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Magnetic And Spintronic Materials For Electronics And Computing

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ABSTRACT

Global information and communications technology energy use is rapidly increasing, traditional CMOS scaling is coming to an end, and the skyrocketing computational needs of artificial intelligence are driving the need for new device physics and computing paradigms. It is a comprehensive review with eleven interconnected sections, which cover the entire history of modern spintronics, from the discovery of giant magnetoresistance (GMR), to tunneling magnetoresistance (TMR) and magnetic tunnel junction (MTJ) physics, followed by three generations of MRAM technology: spin-transfer torque (STT-MRAM), spin-orbit torque (SOT-MRAM), and voltage-controlled magnetic anisotropy (VCMA), and finally to skyrmions, antiferromagnetic spintronics, the recently uncovered phase of altermagnetism, 2D van der Waals magnets, neuromorphic computing hardware, compute-in-memory architectures, and future research directions. The key findings are: STT-MRAM commercialization at the 28 nm node, SOT switching at 0.35ns, VCMA coefficient of over 300 fJ/V•m, experimental confirmation of altermagnetism by spin-resolved angle-resolved photoemission spectroscopy in α -MnTe and CrSb, room-temperature 2D ferromagnetism in Fe₃GaTe₂ with the 2D anisotropy over 19,000% compared with that of CoFeB, colossal tunneling magnetoresistance of over 19,000% in CrI₃ spin-filter heterostructures, and comprehensive synaptic plasticity in 2H-MoTe₂:PVA composite memristors with validated neuromorphic performance by convolutional neural networks. The synthesis finds that the most promising near-term MRAM paths will be a hybrid STT+SOT+VCMA architecture and that there is a diversification of the other

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directions into neuromorphic, topological, and two-dimensional spintronic architectures.

Keywords—spintronics; magnetic tunnel junction; TMR; GMR; STT-MRAM; SOT-MRAM; VCMA; skyrmions; antiferromagnetic spintronics; altermagnetism; 2D van der Waals magnets; CrI₃; Fe₃GeTe₂; Fe₃GaTe₂; neuromorphic computing; compute-in-memory; spin-orbit torque; spin Hall effect; topological insulators; MoTe₂ memristor; domain wall memory; spin-torque nano-oscillators

1. Introduction

There are two crises in the complementary metal-oxide semiconductor (CMOS) electronics industry [7]. The basic physics of making transistors smaller than 10nm is reaching its limits: quantum tunneling leakage, power density, and materials variability of the transistors are challenges that are not only catered by incremental materials substitution in the classical field-effect transistor paradigm [1]. Second, by 2030, data centers and wireless infrastructure will account for 20% of global energy and communication technology (ICT) consumption, and the exponentially growing AI ecosystem will consume 20% of energy. The thermodynamic minimum gate voltage for classical binary switching is in the order of 300 mV, which is unachievable with CMOS technology, irrespective of which material can be used for CMOS, while CMOS logic operations only need 10 to 100 picojoules.

Meanwhile, the von Neumann architecture of a computer with the processor and memory located in different components becomes an increasingly costly “bottleneck” because of the growing data volume in machine learning workloads [72]. The human brain consumes only 10 watts of power, far less than the most powerful digital supercomputers, but computes with up to 10^{15} synapses and 100 billion neurons, doing so locally without transporting data between components. In the context of modern deep learning workloads, over 90% of the energy costs are associated with data transfer between memory and processing Units. Inspired by the massively parallel architecture of the brain, neuromorphic computing has become the most promising paradigm shift from von Neumann processing [15].

In Spintronics [101], the spin of electrons is used as a state variable, and could resolve both the energy and architectural issues. The digital state can be stored by internal ferroic order parameters, while they do not need to be kept constantly turned on, as is done in the present processors. In 2007, the discovery of giant magnetoresistance [3, 8] and the development of tunneling magnetoresistance (TMR) in MgO-based junctions demonstrated the commercialisation potential of the field, and the commercial production of spin-transfer torque magnetic random access memory (STT-MRAM) began at the 28 nm node in 2019, by Samsung and Everspin/GlobalFoundries [13, 17]. Modern spintronics technology has far more applications than MRAM. The following experimental and/or theoretical achievements in magnetism have been accomplished in recent years: long-range magnetic order in atomically-thin van der Waals crystals [37, 30]; a new magnetic phase of altermagnetism, which was both theoretically predicted and experimentally realized [77, 44]; real-space observation of the Skyrmion Hall

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Effect [87]; 19000% tunneling magnetoresistance in CrI_3 spin-filter heterostructures; and discovery of comprehensive synaptic functionalities in 2D transition metal dichalcogenide composite memristors. This is a summary of the developments summarized in this review [88, 66, 92, 106] in the form of a unified account, organized in nine parts, covering fundamental physics, materials science, device engineering, and system-level applications.

2. GMR, TMR, and Magnetic Tunnel Junction Physics

2.1 Giant Magnetoresistance: The Birth of Spintronics

In 1988, Albert Fert and Peter Grunberg made this discovery independently [3, 8] of giant magnetoresistance in ferromagnetic metallic multilayers, which proved to be the foundation of the spin-dependent transport of electrons in magnetic systems. The multilayer $[\text{Fe}/\text{Cr}]_{60}$ exhibited a resistance change of nearly 50% at low temperature (4.2 K), with values significantly lower at room temperature due to enhanced thermal spin-wave scattering. The physical mechanism is based on the spin dependence of scattering at the interfaces between two adjacent ferromagnetic layers: If the magnetizations of the two layers are parallel, majority-spin electrons can move through both layers with a small scattering probability, whereas, if the two layers are antiparallel, both electrons experience scattering at the interface, which increases the resistance by a factor. In 1997[82], GMR read heads started entering the hard disk drive (HDD) as the first commercial spintronic application and set the course for the areal density revolution, which allowed the development of modern storage devices [79].

A simplified example of spin-dependent conductance is shown to be $G = G_0(1 + P_1P_2\cos\theta)$ [3], where P_1 and P_2 are the spin polarizations of the two ferromagnetic electrodes and θ is the relative angle between the magnetizations of the two electrodes. This relation is the fundamental operating principle and is continuously and controllably variable by changing the direction of the magnetization over the angle; therefore, this can be used for digital sensing as well as analog operation.

2.2 Tunneling Magnetoresistance and the MgO Barrier Breakthrough

Another advancement of the GMR technology was tunnelling magnetoresistance, where the distance between the layers was sufficiently small to let the electrons tunnel through the barrier and thus became a quantum mechanical phenomenon. A magnetic tunnel junction consists of two ferromagnetic electrodes with thicknesses less than the MTJ thickness, with an intervening thin insulating layer. The resistance of the MTJ in the parallel configuration is lower than that of the antiparallel configuration. The read signal amplitude provided for binary sensing is the fractional difference (TMR ratio). Instead of amorphous AlO_x barriers [64], the key to the success of the invention was the use of epitaxial MgO. Parkin et al. (1999) demonstrated early MTJs with amorphous AlO_x barriers. For the junctions $\text{Fe}/\text{MgO}/\text{Fe}$ and $\text{CoFeB}/\text{MgO}/\text{CoFeB}$, the MgO layer is used as a symmetry filter that only transmits the Bloch states with Δ_1 electronic polarization: these states have a near-100% spin polarization in the body-centered cubic Fe and CoFeB. The regular tunneling has resulted in TMR values up to 631% at room temperature for the molecular beam epitaxy (MBE) grown $\text{CoFe}/\text{MgO}/\text{CoFe}(001)$ junctions reported by Scheike et al. (2022). An unexpected oscillatory variation of TMR as a function of the thickness of the MgO barrier with a period of about 0.6 nm was also found by Scheike et al., which they explained as resulting from quantum interference

between multiple channels of tunneling. It can also happen that if production is done in a way that results in some sputtered devices being at the local TMR minima, then further optimization of thickness could produce a 50 to 100% increase in the TMR without the use of new materials.

For CoFeB/MgO/CoFeB junctions, the TMR reaches the record value of 604% at room temperature (300 K) [38], and the theoretical value is higher than 1,000% for perfect epitaxial structures [11]. The production sputtered devices showed 200-250%, which is thought to be due to non-uniformity in the thickness of the MgO, interdiffusion at the interface during annealing, and grain boundary scattering. A phenomenon of negative TMR, related to the interfacial resonance states and relevant to the practical application of VCMA-MRAM that the free layer is transiently in orthogonal state during precessional switching, has been reported by the authors Chen et al. (2023).

Table 1. TMR ratio progression across MTJ architectures. The gap between sputtered production (200 to 250%) and MBE epitaxial (631%) reflects interface imperfections. CrI₃ spin-filter TMR represents a qualitatively different mechanism.

Device Type	TMR (RT)	Barrier	Method	Status
In-plane CoFeB/MgO	~150%	AlO _x	Sputtered	Obsolete
Perp. CoFeB/MgO	200-250%	MgO	Sputtered	Production
CoFeB/MgO optimized	~300%	MgO	Sputtered opt.	Advanced R&D
CoFe/MgO epitaxial (Scheike 2022)	631%	MgO	MBE	Research
CrI ₃ spin-filter vdW	>19,000%	CrI ₃	Exfoliated	Research

2.3 Perpendicular Magnetic Anisotropy and Interface Engineering

The high TMR provided by coherent Δ_1 -symmetry tunneling through crystalline MgO, together with perpendicular magnetic anisotropy (PMA) due to Fe-O orbital hybridization at the CoFeB/MgO interface [20], are the two key features that enable the construction of modern STT-MRAM. For 10-year data retention, the thermal stability factor $\Delta = K_{\text{eff}} \cdot V / (k_B \cdot T)$ should be greater than about 60. Due to the need to decrease the thickness of the free layer below 1 nm to lower the switching current, K_{eff} is progressively dominated by the demagnetization term, which poses a potential instability for the system. Through density functional theory calculations, Vojacek et al. (2020) showed that an interface layer of composite Co/Fe at the MgO interface can increase the value of interface anisotropy compared to the conventional CoFeB/MgO, thus allowing stable perpendicular magnetization even for thin free layers with thicknesses below 0.8 nm.

The magnetoresistance ratio for van der Waals CrI₃ as a spin-filter tunnel barrier is found to be magnetic-state-dependent, and to reach its highest value reported in any material system, which is over 19,000% [100] at low temperature. This radical enhancement comes from the layer parity-controlled antiferromagnetism in CrI₃, which causes the CrI₃ layers to be antiferromagnetically coupled when they are a few layers thick, resulting in a spin filter cascade in which only certain spin channels can tunnel

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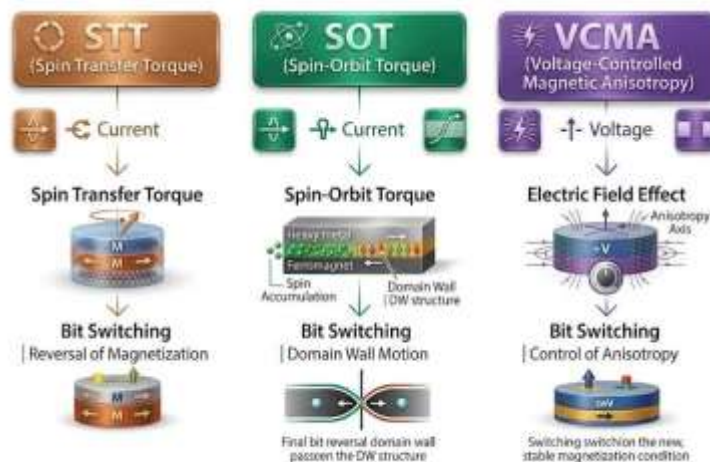
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through all layers simultaneously to give near-complete off-state blocking.

