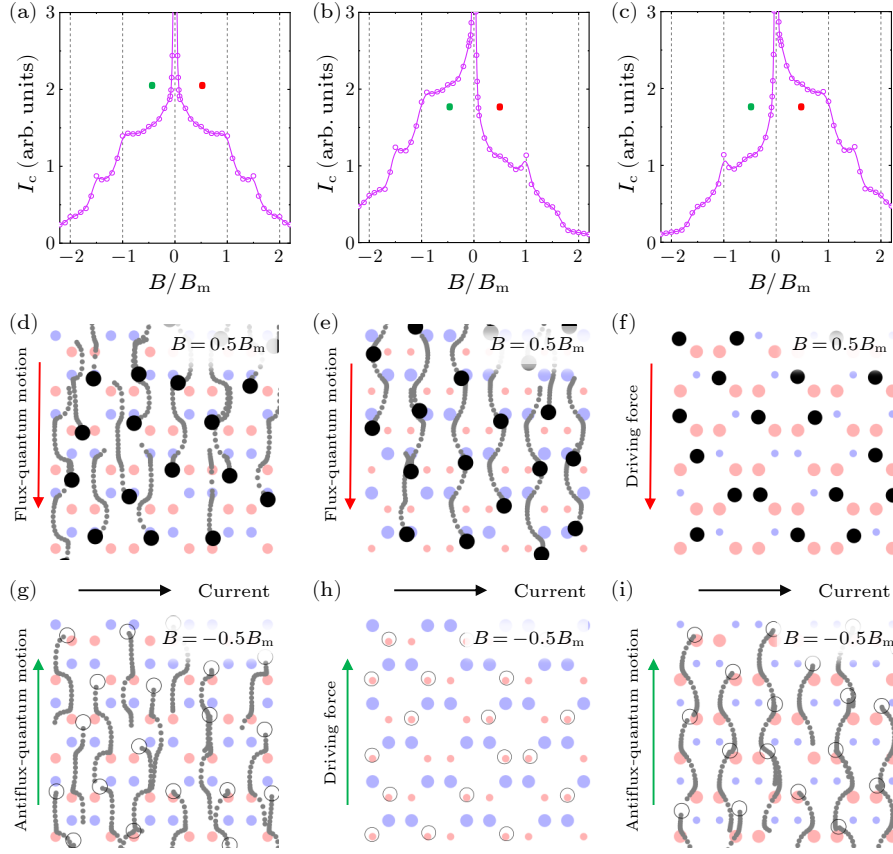


Fig. 3. Molecular dynamic simulations. (a)–(c) MD simulations of I_c – B curves using the charge patterns in sections S1–S3, respectively. (d)–(i) Screen shots of vortex motion/trajectories extracted from Videos 1 [S1, (d) and (g)], 2 [S2, (e) and (h)], and 3 [S3, (f) and (i)], and at $B = 0.5B_m$ (c)–(f) and $B = -0.5B_m$ (g)–(i). Red and blue dots are positive and negative magnetic charges, respectively. Black dots and open circles denote vortices and antivortices, respectively. The current and magnetic field values used for simulations are shown by the green and red points in (a)–(c).

The asymmetric nanomagnets in sections S2 and S3 generate different-sized positive and negative magnetic charges. Both MFM images [Figs. 1(f) and 1(g)] and micromagnetic simulations [insets of Figs. 1(f) and 1(g)] indicate that the wider end of each nanomagnet produces a smaller magnetic charge compared to the narrow end. Furthermore, the total magnetic flux value of the positive charge is equal to that of the negative charge from the same nanomagnet. Consequently, the stray field strength of the smaller positive charge in section S2 is more intense than that of the larger negative charge. Meanwhile, the positive charge attracts antivortices ($B < 0$), while the negative charge attracts vortices ($B > 0$).^[30,31] This results in stronger antivortex pinning under a negative magnetic field compared to vortex pinning under a positive magnetic field. As demonstrated by MD simulations in Video 2 [with corresponding screenshots in Figs. 3(e) and 3(h)], vortices ($B > 0$) navigate smoothly, whereas the antivortices are immobilized and pinned by the smaller yet stronger posi-

tive charges. Similar to the electric nonreciprocal effect in a superconducting diode, the magnetic nonreciprocal effect manifests a magnetic field-driven diode effect, where the system exhibits zero resistance only when the magnetic field is applied in one specific direction.

As mentioned above, magnetic nonreciprocity stems directly from the geometric asymmetry of the nanomagnet. In the case of sample section S3, the asymmetric nanomagnets are geometrically inverted compared to those in section S2, leading to the inverted size and field strength of the positive and negative charges. In this scenario, the smaller and more intense negative charges provide stronger pinning to vortices ($B > 0$), while the larger positive charges provide weaker pinning to antivortices ($B < 0$). This facilitates easier motion for antivortices ($B < 0$) compared to vortices ($B > 0$). This inversion results in the polarity of the magnetic nonreciprocal effect being flipped, which is vividly demonstrated in the MD simulations of Video 3 [with corresponding screenshots in Figs. 3(f) and

3(i)].

