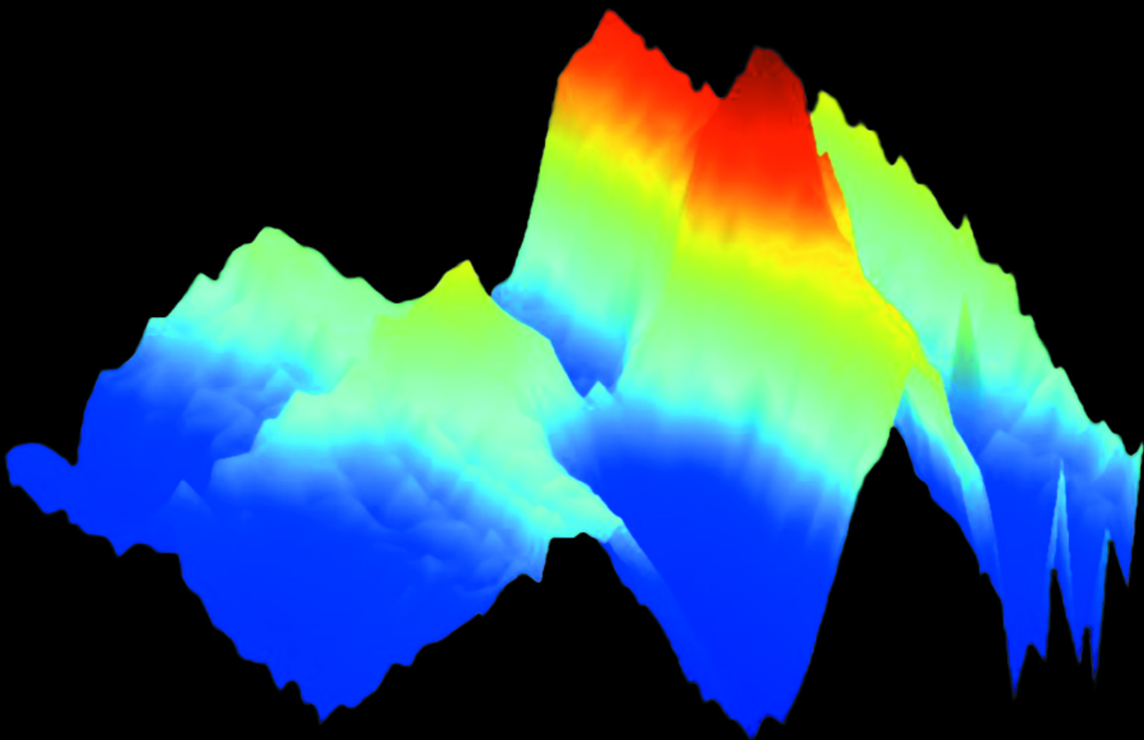
A Hall of spin

The experimental observation of the spin Hall effect could open up a new era in spintronics, as **Vanessa Sih, Yuichiro Kato** and **David Awschalom** explain



Ups and downs "Spin-up" and "spin-down" electrons accumulate on opposite sides of a sample in response to an electric current.

In 1879 Edwin Hall was a graduate student at Johns Hopkins University in Baltimore in the US studying the effects of magnetic fields on electrical currents. Contrary to what was written in his textbook, Hall's intuition told him that the magnetic field should exert a force on the current flowing through the wire, and not on the wire directly. In his paper describing the discovery Hall wrote, "A wire bearing a current is affected [by a magnet] exactly in proportion to the strength of the current, while the size and, in general, the material of the wire are matters of indifference."

Hall measured a voltage in the direction at right angles to the applied current that was proportional to the strength of the magnetic field. He realized that the Lorentz force on the electrons had caused them to drift to one side as they travelled along the wire. This excess build-up of charge created a voltage that is now known as the Hall voltage.

Today, the Hall effect is routinely used to characterize materials such as semiconductors because it provides information about the density, speed and type of charges involved in electrical conduction. Furthermore, because the Hall effect involves no moving parts it can be used to measure magnetic fields, fluid flow and pressure in devices such as car ignitions and antilock brakes without causing wear and tear. And following the discovery of the quantum Hall effect – in which the Hall voltage increases in discrete steps as the current is increased – in 1980, the Hall effect is now used to provide a calibration standard for electrical resistance. Klaus von Klitzing was awarded the 1985 Nobel Prize for Physics for this discovery.

