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Researchers observe ubiquitous superconductive diode effect in thin superconducting films

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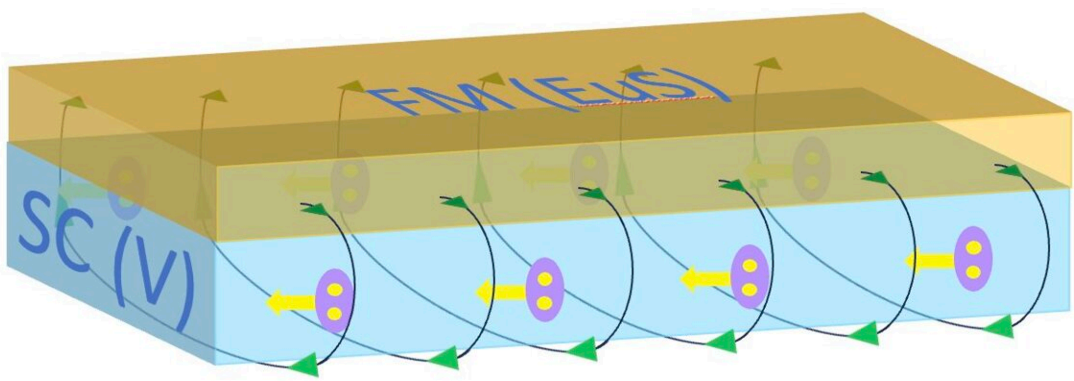


The SC diode design comprises of a thin film bilayer: a ferromagnetic insulator film (golden) atop a SC thin film (blue). The magnetized ferromagnet generates a fringing field (green arrows) induces a Meissner current in the superconductor even in the absence of any applied field. This Meissner current flows in the same direction at both edges, thereby modifying the net current when a voltage is applied in either direction. Thus modified current results in dissipationless current (gold arrows) flow in one direction, while current flow feels resistance in the opposite direction. Credit: Amith Varambally, Yasen Hou and Hang Chi

The so-called superconducting (SC) diode effect has recently attracted significant attention within the physics research community, due to its potential value for developing new technologies. This effect provides a key example of nonreciprocal superconductivity, as materials hosting it are essentially superconducting in one current flow direction and resistive in the other.

Researchers at the Massachusetts Institute of Technology (MIT) in collaboration with IBM Research Europe and other institutes worldwide recently observed this interesting effect in thin films of superconductor materials. Their findings, presented in *Physical Review Letters*, could enable the fabrication of new electronic components, such as better performing diodes (i.e., devices that allow electrical current to flow in a specific direction).

"Our discovery of a SC diode effect was in a way serendipitous, while equally surprising," Jagadeesh Moodera, one of the researchers who carried out the study, told Phys.org. "We were (and are still) studying the elusive Majorana bound states, also known as Majorana fermions, which appear on a superconducting gold surface using a similar thin film stack structure. We took a detour for a 'quick' search of the phenomenon (superconductive diode effect) that was suddenly gathering limelight, with several new reports on this subject appearing since 2020."

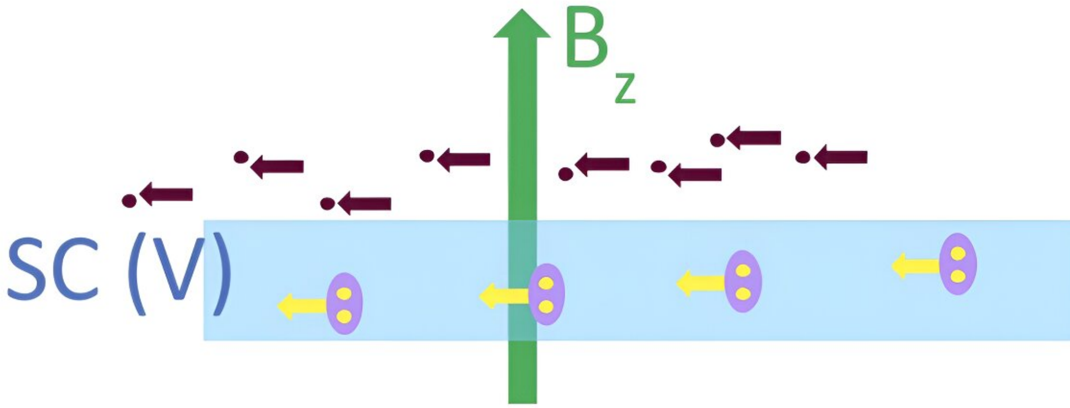
Just a few days after Moodera and his colleagues started investigating the SC diode effect, they successfully observed it in thin superconducting films. Initially, they specifically tried to observe the effect under conditions known to be favorable, specifically when the superconductors were subjected to spin-orbit and exchange fields. However, they soon realized that the effect was ubiquitous in superconducting layers, meaning that it occurred either way, even without these fields.

