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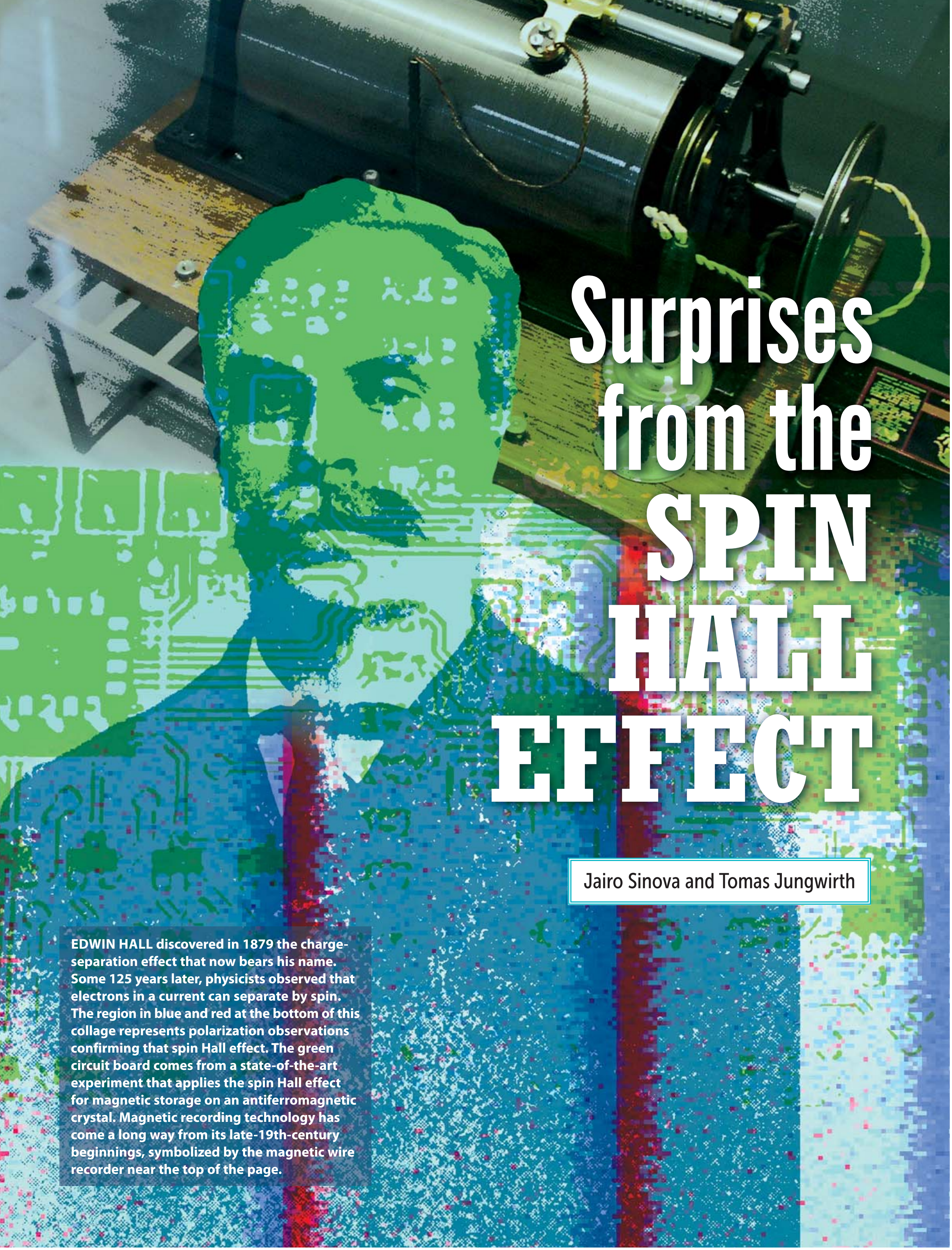
Citation: Physics Today **70**, 7, 38 (2017); doi: 10.1063/PT.3.3625
View online: http://dx.doi.org/10.1063/PT.3.3625
View Table of Contents: http://physicstoday.scitation.org/toc/pto/70/7
Published by the American Institute of Physics



Surprises from the SPIN HALL EFFECT

Jairo Sinova and Tomas Jungwirth

EDWIN HALL discovered in 1879 the charge-separation effect that now bears his name. Some 125 years later, physicists observed that electrons in a current can separate by spin. The region in blue and red at the bottom of this collage represents polarization observations confirming that spin Hall effect. The green circuit board comes from a state-of-the-art experiment that applies the spin Hall effect for magnetic storage on an antiferromagnetic crystal. Magnetic recording technology has come a long way from its late-19th-century beginnings, symbolized by the magnetic wire recorder near the top of the page.

