Team creates simple superconducting device that could dramatically cut energy use in computing

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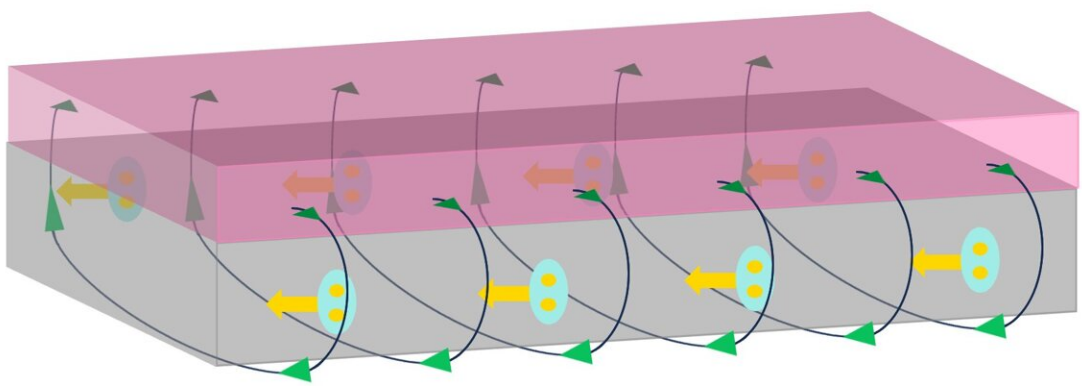

MIT scientists and colleagues have created a superconducting device that could dramatically cut energy use in computing, among other important applications. In one design the diode consists of a ferromagnetic strip (pink) atop a superconducting thin film (grey). The team also identified the key factors behind the resulting current that travels in only one direction with no resistance. Credit: A. Varambally, Y-S. Hou and H. Chi

MIT scientists and colleagues have created a simple superconducting device that could transfer current through electronic devices much more efficiently than is possible today. As a result, the new diode, a kind of switch, could dramatically cut the amount of energy used in high-power computing systems, a major problem that is estimated to become much worse.

Even though it is in the early stages of development, the diode is more than twice as efficient as similar ones reported by others. It could even be integral to emerging quantum computing technologies. The work, which is reported in the July 13 online issue of *Physical Review Letters*, is also the subject of a news story in Physics Magazine.

"This paper showcases that the superconducting diode is an entirely solved problem from an engineering perspective," says Philip Moll, Director of the Max Planck Institute for the Structure and Dynamics of Matter in Germany. Moll was not involved in the work. "The beauty of [this] work is that [Moodera and colleagues] obtained record efficiencies without even trying [and] their structures are far from optimized yet."

"Our engineering of a superconducting diode effect that is robust and can operate over a wide temperature range in simple systems and potentially opening the door for novel technologies," says Jagadeesh Moodera, leader of the current work and a senior research scientist in MIT's Department of Physics. Moodera is also affiliated with the Materials Research Laboratory, the Francis Bitter Magnet Laboratory, and the Plasma Science and Fusion Center (PSFC).

The nanoscopic rectangular diode—about 1,000 times thinner than the diameter of a human hair—is easily scalable. Millions could be produced on a single silicon wafer.

Toward a superconducting switch

Diodes, devices that allow current to travel easily in one direction but not in the reverse, are ubiquitous in computing systems. Modern semiconductor computer chips contain billions of diode-like devices known as transistors. However, these devices can get very hot due to electrical resistance, requiring vast amounts of energy to cool the high-power systems in the data centers behind myriad modern technologies, including cloud computing.

According to a 2018 news feature in *Nature*, these systems could use nearly 20% of the world's power in 10 years.

As a result, work toward creating diodes made of superconductors has been a hot topic in condensed matter physics. That's because superconductors transmit current with no resistance at all below a certain low temperature (the critical temperature), and are therefore much more efficient than their semiconducting cousins, which have noticeable energy loss in the form of heat.

Until now, however, other approaches to the problem have involved much more complicated physics. "The effect we found is due [in part] to a ubiquitous property of superconductors that can be realized in a very simple, straightforward manner. It just stares you in the face," says Moodera.

