Predictable gate-field control of spin in altermagnets with spin-layer coupling

Run-Wu Zhang, Chaoxi Cui, Runze Li,Jingyi Duan,Lei Li,Zhi-Ming Yu and Yugui Yao

Key Lab of advanced optoelectronic quantum architecture and measurement (MOE),
Beijing Key Lab of Nanophotonics & Ultrafine Optoelectronic Systems,
and School of Physics, Beijing Institute of Technology, Beijing 100081, China

Abstract

Spintronics, a technology harnessing electron spin for information transmission, offers a promising avenue to surpass the limitations of conventional electronic devices. While the spin directly interacts with the magnetic field, its control through the electric field is generally more practical, and has become a focal point in the field of spintronics. Here, we propose an innovative mechanism to accomplish this task effectively both with and without relying on spin-orbit coupling. Our method employs two-dimensional altermagnets with valley-mediated spin-layer coupling (SLC), in which electronic states display symmetry-protected and valley-contrasted spin and layer polarization. The SLC facilitates predictable, continuous, and reversible control of spin polarization using a gate electric field. Through symmetry analysis and ab initio calculations, we pinpoint high-quality material candidates that exhibit SLC. We ascertain that applying a gate field of 0.2 eV/A to monolayer Ca(CoN)2 can induce significant spin splitting up to 123 meV. As a result, perfect and switchable spin/valley-currents, and substantial tunneling magnetoresistance can be achieved in these materials using only a gate field. These findings provide new opportunities for generating predictable spin polarization and designing novel spintronic devices based on coupled spin, valley and layer physics.

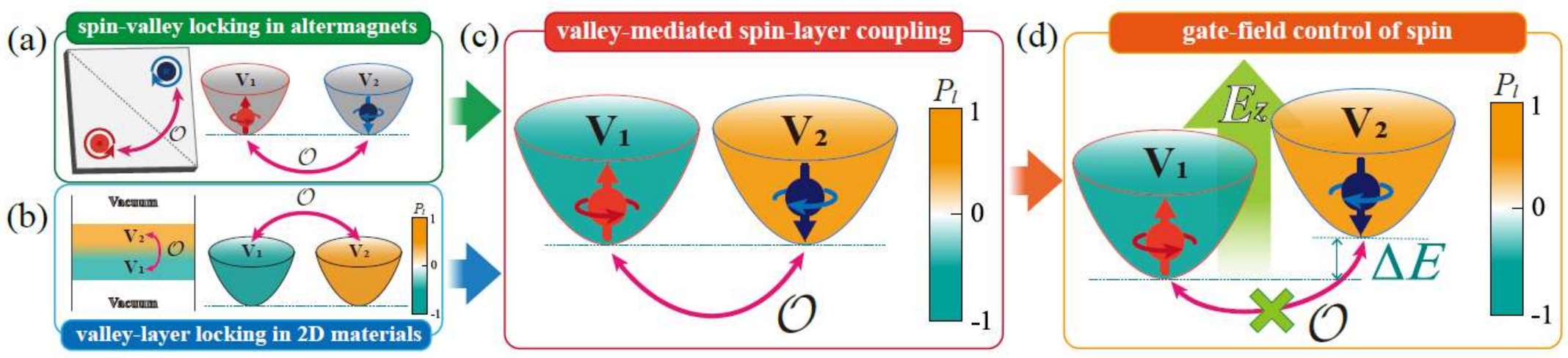

FIG. 1. Illustration of the mechanism of valley-mediated SLC and the electric control of spin. (a) A generic altermagnet with two valleys V_1 and V_2 features intrinsic spin-valley locking, which is protected by certain (magnetic) crystalline symmetry $\mathcal{O}$ rather than time-reversal symmetry $\mathcal{T}$. (b) Meanwhile, a 2D valleytronic material may host $\mathcal{O}$-protected valley-layer locking, where the two valley states have opposite layer polarization (P_l). (c) The combination of spin-valley and valley-layer locking leads to a novel spin-valley-layer coupling: valley-mediated SLC in 2D altermagnets. (d) This effect enables an intuitive, predictable and precise control of the spin polarization by electric gate field.

