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# The rise of polycrystalline antiferromagnetic spintronics: From compatibility to functionality

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When antiferromagnetic spintronics emerged about a decade ago, researchers naturally turned to single crystals and epitaxial thin films. These perfect structures offer well-defined crystal symmetries, clean interfaces, and uniform magnetic order, all seemingly essential for unambiguous spin torque effects and a large anomalous Hall effect in non-collinear magnets, as illustrated in Figure 1A. A representative example is the magnetic Weyl semimetal $EuB_6$, where single crystals enabled precise control of topological electronic states by an external magnetic field, revealing a field-induced unconventional anomalous Hall effect.[1] Such studies showcase the power of perfect crystals for fundamental physics.

Yet perfection comes at a cost. Epitaxial antiferromagnets require lattice-matched substrates, high growth temperatures, and complex buffer layers, which severely limit scalability. Polycrystalline antiferromagnets, by contrast, have long been dismissed as structurally inferior, as shown schematically in Figure 1B. Random grain orientations and disordered grain boundaries were expected to degrade spin transport and frustrate deterministic switching. A growing body of work now overturns this view. Polycrystalline antiferromagnets are not merely compromised substitutes. They offer distinct new functionalities that epitaxial systems cannot match. Their rise is not a story of compromise but one of discovery.

An early and influential breakthrough came from DuttaGupta et al., who demonstrated current-induced Néel vector switching in a polycrystalline PtMn/Pt bilayer,[2] a finding captured in Figure 1C. PtMn is a collinear antiferromagnet with a Néel temperature above 900 K and strong uniaxial anisotropy. Despite a polycrystalline texture with grain size about 10 nm, spin-orbit torques from the adjacent Pt layer reversibly switched the antiferromagnetic order. The switching was read out via the transverse Hall signal, showing distinct high- and low-resistance states that persisted for hours. X-ray magnetic linear dichroism measurements performed by photoemission electron microscopy imaging directly revealed switched domains a few hundred nanometres across. Control experiments without Pt showed only thermal effects. This experiment shattered the long-held belief that epitaxial perfection is required for electrical control of antiferromagnets, proving that even a highly disordered polycrystalline film can host robust, deterministic switching. It also highlighted an unexpected advantage: the thermal stability factor of PtMn exceeds 150 at room temperature, much higher than most previously studied antiferromagnets, making it attractive for non-volatile memory.

An even more striking functionality emerges from polycrystalline textures that cannot be engineered in single crystals. Figure 1D illustrates this key discovery by Zhou et al., who fabricated a $Mn_3Sn$ homojunction with a single-crystalline (0001) bottom layer and a polycrystalline $Mn_3Sn$ top layer.[3] In the single-crystal, all kagome planes lie parallel to the film plane, so an external magnetic field is needed to select the final chiral octupole state. In the polycrystalline top layer, the kagome planes are randomly tilted. When a spin-polarized current is injected from the bottom layer via the magnetic spin Hall effect, its out-of-plane spin polarization splits into components perpendicular and parallel to the local kagome planes. The perpendicular component drives a symmetric rotation of the octupole order and acts as an antiferromagnet-type torque. The parallel component selects the switching chirality and acts as a ferromagnet-type torque. This decomposition, which relies on the random grain orientations of the polycrystalline layer, is extremely challenging to realize in a uniformly oriented single crystal. To achieve this, an unconventional spin current would have to be generated whose polarization is neither parallel nor perpendicular to the kagome planes. The polycrystalline approach thus offers a remarkably simple and practical route. It enables field-free full switching of the chiral antiferromagnetic order at room temperature, with a switching ratio near 100 percent and a threshold current density an order of magnitude lower than in previous designs. Here, the polycrystalline layer is not a flaw but rather the functional core. The switching chirality can be programmed by presetting the octupole direction in the bottom layer, and the zero-field switching is robust against external fields up to 0.3 T. This situation is reminiscent of topological insulators, where polycrystallinity and, in some cases, even amorphization can preserve topological surface states, demonstrating that structural disorder does not necessarily destroy topologically non-trivial electronic properties. The concept that imperfections can be functional could therefore extend beyond antiferromagnets and open up a broader perspective on phenomena made possible by disorder.

