Bismuth-based nanoribbons show 'topological' transport, potential for new technologies

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Researchers have created nanoribbons of an emerging class of materials called topological insulators and used a magnetic field to control their semiconductor properties, a step toward harnessing the technology to study exotic physics and building new spintronic devices or quantum computers.

Unlike ordinary materials that are either insulators or conductors, topological insulators are paradoxically both at the same time - they are insulators inside but conduct electricity on the surface, said Yong P. Chen, a Purdue University associate professor of physics and astronomy and electrical and computer engineering who worked with doctoral student Luis A. Jauregui and other researchers.

The materials might be used for "spintronic" devices and practical quantum computers far more powerful than today's technologies. In the new findings, the researchers used a magnetic field to induce a so-called "helical mode" of electrons, a capability that could make it possible to control the spin state of electrons.

The findings are detailed in a research paper that appeared in the advance online publication of the journal *Nature Nanotechnology* on Jan. 18 and showed that a magnetic field can be used to induce the nanoribbons to undergo a "topological transition," switching between a material possessing a band gap on the surface and one that does not.

"Silicon is a semiconductor, meaning it has a band gap, a trait that is needed to switch on and off the conduction, the basis for silicon-based digital transistors to store and process information in binary code," Chen said. "Copper is a metal, meaning it has no band gap and is always a good conductor. In both cases the presence or absence of a band gap is a fixed property. What is weird about the surface of these materials is that you can control whether it has a band gap or not just by applying a magnetic field, so it's kind of tunable, and this transition is periodic in the magnetic field, so you can drive it through many 'gapped' and 'gapless' states."

The nanoribbons are made of bismuth telluride, the material behind solid-state cooling technologies such as commercial thermoelectric refrigerators.

"Bismuth telluride has been the workhorse material of thermoelectric cooling for decades, but just in the last few years people found this material and related materials have this amazing additional property of being topological insulators," he said.

The paper was authored by Jauregui; Michael T. Pettes, a former postdoctoral researcher at the University of Texas at Austin and now an assistant professor in the Department of Mechanical Engineering at the University of Connecticut; Leonid P. Rokhinson, a Purdue professor of physics and astronomy and electrical and computer engineering; Li Shi, BF Goodrich Endowed Professor in Materials Engineering at the University of Texas at Austin; and Chen

A key finding was that the researchers documented the use of nanoribbons to measure so-called Aharonov-Bohm oscillations, which is possible by conducting electrons in opposite directions in ring-like paths around the nanoribbons. The structure of the nanoribbon - a nanowire that is topologically the same as a cylinder - is key to the discovery because it allows the study of electrons as they travel in a circular direction around the ribbon. The electrons conduct only on the surface of the nanowires, tracing out a cylindrical circulation.

"If you let electrons travel in two paths around a ring, in left and right paths, and they meet at the other end of the ring then they will interfere either constructively or destructively depending on the phase difference created by a magnetic field, resulting in either high or low conductivity, respectively, showing the quantum nature of electrons behaving as waves," Jauregui said.

The researchers demonstrated a new variation on this oscillation in topological insulator surfaces by inducing the spin helical mode of the electrons. The result is the ability to flip from constructive to destructive interference and back.

"This provides very definitive evidence that we are measuring the spin helical electrons," Jauregui said. "We are measuring these topological surface states. This effect really hasn't been seen very convincingly until recently, so now this experiment really provides clear evidence that we are talking about these spin helical electrons propagating on the cylinder, so this is one aspect of this oscillation."

Findings also showed this oscillation as a function of "gate voltage," representing another way to switch conduction from high to low.

"The switch occurs whenever the circumference of the nanoribbon contains just an integer number of the quantum mechanical wavelength, or 'fermi wavelength,' which is tuned by the gate voltage of the electrons wrapping around the surface," Chen said.

It was the first time researchers have seen this kind of gate-dependent oscillation in nanoribbons and further correlates it to the topological insulator band structure of bismuth telluride.

The nanoribbons are said to possess "topological protection," preventing electrons on the surface from back scattering and enabling high conductivity, a quality not found in metals and conventional semiconductors. They were fabricated by researchers at the UT Austin.

The measurements were performed while the nanoribbons were chilled to about minus 273 degrees Celsius (nearly minus 460 degrees Fahrenheit).

"We have to operate at low temperatures to observe the quantum mechanical nature of the electrons," Chen said.

Future research will include work to further investigate the nanowires as a platform to study the exotic physics needed for topological quantum computations. Researchers will aim to connect the nanowires with superconductors, which conduct electricity with no resistance, for hybrid topological insulator-superconducting devices. By further combining topological insulators with a superconductor, researchers may be able to build a practical quantum computer that is less susceptible to the environmental impurities and perturbations that have presented challenges thus far. Such a technology would perform calculations using the laws of quantum mechanics, making for computers much faster than conventional computers at certain tasks such as database searches and code breaking.

More information: Luis A. Jauregui et al. Magnetic field-induced helical mode and topological transitions in a topological insulator nanoribbon, *Nature Nanotechnology* (2016). DOI: 10.1038/nnano.2015.293

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