2.4 Spin-Transfer Torque: The All-Electrical Write Mechanism



Comparison of Spintronic Write Mechanisms: STT, SOT, and VCMA

Figure 1. Comparison of spintronic write mechanisms: STT, SOT, and VCMA

Slonczewski (1996) and Berger (1996) independently proposed a method that can perform an all-electrical write operation without any external magnetic field, called spin-transfer torque (STT) switching [67, 75]. A spin-polarized current flowing through the reference layer picks up the spin orientation, and when it enters the free layer, the angular momentum transfer exerts a torque similar to damping on the free layer, which changes the free layer orientation if the current density is above a critical value. The basic engineering compromise for obtaining low damping, thin free layers, and high spin polarization to lower the threshold current density is in direct conflict with thermal stability requirements. The three challenges are the write current, write speed, and thermal stability, which form this trilemma for the STT-MRAM below 20 nm.

In magnetic tunnel junctions, the field-like torque component is one of the important extensions analysed by Tiwari et al. (2014), where 10-100% of the Slonczewski damping-like torque can be achieved. This field-like component strongly affects both switching asymmetry between parallel-to-antiparallel and antiparallel-to-parallel transitions and write error rate asymmetries, which need to be taken into consideration when designing the circuit.

2.5 Spin-Orbit Torque

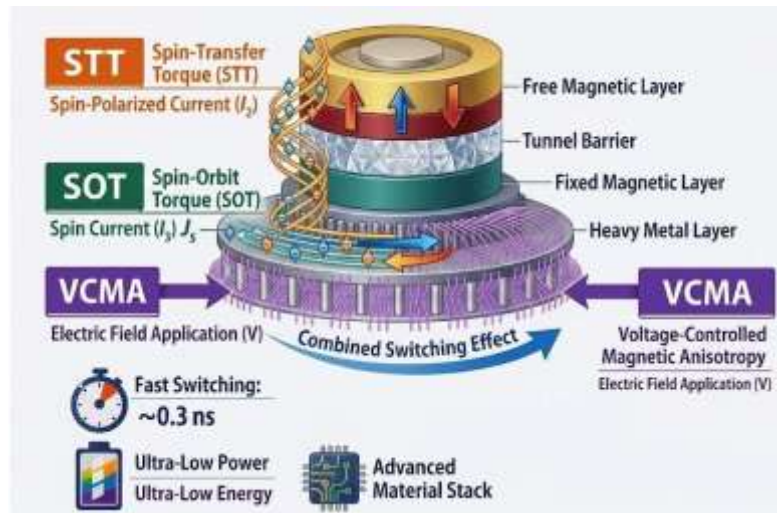


Figure 2. Redesigned hybrid STT + SOT + VCMA architecture.

The spin-orbit torque (SOT) is a mechanism of writing, which is geometrically decoupled [50]: A charge current in the adjacent heavy metal layer creates a transverse pure spin current, which is used to exert torque on the free layer. The major advantages of this decoupling are: switching time of sub-nanoseconds potential; enhanced endurance due to the fact that the tunnel barrier is not stressed during the writing process; and that it can be applied to ferromagnets, ferrimagnets, and antiferromagnets. The damping-like efficiencies of conventional metals are topped with dramatic results for topological insulators: $\text{Bi}_{0.9}\text{Sb}_{0.1}$ has a damping-like efficiency of ~ 52 (Fert & Nguyen Van Dau, 2019), and $\alpha\text{-Sn}$ has a damping-like efficiency of 6.15.

2.6 Voltage-Controlled Magnetic Anisotropy

The write cycle power consumption of voltage-controlled magnetic anisotropy (VCMA) is also the minimum possible, as no current is used, just the capacitive write energy of the MTJ. The mechanism is based on electric field-induced changes in interfacial hybridization, which induce perpendicular magnetic anisotropy [54]. VCMA facilitates precessional switching, a voltage pulse of half of the precessional period initiates and completes the free-layer switching with a write energy of ~ 1 fJ/bit [40], all capacitive with no steady state current consumption. The combination of VCMA and STT will lead to a decrease of several orders of magnitude of the required switching current. The main restriction is that existing VCMA coefficients at practical voltage are not sufficient to ensure reliable switching over the process variation.

3. STT-MRAM: Foundations, Materials, and Scaling Limits

3.1 Commercial Milestone and Production Architecture

STT-MRAM has made its first major commercial breakthrough with volume production of the first commercial devices at Samsung and Everspin/GlobalFoundries [17] for embedded cache applications that will replace SRAM and embedded Flash. For commercial devices, they operate in the 22- to 28 nm CMOS node with write energy of 100-200 fJ/bit, write latency of 5-50ns, and endurance of more than 10^{12} cycles [1]. The first demonstration of ST-MRAM was at the 90-nm node by Rizzo et al. (2013). Intel has revealed new NOR-Flash replacement products using STT-MRAM, which

will take the place of embedded cache and move towards standalone nonvolatile memory applications. The technology relies on the perpendicular magnetic anisotropy at the interface of CoFeB/MgO and STT switching at current densities of 2-5 MA/cm² (2-5 x 10⁶ A/cm²). Commercial production of STT-MRAM was realized by Chung et al. (2016), who demonstrated 4Gb density by using perpendicular CoFeB/MgO MTJ. Samsung, TSMC, GloFo, and Intel are the first to offer embedded STT-MRAM, which is a 22-28 nm CMOS process. The technology readiness level is 9, which is the maximum amongst the MRAM family [21].

3.2 The STT Trilemma at Sub-20-nm Scaling

However, there is a fundamental issue that STT-MRAM is undergoing at sub-20nm scaling. First, the same tunnel barrier through which the read current flows will be through which the write current flows as well, so it will cause progressive dielectric breakdown and degrade reliability. Second, the write latencies (5-50 ns) are far too slow for L1/L2 cache replacement. Third, it is difficult to maintain thermal stability with increasing perpendicular magnetic anisotropy energy densities as the sub-1-nm free-layer thicknesses required for low write currents are approached. Unfortunately, it is not possible to optimize these three requirements together in the conventional CoFeB/MgO/CoFeB structure at scales of less than 20 nm.

The extension of the STT-MRAM roadmap via materials engineering [41, 56] includes Co/Fe composite interfacial layers predicted to have an interface anisotropy (K_i) above 2.5 mJ/m² and operation at cryogenic temperatures, where Lang et al. (2019) showed counterintuitive improvements of the TMR performance at 4 K (an increase up to 250% compared to room temperature) as well as dramatic thermal stability enhancements for CoFeB/MgO perpendicular magnetic tunnel junctions in conjunction to STT or SOT/VCMA based cooperative write mechanisms, which reduce the effective switching current without compromising the speed and reliability of the magnetoresistance.

Table 2. STT-MRAM device parameter comparison across technology generations. Values marked * are simulation or DFT predictions.

Device Type	Jc (A/cm ²)	Write Time	TMR (RT)	Delta	Status
In-plane CoFeB/MgO	~5×10 ⁶	5-10 ns	~150%	~60	Obsolete
Perp. CoFeB/MgO	2-5×10 ⁶	5-20 ns	~200%	80-100	Production
Co/Fe composite/MgO*	~1×10 ⁶	3-10 ns	~200%	>100*	Research
CoFe/MgO epitaxial*	~1×10 ⁶	3-5 ns	~631%	>120*	Research (MBE)
STT+SOT hybrid	~1×10 ⁶	~0.8 ns	~200%	~80	Research
Cryogenic pMTJ (4K)	~5×10 ⁶	5-20 ns	~250%	>200	Research

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4. SOT-MRAM, VCMA, and the Path to Sub-Nanosecond Memory

4.1 Spin-Orbit Torque: Physical Mechanisms

In bilayers of heavy metal and ferromagnet, the spin-orbit torque generated by the heavy metal is a result of two different but related physical effects. The bulk spin Hall effect is an intrinsic topological effect, which is observed as an out-of-plane spin current in response to an in-plane charge current, which does not require disorder [74]. The extra non-equilibrium spin polarization at the interface is generated by the inversion-symmetry-broken spin-orbit coupling of the interfacial Rashba-Edelstein effect [51]. Conventional metals are ranked by the spin Hall angle as follows: β -W (0.3-0.4), β -Ta (0.12-0.15), and Pt (0.08-0.12) [74].

By discovering light metals (Cr) with SOT efficiencies as high as those of β -W, Gupta et al. reported a huge expansion of the materials landscape, even though the intrinsic spin-orbit coupling of Cr is about 10 times smaller than that of β -W. The measured damping-like efficiency of Cr/CoFeB/MgO is close to the value of β -W, which is about 0.27. The early SOT switching was successfully shown by Miron et al. (2011). Liu et al. (2012) reported a giant spin Hall effect in β -Ta, and Pai et al. (2014) addressed this critical thermal stability challenge of W-based SOT stacks by inserting a 0.2 nm Hf diffusion barrier, which not only extended the thermal stability of β -W above 400 degrees Celsius, but also improved PMA by 35% and kept the spin transmission efficiency above 92%. The field of SOT has been extensively reviewed by Gambardella & Miron (2011) and Shao et al. (2021).

4.2 Single-Shot SOT Switching Dynamics

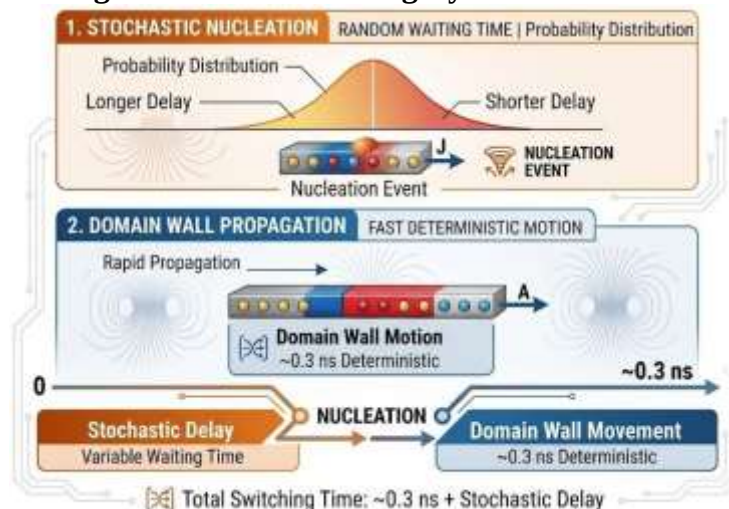


Figure 3. Timeline of SOT switching dynamics, featuring stochastic nucleation and deterministic domain wall movement

The most significant experimental work related to SOT-MRAM thus far is the single-shot time-resolved switching experiment of Grimaldi et al. (2020). This work has shifted the paradigm of the understanding of SOT, switching from ensemble-averaged probability measurements to individual switching trajectories observed on a sub-nanosecond time scale. The important result is that the switching of perpendicularly

magnetized MTJs is a two-stage stochastic process, involving a thermally activated nucleation stage with a waiting time distribution that has an exponential form [46], and a deterministic domain wall propagation stage whose propagation time is ~ 0.3 ns and is independent of thermal fluctuations.

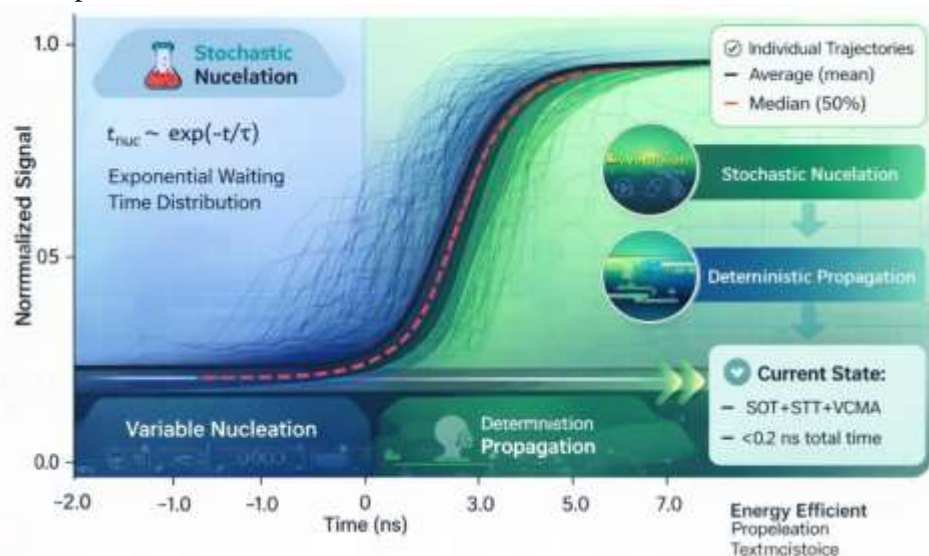


Figure 4. Magnetic domain switching dynamics, showing the transition from stochastic nucleation to deterministic propagation.

