

Viewpoint

Controlling Magnetism with a Flip of a Switch

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Nanoscale engineering of multiferroic thin films enables electric control of a device's interface magnetism, thus offering a promising prospective for ultralow power spintronics.

Subject Areas: **Magnetism, Nanophysics, Electronics**

A Viewpoint on:

Full Electric Control of Exchange Bias

S. M. Wu, Shane A. Cybart, D. Yi, James M. Parker, R. Ramesh, and R. C. Dynes

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Controlling magnetism solely by electrical means is a long-standing scientific challenge receiving ever-increasing attention over the last decade [1]. Electrically controlled magnetism is significant both fundamentally, as it brings together disparate elements of condensed-matter physics, and practically, in that it opens up the prospect of new devices with unprecedented performance [2]. The remarkable progress in this field sparks visions of novel spintronic applications combining memory and logical functionality at high processing speed and ultralow power consumption. A major step in this development is the first demonstration of electric control of the magnetic exchange bias in zero applied magnetic field [3]. This work—reported by Stephen Wu of the University of California, Berkeley, and his colleagues in *Physical Review Letters*—represents the culmination of an impressive effort to tailor the properties of multiferroic materials that combine magnetic and electric polarization.

An applied electric field can't directly affect an electron's magnetic moment. Instead, electric control of magnetism in a material is ruled by spin-orbit coupling, in which an electron's spin orientation (a contributor to the magnetism) depends on its orbital angular momentum (which is responsive to electric fields). Unfortunately, spin-orbit coupling is typically a small effect, making electric switching of collective magnetic states far more challenging than conventional magnetic-field control of magnetization [2]. One way to exert electric control of magnetism is to use materials that not only have a permanent magnetic polarization (ferromagnetism) but also a permanent electric polarization (ferroelectricity). If a coupling exists between the ferroelectric (FE) order and the ferromagnetic (FM) order, then an electric field E can, through its influence on the FE polarization P , control and potentially switch the magnetization M , giving rise to a magnetoelectric (ME) effect. Sizable magnetoelectricity provides a pathway towards dissipationless voltage control of magnetic states.

The simultaneous presence of at least two ferroic order parameters in a single-phase material has been termed intrinsic multiferroicity. However, finding this desired property at room temperature, in conjunction with substantial ME coupling, remains elusive. Nanoengineering of multiferroic materials strives to design sizable order-parameter couplings to enable magnetization response on an applied electric field and, conversely, polarization response on an applied magnetic field. One material that has benefited from nanoengineering is BiFeO₃ (bismuth ferrite, or BFO for short). This compound is multiferroic, but its bulk form has practically no applications due to a weak order-parameter coupling. It is only for thin films of BFO—realized after decades of progress in nanofabrication capabilities—that some of the desired functionality begins to appear [see the timeline in Fig. 1(a)].

The two ferroic orders in BFO are a FE polarization P , and an antiferromagnetic (AF) order η . Despite the high FE and AF ordering temperatures ($T_C = 1103$ K and $T_N = 643$ K, respectively), there is no appreciable P - η coupling in bulk BFO, and the polarization is surprisingly weak. The situation changes drastically in BFO epitaxial thin films [4], in which the polarization increases, the P - η coupling becomes sizable, and a weak FM moment with magnetoelectric P - M coupling evolves. The ferromagnetic order appears because the thin-film geometry suppresses incommensurate long-wavelength spiraling of η , which normally quenches the FM moment in the bulk. In addition, symmetry reduction in heteroepitaxially grown BFO films partially lifts the degeneracy of the otherwise large number of FE and AF domains. The simplified domain structure and η -spiraling suppression give BFO thin films two channels for electric control of magnetism: one through P - η coupling, with its rigid alignment of η relative to P , and the other through P - M coupling between the polarization and the weak FM moment.

Wu and colleagues have taken advantage of the P - η coupling in BFO thin films to create a device with

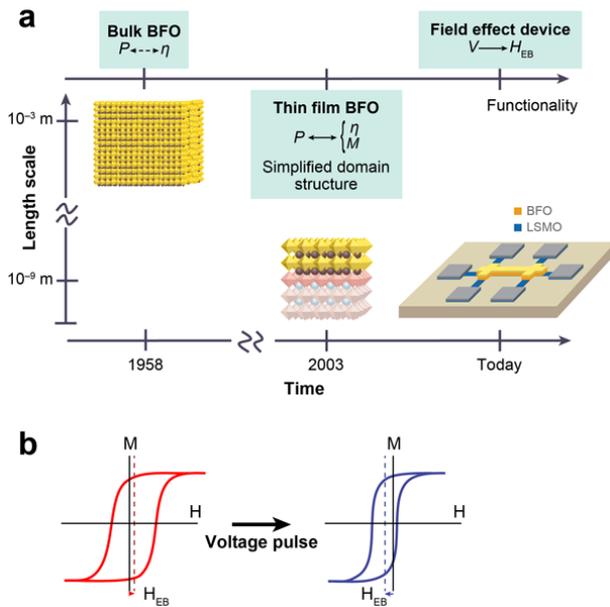


FIG. 1: (a) Timeline of selected milestones in BFO development. Progress in functionality (upper horizontal axis) is mapped against the evolution of characteristic structure sizes (vertical line). The transition from bulk crystals to thin films strengthened order-parameter couplings, reduced domain complexity, and added a weak ferromagnetic moment. Current device development, based on a nanoscale BFO/LSMO exchange bias bilayer, enables voltage control of the exchange bias field H_{EB} . (b) Graphical description of the voltage-controlled exchange bias effect. The LSMO exchange bias field H_{EB} (vertical dashed lines) shifts from a positive (left) to a negative (right) bias when a voltage is applied to the adjacent BFO layer. (APS/Christian Binek/Carin Cain)

