High-temperature superconducting diode

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Abstract

Symmetry plays a critical role in determining various properties of a material. Semiconducting p-n junction diode exemplifies the engineered skew electronic response and is at the heart of contemporary electronic circuits. The non-reciprocal charge transport in a diode arises from doping-induced breaking of inversion symmetry. Breaking of time-reversal, in addition to inversion symmetry in some superconducting systems, leads to an analogous device – the superconducting diode. Following the pioneering first demonstration of the superconducting diode effect (SDE) [1], a plethora of new systems showing similar effect have been reported [2–9]. SDE lays the foundation for realizing ultra-low dissipative circuits, while Josephson phenomena-based SDE can enable realization of protected qubits [10]. However, SDE reported thus far is at low temperatures (∼4 K or lower) and impedes their adaptation to technological applications. Here we demonstrate a superconducting diode working up to 77 K using an artificial Josephson junction (AJJ) of twisted layers of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (BSCCO). The non-reciprocal response manifests as an asymmetry in the magnitude of switching currents and their distributions independent of the twist angle. The asymmetry is tunable with a very small magnetic field applied perpendicular to the junction. We report a record asymmetry of 60 % at 20 K. Crucially, the AJJ at the interface that breaks inversion symmetry shows the SDE, while naturally occurring intrinsic Josephson junctions (IJJ) in the crystal do not. Our results provide a path toward realizing superconducting quantum circuits at liquid nitrogen temperature.

To realize SDE, breaking of inversion and time-reversal symmetry is required [11]. Several proposals for realizing the superconducting analogue of the diode effect [12–14] have been explored. It was followed by successful demonstrations in various systems such as non-centrosymmetric superconductors [1–3], two-dimensional electron gases [4], patterned superconductors [5, 6], superconductor/ferromagnet multilayers [7, 8], and twisted graphene systems [9, 15]. Although several different mechanisms [3, 16–18] have been proposed to describe the observations across systems, the theories are still at their early stage of development. The SDE, which is the result of non-reciprocal response in these systems, manifests in terms of different magnitudes of superconducting switching currents ($I_s^+ \neq I_s^-$) in the two opposite polarities. The effect has been demonstrated as magnetic field induced [1–6] and

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field free [7–9] in nature. In terms of practical usability, however, all reports to date require very low temperatures, 4 K or less, to operate. We overcome this challenge using \textit{c-axis} Josephson junction (JJ) between flakes of a high-$T_c$ cuprate superconductor.

We demonstrate SDE in an artificially created Josephson junction (AJJ) by twisting two layers of BSCCO [19] that can be exfoliated to atomically flat flakes [20–23] sustaining superconductivity down to the monolayer limit [24]. The difference between the magnitude of positive ($I^+_s$) and negative ($I^-_s$) switching currents and their statistical distributions, in these junctions, are tunable with a very small magnetic field applied perpendicular to the plane of the junction. The asymmetry persists from low temperature till superconducting transition temperature ($T_c$, $\sim$ 77 K) of the junction and increases as temperature decreases, reaching a value as high as 60% at 20 K. The diode behavior is observed in terms of the half-wave rectification of a square wave current.

Heterostructures, assembled by twisting two layers of van der Waals materials offer a new platform for emergent electronic responses, entirely different from the constituent materials. In a similar spirit, a recent study [25] proposes the possibility of realizing time reversal symmetry broken high-temperature topological superconductivity at the interface of two 45° twisted BSCCO layers. Thus twisted BSCCO JJs offer a natural platform to explore the physics of SDE. Notably, our work demonstrates that SDE is a feature of the artificial \textit{c-axis} JJs and does not require a special angle, 45°, as long as inversion symmetry is broken.

Fabricating twisted BSCCO junctions, however, are extremely challenging, and many of the junction properties are sensitive to fabrication methods. In the past, there have been numerous studies on artificially created twisted junctions of BSCCO to study the pairing symmetry of the superconducting order parameter. But the fabrication process involved high-temperature oxygen annealing to sustain the superconductivity at the interface. This led to observations of no [26–28] or different [29, 30] angular dependence of the Josephson coupling, different than the anticipated \textit{d}-wave superconductivity in BSCCO [31, 32]. Recently, there has been progress in making twisted BSCCO JJs using room temperature exfoliation [28, 30] and employing cryogenic exfoliation [33].

We fabricate twisted BSCCO JJs following Zhao \textit{et al.} [33]. The junctions are created by re-exfoliating a relatively thicker BSCCO flake into two pieces and stacking them, which ensures alignment of the crystal axis and a well-defined twist angle (with an accuracy of ± 0.5°). The re-exfoliation is done inside an Ar-filled glove box with a low-temperature
stage. To avoid any chemical contamination, Au contacts are directly deposited on the flake through a pre-aligned SiN mask. More details of the device fabrication are discussed in the methods section.

**Experimental data**

Fig. 1a and b show the schematic of the twisted BSCCO crystal structure and the device geometry of the artificial JJ, respectively. The crystal structure of BSCCO is such that it has its own IJJ. The superconducting Cu-O planes in this material, separated by the insulating SrO/BiO buffer layers (green slabs in Fig. 1a), are Josephson coupled and constitute a series of IJJJs in the material structure [34]. By twisting two individual layers of BSCCO, we create an AJJ at the interface, as indicated in Fig. 1a. The twist angle controls [30, 33] the switching current density ($J_s$), and consequently the Josephson energy, of the AJJs (maximum for 0°, and minimum for 45° twist) due to $d$-wave symmetry of the superconducting order parameter in the system.

We made 5 AJJs with different twist angles (two 45°, two 0°, and one 22°). In the main text, we present data of 45° and 0° twisted junctions, and data of other twisted junctions are shown in Supplementary Information Fig. S6 (45° and 0°) and Extended Data Fig. 4 (22°). The SDE is observed in all of the devices with different twist angles, an important aspect of our work. We design our devices such that we can simultaneously measure the junction properties and the two flakes that make the junction (Fig. 1b). We do this to ensure that there is no degradation during the fabrication. First, we check the four terminal resistance with temperature across the junction which shows $T_c$ similar to the pristine BSCCO flake, as shown in the Supplementary Information, Fig. S3. The pristine nature of the fabricated junctions is evident from the fact that the 0° twisted junction has magnitude of switching current density ($J_s$) similar to the IJJJs formed between the Cu-O planes in BSCCO (see Extended data Fig. 1).

