

Magnetochiral Anisotropy in Josephson Diode Effect of All-Metallic Lateral Junctions with Interfacial Rashba Spin-Orbit Coupling

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We explore the role of interfacial Rashba spin-orbit coupling (SOC) for the Josephson diode effect in all-metal diffusive Josephson junctions. Devices with Fe/Pt and Cu/Pt weak links between Nb leads reveal a Josephson diode effect in an in-plane magnetic field with magnetochiral anisotropy according to the point symmetry of Rashba SOC. The Rashba SOC originates from inversion symmetry breaking at the metal-metal interfaces. A control sample with a plain Cu layer as weak link, in contrast, exhibits an axis-symmetric diode effect. The Fraunhofer patterns display an apparent inverted hysteresis that can be traced back to stray fields resulting from the conventional hysteretic vortex pinning in the Nb contacts.

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Hybrid Josephson junctions (JJs) have enabled major advances in fundamental research of superconductivity and are central to contemporary developments in quantum technology. Milestone experiments have led to novel qubit architectures [1–3], memory devices based on magnetic JJs [4], and spin-polarized supercurrents [5,6].

The recent discovery of the Josephson diode effect (JDE) [7–11] has added a new circuit element to future superconducting electronics [12–16]. The JDE can occur when time-reversal symmetry (TRS) and inversion symmetries are broken and is reflected in an asymmetry of positive and negative critical current. Such asymmetry is a manifestation of magnetochiral anisotropy, introduced by Ref. [17]. So far, the diode effect in JJs was mostly observed in semiconductor weak links like InAs or InSb with strong Rashba spin-orbit coupling (SOC) [7,18].

In bilayer metallic films, inversion symmetry is broken by the charge transfer between the metal films, leading to a short-ranged, but strong interface electric field and thus to a Rashba-type Hamiltonian $\mathcal{H}_R = \alpha(\vec{k} \times \hat{z}) \cdot \hat{s}$, where $\vec{k}$ and $\hat{s}$ are the electron's momentum and spin, respectively, and α

is the Rashba constant [19–22]. In momentum space, a characteristic circular spin texture emerges at the Fermi level [23] [Fig. 1(a)]. Interfacial Rashba SOC at metal-metal interfaces is reflected, e.g., in spin-orbit torques [24,25], and was demonstrated at the Cu/Pt interface by spin-injection techniques [26,27]. Strong interfacial spin-orbit interactions have also been observed in Fe/Pt on GaAs in spin-pumping measurements driven by ferromagnetic resonance [28,29].

In contrast, studies on JJs of metallic weak links with interfacial Rashba SOC have been sparse. Senapati *et al.* [34] investigated Cu/Pt bilayers as a weak link in Nb-based JJs. They reported an apparent inverted hysteresis where the central Fraunhofer lobe is located at negative fields for forward field sweeps and vice versa. Similar inverted hysteresis was also found in Al-based JJs with Fe-doped InAs as weak links [35] and in epitaxial CoSi₂/TiSi₂ [36] normal metal-superconductor junctions. To date, no consensus on the origin of the inverted hysteresis has been reached.

In this Letter, we explore the experimental manifestation of the interfacial Rashba SOC in the JDE, demonstrating the possibility to use the JDE as a probe for interfacial Rashba SOC. We investigate the effect of interfacial SOC on the supercurrent in Nb-based lateral JJs with metallic weak links. The JDE is observed only for bilayer Fe/Pt and Cu/Pt. There, the breaking of inversion symmetry leads to interfacial Rashba SOC with the typical twofold symmetry with respect to the orientation of the in-plane magnetic

