Achieving zero resistance in energy flow

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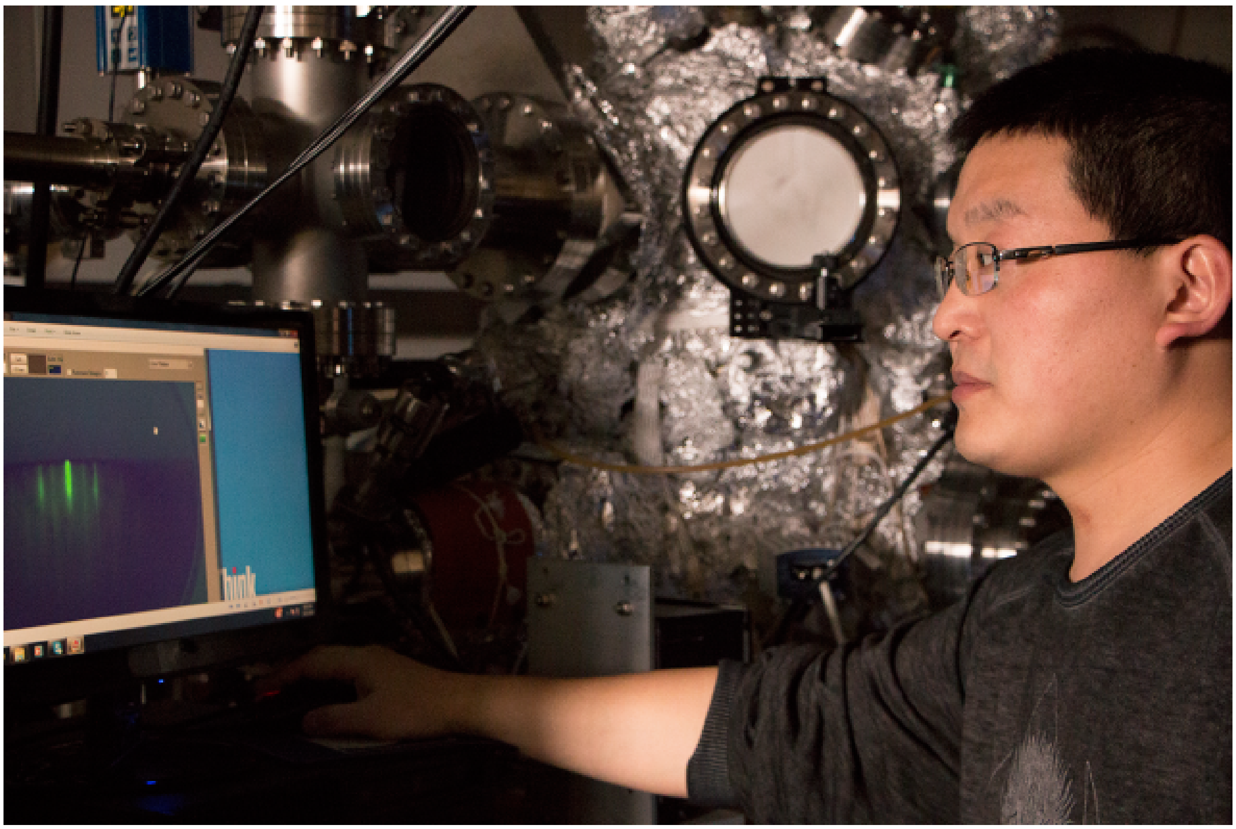

MIT postdoc Cui-Zu Chang works with equipment that can monitor topological insulator thin-film quality as it grows. The bright green vertical bar on computer screen is an indicator of very high-quality film growth. Chang led work in the Moodera group showing the first zero-resistance edge state in a circuit. Credit: Denis Paiste/Materials Processing Center

Laptop computer users operating their devices on their laps will be familiar with the heat they generate, which comes from electrical resistance converting waste energy to heat. Scientists dream of creating electronic devices with little or no resistance to the flow of electricity, in order to reduce heat output, save energy, and extend device capabilities. In the last several years theorists and experimentalists have been trying to achieve this goal using extremely thin materials with special physical properties, called topological insulators (TIs). Recently there has been a breakthrough towards this goal: Dissipationless flow of current has been achieved in TIs when it enters a quantum state without any external magnetic fields—although, as of now, only at extremely low temperatures, its potential can be significant if the operating temperature could be raised.

Topological insulators allow the free flow of electrons only on their surface while blocking the flow of electrons through their bulk. MIT postdoc Cui-Zu Chang, then a doctoral student at Tsinghua University in China, and colleagues at Chinese Academy of Sciences-Institute of Physics, Tsinghua, and Stanford University, reported the experimental demonstration of electrons flowing only along the edge of a topological insulator film circuit, driven by an internal magnetic field, which physicists call the quantum anomalous Hall effect. To provide internal magnetism for their circuit, they added chromium to their material, which was composed of bismuth, antimony, and tellurium. However, the Tsinghua system still showed remnants of electrical resistance to the edge current, frustratingly close to zero resistance.

