Abstract

The phenomenon of non-reciprocal critical current in a Josephson device, termed the Josephson diode effect, has garnered much recent interest. Realization of the diode effect requires inversion symmetry breaking, typically obtained by spin-orbit interactions. Here we report observation of the Josephson diode effect in a three-terminal Josephson device based upon an InAs quantum well two-dimensional electron gas proximitized by an epitaxial aluminum superconducting layer. We demonstrate that the diode efficiency in our devices can be tuned by a small out-of-plane magnetic field or by electrostatic gating. We show that the Josephson diode effect in these devices is a consequence of the artificial realization of a current-phase relation that contains higher harmonics. We also show nonlinear DC intermodulation and simultaneous two-signal rectification, enabled by the multi-terminal nature of the devices. Furthermore, we show that the diode effect is an inherent property of multi-terminal Josephson devices, establishing an immediately scalable approach by which potential applications of the Josephson diode effect can be realized, agnostic to the underlying material platform. These Josephson devices may also serve as gate-tunable building blocks in designing topologically protected qubits.

Introduction

In conventional semiconducting diodes, the value of resistance depends upon the direction of the current flow. This asymmetry has been exploited in applications such as photodetectors, signal rectifiers, and oscillators. A superconducting diode would have dissipationless supercurrent flowing upon application of one current bias polarity, while applying an equivalent bias in the reverse direction would produce conventional dissipative current. Josephson junctions (JJs) with non-reciprocal critical current, i.e. the magnitude of the critical current is dependent upon bias direction, are one avenue to realize a superconducting diode. Recent experimental observations of this effect rely on inherent properties of the materials used to fabricate the devices, with proposed physical mechanisms including breaking of inversion and time reversal symmetries and exotic superconductivity. Asymmetric superconducting quantum interference devices (SQUIDs) can also realize non-reciprocal transport by using large and imbalanced self-inductances, typically in all-metallic Josephson devices, which has precluded electrostatic gating. In a recent work, it was also theorized that interferometers based upon higher-harmonic Josephson junctions can realize the Josephson diode effect, with implementation relying on highly transparent quantum point contact JJs. These approaches are material specific and difficult to scale for potential applications of the Josephson diode effect, such as dissipationless electronics.

Experimental investigations of Andreev bound state spectra in multi-terminal Josephson devices have attracted considerable attention recently due to proposed topologically protected subgap states. Despite technical challenges in realizing these subgap states, other interesting transport phenomena such as multi-terminal Andreev reflections, fractional Shapiro steps, correlated phase dynamics, and semiclassical topological states have been demonstrated. The discovery and characterization of non-reciprocal supercurrent flow in these devices stands to impact and expand upon these phenomena.

In this work, we show experimentally that the Josephson diode effect can occur in a relatively simple platform: a three-terminal Josephson device based on an InAs two-dimensional electron gas (2DEG) proximitized by an epitaxial aluminum layer. We show by means of simulations that this diode effect is a consequence of the synthetic realization of a Josephson current-phase relation (CφR) that contains higher harmonic terms with a phase difference between them provided by a finite applied magnetic field. We further show that this diode can be switched between positive polarity, i.e. the positive-bias critical current is larger than the negative-bias critical current, and negative polarity by means of a small out-of-plane magnetic field or electrostatic gating. This also establishes, more generally, that the Josephson diode effect can be realized in any material system exhibiting the conventional CφR Moreover, these devices may also serve as gate tunable building blocks of superconducting circuits to realize topologically protected qubits.

Discussion

Our results establish a compact, yet scalable and robust approach to realize the Josephson diode effect at practically zero field (smaller in magnitude than Earth's natural field) and achieve a gate-tunable Josephson device with an unconventional CφR. In this work, we have shown data on four devices (See Supplementary Fig. 7 for data from device 4), displaying high reproducibility of the effect. All devices studied showed the diode effect. Importantly, this multi-terminal Josephson diode effect depends only on the three-terminal nature of the device and could thus be integrated with other materials platforms, including those typically used in superconducting qubits. Multi-terminal Josephson devices made from materials with conventional CφR could more broadly realize unconventional physics, such as semi-classical topologically-protected states. The devices presented here could serve to realize such states. Although this requires substantial further exploration beyond the scope of this work, this points to the versatility of this approach.

