CONDENSED-MATTER PHYSICS

Superconducting diode effects

The diode is a well-known component of semiconductor electronics, but equivalent behaviour in superconductors is rare. Now, two demonstrations of a superconducting diode effect show that this is possible, through different mechanisms.

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In semiconductor electronics, one of the elementary building blocks is the p–n junction. These junctions allow current to flow in one direction but block it in the opposite direction. This is called the diode effect. Can we realize the diode effect for supercurrent in superconductors? The answer to this question might seem to be 'no' because of the zero resistivity for supercurrent, and yet if we could do this it would be a great help for superconducting electronics. However, theoretical proposals for a superconducting diode effect date back more than a decade[1]. Now, writing in *Nature Physics*, two groups report superconducting diode effects, in $NiTe_2$ Josephson junctions[2] and in small-twist-angle trilayer graphene[3]. These findings suggest the existence of a common non-reciprocal phenomenon inside superconductors and Josephson junctions, and may bring about a new era in superconducting electronics.

As a macroscopic quantum phenomenon, the central ingredient of superconductivity is the condensate of coherent electron–electron Cooper pairs. This state is described by an order parameter that is a complex number, meaning that it has both an amplitude Δ and a phase ϕ. In a standard superconductor (illustrated in Fig. 1a), twisting the phase generates a supercurrent flow of Cooper pairs through the material with zero resistance, but this mechanism only works up to a critical current value I_c. Similarly, in a Josephson junction (where two superconductors are separated by a thin piece of non-superconducting material, illustrated in Fig. 1b), the phase difference between the two sides of the junction can cause the Cooper pairs to tunnel through the barrier.

The diode effect in superconductors occurs if the critical value I_c depends on the current direction, as shown in Fig. 1c. When the applied current is higher than the critical value, the material becomes a normal metal with a finite resistance. We can label the critical currents for current flow in each direction as I_{c+} and I_{c-}. Hence, if $I_{c+} \neq I_{c-}$, a superconducting diode effect emerges — if we apply a current with amplitude

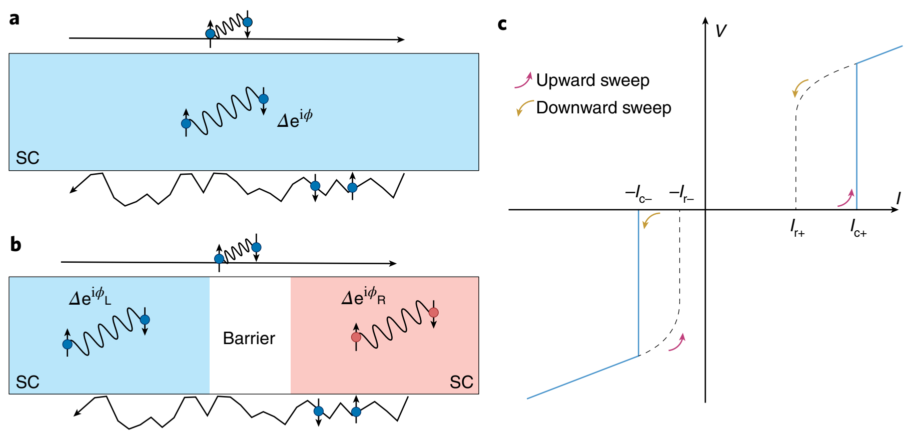

Fig. 1 | Diode effects. a, Diode effect in a superconductor (SC) with an order parameter $\Delta e^{i\phi}$, with supercurrent flowing to the right (straight line) and normal current flowing to the left (wiggly line). **b**, Diode effect in a Josephson junction by sandwiching a barrier between two superconductors with phases ϕ_L and ϕ_R. **c**, Sketch plots of the relationship between current and voltage for superconducting diodes (blue lines) and Josephson diodes (blue lines and dashed grey curves). There are two critical currents, I_{c+} (positive direction) and I_{c-} (negative direction), where the superconductor becomes a normal metal. The diode effect occurs when $I_{c+} \neq I_{c-}$. For a Josephson junction, there are also two critical return currents, I_{r+} and I_{r-}, in the downward sweep measurements. Another non-reciprocal effect occurs when $I_{r+} \neq I_{r-}$.

between I_{c+} and I_{c-}, the system behaves as a superconductor in one direction and a normal metal in the other, as illustrated in Fig. 1a,b.