Today, over 125 years since Edwin Hall's discovery, the Hall effect and its applications remain fertile research areas. Now, two groups have independently measured a new version of the phenomenon based on the internal angular momentum or spin of electrons. Predicted in 1971, the spin Hall effect provides a method of separating electrons with spins pointing in different directions. It is therefore an exciting development for "spintronics" – an emerging area of technology in which both the spin and charge of the electron are manipulated to create new types of microelectronic devices (see box on page 35). In particular, the spin Hall effect could allow spintronic devices to be manufactured with the same techniques that are currently used to make semiconductor devices.

Spin theory

The spin of an electron can have two discrete values, "up" or "down", and this causes the electron to behave like a tiny bar magnet. However, unlike a conventional magnet – in which the microscopic spins all point in the same direction to form a macroscopic north and south pole – the spins in non-magnetic metals and semiconductors usually point in random directions so that they

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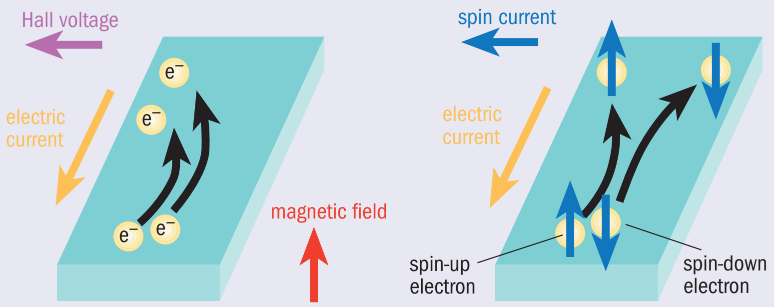
1 The Hall effects



In the classic Hall effect, electrons moving in a thin sample in the presence of a transverse magnetic field experience a force that pushes them towards one side of the sample (left). This force produces a voltage that is linearly proportional to the strength of the current and the magnitude of the magnetic field. In the spin Hall effect (right), "spin-up" electrons are deflected to the one side of the sample and "spin-down" electrons are deflected to the opposite side. This results in a spin current that is perpendicular to the direction of the electric current. No magnetic field is required to produce the spin Hall effect.

produce no overall magnetization.

In 1971 Michel D'yakonov and Vladimir Perel' of the Ioffe Institute in Russia suggested that this quantum property of electrons could lead to a new version of the Hall effect due to a phenomenon called spin–orbit coupling. This coupling arises from the principle of relativity, which explains how an electric field looks like a magnetic field from the point of view of a fast-moving electron. For instance, if the electron reverses its direction of motion, the magnetic field that it sees will also reverse direction. As a result, spin-up electrons will scatter in a different direction from spin-down electrons during collisions with impurities in the conductor, resulting in a spin current (figure 1).

The spin current proposed by D'yakonov and Perel' would therefore result in the accumulation of electron spins with different directions on opposite edges of a conducting channel, analogous to the accumulation of charge that occurs in the classic Hall effect. The term "spin Hall effect", however, was actually coined by Jorge Hirsch of the University of California in San Diego, who independently came across the same idea in 1999. Furthermore, because the process requires electrons to scatter off impurities, it is now referred to as the *extrinsic* spin Hall effect.

In 2003, however, Shuichi Murakami of the University of Tokyo and collaborators, and, the following year, Jairo Sinova of Texas A&M University and co-workers, predicted that a phenomenon called the *intrinsic* spin Hall effect should occur in addition to the extrinsic spin Hall mechanism. The idea is that the effective magnetic field due to the spin–orbit interaction produces a torque on the electron spins that can also produce a spin current. The important distinction between the extrinsic and intrinsic mechanisms is that the intrinsic spin Hall effect arises as a result of the crystal structure of the material, even in the absence of impurities, while the extrinsic spin Hall effect only occurs in the presence of impurity scattering.

The concept of the intrinsic spin Hall effect has lead to considerable discussion in the condensed-matter-physics community, and more than 50 related papers have appeared since Murakami's proposal. In spite of the long history of the theory, however, there had been no experimental confirmation of the spin Hall effect until very recently. And even then, the discovery was somewhat serendipitous.