Fig. 1c shows $dc I-V$ across the junction at 30 K and at fixed $B = 4.3 \mu T$, perpendicular to the junction plane (see Fig. 1b). We discuss the detailed field dependence later. The two colored line plots are for different sweep directions of the bias current as indicated by the arrows. The bias current is swept in the order as shown in the inset. We identify switching ($I_s$) and retrapping currents ($I_r$) in positive and negative bias range with $I_s^+$ and $I_s^-$, as shown
in Fig. 1c. The magnitude of $I_s^+$ is different from $I_s^-$. The observed hysteresis between $I_s$ and $I_r$ is a well-understood physics of an underdamped JJ [35].

To clearly see the difference between the two switching currents $I_s^+$ and $I_s^-$, we plot the $I - V$ curves of the negative bias branch by flipping their signs in Fig. 1d. From the plot, it is clear that $I_s^+$ is larger than $|I_s^-|$. This means that at bias currents $I$, $|I_s^-| < I < I_s^+$, the system will dissipate energy and act like a resistive element in negative bias and be superconducting in positive bias. To quantify the difference between $I_s^+$ and $I_s^-$ we define an asymmetry factor, $\alpha$ as $\alpha = (I_s^+ - |I_s^-|)/(I_s^+ + |I_s^-|) \times 100 \%$. The value of $\alpha$ for the data, shown in Fig. 1d at 30 K, is 17 \%.

Switching of JJs from superconducting to resistive state is stochastic and has a finite distribution at a fixed temperature [36]. To probe the switching statistics for $I_s^+$ and $I_s^-$ in our twisted JJ, we measure $10^4$ switching events for both positive and negative bias currents and compare their distributions. The measurement protocol for switching distribution is discussed in the methods section. As seen in Fig. 1e, the median value of the distribution also shows asymmetry, as was seen in a single sweep. In addition, the spread of the distributions is different – an aspect we discuss later.

We next study the current asymmetry $\alpha$ at different temperatures and with an external magnetic field $B$, applied perpendicular to the plane of the junction. Fig. 2a shows the cross-sectional schematic of the device showing the IJJs formed between Cu-O planes and the AJJ, formed artificially. As depicted in Fig. 2a, the direction of the current across the AJJ is along the c-axis, parallel to applied $B$. Fig. 2b shows the variation of $I_s^+$ and $I_s^-$ with $B$ at 20 K. At each $B$ value, we record 100 switching events with the help of a counter and average it out to get $I_s^+$ and $I_s^-$, which are plotted in Fig. 2b. The measurement protocol is discussed in the methods section. Importantly, we note a pronounced change of $I_s^+$ and $I_s^-$ with a very small magnetic field. Variations of $I_s^+$ and $I_s^-$ show peaks that are shifted from each other along the $B$ axis. The difference in $B$ between the two peaks corresponds to a few flux quanta through the junction area. We calculate $\alpha$ from this data. Fig. 2c,d show the evolution of calculated $\alpha$ with $B$ at 20 and 70 K, respectively. The line plots with different colors are for two sweep directions of $B$ as indicated by the inset arrows. Here, we note the main observation. $\alpha$ is antisymmetric in $B$, $\alpha(B) = -\alpha(-B)$ and peaks at specific fields in both positive and negative directions of $B$. This implies that $I_s^+$ is larger than $|I_s^-|$ at $+B$ and smaller at $-B$. The field modulation of the asymmetry means that the effect we observe
is field induced in nature and can be tuned/controlled by a very small magnetic field $\sim 10 \mu T$. We have measured this device in cryogenic setup 1 using a homemade electromagnet to generate very small fields (see Supplementary Information, section S13 for details).

Additionally, we find the antisymmetric behavior with $B$ is not restricted to the magnitude of $\alpha$ but is also reflected in the switching distribution widths of $I_s^+ = I^+_s$ and $I_s^- = I^-_s$. To see this, we record $10^4$ switching events for specific $B$ values (indicated in Fig. 2d by star and hexagon). Fig. 2e shows the distributions of the two switching currents in $+B$ and $-B$ at 70 K. From the plots, we clearly see the spread of the distribution for $I_s^+$ and $I_s^-$ is flipped with flipping the sign of $B$. This behavior is present at all temperatures below $T_c$ (see Supplementary Information, Fig. S4).

To see how $\alpha$ varies with temperature, we determine its maximum value from the $B$ sweep at each temperature. The extracted value of maximum asymmetry is plotted with temperature in Fig. 2f. Importantly, the asymmetry persists till very close to $T_c$ and increases as the temperature is lowered below $T_c$, reaching a value as high as 60 % at 20 K. This value of asymmetry factor is the highest reported so far at this temperature across systems showing SDE (see Supplementary Information, Section S4 for a comparison of the asymmetry factors and operating temperatures for different systems).

**Half-wave rectification of the superconducting diode**

To show actual diode-like behavior, we demonstrate the half-wave rectification of an $ac$ current. For that, we send a square wave excitation current of specific magnitude and frequency 0.1 Hz, and the voltage drop across the junction is measured. The magnitude of the current is such that it is larger than one of the switching currents ($I_s^+$ or $|I_s^-|$) and smaller than the other. The results at 50 K are shown in Fig. 3. Rectification data at other temperatures are shown in Supplementary Information, Fig. S5. We see half-wave rectification of the negative half-cycle of the supercurrent at $B = 4.2 \mu T$ in Fig. 3a. By an externally applied $B$, the asymmetry of switching currents can be reversed, which in turn changes the rectification nature of the junction. Fig. 3b shows rectification of the positive half-cycle of the supercurrent in presence of $B = -7.9 \mu T$. The rectification ratio, as defined by $V(+I)/V(-I)$, is very high ($\sim 5000$) at 50 K.
Control experiments

All the observations described so far are exclusive to the AJJ at the interface of the two BSCCO flakes. We do several control checks to conclude this. We see negligibly small $\alpha$ ($\sim 0.4\%$) and no significant effect of $B$ on switching current distributions for the pristine BSCCO flake, as shown in the Extended data Fig. 2. Our device geometry and contacts configuration for the measurements are such that the measured response across the junction region includes junction properties at the interface as well as contributions from IJJs of bulk BSCCO flake, as seen in Fig. 2a. However, at smaller bias currents, only the artificial junction contributes by switching from superconducting to a normal state. As the current is increased further, the IJJs come into picture and switch one by one. Crucially, we observe asymmetry in $I_+$ of AJJs and insignificant asymmetry ($\sim 0.8\%$) of IJJs in the same device. Also, the switching current distributions of IJJ do not show any tunability with applied $B$. The data is shown in the Extended data Fig. 3. From all this evidence, it is very clear that the diode behavior arises from the artificial junction created by twisting two flakes of BSCCO at the interface.