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The spin Hall effect and its companion, the inverse spin galvanic effect, have evolved from topics of academic interest to efficient means for fabricating microelectronic magnetic memories.

Science often surprises us. An idea that seems only of academic concern sparks a thought that cascades into new directions, and every so often, one of them leads to a transforming technology. Without the first basic-science step, such a process would be impossible. The spin Hall effect (SHE) is a fascinating example of that scientific multibranching process that also demonstrates how fundamental research is essential for future technology.

The effect is relatively easy to describe. When current flows in a nonmagnetic solid, the moving electrons can feel a spin-dependent deflecting force perpendicular to their velocity. That force drives spin-up electrons predominantly to one side and spin-down electrons predominantly to the other. The result, as illustrated in figure 1a, is a spin current perpendicular to the charge current.

Russian physicists Mikhail Dyakonov and Vladimir Perel first proposed[1] the SHE in 1971. They combined ideas from two sources. One was the anomalous Hall effect, by which a charge current experiences a transverse deflection even absent an external magnetic field. The second was the spin-dependent Mott scattering of electrons off nuclei. In 1929 Nevill Mott recognized that observations of that sort of electron scattering could serve as the first fundamental test of the existence of spin and of the validity of its underlying relativistic quantum theory as described by the Dirac equation.

Mott scattering, the SHE, and a companion effect called the inverse spin galvanic effect (ISGE; see figure 1b) all derive from relativistic spin–orbit coupling. When an electron traverses an electric field, it feels in its own reference frame an effective magnetic field that couples to its spin. That magnetic field is proportional to the cross product of the velocity and the electric field that pushes the electron.

The prediction of the SHE lay dormant for almost three decades. It was revived by Jorge Hirsch,[2] who brought the effect back to light in 1999, and by two groups who, in 2003, suggested that the phenomenon could be intrinsic to a given material—that is, independent of scattering details.[3,4] The effect was observed in 2004 by two teams working with gallium arsenide. (See PHYSICS TODAY, February 2005, page 17.) Yuichiro Kato, Roberto Myers, Arthur Gossard, and David Awschalom used electron-doped GaAs and probed the material's magnetization by monitoring the polarization of reflected light, a technique called Kerr microscopy.[5] We joined Jörg Wunderlich and Bernd Kästner to use the polarized light emission from a GaAs LED to detect the SHE in the hole-doped part of a p–n junction.[6] Subsequently the SHE was observed in metals, and now there are various materials in which the effect can be explored and applied[7]—the most popular choices for metals are platinum, tantalum, and tungsten.

The discovery of the SHE spawned explorations of spin- and charge-based phenomena that are closely intertwined through relativistic quantum physics. Known as spin-orbitronics, those new research directions have come at a furious pace over the past decade. They contributed to the discovery of topological insulators, materials that are insulators in the bulk, that can conduct along their edges, and that exemplify so-called topological matter. (See PHYSICS TODAY, January 2008, page 19.) Even the search in solid-state environments for Majorana fermions, particles that are their own antiparticles, is linked to

