Insulator on the inside, conductor on the outside

Topological insulators are a key topic at the SNI

In recent months, we've mentioned the subject of topological insulators time and time again. But what are these materials that, despite being insulators, also conduct electricity on their edges and surfaces? What hopes are pinned on the new materials, where does their peculiar name come from, and what questions are SNI scientists currently addressing?

Topology

Topology is an area of mathematics that deals with the gradual deformation of structures. For example, since a ball of modeling clay can be turned into a disc simply by deformation, a ball and a disc are considered to be the same shape from a topological perspective. To make a ball into a ring, however, it is necessary to add a hole. A ring and a ball are therefore different shapes from a topological perspective.

The special properties of topological insulators are highly stable and protected – and are retained even in the event of defects or changes in the material.

From a topological perspective, ball and disc are considered to be the same shape. They differ from a ring or a tube which have - from a topological point of view - the same shape.

Promising new materials

Topological insulators represent an entirely new class of materials whose discovery gave rise to a new field of research – some of which is undertaken by scientists from the SNI.

A common property of all topological insulators is that they behave like insulators on the inside, whereas the edges have metallic properties and conduct electricity. A three-dimensional crystal of a topological insulator therefore conducts electricity only on its surface, while no current can flow inside. Two-dimensional, atom-thin topological materials are only conductive at their edges, and in a one-dimensional material the charge carriers can only move at the two ends.

As well as this "hybrid state" somewhere between an insulator and a conductor, the special thing about the materials is that – due to the laws of quantum mechanics – electricity is transmitted almost losslessly in the stated regions. The use of topological materials in electronic components therefore promises to bring unprecedented efficiency without the unwelcome generation of heat.

Moreover, one-dimensional topological insulators have also been mooted as an ideal way to store quantum information. For this, the necessary steps are taken to convert a nanowire into a one-dimensional topological insulator with two "metallic" edge states – conductive regions – at the left and right ends of the wire. From these two states, it is possible to define a qubit – the smallest unit of information in a quantum computer. This qubit is very difficult to destroy and would therefore be well protected against outside interference.

Complex origins

A topological insulator is more than just a combination of a conductive material and an insulating one. Indeed, the differences in electrical conductivity stem from various phenomena that are not readily understood. Getting to grips with these phenomena first requires an explanation of a few basic principles.

“I find it fascinating that we can now produce new materials that don’t occur in nature – simply by stacking up two-dimensional crystals in an ingenious way. These crystals can exhibit completely new properties and can also become topological insulators. That’s what makes this such an exciting area of research.”

Prof. Dr. Christian Schönenberger and his team are also conducting research on topological isolators

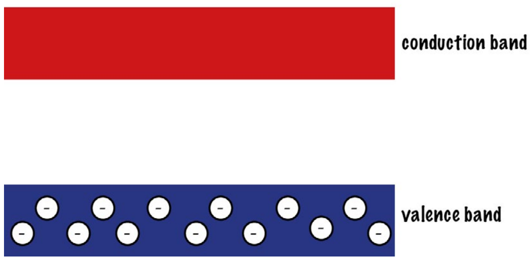
The electrons that whizz around atomic nuclei are responsible for chemical bonding and subsequently for holding materials together. In an insulator, all of the electrons in what is known as the “valence band” participate in bonding with the neighboring atoms. These saturated covalent bonds do not allow the transport of electrical charge – so the material is an insulator.

Physicists describe an insulator in slightly more abstract terms. The bonding electrons occupy all possible states within the valence band. An energy gap separates the fully occupied valence band from a conduction band that contains no electrons while under insulating conditions. This energy gap (or “band gap”) represents the amount of energy that must be supplied in order to “excite” an electron from the valence band into the conduction band – for example, using thermal energy. The bigger the band gap, the more energy must be supplied and the better the insulator.

