

Nanoscale Electrothermal-Switch Superconducting Diode for Electrically Programmable Superconducting Circuits

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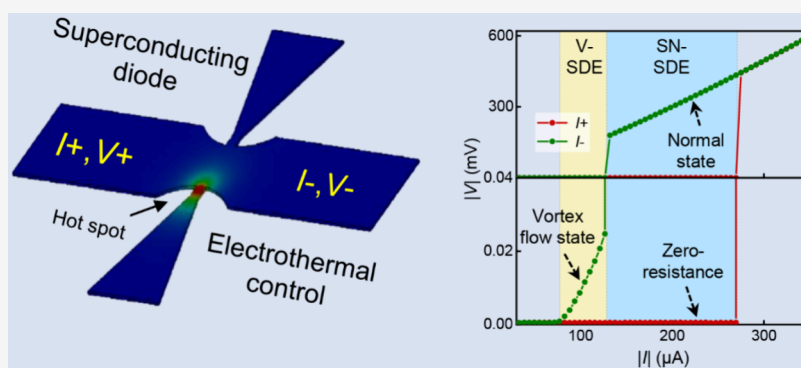
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ABSTRACT: Superconducting diodes enable dissipationless directional transport, yet achieving electrical tunability and scalability remains a major challenge for circuit-level integration. Here, we demonstrate an electrothermal-switch superconducting diode in which a gate-controlled nanoscale hot spot dynamically breaks inversion symmetry in a superconducting nanowire. This mechanism gives rise to two coexisting non-reciprocal transport regimes, one associated with a non-reciprocal superconducting-to-normal transition and the other with ratchet-like vortex dynamics, both originating from the same electrothermal-switch process. The diode exhibits efficiencies up to 42 and 60% for the two regimes, respectively, and can be electrically switched on, off, or reversed in polarity *in situ* by applying a small gate current. These capabilities enable programmable superconducting circuits that realize electrically reconfigurable full-wave and half-wave rectification. The lithography-compatible design, high performance, and gate-controlled functionality establish a scalable platform for programmable superconducting electronics and hybrid quantum systems.

KEYWORDS: superconducting diode, superconducting nanowire cryotron, non-reciprocal transport, superconducting rectifier, programmable superconducting circuits

Superconducting diodes, devices that permit supercurrent flow preferentially in one direction without energy dissipation, have emerged as a powerful platform for exploring symmetry-broken superconducting states and realizing low-power superconducting electronics and quantum technologies.¹ A variety of material platforms and device concepts have been proposed to realize the superconducting diode effect (SDE), including artificial superlattices,^{2,3} patterned superconducting films,^{4–8} ferromagnet-tuned devices,^{9–13} van der Waals structures,^{14–19} twistrionic stacks,^{20–24} and chiral superconductors.^{25,26} In most cases, superconducting non-reciprocity arises from the combined breaking of spatial inversion symmetry and time-reversal symmetry. This is typically enforced through structural asymmetry, magnetic order, or spin–orbit coupling.

Despite these advances, achieving *in situ* and electrically controllable superconducting diode behavior remains challenging. Many existing implementations rely on external magnetic

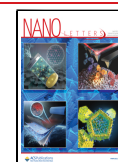
fields to tune the diode response, which limits the local addressability, scalability, and circuit-level integration. Gate-tunable superconducting diodes have recently attracted growing interest,^{8,14,27–35} yet most designs are based on Josephson junctions that require delicate interface engineering and often face challenges in device uniformity and large-scale fabrication. Junction-free approaches, including the van der Waals heterostructure,¹⁶ remain relatively rare and typically exhibit modest rectification efficiencies. Identifying alternative mechanisms that enable electrically tunable, scalable, and high-