Even more surprisingly, subtle quantum transport survives in highly disordered polycrystalline compacts, as shown in Figure 1E. We studied the cubic antiperovskite $Mn_3Zn_{0.5}Ge_{0.5}N$ in sintered polycrystalline powder form, with grain size about 400 nm.[4] We uncovered a cascade of field-induced magnetic phase transitions: from a coplanar triangular phase to a low-symmetry "fork" phase and then to a non-coplanar "flower" phase. These transitions are accompanied by a transverse resistivity that is an even function of the magnetic field — non-zero only below 3.7 K and vanishing above a critical field. This behaviour cannot be explained by the conventional anomalous Hall effect, which is odd in field. We attribute it to topological orbital momenta arising from chiral-chiral interactions. Remarkably, all these observations were made on a powder sample, where crystallographic anisotropies average out. In a single crystal, such an even-in-field signal might be masked by anisotropic contributions; in the polycrystal, the isotropic average reveals a purely exchange-driven effect. This demonstrates that polycrystallinity does not destroy delicate topological transport but can instead provide a clean window into complex spin orders that would otherwise remain hidden.

Polycrystalline antiferromagnets also enable new forms of interfacial coupling that are inaccessible in conventional systems. Figure 1F presents this unique capability, as reported by Asakura et al., who reported omnidirectional exchange bias in all-antiferromagnetic $Mn_3Sn$/MnN bilayers grown on amorphous $SiO_2$/Si substrates.[5] In conventional ferromagnet/antiferromagnet bilayers, the exchange-bias direction is constrained by the shape anisotropy of the ferromagnetic layer. In an all-antiferromagnet bilayer, the absence of net magnetization eliminates shape anisotropy, and the bias direction is set solely by the cooling field. The $Mn_3Sn$/MnN system exhibits a clear exchange-bias shift in Hall resistivity, with an interfacial coupling energy of about $6 \times 10^{-6}$ J m$^{-2}$ at room temperature, comparable to conventional interfaces. Rotating the cooling field from out-of-plane to in-plane produces a corresponding rotation of the bias field. The slight deviation from a simple cosine dependence can be modelled by the randomly oriented kagome planes in the polycrystalline $Mn_3Sn$ layer. This omnidirectional control suggests device architectures where the reference direction can be programmed after fabrication, enabling adaptive or reconfigurable circuits — a functionality impossible with conventional ferromagnetic pinned layers.

It should be emphasized that the interpretation of these polycrystalline phenomena relies heavily on prior single-crystal studies of the same compounds, which established the underlying magnetic order and transport mechanisms. The contrast with epitaxial systems like $EuB_6$ is instructive. Shen et al. beautifully showed how a magnetic field modulates topological electronic states in single-crystalline $EuB_6$.[1] That is a fine demonstration of field-tunable topology in a perfect crystal. But polycrystalline antiferromagnets offer something fundamentally different: new switching mechanisms that rely on random grain orientations (field-free switching), even-in-field