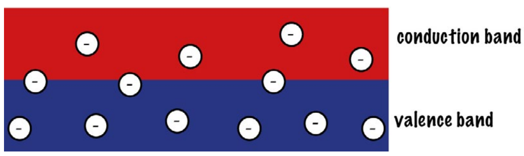
In a metal that conducts electricity, the chemical bonds are not covalently saturated. The conduction band and valence band overlap – in other words, no band gap exists in the first place. As a result, freely mobile electrons are always available, and current can flow without the need for thermal excitation. Metals therefore conduct electricity even at low temperatures.

On the inside, topological insulators have a band gap – like conventional insulators – and do not conduct electricity. But the edges or, in the case of three-dimensional materials, the surfaces of a topological insulator contain states with energies within this band gap. Electrons can adopt these energy states and are therefore able to conduct electricity.

Isolator



Metal



In an insulator, the valence and conduction bands are separated by an energy gap. The energy gap represents the amount of energy that must be supplied to “excite” an electron from the valence band into the conduction band. There is no energy gap in a metal that conducts electricity. As a results, freely mobile electrons are always available and current can flow without the need for thermal excitation.

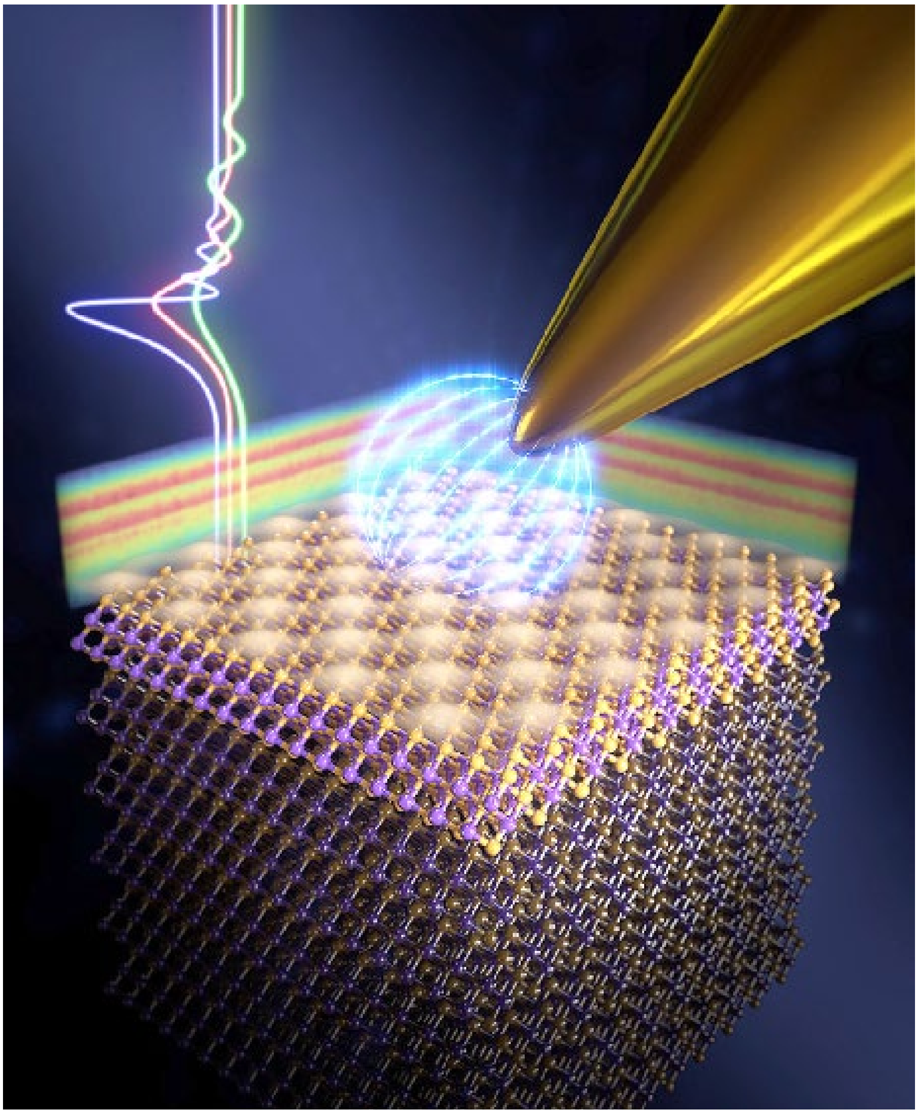
More information about topological insulators:

The birth of topological insulators
Joel E. Moore
Nature 464 (2010), 194–198
https://www.nature.com/articles/re08916?draft=collection

Topologically protected

Every topological insulator is characterized by a topological index. This numerical value is derived from the band structure of the molecule and is extremely difficult to change. If a topological insulator comes into contact with a conventional insulator with a different topological index, the laws of physics are such that the band gap disappears at the point of contact: the material acquires metallic properties at the contact point and becomes an electrical conductor.

This happens when the topological insulator is inside a vacuum, for example. No current flows in the vacuum – in other words, the vacuum is an insulator. However, the band gap disappears at the boundary between the topological material and the vacuum, allowing a current to flow – on the outer surfaces of a three-dimensional body, on the edges of a two-dimensional layer, and on the ends of a one-dimensional nanowire. These properties of the topological insulator are not affected by changes or defects in the material. In technical terms, they are said to be topologically protected.



The gold tip is moved across the surface of the topological insulator and experiences energy loss only at discrete, quantized energies (indicated by the curves). This is related to the image potential states (IPS) that are formed over the conducting surface of the topological insulator and are schematically depicted in the background. (Image: University of Basel, Departement of Physics)

Almost no friction in topological insulators

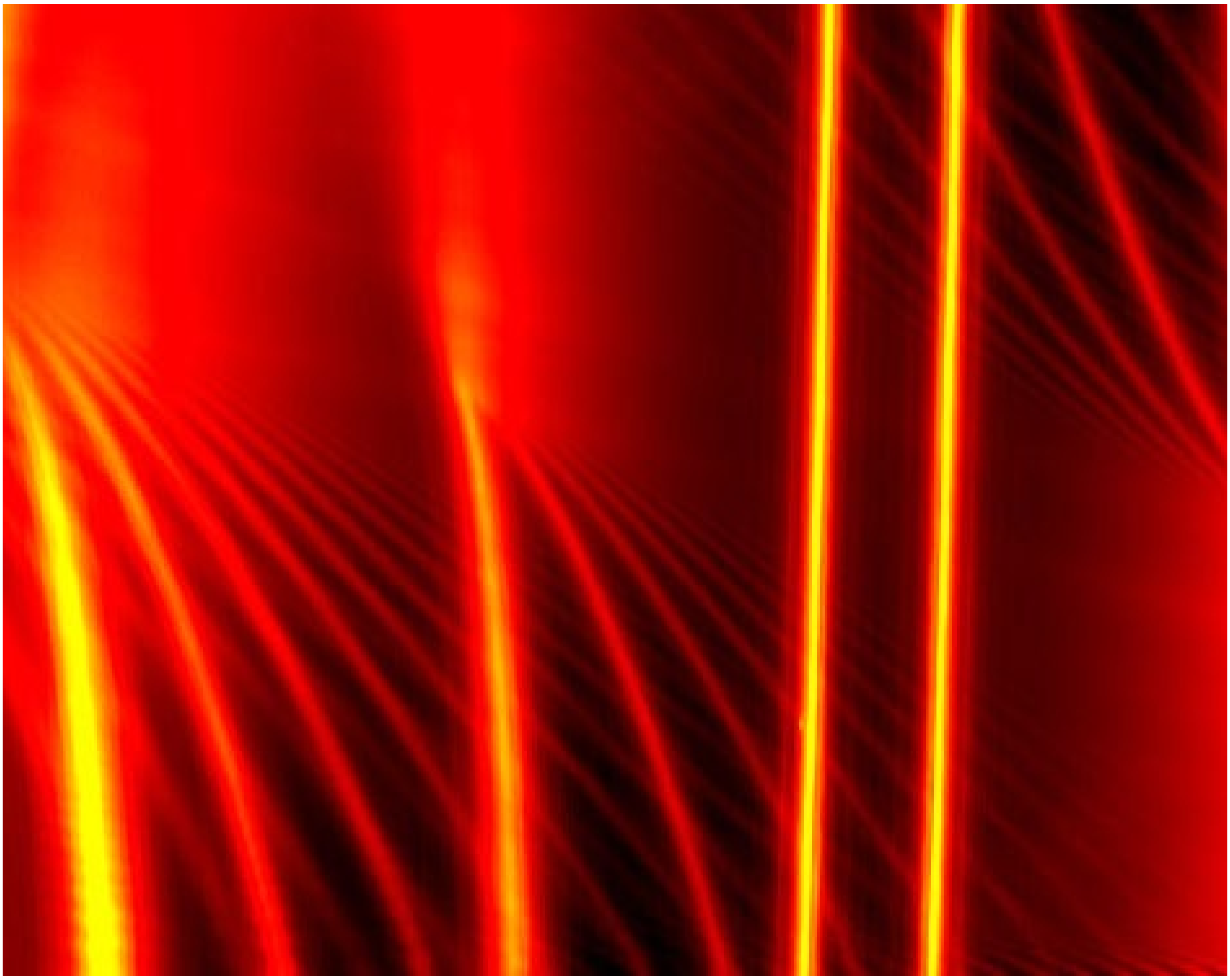
A number of research groups in Basel are studying these highly unusual materials. For example, the group led by Professor Ernst Meyer recently published measurements in Nature Materials demonstrating that significantly less heat is generated by friction in topological insulators than in conventional materials. Moreover, as part of her doctoral dissertation at the SNI PhD School, Dr. Dilek Yildiz used an atomic force microscope in pendulum mode to study the effect of friction on the surface of a topological insulator made of bismuth telluride. “As well as a very slight loss of energy to heat, we described a new quantum mechanical mechanism that allows us to control the friction precisely. This is absolutely crucial when it comes to potential applications,” says Professor Ernst Meyer.