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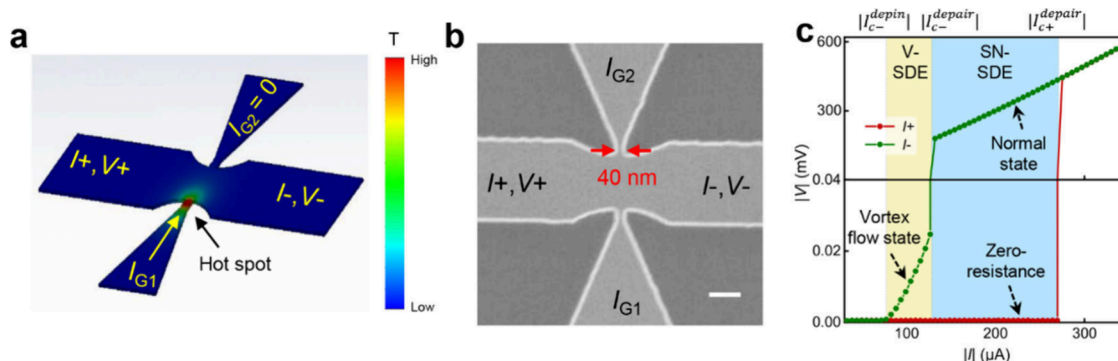


Figure 1. Electrothermal-switch superconducting diode. (a) Schematic of the electrothermal-switch superconducting diode, where a nanoscale hotspot is generated by a small gate current. The resulting thermal gradient locally breaks the spatial inversion symmetry of the superconducting nanowire channel. (b) Scanning electron microscope (SEM) image of a representative device. Two gate leads are symmetrically placed on the upper and lower sides of the main channel. Scale bar = 150 nm. (c) I - V characteristics measured with a gate current $I_{G1} = 10 \mu\text{A}$ applied to one gate lead at 2 K and an external magnetic field of 300 Gs. The top panel shows the high-dissipation regime corresponding to the non-reciprocal superconducting-to-normal transition, and the bottom panel presents a magnified view, highlighting the low-dissipation regime from ratchet-like vortex motion.

performance superconducting diodes, therefore, remains an important open problem.

Here, we introduce an electrothermal-switch superconducting diode that addresses these challenges by exploiting gate-controlled local heating as a dynamic symmetry-breaking mechanism. The device is based on a cryotron-inspired superconducting nanowire architecture,³⁶ in which a small gate current generates a localized nanoscale hotspot. Operating in the regime where the hotspot produces a controllable thermal gradient without fully quenching the nanowire, this electrothermal asymmetry breaks spatial inversion symmetry *in situ*, enabling electrically switchable non-reciprocal superconducting transport without modifying the magnetic field.

This electrothermal-switch mechanism gives rise to two distinct non-reciprocal transport regimes within a single device. At higher bias currents, the diode effect originates from a non-reciprocal superconducting-to-normal transition, while at lower dissipation levels, it arises from asymmetric vortex dynamics associated with biased vortex entry and exit. Both regimes share a common electrothermal origin, providing a unified framework for understanding gate-controlled superconducting non-reciprocity. Beyond the establishment of this mechanism, the device architecture allows direct electrical control over the diode polarity and supports reconfigurable superconducting circuits compatible with standard lithographic fabrication.

The SDE emerges when both spatial inversion and time-reversal symmetry are broken. In our device, inversion symmetry is controllably broken by a nanoscale hotspot generated through a gate current in a superconducting nanowire, producing a local thermal gradient (Figure 1a). The design is inspired by the superconducting nanowire cryotron (nTron), a three-terminal superconducting device,³⁶ that utilizes localized heating from a small gate current to modulate superconductivity. Owing to its ultracompact footprint, immunity to magnetic noise, high fan-out capability, and compatibility with large-scale fabrication,^{37–39} nTron has been deployed in diverse superconducting platforms,^{40–43} including single-flux quantum circuits,³⁹ CMOS-hybrid memories,⁴⁰ large-scale digital circuits,³⁷ and single-photon detectors.⁴² Despite these advances, their potential for generating non-reciprocal superconducting transport has remained unexplored.

