Topological insulators promise computing advances, insights into matter itself

Stephen Ornes, *Science Writer*

For more than 200 years, physicists have wanted to understand why electricity flows through some materials and not others. In some of the first experiments aimed at understanding conductivity, at the start of the 18th century, British autodidact Stephen Gray observed that materials like metals (and some vegetables) conduct electricity, whereas others, like silk or wool, don't. Decades later, in his Philadelphia experiments, Benjamin Franklin used glass as an insulator and metal as a conductor to study electrical discharges from lightning. In the 20th century, quantum physics provided scientists with new tools to probe the properties of electrons, research that—in the early 21st century—has fueled the discovery and understanding of exotic quantum states of matter.

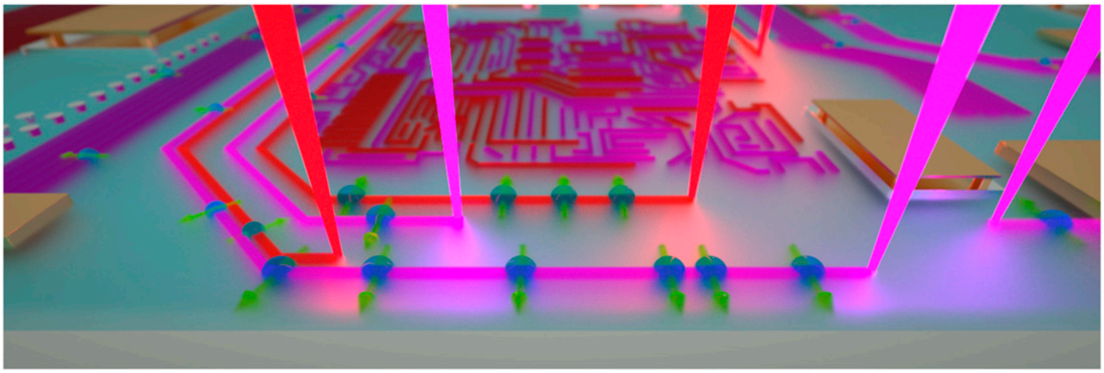
A relative newcomer in the field, and one of growing importance to condensed matter physicists, is the topological insulator: it manipulates electricity unlike anything else known in nature or in the laboratory. In its interior, or bulk, the topological insulator stops current, just like a conventional insulator. But at the edges (in the case of 2D materials) or on the surface (for 3D), the material acts like a conductor. This behavior arises from the atomic structure of the material itself. Small imperfections or changes in the surface won't disrupt or reroute the current.

Although they can be synthesized in the laboratory, topological insulators occur naturally. "You can find it in a piece of rock," says physicist M. Zahid Hasan at Princeton University, who led the 2007 discovery of the first 3D topological insulator. (1) "It's a natural ground state that 3D crystals can have." In that way, a topological insulator is a naturally occurring state of matter, like magnets or superconductors (at superlow temperatures). Because the properties are tied to the structure of the material, you can slice it and the pieces retain the unusual features of the crystal.

Hasan says physicists have had sufficient quantum mechanical knowledge to identify topological insulators since the 1950s, but nobody looked for these potentially revolutionary materials. "Sometimes you have something in plain sight, but you miss it," he says. Now, it seems, plenty of researchers are taking notice.

Charges at the Edges

Physicists usually explain how topological insulators work—insulating on the interior, conducting on the surface—by invoking a phenomenon called the quantum Hall effect, which arises when electrons move through a strong magnetic field. Imagine a stream of electrons traveling along a metal strip. When an up–down magnetic field is applied to the metal strip, it causes the electrons' path to curve, and they pile up on one of the long sides of the strip. The strip accumulates electrons on one side and not on the other. In 1980, German physicist Klaus von Klitzing observed that in such a scenario, the conductivity is quantized, meaning it only exists at certain values that correspond to orbits of the electron (2) (an observation that netted von Klitzing the 1985 Nobel Prize in Physics). More generally, the quantum Hall effect means that strong



Artist's rendition of a circuit in a topological insulator that works via visible or UV light. Image courtesy of Flickr/Peter Allen.

