Researchers find way to observe, control the way electrons spin on the surface of exotic new materials

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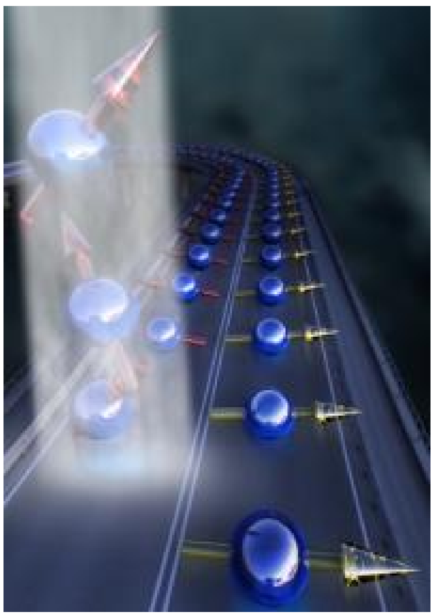

This diagram illustrates how lasers can be used to control an electric current on these new materials. Electrons (blue spheres) travel, as if on a highway, in different directions, with their axis of spin (arrows) aligned differently according to the direction of travel. A circularly polarized laser beam (left) affects only electrons going in one direction, removing them from the flow, leaving a net flow — an electric current — going the other way. Photo: Gedik Group

Exotic materials called topological insulators, discovered just a few years ago, have yielded some of their secrets to a team of MIT researchers.

For the first time, the team showed that light can be used to obtain information about the spin of electrons flowing over the material's surface, and has even found a way to control these electron movements by varying the polarization of a light source.

The materials could open up possibilities for a new kind of devices based on spintronics, which makes use of a characteristic of electrons called spin, instead of using their electrical charge the way electronic devices do. It could also allow for much faster control of existing technologies such as magnetic data storage.

Topological insulators are materials that possess paradoxical properties. The three-dimensional bulk of the material behaves just like a conventional insulator (such as quartz or glass), which blocks the movement of electric currents. Yet the material's outer surface behaves as an extremely good conductor, allowing electricity to flow freely.

The key to understanding the properties of any solid material is to analyze the behavior of electrons within the material — in particular determining what combinations of energy, momentum and spin are possible for these electrons, explains MIT assistant professor of physics Nuh Gedik, senior author of two recent papers describing the new findings. This set of combinations is what determines a material's key properties — such as whether it is a metal or not, or whether it is transparent or opaque. "It's very important, but it's very challenging to measure," Gedik says.

The traditional way of measuring this is to shine a light on a chunk of the solid material: The light knocks electrons out of the solid, and their energy, momentum and spin can be measured once they are ejected. The challenge, Gedik says, is that such measurements just give you data for one particular point. In order to fill in additional points on this landscape, the traditional approach is to rotate the material slightly, take another reading, then rotate it again, and so on — a very slow process.

Gedik and his team, including graduate students Yihua Wang and James McIver, and MIT postdoc David Hsieh, instead devised a method that can provide a detailed three-dimensional mapping of the electron energy, momentum and spin states all at once. They did this by using short, intense pulses of circularly polarized laser light whose time of travel can be precisely measured.

By using this new technique, the MIT researchers were able to image how the spin and motion are related, for electrons travelling in all different directions and with different momenta, all in a fraction of the time it would take using alternative methods, Wang says. This method was described in a paper by Gedik and his team that appeared Nov. 11 in the journal *Physical Review Letters*.

In addition to demonstrating this novel method and showing its effectiveness, Gedik says, "we learned something that was not expected." They found that instead of the spin being precisely aligned perpendicular to the direction of the electrons' motion, when the electrons moved with higher energies there was an unexpected tilt, a sort of warping of the expected alignment. Understanding that distortion "will be important when these materials are used in new technologies," Gedik says.

The team's high-speed method of measuring electron motion and spin is not limited to studying topological insulators, but could also have applications for studying materials such as magnets and superconductors, the researchers say.

One unusual characteristic of the way electrons flow across the surface of these materials is that unlike in ordinary metal conductors, impurities in the material have very little effect on the overall electrical conductivity. In most metals, impurities quickly degrade the conductivity and thus hinder the flow of electricity. This relative imperviousness to impurities could make topological insulators an important new material for some electronic applications, though the materials are so new that the most important applications may not yet be foreseen. One possibility is that they could be used for transmission of electrical current in situations where ordinary metals would heat up too much (because of the blocking effect of impurities), damaging the materials.

In a second paper, appearing today in the journal *Nature Nanotechnology*, Gedik and his team show that a method similar to the one they used to map the electron states can also be used to control the flow of electrons across the surface of these materials. That works because the electrons always spin in a direction nearly perpendicular to their direction of travel, but only electrons spinning in a particular direction are affected by a given circularly polarized laser beam. Thus, that beam can be used to push aside all of the electrons flowing in one direction, leaving a usable electric current flowing the other way.

“This has very immediate device possibilities,” Gedik says, because it allows the flow of current to be controlled completely by a laser beam, with no direct electronic interaction. One possible application would be in a new kind of electromagnetic storage, such as that used in computer hard drives, which now use an electric current to “flip” each storage bit from a 0 to a 1 or vice versa. Being able to control the bits with light could offer a much quicker response time, the team says.

This harnessing of electron behavior could also be a key enabling technology that could lead to the creation of spintronic circuits, using the spin of the electrons to carry information instead of their electric charge. Among other things, such devices could be an important part of creating new quantum computing systems, which many researchers think could have significant advantages over ordinary computers for solving certain kinds of highly complex problems.

Professor of physics Zhi-Xun Shen of Stanford University, who was not involved in this work, says the MIT team has confirmed the theorized structure of the topological surface by using their novel experimental method. In addition to this confirmation, he says, their second paper "is to date one of the most direct experimental evidences for optical coupling" between the laser and the surface currents, and thus "has interesting potential for opto-spintronics."

Provided by Massachusetts Institute of Technology

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