"It turned out that record diode behavior in a superconductor could be realized with simple sculpting of its edges, and thus forming the basis for future easy scaling up of efficient superconducting memory, switch, logic etc., device technology," Moodera explained. "It is noteworthy to point out that two high school juniors who conducted research at MIT over the summer, namely Amith Verambally and Ourania Glezakou-Ebert, were instrumental to this study. This work further emphasizes that breakthrough research happens when least expected, when free to explore, with open mind!"

Superconductors are materials that become superconducting (i.e., they can conduct direct current without losing energy) when cooled down to sufficiently low temperatures. In other words, these materials host dissipation-less electric current, which flows through them with zero resistance up to a maximum value, known as critical current.

When the SC diode effect occurs, this critical current becomes different based on its direction (i.e., on whether it is flowing forward or backward within the material). The key objective of the researchers' study was to probe this effect in thin layers of superconducting materials.

"We fabricated high quality SC films with a ferromagnetic semiconductor layer over it, and measuring the transport current characteristics found huge SC diode effect without the need for an applied magnetic field," Akashdeep Kamra and Yasen Hou explained. "We realized that the fine geometrical details of sides in our lithographically patterned film strips were playing the crucial role in this diode effect. So, we synthesized even simply the SC film and introduced inhomogeneity on one of the sides, creating further asymmetry, to enhance the SC diode effect."



The SC diode design shown above functions when a tiny magnetic field (green) is applied to the SC thin film (blue) thereby generating a Meissner screening current circulating around the edges. This, along with engineered edge asymmetry of the superconductor, leads to a critical current asymmetry. By applying a voltage in either direction, a dissipationless current flows in one direction (gold), while high resistance current flows in the opposite direction (maroon). Credit: Amith Varambally, Yasen Hou and Hang Chi

Interestingly, the materials employed with edge inhomogeneity tuned study were in great part designed by two high school students attending a summer program at MIT, under the supervision of Hou and Moodera. Their creative designs greatly contributed to the team's observation of further enhanced SC diode effect.

"In the past couple of years there have been several reports of the superconducting diode effect on fairly complex multilayer systems, with interpretations that are mostly based on the notion of finite momentum Cooper pairing," Patrick Lee said. "The ingredients are magnetic field or magnetization and spin orbit interaction to engineer an unconventional

SC film. One relatively simple set-up is to sandwich a SC film between a ferromagnet layer to give the magnetization and a heavy metal such as Pt to provide spin orbit coupling. We were interested in testing this proposal."

As they had predicted, Moodera, Hou, Kamra, Lee and their colleagues observed the SC diode effects in the sandwich-like structures they had carefully created. To determine whether this sandwich-like design was key to enabling the effect, they then created control thin superconducting samples, which they expected would not exhibit this effect. To their great surprise, however, these control samples presented an equally strong SC diode effect.

"We found that neither the heavy metal Pt nor the exchange coupling between the ferromagnet and the SC is necessary: the effect is driven by the fringing field at the edge of the ferromagnet," Lee explained. "Eventually we found that we can eliminate the ferromagnet entirely, and a single SC film subject to a very small perpendicular field exhibits the diode effect. The origin of this effect has to do with vortex pinning near the edge. Once we understood that, we purposely created a jagged edge on one side of the film and observed a very large diode effect."

To better understand their observations, the researchers then reviewed previous literature on this topic. They found that while past studies discussed some of the basic physics underlying the SC diode effect, they often did so in an unorganized and dispersive way.

"These papers have escaped the attention of the recent flurry of papers on the subject," Lee said. "So, in addition to producing record breaking diode effects in a very simple way, we also place the recent work in the right context. Any claim of a new effect thus should undertake the exercise of eliminating the 'ubiquitous' features that we found."

The recent work by this team of researchers effectively identifies the physics underlying the SC diode effect in thin SC films, showing that it does not result from a different type of Cooper pairing mechanism. In contrast, it suggests that the SC diode effect is very easy to realize and is linked to the basic inherent properties of SC materials, which have been known for decades.

In the future, the findings gathered by Moodera, Hou, Kamra, Lee and their colleagues could enable the development of new and highly performing SC diodes. In addition to being based on thin materials and thus easier to scale down in size, these diodes could be easy to fabricate and highly efficient.

"In our work, we were unable to identify and understand the mechanism for the emergence of SC diode effect when magnetic field is applied along the current flow direction," Kamra, Hou, Lee and Moodera added. "This remains an intriguing and outstanding challenge to us and the scientific community. We would like to figure this out in the future.

"At the same time, from a device perspective, we would like to determine the temperature and frequency dependence of the SC diode effect so that this could be extended to higher temperature superconductors besides to envisioning robust and fast computing."

More information: Yasen Hou et al, Ubiquitous Superconducting Diode Effect in Superconductor Thin Films, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.131.027001

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