So far, we have discussed the results of a 45° twisted device, but the effect we see is not restricted to this specific twist angle. We observe the same diode behavior in a 0° twisted device as well. Fig. 4a shows the optical image of the 0° twisted device, and Fig. 4b and c show the asymmetric nature of $I_+^-$ and $I_-^-$. The asymmetry $\alpha$ is tunable with $B$ (Fig. 4d), as was the case with the 45° twisted device discussed earlier. Fig. 4e and f show the rectification data at 80 K and its tunability with $B$. In addition, the switching current distribution is tuned by $B$. This indicates the key role of the magnetic field in the underlying mechanism of the SDE. Response of the 0° twisted device implies that the SDE effect is generic to AJJ at the interface and that the order parameter does not play a significant role. However, the order parameter controls the magnitude of the switching current for different twist angles. The data from the 0° twisted device, where our alignment accuracy is $\pm 0.5^\circ$, suggests that even the inadvertent breaking of interfacial inversion symmetry is crucial. As an additional control test, we fabricated a natural step edge device where we do not see switching current asymmetry (see Supplementary Information, Fig. S7e).
Possible mechanisms for SDE

We now discuss possible reasons for observing the SDE in twisted BSCCO JJ. First of all, from the data of 45° and 0° devices, along with the control experiments, it is evident that the diode response originates at the interface where there is broken inversion symmetry between top and bottom crystals. This breaking of inversion symmetry will invariably occur due to the slightest misalignment of the crystal axis of the two flakes during the stacking process. Secondly, strong dependence of $\alpha$ on $B$ implies the necessity of broken time-reversal symmetry. Simultaneous breaking of inversion and time-reversal symmetry is thus key to observing the SDE.

The microscopic mechanism for the SDE we observe in this system is not fully understood. We can eliminate the possible contribution coming from magnetochiral anisotropy [1] in our case as we see SDE with $B$ parallel to both the current flowing directions and the axis of broken inversion symmetry at the junction. Recently, there has been a report by Hou et al. [37] observing SDE based simply on the model of Meissner screening currents in a thin superconductor in presence of perpendicular $B$. But in pristine BSCCO flake which is close to the reported geometry, we see negligible asymmetry. At the artificial junction which is the central part of our device, the Meissner current distribution is more complex. The estimated critical field from the model, where supercurrent vanishes, does not agree with our experimental observation originating from AJJ (see Supplementary Information, Fig. S8).

We speculate that there are two possible mechanisms. Firstly, the screening currents at the AJJ arise from a combination of screening currents of individual flakes in response to the applied $B$ (see Supplementary Information, Fig. S10). In our experiments, the two flakes have different thicknesses. As a result, the AJJ itself could have some asymmetry in critical current density on the two different edges along the c-axis. This spatial asymmetry in critical current density can lead to the observation of different critical currents depending on the bias current polarity. While this mechanism is analogous to the one proposed by Hou et al. [37], the geometry and origin of the effect are different. Secondly, Oersted current induced Josephson vortices (JVs) in the presence of applied $B$ could play an important role in the SDE we observe. Switching from a superconducting state to a normal state at $I_s^+$ or $I_s^-$ is triggered by nucleation and dynamics of the JVs in the insulating region between two Cu-O planes at the junction [38]. To begin with, there can be different barriers [39] to enter
and exit of these JVs due to the uneven edges of the artificial junction plane. The Meissner current, set up in the junction plane to screen the applied perpendicular $B$, can create an additional asymmetry in the barrier heights, which is tunable with $B$. The Lorentz force, in presence of $B$, pushes these JVs towards one of the junction edge depending on the sign of $B$ and start dissipating. This magnetic field tunable barrier height can result in the magnetic field tunable SDE that we observe. The magnetic field over which we see a pronounced variation of $I_s$ (as seen in Fig. 2b) corresponds to a few flux quanta through the junction area. The actual scenario, however, could be more complex in presence of interaction with pancake vortices [40] that can appear in each Cu-O plane and needs further investigation.