Our devices were fabricated on Si substrates using patterned 10 nm thick NbN thin films, a material widely adopted in nTron-

based circuits,^{39,40} single-photon detectors,⁴² superconducting microwave components,⁴⁴ spiking neural networks,⁴⁵ and full-wave bridge rectifiers.⁴ In a conventional nTron, the nanowire width (<100 nm) ensures complete channel quenching when the gate current induces a hotspot. To create a controllable thermal gradient without fully driving the channel into the normal state, we increased the nanowire width to 500 nm (Figure 1b). Two narrow (~ 40 nm) gate leads were symmetrically placed on opposite sides of the nanowire to generate localized hotspots under small gate currents (Figure 1a and b). The four-terminal configuration allows the position of the hotspot and, therefore, the direction of inversion-symmetry breaking to be *in situ* switched by selecting which gate is biased. Detailed fabrication procedures are described in the [Supporting Information](#).

Temperature-dependent resistance measurements revealed a critical temperature $T_c = 9.1$ K (Figure S1a). With no gate current, the current–voltage (I - V) characteristics were symmetric, exhibiting negligible non-reciprocity even under applied magnetic fields (Figure S1b). When a small gate current $I_{G1} = 10 \mu\text{A}$ was applied to the lower gate lead, a localized hotspot formed on the lower side of the nanowire (as illustrated by Figure 1a), breaking inversion symmetry and inducing pronounced non-reciprocal transport, as evidenced from the markedly divergent I - V curves for opposite current directions (top panel of Figure 1c). Only the forward current-sweep curves, which determine the intrinsic critical currents, are shown here; the corresponding reverse-sweep data, used to extract symmetric retrapping currents, are presented in Figure S2.

The chosen gate current slightly exceeds the retrapping current of the gate lead ($I_r = 9.1 \mu\text{A}$), marking the transition from the resistive to superconducting state (Figure S3). Operating slightly above I_r generates a stable nanoscale resistive hotspot without fully suppressing superconductivity in the main nanowire. In contrast, excessive gate currents cause overheating and completely quench superconductivity, eliminating the inversion-symmetry-broken state necessary for the SDE. Notably, the observed non-reciprocity is insensitive to the polarity of the gate current: reversing its direction leaves the diode characteristics unchanged (Figure S4). This confirms that the SDE originates from electrothermal switching since Joule heating depends on the current magnitude rather than its direction. Furthermore, the absence of a clear diode effect for

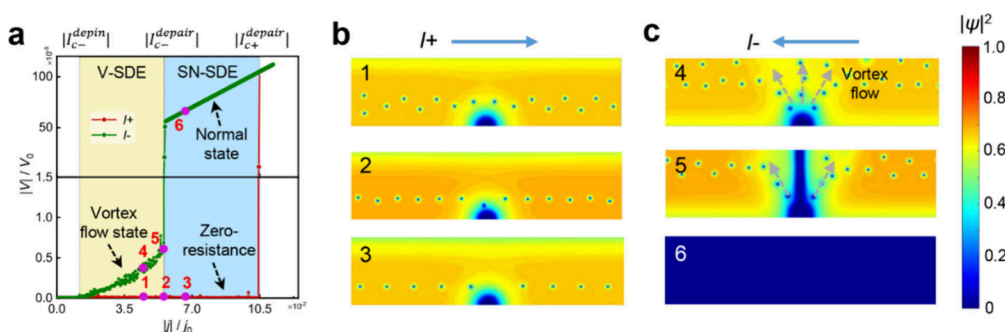


Figure 2. Microscopic mechanism of the superconducting diode effect revealed by TDGL simulations. (a) Simulated I – V characteristics showing two distinct non-reciprocal regimes, consistent with experimental observations. j_0 and V_0 are the dimensionless units of TDGL; for details, see the [Methods](#). (b and c) Snapshots from TDGL simulations ([Video S1](#)) illustrating the spatial distribution of the superconducting order-parameter under (b) positive and (c) negative currents. The snapshots correspond to the I – V points (1–6) indicated in panel a.