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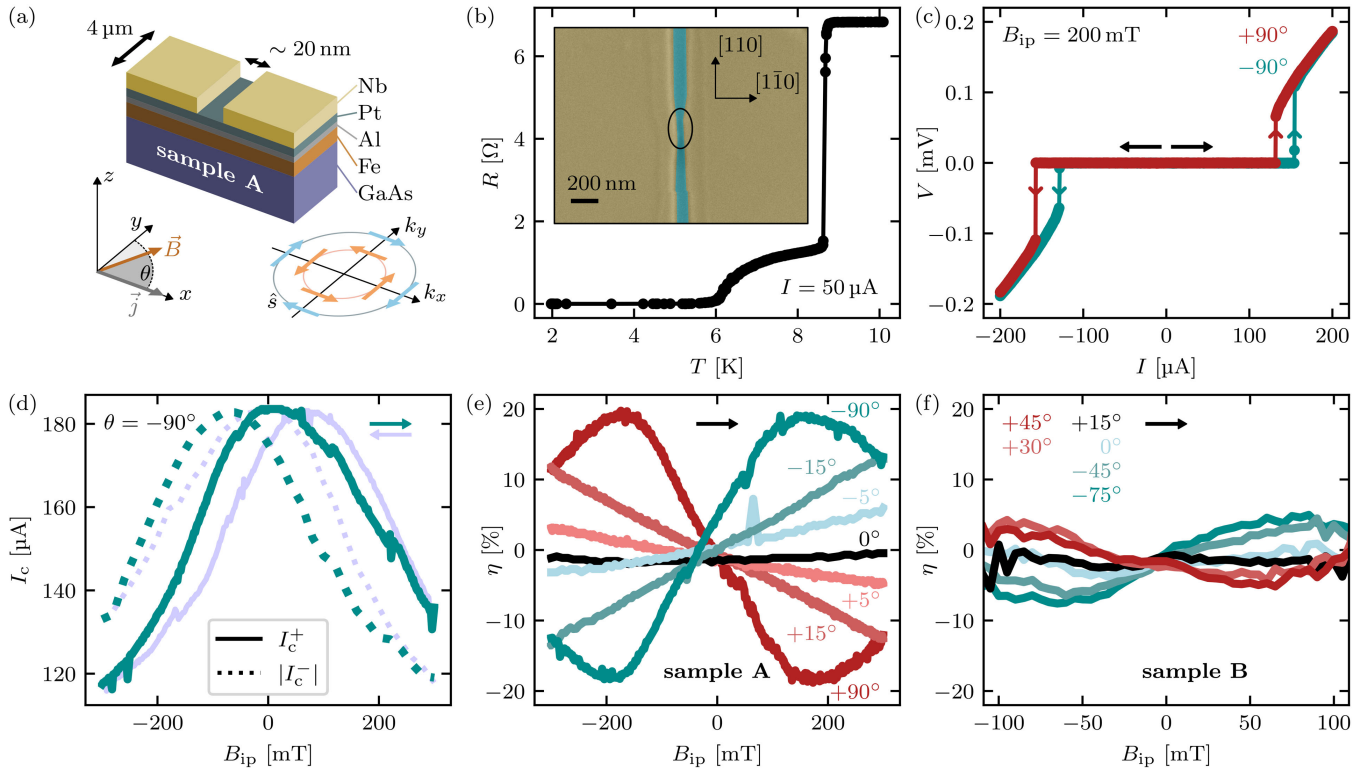


FIG. 1. Diode efficiency under B_{ip} . (a) Device and layer sequence of sample A. The direction of positive applied current defines the x axis. The direction of B_{ip} applied in panels (c)–(f) is indicated by the coordinate system. θ measures the angle between B_{ip} and the direction of the positive current density $\vec{j}$. The bottom right sketch depicts the chiral spin texture of the Rashba SOC at the Fermi level in momentum space. (b) Temperature dependence of the resistance of sample A measured at $I = 50 \mu\text{A}$ in zero magnetic field. Inset: SEM false-color image of the device. The Nb leads are highlighted in yellow; the blue area represents the junction. At the narrowest point, encircled in the SEM image, the gap measures around 20 nm in length and ~ 180 nm in width. The indicated crystallographic axes refer to the GaAs substrate. (c) IV curves of sample A taken at $B_{ip} = 200$ mT applied at $\theta = +90^\circ$ (red) and -90° (blue) in forward field sweep direction. Arrows indicate the sweep direction of I , ramping from zero to 200 μA and from zero to $-200 \mu\text{A}$. (d) In-plane field dependence of I_c of sample A for fixed $\theta = -90^\circ$. Absolute values of I_c at positive (I_c^+) and negative (I_c^-) bias are indicated by solid and dashed lines, respectively. The sweep direction of the applied field is indicated by the colored arrows. (e) Diode efficiency η of sample A as a function of B_{ip} at various in-plane angles θ . The field is swept from negative to positive values. The I_c curves producing the depicted $\eta(B_{ip}, \theta)$ are shown in Supplemental Material [30]. Measurements shown in panels (c)–(e) are taken at 30 mK. (f) $\eta(B_{ip})$ of sample B at various angles θ , measured at 1.8 K. The curves at $\theta = +30^\circ$ and $+15^\circ$ are shifted to create a crossing at zero applied field; see Supplemental Material [30]. All curves in panels (e),(f) are acquired in forward field sweep direction.