This two-step picture has three important implications for the design of MRAM. Stochastic nucleation is an important factor at moderate currents because it becomes the predominant write latency factor. Secondly, the mean nucleation time decreases greatly when the current is raised above the nucleation threshold, while the propagation time is still not reduced considerably. Third, the switching time distributions from the cooperative SOT+STT+VCMA write scheme are centered below 0.3 ns, the current state of the art in MRAM write speed. Zheng et al. (2020) also observed a transition zone between the two regimes where current density was intermediate, which they dubbed a "forbidden zone" for reliable MRAM write operation.

4.3 Field-Free SOT Switching Strategies

The main engineering challenge for the commercialization of SOT-MRAM is deterministic (i.e., without an external symmetry-breaking field) switching of perpendicularly magnetized thin films. Several strategies have been shown to have different pros and cons [83].

Table 3. Comprehensive comparison of field-free SOT switching strategies. Tilted anisotropy and geometric notch stand out for simplicity.

Strategy	Principle	Extra Process	Robustness	Speed
Exchange bias (AFM)	Unidirectional anisotropy from IrMn/PtMn	Yes (+2 layers)	High (>99%)	<1 ns
Tilted anisotropy	Easy-axis tilt breaks sagittal symmetry	Deposition only	~99%	<1 ns

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Geometric notch	Non-uniform current generates an effective field	Litho only	~98%	<1 ns
Interlayer coupling	Neel coupling from the in-plane FM sublayer	Extra FM layer	~99%	<1 ns
Orbital Hall (Cr)	OHE asymmetry in light metal	No extra layer	Demonstrated	~1 ns

4.4 VCMA: From Mechanism to Sub-fJ Switching

The voltage-controlled magnetic anisotropy is a result of the electric field-induced control of the orbital occupation of the interface between the ferromagnet and MgO, through spin-orbit coupling. The VCMA coefficient has been systematically enhanced by five methods: alloy composition optimization, using Heusler alloy electrodes, strain engineering, optimization of the interface crystallization (reaching 150 to 200 fJ/V·m), and heavy element doping [54]. It has been shown that the VCMA coefficient increases to values above 300 fJ/V·m while maintaining the tunneling channel by Ir doping (10%) in Ir: Fe/CoFe/MgO [59]. The estimated switching energy of less than 0.5 fJ/bit is over 200 times lower than the production STT-MRAM. The write energy of VCMA precessional switching is shown to be ~1 fJ/bit [40], which is 150 times smaller than the write energy of production STT-MRAM.

4.5 The STT+SOT+VCMA Convergence

One common theme in the literature is that there is no single best write scheme that performs best with all the performance measures, and the best performance is always obtained from cooperative hybrid schemes. Grimaldi et al. (2020) demonstrated that the combination of the three mechanisms (SOT, STT, VCMA) provides a switching distribution centered at 0.3 ns, which is not achievable by any single mechanism. Pathak et al. 2020 showed that a short SOT assist pulse could shorten the switching time from ~ 8ns to 0.8ns. SOT switching of MTJs for memory applications has been reviewed by Grimaldi et al. (2022) and has lowered the write energy by ~ 35% at the same error rate in simulation.

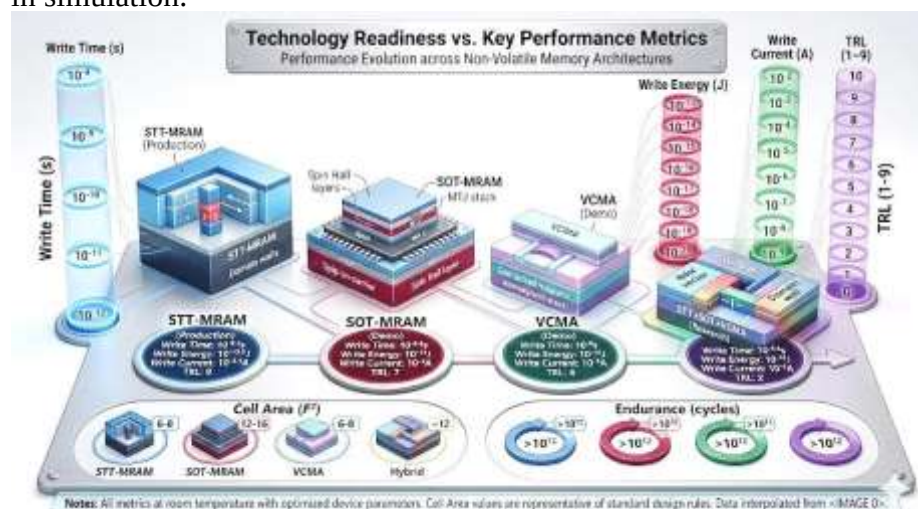


Figure 5. Technology readiness and performance metrics for non-volatile memory architectures.

Table 4. Technology readiness and performance comparison across MRAM paradigms. TRL = Technology Readiness Level (1 = basic research, 9 = production).

Metric	STT-MRAM (Prod.)	SOT-MRAM (Demo.)	VCMA (Demo.)	Hybrid STT+SOT+VCMA
Write time	5-50 ns	0.35-1 ns	0.3-1 ns	<0.3 ns
Write energy	100-200 fJ	200-400 fJ	~1 fJ	~10-50 fJ (proj.)
Endurance	$>10^{12}$	$>10^{12}$	$\sim 10^{12}$	$>10^{12}$
Cell area	6-8 F ²	12-16 F ²	6-8 F ²	~12 F ²
TRL	9	5-6	3-4	3-4

5. Skyrmions, Antiferromagnetic Spintronics, and Altermagnetism

5.1 Magnetic Skyrmion Physics

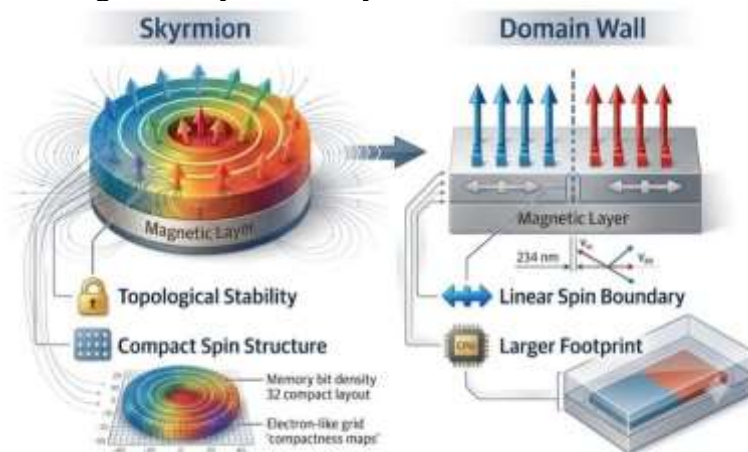


Figure 6. Comparison of magnetic skyrmion spin textures and domain walls.

The spin texture in the form of whirls of spins, called magnetic skyrmions, is topologically non-trivial and stabilized by the Dzyaloshinskii-Moriya interaction (DMI) [24, 57] in non-centrosymmetric materials and interfaces [25]. They have an integer 'topological charge' associated with them, which makes them immune to continuous deformations to topologically trivial configurations and provides them with a particle-like identity and immunity to thermal fluctuations [57]. There is evidence of the existence of skyrmions in sputtered multilayer structures ranging in sizes from sub-10 nm to micron scale at room temperature [87]. The properties of magnetic skyrmion materials have been summarized by Tokura & Kanazawa (2021). Wang et al. (2022) reviewed the basic physics and applications of skyrmions. The critical current required to induce motion of skyrmions is also significantly lower, found to be on the order of 106 A/cm² (1010 A/m²), making them potentially suitable for ultra-low-power operation, compared with the critical current density of domain walls, which is on the order of 107 A/cm² (1011 A/m²).

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5.2 The Skyrmion Hall Effect: First Experimental Observation

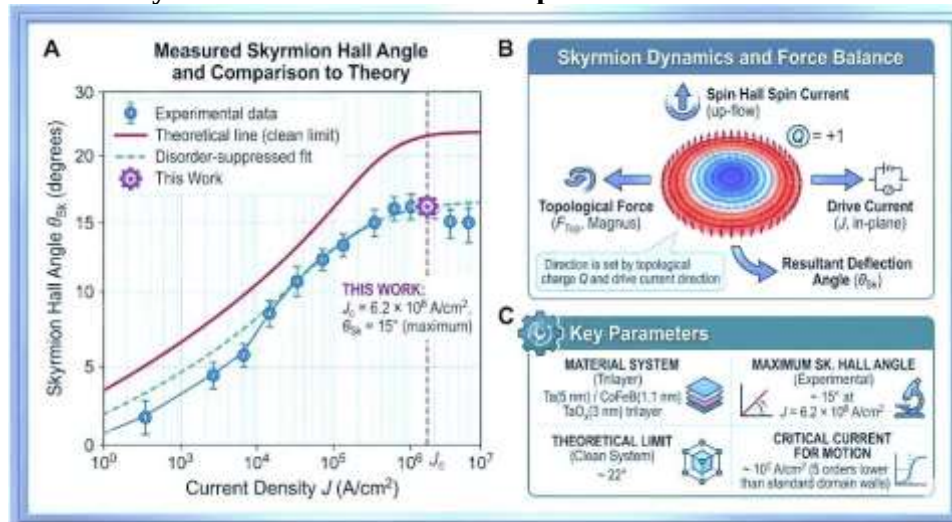


Figure 7. Analysis of skyrmion Hall angle, dynamics, and key system parameters.

The observation of the Skyrmion Hall Effect at room temperature, with a Ta/CoFeB/TaO_xtrilayer sample by differential polar magneto-optical Kerr effect microscopy, is a milestone in the field of topological spintronics. The Skyrmion Hall Effect is the topological counterpart to the electronic Hall effect: topological charge-bearing skyrmions are subjected to a topological Magnus force (Göbel et al., 2021), which deflects them transversely to the applied spin Hall spin torque. The experimental result of the maximum Hall angle of ~ 15 degrees at a current density of 6.2×10^6 A / cm² indicates that the Hall angle is primarily dominated by disorder near the depinning threshold. The random 'creep' motion of skyrmions at low current densities constitutes a natural physical realization of reservoir computing for neuromorphic computing.

