SEMICONDUCTORS / MATERIALS

FEATURE

Topological Insulators

Quantum magic can make strange but useful semiconductors that are insulators on the inside and conductors on the surface

By JOEL E. MOORE / JULY 2011

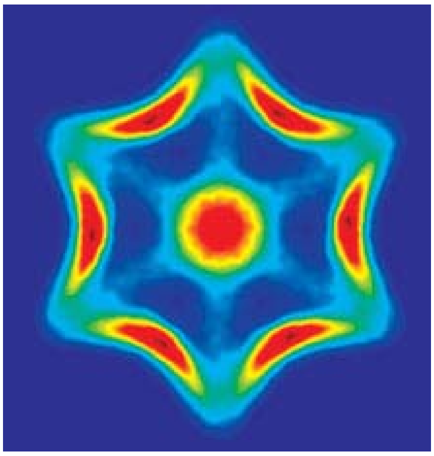
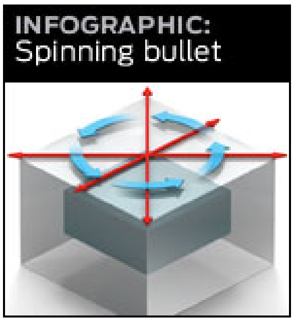


Image: Aharon Kapitulnik and Zhanybek Alpichshev/ Stanford University

SHALLOW CURRENTS: This crystal of bismuth telluride, doped to serve as a source of negative charge carriers, conducts only on its surface. *Click on image for enlargement.*

In science, the usual order is that experiments reveal something and then theorists explain it afterward, if at all. A classic example is superconductivity. It was first noticed in 1911, but it took theorists nearly 50 years to come up with an explanation, and even that explanation does not apply to every superconducting material. But once in a while, we theorists hit on things all by ourselves. And once in a long while, that something turns out to be technologically useful.

Now is one of those times. This is the story of a remarkable theory, hatched in the middle of the past decade, that experimentalists have been pursuing ever since. It is particularly sweet because it is linked to a branch of mathematics—topology—that had until now been mostly beyond any hope of practical application. And the discovery is about as straightforward as it gets: It is possible to produce materials that are insulators on the inside but conductors on the outside.



This is heady stuff, for engineers and physicists alike. The mobility, or speed, of the surface electrons in these materials is increasing dramatically every year. Just as important is their intrinsic stability, a quality that suggests they'd be robust enough to work in practical devices, such as extremely high-capacity interconnects and, one day, maybe even practical quantum computers. Physicists, meanwhile, are deeply intrigued by the possibility of using such materials to simulate new particles and other items of theoretical interest.

Topology is the branch of mathematics concerned with aspects of form that can't be fundamentally altered by stretching. A typical example is the hole of a doughnut: Let's say you deform the doughnut into the shape of a coffee cup. What had been the hole in the doughnut is now the "hole" in the cup's handle. Mathematicians call such features topologically invariant. They can, paradoxically, appear even in a seemingly formless substance such as an electron gas, produced when electrons are confined so that they move in only two dimensions.

In fact, the ability of such a gas to be topologically complex is what led to these new materials. Until recently, electron gases had been found only at the junction of two semiconductors having different electronic properties. These gases are crucial for high electron mobility transistors (HEMTs), a form of field-effect transistor used in radar, imaging, and other applications that require high gain at high frequencies. However, the idea of a 2-D electron gas that exists at the surface of an insulator—and is topologically protected from disorder—was a revelation that emerged from theoretical work done in 2005 and 2006.

Working independently, my group at the University of California (Berkeley and Santa Barbara) and researchers at the University of Pennsylvania and the University of Illinois predicted the existence of "topological insulators," which have insulating interiors but metallic surfaces. We also predicted that though these surfaces would be atomically thin, they would nevertheless be remarkably impervious to disorder and other effects that would tend to destroy their conductivity. That is, they would resist fundamental change, much as the hole does in a stretching, twisting doughnut.

Experimentalists confirmed these predictions in 2008, working with compounds of bismuth. This success triggered an explosion of experimental and theoretical work that continues to this day.

Because of their unique conductive properties, topological insulators will extend the bag of tricks available with electronic devices. There is reason to hope that these topological tricks will transform electronics by making it possible to create robust 2-D electronic gases of arbitrary shape and by allowing the simple manipulation of the spin of an electron. Electron spin is already a crucial property for magnetic storage in your hard drive; topological insulators may also allow it to be used for logic, replacing the microprocessor in your computer with a more energy-efficient and potentially faster design.