field. For Cu weak links, in contrast, the diode efficiency has an even symmetry. All devices exhibit an apparent inverted hysteresis in out-of-plane fields that can be understood as a result of hysteretic vortex pinning in the Nb terminals.

We first examine an epitaxial heterostructure of GaAs(001)/Fe(2.9 nm)/Al(1 nm)/Pt(5 nm)/Nb(50 nm), (sample A). The specific stack is chosen for its strong interfacial SOC arising at both the GaAs/Fe and the Fe/Al/Pt interface [28,29]. The thin layer of Al serves as a spacer, preventing magnetic proximity polarization of the Pt layer while remaining transparent for charge and spin transport [29]. A lateral Nb JJ is realized atop the Pt film by etching a narrow gap into the Nb layer. Figure 1(a) depicts the stack schematically, and an SEM image is shown in the inset of Fig. 1(b).

We study the device resistance R as a function of temperature and observe a two-step behavior characteristic of a hybrid JJ. At $T \approx 8.6$ K, the Nb electrodes become superconducting first, followed by a broad transition to $R = 0$ near $T \approx 6.0$ K [see Fig. 1(b)]. To the best of our knowledge, this is the first instance of an experimental realization of a lateral Josephson junction with an Fe weak link [37,38]. To investigate the signatures of Rashba-type SOC in the present device, we study the critical current I_c under a magnetic field B_{ip} applied in the sample plane. To avoid heating-induced hysteresis, IV curves are acquired by ramping the applied current I first from zero to 200 μA and then from zero to $-200 \mu\text{A}$ while measuring the voltage drop V across the junction in a four-point geometry. At 30 mK, $I_c R_n \approx 3.0$ mV, which is comparable to the superconducting gap Δ and the Thouless energy

$E_{\text{Th}} \approx 1.6 \text{ meV} \approx 1.2\Delta$ (see Supplemental Material [30]). This is consistent with both the short and long junction limits [39]. Figure 1(c) displays two IV curves taken at $B_{\text{ip}} = 200 \text{ mT}$ applied at an angle $\theta = +90^\circ$ (red) and -90° (blue) with respect to I . The difference in I_c under positive (I_c^+) and negative bias (I_c^-) is quantified through the diode efficiency [40] $\eta = 2(I_c^+ - |I_c^-|)/(I_c^+ + |I_c^-|) \times 100\%$. Here, $\eta = -17.8\%$ and 18.0% at $\theta = \pm 90^\circ$, respectively. Figure 1(d) depicts the magnetic field dependence of I_c^+ and $|I_c^-|$ measured at $\theta = -90^\circ$ in both forward (from $-B_{\text{ip}}$ to $+B_{\text{ip}}$, blue) and backward (from $+B_{\text{ip}}$ to $-B_{\text{ip}}$, lavender) field sweep direction. All curves show the expected bell-like shape of a JJ under B_{ip} [18,41,42]. A considerable JDE is observed between I_c^+ and $|I_c^-|$ for both sweep directions. The resulting diode efficiency $\eta(B_{\text{ip}})$ is depicted in Fig. 1(e) for various angles θ in forward field sweep direction. At $\theta = -90^\circ$ (i.e., $\vec{B} \perp \vec{j}$), it features the characteristic shape of a diode effect [13,18,43]. A maximum diode efficiency of $\pm 20\%$ is reached around $\pm 175 \text{ mT}$, and $\eta(B_{\text{ip}})$ exhibits positive polarity (positive cusp at positive field and vice versa). As the field direction is rotated toward $+90^\circ$, the diode efficiency is gradually reduced, vanishes, and changes sign at $\theta = 0^\circ$ (i.e., $\vec{B} \parallel \vec{j}$) before returning to its initial strength with opposite polarity at $+90^\circ$, constituting the typical 2π -periodic magnetochiral anisotropy. Since the reversal of sign in η occurs at $\theta = 0^\circ$, the polarity matches that of an interfacial Rashba SOC inside the weak link.

