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# Spintronic Materials and Magnetic Storage Systems: Recent Advances, Challenges, and Future Perspectives

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**Abstract**
Spintronics exploits the intrinsic spin of electrons, together with their electrical charge, to develop nonvolatile, high-speed, and energy-efficient information technologies. The discovery of giant magnetoresistance and the subsequent development of magnetic tunnel junctions established the material and device foundations of modern magnetic storage. Contemporary spintronic memory systems use nanoscale ferromagnetic layers, antiferromagnetic materials, heavy metals, tunnel barriers, topological spin textures, and two-dimensional magnetic crystals to write, retain, and read information. Spin-transfer-torque magnetic random-access memory has progressed toward embedded commercial applications because of its nonvolatility, compatibility with complementary metal–oxide–semiconductor processing, high endurance, and relatively fast switching. Spin–orbit-torque memory separates the write and read paths and may provide higher endurance and faster operation, although field-free switching, power consumption, and cell-area requirements remain important challenges. This review examines recent advances in spintronic materials and magnetic storage systems, with emphasis on magnetic tunnel junctions, perpendicular magnetic anisotropy, spin-transfer torque, spin–orbit torque, voltage-controlled magnetic anisotropy, domain-wall racetrack devices, magnetic skyrmions, antiferromagnetic memories, two-dimensional magnets, and spintronic neuromorphic hardware. The relationships among material composition, interface quality, thermal stability, switching current, tunnelling magnetoresistance, scalability, and device reliability are discussed. Major barriers include stochastic switching, tunnel-barrier degradation, magnetic variability, fabrication defects, thermal instability, read–write disturbance, and integration with semiconductor manufacturing. Future progress is expected through interface engineering, orbital and spin Hall materials, antiferromagnetic and ferrimagnetic systems, voltage-assisted switching, topological textures, three-dimensional integration, and intelligent device–circuit co-design. Spintronic storage is therefore developing from a specialized memory technology into a broader platform for nonvolatile computing, in-memory processing, artificial intelligence, and energy-efficient electronics.

## Introduction

The continuous growth of cloud computing, artificial intelligence, autonomous systems, mobile electronics, and the Internet of Things has increased the demand for memory technologies that combine high density, rapid access, low energy consumption, long endurance, and nonvolatile data retention. Conventional semiconductor memories provide excellent performance in selected areas, but no single technology simultaneously achieves the speed of static random-access memory, the density of dynamic random-access memory, and the nonvolatility of flash storage. Spintronics offers an alternative approach by using electron spin and its associated magnetic moment as carriers of information. In a magnetic storage device, binary states may be represented by different magnetization directions, magnetic-domain configurations, resistance states, or topological spin structures. Because the magnetic state can persist without continuous electrical power, spintronic memory can reduce standby energy consumption and support instant-on computing. The experimental discovery of giant magnetoresistance in iron–chromium multilayers demonstrated that electrical resistance could be strongly altered by the relative magnetic orientation of adjacent layers. This finding transformed magnetic read-head technology and established the concept of controlling charge transport through spin-dependent scattering. Magnetic tunnel junctions subsequently became the basic storage elements of modern magnetic random-access memory. A conventional magnetic tunnel junction consists of two ferromagnetic electrodes separated by an ultrathin insulating barrier. One magnetic layer acts as a relatively fixed reference layer, whereas the magnetization of the second free layer can be switched. Parallel magnetization produces a lower resistance, while antiparallel magnetization produces a higher resistance. The tunnelling magnetoresistance ratio is commonly expressed as:

