

Magnetic tunnel junctions

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Abstract

Magnetic tunnel junctions (MTJs) underpin modern spintronics, enabling the manipulation of electron spin for information storage, sensing and logic applications beyond conventional charge-based electronics. Among them, MgO-based MTJs have become the benchmark for high-performance spintronic devices because their crystalline barriers support coherent spin-dependent tunnelling, producing large tunnelling magnetoresistance at room temperature. This Primer reviews the materials, fabrication methods and characterization techniques that govern the performance of MgO-based MTJs, emphasizing how atomic-scale structural control enables efficient spin transport. We discuss thin-film deposition techniques such as magnetron sputtering and molecular beam epitaxy, MgO barrier formation and post-deposition annealing and lithographic patterning of multilayer stacks. Structural, magnetic and transport characterization methods, including transmission electron microscopy, X-ray diffraction, magnetometry and electrical measurements, are discussed to elucidate the correlations between interfacial structure, magnetic anisotropy and tunnelling magnetoresistance. Representative results on crystallinity, magnetic properties and transport behaviour are presented alongside switching mechanisms such as spin-transfer torque, spin-orbit torque and voltage-controlled magnetic anisotropy. Emerging directions, including antiferromagnetic tunnel junctions and van der Waals MTJs, are highlighted for their potential to overcome the limitations of conventional materials. We conclude with perspectives on reproducibility, fabrication challenges and future opportunities for ultrafast, non-volatile and energy-efficient MTJ-based technologies.

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Introduction

The relentless pursuit of technological advancement in information processing and storage continues to drive the exploration of physical principles beyond the limits of conventional charge-based electronics. In this context, spintronics has emerged as a transformative paradigm that takes advantage of the electron's spin as well as its charge to enable novel device functionalities¹. At the heart of this field lies the magnetic tunnel junction (MTJ)², a nanoscale structure that not only embodies the core concepts of spintronics but also serves as the workhorse for a generation of non-volatile memory and sensing technologies.

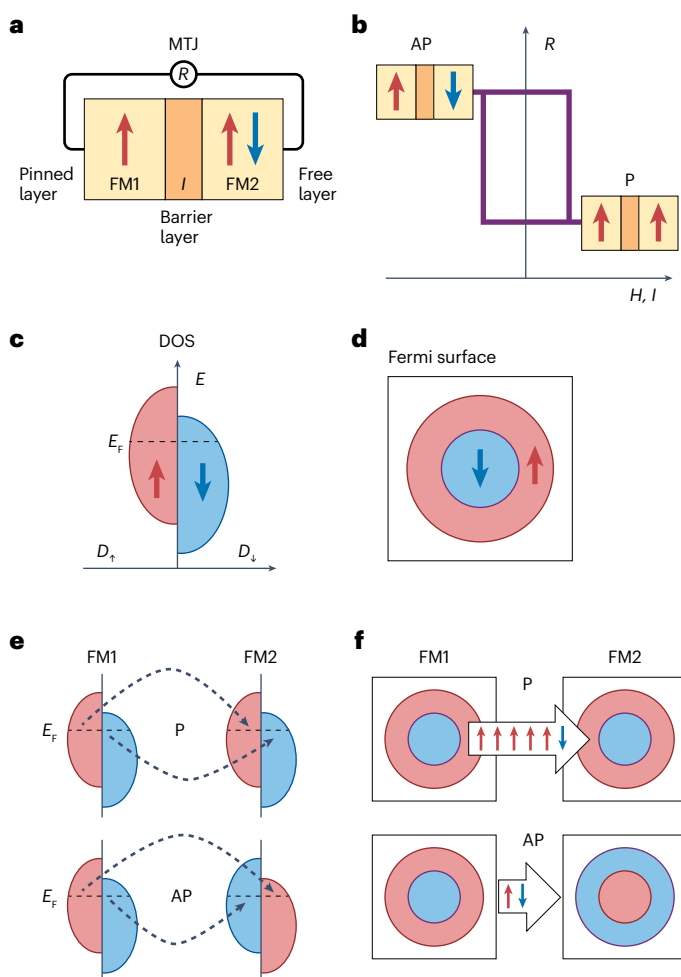


Fig. 1 | TMR in MTJs. **a**, Schematic of an magnetic tunnel junction (MTJ) comprising two ferromagnetic (FM) electrodes (FM1 and FM2) separated by a barrier layer. Magnetizations of electrodes are indicated by arrows. **b**, MTJ's resistance (R) dependent on the relative magnetization: low for parallel (P) and high for antiparallel (AP) configuration. Magnetization of the free layer can be switched by applied magnetic field H or by electric current I . **c**, Density of states (DOS) for majority (D_+) and minority (D_-) spin bands as functions of energy (E) in the two ferromagnets. **d**, Spin-split Fermi surface of a ferromagnet. Red and blue circles denote the Fermi surfaces for up-spin (small red arrow) and down-spin (small blue arrow) electrons. **e**, Mechanism of tunnelling magnetoresistance (TMR) in terms of spin-dependent DOS. Spin conduction channels are indicated by dashed arrows. **f**, Mechanism of TMR in terms of spin-split Fermi surfaces. Conduction (indicated by block arrows) between left and right FM electrodes for P and AP magnetization. The AP conduction is reduced due to a spin mismatch of the Fermi surfaces. E_F , Fermi energy.

Structurally, an MTJ consists of a multilayer stack comprising two ferromagnetic layers separated by an ultrathin insulating tunnel barrier layer, typically ~1 nm thick (Fig. 1a). One ferromagnetic layer, referred to as the pinned layer, has its magnetization direction fixed, often through exchange coupling with an adjacent antiferromagnetic (AFM) pinning layer. The other ferromagnetic layer, known as the free layer, exhibits a magnetization that can be switched between two stable states. The operating principle of an MTJ is governed on the tunnelling magnetoresistance (TMR) effect³. When the magnetizations of the free and pinned layers are aligned in a parallel configuration, the junction exhibits low resistance R_P , whereas, in the antiparallel configuration, the junction exhibits high resistance R_{AP} (Fig. 1b). This binary resistance state forms the basis for data storage, in which the low-resistance and high-resistance states represent logic '0' and '1', respectively. The TMR ratio, defined as $TMR = (R_{AP} - R_P)/R_P$, quantifies the magnitude of this effect. Commercial applications typically require a TMR of ~100% or higher at room temperature to ensure clear signal contrast and fast, reliable readout. This helps to reduce errors caused by thermal fluctuations and device variations.

Although the core concept of MTJ was first proposed in 1975 (ref. 2), a sizable TMR effect at room temperature was not demonstrated until two decades later. This milestone was achieved in FeCo/Al-O/Co and FeCo/Al-O/FeNi junctions with amorphous Al-O barriers (with stoichiometry likely close to Al_2O_3), in which TMR ratios of several tens of percent were observed, laying the foundation for modern MTJ research⁴. Subsequent advances in materials engineering led to the formation of Fe/MgO/Fe and FeCo/MgO/FeCo junctions, in which coherent spin-dependent tunnelling through crystalline MgO barriers produced TMR ratios exceeding 100%^{5,6} (Supplementary Note A and Supplementary Fig. 1). These discoveries established MgO-based MTJs as the standard for high-performance spintronic devices, and they paved the way for their integration into practical technologies such as magnetoresistive random-access memory (MRAM).

The TMR effect originates from the interplay of quantum-mechanical phenomena controlling electron transport. At a fundamental level, it is governed by quantum tunnelling – a process forbidden in classical mechanics⁷. Importantly, the tunnelling probability is spin-dependent⁸. In ferromagnetic metals, an imbalance between spin-up and spin-down electron populations (Fig. 1c) gives rise to spin polarization p , which reflects the unequal contribution of the two spin channels to conduction (Box 1). The spin polarization arises from the spin-split Fermi surfaces typical of ferromagnetic metals (Fig. 1d). A finite spin polarization reflects dominance of one spin channel (the majority spin) in electrical transport and can be experimentally determined from tunnelling conductance asymmetries in ferromagnet–superconductor tunnelling measurements⁸.