Says Moll of the Max Planck Institute for the Structure and Dynamics of Matter, "the work is an important counterpoint to the current fashion to associate superconducting diodes [with] exotic physics, such as finite-momentum pairing states. While in reality, a superconducting diode is a common and wide-spread phenomenon present in classical materials, as a result of certain broken symmetries."

A somewhat serendipitous discovery

In 2020 Moodera and colleagues observed evidence of an exotic particle pair known as Majorana fermions. These particle pairs could lead to a new family of topological qubits, the building blocks of quantum computers. While pondering approaches to creating superconducting diodes, the team realized that the material platform they developed for the Majorana work might also be applied to the diode problem.

They were right. Using that general platform, they developed different iterations of superconducting diodes, each more efficient than the last. The first, for example, consisted of a nanoscopically thin layer of vanadium, a superconductor, which was patterned into a structure common to electronics (the Hall bar). When they applied a tiny magnetic field comparable to the Earth's magnetic field, they saw the diode effect—a giant polarity dependence for current flow.

They then created another diode, this time layering a superconductor with a ferromagnet (a ferromagnetic insulator in their case), a material that produces its own tiny magnetic field. After applying a tiny magnetic field to magnetize the ferromagnet so that it produces its own field, they found an even bigger diode effect that was stable even after the original magnetic field was turned off.

Ubiquitous properties

The team went on to figure out what was happening.

In addition to transmitting current with no resistance, superconductors also have other, less well-known but just as ubiquitous properties. For example, they don't like magnetic fields getting inside. When exposed to a tiny magnetic field, superconductors produce an internal supercurrent that induces its own magnetic flux that cancels the external field, thereby maintaining their superconducting state.

This phenomenon, known as the Meissner screening effect, can be thought of as akin to our bodies' immune system releasing antibodies to fight the infection of bacteria and other pathogens. This works, however, only up to some limit. Similarly, superconductors cannot entirely keep out large magnetic fields.

The diodes the team created make use of this universal Meissner screening effect. The tiny magnetic field they applied—either directly, or through the adjacent ferromagnetic layer—activates the material's screening current mechanism for expelling the external magnetic field and maintaining superconductivity.

The team also found that another key factor in optimizing these superconductor diodes is tiny differences between the two sides or edges of the diode devices. These differences "create some sort of asymmetry in the way the magnetic field enters the superconductor," Moodera says.

By engineering their own form of edges on diodes to optimize these differences—for example, one edge with sawtooth features, while the other edge not intentionally altered—the team found that they could increase the efficiency from 20% to more than 50%. This discovery opens the door for devices whose edges could be "tuned" for even higher efficiencies, Moodera says.

In sum, the team discovered that the edge asymmetries within superconducting diodes, the ubiquitous Meissner screening effect found in all superconductors, and a third property of superconductors known as vortex pinning all came together to produce the diode effect.

"It is fascinating to see how inconspicuous yet ubiquitous factors can create a significant effect in observing the diode effect," says Yasen Hou, first author of the paper and a postdoctoral associate at the Francis Bitter Magnet Laboratory and the PSFC. "What's more exciting is that [this work] provides a straightforward approach with huge potential to further improve the efficiency."

Christoph Strunk is a professor at the University of Regensburg in Germany. Strunk, who was not involved in the research, says, "the present work demonstrates that the supercurrent in simple superconducting strips can become non-reciprocal. Moreover, when combined with a ferromagnetic insulator, the diode effect can even be maintained in the absence of an external magnetic field."

"The rectification direction can be programmed by the remanent magnetization of the magnetic layer, which may have high potential for future applications. The work is important and appealing both from the basic research and from the applications point of view."

Moodera noted that the two researchers who created the engineered edges did so while still in high school during a summer at Moodera's lab. They are Ourania Glezakou-Elbert of Richland, Washington, who will be going to Princeton this fall, and Amith Varambally of Vestavia Hills, Alabama, who will be entering the California Institute of Technology.

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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