Higher-order topology found in 2-D crystal

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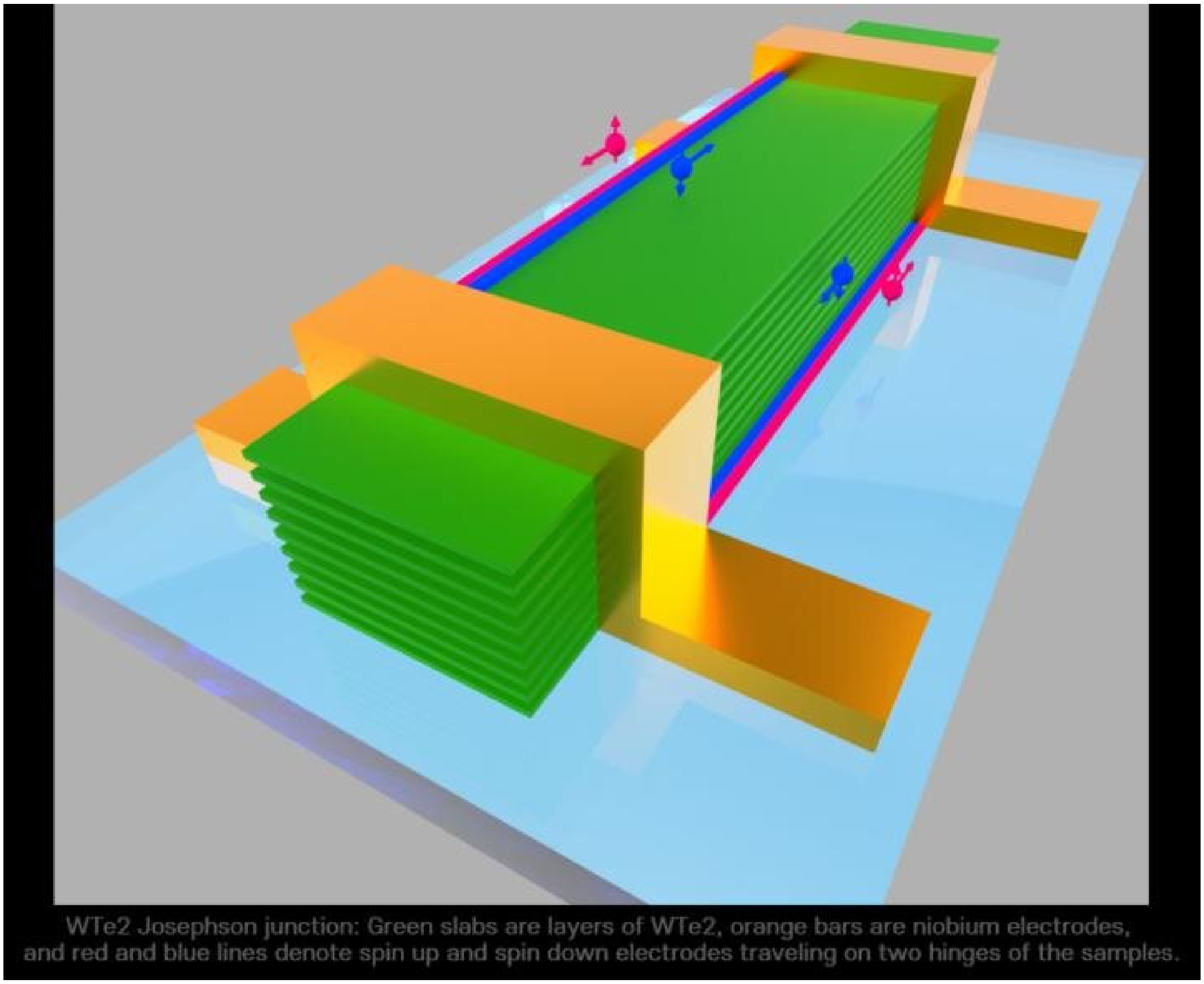

WTe2 Josephson junction: Green slabs are layers of WTe2, orange bars are niobium electrodes, and red and blue lines denote spin up and spin down electrodes traveling on two hinges of the samples. Credit: Gil-Ho Lee (POSTECH)

Over the last decade, the field of condensed matter physics has experienced a golden age with the discovery of new materials and properties, and related technologies being developed at breakneck speed thanks to the arrival of topological physics. Topological physics took off in 2008 with the discovery of topological insulator, a type of material that is electrically insulating in bulk but metallic on the surface.

Since then, scientists have found more exotic topological phases including Dirac semimetals, Weyl semimetals and Axionic insulators. But most recently, materials that are insulating in bulk on surfaces and edges but are metallic only on the hinges or at the corners have been theoretically predicted. These bizarre new materials called higher-order topological insulators are extremely rare and only the element bismuth has been experimentally proven to possibly belong to this category so far.

What is a hinge state anyway? Imagine a box—longer and wider than tall—with flaps on top and bottom that you can open to put things inside. The space inside the box would be called the bulk. Most materials which conduct electricity do so in the bulk. However, in topological insulators, the bulk of the box is electrically insulating but the top and bottom—the flaps—are metallic and maintain surface states. For some materials, the bulk, the top and bottom of the box are insulating but the sides (edges) are metallic. These have edge states which have been demonstrated in magnetic topological insulators. Finally, in higher-order topological insulators, the bulk, top, bottom and sides of the box are all insulating but the hinges and corners of the box are metallic and have disparate hinge or corner states. These hinge states have also been predicted to exist in topological semimetals like bismuth. The hinge states in particular are expected to be promising for the study of spintronics because the direction of their propagation is tied to their spin as well as for Majorana fermions which are actively being investigated for their applications to fault-tolerant quantum computing.