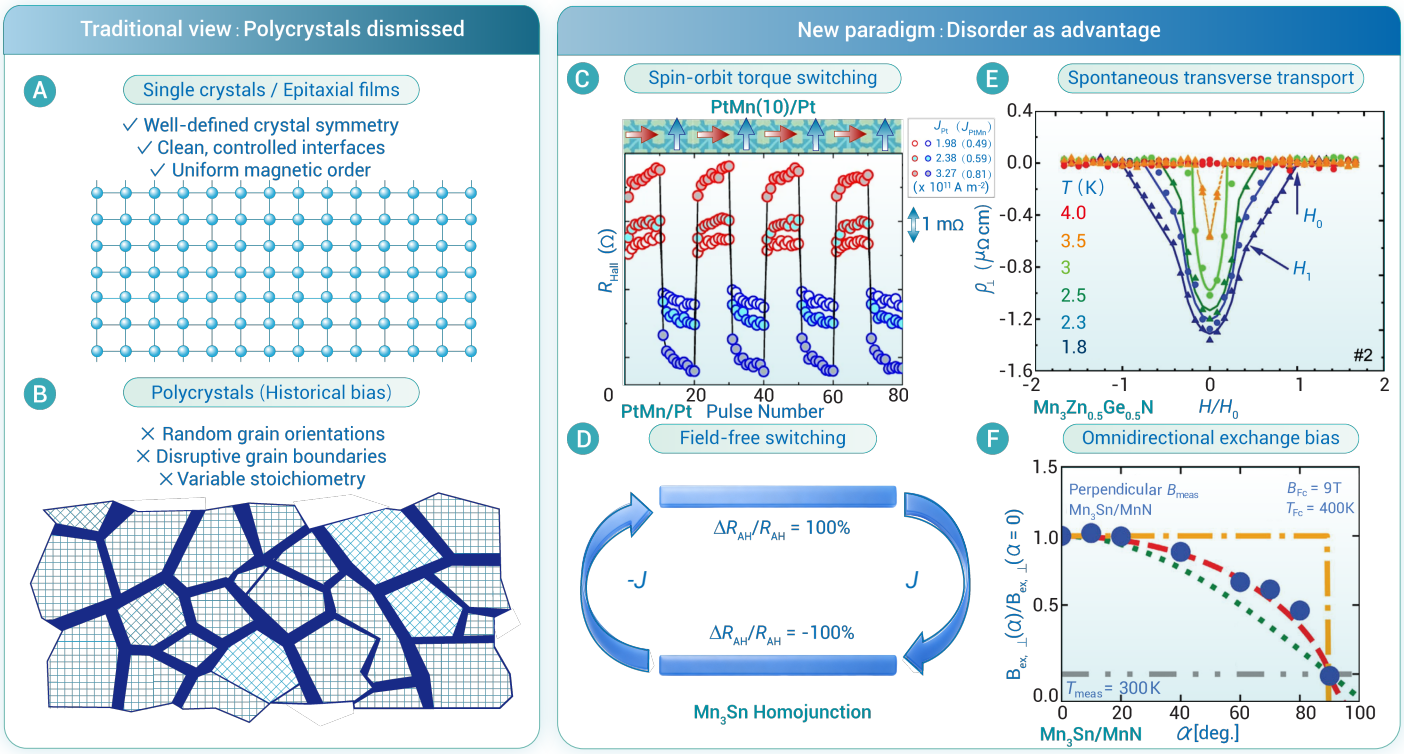



**Figure 1. From perfection to disorder: the rise of polycrystalline antiferromagnetic spintronics** (A) Single crystals and epitaxial thin films were once considered essential, offering well-defined symmetries and uniform order. (B) Polycrystals were dismissed due to expected degradation from random grain boundaries. Breakthroughs have overturned this view, revealing four phenomena uniquely enabled by polycrystallinity: (C) Spin-orbit torque switching in polycrystalline PtMn/Pt showing robust deterministic switching.[2] (D) Field-free full switching in $Mn_3Sn$ homojunction: a polycrystalline top layer with random kagome tilts decomposes spin current into orthogonal torques – impossible in a single crystal.[3] (E) Even-in-field transverse resistivity in $Mn_3Zn_{0.5}Ge_{0.5}N$ powder, revealing hidden topological transport via crystallographic averaging.[4] (F) Omnidirectional exchange bias in $Mn_3Sn$/MnN bilayers: bias direction follows any cooling-field orientation, enabling programmable references.[5]

transport that emerges from crystallographic averaging, and omnidirectional exchange bias that is impossible in ferromagnetic systems. These are not inferior versions of single-crystal effects; they are genuinely distinct physics and unique functionalities enabled by polycrystallinity. Further examples of polycrystalline compounds that exhibit advantageous properties not observed in single crystals include NiO films, Cr films, or sintered $Cr_2O_3$. Single crystals remain the platform of choice for investigating intrinsic topological band structure and clean magnetotransport, as the $EuB_6$ study illustrates. The polycrystalline approach is complementary rather than substitutional.

Grain boundaries can affect magnon coherence and spin relaxation, but the result depends on the dominant relaxation mechanism. For instance, the Elliott–Yafet and D'yakonov–Perel' processes respond differently to grain-boundary scattering, and in some regimes relaxation may not be significantly enhanced. For the device concepts now emerging, these same boundaries become design features. In the $Mn_3Sn$ homojunction, random grain orientations are essential for field-free switching. In $Mn_3Zn_{0.5}Ge_{0.5}N$, crystallographic averaging reveals hidden topological transport. In $Mn_3Sn$/MnN bilayers, the polycrystalline nature enables omnidirectional exchange bias. The design space, including grain size, orientation distribution and defect density, offers new degrees of freedom not available in single crystals. Looking ahead, polycrystalline antiferromagnets are poised to enable all-antiferromagnetic memory, reconfigurable logic, and in-memory computing, not despite their disorder but because of it.

Polycrystalline antiferromagnets are emerging not as compromised versions of single crystals but as a practical, functional platform that turns disorder into advantage. They tolerate imperfections, harness grain boundaries to create new physics, and unlock functionalities that perfect crystals cannot provide. Their rise marks a shift in perspective — away from the pursuit of perfection and toward an appreciation of disorder.

## DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used Deepseek to improve language and generate suggestions for Figure 1. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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## DECLARATION OF INTERESTS

The authors declare no competing interests.