We repeat the same measurements on nonmagnetic weak links in order to substantiate the influence of Rashba SOC and rule out the in-plane $\langle 110 \rangle$ uniaxial magnetic anisotropy of GaAs/Fe [44] as the source of the diode effect. Sputtered Si/SiO₂/Cu(50 nm)/Pt(3.5 nm)/Nb(40 nm) films (sample B) induce Rashba SOC at the Cu/Pt interface [26,27]. A lateral JJ is fabricated following the same methods as for the first sample. The device's critical temperature is near 5 K, and IV characteristics for $T < 5 \text{ K}$ yield $I_c R_n \approx 26 \text{ } \mu\text{V}$ (see Supplemental Material [30]), which is comparable to literature values for similar Cu weak links [34,45]. Similarly to sample A, we record IV curves under B_{ip} at various angles θ . Before each field sweep the sample temperature is brought to 9 K—which is above T_c of the Nb leads—and field-cooled at $\pm 200 \text{ mT}$. This procedure eliminates the hysteretic effect of previous field sweeps as described below, and ensures a well-defined initial state. For sample A, this step was not necessary due to the larger diode efficiency. We extract I_c and calculate the diode efficiency η shown in Fig. 1(f). Compared to Fig. 1(e), the maximum diode efficiency is smaller. Nevertheless, the characteristic Rashba-like magnetochiral anisotropy is observed, where the polarity of $\eta(B_{\text{ip}})$ gradually changes from positive at $\theta = -75^\circ$ to negative at $+45^\circ$, with the sign change occurring around 0° . A larger range of angles was not accessible experimentally. Note that the traces at $\theta = +30^\circ$ and $+15^\circ$ in Fig. 1(f) are slightly shifted to cross with the other curves at zero