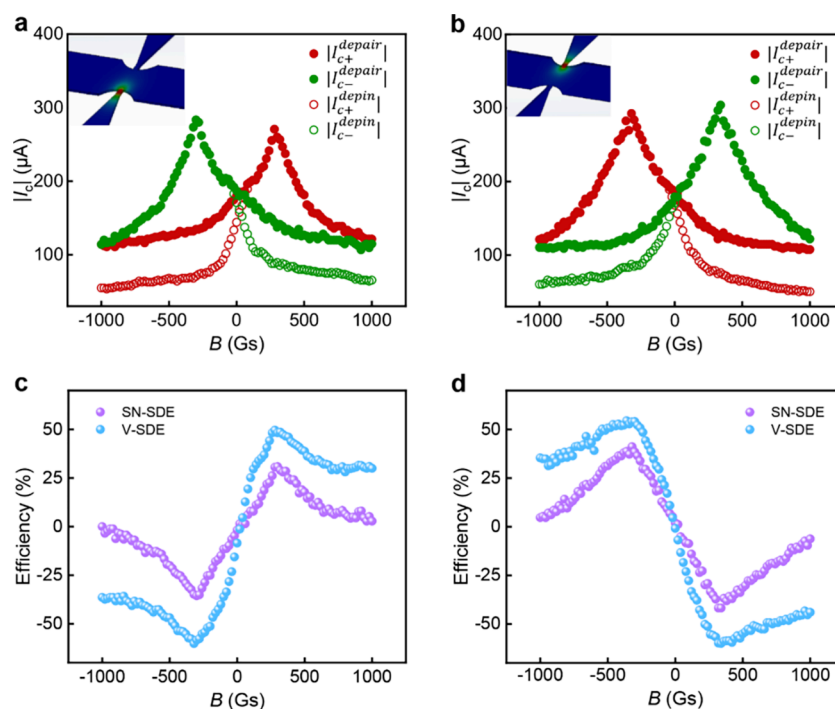


Figure 3. High efficiency and electrical tunability of the electrothermal-switch superconducting diode. (a and b) Magnetic-field dependence of the depairing and depinning critical currents measured for opposite current directions, with a gate current (a) $I_{G1} = 10 \mu\text{A}$ applied to the lower gate and (b) $I_{G2} = 10 \mu\text{A}$ applied to the upper gate. Inset schematics illustrate the corresponding hotspot locations. (c and d) Diode efficiencies corresponding to (c) panel a and (d) panel b.

gate currents below the critical value ([Figure S5](#)) confirms that the hotspot rather than the current bias itself is the essential source of the observed non-reciprocity. These results establish an electrothermal-switch superconducting diode that can be electrically turned on or off *in situ* by a minute gate current.

To further understand the origin of this electrically induced non-reciprocity, we systematically analyzed the current–voltage characteristics in [Figure 1c](#). Interestingly, two distinct non-reciprocal regimes emerge in the device (yellow and blue shaded regions in [Figure 1c](#)). The first regime (blue) clearly displays a diode effect arising from a non-reciprocal superconducting-to-normal transition, characterized by markedly different depairing currents for opposite bias directions ($I_{c-}^{\text{depair}} = 137.5 \mu\text{A}$ and $I_{c+}^{\text{depair}} = 269.5 \mu\text{A}$). Upon magnification (bottom panel of [Figure 1c](#)), an additional low-dissipation regime (yellow) becomes evident, featuring voltages 3 orders of magnitude smaller than the normal-state resistance. This weaker dissipation arises from

vortex dynamics, motion of quantized magnetic flux lines penetrating the type-II superconductor under an applied field. The onset of vortex motion defines the depinning current ($I_{c-}^{\text{depin}} = 82.5 \mu\text{A}$), below which vortices remain pinned and the nanowire retains a zero-resistance state. In the following, we refer to these two regimes as the superconducting-to-normal transition SDE (SN-SDE) and the vortex-motion SDE (V-SDE), respectively.