At a Glance: Spin Hall effect

- In addition to charge, electrons possess intrinsic angular momentum called spin, which is driving a microelectronic revolution called spintronics
- In the spin Hall effect, "spin-up" electrons and "spin-down" electrons accumulate on opposite sides of a semiconductor in response to an electric current
- The phenomenon was first predicted in 1971, but there was little interest in the effect until it was rediscovered in 1999. We now know that there are intrinsic and extrinsic Hall effects
- Two experimental groups have recently observed the spin Hall effect for the first time, although it is not yet certain whether the mechanism is extrinsic or intrinsic
- The spin Hall effect enables spintronics components to be manufactured from semiconductor materials, opening up the possibility of integrated spintronic, electronic and optical devices

Experimental verification

Early attempts to measure the spin Hall effect were likely to have been made using electrical measurements with magnetic contacts in an effort to detect the accumulated spins at the edges of a sample. Although magnets have the interesting property that their electrons are spin polarized (i.e. they point in the same direction), making them a natural choice for a source or filter for electron spins, such measurements can be swamped by more pronounced effects such as magnetoresistance. Optical methods, on the other hand, offer a sensitive and local method of measuring spin polarization.

In December 2004 two of the present authors (YK and DA) and colleagues at the University of California, Santa Barbara reported the observation of the spin Hall effect for the first time. The experiment was based on an effect called Kerr rotation, whereby the polarization of a light beam rotates when the beam reflects off a material. The amount of rotation is proportional to the magnetization of the material, so by measuring the amount of Kerr rotation we can determine the relative number of spin-up and spin-down electrons present.

First, we passed a current through a slab of gallium arsenide that was cooled to a temperature of 30 K, and then scanned a focused laser over specific regions of the surface with a Kerr microscope in order to create a 2D image of the spin polarization. We were able to detect spin polarizations of just a few electron spins per cubic micron – a resolution so high that it took about 30 hours to build a map of the spin polarization across the entire device.

The outcome was astonishingly clear: spin-up electrons collected on the left-hand side of the sample with respect to the applied current and spin-down electrons collected on the right-hand side (figure 2). More than 30 years after it was predicted, the spin Hall effect had finally been observed! What was remarkable, however, was that we were not searching for the spin Hall effect at all. Instead, we had been working on another experiment where we had found a mysterious peak in the data; it was not until we had spent many days exhausting all other possible explanations that we finally turned to the spin Hall effect.

An electronic revolution

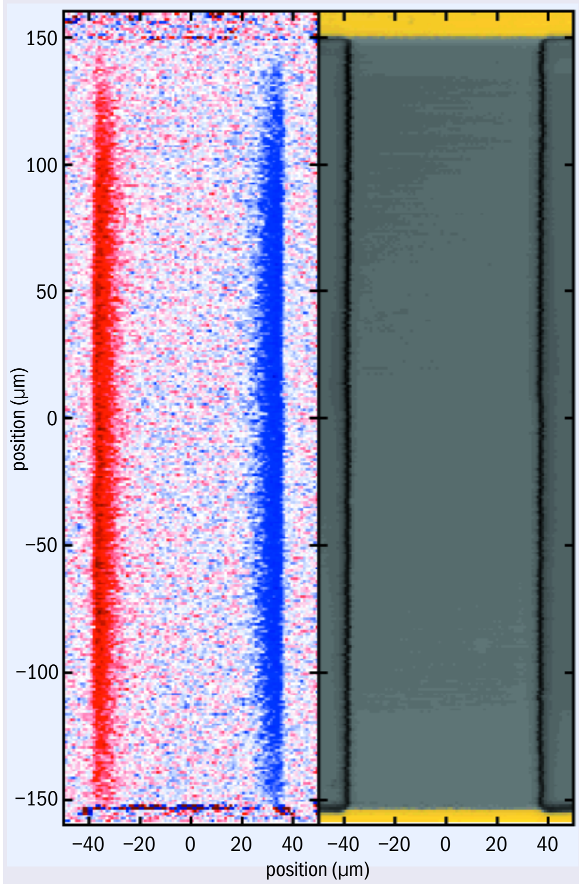
In spintronics, researchers exploit the spin of electrons as well as their electric charge to create devices with more functions than traditional electronics offers. Several applications already employ such spin-dependent effects, such as spin-valve read heads that have enabled higher data-storage densities in hard-disk drives. Another example is magnetic random access memory, which is able to store information even when all electrical power to a device is switched off.