5.3 Domain Wall Memory in Synthetic Antiferromagnets

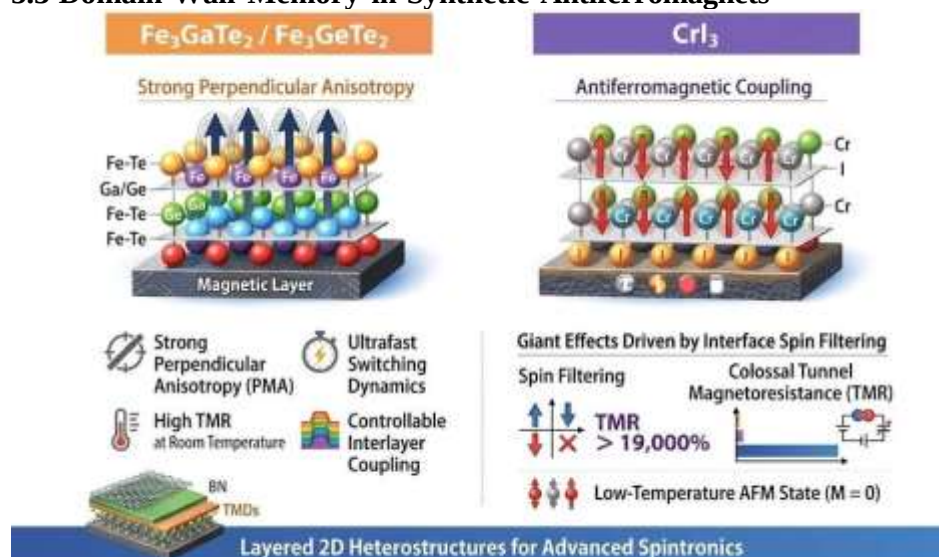


Figure 8. 2D van der Waals magnets and layered heterostructures for spintronics

Domain wall physics [102] is a common theme for the SOT switching papers and the

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papers on neuromorphic devices. Duine et al. (2018) have reviewed synthetic antiferromagnetic spintronics. The achieved velocities for W/CoFeB/MgO are 50-100 m/s [55] and for optimized synthetic antiferromagnets, racetrack structures are around 200 m/s [60]. A key open question is how to push domain wall velocity up to ~ 1 km/s, roughly 5-10 times higher than the velocities currently achieved in W/CoFeB/MgO and synthetic antiferromagnet racetrack structures, in order to make domain-wall racetrack memory commercially viable. The three key advantages of the synthetic antiferromagnet architecture for domain wall memory are that: (1) the net magnetization is close to zero and so the domain wall displacement is not influenced by stray fields; (2) the domain wall velocity when using the synthetic antiferromagnet architecture surpasses the velocity of the domain walls in single-ferromagnet tracks due to the exchange torque between the antiparallel layers; and (3) the sensitivity to defect pinning is not present in the synthetic antiferromagnet architecture. Bläsing et al. (2020) have reviewed magnetic racetrack memory.

5.4 Antiferromagnetic Spintronics: Electrical Switching of CuMnAs

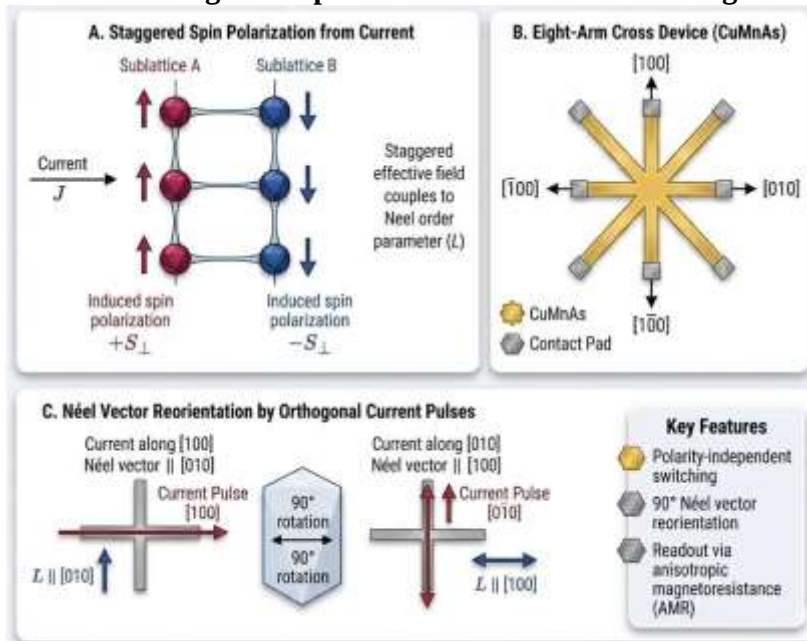


Figure 9. Inverse spin galvanic effect and Néel vector reorientation in an eight-arm cross device

A novel experimental finding was reported by Wadley et al. (2016) that exploits the inverse spin galvanic effect. Under spatial symmetry inversion, two sublattices of manganese occupy crystallographically equivalent positions with respect to each other in tetragonal CuMnAs. The two spin sublattices are induced with the same magnitude but opposite sign, giving rise to an effective staggered field that directly and strongly interacts with the Néel order parameter, thus allowing reorientation of the Néel vector by an all-electrical stimulus. CuMnAs's properties are not typical in the sense that it has a Néel temperature of 480K, ensuring thermal stability, and a resistivity of ~ 160 microhm-cm at room temperature, suitable for semiconductor fabrication. The antiferromagnets offer magnon dynamics in the terahertz range, which are some 100

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times faster than in ferromagnetic materials [4, 105], and they are also free of stray magnetic fields, allowing for integration without cross-talk with antiferromagnets [39]. Gomonay & Loktev (2014) laid the theoretical foundations. The review of emerging antiferromagnets for spintronics has been done by Chen et al. (2024).

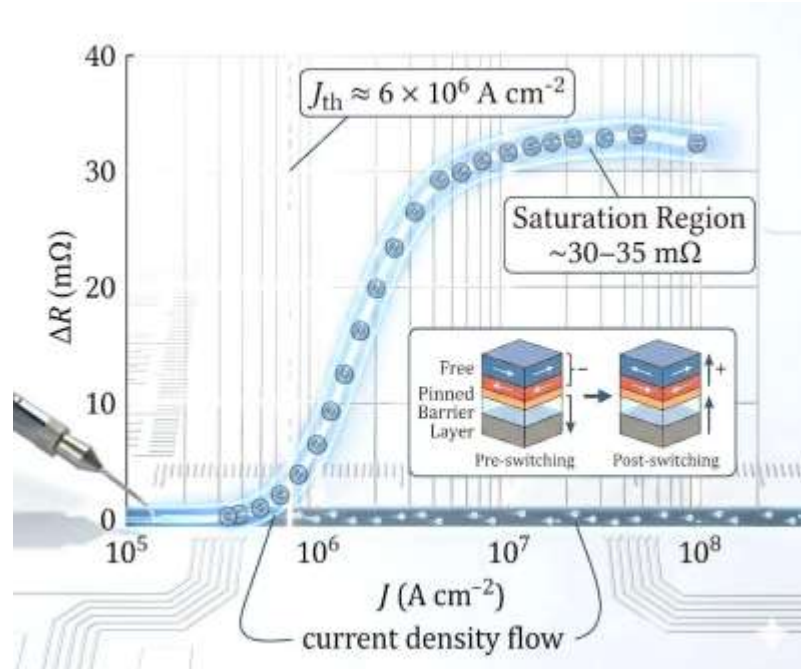
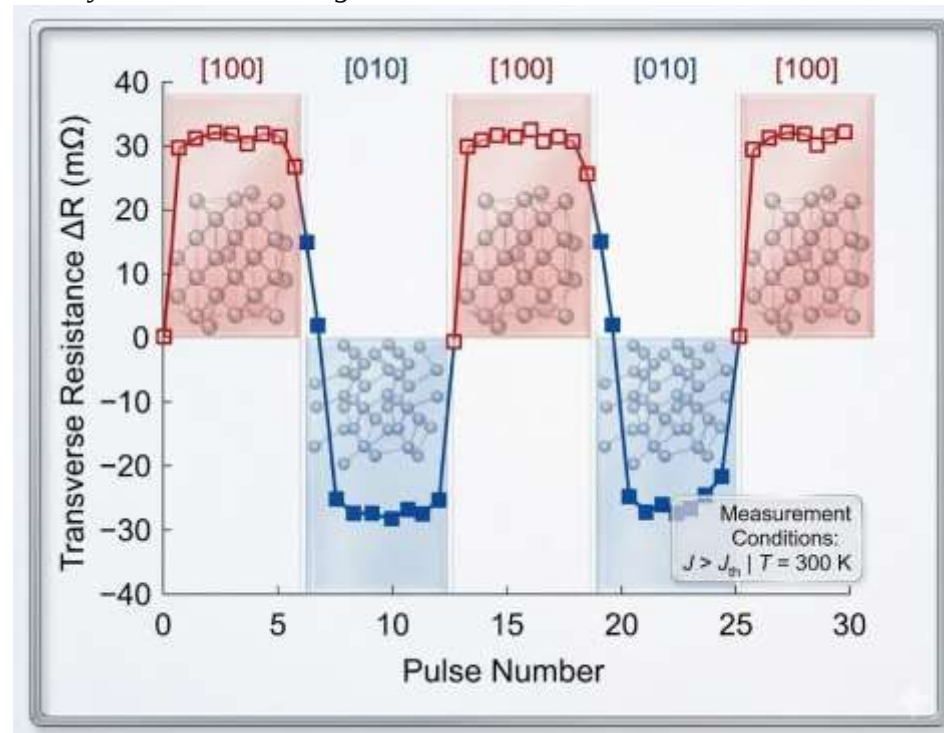


Figure 10 .Resistance change versus current density, showing the threshold current density and saturation region



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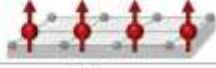
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Figure 11. Transverse resistance vs. pulse number demonstrating switching behavior

5.5 Altermagnetism: The Third Magnetic Phase

Property	Ferromagnetism (FM)	Antiferromagnetism (AFM)	Altermagnetism (AM)
Spin Structure (Unit Cell)			
Net Magnetization	Non-zero	Zero	Zero
Time-Reversal Symmetry (T)	Broken	Preserved	Broken
Spin Splitting in k -space	Uniform sign	None (Kramers degenerate)	Alternating sign (d-, g-, i-wave)
Magnon Frequency	GHz	THz	THz
Stray Fields	Present	Absent	Absent
Switching Method	Magnetic field / STT / SOT	Current-induced (Néel vector)	Current / SOT (spin-splitter torque)
Key Advantage	Strong readout (large M)	No stray field, ultrafast	Strong spin splitting + no stray field

Representative Performance Benchmarks		
SOT Efficiency (θ_{SH} or equiv.) Pt: ~ 0.1 β -W: $\sim 0.3-0.4$	AFM Switching Speed CuMnAs: sub-10 ns (electrical)	Altermagnet Performance RuO ₂ : $\theta_{SS}^{torque} = 28\%$ Spin Hall angle = 0.183 RuO ₂ /TiO ₂ /RuO ₂ TMR $\approx 500\%$

Figure 12. Table comparing magnetic properties and performance benchmarks for FM, AFM, and AM architectures

The condensed matter physics community had identified only two magnetic phases ferromagnetism and antiferromagnetism for most of the twentieth century. However, the idea of Smejkal, Sinova, and Jungwirth in Physical Review X (2022) was to introduce a more powerful symmetry language of the spin groups to collinear magnetism. The outcome of this is the surprising but important discovery that there are three different phases of magnetic order that are collinear. Altermagnetism is the result of the merging of the macroscopic properties of both ferromagnetism and conventional antiferromagnetism and overcomes the major drawbacks of each. Altermagnets have strong time-reversal symmetry breaking and large spin-momentum splitting similar to ferromagnets, and they have zero net magnetization, and the dynamics of the magnons are in the terahertz range, similar to antiferromagnets.