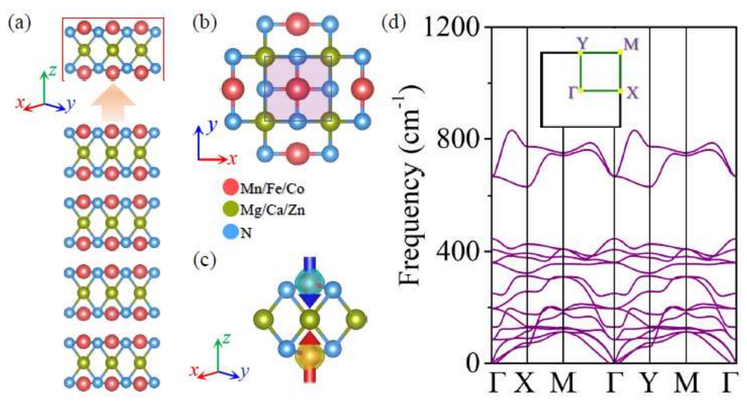

FIG. 2. (a) Schematic showing the process of stripping monolayer candidates (red dashed area) from the bulk. (b) Top view of the crystal structure of monolayer $A(BN)_2$. (c) Spatial spin-density distribution of ML-CaCoN, showing the magnetic moments are mainly localized around the top and bottom Co atoms with opposite directions. (d) Phonon spectrum of the ML-CaCoN.

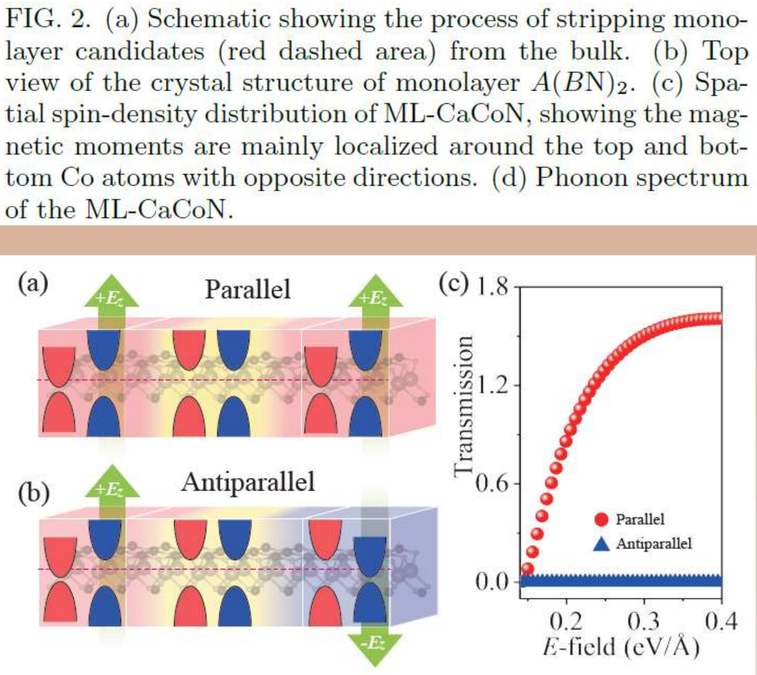

FIG. 4. Schematic of giant TMR device based on ML-CaCoN. (a-b) Parallel and antiparallel configurations of the TMR device, which are achieved by applying gate field rather than magnetic field. (c) Total transmission as a function of electric field (E_z) for the $Ca(CoN)_2$ tunnel junction in parallel (red dots) and antiparallel (blue triangles) configurations.