As a result of a finite spin polarization, in the parallel state of an MTJ, majority-spin electrons from one electrode encounter a high density of available states in the other electrode, leading to a high tunnelling probability and low resistance (Fig. 1e). By contrast, in the antiparallel state, majority-spin electrons face a low density of states, strongly suppressing the tunnelling current and resulting in high resistance. At a phenomenological level, Jullière's model² relates the TMR ratio directly to the spin polarizations (p_i) of the two electrodes, $TMR = \frac{2p_1p_2}{1 - p_1p_2}$. Although this model provides a useful qualitative description for polycrystalline MTJs, it fails to account for electronic band anisotropy, symmetry effects and interfacial details in crystalline systems, and thus generally falls short in quantitative prediction of TMR.

Box 1 | Basics of TMR

Spin polarization

Spin polarization quantifies the imbalance between up-spin ($\uparrow$) and down-spin ($\downarrow$) carriers in a Fermi system that is the origin of spin-dependent transport phenomena in magnetic tunnel junctions (MTJs). A general definition is $p = \frac{n^\uparrow - n^\downarrow}{n^\uparrow + n^\downarrow}$, in which $n^{\uparrow(\downarrow)}$ may represent the number of electrons, the density of states (DOS) or the current for a given spin channel, depending on the context.

Spin-conserving tunnelling

In the context of MTJs, a specific and widely used definition utilizes the spin-dependent DOS: $p_{\text{DOS}} = \frac{D^\uparrow(E_F) - D^\downarrow(E_F)}{D^\uparrow(E_F) + D^\downarrow(E_F)}$, which reflects the imbalance in the density of available states for each spin at the Fermi energy E_F . In a simple free-electron model, the relevant spin polarization reduces to $p_{\text{DOS}} = \frac{k^\uparrow - k^\downarrow}{k^\uparrow + k^\downarrow}$, in which $k^\uparrow$ and $k^\downarrow$ are up-spin and down-spin Fermi wave vectors²³⁸.

Jullière's formula

Jullière's model provides a simple relationship between spin polarization and tunnelling magnetoresistance (TMR) in MTJs. Under the assumption that conductance in each spin channel is proportional to the corresponding spin-dependent DOS, the conductances for parallel-aligned and antiparallel-aligned MTJ are $G_P \propto D_1^\uparrow D_2^\uparrow + D_1^\downarrow D_2^\downarrow$ and $G_{AP} \propto D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow$. Expressing these in terms of the spin polarizations p_1 and p_2 of the two electrodes yields Jullière's formula²: $\text{TMR} = \frac{G_P - G_{AP}}{G_{AP}} = \frac{2p_1 p_2}{1 - p_1 p_2}$. Although this model captures the qualitative relation between electrode spin polarization and TMR, it is limited by its global DOS description and neglects the momentum-dependent and symmetry-dependent nature of real tunnelling.

$k_{\parallel}$ -conserved transport

In crystalline MTJs, the transverse momentum $k_{\parallel}$ is conserved in the tunnelling process. Consequently, the total conductance is determined by contributions from all individuals $k_{\parallel}$ -channels: $G = \frac{e^2}{h} \sum_{\sigma, k_{\parallel}} T^{\sigma}(k_{\parallel})$, in which σ denotes the spin ($\uparrow$ and $\downarrow$). $T^{\sigma}(k_{\parallel})$ is the transmission probability for each $(k_{\parallel}, \sigma)$ -channel, which depends on the band structure of the whole MTJ. As a result of $k_{\parallel}$ conservation, a more

appropriate measure of spin asymmetry is the momentum-

dependent spin polarization, $p_{k_{\parallel}} = \frac{N_{\parallel}^{\uparrow}(k_{\parallel}) - N_{\parallel}^{\downarrow}(k_{\parallel})}{N_{\parallel}^{\uparrow}(k_{\parallel}) + N_{\parallel}^{\downarrow}(k_{\parallel})}$, which explicitly

captures the $k_{\parallel}$ -resolved character of transport. Here $N_{\parallel}^{\sigma}(k_{\parallel})$ denotes the number of available conduction channels for a given $(k_{\parallel}, \sigma)$, determined by the projection of the Fermi surface onto the transport direction²³⁹.

Effect of barrier

The insulating barrier has two key roles in determining TMR. First, the decay rate of evanescent states, κ , is strongly $k_{\parallel}$ -dependent. For example, near the conduction band edge, E_C , it varies as $\kappa^2(k_{\parallel}) = \frac{2m^*}{\hbar^2}(E_C - E) + k_{\parallel}^2$, in which m^* is an effective mass. This makes states with large $k_{\parallel}$ typically decay faster, effectively focusing the tunnelling current to regions near the Brillouin zone centre ($\bar{\Gamma}$ point).

Second, the decay rate is symmetry-dependent: the barrier transmits only those electrode Bloch states that couple efficiently to the slowest-decaying evanescent states of matching orbital symmetry^{9,10}. In the canonical Fe/MgO/Fe (001) MTJ, up-spin Δ_1 states couple to the weakly decaying MgO Δ_1 evanescent band, whereas states of other symmetries couple to rapidly decaying modes and are strongly suppressed. This symmetry filtering produces a highly spin-polarized tunnelling current and a large TMR.

Interface transmission function

The combined effects of the spin-polarized electrodes and the tunnelling barrier are described by the interface transmission function, $\tau^{\sigma}(k_{\parallel})$ (ref. 11). For a given $(k_{\parallel}, \sigma)$, the transmission across a barrier layer of thickness d can be written as $T^{\sigma}(k_{\parallel}) = \tau_1^{\sigma}(k_{\parallel}) e^{-2\kappa(k_{\parallel})d} \tau_2^{\sigma}(k_{\parallel})$, in which $\tau_i^{\sigma}(k_{\parallel})$ is the interface transmission function of electrode i ($i = 1, 2$). These incorporate orbital-symmetry matching, group velocity and interfacial hybridization, and define the interface transmission polarization,

$P_{\tau}(k_{\parallel}) = \frac{\tau^{\uparrow}(k_{\parallel}) - \tau^{\downarrow}(k_{\parallel})}{\tau^{\uparrow}(k_{\parallel}) + \tau^{\downarrow}(k_{\parallel})}$, which provides a more accurate description of spin polarization for a particular MTJ.

In crystalline MTJs with negligible diffuse scattering, the transverse wave vector $k_{\parallel}$ is conserved during the tunnelling process, and the TMR is governed by the matching of spin-polarized Fermi surface states (Fig. 1f). In such systems, TMR arises from the stronger transmission in the parallel configuration, in which the Fermi surfaces of the two electrodes are well matched, and the weaker transmission in the antiparallel configuration due to their mismatch. Moreover, in crystalline MTJs, an accurate description of spin-dependent transport requires accounting for the symmetry of the incoming and outgoing Bloch states in the electrodes as well as the evanescent states in the tunnel barrier⁹. In particular, the matching between the majority-spin Δ_1 -symmetry band of Fe (001) and the Δ_1 -symmetry evanescent state in MgO (001) gives rise to a large positive spin polarization and the giant TMR observed in Fe/MgO/Fe (001) junctions¹⁰. For a more detailed discussion of spin-polarized tunnelling and the origin of TMR, see elsewhere¹¹ and Box 1.

Control of the free layer's magnetization is essential for deterministic information writing, and it dictates the energy efficiency and speed of MTJs. Nowadays, three main approaches are used to achieve such control: spin-transfer torque (STT), spin-orbit torque (SOT) and voltage-controlled magnetic anisotropy (VCMA). STT^{12–15} relies on a spin-polarized current flowing through an MTJ, which transfers angular momentum to the free layer and reverses its magnetization. This two-terminal scheme underlies modern MRAM technology but requires relatively high current densities. By contrast, SOT^{16–18} relies on a lateral charge current in an adjacent heavy-metal layer that generates spin angular momentum, either as a transverse spin current via the spin Hall effect^{17,19} or as an interfacial spin accumulation via the Rashba–Edelstein effect²⁰, thereby exerting torque on the free layer without current flow through the tunnel barrier. This approach allows faster, more durable operation but requires a three-terminal geometry, which increases design complexity. VCMA^{21–24} utilizes electric-field modulation of

interfacial anisotropy to assist or induce magnetization reversal with minimal current, often complementing STT or SOT to lower switching energy.