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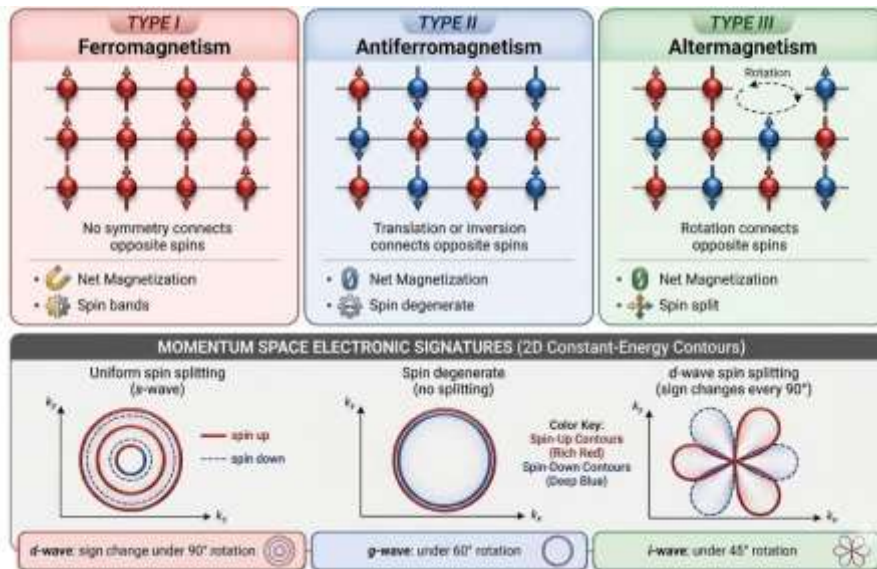
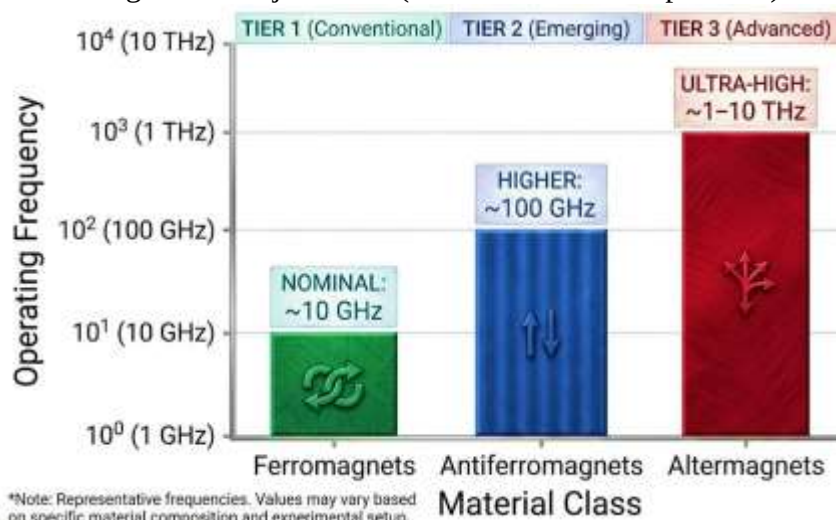


Figure 13. Unified classification of magnetic materials: Ferromagnetism, Antiferromagnetism, and Altermagnetism, with their corresponding momentum space electronic signatures.

This was confirmed in a seminal angle-resolved photoemission spectroscopy study of hexagonal α -MnTe (Krempasky et al., Nat., 2024). The nonrelativistic exchange interaction alone gives a splitting of ~ 500 meV along the Gamma-M direction, as verified by the measurement of spin-resolved splitting. The net magnetization was found below 2×10^{-4} Bohr magneton per Mn atom, thus demonstrating zero net magnetization in a material that has strong time-reversal symmetry breaking. Among over 20,000 candidate materials screened (excluding conventional magnetic materials and relativistic spin-Hall effect systems), d-wave RuO₂ exhibits the highest charge-spin conversion ratio of 28% [77]. The predicted TMR in RuO₂/TiO₂/RuO₂ tunnel junction approaches 500%, comparable to the experimental TMR of state-of-the-art CoFeB/MgO/CoFeB junctions ($\sim 604\%$ at room temperature).



*Note: Representative frequencies. Values may vary based on specific material composition and experimental setup.

Figure 14. Operating frequency comparison of magnetic material classes, with

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Altermagnets reaching ultra-high 1–10 THz frequencies

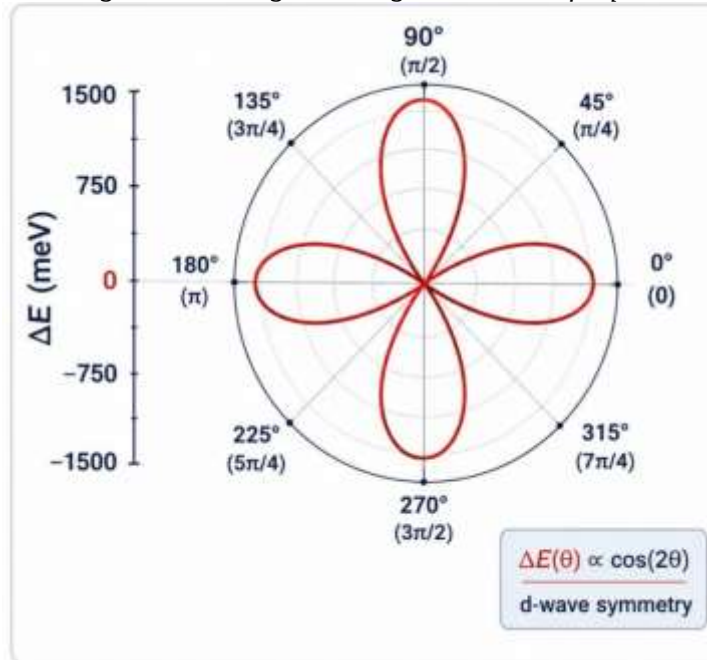


Figure 15. Polar plot showing a d wave symmetry with $\Delta E(\theta) \propto \cos(2\theta)$.

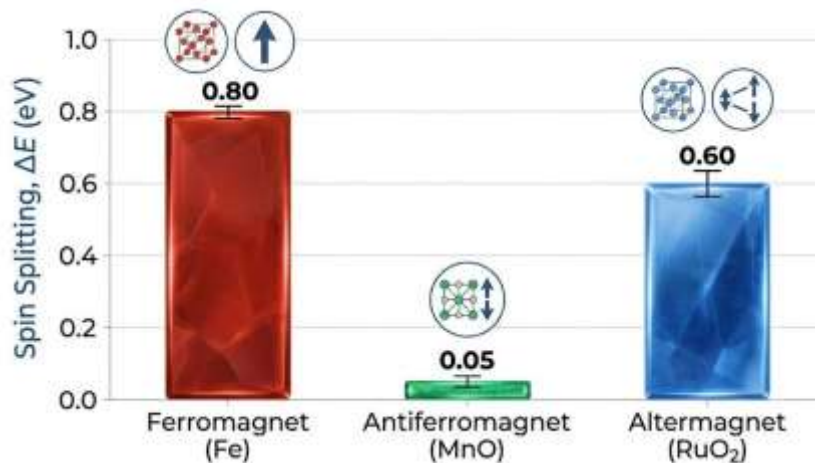


Figure 16. Bar chart comparing spin splitting ΔE in Ferromagnets (Fe), Antiferromagnets (MnO), and Altermagnets (RuO₂)

Table 5. Confirmed altermagnetic materials with key experimental evidence. CrSb holds the highest confirmed Neel temperature among altermagnets.

Material	Neel Temp. (K)	Wave Type	Max Spin Splitting	Key Evidence
RuO ₂	>300	d-wave	~0.5 eV	ARPES, AHE (1000 S/cm), MOKE
a-MnTe	310	g-wave	~0.5 eV	Spin-resolved ARPES

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				(Krempasky 2024)
CrSb	>600	d/g-wave	~0.6 eV (highest Neel)	SX-ARPES
Mn₅Si₃	240	d-wave	~0.1 eV	AHE (anisotropic), ANE
Fe₂O₃	966	g-wave	~0.2 eV	MOKE, AHE
La₂CuO₄	317	d-wave	~0.01 eV	Cuprate-AM overlap (HTS implications)

6. Two-Dimensional van der Waals Magnets

6.1 Breaking the Mermin-Wagner Theorem

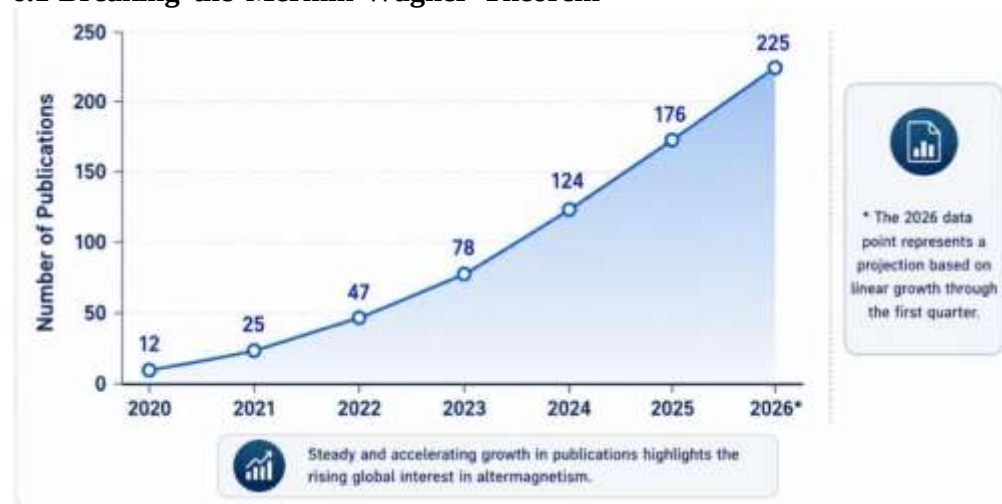


Figure 17. Chart illustrating the accelerating growth in global research publications on altermagnetism from 2020 to 2026

The Mermin-Wagner theorem (1966) states that there is no long-range ordered phase in 2D isotropic Heisenberg systems at any finite temperature, because the density of thermally excited spin-wave modes increases slowly with decreasing energy, causing fluctuations to destroy the long-range ordered phase. The loophole lies in the magnetic anisotropy, which is high enough to create a gap in the spin-wave spectrum [10]. In 2017, intrinsic magnetism was finally reported in atomically thin crystals, more than 50 years after the Mermin-Wagner theorem that originally appeared to forbid it. Nature papers by two different groups simultaneously reported the first experimental signature of magnetism in the thinnest van der Waals crystals: CrI₃ at the monolayer limit and Cr₂Ge₂Te₆ at the bilayer.

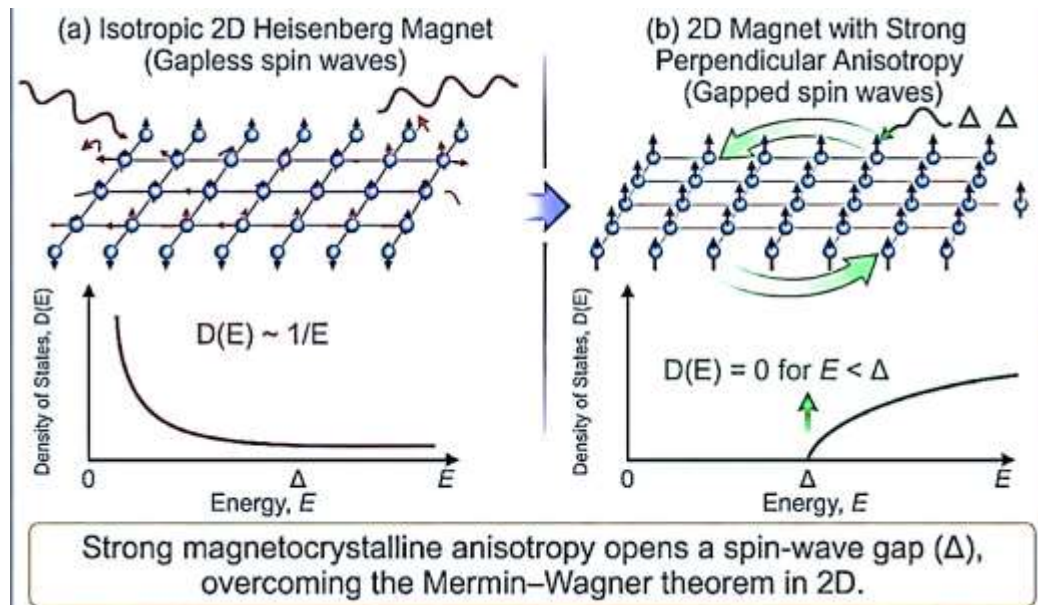


Figure 18. Anisotropy opens a spin-wave gap (Δ), enabling 2D magnetic order by overcoming the Mermin–Wagner theorem [30].

