Superconducting devices

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Low-loss electronics with superconducting diodes

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Two papers report advances in high-efficiency superconducting diodes and multiple-diode rectifiers, which are required for the development of power management systems in scalable quantum circuits.

Superconductors can potentially be used to make energy-efficient electronics due to their zero electrical resistance and macroscopic quantum coherence. But to create practical circuits, non-reciprocal superconducting circuit elements — analogous to semiconductor diodes — are needed. In conventional electronics, diodes allow current to flow in one direction, while blocking it in the other, due to electrons and holes experiencing different conducting behaviour. They are used to convert alternating current (a.c.) inputs to direct currents (d.c.) and thus provide efficient power delivery. However, achieving this functionality in superconductors is a far more complex task due to their zero resistance and, in a sense, the unipolar nature of charge-carrying Cooper pairs. It is therefore necessary to create a superconducting diode effect that can operate efficiently without introducing a high resistance or requiring large magnetic fields[1,2].

Several experimental demonstrations of the superconducting diode effect have been reported, with various theoretical mechanisms proposed to explain the supercurrent rectification. These mechanisms include the emergence of helical phases due to the interplay between spin–orbit and Zeeman couplings[3,4], topological phase transitions triggered by orbital coupling of magnetic fields[5], the coexistence of several correlated phases with dynamically coupled order parameters[6], and inhomogeneous Meissner screening in combination with asymmetric surface barriers for edge-protruding vortices[7,8]. Although these demonstrations are typically limited to just a few devices, the development of useful circuits based on superconducting diodes remains a challenge. Writing in *Nature Electronics*, two independent groups of researchers now report superconducting-diode-based a.c.-to-d.c. rectifiers capable of operating up to the megahertz range[9,10].

In 2005, a vortex superconducting diode effect was theoretically proposed based on an asymmetric surface barrier effect[8]. In type-two superconductors, magnetic flux can enter in the form of quantized vortices. A supercurrent exerts a Lorentz-like force on the vortices, which is directed perpendicular to the flow direction. As shown in Fig. 1, in the presence of a perpendicular magnetic field, Meissner-like currents circulate clockwise and create an edge barrier for vortex entry. An additional transport current adds to the Meissner currents and increases the surface barrier on one side and reduces it on the other. The higher barrier sets the critical current for vortex entry and thus for the onset of resistance. For symmetric edges, the barrier is the same for upward and downward transport current.

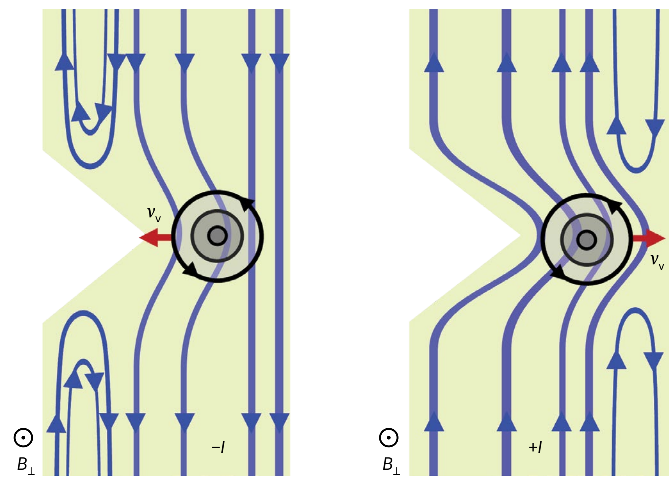

Fig. 1 | Superconducting diodes based on the vortex diode effect. In an out-of-plane magnetic field, diamagnetic currents flow at the edges that create a surface barrier for vortices. A downward oriented transport current ($-I$) leads to an asymmetry of the surface barrier: it decreases at the left and increases at the right edge. If a notch is patterned in addition, it breaks the inversion symmetry, suppressing the surface barrier more strongly at the notch side for $-I$ (left panel). If the transport current is reversed ($+I$), the surface barrier is reduced on the right edge as well (right panel), but less than for $-I$. Hence, vortex entry from the right is easier and the corresponding critical current is lower than in the first case. v_v is the velocity of the vortex motion generated by a total current and $B_\perp$ is an out-of-plane magnetic field.

This changes if a notch is added on one side, which breaks the spatial symmetry and deflects some of the Meissner current flow lines (Fig. 1). This lowers the surface barrier more strongly at the notched side. Hence, the critical value of the transport current depends on its orientation. The asymmetry of the critical current switches, if the orientation of the perpendicular field is reversed.

In one approach, Matteo Castellani, Karl Berggren and colleagues — who are based at the Massachusetts Institute of Technology — created superconducting diodes using niobium nitride films with triangular notches cut into one of their edges[9]. By connecting four such diodes in a superconducting loop, they were able to create bridge rectifiers with a 50% power efficiency for continuous a.c.-to-d.c. conversion at frequencies up to 3 MHz, and even up to 50 MHz in burst mode. In addition, inverting the field orientation induced a reversed diode polarity, which is an essential capability for power management in cryogenic devices.

In the other approach, Josep Ingla-Aynés, Jagadeesh Moodera and colleagues — who are based at the Massachusetts Institute of Technology, the University of California, Riverside, and SEEQC, Inc. — engineered edge asymmetric diodes based on vanadium/europium sulfide films[10]. Asymmetry at the edges, in combination with a remanent magnetic field emanating from the europium sulfide film, resulted in a superconducting diode bridge with an efficiency of up to 42% at cryogenic temperatures. The device efficiently converted a.c. to d.c. only up to 40 kHz. However, the innovation here lies in the use of remanent fields that leverage asymmetric vortex surface barriers. By minimizing the need for an external magnetic field, these diodes could be integrated with existing superconducting systems.

Both studies highlight the potential of superconducting diodes for energy-efficient quantum electronic circuits. The ability to convert a.c. to d.c. efficiently at cryogenic temperatures is essential for scaling up superconducting technologies, as this would mitigate heat dissipation, noise and decoherence. Moreover, these diodes enable more compact and efficient cryogenic power management — a critical functionality for integrating superconducting rectifiers within the circuits of detectors and quantum processors.

The development of efficient superconducting diodes is an important step towards practical and scalable low-loss superconducting electronics. However, key challenges remain. To start, minimizing heating effects and ensuring device reproducibility will be critical next steps. To avoid the application of magnetic fields, other approaches to breaking time reversal symmetry need to be explored. This could simplify the integration of non-reciprocal elements into quantum circuits and reduce potential electromagnetic interference. In addition, advances in materials science and device engineering should focus on enhancing efficiency and on increasing the operational frequency range of the superconducting a.c.-to-d.c. converters. Achieving near-unity efficiency could, in particular, transform power management in superconducting electronics, making these systems not only faster but also more energy efficient.

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Competing interests

The authors declare no competing interests.