To further confirm that the observed dual-regime non-reciprocity originates from the electrothermal dynamics rather than structural asymmetry, we performed time-dependent Ginzburg–Landau (TDGL) simulations (see the [Methods](#)).⁵ The simulated I – V characteristics successfully reproduce the experimentally observed two-stage non-reciprocity ([Figure 2a](#)). [Video S1](#), with representative screenshots shown in [Figure 2b](#) and [c](#), illustrates the spatial evolution of the superconducting order parameter (Cooper-pair density) under opposite current

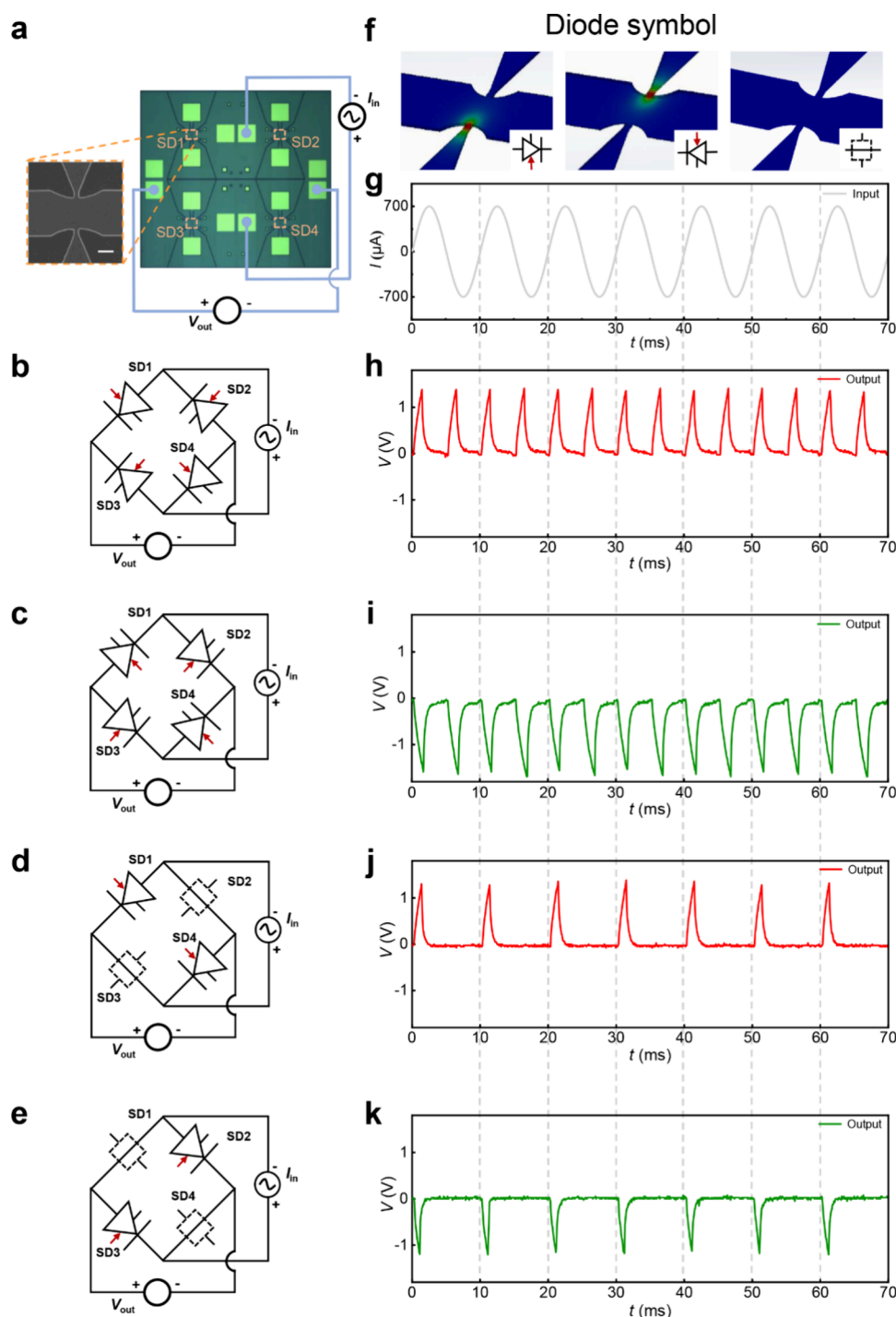


Figure 4. Electrically programmable superconducting electric circuit. (a) Optical microscope image of a bridge circuit composed of four identical electrothermal-switch diodes (orange dashed boxes). A SEM image of the upper left diode is shown on the left. Scale bar = 150 nm. (b–e) Circuit diagrams showing different diode configurations of the superconducting bridge in panel a. (f) Circuit symbols representing the electrothermal-switch diodes with reversed polarities (left and middle) and as a deactivated superconducting wire (right); the red arrows indicate the gate currents. (g) Sinusoidal input signal with a frequency of 100 Hz. (h–k) Measured output rectifications corresponding to the circuit diagrams in panels b–e: (h and i) full-wave rectifications with opposite polarities and (j and k) half-wave rectifications with opposite polarities.

directions. When a magnetic field is applied, vortices penetrate the superconducting nanowire. Their motion dissipates energy and generates finite resistance, even though the sample remains globally superconducting. According to the Bean–Livingston model, the nanowire edges act as potential barriers for vortex entry and exit.⁴⁶ The gate-induced hotspot locally reduces the superconducting condensation energy, thereby lowering the

edge barrier and creating an easy-entry pathway for vortices (Figure 2b and c).

For a positive current, the Lorentz force drives vortices from the upper edge toward the lower one, allowing them to exit freely through the hotspot, while the intact upper barrier prevents further vortex entry (Video S1 and Figure 2b). The system therefore maintains a zero-resistance state up to a large lowering