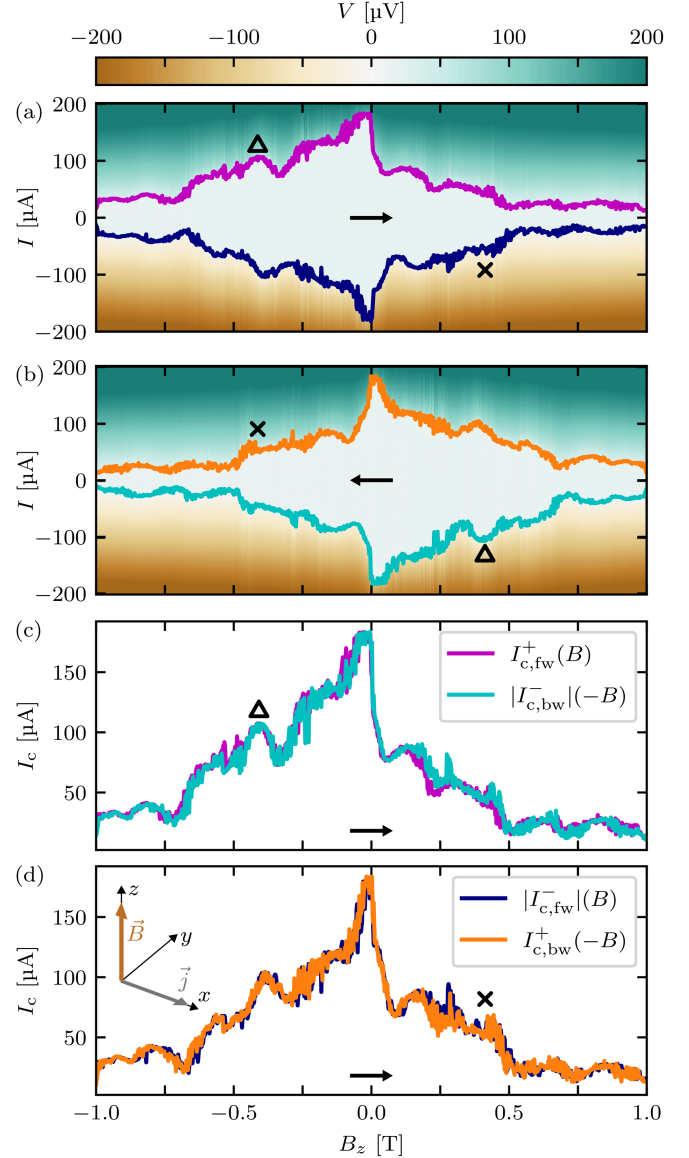


FIG. 2. Interference pattern of sample A under B_z in (a) forward and (b) backward field sweep direction, as indicated by the arrows. The extracted I_c curves are overlaid in different colors. The triangles indicate a feature that is reproduced only by the inversion of current, field, and field sweep direction. The cross marks the position that is obtained by inverting only field and current direction. (c) Comparison of $I_{c, \text{fw}}^+$ [see top half of data in panel (a)] with $|I_{c, \text{bw}}^-|$ [bottom half of panel (b)]. Note that the field axis of $|I_{c, \text{bw}}^-|$ is flipped to match the forward field sweep direction. (d) Equivalent comparison of $|I_{c, \text{fw}}^-|$ [bottom half of panel (a)] and $I_{c, \text{bw}}^+(-B)$ [top half of panel (b)]. The measurements are taken at 30 mK. The inset of panel (d) shows the direction of the applied field.

magnetic field (see Supplemental Material [30] for details). Importantly, the polarity of the diode effect is the same for both Fe/Pt and Cu/Pt systems. This is consistent as Fe and Cu share a similar work function ($W_{\text{Fe}} \approx 4.7 \text{ eV}$, $W_{\text{Cu}} \sim 4.5 \text{ eV}$), thus producing the same sign for the

Rashba SOC when interfaced with Pt ($W_{\text{Pt}} \sim 5.6$ eV) [46]. The similarity of the results for both samples suggests that the effect is most likely related to Rashba-type SOC rather than the ferromagnetism of the Fe film of sample A.

Next, we analyze the diode efficiency in JJs where weak links are 50 nm Cu films with no metal-metal interfaces and negligible bulk SOC (sample C) [47,48]. Details on the fabrication process and device characterization are given in Supplemental Material [30]. Also in this device, a diode efficiency between -50% and $+20\%$ is observed. However, in contrast to the bilayer devices with Rashba interfaces where $\eta(\theta)$ displays a point symmetric shape, the diode efficiency of sample C is approximately even in θ (see Supplemental Material [30]). In this case, the Rashba SOC can be excluded as the origin of the diode effect. The assignment to an alternative mechanism requires further investigation.

A central result of this Letter is that only for devices with metal-metal interfaces (samples A and B), the observed angle dependence points toward Rashba SOC. For sample A (GaAs/Fe/Al/Pt), where strong Rashba SOC has been reported [28,29], the diode effect is more pronounced than for sample B (Cu/Pt), which is known to have weaker SOC [26,27]. This strongly supports the conclusion that the JDE is tuned by purely changing the interfacial configuration, while bulk SOC does not play a significant role. This is consistent with observations by Senapati *et al.* [34] on comparable structures.

In addition to the JDE, a substantial hysteretic shift in magnetic field is observed in Fig. 1(d) when comparing the curves of I_c^+ measured with opposite field sweep directions (solid lines). The dashed traces representing $|I_c^-|$ are shifted in the same fashion. Remarkably, this shift does not conform with conventional magnetic hysteresis; instead it is characterized by an inverted order. For all samples, we also observe a notable inversely hysteretic shift in a perpendicular field B_z between the forward and backward sweep direction, as analyzed in detail in End Matter. We propose a mechanism based on the hysteretic vortex pinning inside the Nb leads [49].

Finally, we investigate the supercurrent interference of sample A in a perpendicular magnetic field. Figures 2(a) and 2(b) display the interference pattern of the junction's IV characteristic as a function of B_z in forward and backward field sweep direction, respectively. Notably, $I_c(B_z)$ exhibits a pronounced asymmetry about $B_z = 0$. The deviation from the standard Fraunhofer pattern can be attributed to the spatial inhomogeneity of the junction's critical current density owing to fabrication imperfections. The apparent noise is related to spontaneous flux jumps in the Nb leads (see End Matter for more details). Upon comparing the forward and backward sweeps, a similar inverted hysteresis is present; see Supplemental Material [30].