Although the conventional MTJ remains the most widely studied, the concept has expanded into a diverse family of devices. For instance, spin-filter MTJs utilize insulating magnets, in which an applied magnetic field switches the AFM ordering of the barrier into a ferromagnetic state, yielding a giant spin-filter TMR effect^{25–27}. However, as this ferromagnetic state is typically metastable, such junctions are generally unsuitable for non-volatile applications. Another variant is the multiferroic tunnel junction, which incorporates a ferroelectric insulator as the tunnelling barrier between two ferromagnetic electrodes^{28,29}. In a multiferroic tunnel junction, the relative magnetization of the two ferromagnetic electrodes and the ferroelectric polarization of the tunnelling barrier can be independently tuned, allowing both TMR and tunnelling electroresistance effects to occur simultaneously^{30–33}. This allows multiple non-volatile resistance states and synaptic functionality³⁴.

A recent and exciting advance is the prediction^{35–37} and realization^{38–41} of antiferromagnetic tunnel junctions (AFMTJs), which use AFM electrodes and take advantage of the Néel vector (or a higher-order magnetic moment such as an octupole) as the state variable. Antiferromagnets with globally broken time-reversal symmetry, including non-collinear antiferromagnets⁴² and altermagnets⁴³, can exhibit momentum-dependent spin polarization (MDSP), enabling finite TMR in AFMTJs⁴⁴ (Supplementary Note B). Their terahertz-frequency spin dynamics and lack of stray magnetic fields enable ultrafast switching while providing intrinsic robustness against external magnetic perturbations, facilitating high-density memory integration⁴⁵. In addition, the emergence of van der Waals magnetic tunnel junctions (vdW-MTJs)^{33,46–48} based on two-dimensional materials offers new opportunities for atomic-scale interface control and coherent spin transport. Their clean, atomically sharp interfaces and tunable stacking enable efficient modulation of spin polarization and magnetoresistance, bridging spintronics with low-dimensional materials physics.

These breakthroughs stem from advances in the fabrication and characterization of MTJs, in which atomic-scale control of layer thickness, interfacial symmetry and crystallographic texture govern spin-dependent transport. Correlating structural precision with magnetic and electronic performance has been essential for achieving reproducible, high-efficiency devices. Continued progress will hinge on further improving these capabilities, extending characterization to ultrafast regimes, integrating novel materials and developing scalable synthesis methods that preserve interfacial coherence.

In this Primer, we present an overview of MTJs, with a focus on mainstream devices using ferromagnetic electrodes and MgO tunnel barriers. It discusses the underlying physics, materials and performance characteristics that define MgO-based MTJs, emphasizing how atomic-scale structural control governs spin-dependent transport. Key aspects of fabrication, including thin-film growth by sputtering and molecular beam epitaxy (MBE), MgO barrier formation, post-growth annealing and device patterning, are described alongside structural, magnetic and transport characterization methods that reveal correlations among interfacial quality, anisotropy and spin polarization. Switching mechanisms based on STT, SOT and VCMA are reviewed, with representative examples illustrating their operation. Although this Primer does not provide a detailed discussion of the properties of AFMTJs and vdW-MTJs, these topics are briefly addressed in the Outlook, and a more comprehensive analysis of the fundamentals, fabrication, characterization and potential applications of AFMTJs is presented in

Supplementary Note B. The Primer concludes with perspectives on reproducibility, fabrication challenges and future opportunities for ultrafast, non-volatile and energy-efficient spintronic technologies.

Experimentation

In this section, we outline the key experimental approaches used to fabricate, process and characterize MTJs, highlighting the critical role of materials growth, interface control and device engineering in achieving high-performance spintronic functionality. It covers thin-film deposition techniques, tunnel barrier formation, thermal processing and nanopatterning, followed by structural, magnetic and electrical characterization methods, providing a comprehensive framework for understanding how fabrication and measurement strategies govern TMR and overall device behaviour.

Thin-film deposition techniques

Various deposition techniques can be used to fabricate MTJ thin films comprising metal or alloy layers and one or more oxide layers. The most commonly used methods are summarized below.

Sputtering deposition. Sputtering deposition is a physical vapour deposition technique that forms thin films by ejecting material from a target through the sputtering process. Argon or another inert gas at a working pressure of typically 10^{-1} – 10^{-2} Pa is introduced to create plasma around the sputtering target, while a direct current (d.c.) or radio-frequency voltage is applied to the target. Before deposition, an MTJ sputtering system is usually pumped down to a base pressure of 10^{-5} – 10^{-6} Pa to minimize oxygen, water vapour and hydrocarbon contamination. The target material is then sputtered from the surface by bombardment of energetic plasma particles. The sputtered material is deposited on a substrate in the same vacuum chamber. d.c. sputtering deposition is well suited for depositing alloy films, as the film composition directly follows that of the target. Both d.c. and radio-frequency sputtering deposition have many control parameters, such as sputtering power, gas pressure, gas type, distance between target and substrate, and substrate temperature. The deposition conditions strongly influence the film's growth rate and key structural qualities, including crystal orientation, surface roughness and grain size. Sputter damage in MTJs can be minimized by lowering sputtering power and avoiding substrate bias, optimizing the working pressure, selecting appropriate sputtering gases (such as Ar, Kr, Ne or their mixtures) and carefully controlling interface formation. The sputtering deposition method is widely used in both basic research with small substrates and mass-manufacturing with large substrates such as 300 mm wafers.

MBE. MBE is a physical vapour deposition method to prepare epitaxial thin films by evaporation in ultrahigh vacuum, typically at base pressures below 10^{-7} Pa for epitaxial MTJ materials. MBE is suited to prepare high-quality epitaxial or single-crystalline films because the ultrahigh vacuum atmosphere promotes surface diffusion of deposited atoms, which is essential for epitaxial growth. Both metallic and insulating materials can be evaporated by the electron beam evaporation technique.

Pulsed laser deposition. Pulsed laser deposition is widely used for growing complex oxide thin films, such as perovskite oxides, under high oxygen pressures needed to suppress the formation of oxygen vacancies. In fact, pulsed laser deposition is often the only reliable

method for depositing perovskite oxide films without significant oxygen deficiency, owing to its ability to maintain stoichiometry in oxygen-rich environments. Such oxide-based MTJs are particularly important for fundamental studies of strongly correlated phenomena of complex oxides. In particular, this technique has been successfully used to prepare fully epitaxial $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3/\text{SrTiO}_3/\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$ tunnel junctions exhibiting giant TMR effects at low temperature⁴⁹.

However, despite its strengths in oxide growth, pulsed laser deposition is generally unsuitable for metal-based MTJs and scalable device fabrication because it performs poorly for the metallic layers and metal–oxide interfaces, introducing particulates, poor uniformity over a wide area, roughness and interfacial damage, and limited large-area uniformity. Techniques such as sputtering or molecular beam epitaxy are generally preferred owing to their superior interface control and scalability.

Tunnel barrier formation

Direct deposition of oxide barrier layer. The simplest method to prepare a crystalline MgO (001) tunnel barrier is to directly deposit an MgO layer on a bottom ferromagnetic electrode layer by electron beam evaporation of MgO source material⁵⁰ or radio-frequency magnetron sputtering from an MgO target⁵¹. In the sputtering deposition, special care must be taken to avoid over-oxidation of the bottom ferromagnetic layer^{52,53}.

