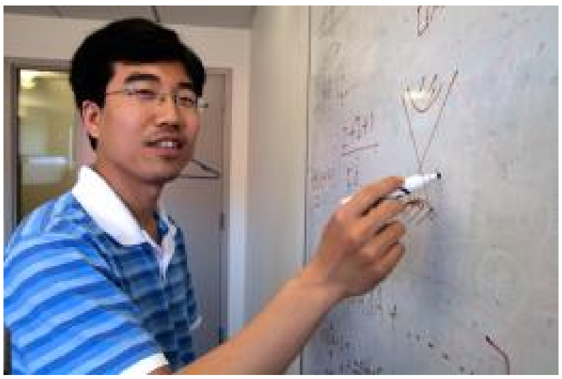
Super-efficient Transistor Material Predicted

May 15 2009, by Lauren Schenkman



Xiao-Liang Qi. (Photo by Lauren Schenkman.)

(PhysOrg.com) -- New work by condensed-matter theorists at the Stanford Institute for Materials and Energy Science at SLAC National Accelerator Laboratory points to a material that could one day be used to make faster, more efficient computer processors.

In a paper published online Sunday in Nature Physics, SIMES researchers Xiao-Liang Qi and Shou-Cheng Zhang, with colleagues from the Chinese Academy of Sciences and Tsinghua University in Beijing, predict that a room temperature material will exhibit the quantum spin Hall effect. In this exotic state of matter, electrons flow without dissipating heat, meaning a transistor made of the material would be drastically more efficient than anything available today. This effect was previously thought to occur only at extremely low temperatures. Now the race is on to confirm the room-temperature prediction experimentally.

Zhang has been one of the leading physicists working on the quantum spin Hall effect; in 2006 he predicted its existence in mercury telluride, which experimentalists confirmed a year later. However, the mercury telluride had to be cooled by liquid helium to a frigid 30 millikelvins, much too cold for real-world applications.

In their hunt for a material that exhibited the quantum spin Hall effect, Zhang and Qi knew they were looking for a solid with a highly unusual energy landscape. In a normal semiconductor, the outermost electrons of an atom prefer to stay in the valence band, where they are orbiting atoms, rather than the higher-energy conduction band, where they move freely through the material. Think of the conduction band as a flat plain pitted with small valence-band valleys. Electrons naturally "roll" down into these valleys and stay there, unless pushed out. But in a material that exhibits the quantum spin Hall effect, this picture inverts; the valence-band valleys rise to become hills, and the electrons roll down to roam the now lower-energy conduction band plain. In mercury telluride, this inversion did occur, but just barely; the hills were so slight that a tiny amount of energy was enough to push the electrons back up, meaning the material had to be kept extremely cold.

When Zhang, Qi and their colleagues calculated this energy landscape for four promising materials, three showed the hoped-for inversion. In one, bismuth selenide, the theoretical conduction band plain is so much lower than the valence band hills that even room temperature energy can't push the electrons back up. In physics terms, the conduction band and valence band are now inverted, with a sizeable difference between them.

"The difference [from mercury telluride] is that the gap is much larger, so we believe the effect could happen at room temperature," Zhang explained.

Materials that exhibit the quantum spin Hall effect are called topological insulators; a chunk of this material acts like an empty metal box that's completely insulating on the inside, but conducting on the surface. Additionally, the direction of each electron's movement on the surface decides its spin, an intrinsic property of electrons. This leads to surprising consequences.

Qi likens electrons traveling through a metal to cars driving along a busy road. When an electron encounters an impurity, it acts like a frustrated driver in a traffic jam, and makes a U-turn, dissipating heat. But in a topological insulator, Qi said, "Nature gives us a no U-turn rule." Instead of reversing their trajectories, electrons cruise coolly around impurities. This means the quantum spin Hall effect, like superconductivity, enables current to flow without dissipating energy, but unlike superconductivity, the effect doesn't rely on interactions between electrons.

Qi points out that, because current only flows on their surfaces, topological insulators shouldn't be seen as a way to make more efficient power lines. Instead, these novel compounds would be ideal for fabricating tinier and tinier transistors that transport information via electron spin.

"Usually you need magnets to inject spins, manipulate them, and read them out," Qi said. "Because the current and spin are always locked [in a topological insulator], you can control the spin by the current. This may lead to a new way of designing devices like transistors."

These tantalizing characteristics arise from underlying physics that seems to marry relativity and condensed matter science. Zhang and Qi's paper reveals that electrons on the surface of a topological insulator are governed by a so-called "Dirac cone," meaning that their momentum and energy are related according to the laws of relativity rather than the quantum mechanical rules that are usually used to describe electrons in a solid.

"On this surface, the electrons behave like a relativistic, massless particle," Qi said. "We are living in a low speed world here, where nothing is relativistic, but on this boundary, relativity emerges."

"What are the two greatest physics discoveries of the last century? Relativity and quantum mechanics." Zhang said. "In the semiconductor industry in the last 50 years, we've only used quantum mechanics, but to solve all these interesting frontier problems, we need to use both in a very essential way."

Zhang and Qi's new predictions are already spurring a surge of experiments to test whether these promising materials will indeed act as room-temperature topological insulators.

"The best feedback you can get is that there are lots of experiments going on," he said.

More information: www.nature.com/nphys/journal/v … t/abs/nphys1270.html

Provided by SLAC National Accelerator Laboratory (news : web)