Interestingly, the combined transformations $I_c^+ \rightarrow I_c^-$ and $+B_z \rightarrow -B_z$ do not lead to a match of the corresponding

curves that is expected from TRS. The reason is that the hysteretic stray fields from the pinned vortices must be included to reverse *all* magnetic fields. Thus, a proper check for TRS also has to reverse the field sweep direction, not only I_c and the applied field B_z . As an example, the value of $I_{c,\text{fw}}^+$ near -0.4 T in Fig. 2(a) marked by the triangle is not reproduced in $-I_{c,\text{fw}}^-$ at $+0.4$ T, as indicated by the cross. However, it is equal to $-I_{c,\text{bw}}^-$ at $+0.4$ T and the opposite sweep direction, as highlighted by the triangle in Fig. 2(b). For a direct comparison, $I_{c,\text{fw}}^+$ and $|I_{c,\text{bw}}^-|$ are plotted together in Fig. 2(c). For the latter, the field axis is reversed to account for the backward sweep direction. The curves overlap in all prominent features. Similarly, $|I_{c,\text{fw}}^-|$ and $I_{c,\text{bw}}^+$ can be matched, as shown in Fig. 2(d). In Supplemental Material [30] it is demonstrated that other combinations do not result in an adequate overlap.

To summarize, Nb-based Josephson junctions comprising Fe/Al/Pt and Cu/Pt weak links reveal the signatures of Rashba SOC in diffusive, all-metallic Josephson junctions. An apparently inverted hysteresis is traced back to the standard hysteresis of pinned vortices in the Nb leads. The consideration of this pinning effect is crucial in superconducting electronics where the phase bias is a key parameter.

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C. H. B., C. S., and D. S. conceptualized the experiments. M. M. and D. S. made the devices. M. M., D. S., L. B., J. B., and C. Y.-C. performed the measurements. M. K. and T. N. G. M. provided samples. M. M., C. S., and D. S. analyzed the data. M. M., C. S., and D. S. wrote the manuscript with inputs from C. H. B., M. K., and P. H. All authors contributed to the discussions.

Data availability—The data that support the findings of this article are openly available [50].

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End Matter

Here, we discuss the origin of the peculiar phenomenon of inverted hysteresis, which is explained below in terms of a consequence of the stray field of conventionally pinned vortices in hard superconductors. Previous reports on the inverted hysteresis of critical currents in JJs of type-II superconductors have been linked to the presence of Rashba SOC inside the JJ [34] as well as triplet-pair superconductivity [35,36]. Since we find inverted hysteresis in all junctions with and without SOC, the effect appears not to be related to SOC. A more conventional explanation takes into account hysteretic vortex pinning as described by Bean’s critical state model [49]. Depending on the sequence of the field sweep procedure, the pinned vortices can create a stray field that opposes the externally applied field B_z and produces a net zero flux through the JJ before B_z is swept past zero.

Figure 3(a) shows $I_c(B_z)$ for sample B where B_z is swept from -20 to $+20$ mT (forward, dark gray) and from 20 to -20 mT (backward, light gray) after field cooling at

± 20 mT. An inversely hysteretic shift of the interference patterns in forward and backward field sweep direction of around ∓ 10 mT is observed. Experimental artifacts from remnant fields stored in the coils are ruled out as the origin of the inverted hysteresis in Supplemental Material [30]. The $I_c(B_z)$ traces feature a broad inversely hysteretic bump with several jumps of I_c while the field is swept. The switching pattern varies for several repetitions of the sweep (see Supplemental Material [30]). We assign the discontinuities to flux jumps in the junctions resulting from spontaneous changes in the stray magnetic field of vortices pinned in the Nb strips near the junction. The instabilities in the stray field are caused by random depinning events as the applied field changes. Between these jumps, Fig. 3(a) reveals a smooth change of I_c over $1-3$ mT. In this way, short intervals of an intrinsically clean Fraunhofer pattern are probed multiple times, until the flux in the junction exceeds a few flux quanta and $I_c(B_z)$ is featureless (see Supplemental Material [30] for more details). Flux jumps in $I_c(B_z)$ are also seen for sample A in Fig. 2 on the