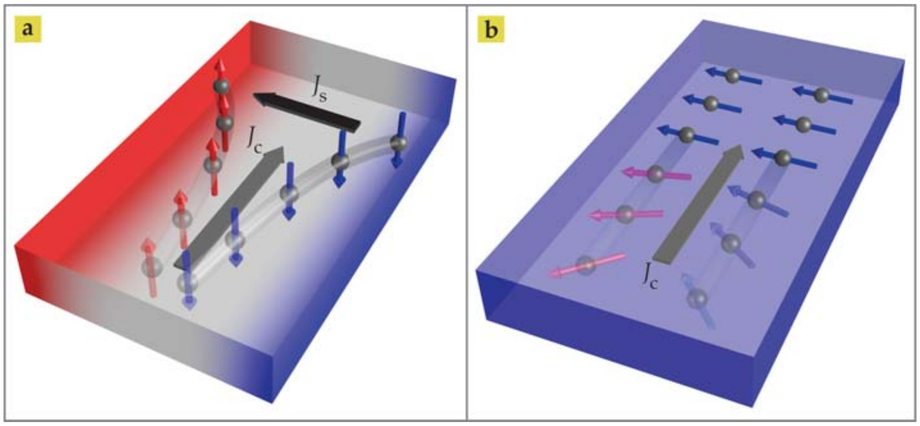

FIGURE 1. SPIN SEPARATION AND ALIGNMENT. In the spin Hall effect, **(a)** spin-dependent deflections due to spin–orbit coupling generate a spin current, J_s (black arrow), transverse to a charge current, J_c (gray arrow). The spin polarization is perpendicular to the plane defined by the charge and spin currents. In the inverse spin galvanic effect, **(b)** a charge current generates an in-plane, nonequilibrium polarization perpendicular to the current. The phenomenon often accompanies the spin Hall effect.

the quantum limit of the SHE. That endeavor in particular has prompted researchers to reexamine the importance of spin–orbit coupling in many areas of solid-state physics.

Topological insulators and Majorana fermions represent now fully fledged fields that most physicists have heard about. But many may not be aware of the surprising path that the SHE has taken from a purely academic subject to a practical tool for magnetic random access memories (MRAMs) and for antiferromagnetic spintronics. That outcome beautifully exemplifies how investing in basic science can pay dividends for future technologies.

The path that took us from the origin of the spin Hall effect to the present day is as inspiring as it was impossible to predict.

Writing in the 21st century

Recording technologies come and go, but magnetic recording is a keeper. The magnetic wire recorder was conceived in 1878, a year after Thomas Edison's invention of the phonograph, and was realized two decades later. It evolved into the tape recorder and hard disk drive. It also led to magnetic core memory, whose run as the main type of random access storage lasted from the mid 1950s to the mid 1970s and whose resistance to radiation damage made it vital for space exploration and the shuttle program. All those devices relied on 19th-century physics: Maxwell's equations.

Nowadays magnetic recording enables an hour of video to be uploaded onto the internet every second of every day, and few of us worry about the physical limits of data storage. For today's magnetic recording needs, 20th-century spintronics is essential. It helps readout in a decisive way via giant magnetoresistance and tunneling magnetoresistance, spin-dependent phenomena found in structures of alternating ferromagnetic and nonmagnetic conducting or insulating layers. For giant and tunneling magnetoresistance, the resistance of a device depends dramatically on whether the magnetization of adjacent ferromagnetic layers is parallel or antiparallel. Thanks to those phenomena, read heads are more sensitive and more information can be packed onto hard drives. They also paved the way for a transition from solid-state core memories with macroscopic magnetic bits to microelectronic MRAM chips.

For writing, hard drives and commercial MRAMs still rely on 19th-century physics involving the coupling between an electromagnet used for writing and a permanent magnet that provides storage. Revisiting the means of writing magnetic information on MRAMs had to wait for the 21st century, when researchers began to explore the possibility of using a scalable electrical approach rather than relying on an external magnetic field. Figure 2 depicts the modern MRAM architecture.

The earliest 21st-century variant, illustrated in figure 3a, exploits a phenomenon called spin-transfer torque (STT). Spin-polarized carrier electrons pass from a reference ferromagnetic layer through a spacer to an adjacent recording ferromagnetic film. There, under the action of a weak reading current, they can probe the magnetic state of the bit. Or, if a stronger writing current is applied, they can transfer angular momentum to the magnetic bit, thus exerting a torque that switches it. MRAMs utilizing STT are already in early stages of production,[8] and the technology was recognized for its potential for nonvolatile main computer memories in the 2014 Magnetism Roadmap, a review written by international experts and intended to guide emerging research directions in magnetism.[9] (A nonvolatile memory can retrieve information even after the computer has been turned off and back on.)

Unfortunately, STT has a significant drawback: The writing current has to flow through the high-resistance, thin spacer, which can overheat and damage the bit. The SHE and its companion, the ISGE, came to the forefront a few years ago with the concept of spin–orbit torque (SOT), a means of overcoming the limitations of STT. Spin–orbit torque gets its name because it is relativistic spin–orbit coupling that leads to the torque felt by the recording ferromagnet.