High-resolution fingerprinting

The team led by Professor Dominik Zumbühl developed a method that could pave the way for individual examination of conductive regions in a topological insulator. Using momentum resolved tunneling spectroscopy, the scientists recently managed to create an exact fingerprint of the conductive regions of a quantum Hall system in nanometer resolution. These systems also show the formation of conductive regions at the edges (edge channels), and the researchers believe that the method will also be suitable for the detailed analysis of topological insulators.

Searching for new materials

One of the tasks of Professor Christian Schönenberger’s research group



Measured tunneling current and its dependence on the two applied magnetic fields: The fans of red/yellow curves each correspond to a fingerprint of the conducting edge states. Each individual curve separately shows one of the edge states. (Image: University of Basel, Department of Physics)

is to search for completely new materials with the properties of a topological insulator.

Within the framework of an ERC Advanced Grant, the group is investigating what are known as van der Waals heterostructures. These are stacks of two-dimensional crystals consisting of individual atomic layers of different materials held together by van der Waals forces.

“I find it fascinating that we can now produce new materials that don’t occur in nature – simply by stacking up two-dimensional crystals in an ingenious way. These crystals can exhibit completely new properties and can also become topological insulators. That’s what makes this such an exciting area of research,” says Christian Schönenberger.

We are bound to hear a great deal more about topological insulators over the coming years – and it remains to be seen whether they will ultimately be used in electronic components or play a role in the development of powerful quantum computers.