Post-oxidation of metallic layer. Amorphous Al–O tunnel barriers are typically formed by post-oxidation of metallic Al layers. To achieve a high-quality Al–O tunnel barrier, an atomically flat sub-nanometre-thick Al layer with no pinholes must be first deposited by sputtering or MBE. To obtain such an Al layer, the film should crystallize in the fcc (111) orientation because the Al (111) surface is energetically very stable. There are two techniques for post-oxidation: natural oxidation in O_2 atmosphere and plasma oxidation. By plasma oxidation of Al, magnetoresistance ratios above 70% have been achieved at room temperature⁵⁴. MgO (001) tunnel barriers are commonly fabricated by sputtering, but they can also be formed by natural oxidation. A high-quality MgO (001) tunnel barrier with thickness of about 1–1.5 nm can be fabricated by a cyclic process in which ~0.2 nm Mg layers are deposited and subsequently oxidized, with several such deposition–oxidation cycles yielding the desired barrier⁵⁵. The post-oxidation method is commonly used in mass-manufacturing of MgO-based MTJ films on large wafers because of its high process stability.

Thermal annealing

Thermal annealing is a critical step in MTJ fabrication, as achieving high TMR generally requires an epitaxial (or textured) junction structure formed at elevated temperatures. The said step can be achieved using two approaches. In the first, epitaxial growth is directly templated by the substrate of buffer layers, often requiring high-temperature deposition and/or in situ annealing after each layer at temperatures of ~200–600 °C (refs. 5,6,56,57). In the second and more widely used approach, amorphous CoFeB layers are deposited on both sides of an MgO barrier that typically exhibits a preferred (001) orientation even in the as-deposited state. Post-growth annealing at ~300–500 °C then induces CoFeB crystallization in registry with the MgO barrier^{51,58}. In these junctions, the as-deposited TMR is typically only a few tens of percent but increases to several hundred percent after annealing, underscoring the critical role of thermal processing. The crystallization of CoFeB, governed by a relatively modest

activation energy of approximately 150 kJ mol^{−1} (ref. 59) can proceed rapidly; for example, annealing at 500 °C can raise the TMR to ~250% within about 30 s. This TMR enhancement is generally accompanied by an initial decrease in R_p owing to the emergence of coherent tunneling, followed by a gradual increase arising from scattering induced by defects and disorder.

The boron concentration in CoFeB electrodes is typically ~20 at.%, and it can vary from ~10 at.% to ~30 at.%. Higher boron content increases the crystallization temperature of CoFeB, improving thermal stability by delaying interdiffusion with adjacent layers and enabling annealing above 400 °C (ref. 60). Therefore, lower boron concentrations are used in hard disk drive (HDD) read head MTJs, in which post-annealing must remain below 300 °C; conversely, higher boron concentrations are preferred for STT-MRAM to ensure greater thermal robustness. Higher boron content has also been shown to be beneficial in obtaining higher VCMA coefficients⁶¹.

These trends demonstrate that precise control of the annealing conditions is essential when optimizing the MTJ resistance in addition to maximizing TMR⁶².

Patterning of MTJs

A typical patterning process for MTJ nanopillar devices is illustrated schematically in Fig. 2. The fabrication of high-performance MgO-based MTJs involves sequential deposition, lithography and etching to form nanopillars, followed by passivation, insulation and electrode formation under controlled vacuum conditions to prevent oxidation and sidewall damage. The use of a hard mask layer is effective in suppressing device-to-device variations in the junction shape and area, whereas the silicon nitride (SiN) passivation layer improves device reliability and yield. In basic research, however, the fabrication process can be simplified, for example, by omitting the hard mask layer and/or SiN passivation layer, to reduce process complexity and enable more rapid exploration of material properties. On the other hand, the complementary metal–oxide–semiconductor (CMOS) integration process for STT-MRAM is more complex than that illustrated in Fig. 2. Typical lateral size of MTJ nanopillars is around 30–40 nm in the latest commercial STT-MRAM and HDD read heads, whereas the smallest reported MTJ size is below 10 nm in basic research.

Structural characterization

The structural properties of MTJs are commonly characterized using high-resolution transmission electron microscopy (TEM)^{63,64}; X-ray diffraction^{65,66}; X-ray reflectivity^{67,68}; and scanning probe techniques, such as scanning tunnelling microscopy^{69,70} and atomic force microscopy⁷¹. High-resolution TEM enables atomic-scale imaging of cross-sectional layer structure, allowing direct assessment of layer thickness, crystallinity and interface sharpness. When combined with electron energy loss spectroscopy^{72,73}, it provides elemental mapping and interfacial oxidation state analysis. X-ray diffraction offers insights into the crystallographic orientation and phase purity of multilayers, as well as strain and grain structure over large areas, complementary to the local data from TEM. X-ray reflectivity is a non-destructive method that yields precise measurements of individual layer thickness and interface roughness by analysing interference fringes, providing wafer-scale information. Atomic force microscopy quantifies surface roughness before and after film growth, typically targeting sub-0.2 nm levels for high-performance MTJs; conversely, scanning tunnelling microscopy, particularly in its spin-polarized mode, probes local density of states and spin polarization at the atomic level.

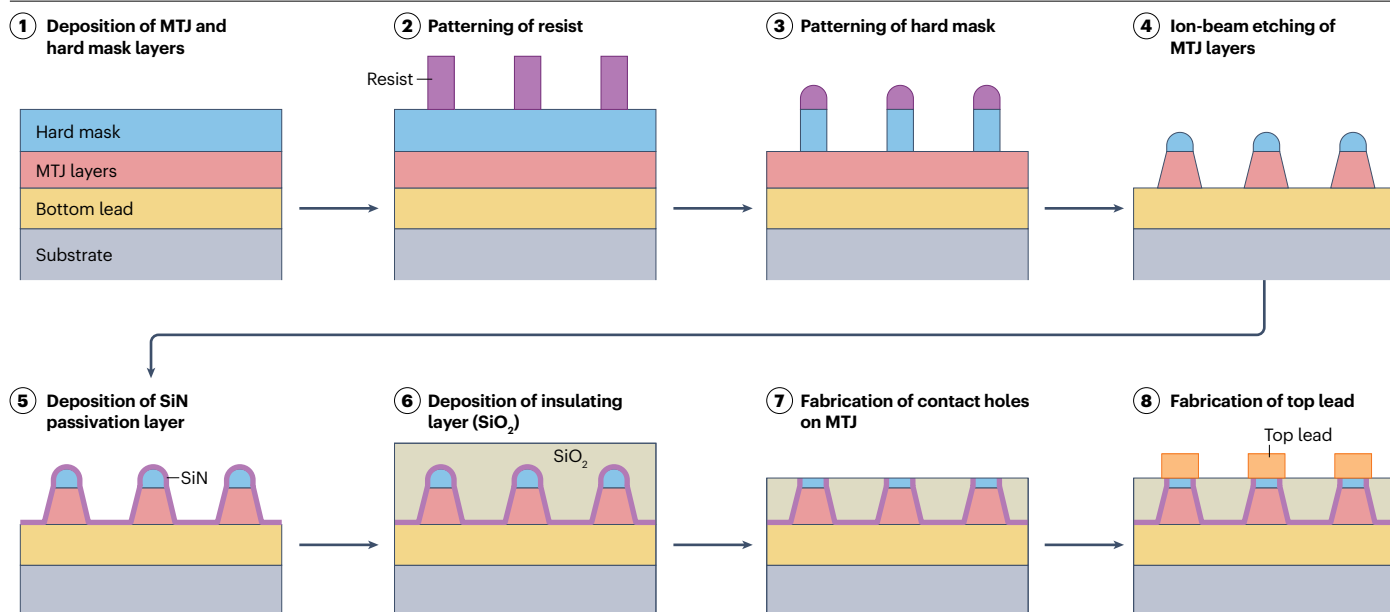


Fig. 2 | Schematic illustration of the microfabrication process used to fabricate MTJ pillars. (1) Magnetic tunnel junction (MTJ) layers are deposited on a bottom lead electrode, and a hard mask layer made of TiN or Ta is deposited on the MTJ layers by physical vapour deposition. (2) Resist patterns are fabricated by spin coating of resist and optical lithography or electron-beam lithography, followed by an exposure process. (3) The hard mask layer is etched into nano-pillars by reactive ion etching. (4) The MTJ layers are patterned into nano-pillars using ion-beam etching. This is one of the most important steps to fabricate

high-performance MTJs. Special care should be taken to prevent re-deposition of etched materials and to avoid etching damage on the MTJ side walls. (5) MTJ side walls are covered with a passivation layer such as SiN by chemical vapour deposition. (6) An insulating layer such as SiO₂ is subsequently deposited. Ideally, steps (4)–(6) should be carried out without breaking a vacuum to avoid unwanted oxidation of MTJ side walls. (7) Contact holes are fabricated on the MTJ nano-pillars. (8) Top lead electrode is fabricated on each MTJ by using deposition, lithography and etching techniques.