Figures 3b and 3c show the SHE and ISGE variants of the mechanism. Note that in both cases, the MRAM bit now includes a thin, heavy-metal layer between the recording ferromagnet and the conducting contact. Heavy metals maximize the effects of spin–orbit coupling and thus are preferred for applications of the SHE and the ISGE.

In the first variant (figure 3b), as currents flow along the contact and the heavy-metal layer, the SHE generates a spin current that flows upward into the recording ferromagnet; the SHE effectively turns the heavy-metal layer into a spin injector. The switching of the recording ferromagnetic bit is then due to a transfer of spin angular momentum from carriers to magnetization as in STT.[7,10,11] In the ISGE variant (figure 3c), a charge current generates a nonequilibrium spin polarization at the interface between the heavy-metal layer and the ferromagnet, rather than a spin current. The current-induced polarization can switch the ferromagnetic bit.

We emphasized above that spin–orbit coupling must be present for either the SHE or ISGE mechanism to work. In addition, it turns out that inversion symmetry must be broken.[10–13] In typical applications, the breaking is achieved, as in figures 3b and 3c, by a bilayer structure involving the heavy metal and the recording ferromagnet. In such architectures, the SHE and the ISGE are often inseparable companions. Their relative contributions to SOT depend on the details of the materials and the interface between the heavy metal and recording ferromagnet.

The application of the SHE and the ISGE to SOT is an amazing turn of events in the world of spin–orbit coupling. Many physicists had thought of spin–orbit coupling as an effect that destroys spin polarization by facilitating spin-flip scattering. However, with the SHE and the ISGE, the whole thing is turned around: Via spin–orbit coupling, the lattice generates spin polarization instead of destroying it. Remarkably, SOT can be even more efficient than STT in the sense that SOT switching can be faster and can require less current. Those features make SOT particularly attractive for fast processor memories and suggest that SOT will be a technology at the top level of the computer memory hierarchy.

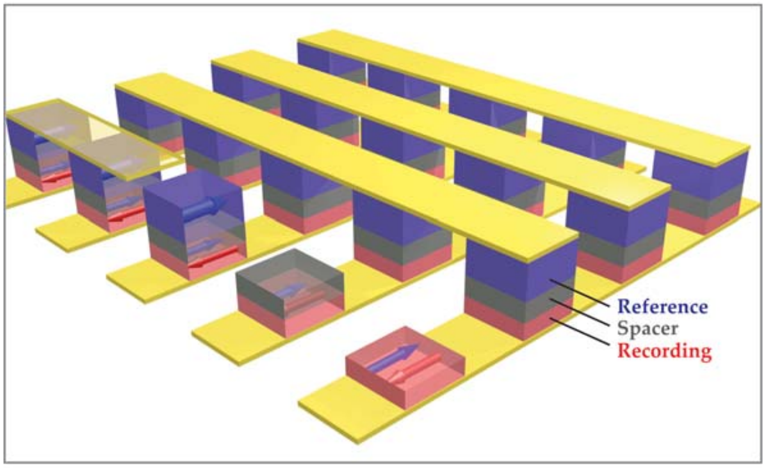

FIGURE 2. TWENTY-FIRST CENTURY MRAM. The modern magnetic random access memory comprises myriad bits, each of which includes a reference magnetic layer separated from a recording ferromagnet by a nonmagnetic spacer. The reference layer is static, but the recording ferromagnet is switchable, as indicated by the two directions of spin arrows.

What is the source of SOT's superior switching? In STT, each electron can transfer only one quantum unit of spin angular momentum as it travels from the reference ferromagnet to the recording ferromagnet. In the SHE and ISGE writing mechanisms, each scattering of a carrier electron generates a small