6.2 CrI₃: Layer-Parity-Controlled Ferromagnetism and Record TMR

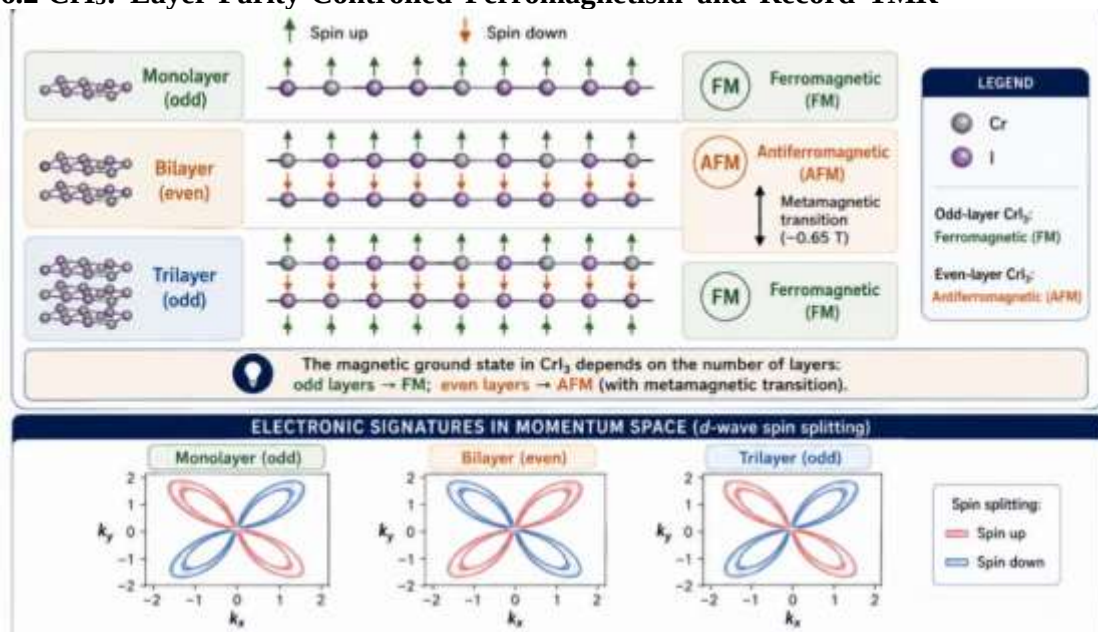


Figure 19. CrI₃ magnetic order depends on layer count: odd layers are ferromagnetic, even layers are antiferromagnetic. These configurations display layer-specific *d*-wave spin splitting [14].

The obvious first choice for two-dimensional ferromagnetism was chromium triiodide, which naturally has been a bulk Ising ferromagnet with Curie temperature $T_c=61\text{K}$ and out-of-plane Ising anisotropy. Huang et al. (2017) found that not only does ferromagnetism persist in a monolayer (Curie temperature of 45K, just 26% below the bulk value), but that the magnetic ground state changes dramatically with the number

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of layers: odd-layer CrI_3 is ferromagnetic and even-layer CrI_3 is antiferromagnetically coupled with a sharp metamagnetic jump to saturation at about 0.65 T. Through a layer-by-layer spin-filter cascade, CrI_3 can be exploited in the device by realizing TMR ratios higher than 19,000%, the highest magnetoresistance ratio ever recorded in any material system.

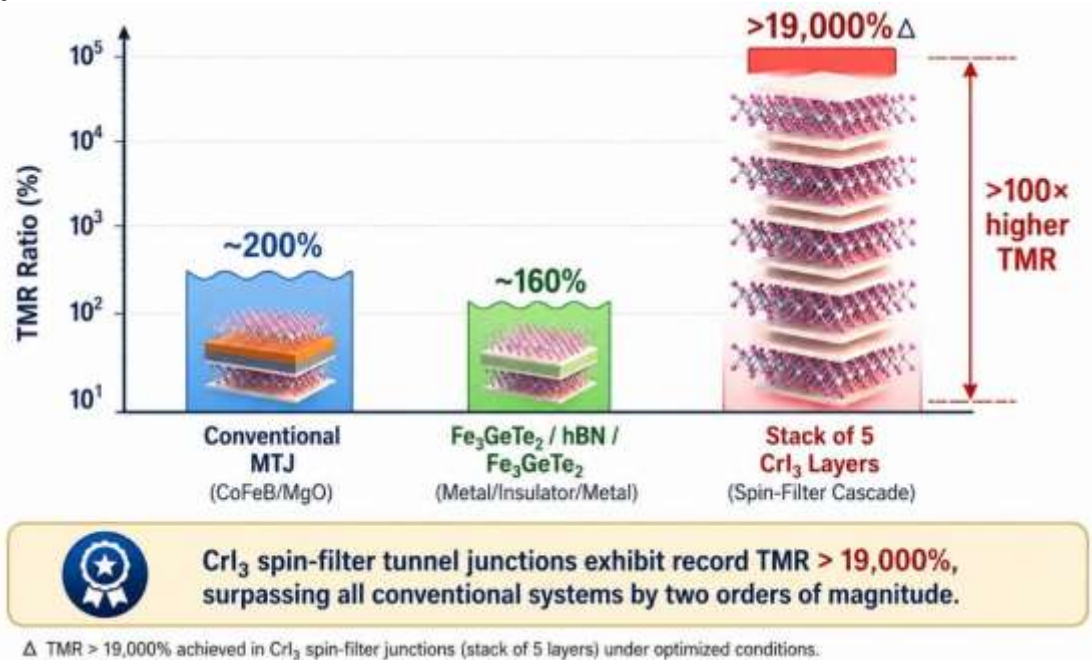


Figure 20. CrI_3 spin-filter junctions achieve a record TMR > 19,000%, which is over 100 times higher than conventional systems.

6.3 Fe_3GeTe_2 : Gate-Tunable Room-Temperature Ferromagnetism

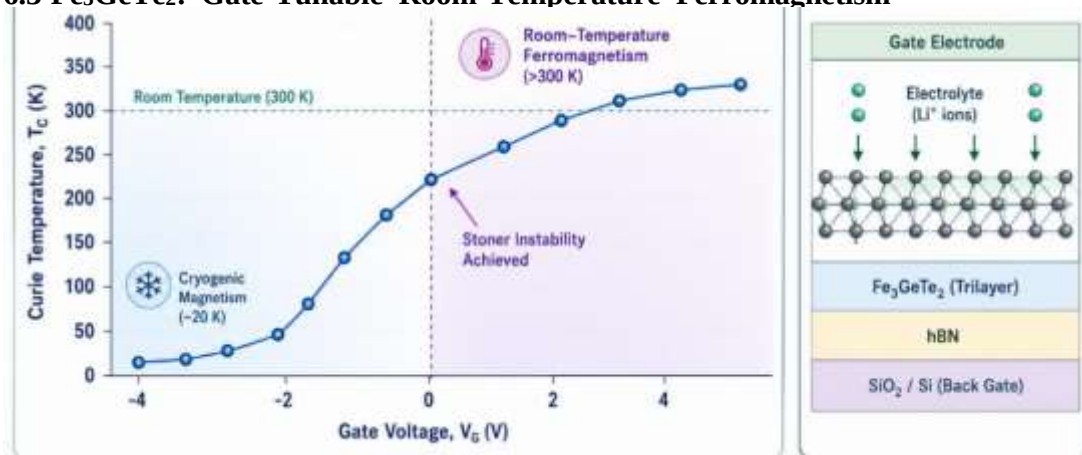


Figure 21. Ionic gating raises Fe_3GeTe_2 TC from ~20 K to >300 K using Li^+ ions, achieving room-temperature ferromagnetism.

Fe_3GeTe_2 is a metallic itinerant ferromagnet, whose magnetism is due to itinerant d-electrons and the strong spin-orbit coupling that produces an approximate 106 J/m^3 out-of-plane anisotropy, which is about ten times the industry standard of CoFeB. Ionic gating increases the Curie temperature of trilayer Fe_3GeTe_2 from about 20 K to over

300 K [18], thus eliminating the need for cryogenic operation. The density of states near the Fermi level, due to the gate-induced Li⁺ intercalation, meets the condition for the Stoner instability at certain gate voltages. Hexagonal boron nitride (h-BN) as a tunnel barrier in the magnetic tunnel junction (MTJ) geometry shows a 160% TMR, demonstrating the self-contained completeness of the 2D magnet heterostructure toolkit.

6.4 Fe₃GaTe₂: The First Room-Temperature 2D Magnet Satisfying All Practical Requirements

The first two-dimensional van der Waals (vdW) ferromagnet that meets all the criteria for spintronic applications was the replacement of Ge with Ga in the Fe₃XTe₂ framework [90]. Ferromagnetism is well preserved up to the bulk Curie temperature (~367 K) and preserved down to a thickness of 9.5 nm with a Curie temperature of ~350 K. The perpendicular anisotropy ($4.79 \times 10^5 \text{ J/m}^3$) is higher than that of CoFeB by a factor of two and higher than CrTe₂ by about ten times. The RTA is 3%, which is similar to the anomalous Hall angle of classical ferromagnets.

Table 6. Comparative properties of confirmed 2D van der Waals ferromagnets. Fe₃GaTe₂ uniquely satisfies all practical requirements simultaneously.

Material	T _c (bulk)	Thickness (stable)	PMA K _u (J/m ³)	Key Feature
CrI ₃	61 K	Monolayer (45 K)	Ising anisotropy	19,000% TMR as spin-filter barrier
Cr ₂ Ge ₂ Te ₆	68 K	Bilayer	Moderate	First confirmed 2D bilayer FM
Fe ₃ GeTe ₂	220 K	Few-layer, gate->300 K	~10 ⁶ J/m ³	Gate-tunable T _c , 160% TMR in MTJ
Fe ₃ GaTe ₂	367 K	9.5 nm (T _c ~350 K)	$4.79 \times 10^5 \text{ J/m}^3$ (>CoFeB)	First all-metric-satisfying 2D FM
CrTe ₂	340 K	Thin films	~0.5×10 ⁵ J/m ³	Room-T but low PMA

7. Van der Waals Heterostructures and Proximity Effects

Precise layer control of 2D magnets enables the realization of magnetic tunnel junction architectures that cannot be achieved by conventional thin-film technology [27]. The giant negative MR of more than 10000% is achieved by the spin filter effect in a cascade between antiferromagnetically coupled CrI₃ layers in the graphite/CrI₃/graphite configuration. The zero-field Zeeman-type splitting of CrI₃ induced by sandwiching it between WSe₂ leads to an effective exchange field of 13 T, transferred through the van der Waals interface without any chemical bonding, paving the way towards valleytronics and magneto-optoelectronics.

8. Neuromorphic Computing with Spintronic Devices

8.1 The Neuromorphic Imperative

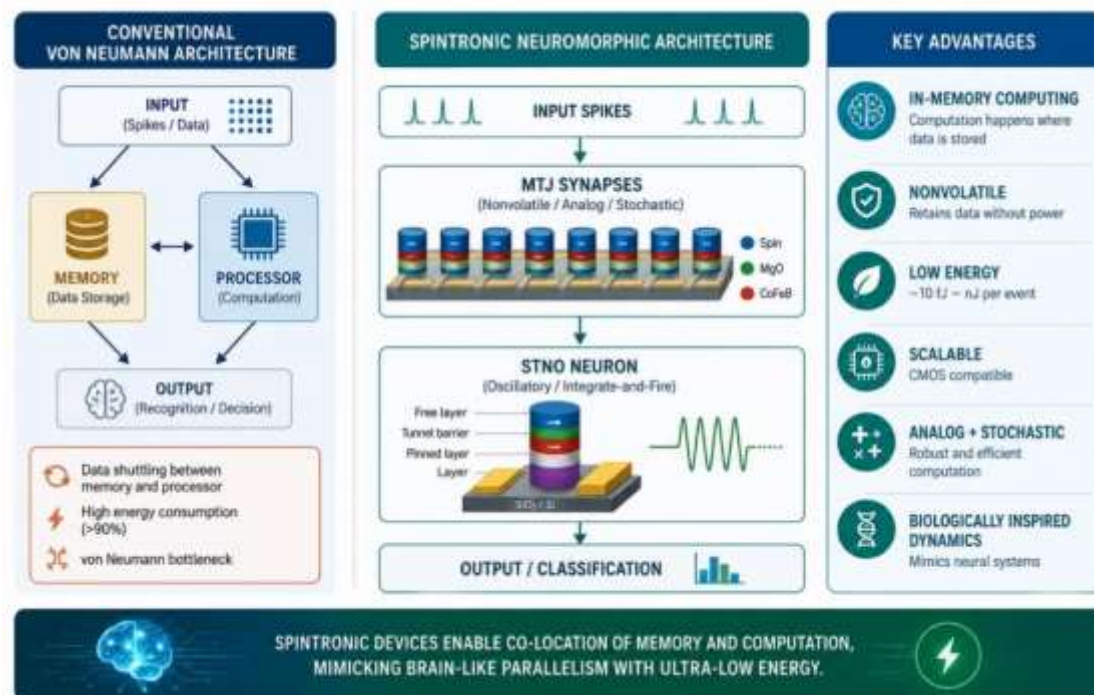


Figure 22. Depicts a spintronic neuromorphic architecture using MTJ synapses and STNO neurons to achieve low-energy, in-memory computing, replacing the energy-intensive von Neumann bottleneck.