current amplitude, $|I_{c+}^{\text{depair}}|$. For a negative current, by contrast, the Lorentz force injects vortices through the hotspot, establishing a vortex-flow channel that produces a finite resistance corresponding to the V-SDE regime. As the magnitude of the negative current exceeds $|I_{c-}^{\text{depair}}|$, enhanced Joule heating completely quenches the superconductivity in the channel (Video S1 and Figure 2c), giving rise to the high-voltage SN-SDE regime. Simulated temperature maps (Video S2 and Figure S6) and electrothermal control results (Figure S7) corroborate these sequential transitions. These results reveal that both SN-SDE and V-SDE arise from a unified electrothermal-switch mechanism: gate-controlled hotspots concurrently modulate vortex dynamics and local superconductivity, leading to electrically tunable non-reciprocal transport.

Achieving high diode efficiency in a scalable superconducting platform is crucial for circuit-level applications. Our lithographically defined electrothermal-switch diodes satisfy this requirement, combining robust performance with inherent scalability. Figure 3a shows the magnetic field dependence of the depairing and depinning currents for opposite current directions, while Figure 3c presents the corresponding diode efficiencies, defined as $\eta = \frac{|I_{c+}| - |I_{c-}|}{|I_{c+}| + |I_{c-}|} \times 100\%$, where the sign of η denotes the diode polarity. Under a zero magnetic field, the diode effect is absent, even with an active gated hotspot (Figure S8). The diode efficiency exhibits a maximum at a magnetic field of approximately 320 Gs, beyond which it decreases. This behavior is determined by the interplay between the hotspot-induced spatial symmetry breaking and the Meissner screening currents, following the same mechanism discussed in ref 10. For the current direction with the larger critical current, only the depairing current $|I_{c}^{\text{depair}}|$ is observed, whereas the opposite direction exhibits both depinning and depairing currents, with $|I_{c}^{\text{depair}}| > |I_{c}^{\text{depin}}|$. Consequently, the efficiency of V-SDE consistently exceeds that of SN-SDE (Figure 3c). The maximum efficiencies reach 42% for SN-SDE and 60% for V-SDE, remarkably high values that reflect strong non-reciprocity and stable rectification (Figure S9).