$$\mathbf{TMR = [(RAP - RP)/RP] \times 100}$$

where **RAP** is the resistance in the antiparallel state and **RP** is the resistance in the parallel state. A large TMR ratio increases the electrical distinction between stored states and improves read reliability. The demonstration of coherent spin-dependent tunnelling through crystalline magnesium oxide barriers produced room-temperature magnetoresistance ratios of approximately 180–200% in Fe/MgO/Fe and related junctions. CoFeB/MgO/CoFeB structures subsequently reached approximately 230% room-temperature magnetoresistance and became central to practical MRAM because amorphous CoFeB could crystallize favourably at the MgO interface during annealing. Recent developments have extended spintronic storage beyond conventional magnetic tunnel junctions. Spin–orbit torques, antiferromagnetic order, magnetic skyrmions, domain walls, voltage-controlled anisotropy, and two-dimensional materials provide new approaches to writing, moving, and reading magnetic information. A 2025 two-dimensional magnetic tunnel p–n junction study reported a room-temperature TMR ratio of approximately 1,100% under its stated experimental conditions, highlighting the potential of atomically thin interfaces for future low-power spin electronics.

### Fundamental Spintronic Materials and Magnetic Tunnel Junctions

Spintronic device performance is strongly controlled by the electronic and magnetic properties of the constituent materials. Ferromagnetic metals such as iron, cobalt, nickel, and their alloys provide spin-polarized electronic states. CoFe and CoFeB alloys are widely used in magnetic tunnel junctions because they combine high spin polarization, suitable magnetic properties, and compatibility with magnesium oxide barriers. The quality of the ferromagnet–insulator interface is particularly important. Roughness, oxidation, atomic intermixing, boron accumulation, and crystal defects can disrupt coherent tunnelling and reduce magnetoresistance. The MgO barrier is commonly only about one nanometre thick, making device behaviour highly sensitive to thickness variations and pinhole defects. Coherent tunnelling through MgO selectively transmits electronic states with favourable crystal symmetry. This symmetry filtering generates a large difference between the conductance of parallel and antiparallel magnetization configurations. Independent studies in 2004 established large room-temperature magnetoresistance in crystalline Fe/MgO/Fe and textured MgO-based junctions, providing a major technological

foundation for high-performance magnetic memory. The reference system of a practical magnetic tunnel junction frequently contains a synthetic antiferromagnet. Two ferromagnetic layers are separated by a thin nonmagnetic spacer and coupled in opposite directions. This configuration reduces stray magnetic fields acting on the free layer and stabilizes the reference magnetization. The free layer must satisfy conflicting requirements. It should remain stable for many years when no write current is applied, but it must also switch using a sufficiently small electrical pulse. Thermal stability is frequently represented through the dimensionless factor:

$$\Delta = Eb/kBT$$

where **Eb** is the magnetic energy barrier, **kB** is the Boltzmann constant, and **T** is absolute temperature. A high value of Δ improves data retention, but it generally increases the energy required for magnetization reversal. Perpendicular magnetic anisotropy has become essential for scaling magnetic tunnel junctions to small dimensions. In perpendicular systems, the stable magnetization directions point normal to the film plane. This orientation can provide improved thermal stability at smaller lateral dimensions compared with conventional in-plane devices. A major milestone was the demonstration of a perpendicular-anisotropy CoFeB–MgO junction that combined high thermal stability, a large magnetoresistance signal, and a low switching-current density. The interfacial anisotropy at the CoFeB/MgO boundary enabled perpendicular magnetization without requiring a thick magnetic layer. Material selection must also account for magnetic damping. Low damping reduces the current required for switching because less angular momentum is dissipated during magnetization motion. However, extremely low damping can increase switching oscillations and make reversal timing less predictable. Device optimization therefore requires balancing anisotropy, saturation magnetization, damping, volume, interface quality, and thermal stability. Alternative tunnel barriers and magnetic electrodes are being investigated to improve voltage tolerance, resistance–area product, and magnetoresistance. Heusler alloys may provide high spin polarization, while ferrimagnetic materials can combine reduced net magnetization with strong magnetic order. Two-dimensional magnets and van der Waals barriers can create atomically sharp interfaces without conventional lattice-matching constraints.