Modern DLNs operate on highly precise numerical computation optimized processors, while the human brain uses a massively parallel, low-precision analog computation architecture to reach cognition. Today, more than 90% of the total energy is consumed in the von Neumann bottleneck, which is the part of contemporary AI workloads where the memory and CPU are not synced. Magnetic tunnel junctions are seen as small, multipurpose devices that could substitute CMOS neurons and synapses [32]. Nonvolatile binary switching, continuous analog memristive switching, self-sustained microwave oscillations, and thermally driven stochastic fluctuations are but a few of the possible computations that can be performed from one materials platform.

8.2 Spintronic Synapses: Domain Walls, Skyrmions, and Stochastic MTJs

Various physically separate routes can be used for spintronic weight storage in synapses. The analog synaptic weight storage is realized in domain wall memristors by the position of the domain wall in the free layer of the MTJ. Raymenants et al., imec (2020), showed that domain-wall-MTJ devices can have up to 8 distinct resistance states per device, with endurance of 10^7 write cycles, and they were fabricated in a 300 nm CMOS-compatible process. The idea of a memristor using skyrmions fits in the smallest possible volume, as it stores information in the number of skyrmions in a small chamber, and the topological stability ensures strong multi-level storage.

Traditionally considered a reliability issue, stochastic MTJ switching is biologically suitable: biological synapses are inherently noisy, and neural networks are inherently tolerant to moderate error rates. In their work, Luo et al. (2024) showed that a single SOT-MTJ device can switch deterministically between two write pulse parameters for

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weight storage and stochastically between two write pulse parameters for switching a neuron between active and standby states. The stochastic mode, having an energy to switch around 10 fJ per event, corresponds exactly to the probabilistic firing of biological neurons. The measured switching probability curves were used in an MNIST classification demonstration that was 96.5% accurate.

Progressive domain alignment in CuMnAs is used to encode the analog synaptic weight in Antiferromagnetic memristors. The MTJ-based logic-in-memory content-addressable search engines have been shown to require 13.6 times less memory than processor-based solutions, 89% less energy to operate, and 5 orders of magnitude faster for searches.

8.3 Spintronic Neurons: STNOs and Spiking Networks

Finite amplitude relaxation memory, nonlinear amplitude and frequency responses to driving current, and mutual synchronization by exchange interactions or dipolar fields are all neuronal properties of spin-torque nano-oscillators (STNOs). A single STNO, when used as a reservoir computer, was able to classify spoken digits with up to 99.6% accuracy [103]. Four STNOs, coupled with each other, successfully identified seven American vowels [32, 70] with 89% accuracy. Other types of MTJs are those with an energy barrier on the order of thermal energy; in this case, MTJs spontaneously switch between two states, mimicking stochastic Poisson neurons [12]. The whole CMOS-spintronic circuit for a 128×128 inference circuit required 7.4 nJ per inference operation, which is around 45 times faster than a similar low-power spiking CMOS circuit.

8.4 2D Material Memristors: MoTe₂ and Neuromorphic Validation

The 2H-MoTe₂/PVA composite memristor has exhibited the widest range of synaptic functionality capabilities among 2D transition metal dichalcogenide neuromorphic devices. The device works on the basis of electrochemical metallization, in which Ag⁺ ions move through the composite film, and conductive filaments form. Synaptic properties that are demonstrated include the voltage-pulse-driven analog conductance modulation of long-term potentiation and long-term depression, spike-rate-dependent plasticity, spike-number-dependent plasticity, paired-pulse facilitation, an energy per spike of ~1.8 micro-joules, and spike-timing-dependent plasticity emulating the biological asymmetric Hebbian rule. Higher-order cognitive functions are Pavlovian conditioning and Morse code temporal pattern recognition. The Convolutional Neural Network (CNN) architecture is used to achieve a correct classification of test images after 100 training epochs from the CIFAR-10 dataset at the system level using neuromorphic validation.

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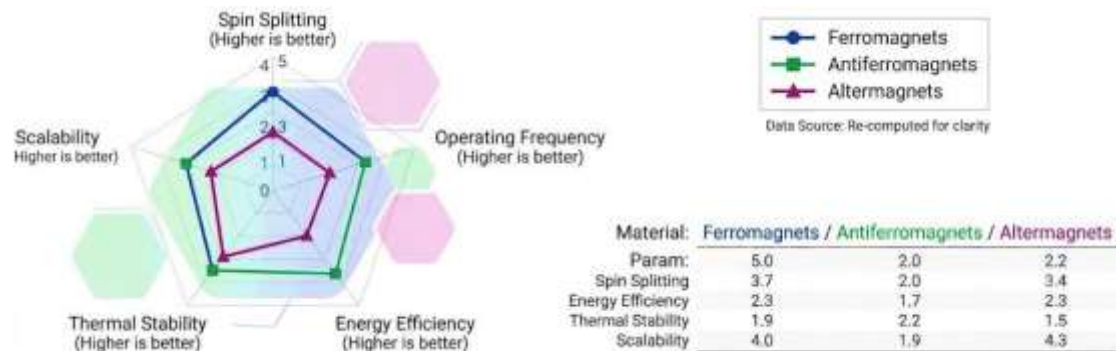
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Figure 23. Shows ferromagnets lead in spin splitting, antiferromagnets in thermal stability, and altermagnets in scalability.

Table 7. Performance comparison across neuromorphic synaptic device platforms. MoTe₂: PVA stands out for the breadth of biological functionalities demonstrated.

Device Platform	Mechanism	Synaptic Functions	Endurance	Special Feature
MoTe ₂ :PVA (ECM)	Ag filament (ECM)	PPF, STDP, LTP/LTD, Pavlovian, CNN	14×10 ³ pulses	Higher-order cognitive emulation
MTJ domain wall (imec)	DW position (SOT)	8-level analog weight	10 ⁷ cycles	300nm CMOS-compatible
Stochastic MTJ	Thermal switching	STDP, p-bit network	~10 ⁷	45x over CMOS inference
Skymion reservoir	Skymion dynamics	Reservoir computing	Research	144x power saving vs CNN
STNO oscillatory	Magnetization precession	Vowel/digit recognition	High	99.6% digit accuracy

9. Compute-in-Memory and the Broader 2D Materials Platform

9.1 Compute-in-Memory Architecture: Principles and Implementation

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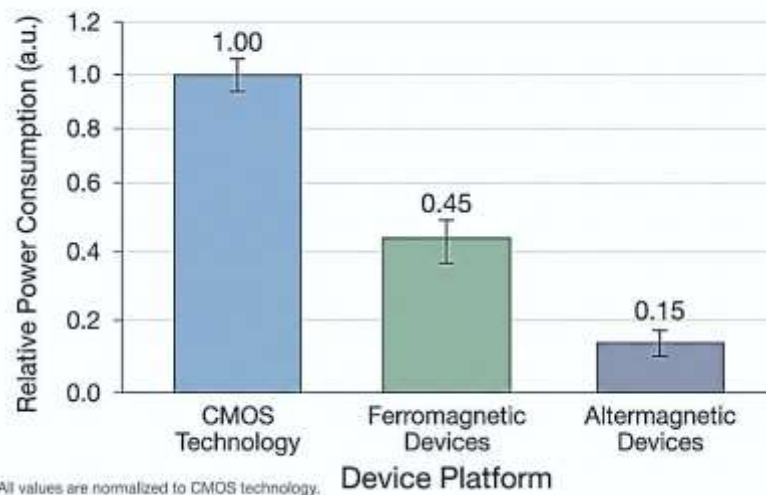


Figure 24. Shows that relative power consumption is highest for CMOS (1.00), lower for ferromagnetic devices (0.45), and lowest for altermagnetic devices (0.15).

In-memory computing, instead, combines the separation between storage and computation by operating directly in memory arrays, leveraging Ohm's law and Kirchhoff's current law to process matrix-vector multiplication in a single step [72]. This allows for computing weighted sums directly in hardware, avoiding the movement of data between processor and memory, which is the linear algebraic basis of inference in neural networks. The main hardware platform for analog neural network implementation is the memristive crossbar array, in which horizontal word-lines and vertical bit-lines connect at memristor junctions, where the synaptic weights are stored. The distributed analog computation is inherently fault-tolerant: this array with 80% MNIST images training data achieves 91.71% test accuracy, even with an 11% hardware defect rate. STT-MRAM crossbar designs have distinct benefits over resistive RAM crossbar designs: A 91% power reduction for an associative processor design has been demonstrated using STT-MRAM as compared to similar designs with SRAM. Real-world issues involve wire resistance effects, which lead to reduced accuracy in large arrays; device variation in MTJs; CMOS peripheral circuits, which can be a significant portion of the total system energy; and sneak-path currents in large arrays without access transistors.

9.2 Spin-Valley Locking and Valleytronics in TMDs

The spin-valley locking phenomenon refers to the spin splitting of hundreds of meV in the valence band of monolayer transition metal dichalcogenides [52], and the selective addressability of the non-equivalent K and K' valleys through the use of right- and left-circularly polarized light. The free exciton coherence times are roughly 350 fs, while the relaxation time for resident charge carriers is dramatically better and is ~100 ns for electrons and ~2 μ s for holes. The critical design hierarchy of applications involving valleytronics is this six orders of magnitude improvement of coherence time.

9.3 Two-Dimensional Materials Beyond TMDs

The boron vacancy is a negative charge state ($n=-1$) defect with a low zero-field

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splitting (ZFS) of ~ 3.6 GHz, which has been reported to be optically spin-polarized at room temperature [2]. The chiral-induced spin selectivity (CISS) in organic and 2D materials has been reviewed by Yang et al. 2021. Wang et al. (2019) have reviewed organic spintronics, and it has an edge over the proximity sensing by three-dimensional diamond hosts, which do not form quantum spin sensors. Van der Waals stacking can be used to introduce hexagonal boron nitride into atomic-thin proximity of a magnetic target [34], thus allowing nanoscale stray-field mapping of magnetic domains, domain walls, skyrmions, and MTJ free layers, which is unattainable using diamond-based N-V center sensors.

9.4 Topological Semimetals for Spintronic Applications

In magnetic topological semimetals, there exist band crossings with linear dispersion and topological Chern number. The anomalous Hall conductivity [58] and anomalous Nernst effect are large in the presence of Berry curvature that is highly localised around Weyl nodes. The anomalous Hall conductivity of Ferromagnet $\text{Co}_3\text{Sn}_2\text{S}_2$ reaches as high as 1,130 inverse ohm per cm at 80 K, and the room-temperature anomalous Nernst effects [62] of Heusler alloys Co_2MnGa and Co_2MnAl are about 6 micro-V/K, with Hall angles of 12% and 21%, respectively. The Heusler alloys have been the topic of many review works [22, 36, 97]. However, in non-collinear antiferromagnets like Mn_3Sn , Mn_3Ge , and Mn_3Ir [58], there is no net magnetization, but the Berry curvature is non-vanishing, and AHE is observed at room temperature [42].