These applications are based on metallic devices, but there is a strong interest in developing semiconductor devices for spintronics because they can be easily manufactured. Moreover, semiconductor spintronics opens up new possibilities for devices that integrate logic and magnetic storage.

For such devices to work, however, we need to find ways to inject, transport and manipulate electron spins as efficiently as possible, as well as finding ways to detect them. For example, electrons with specific spin orientations can be injected into a semiconductor from a ferromagnet, and much progress has been made in the development of magnetic semiconductors. As for transporting spin information, the challenge is to do it without disturbing the electron spin states – i.e. ensuring that they remain "coherent". The long coherence times in gallium arsenide, for example, allow spins to be dragged over distances of hundreds of microns using electric fields. As for controlling and manipulating electron spins, recent results have extended standard techniques, which employ magnetic and microwave fields, to use pulses of light, electric fields and mechanical strain.

There has also been much recent progress in detecting electron spins, particularly using optical effects. For instance, the local detection of electron spins in semiconductors is possible using polarized photoluminescence or Kerr rotation. The spin Hall effect is important in bringing semiconductor spintronics one step closer, since it enables spin polarization to be produced electrically without the use of magnetic materials. This make it more compatible with current semiconductor-device manufacturing techniques.

2 Spin opposites



In the Santa Barbara experiment the spin Hall effect was discovered using an optical technique called Kerr microscopy, which produced a 2D image of the spin polarization (left) and reflectivity (right) in a sample of gallium arsenide. Red indicates positive spin polarization, while blue indicates negative spin polarization. The reflectivity graph shows the edges of the sample (black), as well as the highly reflective metal contacts (gold).

Shortly afterwards Joerg Wunderlich of the Hitachi–Cambridge Laboratory in the UK and co-workers published an independent observation of the spin Hall effect in a 2D gas of "holes" – positively charged quasiparticles that can be thought of as missing electrons. Crucially, holes also possess spin. The Hitachi–Cambridge team used a specially designed gallium-arsenide light-emitting diode to probe spin polarization at the edges of a sample, which had been cooled to a temperature of 4.2 K. The polarization of the emitted light depends on the direction of hole spins, thereby allowing the spin polarization to be detected. Wunderlich and co-workers found that the polarization of this light changes sign for the opposing edges. The polarization also changes sign when the direction of the electrical current is reversed, which again is consistent with the spin Hall effect.

A nonmagnetic spin source

One of the most exciting aspects of these two discoveries is their implications for spintronics. Because the spin Hall effect can generate a spin current and spin polarization via an electrical current, this means that external magnetic fields or magnetic materials are not required. Such a nonmagnetic spin source can therefore be used to build devices that do not suffer from problematic "fringe" fields. It should be noted, however, that the spin polarization observed is very small (only about one electron in 10 000 is spin polarized in our experiment, for example). Furthermore, we need to study the spin Hall effect at higher temperatures before we can determine how useful it will be for prac-

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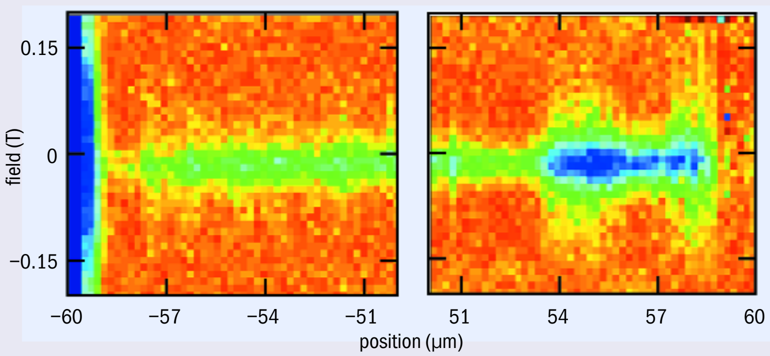
3 Spins in a 2D electron gas

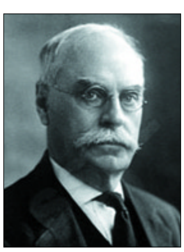


Kerr microscopy is sensitive to the amount of spin polarization in a material and allows us to image the spin Hall effect in a 2D electron gas as a function of position and the strength of an applied magnetic field. The *internal* magnetic field in this sample causes spins to be polarized throughout the channel (left), but the spin Hall effect enhances spin polarization (green and blue regions) near the right-hand edge of the sample (right).

tical spintronic devices.