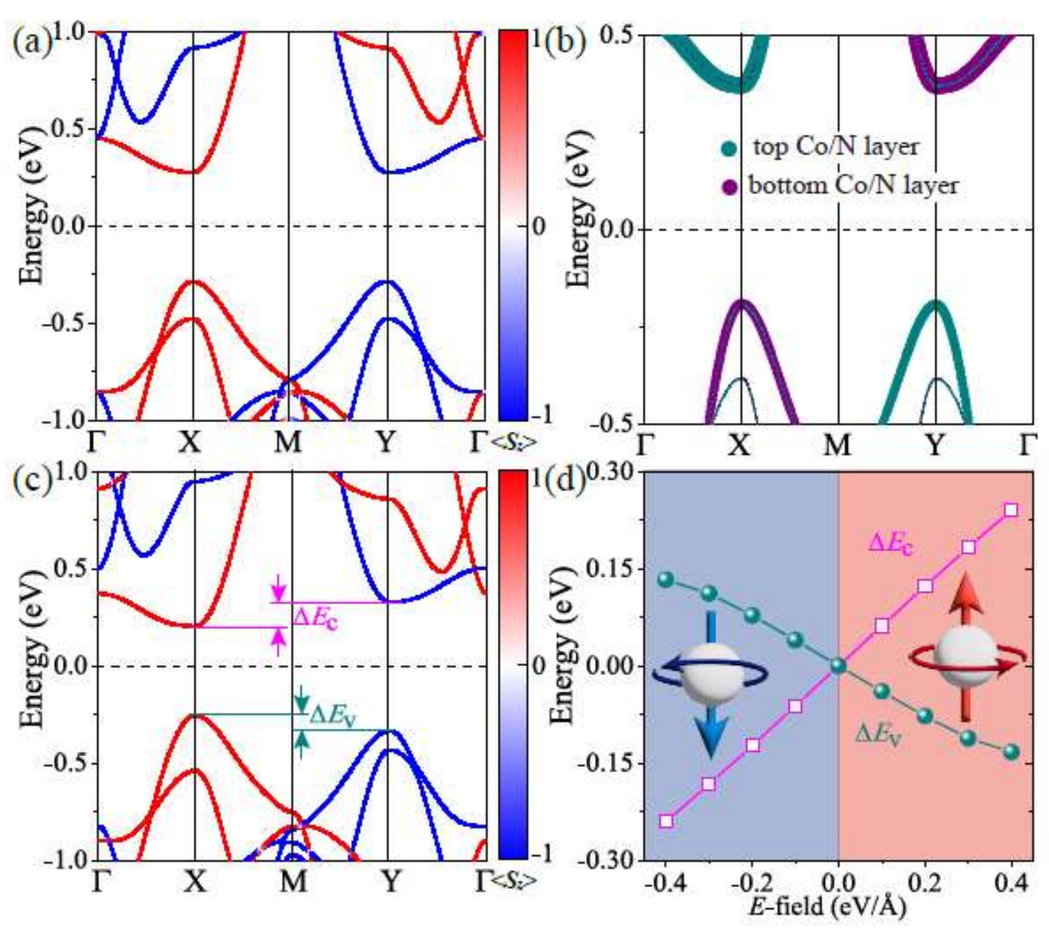

FIG. 3. (a) Band structure of ML-CaCoN in the AM configuration with SOC. The color denotes the out-of-plane spin polarization (s_z). (b) Orbital-projected band structures, showing the low-energy bands are mainly contributed by Co and N atoms. (c) Band structure of ML-CaCoN under a gate field of $E_z = 0.2$ eV/Å. (d) Spin (valley) splitting for VBM (ΔE_v) and CBM (ΔE_c) [indicated in (c)] versus the applied gate field.

In conclusion, we have demonstrated that altermagnets with spin-layer coupling (SLC), can serve as a platform to realize gate-field control of spin. We have introduce the symmetry restriction of valley-mediated spin-layer coupling and found ideal material, Ca(CoN)2 family. Our work provide a new method to control the spin. ***arXiv preprint arXiv:2306.08902 (2023).***