**Spin-Transfer-Torque and Spin–Orbit-Torque Magnetic Memory**

Early MRAM technologies commonly used magnetic fields generated by current-carrying lines to switch storage cells. As memory arrays became smaller, field-based writing produced high power consumption and unwanted interference between neighbouring cells. Spin-transfer torque provided a more scalable mechanism by allowing a spin-polarized current to switch the free magnetic layer directly. When an electrical current passes through the reference layer, its electrons become spin polarized. The current transfers angular momentum to the free layer, producing a torque on its magnetization. If the current exceeds a critical level and is applied for sufficient time, the magnetization reverses. Spin-transfer-torque MRAM generally uses a one-transistor–one-magnetic-tunnel-junction structure. The access transistor selects the cell and supplies the write current. Reading is performed using a smaller current that measures the tunnel-junction resistance. STT-MRAM provides nonvolatility, fast access, high endurance, radiation tolerance, and compatibility with semiconductor back-end processing. It is particularly attractive for embedded memory, cache applications, automotive electronics, industrial control, and systems requiring frequent power interruption. A central limitation is that the write current passes directly through the ultrathin MgO tunnel barrier. High-current pulses can produce dielectric stress, localized heating, defect generation, and eventual barrier failure. Increasing the write current improves switching probability and speed but reduces device lifetime. STT switching is also stochastic because thermal fluctuations influence the initial direction and timing of magnetization reversal. At short pulse widths, the distribution of switching times can become broad. Reliable operation requires a write voltage high enough to produce an acceptably low error rate under process and temperature variations. Read disturbance occurs when the read current unintentionally contributes to switching. Reducing the read current lowers disturbance risk but also decreases the sensing signal. Circuit designers must therefore balance read margin, access speed, power consumption, and reliability. Spin–orbit-torque MRAM separates the reading and writing paths. A charge current flows laterally through a heavy-metal or spin–orbit material beneath the magnetic free layer. Spin Hall and interfacial effects convert part of the charge current into a transverse spin current, which exerts torque on the adjacent magnetization. The use of a separate write channel avoids forcing the write current through the tunnel barrier. This architecture can provide high endurance and very fast switching. The demonstration of spin-torque switching generated by the large spin Hall effect of tantalum established the viability of strong current-induced torques from heavy metals. Conventional perpendicular SOT devices often require an in-plane magnetic field to break symmetry and determine the switching direction. Such an external field is unsuitable for dense integrated memory. Field-free switching has therefore become one of the most important research goals. Strategies for field-free operation include exchange bias from antiferromagnetic materials, tilted magnetic anisotropy, lateral structural asymmetry, magnetic hard masks, composition gradients, ferroelectric control, and combined SOT–STT excitation. A PtMn/ferromagnet system demonstrated spin–orbit-torque switching without an externally applied magnetic field by using antiferromagnetic exchange bias. Three-terminal SOT cells generally occupy more area than one-transistor STT cells because separate read and write connections are needed. Research therefore focuses on compact cell layouts, shared write lines, vertical integration, improved spin-current generation, and lower-current switching. Voltage-controlled magnetic anisotropy can supplement STT or SOT switching. Applying an electric field across the tunnel barrier temporarily modifies interfacial magnetic anisotropy, lowering the energy barrier during the write pulse. The anisotropy returns to its retention value after the voltage is removed. This approach may reduce switching energy but requires precise pulse timing and reliable dielectric operation.

