Current takes a surprising path in quantum material

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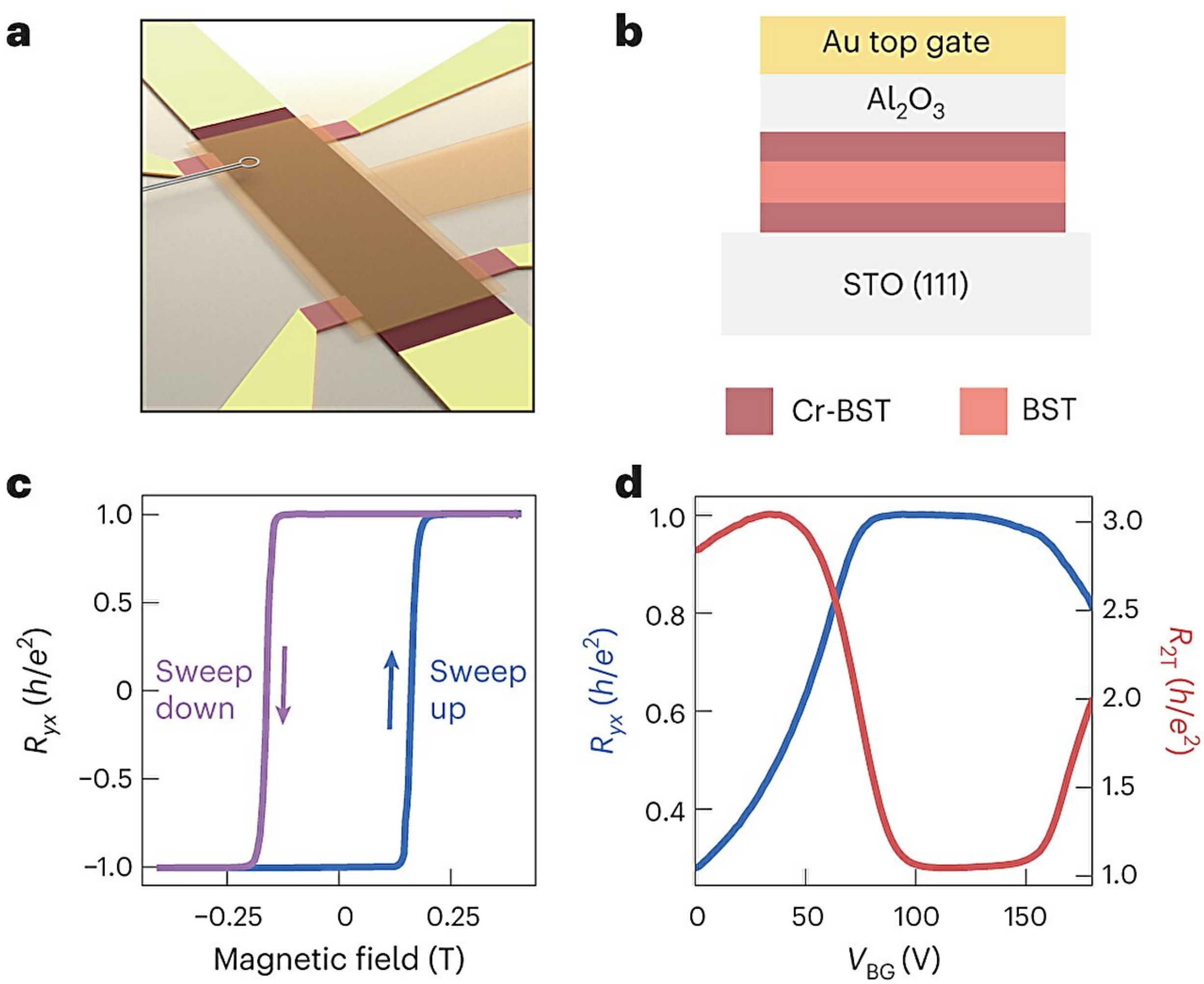