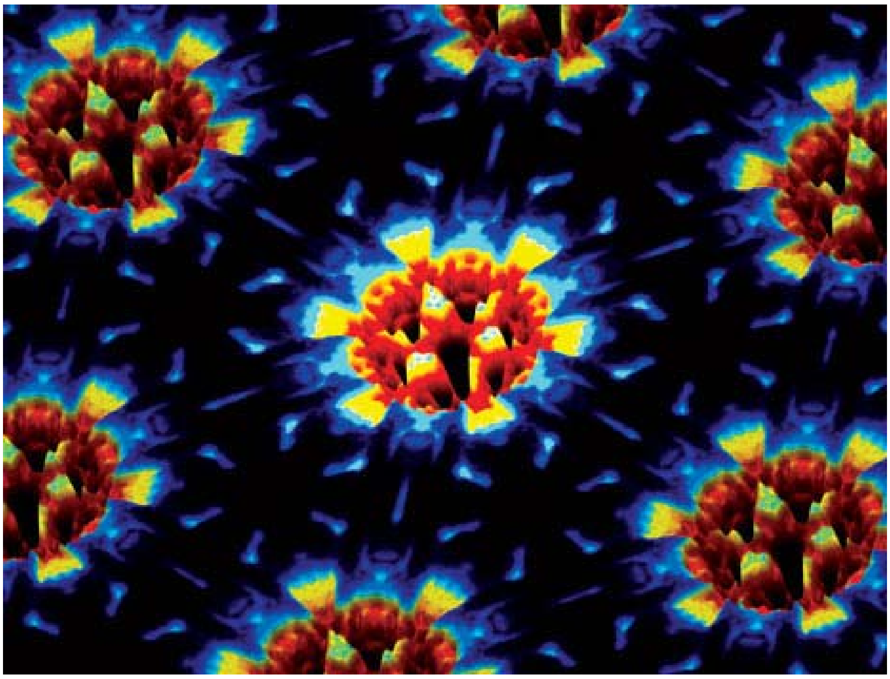


Image: Ali Yazdani and Pedram Roushan/Princeton University

UNSTILL WATERS: These patterns [top] form on a topological insulator when the wavelike nature of the electrons on its surface causes them to scatter off defects in the material and then combine with one another, sometimes reinforcing, sometimes canceling out. These images also provide evidence that the electrons are spin-locked, or moving in a direction determined by their spin.

First, though, a little background. Okay, a lot of background. (Remember, in this case the theory is not an afterthought; it's the main story.)

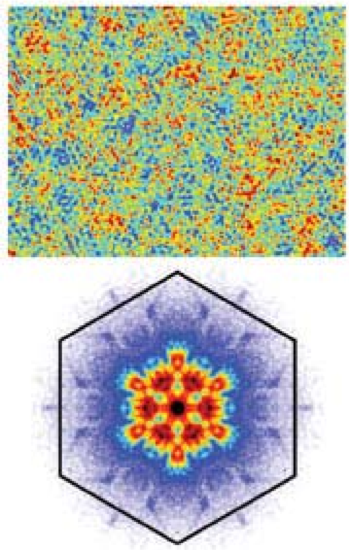
To understand topological insulators, you must first grasp how a conventional semiconductor junction creates a 2-D electron gas. This issue is not merely academic—the same technique (it's called modulation doping) used to create the best such gases for academic research is also used to create the HEMTs in cellphones and other demanding applications.

A central idea of quantum mechanics is that electrons confined to a small spatial volume take on the properties of electrons confined within atoms or molecules. Confined electrons can have only certain discrete energy levels, or "eigenstates." As an example, for the electron in a hydrogen atom the lowest such level—the energy that binds the electron to the nucleus—has an energy of 13.6 electron volts.

Scientists have learned how to confine an electron's motion in one, two, or all three directions, creating what are known as quantum wells, wires, and dots, respectively. Quantum dots are occasionally referred to as artificial atoms, because the confined electron's energy levels resemble those of an atom. In a quantum well, an electron moves freely in two directions, but in the third one it bumps up against a wall, called a trapping potential; if the trapping potential is strong enough, the electrons will be confined in the lowest-energy eigenstate in this direction. The electron can't change how it moves in this confined condition unless a shot of energy kicks it to an excited state, something that won't happen if the temperature's low enough. Consequently, we say that electron motion in the third direction is frozen out, that is, totally fixed; the electrons therefore move in only two directions. In other words, they're perfectly arranged in a plane, which we call a 2-D electron gas.