**Domain-Wall, Skyrmion, and Racetrack Magnetic Storage**

Racetrack memory stores information in a magnetic nanowire rather than in an array of stationary isolated cells. Bits are represented by magnetic domains or topological spin textures that move along the track under electrical excitation. Fixed write and read elements can access many bits stored within the same track. In domain-wall racetrack systems, the boundaries separating oppositely magnetized domains are moved through spin-transfer or spin–orbit torque. Such architectures may provide high storage density because numerous data states can occupy one nanowire. Reliable operation requires precise domain-wall positioning. Structural defects, edge roughness, grain boundaries, and variations in magnetic anisotropy can pin domain walls. Excessive current may cause walls to overshoot their intended locations, whereas insufficient current may fail to move them. Notches and engineered anisotropy regions can provide defined storage positions, but strong pinning increases the current required for motion. Device design must balance stable positioning with efficient movement. Domain-wall interactions and changes in velocity can also cause bit spacing errors. Magnetic skyrmions are nanoscale swirling spin textures characterized by topological properties. Their small dimensions and potential motion under relatively low currents have generated interest in ultradense racetrack memory. Information may be represented by the presence or absence of a skyrmion at a selected position. Computational studies have investigated the creation, motion, spacing, and detection of skyrmions in racetrack devices. Skyrmion–skyrmion repulsion and skyrmion–edge interactions affect storage density and movement reliability. Crowding near the end of a racetrack can modify skyrmion size or lead to data loss. The skyrmion Hall effect causes many skyrmions to move at an angle to the applied current. This transverse motion can drive them toward track edges, where they may be destroyed. Antiferromagnetic skyrmions, synthetic antiferromagnetic structures, and skyrmionium textures have been proposed to reduce unwanted transverse displacement. Thermal stability represents another major issue. Very small skyrmions offer high density but may collapse through thermal fluctuations or escape through the track boundary. Material disorder can either pin skyrmions beneficially or obstruct their movement. The lifetime therefore depends on geometry, magnetic field, temperature, defects, and energy barriers.Writing a single skyrmion at a precise location, moving it without loss, and reading it electrically remain significant engineering challenges. Proposed detection methods include the topological Hall effect, magnetoresistive junctions, and local magnetic sensors. Domain-wall and skyrmion devices are also being explored for neuromorphic computing. A movable wall can create multiple resistance levels rather than only two binary states. In 2024, domain-wall magnetic tunnel junctions were experimentally used to implement spintronic synaptic and neuronal functions, demonstrating the possibility of integrating memory and computation in the same magnetic hardware.

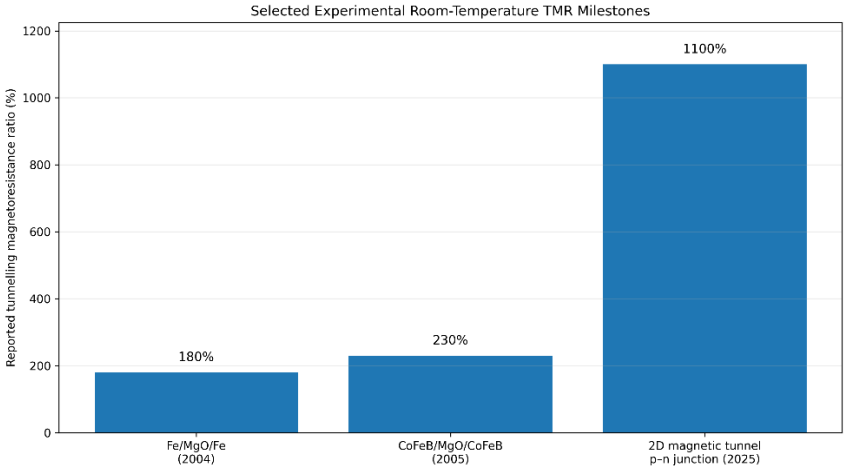
**Antiferromagnetic, Ferrimagnetic, and Two-Dimensional Spintronics**

