npj | spintronics

Editorial

https://doi.org/10.1038/s44306-025-00077-0

Revolutions of multiferroic materials

Multiferroic materials, which simultaneously exhibit ferroelectric and magnetic orders, provide a unique platform to explore the interplay between charge and spin degrees of freedom for spintronics applications. These materials enable novel functionalities and applications, making them a focal point of research in condensed matter physics and materials science. This Editorial highlights current stage of multiferroic research and discusses future directions in this rapidly evolving field.

Multiferroic materials have captivated researchers for over two decades due to their unique ability to couple electric and magnetic properties, a phenomenon known as multiferroic coupling. This coupling enables exotic interactions, such as electric-field control of magnetism and magnetic-field control of electric polarization, with significant potential for technological applications[1]. Our collection, *Multiferroics for spintronics*, aims to highlight latest breakthroughs and progress where the fundamental physics and materials science of magnetoelectric and multiferroic phenomena intersect with the discovery of novel functionalities for spintronics applications.

The interplay between electric and magnetic order parameters in multiferroics is governed by crystal symmetry and the interactions between spin and lattice degrees of freedom. In Type-I multiferroics, such as bismuth ferrite ($BiFeO_3$)[2], ferroelectricity and magnetism arise from distinct mechanisms and result in weak coupling. In contrast, Type-II multiferroics, like rare-earth manganites (e.g. $TbMnO_3$[3]), exhibit ferroelectricity induced by magnetic order, leading to strong coupling between the two order parameters. Recent advancements include the discovery of new materials with enhanced magnetoelectric performance through epitaxial strain[4] and atomic-scale material design[5], and the ability to manipulate antiferromagnetic domain structures in $BiFeO_3$ using electric fields[6]. Another promising approach is the realization of multiferroic behavior in heterostructures, where engineered interfaces between ferroelectric and ferromagnetic materials exhibit strong magnetoelectric effects, enabling electric-field control of magnetization. Despite these advances, challenges remain for spintronics applications, including weak magnetoelectric coupling at room temperature, limited material choices, and difficulties in integrating multiferroics into nanoscale devices[1]. These limitations have spurred researchers to explore new directions, such as discovering materials with enhanced magnetoelectric coupling and developing novel concepts to achieve stronger coupling. Emerging materials are expected to overcome these challenges while opening new frontiers in quantum and spintronics materials research.

The discovery of two-dimensional materials, such as graphene and transition metal dichalcogenides, has revolutionized condensed matter physics and this trend is now extending into multiferroics. Although research on two-dimensional multiferroics is still in its early stages, initial findings of type-II multiferroic order in a single atomic layer compound suggest that reduced dimensionality can enrich the design platform to achieve enhanced coupling between electric and magnetic order parameters[7]. Furthermore, the flexibility and tunability of 2D materials also make them ideal for integration into flexible electronics and van der Waals heterostructures. Beyond traditional insulating or semiconducting multiferroics, a new class of materials known as ferromagnetic polar metals has been recently discovered[8,9]. These materials combine magnetic order and polar structural distortions, which break both time reversal and space inversion symmetries, with a similar fashion as conventional insulating multiferroic materials, while in exotic metallic systems. Therefore, such system offers a unique platform to explore the interplay between magnetoelectric coupling and metallicity, which might have profound implications for next-generation spintronic and magnetoelectric devices.

In addition to static coupling, the dynamic behaviors of multiferroic systems have garnered significant attention as well. Spin waves, or magnons, are collective spin excitations that propagate through magnetic materials without the motion of electrons. Recent advances have also demonstrated electric-field controlled magnon propagation in multiferroic bismuth ferrite[10,11], highlighting their potential for low-power, high-speed magnonic devices. A recent work has realized an exotic room temperature magnetoelectricity in $SrTiO_3$, through a coherently controlled lattice vibrations triggered by intense circularly polarized terahertz electric field[12], which sparks research interests of multiferroicity into an ultrafast (~ps) domain.

The field of multiferroic materials is undergoing a transformative phase, driven by the emergence of two-dimensional multiferroics, magnetic polar metals, magnonic devices and ultrafast-manipulated multiferroic materials. Future work will likely focus on discovering materials with enhanced properties, exploring novel correlated coupling phenomena between polarity and magnetism, designing new device architectures based on magnetic/structural excitations, and integrating multiferroic materials with other quantum materials, such as topological insulators and superconductors. As research into multiferroic materials continues, it is evident that the field holds immense potential for new discoveries and applications in spintronics. We are just starting to explore the profound physics and vast potential of these materials, with groundbreaking advancements in science and technology poised to emerge in near future.

Pu Yu[1,2] ✉
[1]State Key Laboratory of Low-Dimensional Quantum Physics and Department of Physics, Tsinghua University, Beijing, China. [2]Frontier Science Center for Quantum Information, Beijing, China.
✉e-mail: yupu@tsinghua.edu.cn

Published online: 27 March 2025

References

1. Spaldin, N. A. & Ramesh, R. Advances in magnetoelectric multiferroics. *Nat. Mater.* **18**, 203–212 (2019).
2. Wang, J. et al. Epitaxial BiFeO3 multiferroic thin film heterostructures. *Science* **299**, 1719–1722 (2003).
3. Kimura, T. et al. Magnetic control of ferroelectric polarization. *Nature* **426**, 55–58 (2003).
4. Lee, J. H. et al. A strong ferroelectric ferromagnet created by means of spin-lattice coupling. *Nature* **466**, 954–958 (2010).
5. Mundy, J. et al. Atomically engineered ferroic layers yield a room-temperature magnetoelectric multiferroic. *Nature* **537**, 523–527 (2016).
6. Heron, J. et al. Deterministic switching of ferromagnetism at room temperature using an electric field. *Nature* **516**, 370–373 (2014).
7. Song, Q. et al. Evidence for a single-layer van der Waals multiferroic. *Nature* **602**, 601–605 (2022).

8. Zhang, J. et al. A correlated ferromagnetic polar metal by design. *Nat. Mater.* **23**, 912–919 (2024).
9. Zhang, H. et al. A room temperature polar magnetic metal. *Phys. Rev. Mater.* **6**, 044403 (2022).
10. Huang, X. et al. Manipulating chiral spin transport with ferroelectric polarization. *Nat. Mater.* **23**, 898–904 (2024).
11. Chai, Y. et al. Voltage control of multiferroic magnon torque for reconfigurable logic-in-memory. *Nat. Commun* **15**, 5975 (2024).
12. Basini, M. et al. Terahertz electric-field-driven dynamical multiferroicity in SrTiO3. *Nature* **628**, 534–539 (2024).