We confirm that the device can be driven into an effective two-terminal regime by selectively gating two of the junction legs, where the diode effect is indeed absent. Inversion symmetry breaking, which is necessary for realizing non-reciprocal critical currents, is achieved by the presence of the third terminal. We emphasize that this mechanism is entirely distinct from previous works, which either relied on specific material properties, or on an imbalance of self-inductances in devices requiring large critical currents. In contrast, we demonstrate gate-tuning of the diode efficiency (magnitude and sign) by modifying $J_c(x)$ and demonstrate nonlinear signal integration enabled by the multi-terminal nature of our device, which may have applications in neuromorphic computing architectures. Previously minimal gate tunablity of superconducting diode has been demonstrated in trilayer graphene devices through magnetic field training combined with simultaneous gating. The underlying mechanism for the diode effect remains an open question in that system. In contrast, we demonstrate all-electrostatic tuning of the diode efficiency, Q, by simply modifying $J_c(x)$.

We point out that Q can be further increased by the addition of more terminals, which would lead to the generation of higher harmonics in the CφR. If, in addition, the junctions themselves use materials that can intrinsically realize higher harmonics, this may yet further enhance Q.

Our simulations also provide a tool to model current distribution in three-terminal Josephson devices, which may help in optimizing the design for multi-terminal Josephson junctions where multiple superconducting electrodes are coupled via a central common region. We have also studied the temperature dependence of the diode efficiency, which reveals that it is robust against thermal effects at low enough temperatures where the critical current saturates. Additional integration of ferromagnetic materials may allow the device to function at precisely zero applied field, though the current devices already require a field of only a few μT.

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New superconducting diode could improve performance of quantum computers and artificial intelligence

U of M researchers' device is more energy efficient and versatile than past models.

A University of Minnesota Twin Cities-led team has developed a new superconducting diode, a key component in electronic devices, that could help scale up quantum computers for industry use and improve the performance of artificial intelligence systems. Compared to other superconducting diodes, the researchers' device is more energy efficient; can process multiple electrical signals at a time; and contains a series of gates to control the flow of energy, a feature that has never before been integrated into a superconducting diode.

The paper is published in *Nature Communications*, a peer-reviewed scientific journal that covers the natural sciences and engineering.

A diode allows current to flow one way but not the other in an electrical circuit. It's essentially half of a transistor, the main element in computer chips. Diodes are typically made with semiconductors, but researchers are interested in making them with superconductors, which have the ability to transfer energy without losing any power along the way.

"We want to make computers more powerful, but there are some hard limits we are going to hit soon with our current materials and fabrication methods," said Vlad Pribiag, senior author of the paper and an associate professor in the University of Minnesota School of Physics and Astronomy. "We need new ways to develop computers, and one of the biggest challenges for increasing computing power right now is that they dissipate so much energy. So, we're thinking of ways that superconducting technologies might help with that."

The University of Minnesota researchers created the device using three Josephson junctions, which are made by sandwiching pieces of non-superconducting material between superconductors. In this case, the researchers connected the superconductors with layers of semiconductors. The device's unique design allows the researchers to use voltage to control the behavior of the device.

Their device also has the ability to process multiple signal inputs, whereas typical diodes can only handle one input and one output. This feature could have applications in neuromorphic computing, a method of engineering electrical circuits to mimic the way neurons function in the brain to enhance the performance of artificial intelligence systems.

"The device we've made has close to the highest energy efficiency that has ever been shown, and for the first time, we've shown that you can add gates and apply electric fields to tune this effect," explained Mohit Gupta, first author of the paper and a Ph.D. student in the University of Minnesota School of Physics and Astronomy. "Other researchers have made superconducting devices before, but the materials they've used have been very difficult to fabricate. Our design uses materials that are more industry-friendly and deliver new functionalities."

The method the researchers used can, in principle, be used with any type of superconductor, making it more versatile and easier to use than other techniques in the field. Because of these qualities, their device is more compatible for industry applications and could help scale up the development of quantum computers for wider use.

“Right now, all the quantum computing machines out there are very basic relative to the needs of real-world applications,” Pribiag said. “Scaling up is necessary in order to have a computer that's powerful enough to tackle useful, complex problems. A lot of people are researching algorithms and usage cases for computers or AI machines that could potentially outperform classical computers. Here, we’re developing the hardware that could enable quantum computers to implement these algorithms. This shows the power of universities seeding these ideas that eventually make their way to industry and are integrated into practical machines.”

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In addition to Pribiag and Gupta, the research team included University of Minnesota School of Physics and Astronomy graduate student Gino Graziano and University of California, Santa Barbara researchers Mihir Pendharkar, Jason Dong, Connor Dempsey, and Chris Palmstrøm.

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