Antiferromagnetic materials contain magnetic moments aligned in opposite directions, producing little or no net magnetization. Their weak stray fields could allow neighbouring devices to be placed close together without strong magnetic interference. Antiferromagnets can also exhibit very fast spin dynamics, potentially reaching terahertz frequencies. Their magnetic states are resistant to external magnetic-field disturbance, which is attractive for high-density and robust information storage. However, the absence of a strong net magnetization makes their states difficult to manipulate and detect. A major advance occurred with the demonstration of room-temperature electrical switching between stable antiferromagnetic configurations in CuMnAs devices. Current-induced relativistic torques reoriented the antiferromagnetic Néel vector, while anisotropic electrical resistance provided readout. Subsequent research has investigated $Mn_2Au$, PtMn, IrMn, and other antiferromagnetic systems. These materials may act as active storage media, spin-current generators, exchange-bias layers, or components of field-free SOT devices. Some reported electrical switching signals in antiferromagnets can be influenced by Joule heating, structural changes, or electromigration. Distinguishing genuine magnetic switching from nonmagnetic resistance changes

requires magnetic imaging, control experiments, temperature analysis, and repeated-device testing. Ferrimagnetic materials contain oppositely aligned magnetic sublattices of unequal magnitude. Near their magnetic-compensation point, the net magnetization can become small while magnetic order remains strong. Ferrimagnets may combine fast dynamics, low stray fields, and easier electrical detection than fully compensated antiferromagnets. Two-dimensional magnetic materials have opened another direction in spintronic research. Atomically thin crystals can be assembled into van der Waals heterostructures with relatively clean interfaces. Their magnetic, electronic, and optical properties may be controlled through electrical gates, strain, layer number, stacking angle, and chemical composition. Two-dimensional tunnel junctions may reduce interfacial disorder and enable new spin-filtering mechanisms. The reported 1,100% TMR in a two-dimensional magnetic tunnel p–n junction indicates that semiconductor band alignment and atomically thin magnetic interfaces may strongly amplify spin-dependent transport. However, reproducible wafer-scale growth, room-temperature magnetism, air stability, and semiconductor integration remain unresolved challenges. Topological insulators, Weyl semimetals, and other quantum materials are also being investigated as efficient generators of spin–orbit torque. Their surface or bulk electronic structures may provide strong spin–charge conversion using lower electrical currents than conventional heavy metals. Device implementation requires control of crystal quality, interfaces, resistivity, and compatibility with fabrication temperatures.

**Reliability Challenges and Future Perspectives**

The continued development of spintronic storage depends on reducing device variability. At nanoscale dimensions, small changes in free-layer thickness, edge shape, tunnel-barrier thickness, anisotropy, and local defects can substantially alter resistance, switching current, and thermal stability. Patterning magnetic tunnel junctions can damage their sidewalls and create redeposited material. Sidewall oxidation may reduce magnetic volume, increase leakage, or create uncontrolled switching regions. Improved etching, encapsulation, cleaning, and self-aligned fabrication are therefore essential. Tunnel-barrier reliability is critical for STT-MRAM. The barrier must be thin enough to provide useful resistance and magnetoresistance, but thick and uniform enough to withstand repeated write pulses. Barrier breakdown, trap generation, and resistance drift can limit endurance. Temperature influences nearly every aspect of magnetic memory. Higher temperatures reduce anisotropy and retention while changing resistance and switching probability. Low temperatures can increase switching current or alter transistor performance. Automotive and aerospace applications require reliable behaviour across broad temperature ranges. Magnetic retention must be guaranteed statistically across billions of cells. A nominal thermal-stability value is insufficient if a small fraction of cells contains severe structural defects. Reliability analysis should include distributions rather than only average measurements. Write-error rate is another critical metric. A memory may switch successfully in most operations but remain unsuitable if rare failures exceed the system's error-correction capability. Pulse amplitude, duration, temperature, device aging, and process variation all influence switching probability. Future STT-MRAM research will seek lower switching current without sacrificing retention. Promising approaches include double-interface free layers, optimized CoFeB compositions, low-damping materials, voltage-assisted switching, improved reference layers, and smaller resistance–area products. SOT-MRAM development will emphasize field-free switching, compact cell structures, reduced channel resistance, and stronger spin–charge conversion. Heavy metals, antiferromagnets, topological materials, and orbital-current systems are being studied as torque-generating layers. Three-dimensional integration may allow magnetic tunnel junctions to be stacked above logic circuits. Because magnetic elements can be fabricated within the back-end interconnect structure, spintronic memory may be placed close to processing units, reducing the energy and delay associated with data movement. Compute-in-memory systems use memory cells to perform logical or arithmetic operations. Magnetic tunnel junction arrays can execute Boolean operations, matrix calculations, pattern matching, and probabilistic computing. Nonvolatility permits intermediate results to remain stored without continuous power. Spintronic devices are also being adapted for artificial intelligence. Stochastic magnetic switching can generate random numbers or probabilistic neurons, while domain walls and multistate magnetic junctions can emulate synaptic weights. Hardware–software co-design is required because device variation and nonlinear response can either degrade accuracy or be used as computational resources. Long-term commercial success will depend on more than achieving a laboratory record. Materials must be manufacturable on full wafers, compatible with semiconductor thermal budgets, reproducible across large arrays, and stable for the required product lifetime. Device models must connect atomic-scale interfaces with circuit and system performance. Life-cycle considerations should also receive greater attention. Spintronic devices can reduce operating energy, but their fabrication may require tantalum, platinum, ruthenium, rare-earth elements, or other resource-intensive materials. Future research should examine material availability, deposition efficiency, waste reduction, and end-of-life recovery.