Now an international team of scientists from the United States, Hong Kong, Germany, and South Korea have identified a new higher-order topological insulator. It is a layered two-dimensional transition metal dichalcogenide (TMDC) called WTe2. This is a famous material in condensed matter physics that displays a variety of exotic properties from titanic magnetoresistance to quantized spin hall effect. It was the first example of a Type-II Weyl semimetal that can be made into devices that are only one layer in thickness and is exfoliatable like graphene. WTe_2 has also shown to superconduct under pressure which means electrons form pairs and a supercurrent travels through it without any resistance.

Adding to this carnival of properties, theoretical physicists in 2019 envisioned WTe_2 and its sister material $MoTe_2$ to be higher-order topological insulators with metallic hinge states. Many research teams around the world have since searched for evidence of these exotic states in WTe_2 and $MoTe_2$ and some recent results have shown that there are extra conductive states at their edges. But the researchers were unable to identify if these were truly edge states or the highly sought-after hinge states.

In a study published in *Nature Materials* on July 6, 2020, the team led by Kin Chung Fong (Raytheon BBN Technologies), Mazhar N. Ali (Max Plank Institute of Microstructure Physics and also Material Mind Inc.), Kam Tuen Law (Hong Kong University of Science and Technology) and Gil-Ho Lee (Pohang University of Science and Technology, and the Asia Pacific Center for Theoretical Physics) took a new approach by using the Josephson junctions to spatially resolve the supercurrent flow and to show that WTe_2 does indeed appear to have hinge states and be a higher-order topological insulator (Link to paper).

Josephson junctions are an incredibly important device and tool in physics. They are used in a variety of technological applications including magnetic resonance imaging (MRI) machines as well as in qubits, which are building blocks of quantum computers. These junctions are formed when two superconducting electrodes like niobium (Nb) are connected by a non-superconducting bridge like a high-quality WTe_2 in a thin film device. When the temperature is lowered enough, the supercurrent that is injected from one Nb electrode can travel across the bridge without resistance to the other Nb electrode. Therefore the overall device shows zero resistance and is said to be superconducting.

However, no infinite amount of supercurrent can be sent across the bridge while retaining superconductivity. When the injected current exceeds a critical current, the junction turns into a normal state and exhibits finite resistance. The Josephson effect states that as a function of the applied magnetic field, the critical current will oscillate in a Fraunhofer pattern between high and low values due to the changing phase of the superconducting wave-function across the sample.

The team realized that hidden in this oscillation is location information of the supercurrent while it travels in the sample. By taking an inverse Fourier transform of the Fraunhofer pattern, the researchers were able to visualize the supercurrent flow in the sample and found that it indeed travels on the sides of the WTe_2 device. However, this was not enough to distinguish the edge states from the hinge states.

As shown in the figure below, due to a quirk in the symmetry-based origin of the hinge states, not all hinges are identical on the WTe_2 sample. For example, there are metallic hinge states on top left and bottom right hinges on the sample but not on the top right or bottom left. This is different from an edge state, which would simply be existing on the entirety of the left and right sides of the sample. Regarding this, Kin Chung Fong of Raytheon BBN Technologies explains, "We used this difference to our advantage. By connecting superconducting electrodes on just the top half of the sample and not the bottom half, we realized we would see a different Fraunhofer pattern if hinge states existed and not edge states." He further commented, "In this configuration, electrodes would connect to only one of the hinge states (i.e. top left and not bottom right), which would show a distinct Fraunhofer pattern. If there were edge states, this configuration wouldn't be any different than connecting to both the bottom and top halves of the sample and the Fraunhofer would look the same." When they carried out this challenging experiment, they observed the hallmark of the hinge state, not the edge state.

"But that's not all. WTe_2 is a fairly low-symmetry orthorhombic material with high crystalline anisotropy. The different directions in the crystal are not equivalent and we also theorized and confirmed that the hinge states existing in WTe_2 aren't all equivalent either. In some directions, they mix into the bulk while in other directions they don't," explained Kam Tuen Law at Hong Kong University of Science and Technology.

"There is a variety of exciting physics to be explored in these compounds in the near future now that hinge states have been found in WTe_2," remarked Gil Ho Lee of Pohang University of Science and Technology. He added, "The possibility for dissipationless interconnections, true 1D superconducting nano-wires and spintronics devices, topological superconductivity, Majorana fermions and correspondingly topological quantum computers are all on the horizon."

Mazhar N. Ali at the Max Plank Institute of Microstructure Physics explained, "WTe_2 may be the second material shown to host hinge states, but it is very different from the other candidate, bismuth. Being 2-D, WTe_2 is easily fabricable into nano-devices with controlled surfaces, and can be layered on top of other 2-D materials in heterostructures and even on top of itself when slightly twisted to form a Moire superlattice." He added, "Its sister material $MoTe_2$ is expected to exhibit the same hinge states but it is an intrinsic superconductor at low temperatures." He concludes, "How can these hinge states be modified, controlled, and used? There are a lot of exciting research opportunities ahead."

More information: Yong-Bin Choi et al, Evidence of higher-order topology in multilayer WTe2 from Josephson coupling through anisotropic hinge states, *Nature Materials* (2020). DOI: 10.1038/s41563-020-0721-9

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