Another crucial issue if we are ever to engineer and control the spin Hall effect is to determine whether the dominant effect observed is extrinsic or intrinsic. To investigate this, our group at Santa Barbara repeated our experiment with a strained indium-gallium-arsenide wafer. The strain modifies the shape of the crystal and induces an additional effective magnetic field from the point of view of the electrons, which should affect the intrinsic spin Hall effect but not the extrinsic effect. However, we found no significant change when the effective magnetic field changed, suggesting that the mechanism behind the observed spin Hall effect in our samples is extrinsic. The next step is to repeat the experiment using semiconductors with different levels of impurities.

The Hitachi–Cambridge group, on the other hand, claims that its result is of intrinsic origin because the effective magnetic fields in its sample are very large. Theoretical work has shown that the intrinsic spin Hall effect should appear when the effective magnetic fields are large enough to rotate spins within the time between scattering events in the sample, and holes are indeed subject to much larger effective magnetic fields than electrons. In addition, the Hitachi–Cambridge sample is engineered such that the holes are separated from impurities, which means that the time between scattering events is longer than the variety of samples studied by our group. The measurement of the spin Hall effect in a 2D hole gas has generated considerable interest in studying the effect in related structures, particularly to test "evolving models" of the intrinsic spin Hall effect.



Edwin Hall
The Hall effect is still pertinent today, more than 125 years since it was discovered.

Recently, the present authors and co-workers at Santa Barbara measured the spin Hall effect in a 2D *electron* gas to see whether the effect was different from what we had observed in bulk crystals. The samples had effective magnetic fields that were perpendicular to the sample plane, unlike those in the previous experiments. Using Kerr microscopy, we imaged the spin polarization due to the spin Hall effect in the presence of effective magnetic fields with surprisingly complex structures (figure 3). However, we found that the spin polarization was similar for a range of different fields, and since the orientation of the fields was out of plane, the results suggest that the dominant mechanism in this system is the extrinsic spin Hall effect.

Outlook

Theorists have responded quickly to the experimental confirmation of the spin Hall effect. Some argue that the origin is intrinsic, despite the experimental results in strained indium gallium arsenide, since there exists an effective magnetic field that does not depend on strain. Others have developed a theory that allows them to calculate the magnitude of the extrinsic spin Hall effect in order to directly compare it with the results of both the Santa Barbara and Hitachi experiments. The controversy over the dominant mechanism responsible for the spin Hall effect clearly shows that more measurements and theoretical analysis are needed before it can be fully understood.

Some of the theoretical issues concerning the spin Hall effect more generally, such as the effect of disorder and sample geometry, are also being addressed. For example, in 2004 Jun-ichiro Inoue of Nagoya University in Japan and collaborators found that the intrinsic spin Hall effect vanished when their model allowed electron scattering under certain conditions. Other groups have recently developed interesting computer simulations in order to predict how spin polarization is affected in different shaped samples, which should be testable in future experiments.

On a more practical level, the spin Hall effect offers a promising method with which to spatially separate electron spins, which makes it a solid-state analogue of a Stern–Gerlach device. This effect could be applied in the preparation, manipulation and detection of electron spin polarization in semiconductor spintronic devices. For example, one could make a simple spin-readout device, in which the direction of a transverse electrical current could be determined based on the initial spin polarization. Furthermore, the spin Hall effect provides new insights on the effects of spin–orbit coupling and the nature of spin currents and spin accumulation.

Edwin Hall's intuition may have been sharp enough to allow him to question the physics of his day, but even he could not have predicted that his namesake would still be found in leading physics journals more than a century later.

More about: Spin Hall effect

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