Values are selected literature milestones measured in different material systems, device geometries, and bias conditions; they are not a controlled head-to-head comparison.

Singh and Sohail (2026) examined medical negligence in Malaysian hospitals through a qualitative thematic analysis of medico-legal court cases. Their study explored organisational and governance-related factors contributing to healthcare failures, including communication problems, documentation weaknesses, and inadequate risk management systems. The findings emphasized the importance of strengthening healthcare governance and adopting system-based approaches to improve patient safety.

Qazi and Sohail (2026) investigated the factors influencing investors' intention to participate in socially responsible investing among Pakistan Stock Exchange investors. The study focused on attitude, subjective norms, and perceived behavioral control as key determinants of investment intention. The results indicated that investors' positive attitudes significantly influence their willingness to engage in socially responsible investment practices.

Mousumi and Sohail (2026) studied the relationship between service quality, customer engagement, and customer loyalty in the Malaysian telecommunications sector. Their research highlighted that effective service quality dimensions, including reliability, responsiveness, and customer support, contribute to stronger customer relationships. The study suggested that improving service quality can enhance customer engagement and promote long-term loyalty.

**Summary**

Spintronic materials have transformed magnetic storage from field-written metallic memory into nanoscale nonvolatile devices controlled by spin-polarized currents, spin–orbit torques, electrical fields, domain-wall motion, and topological spin textures. Magnetic tunnel junctions based on CoFeB and MgO remain the central components of practical MRAM. Large tunnelling magnetoresistance provides reliable electrical readout, while perpendicular magnetic anisotropy supports smaller and more thermally stable storage elements. STT-MRAM offers a strong combination of density, nonvolatility, speed, endurance, and semiconductor compatibility. Its major challenges are write-current reduction, tunnel-barrier reliability, stochastic switching, and read disturbance. SOT-MRAM separates the read and write paths and may achieve higher endurance and faster switching, but field-free operation, write-channel power, and cell size require further improvement. Domain-wall and skyrmion racetrack memories could store multiple bits in a single magnetic track. Their practical development depends on reliable nucleation, controlled movement, precise positioning, thermal stability, and electrical detection. Antiferromagnetic systems may enable ultrafast and high-density devices with low magnetic crosstalk, while two-dimensional magnets offer atomically sharp and electrically tunable interfaces. Future magnetic storage will increasingly combine spintronic devices with logic, in-memory computation, probabilistic processing, and neuromorphic systems. Progress will require coordinated advances in materials science, nanofabrication, magnetic characterization, device physics, circuit design, reliability engineering, and manufacturing integration.

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