Conclusions

In summary, we report the superconducting diode effect in artificially created Josephson junctions of twisted BSCCO. Our work demonstrates the highest asymmetry in magnitudes of switching currents reported so far of 60 % at 20 K. While the magnitude of the switching current is tuned by twist angle and sets the Josephson energy of these junctions, the asymmetry on the other hand is tuned by an independent knob – a very small magnetic field ($\sim 10 \, \mu T$) applied perpendicular to the junction plane. The asymmetry persists even at 80 K for some twist angles. Demonstration of superconducting diode effect above liquid nitrogen boiling point (77 K) is a significant advancement that will ease its adaptation to real applications in circuits with ultra-low dissipation. The required small fields to tune asymmetry can be generated on-chip allowing greater design flexibility. Protected qubits [10] based on the Josephson diode operating at higher temperatures could lead to a new architecture for quantum devices.
Fig 1. Asymmetry of switching currents in a 45° twisted artificial Josephson junction of BSCCO. (a) Schematic of twisted BSCCO (not to scale). One unit cell of BSCCO is rotated at a specific angle with respect to the other unit cell. In each unit cell, the Cu-O planes are separated by insulating SrO/BiO buffer layers (green slabs) and constitute an intrinsic Josephson junction (IJJ). At the interface of the twisted region, an artificial Josephson junction (AJJ) is formed. (b) Schematic of the twisted BSCCO device with Au contacts for measurements. Electrodes 1 and 6 are used as source and sink for the current, and properties across the twisted junction are measured with electrodes 3 and 4. Magnetic field $B$ is perpendicular to the junction plane. (c) $dc$ $I - V$ characteristic across the junction at 30 K. The two different colored line plots are for two different sweep directions of the biasing current, indicated by the arrows. Switching currents ($I_s^+$) and retrapping currents ($I_r$) for positive and negative bias regimes are marked with a superscript. The current through the device is swept in the order as shown in the inset. (d) Absolute values of $I$ and $V$ for both positive and negative bias range for the same data in (c) at 30 K. The solid cyan and green curves are for switching branch. The dashed cyan and green curves are for the retrapping branch. This plot clearly shows the asymmetry in the magnitude of $I_s^+$ and $I_r^-$. (e) Histograms of the switching currents, $I_s^+$ and $I_s^-$ at 30 K. $10^4$ switching events were taken to get the distributions. The median values of these distributions also show asymmetry between the magnitude of $I_s^+$ and $I_s^-$. 
Fig 2. Switching current asymmetry with perpendicular magnetic field and temperature for the 45° twisted BSCCO junction. (a) Cross-sectional schematic of the twisted BSCCO device. At the junction, current (I) flows along the c-axis of BSCCO. Applied $B$ is parallel to $I$ but perpendicular to the junction plane. An equivalent picture at the junction comprising of IJJs and AJJ is shown on the right. (b) Variation of switching currents, $I^+_s$ and $I^-_s$ with $B$ at 20 K. For each value of $B$, 100 switching events were recorded with the help of a counter and were averaged to get $I^+_s$ and $I^-_s$. The measurement is done in cryogenic setup 1 with a homemade electromagnet. We have subtracted $-5 \mu T$ from the data due to an offset value of $B$ in the measurement setup (see Supplementary Information, section S13 for details). (c) Asymmetry of switching currents $\alpha$ with the externally applied magnetic field $B$ at 20 K. $\alpha$ is calculated from (b), as described in the main text. The two different colored line plots are for different sweep directions of $B$, indicated by the arrows. (d) Variation of calculated $\alpha$ with $B$ at 70 K from the same device. (e) Distributions of switching currents ($I^+_s$ and $I^-_s$) at 70 K for two different $B$ values, as indicated in (d) by star and hexagon. The spread of the distributions changes by the change in sign of $B$. (f) The maximum value of the asymmetry factor as a function of temperature. At each temperature, maximum asymmetry is obtained from the $B$ sweep. The asymmetry persists below $T_c$ of the junction and increases as the temperature is lowered reaching a value as high as 60 % at 20 K.
Fig 3. Half wave rectification of the superconducting diode. (a) Half wave rectification of the current by the device at 4.2 $\mu$T magnetic field and at 50 K. A square wave excitation current of frequency 0.1 Hz was sent through the device and the voltage drop across the junction was measured. The magnitude of the square excitation current is larger than $|I_{s}^-|$ and smaller than $I_{s}^+$ and hence there is a voltage drop only in the negative half-cycle of the current resulting in rectification. (b) Rectification by the device at 50 K but at $-7.9$ $\mu$T field. At this field value, $|I_{s}^-|$ becomes larger than $I_{s}^+$ and voltage drop across the junction appears in the positive half-cycle of the current.
Fig 4. Superconducting diode behavior of 0° twisted BSCCO Josephson junction. (a) Optical micrograph image of 0° twisted BSCCO JJ. The scale bar is 20 micrometer. (b) dc $I - V$ characteristic of the junction at 80 K. The two curves for the up and down sweep of bias current, indicated by the two arrows, sit on top of each other indicating no hysteresis. (c) Absolute values of $I$ and $V$ are plotted to clearly see the asymmetry. Here $|I_s^-|$ is larger than $I_s^+$. (d) Variation of asymmetry factor $\alpha$ (defined in the text) with $B$ at 80 K. $B$ is applied perpendicular to the junction plane. For each $B$ value, 100 switching events were recorded and averaged to get $I_s^+$ and $I_s^-$. The $\alpha$ is calculated from the average values of $I_s^+$ and $I_s^-$. The two different colored curves indicate two sweeping directions of $B$, as indicated by the arrows. Similar to the 45° device, we see $\alpha$ to be antisymmetric with $B$. The measurement has been done in setup 2 with a superconducting magnet. We have subtracted an offset value of $-1.15$ mT to position the zero of $B$ in between the two extrema of $\alpha$. The offset is likely due to the trapped flux in the superconducting magnet (see Supplementary Information, section S13 for details). (e),(f) Half-wave rectification response of the junction at 80 K for two different $B$ values. (g),(h) Distributions of the switching currents ($I_s^+$ and $I_s^-$) at two different $B$ values. $10^4$ switching events were recorded to get the histograms.
Methods

A. Device fabrication

We developed the cryogenic exfoliation setup for fabrication of the BSCCO Josephson junctions. It is a completely dry pick-up and transfer method and can be employed to exfoliate various 2D materials. The cryogenic exfoliation technique allows re-exfoliation of a relatively thicker BSCCO flake, which is pre-exfoliated on a Si/SiO$_2$ chip. Re-exfoliation from the same flake ensures the alignment of the crystal axis. The re-exfoliated flake is rotated by a specific angle and immediately transferred onto the same flake to form a twisted junction. The low-temperature exfoliation method is very efficient in preventing the degradation of interfacial superconductivity.

Inside an Ar-filled glove box, we exfoliate BSCCO from an optimally doped bulk crystal by scotch tape technique on plasma-cleaned Si/SiO$_2$ substrate. The Si/SiO$_2$ substrate is heated inside the Ar-filled glove box overnight before exfoliation to remove any adsorbed gases. The substrate with exfoliated BSCCO is then placed on a cold stage under a microscope. We pass liquid nitrogen through the stage to cool it. Once the temperature of the stage reaches $-25^\circ$ C, we attach hemispherical polydimethylsiloxane (PDMS) stamp with the appropriately identified thicker BSCCO flake. The temperature of the stage is lowered further. At around $-90^\circ$ C the PDMS stamp goes through its glass transition point. Consequently, it gets detached automatically from the substrate by partially cleaving thick BSCCO flake into two pieces. Next, we quickly rotate the upper stage on which PDMS is mounted by a specified angle (with $\pm 0.5^\circ$ accuracy) and re-assemble it. The cold stage is then warmed slowly to $10^\circ$ C and the hemispherical stamp is detached. After the stack reaches room temperature, we take it out and align it with a SiN mask inside a clean room for contact deposition. 70 nm Au contacts are deposited by e-beam evaporation. For more details on cryogenic exfoliation, see Supplementary Information, Section S1. The thicknesses of all measured devices are tabulated in Supporting Information, section S12.
B. Measurements

1. $dc$ $I-V$ measurements

$dc$ voltage from NI DAQ is fed to a series resistor ($10$ kΩ). The outcoming $dc$ current is sent through the device by the current injecting electrode. The current is then collected by a current-to-voltage converter and measured with NI DAQ. The voltage drop across the device is also measured with the DAQ after amplification by a voltage preamplifier.