voltage-controlled exchange bias [3]. Exchange bias is an emergent interface phenomenon of adjacent FM and AF thin films that are coupled through quantum-mechanical exchange. In the proximity of the AF “pinning layer,” the FM film experiences unidirectional magnetic anisotropy, which exhibits itself in a shift of the FM hysteresis loop along the magnetic field axis by the exchange bias field H_{EB} [see Fig. 1(b)]. Exchange bias is an important mechanism for a large class of today’s passive spintronic devices. Magnetic read heads, for instance, utilize tunnel magnetoresistance, in which exchange bias pins the magnetization orientation of a reference FM layer relative to a FM sensing layer.

The exchange bias is set during fabrication of the FM and AF films, and it usually remains fixed. However, providing voltage control over exchange bias is a key component of many proposed spintronic devices, such as ultralow power, nonvolatile memory devices that perform logic operations [5]. Typically, this involves flipping the direction of AF interface spins in an exchange bias bilayer with an electric field. The archetypical ME pinning layer utilized for voltage-controlled exchange bias is AF chromia ($\alpha\text{-Cr}_2\text{O}_3$) [6]. Despite the smallness of its

linear ME effect, isothermal voltage control of exchange bias has been achieved in $\text{Cr}_2\text{O}_3/\text{CoPd}$ at room temperature [7]. Here, nonlinear reversal of AF interface magnetization has been exploited for bipolar switching of H_{EB} . A weakness of this approach lies in the need for a small symmetry-breaking magnetic field H . Wu *et al.* break new ground by achieving, for the first time, electric isothermal control of exchange bias in the absence of an applied H field [3].

In their experiment, a voltage pulse stimulates reversible bipolar switching of H_{EB} [Fig. 1(b)]. This breakthrough became possible in a nanofabricated device where a laser-deposited thin film of BFO and a metallic FM layer of $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO) form an exchange bias heterostructure [lower right of Fig. 1(a)]. The voltage pulses control the polarization of the BFO pinning layer, which couples to the AF order parameter and thus affects the AF interface magnetization. Ultimately, exchange coupling at the BFO/LSMO interface leads to a shift in the LSMO exchange bias field.

This electrical switching of the exchange bias is a first step towards full control of magnetism with electric fields. Voltage-controlled magnetism can be superior to magnetization switching with electric currents—both traditional currents (that alter magnetization through magnetic field generation) and spin-polarized currents (that alter magnetization through spin-torque transfer). Voltage control minimizes electric power consumption and the production of Joule heat. Heating through dissipation represents the major bottleneck for advances in integrated electronics based on complementary metal-oxide-semiconductor (CMOS) technology. For more than four decades, CMOS technology followed Moore’s “law” through scaling, creating ever smaller feature sizes. At some point, however, the separations become so small that quantum-mechanical tunneling begins to produce unacceptable levels of heat. Spintronic technology utilizing voltage-controlled magnetism is a promising solution for the CMOS scaling dilemma.

The bipolar, fully electric control of exchange bias demonstrated by Wu *et al.* is among the most sophisticated realizations of voltage-controlled magnetism today. After the humble beginnings with bulk BFO, today’s nanoengineered BFO films provide ME functionality to realize field-effect devices. However, more work is needed to utilize BFO for room-temperature spintronic applications. Alternatives to BFO, and multiferroics in general, exist and should not be overlooked. For example, the nanoengineering of ME antiferromagnets with voltage-controllable boundary magnetization is just in its infancy and promises potential for voltage-controlled spintronics [7]. In addition, new room-temperature single-phase bulk multiferroics with large effective ME coupling have emerged [8]. Polarization switching of FE barriers in tunnel junctions with FM electrodes allows for ME control of spin transport [9], and electric field-pulses switch magnetization in ultrathin magnetic films through control of magnetocrystalline anisotropy [10]. In light of those rep-

representative achievements, one can expect a bright future for voltage-controlled magnetism and its spintronic applications.

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Christian Binek is Associate Professor in the Department of Physics and Astronomy at the University of Nebraska-Lincoln, USA. He received his Ph.D. in Germany at the University of Duisburg-Essen in 1995, followed by a Habilitation in 2001. His main research interests lie in magnetic interface effects, with special emphasis on electrically controlled magnetism and spintronics, as well as fundamental thermal physics. Dr. Binek is currently Visiting Professor at the Nanoscience Cooperative Research Center (nanogune) in San Sebastian, Spain.