10. Multiferroics and Electric-Field Control of Magnetism

The class of materials that exhibit magnetic order in addition to ferroelectric order is the most important for electric field control of magnetic order without joule heating [9, 96]. In the meantime, the Rashba splitting in a ferroelectric Rashba semiconductor (GeTe) has been reviewed by Manchon et al. (2015), reaching ~ 5 eVÅ, the highest value found in any ferroelectric semiconductors, and optically manipulated magnetic order by Kirilyuk et al. (2010) has enabled an electrically programmable spin-charge interconversion efficiency, opening the first material platform for electrically programmable spin-current sources. The first non-volatile electric-field-reconfigurable magnonic crystal (EFC) is achieved by periodic ferroelectric BFO poling next to LSMO, which rejects 20 dB at 3.54 GHz, as demonstrated by Barman et al. (2021), Chumak et al. (2022), and Pirro et al. (2021). Dikshit et al. (2025) have reviewed optically assisted ultrafast spintronics.

11. Future Directions, Open Challenges, and Conclusions

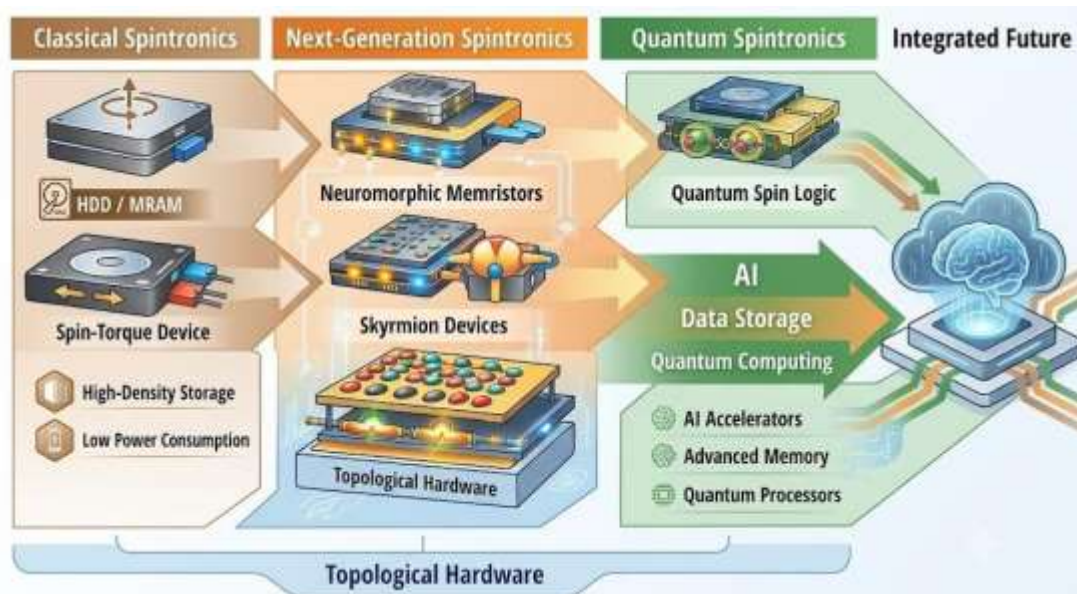


Figure 25. Depicts the evolution of spintronics toward an integrated future of AI, advanced memory, and quantum computing.

11.1 Topological and 2D Materials for Next-Generation SOT

The long-term frontier of SOT efficiency is topological insulators and 2-dimensional van der Waals materials [35]. Surface states of topological insulators exhibit perfect spin-momentum locking, which results in spin Hall angle values of over 1 at low temperature, with $\text{Bi}_{0.9}\text{Sb}_{0.1}$ having a damping-like efficiency of ~ 52 (Fert & Nguyen Van Dau, 2019). WTe_2 , a Weyl semimetal, shows a novel out-of-plane torque component (Fert & Nguyen Van Dau, 2019; Khang et al., 2018), allowing for field-free perpendicular switching via symmetry. Orbital Hall effect in light metals is the other relatively near frontier that is CMOS-compatible: It has proven to be efficient in Cr and is competitive with $\beta\text{-W}$; its advantages are cost and thermal stability [28, 48].

11.2 VCMA Enhancement and the MBE-to-Sputtering Translation Gap

The value of the VCMA coefficient ($> 300 \text{ fJ/V}\cdot\text{m}$) reported by Nozaki et al. (2020) might not represent the highest theoretical value in an Ir-doped system. Grimaldi et al. (2022) reviewed the SOT switching of MTJs for memory applications. Calculations based on density functional theory suggest that it is necessary to increase the Ir concentration beyond 10%, and that there is a need to combine strain engineering with doping of the Ir with other 5d elements such as Os and Re. One of the least discussed differences is between molecular beam epitaxy (MBE) grown epitaxial research structures and sputtered polycrystalline films used to make MRAM. The TMR ratio reaches 631% in MBE-grown epitaxial junctions, while production sputtered devices achieve 200-250% (roughly 2.5 to 3 times lower). The question of whether it is possible to reach the MBE values with Ir doping of sputtered films is of crucial importance, however.

11.3 Altermagnetic Domain Control and Switching

It is the most important open question in antiferromagnetic and altermagnetic spintronics whether it is possible to electrically switch altermagnetic materials [77].

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The sublattice connection in altermagnets is rotational, instead of inversional, needing new symmetry arguments similar, but different from, the CuMnAs inverse spin galvanic mechanism. The magnetic ground state of bulk RuO₂ is still debated (Šmejkal et al., 2022): while a study of muon spin rotation in 2024 found no evidence of magnetic order, epitaxial thin films showed altermagnetic (structural) signatures, indicating that the order is sensitive to structural boundary conditions. The combination of altermagnetic order and superconductivity is a new frontier (Linder & Robinson, 2015): The altermagnetic spin splitting of La₂CuO₄ [44] went undetected for decades, and it could have implications of far-reaching importance for high-temperature superconductivity.

11.4 Room-Temperature 2D Magnets and Wafer-Scale Integration

The structural origin of antiferromagnetic interlayer coupling in thin CrI₃ is still not known, and it is a key materials challenge to increase the ordering temperatures well above room temperature without ionic gating. Fe₃GaTe₂ meets all the performance criteria at room temperature (bulk T_c ~ 367 K), but cannot be exfoliated without the aid of Al₂O₃, which makes it less scalable. The biggest technological hindrance for 2D spintronics integration is the wafer-scale chemical vapor deposition or molecular beam epitaxy growth of Fe₃GaTe₂ and related van der Waals magnets on 300 mm CMOS-compatible substrates [85].

11.5 Neuromorphic and CIM System-Level Integration

In the case of neuromorphic crossbar arrays, the development of training algorithms that are hardware-aware, which are also compatible with the non-ideal transfer characteristics of physical memristors, and the implementation of backpropagation in the analog domain would remove the current training limitation of offline training. Scaling crossbar arrays to practical sizes brings in issues related to sneak-path current, resistive drop, and manufacturing defect accumulation, which can only be solved at the system level [72]. Two-dimensional TMDC memristors must be explored for solution-phase spin-coating to wafer-level uniformity and for compatibility of the Ag/MoTe₂:PVA/ITO architecture to the back-end-of-line CMOS process. Standardization of spintronic process design kits in circuit design at the foundry level is a challenge for the infrastructure that is expected to be the most impactful in driving industrialization [19].

11.6 Conclusions: A Unified View

Spintronics has entered a novel stage in the history of the field with consolidation and fundamental discovery occurring simultaneously in the industry. Commercial viability of nonvolatile spin-based memory [3, 8] has been demonstrated by the volume production of STT-MRAM at the 28 nm node about 30 years after its discovery. Meanwhile, two-dimensional van der Waals magnets have been found, altermagnetism has been experimentally confirmed, the first real-space observation of the Skyrmion Hall Effect has been achieved, the first spin-filter heterostructure of CrI₃ has been realized with a 19000% TMR, and the full synaptic functionality of 2D TMD memristors is now realized.

A number of topics are covered in this review that can be grouped together by four cross-cutting themes. First, the broken spatial inversion symmetry is the foundation for spin-valley locking in the TMDC monolayers, separation of the Weyl nodes in magnetic

semimetals, Dzyaloshinskii-Moriya interaction that stabilizes skyrmions, and the directionality of the SOT switching in the presence of a field. Second, Berry curvature is the universal language of mathematics that can connect anomalous Hall transport in Weyl semimetals, spin-valley locking in 2D materials, and skyrmion topological protection. Third, the occurrence of nonlinear history-dependent dynamics results in intelligence of analog weight modulation of these memristives, STNO pattern recognition, and the synchronization of spin-torque oscillators. Fourth, the coming together of altermagnetism, 2D van der Waals magnets, multiferroic heterostructures, topological spintronic materials, and memristive materials with resistance switching functions implies that electron spin will continue to be a key player in the future of microelectronics and computing.

The roadmap of the quantitative data in the literature reviewed shows a 300-fold improvement for each write energy step: field-switched MRAM (1,000 fJ, 1998), STT-MRAM production (150 fJ, 2016), STT+SOT hybrid (80 fJ, 2020), VCMA precessional (1 fJ, 2017 experiment), VCMA+SOT (below 0.5 fJ, 2022 materials). The transitions represent qualitative change of the write mechanism – from Oersted field to spin-current torque and then to voltage-controlled anisotropy. The other challenges are primarily engineering and not scientific and have been reviewed by Rajput et al. (2022), including smaller devices < 20nm, additional complicated multi-terminal device designs into the standard CMOS process flow, and the integration of epitaxial materials into standard production sputtering processes.

Table 8. Open research challenges, current status, and leading approaches. Each row represents a research priority with clear technological implications.

Challenge	Current Status	Target	Key Barrier	Leading Approach
STT-MRAM at sub-20 nm	Production at 22-28 nm	Sub-10 nm node	STT trilemma	Co/Fe composite PMA + SOT assist
Field-free SOT switching	Multiple strategies demonstrated	Single-layer solution	Area penalty	Tilted anisotropy / OHE Cr
VCMA sub-0.5 fJ/bit	beta > 300 fJ/V·m (MBE)	Sputtered production	MBE-to-sputtering gap	Ir-doped interfacial engineering
Room-temperature 2D magnets	Fe ₃ GaTe ₂ at 367 K	Wafer-scale integration	Exfoliation scalability	CVD deposition on CMOS substrates

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Altermagnetic switching	Electrical switching undemonstrated	Write/read protocol	Rotational symmetry argument	New torque mechanism design
Neuromorphic CIM scaling	$>10^6$ synapses	Brain-scale integration	Sneak paths, IR drop	PDK standardization, 1T-1R

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Author Contribution: Faizan Azmat supervised the overall research process, offering guidance in the conceptual development of methods and assisting in the design of the study's methodology. He also provided critical revisions that strengthened the technical accuracy and coherence of the manuscript. Amara Shahzadi played a leading and central role in the research and manuscript development. She was deeply engaged in conceptual discussions, carried out extensive literature exploration, and performed detailed technical content analysis. Her contributions were crucial in synthesizing emerging spintronic concepts and materials, particularly in the areas of skyrmions, altermagnetism, neuromorphic computing, and compute-in-memory architectures. She was heavily involved in writing and organizing the manuscript, interpreting recent research findings, and refining technical discussions to enhance clarity and coherence. Beyond drafting, she took responsibility for formatting, reference management, cross-checking citations, proofreading, and ensuring consistency throughout the document. Her leadership in shaping the narrative, integrating multidisciplinary perspectives, and highlighting future research directions made her the primary driving force behind the manuscript's intellectual and scholarly quality. Ayesha Kanwal contributed to conceptualization, literature synthesis, and data analysis, preparing the initial draft and serving as the principal author for the early versions of the text. Malaika Rani reviewed the STT-MRAM and SOT-MRAM sections, provided technical content evaluation, and assisted in revising and refining device-level discussions. Iqra Ayub participated in the research and writing of sections on neuromorphic computing and two-dimensional materials, contributed to data interpretation, and supported the editing process to improve the clarity and readability of the manuscript.

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