2. Measurement of switching current distributions

For distributions of switching currents with $10^4$ switching events, we employ a counter (Tektronix FCA 3100) for faster measurements. A symmetric triangular wave current (larger than $I_s$) of frequency $10$ Hz from a Keysight 33600A function generator is sent through the device. A $dc$ offset current is added to the triangular current. The offset makes the triangular current go from $0$ to $+I$ or $0$ to $-I$. The minimum and maximum value of the triangular current ensures the device switches from superconducting to the normal state and again returns to the superconducting state in each cycle of the triangular current. The counter measures the time interval between two events – when the voltage drop across the device is zero at $I = 0$ and when it reaches a non-zero pre-defined value because of switching from superconducting to normal state. From the measured time interval, we convert it to switching currents ($I_s^+$ and $I_s^-$). More details are provided in Supplementary Information, Section S2.

3. Measurement of switching currents with $B$

Instead of taking single $I-V$ curves and finding out $I_s^+$ and $I_s^-$, we take 100 switching events with a counter and average them to get $I_s^+$ and $I_s^-$ at each $B$. Here, $B$ is the slow axis for the measurement. A homemade electromagnet was used to get a very small $B$. The device, along with the electromagnet, was enclosed inside a cryoperm box to shield the device from outside stray fields. Extreme care has been taken to calibrate the actual fields inside the shielded cryoperm box. Details are provided in Supplementary Information, section S13.
Data availability

The data supporting the findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions

S.G. and V.P. fabricated the devices. A.B. and K. helped in device fabrication. S.G and A.B. did the measurements. D.A.J., R.K., and A.T grew the BSCCO crystals. S.G. and
M.M.D. wrote the manuscript. All authors provided inputs to the manuscript. M.M.D. supervised the project.

**Competing interests**

The authors declare no competing financial interests.
Extended Data Fig. 1. Modulation of switching current with twist angle. (a) Cross-sectional schematic of twisted BSCCO junction. (b) Equivalent picture of the junction, marked by the dashed rectangle in (a). In the bulk of each BSCCO flake, there are series of intrinsic Josephson junctions (IJJs). At the twisted interface of two BSCCO flakes, an artificial Josephson junction (AJJ) is formed. (c), (d) $dc I−V$ characteristics of 0° and 45° twisted junction at 12 K, and 10 K, respectively. Current in the $x$-axis is normalized with the area ($A$) of the junctions to get current densities ($J$). The blue-shaded region originates at the interface due to AJJ, while the red-shaded area is the contribution of IJJs coming from bulk. The switching current density of 45° device is suppressed by a factor of 20 compared to 0° twisted device.
Extended Data Fig. 2. Negligible current asymmetry in pristine BSCCO. (a) Schematic of the measurement scheme. Current is sourced and collected with electrodes 1 and 6. Voltage drop across BSCCO is measured with electrodes 2 and 3. (b) $I-V$ characteristic across pristine BSCCO at 60 K. Negative bias switching branch is flipped to compare it with the positive bias switching branch. (c) Switching current asymmetry for positive and negative bias with $B$, applied perpendicular to the device plane. Asymmetry across BSCCO is very small. (d), (e), (f) Distributions of switching currents ($I^+_s$ and $I^-_s$) at three different magnetic fields (marked by hexagon, square and star in (c)), $-12$, $4.1$, and $7 \, \mu T$. 
Extended Data Fig. 3. Negligible current asymmetry in intrinsic Josephson junction (IJJ). (a) Schematic of the measurement scheme. (b) $I-V$ characteristic across the junction at 60 K. The different colored curves are for positive and negative switching branches. AJJ switches at a smaller bias current, marked by a blue dashed rectangle. IIJ switches at a higher bias current, marked by the red dashed rectangle. (c) Asymmetry between positive ($I^+_s$) and negative ($I^-_s$) switching currents with $B$. At each $B$, 100 switching events were recorded and averaged to get $I^+_s$ and $I^-_s$. (d), (e), (f) Distributions of switching currents ($I^+_s$ and $I^-_s$) at three different magnetic fields (marked by hexagon, square and star in (c)), −36, 4.1, and 44.5 μT.
Extended Data Fig. 4. Superconducting diode behavior of 22° twisted BSCCO Josephson junction. (a) Optical micrograph image of 22° twisted BSCCO JJ. The scale bar is 20 micrometer. (b) dc $I-V$ characteristic of the junction at 50.4 K and at $B = -0.1$ mT. The two curves are for the up and down sweep of bias current. (c) Absolute values of $I$ and $V$ are plotted to clearly see the asymmetry. Here $|I_s^-|$ is larger than $I_s^+$. (d) Variation of asymmetry factor $\alpha$ (defined in the text) with $B$ at 50.4 K. $B$ is applied perpendicular to the junction plane. For each $B$ value, 100 switching events were recorded and averaged to get $I_s^+$ and $I_s^-$. The $\alpha$ is calculated from the average values of $I_s^+$ and $I_s^-$. Although $\alpha$ of the 22° device varies with $B$ qualitatively like the 45° and 0° devices, there are more complex details to it. The measurement has been done in cryogenic setup 2 with a superconducting magnet. An offset value of 1 mT has been subtracted due to the trapped flux in the superconducting magnet (see Supplementary Information, section S13 for details). (e),(f) Half-wave rectification response of the junction at 50.4 K for two different $B$ values. (g),(h), (i), and (j) Distributions of the switching currents ($I_s^+$ and $I_s^-$) at different $B$ values. $10^4$ switching events were recorded to get the histograms.
Supplementary Information: High-temperature superconducting diode

S1. Cryogenic exfoliation to make twisted BSCCO JJ

Fig. S1. **Twisted BSCCO device fabrication by cryogenic exfoliation** (a) 50-60 nm thick BSCCO flake exfoliated on Si/SiO₂. (b) Re-exfoliation of the thick BSCCO flake with a hemispherical PDMS stamp at low temperature (-90° C) on a cold stage. (c) The hemispherical PDMS stamp is quickly rotated by an angle and stacked onto the bottom flake. (d) The cold stage is warmed to 10° C, and PDMS is slowly removed (e) The Gold (Au) electrodes are deposited through a SiN stencil mask on top of both flakes.