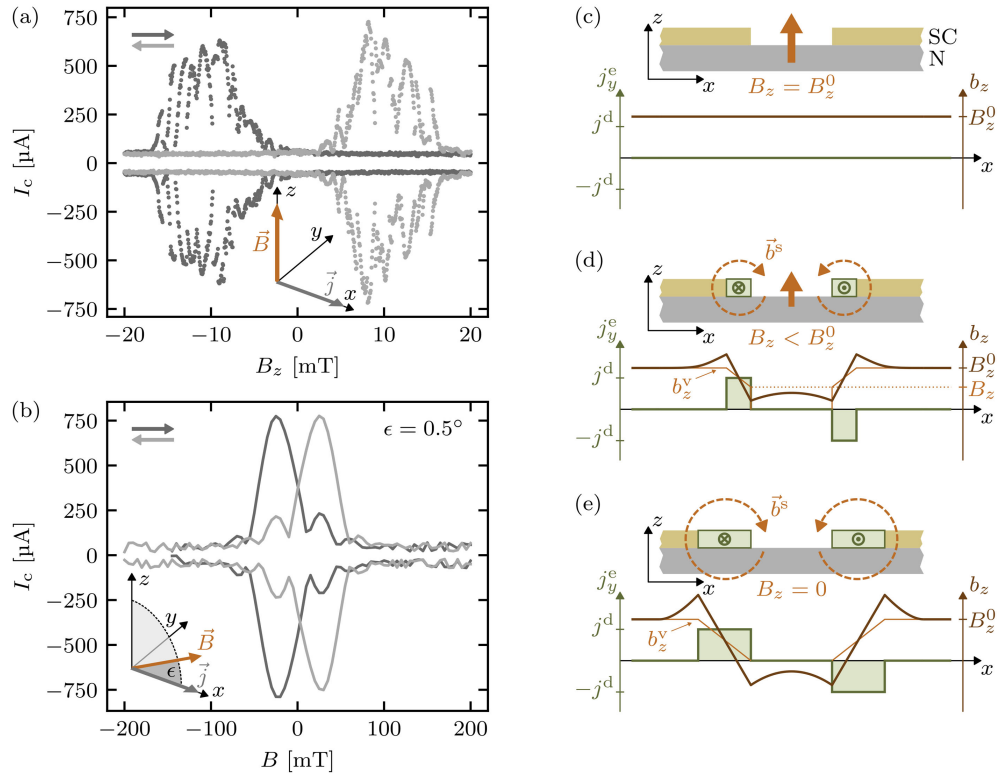


FIG. 3. Inverted hysteresis in sample B. (a) $I_c(B_z)$ in forward (dark) and backward (light) field sweep direction. (b) $I_c(B)$ for B applied along the current direction with a small misalignment of $\epsilon = 0.5^\circ$ from the sample plane. All measurements are taken at 1.8 K. (c)–(e) Schematic cross section of a generic JJ in a superconductor (SC) on top of a normal conductor (N). $b_z(x)$ denotes the local magnetic field given by the external field B_z , the field b_z^v generated by the vortex distribution inside the Nb leads, and the stray magnetic field $\vec{b}^s$ induced by the edge currents $\vec{j}_y^e$. The corresponding profiles of $b_z(x)$, $b_z^v(x)$ and $j_y^e(x)$ according to the critical state model [49] are shown at different stages during a downward field sweep after field cooling at B_z^0 . For better visibility, the contribution of b_z^s is exaggerated. For the discussion of the field profile, see Supplemental Material [30].

few mT scale across the whole field range, as demonstrated in Supplemental Material [30].

Flux jumps are avoided when applying the magnetic field essentially parallel, but with a small misalignment angle $\epsilon = 0.5^\circ$ from the sample surface. In this configuration, vortices thread the Nb film over the full width of the contacts. Hence, each vortex is expected to contribute only a small amount $\phi = \phi_0 \sin \epsilon \simeq 0.01\phi_0$ to the magnetic flux in the junction, leading to a nearly regular, but still inversely hysteretic Fraunhofer pattern with several side lobes in Fig. 3(b). We note an asymmetry in magnitude and width between the left and right secondary lobes with respect to the field sweep direction that is qualitatively comparable to the findings of Senapati *et al.* [34]. Following the same protocol, sample C is tested for hysteretic behavior under B_z , revealing similar inverted hysteresis, as shown in Supplemental Material [30].