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magnetic fields can be used to manipulate certain types of materials so that electrons move along the edges but remain in place in the middle.

But where do we find those materials? Until about 10 years ago, physicists didn't know. That changed in 2005, when two seminal papers essentially laid out a roadmap, convincing physicists they might find materials with this exotic property (3, 4). In one of those papers (3), University of Pennsylvania physicists Eugene Mele and Charles Kane predicted that the effect should occur in graphene, a semiconductor made of sheets of carbon atoms. The researchers predicted, importantly, that magnetic fields from the spin of the electrons themselves should cause the quantum Hall effect, even without an applied magnetic field. (This is known as the spin quantum Hall effect.)

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It didn't take long for other teams to find materials, using that paper (3) as a guide. In 2007, Shou-Cheng Zhang at Stanford University in California led an international collaboration that confirmed the spin quantum Hall effect predictions in wafers of mercury telluride, a chemical compound that occurs naturally as coloradoite, a mineral ore. (5) "It only took about a year from the theoretical prediction to the first experimental discovery of topological insulators," says Zhang. "In comparison, it took 100 years to experimentally observe gravitational waves."

As Zhang and his team chased the quantum spin Hall effect in flat materials, Hasan and his collaborators were looking in 3D materials. Hasan's team's report of the first 3D topological insulator, in bismuth antimony, appeared in 2008 (1). What followed those first pivotal steps, says Mele, was an "explosion" of research. "Once we knew how to look for them in three dimensions, the genie was out of the bottle," he says. Physicists have now verified more than 20 materials that act like topological insulators. Hasan estimates that there are more than 100 of these materials predicted, many of which have yet to be carefully studied.

"For condensed matter physicists, this is like the Big Bang," says physicist Yong Chen at Purdue University in West Lafayette, Indiana.

Pushing the Boundary

Topological insulators' properties make these materials appealing for new technologies that require quantum-level manipulations. Chen, whose laboratory focuses on improving the quality of existing topological insulators, points to spintronics as a field likely to benefit from the material. Spintronics focuses on understanding and controlling an intrinsic property, called electron spin, which behaves like a tiny bar magnet.

Spintronics has been touted as a potential, low-power successor to conventional means of powering computers. Silicon transistors used today can turn current on or off, but all that switching generates heat. Instead of current, a spintronics system would rely on electron spin. Spin occurs in one of two states, up or down. In a topological insulator, an electron's spin correlates with its motion, suggesting that if a device can control the path of the electron, it can also control the spin, which means those "up" or "down" spin states could be controlled like computer bits. Such a device would theoretically stay cool. Quantum-mechanical circuits may soon be within reach. Last August, a team from Pennsylvania State University and the University of Chicago demonstrated a way to use visible or UV light to "draw" circuits on a topological insulator. The circuits remained in place for several hours; the scientists likened their approach to a "quantum Etch-a-Sketch" (6).

Other researchers are looking at combining topological insulators with superconductors. Theory suggests that combining these two materials may produce quasiparticles that behave like Majorana fermions, chargeless particles that have been proposed as a way to encode and process information in quantum computers. However, Chen thinks that application will take decades to develop.

But the field remains in its infancy. Chen notes that until one or two years ago, most topological insulators being studied had impurities in their interior, which meant they often had some residual conductance. In 2014, he and his collaborators reported on the purest one to date: bismuth antimony tellurium selenide synthesized in the laboratory. The material can be made to not conduct any current in its interior, even close to room temperature (7).

Mele says that although topological insulators may improve technology, they're even more important as a tool for probing quantum electronic properties, and hence elucidating fundamental properties of matter itself. "People want to think about having lower power for their smart phones, or a faster computer, but that's the wrong point of view," he says. "There's going to be something completely unexpected from our current point of view, of building things in terms of electronics. The biggest win in this area is going to be for stuff we haven't thought of yet."

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