Magnetic characterization

The magnetic properties of MTJs are characterized by using a comprehensive suite of techniques, including vibrating sample magnetometry⁷⁴, superconducting quantum interference device (SQUID) magnetometry⁷⁵, magneto-optical Kerr effect⁷⁶, ferromagnetic resonance (FMR)⁷⁷, and synchrotron-based X-ray absorption spectroscopy and X-ray magnetic circular dichroism⁷⁸. Vibrating sample magnetometry and SQUID magnetometry measure magnetic hysteresis loops to determine parameters such as saturation magnetization, coercivity and magnetic anisotropy. Magneto-optical Kerr effect is a widely used, non-contact optical technique for probing magnetization in magnetic materials, especially thin films and nanostructures, by analysing how polarized light changes upon reflection from a magnetized surface. It provides rapid magnetic hysteresis measurements and enables distinction between in-plane and out-of-plane magnetization. FMR characterizes dynamic magnetic properties such as the Gilbert damping constant, anisotropy fields and exchange stiffness, with changes in linewidth or resonance fields providing insights into annealing and interface effects. X-ray absorption spectroscopy and X-ray magnetic circular dichroism deliver element-specific analysis of spin and orbital moments, allowing detailed evaluation of interfacial magnetism, spin polarization and magnetic proximity effects across multilayer interfaces.

Magnetization orientation. Early MTJs using Al-O or MgO tunnel barriers were of the in-plane type (i-MTJs), in which the magnetizations lie within the film plane driven by in-plane magnetic anisotropy (IMA). CoFeB/MgO/CoFeB-based i-MTJs remain widely used today in HDD

read heads and TMR magnetic sensors. By contrast, perpendicular MTJs (p-MTJs), in which the magnetizations are oriented normal to the film plane, were developed around 2010 (refs. 79,80) and have since become central to STT-MRAM technologies. Out-of-plane magnetization arises when the perpendicular magnetic anisotropy (PMA), originating from bulk or interfacial contributions, exceeds the shape anisotropy of the thin film.

A free layer with PMA is generally preferred over IMA in STT-MRAM for several key reasons. First, at lateral dimensions below ~50 nm, PMA can overcome shape anisotropy, thereby enhancing thermal stability and data retention. Second, p-MTJs exhibit lower critical switching current densities owing to more favourable reversal mechanisms. Third, magnetization dynamics in p-MTJs tend to be more coherent, which improves switching reliability. Last, at small feature sizes, circular p-MTJs are easier to pattern and scale than elongated i-MTJs. For these reasons, PMA-based STT-MRAM offers superior scalability to IMA-based designs. A similar trend is observed in SOT-MRAM: PMA remains the dominant configuration for scalable devices aimed at embedded and high-density memory applications, although IMA-based SOT structures continue to be explored for specialized switching schemes and emerging spintronic concepts.

Electrical characterization

TMR measurements. TMR is typically measured via four-point d.c. set-ups in which resistance is recorded while sweeping magnetic field (at the rate of a few oersteds per second) to toggle between parallel and antiparallel states, usually keeping the bias voltage applied to the

MTJ below 10 mV. For MTJs with sufficiently high resistance ($\geq 100\times$ contact resistance), two-point measurements may be used. A specialized method, current-in-plane tunnelling, allows non-destructive TMR and resistance-area measurement directly on unpatterned MTJ films⁸¹. Current-in-plane tunnelling requires a conductive, oxidation-resistant cap layer (such as Ru or Pt/Ta) to enable efficient in-plane current injection.

Bias dependence of TMR. TMR decreases with increasing bias voltage owing to inelastic scattering such as spin-flip tunnelling and magnon excitation. The voltage at which TMR drops to half of its zero-bias value ($V_{1/2}$) serves as a benchmark for interface quality and spin filtering robustness. Devices with symmetric interfaces and clean MgO barriers often show higher $V_{1/2}$ values, indicating more stable performance under operating voltage ranges.

Temperature dependence of TMR. TMR generally decreases with increasing temperature owing to thermal excitation of magnons and loss of spin coherence. Temperature-dependent measurements reveal activation energies of spin scattering processes and the thermal robustness of the tunnelling barrier.

Electrical switching measurements. Switching is characterized by applying current or voltage pulses to toggle MTJ resistance states between parallel and antiparallel. The pulse duration ranges from d.c. to sub-nanosecond, depending on the mechanism (STT, SOT or VCMA). Critical switching current or voltage is usually determined at the 50% switching probability point. In general, the error rate corresponding to a measured switching voltage or current should be specified, given that higher currents or voltages generally lead to lower error by increasing switching probability. Measurements are often repeated over many cycles to evaluate switching reliability, endurance and thermal stability. For spin-orbit or voltage-induced switching, an external in-plane magnetic field may be required to break symmetry. Time-resolved techniques using fast oscilloscopes or time interval analysers capture the dynamic response and switching stochasticity, which is crucial for assessing the values of the write-error rate and energy-delay performance.

Table 1 provides a comparative summary of experimental techniques commonly used for structural, magnetic and transport characterization of MTJ films and devices.

Theoretical modelling

Predictive modelling of MTJ properties relies extensively on advanced computational techniques based on density functional theory (DFT). Widely used electronic-structure packages include VASP^{82,83}, Quantum ESPRESSO⁸⁴, WIEN2k⁸⁵ and SIESTA⁸⁶. These tools enable quantitative calculations of electronic structure, magnetic moments, exchange interactions, magnetic anisotropy (including VCMA effects) and spin polarization in magnetic materials, as well as the corresponding properties of MTJs. In addition, DFT enables the analysis of complex band structures of insulating barriers, which determine decay rates of evanescent states and thus have a central role in spin-dependent tunnelling⁹. First-principles transport calculations that combine DFT with non-equilibrium Green's function methods, which are, for example, implemented in QuantumATK⁸⁷ and SMEAGOL⁸⁸, are widely utilized to compute spin-dependent transmission and current-voltage characteristics of realistic MTJs. DFT calculations reveal how the slow decay of the majority-spin Δ_1 state underpins the giant TMR effect

in Fe/MgO/Fe MTJs¹⁰, a theoretical prediction that has preceded and guided subsequent experimental confirmations. Increasingly, these approaches are complemented by beyond-DFT computational methods, such as DFT+U⁸⁹, hybrid functionals⁹⁰, dynamical mean-field theory⁹¹, and high-throughput or machine learning-assisted approaches to accelerate MTJ materials discovery^{92,93}.

Results

Structural characterization

High-performance MgO-based MTJs rely critically on structural optimization. In particular, (001)-crystalline or highly textured junction enable coherent tunnelling of Δ_1 -symmetry electrons, resulting in large TMR. Interface roughness, pinholes, interdiffusion and improper oxidation strongly degrade TMR, whereas atomically smooth, well-oxidized MgO barriers correlate with the highest room-temperature TMR values ($>600\%$). Structural characterization by TEM, X-ray diffraction and X-ray reflectivity shows that top-performing MTJs exhibit sharp, coherent interfaces with roughness below ~ 0.3 nm and no secondary phases.

