Researchers predict a new state of matter in semiconductors

14 December 2006

Conventional matter exists in three familiar forms-solid, liquid and gas. But under special circumstances, quantum theory predicts exotic states of matter, such as superconductors in which electrons flow with no resistance and Bose-Einstein condensates in which atoms move as a collective whole. Now, in the Dec. 15 issue of the journal *Science*, three Stanford physicists theorize a new state of matter that may pave the way for electronic devices that dissipate less energy and generate less heat.

"Searching for new states of matter has become the holy grail of condensed matter physics, just as the quest for new elements dominated chemistry and the pursuit of new subatomic particles dominates particle physics," says physics Professor Shoucheng Zhang, who also holds courtesy appointments in the Applied Physics and Electrical Engineering departments.

With graduate student Taylor Hughes and former graduate student and current Princeton University postdoctoral fellow Andrei Bernevig, Zhang proposed the existence of the so-called "quantum spin Hall state," which has extraordinary properties. The U.S. Department of Energy and National Science Foundation funded their work.

Say 'cheese'

To understand the quantum spin Hall state, it's key to first understand the related quantum Hall state. Imagining a cheese sandwich will help. Swap semiconductor sheets for the bread, and turn the cheese into an electron gas. Instead of sticking your cheese sandwich in the fridge, place your semiconductor-electron gas concoction in an environment where it's way colder (below 1 degree Kelvin). Apply an intense magnetic field of several Teslas-more than 10,000 times greater than Earth's magnetic field.

"In such a state, the electrical current does not flow through the two-dimensional sheet, but is confined at the edges," Zhang explains. "The current at a given edge flows without dissipation, and only in one direction; it cannot be scattered backward by impurities."

In essence, current flows only around the bread crusts. "This property gives rise to the remarkable observation of quantized Hall voltage measured in the direction perpendicular to the current flow." In contrast, in conventional electronics, currents flow in the same direction as applied voltage, and the resistance can take arbitrary or nonquantized values. That means greater energy dissipation.

So that's the recipe for creating the quantum Hall effect, which Zhang calls "one of the most profound phenomena in physics." The stuff of dreams, the quantum Hall effect was the basis of Nobel Prizes in 1985 and 1998.

A new state

Physicists often use math to convert complex physics concepts into terms of shape, or topology. It makes it easier to describe the extraordinary properties of different states of matter. "If one performs smooth distortions of the donut, one can never get rid of the hole in its center and transform it into a sphere," Zhang says. "Similarly, the electronic state of the quantum Hall effect is topologically distinct from that of any conventional semiconductor states."

As cool and exotic as the quantum Hall state is, it has a serious drawback, Zhang notes. "Unfortunately, the quantum Hall effect can only be realized under high magnetic field and low temperature, and cannot, therefore, be used for semiconductor devices operating under ambient conditions."

In their report in Science, the three Stanford researchers proposed that a new state, called the quantum spin Hall effect, could be realized without applying an external magnetic field. They stacked and skewed alternating layers of mercury telluride and cadmium telluride. Just as in a slightly skewed stack of checkerboards, where red squares are bordered by black squares and vice versa, the material made a crystal lattice structure similar to that of the silicon or gallium arsenide of semiconductors. The researchers say that by controlling the thickness of wells in the mercury telluride, the result will be a quantum phase transition into a new state that is distinct from that of conventional semiconductor states.

Conventional semiconductors are insulators at low temperatures. That means the resistance of the material is so high that no current can flow. But insulators can be turned into conductors-materials with some resistance, but not enough to stop current from flowing-using n-type doping, which adds electrons to the material, or p-type doping, which removes electrons to leave behind holes.

But matter in the quantum spin Hall state can carry electric currents without any doping, Zhang says. Just like with the quantum Hall effect, electrical current flows only at the edges of the sample.

What's more, the quantum spin Hall state would display an "extraordinary" property, Zhang says. On any given edge, electrons oriented with their spins aligned pointing up would flow in one direction, while the electrons oriented with their spins aligned pointing down would flow in the opposite direction. Because impurities usually do not flip the spin orientation, they cannot easily scatter the electrons into the backward direction, thus leading to far less energy dissipation or heat generation compared to conventional semiconductors. Basically, the quantum spin Hall effect has most of the desirable features of the quantum Hall effect, but without the cost of applying a huge magnetic field to a device, Zhang says.

"Similar to the quantum Hall effect, the quantum spin Hall effect is also topologically distinct from any conventional semiconductors," says Zhang. "In this precise mathematical sense, the quantum spin Hall effect is a topologically distinct new state of matter."

Putting theory to the test

Since quantum wells in mercury telluride/cadmium telluride sheets can be readily fabricated, it is possible to experimentally test the theoretical predictions of Zhang, Bernevig and Hughes. A research group at the University of Würzburg in Germany, under the direction of Professor Laurens Molenkamp, is currently doing this.

If the theory pans out, the quantum spin Hall effect may eventually inspire room-temperature devices with new capabilities. Zhang notes the potential for getting around a well-known roadblock of the electronics industry, the dictum saying the number of transistors fitting on a computer chip will double every 18 months: "Transistors built based on the quantum spin Hall effect are expected to dissipate far less heat compared to conventional transistors, thus paving the way for extending Moore's law."

In fact, hoping to turn Zhang's vision into a commercial reality, the Microelectronics Advanced Research Corporation, a consortium of leading U.S. semiconductor companies, has started to fund his research on the quantum spin Hall effect.

Source: Stanford University

APA citation: Researchers predict a new state of matter in semiconductors (2006, December 14) retrieved 15 June 2021 from https://phys.org/news/2006-12-state-semiconductors.html