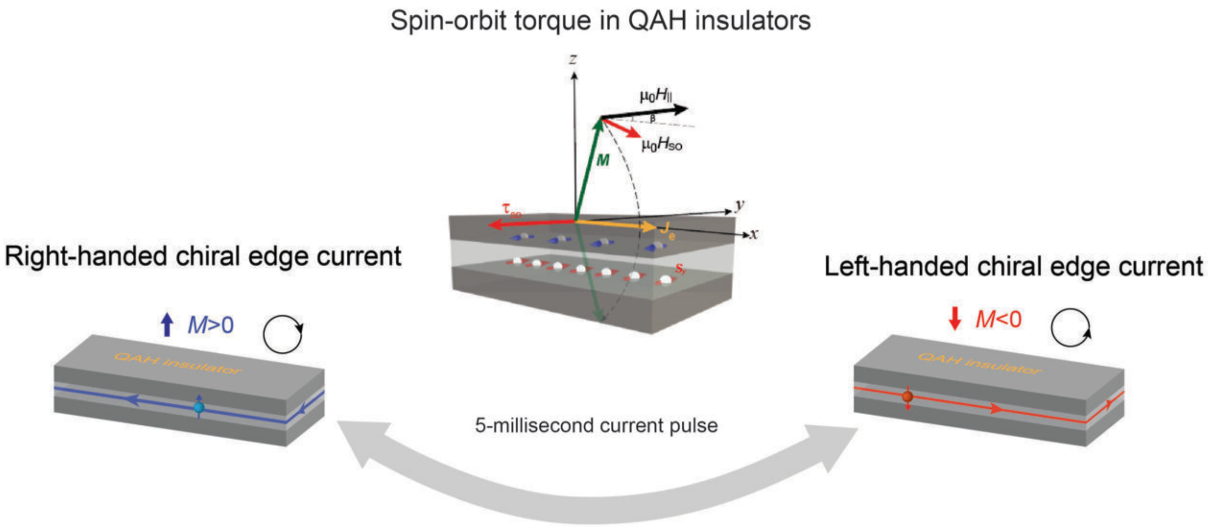
Electrical control of quantum phenomenon could improve future electronic devices

October 19 2023



A new method by Penn State researchers conveniently changes the direction of electron flow in materials that exhibit the quantum anomalous Hall (QAH) effect—a phenomenon in which the flow of electrons along the edge of a material does not lose energy. The method takes advantage of a physical mechanism called spin-orbit torque, which is related to the material's internal magnetism. Applying a five-millisecond current pulse to the material impacts the internal magnetism and changes the discretion of electron flow (e.g. from right-handed to left-handed). Credit: Chang Lab/Penn State

A new electrical method to conveniently change the direction of electron flow in some quantum materials could have implications for the development of next-generation electronic devices and quantum computers.

A team of researchers from Penn State developed and demonstrated the method in materials that exhibit the quantum anomalous Hall (QAH) effect—a phenomenon in which the flow of electrons along the edge of a material does not lose energy. The team described the work in a paper in the journal Nature Materials.

"As electronic devices get smaller and computational demands get larger, it is increasingly important to find ways to improve the efficiency of information transfer, which includes the control of electron flow," said Cui-Zu Chang, Henry W. Knerr Early Career Professor and associate professor of physics at Penn State and co-corresponding author of the paper. "The QAH effect is promising because there is no energy loss as electrons flow along the edges of materials."

In 2013, Chang was the first to experimentally demonstrate this quantum phenomenon. Materials exhibiting this effect are referred to as QAH insulators, which are a type of topological insulator—a thin layer of film only a couple dozen atoms thick—that have been made magnetic so that they only conduct current on their edges. Because the electrons travel cleanly in one direction, the effect is referred to as dissipationless, meaning no energy is lost in the form of heat.

"In a QAH insulator, electrons on one side of the material travel in one direction, while those on the other side travel in the opposite direction, like a two-lane highway," Chang said. "Our earlier work demonstrated how to scale up the QAH effect, essentially creating a multilane highway for faster electron transport. In this study, we develop a new electrical method to control the transport direction of the electron highway and provide a way for those electrons to make an immediate U-turn."

The researchers fabricated a QAH insulator with specific, optimized properties. They found that applying a five-millisecond current pulse to the QAH insulator impacts the internal magnetism of the material and causes the electrons to change directions. The ability to change direction is critical for optimizing information transfer, storage, and retrieval in quantum technologies.

Unlike current electronics, where data is stored in a binary state as on or off—as one or zero—quantum data can be stored simultaneously in a range of possible states. Changing the flow of electrons is an important step in writing and reading these quantum states.

"The previous method to switch the direction of electron flow relied on an external magnet to alter the material's magnetism, but using magnets in electronic devices is not ideal," said Chao-Xing Liu, professor of physics at Penn State and co-corresponding author of the paper.

"Bulky magnets are not practical for small devices like smartphones, and an electronic switch is typically much faster than a magnetic switch. In this work, we found a convenient electronic method to change the direction of electron flow."

The researchers previously optimized the QAH insulator so that they could take advantage of a physical mechanism in the system to control its internal magnetism.

"To make this method effective, we needed to increase the density of the applied current," Liu said. "By narrowing the QAH insulator devices, the current pulse resulted in very high current density that switched the magnetization direction, as well as the direction of the electron transport route."

This shift from magnetic to electronic control in quantum materials, according to the researchers, is similar to a shift that has occurred in traditional memory storage. While the storage of information on original hard drives and floppy disks involved the use of magnets to create a magnetic field and write data, newer "flash memory" such as that used in USB drives, solid state hard drives, and smartphones is written electronically. Promising new technologies to scale up memory, such as MRAM, similarly rely on physical mechanisms related to internal magnetism.

Beyond the experimental demonstration, the research team also provided a theoretical interpretation of their methodology.

The team is currently exploring how to pause electrons on their route—to essentially turn the system on and off. They are also pursuing how to demonstrate the QAH effect at higher temperatures.

"This effect, as well as current requirements for quantum computers and superconductors, require very low temperatures near absolute zero," Chang said. "Our long-term goal is to replicate the QAH effect at more technologically relevant temperatures."

More information: Electrical Switching of the Edge Current Chirality in Quantum Anomalous 2 Hall Insulators, *Nature Materials* (2023). DOI: 10.1038/s41563-023-01694-y.
www.nature.com/articles/s41563-023-01694-y

Provided by Pennsylvania State University

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