Semiconductors are good at creating these confined electronic states because they react sensitively to changes in their environment. Despite its name, a pure semiconductor is actually an insulator. To make it conduct first requires doping with an impurity that provides an excess of charge carriers, either electrons or holes. Properly arranged and packaged, devices consisting of several layers of these semiconductors will conduct well only when you apply an electrical field to one of the layers by means of an external voltage or current. In a 2-D electron gas, the charge carriers concentrate at the interface between two different layers—for example, a layer of gallium arsenide against one of aluminum gallium arsenide.

Modulation doping is a way of keeping the doping impurities away from the interface where the electrons travel. As a result, the charge carriers in the 2-D electron gas can move almost perfectly freely. At low temperature, in a gas contained in AlGaAs-GaAs structures, electrons can travel, on average, several millimeters before colliding with an impurity, a distance many times farther than in a typical metal.



Images: Ali Yazdani

HOT SPOTS: This image [center] of the alloy bismuth antimony can be analyzed mathematically into a "map" [left] that shows visible disorder; despite this disorder, the surface remains conducting.

The conducting nature of the surface layers of topological insulators has to do with an aspect of the electron's quantum soul: its spin. Spin is the elusive quantum-mechanical property that underlies magnetism. When the electrons in a region of a material all have the same spin state, that region becomes a magnet. This principle underlies all forms of magnetic storage, such as hard disk drives: When the spins of the electrons in an infinitesimal area of the disk are aligned one way, a 0 is stored there; if the alignment is in the opposite direction, a 1 is stored. Researchers are now attempting to create radically new "spintronic" devices that would exploit the spin of electrons rather than their movement.

So what exactly is spin? You'll be sorry you asked. Elementary physics tells us that any particle has an angular momentum determined by its motion through space. Consider a curve ball thrown by a baseball pitcher. The ball seems to have two types of angular momentum: Its center of mass is moving through space, but the ball is also spinning around some axis, and the spin's friction with air causes the ball to curve. For a baseball, the spin angular momentum is really just the ordinary angular momentum of the particles making up the baseball, and it decreases as the ball becomes smaller.

We can picture an electron as the limit of an infinitesimal baseball whose rotation speeds up as the ball becomes smaller. There is a catch: The electron has no "size," in accordance with our current understanding of quantum mechanics. And yet it still carries a small amount of angular momentum—its spin—even when sitting still.

One prediction of Einstein's theory of relativity is that when electrons are moving fast enough, their spin and their ordinary motion should interact. Spin interacts strongly with a magnetic field (thus its importance in magnetism), but a particle moving rapidly through an *electrical* potential sees an effective *magnetic* force on its spin. Although this interaction is very weak in such atoms as hydrogen, where the electrons move much more slowly than the speed of light, it becomes much stronger in an atom with a large atomic number, such as bismuth.

This "spin-orbit coupling" acts strongly on electrons moving through a semiconductor made of such heavy atoms. In a few materials, this force has a dramatic consequence: The material is no longer truly semiconducting. Instead, a chunk of the material is insulating in its center but conducting at the surface, where it has a 2-D electron gas. In rough terms, the electronic wave functions in the bulk are "knotted up"; unknotting them at the surface requires a metallic layer.

So why does this arrangement beat the obvious alternative, which would involve coating an ordinary semiconductor with a thin layer of metal? It turns out that the topological insulator surface differs in two key ways from that of other 2-D electron gases, and both are subtle results of the spin-orbit interaction.

First, there's the insulator's magnetic side. In a normal metal, an electron moving in a particular direction can have a spin axis that points in any direction. But in the metallic surface of a topological insulator, the spin axis is determined completely by the direction of the electron's motion. That is, all electrons align identically and rigidly with respect to the direction they're going in. So when they're all going in the same direction—as part of a current—they collectively function as a magnet. This effect is present in ordinary quantum wells but is 100 to 1000 times as strong in topological insulators.

Researchers have proposed several devices that take advantage of this strong coupling between current density and magnetic moment. Imagine putting a magnetic layer, such as that used to store bits in a hard disk, on top of a topological insulator. By running a small current in the topological insulator, one could efficiently read bits stored in the magnetic layer; by running a larger current, the spin density induced in the topological insulator could flip the state of the magnetic bit, thereby writing over it.

Second, topological insulators are wonderfully robust in the face of disorder. They retain their unique insulating/surface-conducting character even when dosed with impurities and harried by noise. This ability is just another manifestation of a paradox of quantum behavior, which is unpredictable on a quantum level but highly reliable on a macro level.