MgO-based MTJs are achieved using either fully epitaxial or highly textured junction structures, both of which support large TMR. Cross-sectional TEM confirms the epitaxial Fe(001)/MgO(001)/Fe(001) structure grown on single-crystal MgO (001) substrates using appropriate seed or buffer layers (Fig. 3a), which exhibits room-temperature TMR ratios of up to 188%^{5,50}. Highly textured CoFe(001)/MgO(001)/CoFe(001) MTJs deposited on amorphous SiO₂ substrates with strongly textured underlayers (Fig. 3b) achieve room-temperature TMR ratios of approximately 220%⁶. In both cases – fully epitaxial or highly textured junction structures – the large TMR originates from similar local crystalline structures, indicating a common underlying physical mechanism. However, epitaxial and textured MTJ stacks require preservation of fourfold in-plane crystallographic symmetry throughout the multilayer, which complicates integration with practical device architectures that typically use fcc (111) pinning layers with threefold symmetry.

The CoFeB/MgO/CoFeB MTJ structure overcomes this crystallographic symmetry constraint while maintaining large TMR⁵¹. In the as-deposited state, the CoFeB electrodes are amorphous, whereas the MgO barrier is (001)-oriented and textured (Fig. 3c). Post-annealing induces solid-phase epitaxial crystallization of CoFeB at the MgO interfaces, resulting in a highly textured bcc CoFeB(001)/MgO(001)/CoFeB(001) structure⁹⁴ (Fig. 3d) and room-temperature TMR ratios exceeding 200%⁵¹. During annealing, boron is largely expelled from the CoFeB layers into adjacent layers, a process essential for the formation of the bcc (001) texture⁹⁵. The choice of cap layer is critical. Materials such as Ta are particularly effective because they act as boron sinks during annealing, thereby promoting the crystallization of CoFeB into the bcc (001) structure. By contrast, other cap layer materials suppress this crystallization when deposited on CoFeB, which results in a substantial reduction of the TMR ratio⁹⁶ (Fig. 3e). To further enhance thermal stability and suppress undesired interdiffusion, especially under high-temperature processing conditions, thin diffusion-blocking layers such as W, Mo or Hf spacers are often inserted between CoFeB and Ta to limit Ta and B migration and preserve interface quality^{97,98}.

Magnetic characterization

Saturation magnetization M_s of the most used ferromagnets in MTJ, CoFeB, typically ranges from 1,000 emu cm⁻³ to 1,200 emu cm⁻³ and increases after annealing due to boron out-diffusion and crystallization.

Table 1 | A comparative summary of experimental techniques for the characterization of MTJ films and devices

Method	Level (film or device)	Information provided	Notes
High-resolution transmission electron microscopy; includes cross-section and EELS	Film (local regions)	Layer thickness, crystal structure, interface quality (roughness, interdiffusion), interfacial chemistry (via EELS)	Atomic-scale imaging; local analysis only (nm field of view); not a non-destructive measurement
X-ray diffraction	Film (global)	Crystal structure/phases, texture (such as MgO (001) orientation), grain size (via peak broadening), strain and lattice mismatch	Probes large area (mm–cm); confirms overall crystallinity
X-ray reflectivity	Film (global)	Layer thicknesses, interface and surface roughness, density of layers (via critical angle)	Sensitive to thickness with <0.1 nm precision; complements EELS for large-area average
Atomic force microscopy/STM	Film (local)	Surface morphology and roughness, presence of pinholes or defects; STM can probe local electronic states.	Atomic force microscopy gives root mean square roughness over μm area; STM requires conductive surface; ensures smooth template for barrier
Vibrating sample magnetometry and SQUID magnetometry	Film or device array	Magnetization hysteresis loops: saturation magnetization and coercive field, loop shape (single or multi-phase switching), anisotropy type (via easy axis direction)	Requires sufficient film area or patterned test arrays; SQUID is ultrasensitive (good for ultrathin films with thicknesses of 1 nm or less)
Magneto-optical Kerr effect magnetometry	Film or device	Kerr hysteresis loops: fast mapping of coercive and anisotropy fields, imaging domain patterns in films	Laser spot size $\sim\mu\text{m}$ –mm; can distinguish in-plane versus out-of-plane magnetization components; useful for quick loop measurements
Ferromagnetic resonance	Film, device array or single device	Dynamic magnetic properties: Gilbert damping, effective anisotropy field, g-factor, detect coupling (multiple modes)	Can be done in cavity or broadband; flip-chip approach on coplanar wave guide allows direct measurement of unpatterned films
X-ray absorption spectroscopy and XMCD	Film or device	Element-specific probe of spin and orbital magnetic moments, interface magnetization, degree of spin polarization (via XMCD)	Requires synchrotron; depth-sensitive (surface/interface) by electron yield modes; can detect interfacial oxidation (via spectral shifts)
d.c. TMR measurement	Device	TMR ratio (parallel vs antiparallel resistance), resistance-area product (with area known), device resistance, uniformity of switching field (via minor loop)	Four-point preferred; low bias used for intrinsic TMR; must pattern devices unless using current in-plane tunnelling
Current in-plane tunnelling	Film (wafer-level)	TMR and resistance area on unpatterned film (average over probe area), quick mapping across wafer	Requires conductive cap and often a smooth conductive buffer; uses multiple probe spacing measurements
Bias-dependent TMR	Device	TMR versus voltage characteristics; indicates magnon/phonon contributions and barrier quality (such as symmetry filtering)	Can be done via d.c. sweep or a.c. lock-in; a rapid drop in TMR at low bias indicates inelastic tunnelling channels
Temperature-dependent TMR	Device or film	Variation of TMR with temperature; assesses thermal robustness of spin polarization; provides information on defect-assisted tunnelling	Requires cryostat or heater; may demonstrate high TMR at low temperature in half-metal electrodes
Electrical switching measurements	Device	Critical switching current/voltage, switching dynamics (speed, incubation time), thermal stability factor	Performed on nanopillar MTJs; high current pulses can cause Joule heating (care needed); reveals write energy and reliability (error rates)

a.c., alternating current; d.c., direct current; EELS, electron energy loss spectroscopy; MTJ, magnetic tunnel junction; SQUID, superconducting quantum interference device; STM, scanning tunnelling microscopy; TMR, tunnelling magnetoresistance; XMCD, X-ray magnetic circular dichroism.

In perpendicular MTJs with strong interfacial anisotropy, the in-plane anisotropy field of the free layer (often a few thousand gauss) depends on oxidation at the MgO interface, the adjacent heavy-metal layer, and annealing conditions. For example, with $M_s = 1,200 \text{ emu cm}^{-3}$ and an anisotropy field of 8,000 Oe, the anisotropy energy density reaches $K \approx 4.8 \times 10^6 \text{ emu cm}^{-3}$. The thermal stability factor (TSF), defined as $\Delta E/k_B T$, quantifies the robustness of data retention against thermal fluctuations; a value of TSF ≈ 60 is the standard target for 10 year non-volatile memory retention at room temperature. This criterion can be satisfied for device sizes of approximately 20 nm with the above material parameters. To maintain TSF ≥ 60 in smaller perpendicular MTJs, the anisotropy energy can be increased by stacking multiple CoFeB–heavy metal or CoFeB–MgO interfaces^{99,100}, incorporating shape anisotropy through narrow pillar geometries¹⁰¹, or using ferromagnets

with bulk perpendicular anisotropy¹⁰², though the latter often results in reduced TMR. Values for damping constant α measured by FMR typically fall in the 0.005–0.01 range, with crystallization lowering impurity scattering, whereas excessive annealing may raise damping due to increased magnon scattering¹⁰³.