This non-reciprocal effect can also be produced in a Josephson junction, where it is called the Josephson diode. In this case, in addition to $I_{c+} \neq I_{c-}$, there is another non-reciprocal effect. Owing to the finite capacitance of devices, these junctions can be hysteretic and have a return critical current I_r during downward sweep measurements that is different from I_c on the upward sweep. If I_r depends on direction as $I_{r+} \neq I_{r-}$, a Josephson diode relying on voltage history occurs, as in Fig. 1c.

The diode effects are governed by symmetry properties[4]. For example, the inversion symmetry breaking inherent in a p–n junction plays a vital role in semiconducting diodes. Similarly, the voltage-dependent $I_{r+} \neq I_{r-}$ in Josephson junctions implies that inversion symmetry is broken[5]. However, for the superconducting diode effect at zero voltage, the breaking of inversion symmetry is not the only requirement. Another crucial symmetry for superconducting diodes is time-reversal symmetry. The Onsager reciprocal relations mean that the responses of a time-reversal-invariant system under two opposite external fields are related to each other by the time-reversal operation. If the applied voltage is zero, the inversion symmetry remains intact. So, a superconducting diode effect at zero voltage must imply that time-reversal symmetry is broken. If this occurs without a magnetic field being applied, it means that the time-reversal symmetry must be broken by something inherent in the material.

As magnetic fields break the time-reversal symmetry, the superconducting diode effect can be generated by an in-plane magnetic field. For example, in a two-dimensional material, Rashba spin–orbit coupling under an in-plane magnetic field can generate a momentum shift of the Fermi surface that can induce Cooper pairing to occur with a finite centre-of-mass momentum[6–8]. This finite-momentum phase shifts the centre of critical current so that $I_{c+} \neq I_{c-}$. The work by Banabir Pal and colleagues provides direct evidence for this scenario[2]. They used a Dirac semimetal $NiTe_2$ as the barrier for a Josephson junction. Because the Fermi surface of this material is split in a similar way to Rashba spin–orbit coupling, the Josephson diode can be explained well by the phenomenological theory of finite-momentum pairing[2,6].

Jiang-Xiazi Lin and colleagues showed that small-twist-angle trilayer graphene on top of WSe_2 provides another example of superconducting diode effects[3]. In the graphene, the superconductivity exhibited $I_{c+} \neq I_{c-}$ after an out-of-plane magnetic field was used to 'train' the sample, in the sense that its behaviour was different before and after the field was applied. The sign of the non-reciprocal effect can be reversed by reversing the direction of the training field. This result is probably related to valley polarization and strong electron correlation in twisted graphene. However, future studies are needed to determine the microscopic origin of both the field training and the diode effect.

Unlike the semiconductor diode effect, the superconducting diode effect at zero voltage requires breaking of time-reversal symmetry. In general, this effect is small as the superconducting pairing is difficult to form in this situation. To enhance this, it is necessary to search for unconventional superconductors, such as non-centrosymmetric superconductors. It is also necessary to explore special tunnelling barriers in Josephson junctions — for instance, two-dimensional materials — to achieve a large diode effect. Finally, we want to mention two other papers in this field, where superconducting diode effects were reported in a Nb/V/Ta superlattice with magnetic fields[9] and in a field-free van der Waals Josephson junction made with Nb_3Br_8 (ref. [10]). Once the various mechanisms for this effect are understood in full, the advent of the superconducting diode effect should lead to great improvements in superconducting electronics. ❐

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Competing interests

The authors declare no competing interests.