Magnetic imaging of a QAH effect sample. **a**, Schematic of a SQUID pickup loop imaging stray magnetic fields above a Hall bar sample of dimensions 200 × 75 μm^2. **b**, Cross-section of the sample. A four-quintuple layer (QL) of undoped BST is sandwiched between two three-QLs of Cr-doped BST. A gold layer insulated from the thin film by 40 nm of Al_2O_3 is used as a top gate extending beyond the Hall bar, as shown in **a**. V_{BG} is applied through the STO substrate. **c**, Hall resistance versus magnetic field at V_{BG} = 110 V showing a hysteresis loop. **d**, Hall resistance (R_{yx}, blue) and two-terminal resistance (R_{2T}, red) versus V_{BG} at zero magnetic field with the sample magnetized at +0.4 T. Credit: *Nature Materials* (2023). DOI: 10.1038/s41563-023-01622-0. https://www.nature.com/articles/s41563-023-01622-0

Cornell researchers have used magnetic imaging to obtain the first direct visualization of how electrons flow in a special type of insulator, and by doing so they discovered that the transport current moves through the interior of the material, rather than at the edges, as scientists had long assumed.

The finding provides new insights into the electron behavior in so-called quantum anomalous Hall insulators and should help settle a decades-long debate about how current flows in more general quantum Hall insulators. These insights will inform the development of topological materials for next-generation quantum devices.

The team's paper, "Direct Visualization of Electronic Transport in a Quantum Anomalous Hall Insulator," was published August 3 in *Nature Materials*. The lead author is Matt Ferguson, Ph.D. '22, currently a postdoctoral researcher at the Max Planck Institute for Chemical Physics of Solids in Germany.

The project, led by Katja Nowack, assistant professor of physics in the College of Arts and Sciences and the paper's senior author, has its origins in what's known as the quantum Hall effect. First discovered in 1980, this effect results when a magnetic field is applied to a specific material to trigger an unusual phenomena: The interior of the bulk sample becomes an insulator while an electrical current moves in a single direction along the outer edge. The resistances are quantized, or restricted, to a value defined by the fundamental universal constant and drop to zero.

A quantum anomalous Hall insulator, first discovered in 2013, achieves the same effect by using a material that is magnetized. Quantization still occurs and longitudinal resistance vanishes, and the electrons speed along the edge without dissipating energy, somewhat like a superconductor.

At least that is the popular conception.

"The picture where the current flows along the edges can really nicely explain how you get that quantization. But it turns out, it's not the only picture that can explain quantization," Nowack said. "This edge picture has really been the dominant one since the spectacular rise of topological insulators starting in the early 2000s. The intricacies of the local voltages and local currents have largely been forgotten. In reality, these can be much more complicated than the edge picture suggests."

Only a handful of materials are known to be quantum anomalous Hall insulators. For their new work, Nowack's group focused on chromium-doped bismuth antimony telluride—the same compound in which the quantum anomalous Hall effect was first observed a decade ago.

The sample was grown by collaborators led by physics professor Nitin Samarth at Pennsylvania State University. To scan the material, Nowack and Ferguson used their lab's superconducting quantum interference device, or SQUID, an extremely sensitive magnetic field sensor that can operate at low temperatures to detect dauntingly tiny magnetic fields. The SQUID effectively images the current flows—which are what generate the magnetic field—and the images are combined to reconstruct the current density.

"The currents that we are studying are really, really small, so it's a difficult measurement," Nowack said. "And we needed to go below one Kelvin in temperature to get a good quantization in the sample. I'm proud that we pulled that off."

When the researchers noticed the electrons flowing in the bulk of the material, not at the boundary edges, they began to dig through old studies. They found that in the years following the original discovery of the quantum Hall effect in 1980, there was much debate about where the flow occurred—a controversy unknown to most younger materials scientists, Nowack said.

"I hope the newer generation working on topological materials takes note of this work and reopens the debate. It's clear that we don't even understand some very fundamental aspects of what happens in topological materials," she said. "If we don't understand how the current flows, what do we actually understand about these materials?"

Answering those questions might also be relevant for building more complicated devices, such as hybrid technologies that couple a superconductor to a quantum anomalous Hall insulator to produce even more exotic states of matter.

"I'm curious to explore if what we observe holds true across different material systems. It might be possible that in some materials, the current flows, yet differently," Nowack said. "For me this highlights the beauty of topological materials—their behavior in an electrical measurement are dictated by very general principles, independent of microscopic details. Nevertheless, it's crucial to understand what happens at the microscopic scale, both for our fundamental understanding and applications. This interplay of general principles and the finer nuances makes studying topological materials so captivating and fascinating."

More information: G. M. Ferguson et al, Direct visualization of electronic transport in a quantum anomalous Hall insulator, *Nature Materials* (2023). DOI: 10.1038/s41563-023-01622-0.
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