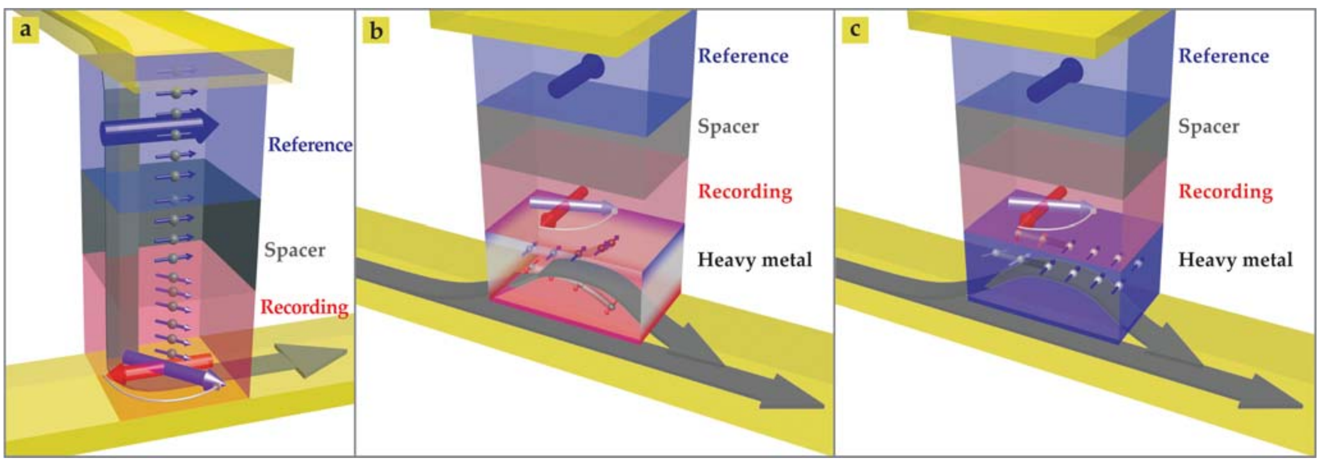

FIGURE 3. FLIPPING THE BIT. In the spin-transfer torque mechanism, **(a)** a current (gray arrow) of polarized electrons from a reference ferromagnet passes down through a spacer into a recording ferromagnet. Within a few atomic monolayers of entering the recording magnet, the flowing electrons align with the instantaneous recording magnetization (large purple arrow in the recording medium). This alignment results in a torque (curved white arrow) on the recording ferromagnet that ultimately causes the recording magnetization to flip from its original orientation (large red arrow). In the snapshot shown here, the recording magnetization is about ⅔ of the way to being flipped. Note that the time scale for the full reversal is much greater than the time needed for the current to flow from the reference ferromagnet through the recording ferromagnet. A second mechanism, spin–orbit torque, can be driven by the spin Hall effect (SHE) or by the inverse spin galvanic effect (ISGE). **(b)** In the SHE variant, as current flows along the contact and the heavy-metal layer, a spin current is generated that flows upward into the recording ferromagnet and flips its magnetization. **(c)** In the ISGE mechanism, electrons become polarized at the interface of a heavy metal and a ferromagnet; the polarized electrons then switch the magnetization of the recording ferromagnet. In structures such as those shown in panels b and c, with heavy-metal and ferromagnetic recording layers, both the SHE and the ISGE contribute to spin–orbit torque.

amount of polarization, thanks to spin–orbit coupling. Hence, with every scattering event, the carrier electron applies a small amount of torque to the recording ferromagnet. SOT replaces STT's large one-time push with many small pushes to switch the recording magnetization.

With SOT, the recording magnet reverses its magnetic moment with no need for a reference ferromagnet. A coordinated sequence of angular-momentum-conserving processes flips the bit. The magnet is thus like a falling cat, which manages angular momentum along its body to flip itself and land safely on its feet without violating a sacred conservation law.