Electrical characterization

Early MTJ demonstrations exhibited very low magnetoresistance, with Jullière's 1975 Fe/Ge/Co junctions (likely involving an oxidized Ge barrier) showing $\sim 14\%$ ² and IBM's early-1980s Ni/NiO devices only $\sim 1\text{--}2\%$ ¹⁰⁴, both measured at 4.2 K. Notably, only the work on IBM's devices correlated the tunnel resistance with magnetization switching, providing solid evidence for the TMR effect. With the adoption of Al–O as a barrier, in which pinholes could be effectively eliminated, TMR

values increased to the tens of percent^{4,105}. However, most common ferromagnetic materials have spin polarizations of about 50%, which, according to Jullière's formula, limits the maximum TMR to roughly 70%³. It was later revealed that certain materials, such as MgO, exhibit symmetry-filtering properties, preferentially transmitting Δ_1 Bloch states with nearly 100% spin polarization at the Fermi energy^{10,106}. This breakthrough was experimentally demonstrated in CoFe/MgO/CoFe junctions, in which crystalline MgO barriers enabled TMR values up to 200%, marking a pivotal advance in MTJ performance^{5,6}. Further improvements in deposition and annealing pushed TMR beyond 300% by 2008 in CoFeB/MgO-based structures^{51,58}. The current record is ~631% at room temperature, achieved in an epitaxial CoFe/MgO/CoFe junction, with a corresponding low-temperature value of ~1,143% at 10 K, highlighting the effect of symmetric interfaces and coherent tunnelling⁵⁶. Historical milestones in the development of MgO-based MTJs can be found in Supplementary Note A and Supplementary Fig. 1.

Heusler alloy electrodes such as iron-doped Co₂MnSi have achieved TMR values up to 2,610% at 4.2 K and 429% at room temperature⁵⁷. In p-MTJs^{79,80}, the ferromagnetic layer, however, is typically much thinner – around 1 nm of CoFeB – compared with the several nanometres in in-plane-anisotropy MTJs, resulting in TMR ratios of 100–300% in most devices¹⁰⁷. Maintaining the structural, chemical and magnetic integrity of such thin CoFeB during high-temperature annealing is challenging.

Importantly, in p-MTJs, magnetic failure, manifested as degradation or complete loss of PMA, typically precedes transport-related degradation during thermal annealing. The ultrathin CoFeB layer becomes magnetically unstable before significant impurity diffusion

into the MgO barrier occurs¹⁰⁸. Maintaining robust PMA throughout thermal processing is therefore a critical requirement for reliable p-MTJ operation. To simultaneously achieve high TMR and strong PMA, several material engineering strategies have been developed. For example, incorporating diffusion-barrier layers such as Mo between the heavy-metal underlayer and CoFeB effectively suppresses intermixing and limits unwanted atomic diffusion during annealing, thereby stabilizing magnetic anisotropy and preserving device performance^{61,108}. In parallel, alternative tunnel barrier materials, such as Mg₄₀Fe₁₀O₅₀, have been explored to enhance interfacial stability and improve thermal robustness while maintaining high TMR¹⁰⁹.

Another effective strategy is the insertion of an ultrathin Mg interlayer between CoFeB and MgO. This approach is particularly beneficial for very thin tunnel barriers or under growth conditions in which radio-frequency-sputtered MgO can otherwise over-oxidize the underlying CoFeB layer^{52,110}. The Mg insertion layer mitigates interfacial oxidation and helps to preserve spin polarization at the CoFeB–MgO interface. In addition, rapid thermal annealing is commonly used to minimize prolonged high-temperature exposure, thereby reducing the risk of premature magnetic degradation while still enabling the interfacial crystallization processes required for TMR enhancement¹¹¹.

One key parameter for MTJs is the resistance-area product, which influences current drivability and write voltage for STT-switched MTJs. In practical perpendicular STT-MRAM devices, resistance-area values around 10–30 $\Omega \mu\text{m}^2$ are common, whereas cutting-edge HDD read heads require resistance-area values below ~0.5 $\Omega \mu\text{m}^2$ to maintain low sensor resistance and match impedances of a few hundred ohms.

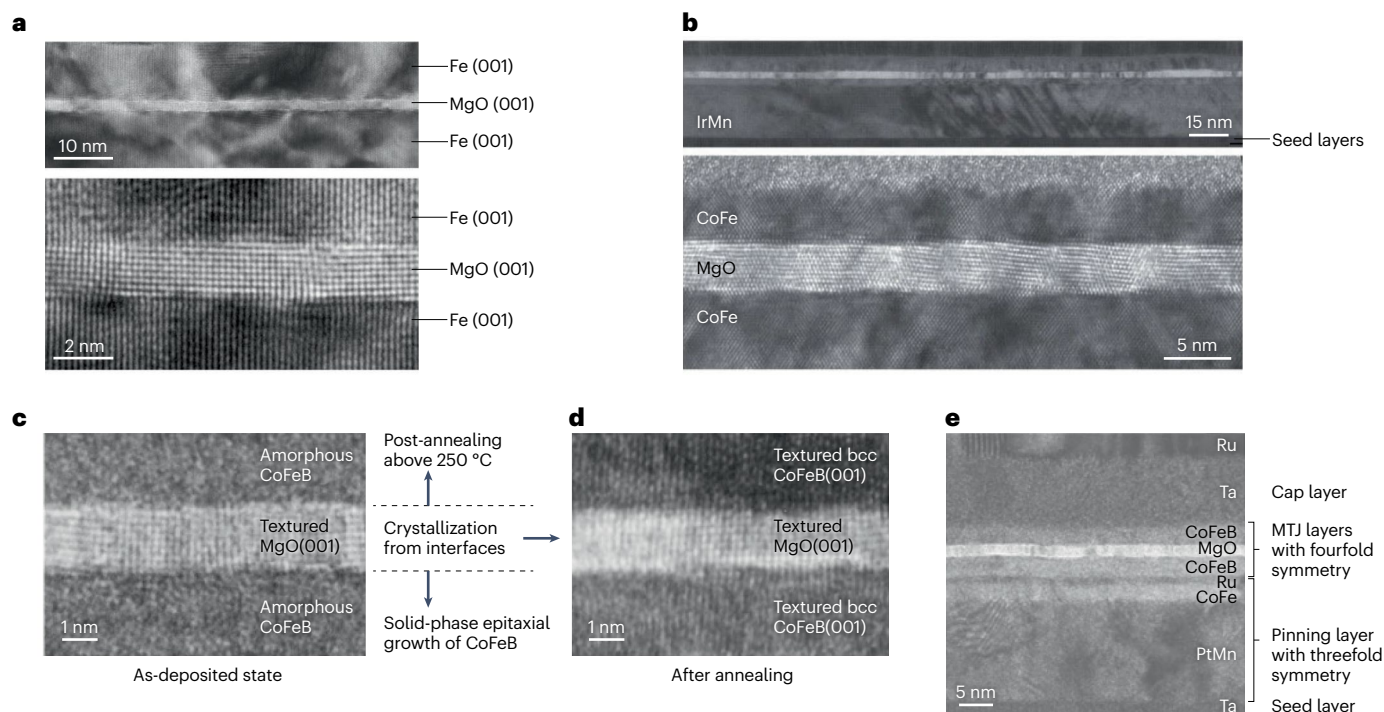
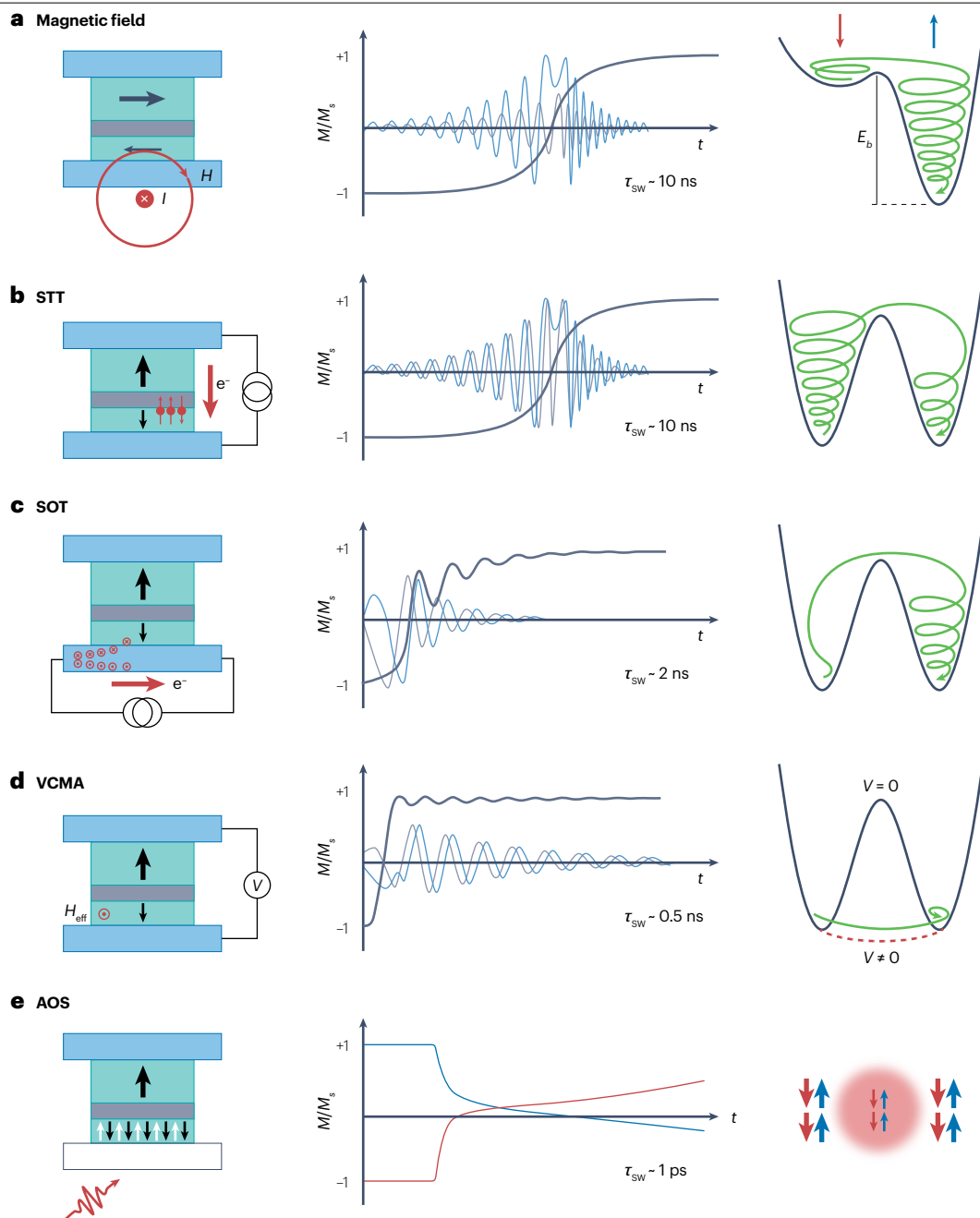