In the following, we explain the observed inverted hysteresis based on the critical state model [49]. This model considers strongly pinned vortices that gradually enter or exit a superconducting slab from the sides when the diamagnetic edge current exceeds the depinning current j^d locally. Confined in vortices, the magnetic flux penetrates

much deeper than the London penetration depth. According to Maxwell's equation $\nabla \times \vec{b} = \mu_0 \vec{j}^e$, the gradual penetration of the local flux density $\vec{b}$ introduces an edge current density $\vec{j}^e$ in the outer regions of the superconductor until $|\vec{j}^e|$ equilibrates at j^d . These edge currents can largely exceed those present in the Meissner state. According to Ampère's law, the edge currents $\vec{j}^e$ generate a stray magnetic field $\vec{b}^s$. Figures 3(c)–3(e) outline that the z component b_z^s can overcompensate the externally applied field B_z in the junction area, causing an apparent inverted hysteresis in the flux. We depict a cross section along the length of the junction in the xz plane subject to an external field B_z . In this simplified geometry, Maxwell's equation reduces to

$$-\frac{db_z(x)}{dx} = \mu_0 j_y^e(x) \quad (\text{A1})$$

such that the edge current $\vec{j}^e$ flows in y direction. The estimated local magnetic flux density $b_z(x) = B_z + b_z^v(x) + b_z^s(x)$, where $b_z^v(x)$ denotes the field contribution

from the locally varying vortex density, is illustrated together with the edge current $j_y^e(x)$. Initially, a field $B_z^0 < B_{c2}$ is applied in positive z direction [see Fig. 3(c)], where B_{c2} is the upper critical field. By cooling below T_c in fixed B_z , the Nb leads are brought into a fully penetrated Abrikosov state, such that $b_z(x) = B_z^0$ both inside the junction as well as inside the leads. No edge currents are induced. Upon reducing the applied field below B_z^0 , vortices start to be pushed out near the edges of the Nb strips such that a gradient of b_z^y forms near the edges. Thus we expect $j_y^e(x) \simeq \pm j^d$ in these regions as depicted in Fig. 3(d). The resulting stray field $\vec{b}^s$ adds a negative z component in the area of the junction. When $B_z = 0$, the field in the junction area is $b_z = b_z^s < 0$ [see Fig. 3(e)]. Consequently, the point of net zero flux enclosed in the junction must be reached while $B_z > 0$ during a backward field sweep and $B_z < 0$ during a forward sweep. Taking $j^d \simeq 50 \times 10^6$ A/cm² (see Refs. [51–54] and Supplemental Material [30]), the magnitude of the stray field at zero applied field can be estimated to be ~ 3 –4 mT for the case of sample B (see Supplemental Material [30]). Given the crudeness of the model, such values are consistent with the shifts of ± 10 mT seen in Fig. 3(a). Furthermore, the jumps

in $I_c(B_z)$ visible in Figs. 2 and 3(a) as well as the minor loop behavior of sample C can be explained with this model, as discussed in Supplemental Material [30]. Also the inverted hysteresis observed under in-plane fields in Fig. 1(d) can be understood by the critical state model if we take into account a small residual out-of-plane component in the applied field. The contribution of each vortex to b_z^s is strongly reduced due to the in-plane orientation. On the other hand, B_{ip} in Figs. 1(d)–1(f) is on the order of hundreds of mT, resulting in a much larger number of vortices compared to the case of Fig. 3(a), thus producing a comparable hysteretic effect. Because of the small contribution of the pinned in-plane vortices to the stray field b_z^s , flux jumps cannot be resolved.

It should be emphasized that the mechanism outlined above is unrelated to the flux focusing effect that occurs in the Meissner state. The discussed edge currents are distinct from Meissner currents in that they arise from the inhomogeneous and hysteretic vortex distribution. Thus they can persist even when the external field is zero and give rise to an offset field in the junction that remains finite at zero applied field. Our observation is consistent with that of Ref. [55].