Some 2D materials are chemically unstable in the atmosphere. Therefore, the device fabrication of those 2D materials is challenging. In this work, we developed cryogenic exfoliation, pick-up, and transfer methods for 2D materials following Zhao *et al.* [33]. BSCCO degrades with time; hence we used hemispherical PDMS dry transfer techniques for the twisted device fabrication in the glove box environment. The hemispherical PDMS stamp is made using Sigma Aldrich Sylgard 184 silicon elastomer base and curing agent mixture with a ratio of 10:1. After that, we cut Gel-Pak (part no- 40x40-0170-X4) PDMS into cylindrical
pieces with a diameter of $\sim 2$ mm and put the viscous mixture of Sylgard 184 on those pieces, then baked at $100^\circ$ C for 15 min. For the exfoliation of BSCCO crystal, we used a Si/SiO$_2$ substrate, which was cleaned by O$_2$ plasma for 90 s and heated at $150^\circ$ C overnight. Then we exfoliate BSSCO (Bi-2212) crystal by the mechanical scotch tape method and transfer the exfoliated BSCCO flake onto the pre-cleaned Si/SiO$_2$ substrate. Then we put the substrate on the cryogenic stage and search for thick ($\sim 40-60$ nm), flat, and uniform BSCCO flake through the optical microscope. Once we identify the desired flake, we cool down the cryogenic setup using liquid nitrogen. When the temperature reaches $-25^\circ$ C, we attach a hemispherical PDMS stamp to the BSCCO flake and wait for the temperature to reach $\sim -90^\circ$ C. At this temperature, the PDMS goes through the glass transition state. Because of that, the PDMS meniscus automatically detaches from the BSCCO flake. During this detachment, some part of the flake cleaves and attaches to the PDMS stamp. Then we quickly rotate the PDMS stamp at an angle (with an accuracy of $\pm 0.5^\circ$) and drop the PDMS-attached BSCCO flake on top of the bottom flake, as shown in Fig. S1. Then, we warm the cold stage to $10^\circ$ C and slowly remove the hemispherical PDMS stamp. Finally, we align a SiN mask with the flakes and deposit 70 nm thick gold (Au) metal electrodes by e-beam evaporation. After completing device fabrication, we immediately load the device in a high vacuum cryostat for measurement.

S2. Protocol for measuring switching currents with counter

Tektronix FCA 3100 frequency counter and Keysight 33600A waveform generator are used to measure the statistics of switching currents. This measurement protocol is much faster than taking several $dc I-V$ characteristics and then finding out the distributions. The counter measures the time interval between two events. From the measured time interval, we then convert it to the switching current. We send a symmetric triangular current wave of frequency 10 Hz and a magnitude larger than the switching currents, through the device. A $dc$ offset current with appropriate magnitude is added to the triangular current. For example, in Fig. S2 the triangular current goes from 0 to the positive maximum value after adding an offset. The role of the $dc$ offset current is to ensure that at each cycle of the triangular current, the system goes from superconducting to the normal state. We feed a square wave reference signal with arbitrary amplitude but with the same frequency of 10 Hz.
to one of the ports (port A in Fig. S2a) of the counter. A 90° phase difference is added to the triangular current with respect to the square reference signal. As a result, the triangular current has a rising edge when the reference square wave has a falling edge, as shown in Fig. S2a. We configure the counter such that it triggers at this point and starts measuring the time. At this point, the system is in the superconducting state. This is the first event. The voltage drop (due to the triangular current wave) across the device is fed to the other port of the counter (port B in Fig. S2a). The second event triggers when the voltage drop across the device (fed to port B of the counter) reaches a predefined value, as indicated by the dashed horizontal line in Fig. S2c. At this point, the system has switched to the normal state. We calculate the switching currents from this measured time interval between the two events. At each cycle, the counter measures the time interval. We take $10^4$ such counts for the distributions.
**Fig. S2.** Switching statistics measurement using a frequency counter (a) Circuit diagram for the measurement of the switching statistics. The square wave signal is directly connected to one of the ports of the counter. A triangular voltage source is connected to the device under test (DUT) through a series resistor, and the voltage drop across the junction is connected to the other port of the counter after amplification. (b) Triggering action of the counter for the two events. The square signal is a reference for triggering the first event when the system is in the superconducting state. (c) $dc I-V$ characteristic of the 45° twisted device at 30 K. The switching of the device from superconducting to normal state is identified when the voltage drop reaches 0.2 mV. This is the second trigger point for the counter. From the measured time interval between events 1 and 2, we calculate the switching currents.
S3. Superconducting transition temperature ($T_c$) of artificially made JJ and pristine BSCCO

We measure four probe $R$ vs $T$ across the artificial junction and pristine BSCCO for all the devices. Fig.S3a and Fig.S3b show the $R$ vs $T$ of the 45° and 0° devices of the main manuscript. The superconducting transition temperatures ($T_c$) of the junction and that of the pristine BSCCO flake are close for both 45° and 0° devices.
**Fig. S3.** $R$ vs $T$ response of 45° and 0° twisted device. (a) Schematic of four probe $R$ vs $T$ measurements. We simultaneously measure the junction (by blue voltmeter) and pristine BSCCO (by red voltmeter) to ensure no degradation during fabrication steps. (b) $R$ vs $T$ response of the 45° twisted device. The blue and red curves are the response from the twisted junction and pristine BSCCO, respectively. The inset shows an optical micrograph of the device. The scale bar is 20 µm. (c) $R$ vs $T$ response of the 0° twisted device. The blue and red curves are the response from the twisted junction and pristine BSCCO, respectively. The inset shows an optical micrograph of the device. The scale bar is 20 µm.