Dissipationless transport

Improving upon his earlier work, Chang and colleagues in the group of Jagadeesh Moodera, along with collaborators from Penn State, Stanford and Northeastern University, achieved robust quantum anomalous Hall state and near dissipationless electron transport in topological insulators. Chang and colleagues at MIT replaced chromium with vanadium to obtain atomically thin layers of their magnetic topological insulators. They stacked sample films of this material on a base of strontium titanate. They reported early results of this work in *Nature Materials* in May 2015, achieving very slight resistance to current flowing lengthwise along their sample.

Via local and nonlocal measurements, Chang and colleagues at MIT and Penn State University with further optimization achieved zero resistance to current flowing lengthwise along the edge of their sample circuit at the extremely low temperature of 25 millikelvins (0.025 kelvins), a state physicists call "dissipationless chiral edge transport." This lack of resistance is independent of length, they say in a *Physical Review Letters* paper published in July 2015. Moodera's group is part of the Francis Bitter Magnet Laboratory and MIT Department of Physics.

"In this system, there is a very special edge channel," Chang explains. "The bulk is insulating but the chiral edge channel is metallic and spin polarized, so it's very useful for the next generation electronics and spintronics with low power consumption."

"A signal entering this system can propagate a long distance without losing any of its energy. While presently it can only be realized at very low temperatures, there are indications that this can be raised," Chang says. Observing this kind of quantum anomalous Hall state below 1 kelvin requires a special piece of equipment called a cryostat, so work continues to produce this effect at a higher temperature.

Vanadium advantages

Adding an extra element such as chromium or vanadium to introduce a special property (such as magnetism) to a material is known as doping. The vanadium-doped system showed three distinct advantages over the chromium-doped system:

- twofold increase in the temperature above which the material loses magnetism (its Curie temperature), allowing the vanadium system to operate at zero resistance at a slightly higher but still very cold temperature;
- 10 times increase in the stability of its intrinsic magnetism (its coercive field); and
- one-half reduction in its carrier density.

The vanadium system spontaneously shows magnetism at below about 23 kelvins. Results show this quantum anomalous Hall state can survive in a vanadium-doped system up to 5 kelvins (-450 degrees Fahrenheit). However, above 5 kelvins, the effect disappears and the normal resistance of the bulk material appears.

While their sample film is still extremely thin—about 4 nanometers—the device studied is about 1 mm long by 0.4 mm wide, which is relatively large compared with other studies of quantum spintronic phenomena. "We make this kind of sample so big to preserve the delicate properties of the film. These films are very sensitive to water and air, which degrades the film properties," Chang explains.

Chang worked for five years in his doctoral studies at Tsinghua University searching for the quantum anomalous Hall effect, which was predicted in 1988 by F. Duncan M. Haldane at Princeton, he notes. "In a recent theoretical paper, no quantum anomalous Hall effect was predicted in a vanadium-doped topological insulator, whereas we experimentally showed the opposite is true, that this system is better for observing quantum anomalous Hall effect!" Chang says.

Three conditions needed

The 2006 discovery of topological insulators made the realization of quantum anomalous Hall effect practical. Chang cites three conditions to realize this effect: atomically flat thin TI film; introducing magnetism into the TI film; and tuning the chemical potential (Fermi level) into the gap induced by magnetism. After an intense search, Chang first observed the quantum anomalous Hall state in Oct. 9, 2012, in a sample of chromium-doped bismuth antimony, simultaneously showing a noticeable decrease in longitudinal resistance, according to a report on the evolution of their work published Feb. 26 in the Journal of Physics: Condensed Matter. Separately, a group at Tokyo University which included Joseph Checkelsky, now assistant professor of physics at MIT, confirmed the Tsinghua work and also observed the quantum anomalous Hall effect in the same system, Chang says.

"If you can realize this effect at room temperature, it will significantly change our life. You can use this kind of effect to develop quantum electronics including the quantum computer," Chang says. "In this kind of computer, there is minimal heating effect; the current flow is completely dissipationless; and you can also communicate over very long distance."

Although a superconductor can also reach zero resistance at low temperature, it is not spin-polarized, so it can transfer only electrical information but not spin information, Chang explains. The advantage of the quantum anomalous Hall effect, or topological edge state, is that the edge current is spin-polarized and robust, so it can be used to transfer information.

More information: C.-Z. Chang et al. Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator, *Science* (2013). DOI: 10.1126/science.1234414

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