While inverting the asymmetric nanomagnet structure can effectively reverse the magnetic nonreciprocal effect, this method is not *in situ*, as the geometric structure of the nanomagnet cannot be changed post-fabrication of the sample device. However, ASIs provide the advantage of *in situ* reconfigurability of their magnetic charge patterns through the application of in-plane polarizing fields, allowing for programmable control of vortex dynamics. MFM images of Figs. 4(a)–4(c) illustrate the magnetic charge patterns of the inversely magnetized state compared to Figs. 1(e)–1(g). When the magnetization state of nanomagnets in ASIs is reversed, the polarities of magnetic charges are switched. In the case of section S1 with symmetric nanomagnets, given that the size and strength of the positive and negative charges remain consistent, reversing the magnetization of the nanomagnets does not change the relative pinning strengths between vortices and antivortices. The transport results continue

to show a magnetically symmetric response, as evidenced by the experimental data in Fig. 4(d) and the simulation data in Fig. 4(g). Conversely, reversing the magnetization of asymmetric nanomagnets results in inverted sizes and strengths of positive and negative magnetic charges [see Figs. 4(b) and 4(c) compared to Figs. 1(f) and 1(g), respectively], which in turn inverts the relative pinning strengths between vortices and antivortices. For instance, in sample section S2, the smaller but stronger negative charge leads to a greater pinning strength for vortices, resulting in higher critical currents under a positive magnetic field, as shown in the experimental result in Fig. 4(e) and the MD simulation result in Fig. 4(h). This process enables an *in situ* reversible magnetic nonreciprocal effect. The magnetic nonreciprocity of section S3 is also inverted, as depicted in Figs. 4(f) and 4(i). The inverted magnetic nonreciprocal effects for sections S2 and S3 are directly observable in Videos 4 (section S2) and 5 (section S3), respectively.

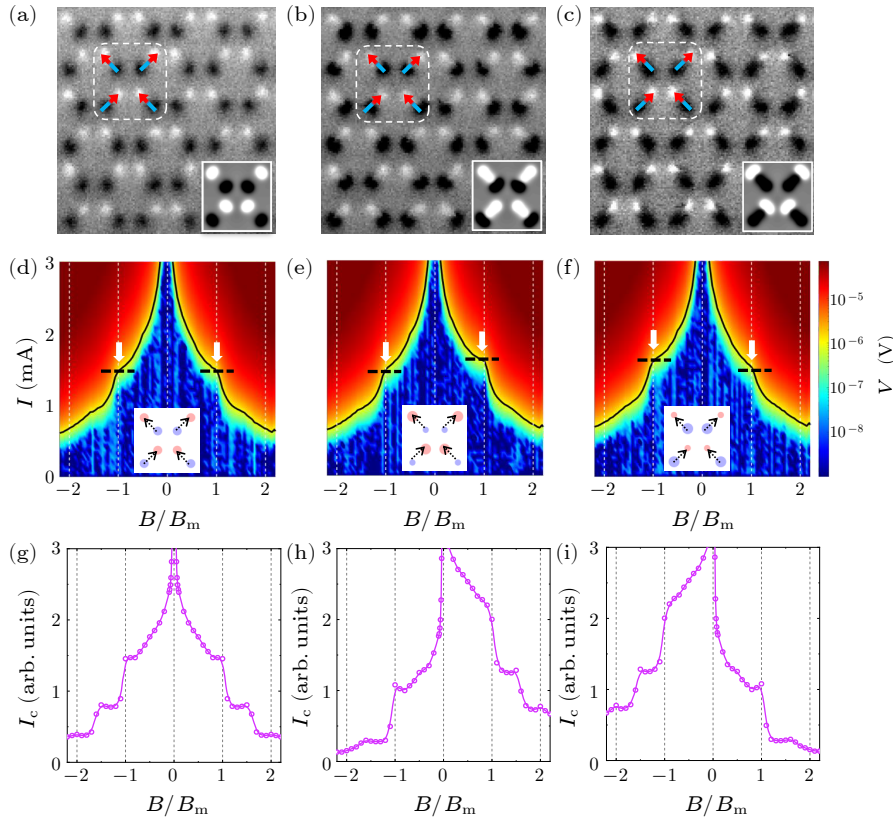


Fig. 4. *In situ* reversible magnetic nonreciprocal effect. (a)–(c) MFM images of inversely magnetized ASIs in sections S1–S3, respectively. (d)–(f) Experimental dissipation voltage induced by vortices/antivortices motion, corresponding to (a)–(c). (g)–(i) Corresponding MD simulations of I_c – B curves.

We introduced a novel ASI-superconductor heterostructure comprised of asymmetric nanomagnets situated on top of a superconducting film. These asymmetric nanomagnets generate positive and negative magnetic charges of nonidentical sizes and strengths, which provide different pinning forces on vortices and antivortices, leading to their distinct motion behaviors. Under specific currents, this system exhibits zero resistance in only one direction of the magnetic field while becoming resistive in the

opposite direction, functioning as a magnetic field-driven superconducting diode. Owing to the reconfigurability of ASIs, the polarity of the magnetic nonreciprocity can be reversed *in situ* by inverting the magnetization state of the ASI. Further investigation is required to explore the temperature dependence of these magnetic nonreciprocal effects and the in-plane field hysteresis effects. Beyond the square-ASI, our method of employing asymmetric nanomagnets is adaptable to other ASI structures, including

but not limited to kagome-ASI,^[32,33] pinwheel (or chiral)-ASI,^[31,34] and square-charge-ice-ASI.^[30,35] Our research underscores that ASI offers a pinning potential-by-design strategy for modulating superconductor properties and introduces novel functionalities to enhance superconducting electronics.

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