Such robustness was apparent in superconductivity, the first macroscopic quantum behavior discovered, as well as in its related phenomenon, superfluidity (the ability of supercold helium to flow without viscosity). Both superfluids and superconductors show their properties in real materials that invariably contain impurities and inhomogeneities.

One source of this robustness is the topological invariance mentioned earlier. Just as the hole in a doughnut remains a hole even when you wrench the material into the shape of a coffee cup, 2-D electron gases have robust topological states that retain their character in the face of disorder. These states were originally observed in such gases only at very low temperatures and in very high magnetic fields.

In the summer of 2006, the three research groups mentioned above predicted the existence of topological insulators by considering the possibility that topological invariants may come from spin-orbit coupling. As one of the people involved in these predictions at the University of California, I can give some anecdotal insight into how they came to happen.

We were inspired by a key 2005 paper [PDF] by Charles Kane and Eugene Mele of the University of Pennsylvania. It explained a model system in one lower dimension: A 2-D system such as a quantum well can have one-dimensional quantum wires at its edge, generated by spin-orbit coupling.

At that time, physicists had already found many topological states in 2-D systems, both experimentally and theoretically, but the Kane-Mele proposal was different in several obvious and not-so-obvious ways. I spent the spring of 2006 working with Leon Balents of UCSB to find a different formulation of the work of Kane and Mele that would let us understand its connection to these older phases. After a few weeks of intense mathematical fiddling, usually with a World Cup match playing in the background, it became clear that there could be a 3-D version of their state, which was quite a surprise since we (and others) thought of topological states as requiring 2-D systems and low temperatures.

Interest in topological insulators remained somewhat limited until the experimental discovery of the first such material (a bismuth-antimony alloy) by a Princeton/Lawrence Berkeley National Laboratory team led by M. Zahid Hasan. Their measurement, published in *Nature* in 2008, found clear evidence for the distinctive surface electronic motion predicted by theory. That began a rush of discoveries that have continued unabated, including the discovery of the second-generation topological insulators bismuth selenide and bismuth telluride. These materials are expected to show topological insulator behavior up to room temperature in sufficiently small samples and have surface metallic layers only a few nanometers thick.

Of course, this being quantum physics, it gets even weirder. It turns out that an electron moving in a semiconductor has an effective mass that can be very different from its mass in a vacuum—a factor of 10 in either direction is not unusual. It's like a horse that can turn into either an elephant or a dog. And it means that the electrons at the surface of a topological insulator, unlike those in an ordinary 2-D electron gas, have an effective mass of *zero*.

Strangely enough, zero-mass electrons had already been known in another exotic environment, that of the 1-atom-thick sheet of hexagonally arranged carbon atoms known as graphene. The origin of the zero-mass effect in graphene has nothing to do with spin, but it has a similar technological implication: It can enable very fast electronic devices. For instance, the first 100-gigahertz transistor [PDF] was recently demonstrated by IBM scientists using a device based on graphene.

The zero-mass effect of topological insulators allows other possibilities less obvious than fast devices. For example, the number of charge carriers in a zero-mass material is much more sensitive to an applied electrical field than in a typical semiconductor. This process is known as field doping, in an analogy to the standard process of controlling carrier density by chemical doping, but it has an advantage that chemical doping does not. You can reverse field doping rapidly by changing the electrical field, whereas chemical doping is essentially permanent.

Put together all these advantages—fast electrons, sensitivity to applied fields, reversibility of doping, and robustness in the face of noise—and you can see why topological insulators have excited the engineering community. They may even help us build one of the chief objects of desire of applied physics: the quantum computer. Scientists at Microsoft and elsewhere have stated their belief that the topological quantum computer is the most viable route to this goal, and one design for such a computer is based on interfaces between topological insulators and superconductors. But there remain some daunting practical challenges in making such interfaces operate reliably at useful temperatures.

It is possible that topological insulators and graphene will be remembered as the first materials to be experimentally discovered in the 21st century that compare with the great accomplishments of the 20th. The range of possible technologies enabled by these remarkable materials is becoming clearer, and far more is likely to come than we can now discern.

About the Author

Joel E. Moore received his Ph.D. in physics from MIT and has been on the faculty of the University of California, Berkeley, since 2002. He was part of the collaboration that first predicted topological insulators in three dimensions. Moore says he's been "amazed" by the subsequent flood of experimental work in the field, which among other things confirmed the materials' existence in 2008. "The hard work of many other people connected our mathematical conjecturing to reality," he says.