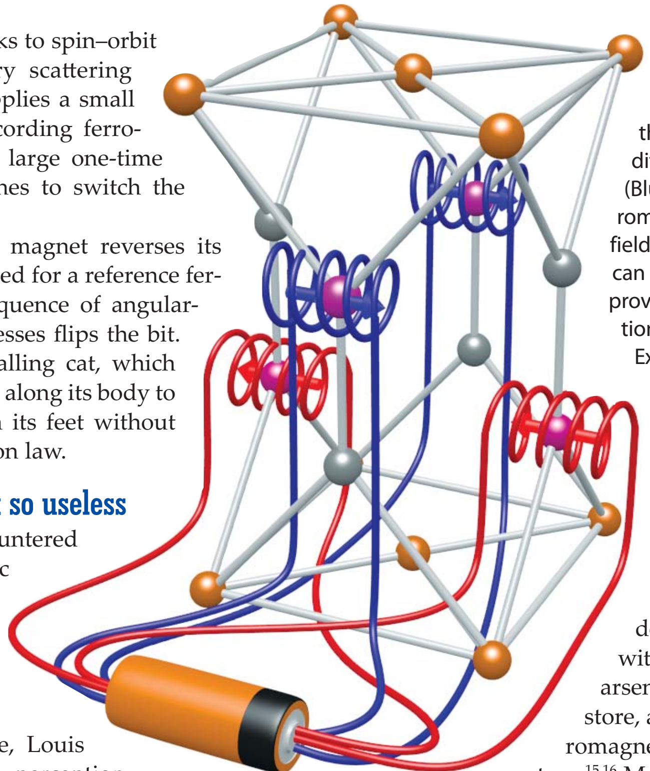

FIGURE 4. ATOMIC-SCALE solenoid. This fanciful solenoid generates a staggered magnetic field that points in different directions at different atoms in an antiferromagnet. (Blue and red arrows indicate the antiferromagnet's antiparallel spins.) Effective fields created through spin–orbit torque can act in an equivalent way and thus provide the means for efficient manipulation of the antiferromagnetic moments. Experiments have already demonstrated that electrical writing pulses enable reliable switching between distinct antiferromagnetic memory states that can be read electrically.[14–16]

Antiferromagnets are not so useless

The latest twist we have encountered in the intertwined academic and applied paths of the SHE and the ISGE points toward the prospect of making antiferromagnetic microelectronic memories a reality.

In his 1970 Nobel lecture, Louis Néel expressed the common perception that antiferromagnets, whose existence he had predicted, are interesting but useless. Antiferromagnets are magnetically ordered materials in which the spins alternate being up or down from one atom to the next; as a result, their total magnetization vanishes. That lack of magnetization is the key reason why, unlike for a ferromagnet, an antiferromagnet's spin orientation cannot be easily manipulated by an external magnetic field and why Néel did not see antiferromagnets as being useful for applications. On the other hand, if one could manipulate them efficiently, antiferromagnets would have inherent advantages over ferromagnets. They would be natural materials for nonvolatile, radiation- and magnetic-field-insensitive technologies; neighboring bits would not disturb each other because of the absence of stray fringing fields; and the resonance frequencies setting the limit to writing speed would be in the terahertz range, as opposed to the gigahertz frequencies relevant for ferromagnetics.

To efficiently reorient the spins in an antiferromagnet, an applied field would somehow have to alternately flip directions at an atomic scale. Figure 4 shows a playful depiction in which hypothetical atomic-scale solenoids wrap around atoms in an antiferromagnetic crystal and generate opposite magnetic fields on opposite spin sublattices. (A spin sublattice comprises spins that are all directed the same way.) Over the course of a nearly 100-year history of investigation, researchers did not imagine a feasible mechanism for generating the fanciful solenoids' staggered fields. But lessons learned from the SHE and the ISGE have changed that.

It turns out that efficient SOTs generated by the SHE or the ISGE are not limited to magnets with ferromagnetic order. In 2014 we and colleagues proposed that in antiferromagnets with a particular symmetry, the effective fields induced by the SHE or the ISGE can flip the directions of the antiferromagnetic spin sublattices.[14] Spin–orbit coupling thus provides a uniquely efficient means for the manipulation of antiferromagnetic moments.

Last year the proposal was demonstrated. Investigators working with a single-crystal copper manganese arsenic film showed they could write, store, and read information on an antiferromagnetic memory cell at room temperature.[15,16] Moreover, the expected ability to use picosecond-long writing pulses has been verified. Those successes, combined with the structural and fabrication compatibility of the CuMnAs antiferromagnet with silicon and common microelectronic circuitry, have opened a new chapter in the R&D story of magnetic memories. This new research direction inspired by antiferromagnetic memory will be acknowledged in the upcoming 2017 Magnetism Roadmap.

Antiferromagnetic spin-orbitronics, just taking its first steps, is sure to open many new paths. Apart from memory-logic devices, antiferromagnets have an unparalleled potential to facilitate synergies of spintronics with other highly active fields of condensed-matter physics, such as investigations of topological matter.[17] The path that took us from the origin of the SHE to the present day is as inspiring as it was impossible to predict. What we can foresee with almost absolute certainty is that we have not seen the last of its twists and turns.

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