**S4.** Comparison of maximum current asymmetry and operating temperature with earlier reports

A variety of systems have been used to probe the superconducting diode effect. Here we tabulate some of the key results showing the reported values of maximum asymmetry and the operating temperatures.
| Author                  | System                  | Maximum asymmetry (\(\frac{\Delta I_c}{I_{c_+} + |I_{c_-}|} \times 100\%\)) | Maximum operational temperature |
|------------------------|-------------------------|--------------------------------------------------------------------------------|--------------------------------|
| Ando et al. [1]        | Nb/V/Ta                 | 1.8 % at 4.2 K                                                                | 4.35 K                        |
| Narita et al. [7]      | Nb/V/Co/V/Ta            | 3.9% at 1.9 K at -0.04 T                                                        | 2.4 K                         |
| Wu et al. [8]          | NbSe$_2$/ Nb$_3$Br$_8$/ NbSe$_2$ | 14.2% at 35 mT, 20 mK                                                         | 3.86 K                        |
| Bauriedl et al. [6]    | hBN/NbSe$_2$/hBN        | 35 % at 35 mT at 1K                                                           | 4.3 K                         |
| Lin et al. [9]         | MATTLG                  | 55% at T= 20 mK                                                               | 1.6 K                         |
| Pal et al. [41]        | Nb/NiTe$_2$/Nb          | 40% at B$_y$ = 12 mT at 60 mK                                                   | 4 K                           |
| Shin et al. [42]       | CrPS$_4$/NbSe$_2$/CrPS$_4$ | 7-9 % at B=10 mT at 1.55 K                                                     | 4.5 K                         |
| Our device             | twisted BSCCO JJ        | 60 % at 20 K                                                                  | 80 K                          |

TABLE I. Literature review of SDE observed in a large variety of systems and comparison of maximum asymmetry and operating temperature with our device.

S5. Tunability of switching distributions with magnetic field

As shown in the main manuscript, the asymmetry \(\alpha\) is antisymmetric in \(B\). The antisymmetric nature is also reflected in the distribution spread of switching currents \(I_{s+}\) and \(I_{s-}\). In the main manuscript, we have shown the spread of the distribution changes with a change in sign of \(B\) near maximum asymmetry \(\alpha\). We observe similar behavior away from maximum \(\alpha\) as well. Fig. S4a-d show the switching current distributions at higher \(B\) values at different temperatures; there is a very small asymmetry between the magnitude of \(I_{s+}\) and \(I_{s-}\) for the 45° twisted device. At all temperatures, the spread of the distributions of \(I_{s+}\) and \(I_{s-}\) flips with the change in sign of \(B\). The details of the histograms are not fully understood and further studies are needed.
Fig. S4. Switching distributions with $B$ at different temperatures for 45° twisted BSCCO JJ. The histograms are the result of $10^4$ switching events for both positive and negative switching currents. The spread of the distributions for $I_s^+$ and $I_s^-$ are different, and flips sign with the flipping sign of $B$.

S6. Half-wave rectification at various temperatures by 45° twisted device

Fig. S5 shows the half-wave rectification of a square wave current by the 45° twisted junction at different temperatures. The rectification nature is tunable with applied magnetic field $B$, as shown in Fig. S5a, and b. In Fig. S5c, we show half-wave rectification of 1000 cycles at 50 K. Out of 1000 cycles, we see 7 events where the switching happened in the positive cycle.
Fig. S5. **Half-wave rectification at different temperatures.** (a), (b) Rectification action by the 45° twisted junction at 10 K and at 65 K. (c) Rectification of 1000 cycles at 50 K.

**S7. Asymmetric $I-V$ for another set of $0^\circ$ and $45^\circ$ twisted JJ**

We have fabricated another set of $0^\circ$ and $45^\circ$ devices. \textit{dc} $I-V$ characteristics and the asymmetry in the switching current of these devices are shown in Fig. S6. We have not done a detailed field dependence study on these devices.
Fig. S6. Switching current asymmetry for other 45° and 0° twisted devices. (a), (b) $I - V$ characteristic and switching current asymmetry for a second 0° twisted device at 70 K. (c) $I - V$ characteristic for a second 45° twisted device at 10 K. (d) Asymmetry in switching currents of the 45° twisted device at the same temperature (10 K). The region marked by the dashed square box in (c) is zoomed in.

S8. Control experiment in a BSCCO step edge device

As an additional control test, we study the response of IJJs where there is no artificial junction. We use a natural step edge BSCCO flake to do this. The natural step edge appears stochastically during the exfoliation process. Gold electrodes are deposited to make electrical contacts to the flake using the shadow mask evaporation technique. Fig. S7a, b show cross-sectional schematic and optical micrograph of the step edge device. As shown in Fig. S7a, the current path will involve IJJs along the c-axis at the step edge. Fig. S7c
shows $R$ vs $T$ across the natural step edge and pristine BSCCO. In Fig. S7d, $dc$ $I - V$ characteristics of the step edge device are shown for two opposite sweep directions of bias current. The negative bias switching branch is plotted by flipping its sign along with the positive bias switching branch in Fig. S7e. No significant difference is seen between $I_s^+$ and $I_s^-$, as was the case for IIJs of the twisted devices in the main manuscript. Fig. S7f shows the branching in the $dc$ $I - V$ characteristics at 24 K, a signature for c-axis transport involving IIJs [34].

![Control measurement in a BSCCO step edge device](image)

**Fig. S7. Control measurement in a BSCCO step edge device.** (a) Cross-sectional schematic of the step edge device. (b) Optical micrograph of the device. The scale bar shown in the figure is 20 µm. Step edge appears spontaneously during the exfoliation process. (c) $R$ vs $T$ response across step edge and pristine BSCCO. (d) $dc$ $I - V$ characteristics across the step edge at 24 K. Different colors are used for two sweep directions of bias current, as indicated by the arrows. (e) The same $dc$ $I - V$ characteristics of (d), but the negative bias switching branch is flipped to compare with the positive bias switching branch. No significant asymmetry is there between the switching currents for positive and negative bias. (f) Branching in $dc$ $I - V$ response across the step edge. The branching appears due to the IIJs at the step edge.
S9. Meissner current contribution

We discuss the role of Meissner screening current in presence of a magnetic field $B$. Recently, Hou et al. reported the superconducting diode effect in a thin film superconductor in presence of $B$, applied perpendicular to the film plane [37]. They attribute the observed effect to the Meissner screening current and unequal critical current densities of the two edges of the thin film superconductor. The in-plane screening current adds up to the applied bias current at one edge of the thin film and subtracts at the other edge. The combined current distribution leads to the different magnitudes of the switching currents for positive and negative bias in presence of $B$.

