



Molecular ferroelectric altermagnetism by design

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Spintronics exploits magnetic order parameters to encode binary information and utilizes spin-dependent transport for data processing [1]. To date, most spintronic devices have been based on ferromagnetic materials, which offer straightforward information writing and reading through manipulation and detection of their magnetization. A prototypical device is the magnetic tunnel junction (MTJ), where non-volatile memory readout is achieved via the tunneling magnetoresistance (TMR) effect—distinct resistance states arising from parallel and antiparallel alignments of ferromagnetic electrodes. MTJs serve as the building blocks of magnetic random-access memories (MRAMs), which have already found commercial applications.

Recent efforts have focused on improving energy efficiency and speed of magnetic switching in such devices. Conventional methods for magnetic switching—such as external magnetic fields or spin torques—require substantial electric currents and thus suffer from high energy dissipation. Voltage-controlled magnetic switching offers a promising route toward low-power spintronics. However, electric fields preserve time-reversal symmetry and therefore cannot directly reverse magnetization. This has driven interest in multiferroic materials, where magnetization is coupled to ferroelectric polarization and can be manipulated via the magnetoelectric effect. Yet, practical room-tempera-

ture multiferroics with strong coupling remain elusive.

The speed of magnetic switching is fundamentally tied to the dynamics of the magnetic order. In ferromagnets, dynamics are limited to the GHz range, constraining operational speed and leaving little room for further optimization. Antiferromagnets, by contrast, exhibit THz-scale dynamics and generate no stray fields, making them ideal candidates for high-speed, high-density spintronic devices. However, their zero net magnetization renders them “invisible” to conventional spin transport, posing challenges for both readout and deterministic electrical writing. Recently, a new class of materials—altermagnets—has emerged as a promising solution. These are collinear antiferromagnets that exhibit non-relativistic, momentum-dependent spin splitting despite global spin degeneracy [2]. Theoretical and experimental studies show that altermagnets with *d*-wave, time-reversal-even spin textures can support spin-dependent transport, including sizable TMR effects [3,4], due to momentum-dependent spin polarization.

The emergent spin-dependent transport in the absence of net magnetization suggests that these properties can be manipulated without reversing magnetic moments. This has led to the concept of altermagnetic multiferroics: antiferromagnetic materials with noncentrosymmetric polar structures that host both ferroelectric polarization and non-relativistic spin textures [5–7]. Unlike conventional multiferroics, where ferroelectric switching aims to flip magnetic moments, in altermagnetic multiferroics, polarization reversal alters the momentum-dependent spin polarization

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while preserving the underlying antiferromagnetic order. This enables direct, current-free control of spin transport, offering a path to ultra-low-power devices. For example, using such a material as a barrier in a multiferroic tunnel junction could generate a spin-filtering TMR by electrically tuning the matching between momentum-resolved spin polarizations in the electrodes and evanescent states in the barrier—without changing any magnetic order parameters.

A key challenge, however, is that in previously proposed altermagnetic multiferroics, the polar axis is often fixed (typically out-of-plane). In such cases, ferroelectric switching significantly alters the electrostatic potential (e.g., barrier height), leading to a large resistance change that can dominate and mask the more subtle spin-matching effects, thereby obscuring the magnetic contribution.

Published on *SCIENCE CHINA Physics, Mechanics & Astronomy*, Zhu et al. [8] propose a novel design based on molecular ferroelectric altermagnets, which may overcome this challenge. In these materials, ferroelectric polarization arises from the alignment of molecular dipoles—highly tunable, structurally flexible, and independently controllable units. The authors show that parallel, antiparallel, and non-collinear dipole alignments can be engineered, enabling precise control over both the magnitude and orientation of polarization. This allows the momentum-dependent spin polarization to be toggled on/off, reversed in sign or altered in magnitude—all without disturbing the underlying antiferromagnetic order. Using tight-binding models and first-principles calculations, they demonstrate this effect in hybrid organic-inorganic perovskites (e.g., $[\text{MA}]_2\text{MnCl}_4$) and metal-organic frameworks, predicting large, electrically switchable spin splittings.

This work establishes a general framework for emergent multiferroic altermagnets, where molecular flexibility enables decoupled control of electrostatic and spin-texture effects. Although current molecular systems typically exhibit

low magnetic ordering temperatures and potentially small coercive fields due to weak exchange interactions and soft lattices—limiting immediate practical applications—the proposed design principle is transformative.

Recent breakthroughs—such as giant TMR in 2D antiferromagnetic MTJs (AFMTJs) [9] and perpendicular Néel vector switching by asymmetric spin torques [10,11]—suggest that practical antiferromagnetic spintronics is within reach. Integrating the highly tunable multiferroic altermagnets proposed by Zhu et al. into AFMTJs could enable multi-level memory through combined spin-torque writing and electric-field-controlled spin filtering [12]—paving the way for next-generation, energy-efficient, high-density spintronic devices.

- 1 E. Y. Tsymlal, and I. Žutić, *Spintronics Handbook: Spin Transport and Magnetism, Second Edition: Nanoscale Spintronics and Applications—Volume Three*, 2nd ed (Taylor & Francis, CRC Press, Boca Raton, 2019).
- 2 L. Šmejkal, J. Sinova, and T. Jungwirth, *Phys. Rev. X* **12**, 031042 (2022).
- 3 D. F. Shao, and E. Y. Tsymlal, *npj Spintronics* **2**, 13 (2024).
- 4 D. F. Shao, S. H. Zhang, M. Li, C. B. Eom, and E. Y. Tsymlal, *Nat. Commun.* **12**, 7061 (2021).
- 5 X. Duan, J. Zhang, Z. Zhu, Y. Liu, Z. Zhang, I. Žutić, and T. Zhou, *Phys. Rev. Lett.* **134**, 106801 (2025).
- 6 M. Gu, Y. Liu, H. Zhu, K. Yananose, X. Chen, Y. Hu, A. Stroppa, and Q. Liu, *Phys. Rev. Lett.* **134**, 106802 (2025).
- 7 H. Mavani, K. Huang, K. Samanta, and E. Y. Tsymlal, *Phys. Rev. B* **112**, L060401 (2025).
- 8 Z. Zhu, Y. Liu, X. Duan, J. Zhang, B. Hao, S. H. Wei, I. Žutić, and T. Zhou, *Sci. China-Phys. Mech. Astron.* **68**, 127562 (2025).
- 9 W.-M. Zhao, Y.-L. Liu, L. Yang, C. Tan, Y. Yang, Z. Zhu, M. Chen, T. Yan, R. Hu, J. Partridge, et al., arXiv: [2507.12735](https://arxiv.org/abs/2507.12735).
- 10 S.-S. Zhang, Z.-A. Wang, B. Li, W.-J. Lu, M. Tian, Y.-P. Sun, H. Du, and D.-F. Shao, arXiv: [2506.10786](https://arxiv.org/abs/2506.10786).
- 11 W. He, T. Zhang, Y. Zhou, C. Wan, H. Wu, B. Cui, J. Xia, R. Zhang, T. Guo, P. Chen, et al., *Nat. Electron.* **7**, 975 (2024).
- 12 K. Samanta, D. F. Shao, and E. Y. Tsymlal, *Nano Lett.* **25**, 3150 (2025).