The scalability and reproducibility of these diodes enable the realization of multi-element superconducting circuits. To demonstrate an electrically tunable circuit, we fabricated a full-wave bridge rectifier consisting of four identical electrothermal-switch diodes (Figure 4a).^{4,6} Configuring the diode polarities as illustrated in Figure 4b yields full-wave rectification (Figure 4h, an enlarged view of the data shown in Figure S10) under an applied alternating current drive (Figure 4g). The operational status of each diode during different temporal intervals is illustrated in Figure S11 and Table S1. Beyond magnetic field modulation, where diode polarity can be reversed by changing the applied field (Figure 3a and c), the electrothermal-switch diode offers direct, local, and reversible electrical tunability. As shown in Figure 3b and d and Figure S9, applying a gate current to the opposite-side electrode relocates the hotspot, thereby inverting the direction of inversion-symmetry breaking and switching the diode polarity. Consequently, the polarity of the full-wave bridge rectifier can be reprogrammed *in situ* without adjusting the magnetic field (Figure 4c and i).

This electrical programmability also enables independent control of individual diodes within a circuit, in contrast to global magnetic field schemes where all elements respond collectively.^{4,6} For the same bridge circuit (Figure 4a), setting the gate currents of two selected diodes to zero deactivates their non-reciprocity, converting the bridge into a half-wave rectifier

(circuit schematic in Figure 4d, with corresponding data in Figure 4j). The deactivated diodes behave as ordinary superconducting wires with higher, direction-independent critical currents (Figure S12). The half-wave rectifier polarity can also be reversed by reconfiguring the diode states (Figure 4e and k). Thus, the ability to electrically switch on/off diode polarities *in situ* enables multifunctional superconducting circuits, a level of programmability previously unattainable in architectures constrained by global magnetic field control.

The circuit rectification is demonstrated at 100 Hz, a frequency constrained by the low-pass filters in our cryogenic measurement setup, necessary for noise reduction in transport experiments, rather than by any fundamental limitation of the device physics. Based on the material properties and the nTron-like operating mechanism, we estimate that the rectification bandwidth could extend to the gigahertz range (see the Supporting Information for details). Additionally, to facilitate assessment of the device potential in programmable superconducting circuits, the Supporting Information provides an analysis of the steady-state gate power, switching energy, and operational dissipation.

We have demonstrated a nanoscale electrothermal-switch superconducting diode, in which a gate-controlled localized hotspot enables *in situ* and reversible breaking of spatial inversion symmetry in a superconducting nanowire. This electrothermal mechanism gives rise to two distinct diode effects, a non-reciprocal superconducting-to-normal transition and a vortex-motion-induced diode effect, both governed by a unified physical origin. By combining electrical transport measurements with time-dependent Ginzburg–Landau simulations, we reveal how localized electrothermal asymmetry simultaneously modulates vortex entry barriers and superconducting depairing, establishing a microscopic framework for electrothermally driven non-reciprocal superconductivity. The ability to electrically switch the diode polarity and functionality without modifying the magnetic field highlights electrothermal control as a versatile and scalable strategy for engineering superconducting non-reciprocity. More broadly, this electrothermal-switch platform may enable new opportunities for energy-efficient superconducting logic and electrically reconfigurable components in quantum information systems.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.nanolett.6c00080>.

Methods for sample fabrication, experiments, and G–L simulations, Figures S1–S19, and Tables S1–S4 (PDF)

G–L simulations for unconventional superconducting vortex diode effects with inversion antisymmetry (Video S1) (MP4)

G–L simulations for unconventional superconducting vortex diode effects with antisymmetry breaking (Video S2) (MP4)

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Notes

The authors declare no competing financial interest.

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