Our device geometry however is different. Instead of a single thin film, we have a twisted junction of two flakes. The Meissner current distribution at the junction will be more complex. Nonetheless, we follow the same model and the results are shown in Fig. S8 by the black dashed lines. According to the model, the switching currents should become zero at $B_s = \frac{\phi_0}{2\sqrt{3}\pi \xi \lambda_p}$. Here, $\phi_0$, $\xi$, $\lambda_p = 2\lambda^2/d$ are magnetic flux quantum, superconducting coherence length, and Perl length. $\lambda$ and $d$ are the London penetration depth and thickness of the superconductor. If we extrapolate the dashed lines, the magnetic field where the switching currents reduce to zero is $\sim 20$ $\mu$T to 30 $\mu$T. But the value of $B_s$ (with in-plane $\xi = 3.2$ nm, $\lambda = 250$ nm, and $d = 30$ nm) we get is $\sim 13$ mT, which is very high compared to the observed values.

Fig. S8. Meissner current contribution. Evolution of switching currents with $B$ for the 45° twisted BSCCO JJ at 20 K. The dashed lines are from the model calculation following ref. [37] that involve the Meissner screening currents.
S10. Checking asymmetry in the normal state of the AJJ

To check whether the asymmetry in switching current is due to contact related issues, normal state $\frac{dV}{dI}$ is measured at different magnetic fields for up and down directional sweep of biasing current. Fig. S9 shows the $\frac{dV}{dI}$ response at a particular $B$. It is clear from Fig. S9 that for up and down direction biasing current sweep normal state differential resistance is not different within the noise limit. The asymmetry of switching current that we observe is not related to contacts.

Fig. S9. Normal state $\frac{dV}{dI}$ response of the 45° twisted junction at 100 K for an applied magnetic field of 27 μT.

S11. Possible mechanisms for superconducting diode effect

In the main manuscript, we have speculated on two mechanisms that can lead to the observed SDE in twisted BSCCO JJ. Fig. S10a shows a schematic of the twisted BSCCO structure. In response to an applied $B$, there will be screening currents in both the flakes. The screening currents are shown in Fig. S10a with different colors. The combined effect of the two screening currents at the junction area is complex. Since the thicknesses of the top and bottom BSCCO flakes are never the same in our experiments, the effect of screening currents at the junction can lead to different critical current densities at the two edges. The spatial asymmetry in critical current densities can lead to different magnitudes of critical currents for the two edges.
An alternate mechanism that could lead to the SDE is based on the asymmetric edge barrier for vortex entry and exit. In the inset of Fig. S10b we have shown the two edges of the artificial Josephson junction with different colors. These two edges can have different edge barriers for vortex entry and exit. The generated screening current due to applied $B$ can further modify these edge barriers asymmetrically as shown in Fig. S10b. Reversing the magnetic field reverses the edge barriers asymmetry of the two edges. The switching at $I^+_s$ and $I^-_s$ appears when the vortices (current-induced) enter the system from one of the two edges and start dissipating. The field-dependent asymmetry that we observe could originate from the field-dependent asymmetric edge barrier.

**Fig. S10.** Visualization of screening currents at the artificial junction and the edge barrier for entry and exit of the vortices. (a) Twisted structure of two BSCCO flakes. The applied $B$ sets up Meissner currents in the two flakes, as shown by different colors. (b) Tuning of edge barriers with $B$ for vortex entry and exit in the system.

**S12. Thickness of the measured devices:**

We have performed AFM measurements to get the thicknesses of the individual BSCCO flakes for the measured devices. Thickness data is tabulated below.
TABLE II. Thickness chart of the measured 0° and 45° devices. D1 and D2 are extensively measured. Data of these two devices are shown in the main manuscript. Data for D3 and D4 are shown in section S7.

| Device No. | Twist angle | Top flake thickness | Bottom flake thickness |
|------------|-------------|---------------------|------------------------|
| D1         | 45°         | 24 nm               | 13 nm                  |
| D2         | 0°          | 50 nm               | 30 nm                  |
| D3         | 45°         | 60 nm               | 30 nm                  |
| D4         | 0°          | 32 nm               | 24 nm                  |

S13. Measurement setup for field dependent asymmetry:

We have measured our devices in two different setups. Setup 1 is a closed-cycle cryogenic probe station (Lakeshore CRX-6.5 K) with a homemade electromagnet. Setup 2 is a wet cryostat (Oxford instrument) with an inbuilt superconducting magnet.

The homemade electromagnetic coil in setup 1 is a solenoidal coil made up of 1200 turns of copper wire (diameter 0.2 mm) with an inner radius of 19.5 mm, an outer radius of 24.5 mm, and a width of 12 mm. The fabricated devices are mounted at the center of this homemade solenoid coil. The direction of the generated magnetic field is perpendicular to the plane of the BSCCO flake. The electromagnet along with the device is then covered from all sides using a cryoperm magnetic shield, which prevents any stray magnetic field from affecting the device. Fig. S11a shows the cryoperm magnetic shield. We have modified the inside design of a closed-cycle cryogenic probe station (Lakeshore CRX-6.5 K) to accommodate the entire assembly of the coil and the shield, as shown in Fig. S11b. The 45° twisted device presented in the main manuscript is measured in this homemade electromagnetic setup (setup 1) inside the probe station.

Setup 2 is the Oxford instrument wet cryostat where an inbuilt superconducting magnet generates the magnetic field perpendicular to the device plane. This setup has no magnetic shielding. The data of the 0° and 22° twisted devices, presented in the main manuscript, are taken in this setup 2.

To accurately determine the actual magnetic fields at the position of the device, we calibrate the magnetic fields in both setups. The calibration is done by the Bartington Mag-
01H single-axis fluxgate magnetometer with Mag G probe DR2909 sensor. The sensor has a measuring range of 0 to 2 mT with a sensitivity of 1 nT. We place the sensor at the position of the device, perpendicular to the device plane. By sending a current through a Keithley source meter (model no. 2635A) we measured the field generated by the electromagnets.

Fig. S11. Magnetic coil setup and cryoperm shield in the Lakeshore probe station. (a) The cryoperm shielding. It prevents stray magnetic fields from affecting the devices low temperatures. (b) Inside design of the Lakeshore probe station with magnetic coil and cryoperm shield.