Fig. 3 | Cross-sectional transmission electron microscopy images of MTJs. **a**, Fully epitaxial Fe(001)/MgO(001)/Fe(001) magnetic tunnel junction (MTJ). **b**, Textured CoFe(001)/MgO(001)/CoFe(001) MTJ. **c,d**, CoFeB/MgO/CoFeB MTJ in as-grown state (part **c**) and after annealing (part **d**). **e**, CoFeB/MgO/

CoFeB MTJ fabricated on technologically relevant pinning layer with threefold crystalline symmetry. Part **a** reprinted from ref. 5, Springer Nature Limited. Part **b** reprinted from ref. 6, Springer Nature Limited. Part **e** adapted with permission from ref. 51, AIP.



Another key performance indicator of the MTJs is the voltage at which TMR drops to half of its zero-bias value, $V_{1/2}$. This voltage has a value of 0.5–1 V in single-barrier MTJs⁵, and it is limited by interface quality and spin scattering. By contrast, double-barrier MTJs have demonstrated significantly higher $V_{1/2}$ values of nearly to 2 V (ref. 112), owing to bias voltage division and enhanced symmetry-filtered tunnelling. These elevated values are attributed to coherent tunnelling through the Δ_1 band and highly crystalline, symmetric interfaces. Proper annealing and epitaxial growth are essential to achieving high $V_{1/2}$ values and sustaining large TMR under bias. Finally, the TSF of a device is typically measured electrically, either by recording TMR hysteresis loops under

varying magnetic field sweep rates or by measuring the I_c of the STT switching as a function of pulse duration¹¹³.

Magnetization switching in MTJs

STT switching. Magnetic fields were the original means of switching MTJs, but their limitations in scalability, switching speed and energy efficiency quickly became evident (Fig. 4a). STT has since emerged as a far superior alternative, effectively addressing these drawbacks^{12,15} (Fig. 4b). STT operates by driving a spin-polarized current perpendicularly through the MTJ (Fig. 5a), exerting torque on the free layer's magnetization. When a bias voltage pushes electrons from the pinned to

Fig. 4 | Schematic representation of different switching mechanisms in MTJs.

For each switching mechanism, the device geometry is shown on the left, the temporal evolution of the normalized magnetization components m_x , m_y , and m_z (with M/M_s denoting magnetization normalized to its saturation value M_s) is shown in the middle, and the corresponding energy landscape is shown on the right. The two minima represent the bistable magnetic states, separated by the anisotropy energy barrier E_b . Green curves indicate representative switching trajectories in the energy landscape, whereas red and blue arrows denote transitions between the two stable states. The characteristic switching time is denoted by τ_{SW} . In voltage-driven schemes, V represents the applied voltage that modulates magnetic anisotropy and the effective barrier height. **a**, Magnetic field-induced switching. An external magnetic field H generates a Zeeman torque on the free layer's magnetization, leading to a precessional motion counteracted by Gilbert damping. When the applied field strength exceeds the coercive field, the magnetization reverses. Although switching can be achieved on nanosecond timescales, this approach is not scalable owing to the difficulty of generating localized magnetic fields. In the schematic, the magnetic field is produced by an electrical current I flowing in a perpendicular direction to the plane (denoted by $\times$), which generates a circular magnetic field (red loop) according to Ampère's law. **b**, Spin-transfer torque (STT) switching. A spin-polarized current flowing through the magnetic tunnel junction (MTJ) barrier exerts a torque on the free layer's magnetization. Initially, STT acts against damping to drive the magnetization across the energy barrier. Once the magnetization crosses the equator of the unit sphere, the spin torque and damping align to accelerate switching. Typical

switching times are ~ 10 ns, but faster write speeds are possible with higher applied current. **c**, Spin-orbit torque (SOT) switching. The in-plane spin current is generated via the spin Hall effect in an adjacent heavy-metal layer. Owing to the orthogonal configuration of the torque with respect to the free layer magnetization (for perpendicular free layers), the first half of the switching process is significantly faster than for STT. Consequently, SOT switching generally achieves faster switching times, typically a few nanoseconds or less. **d**, Voltage-controlled magnetic anisotropy (VCMA) switching. An applied voltage V across the MTJ reduces the anisotropy energy barrier of the free layer during the voltage pulse (indicated by the red dashed curve). This enables the magnetization to precess about an effective field H_{eff} directed into the plane. If the voltage pulse is removed at the correct moment (typically half a precession cycle), the magnetization relaxes into the reversed state. VCMA switching typically achieves switching times of ~ 0.5 ns. **e**, All-optical switching (AOS). An ultrafast femtosecond laser pulse (red arrow) rapidly heats the electron and spin systems of a ferrimagnetic free layer above the Curie temperature. The red and blue curves represent the time-dependent magnetizations of the two antiferromagnetically coupled sublattices (M_1 and M_2) (for example, in Co–Gd alloys). Owing to their different demagnetization rates, one sublattice quenches faster than the other, leading to a transient ferromagnetic-like state in which both moments become aligned. The subsequent exchange-driven angular momentum transfer between the sublattices drives reversal, after which both magnetizations recover with opposite orientation, as indicated by the red and blue arrows. This process enables deterministic switching on a sub-picosecond timescale.

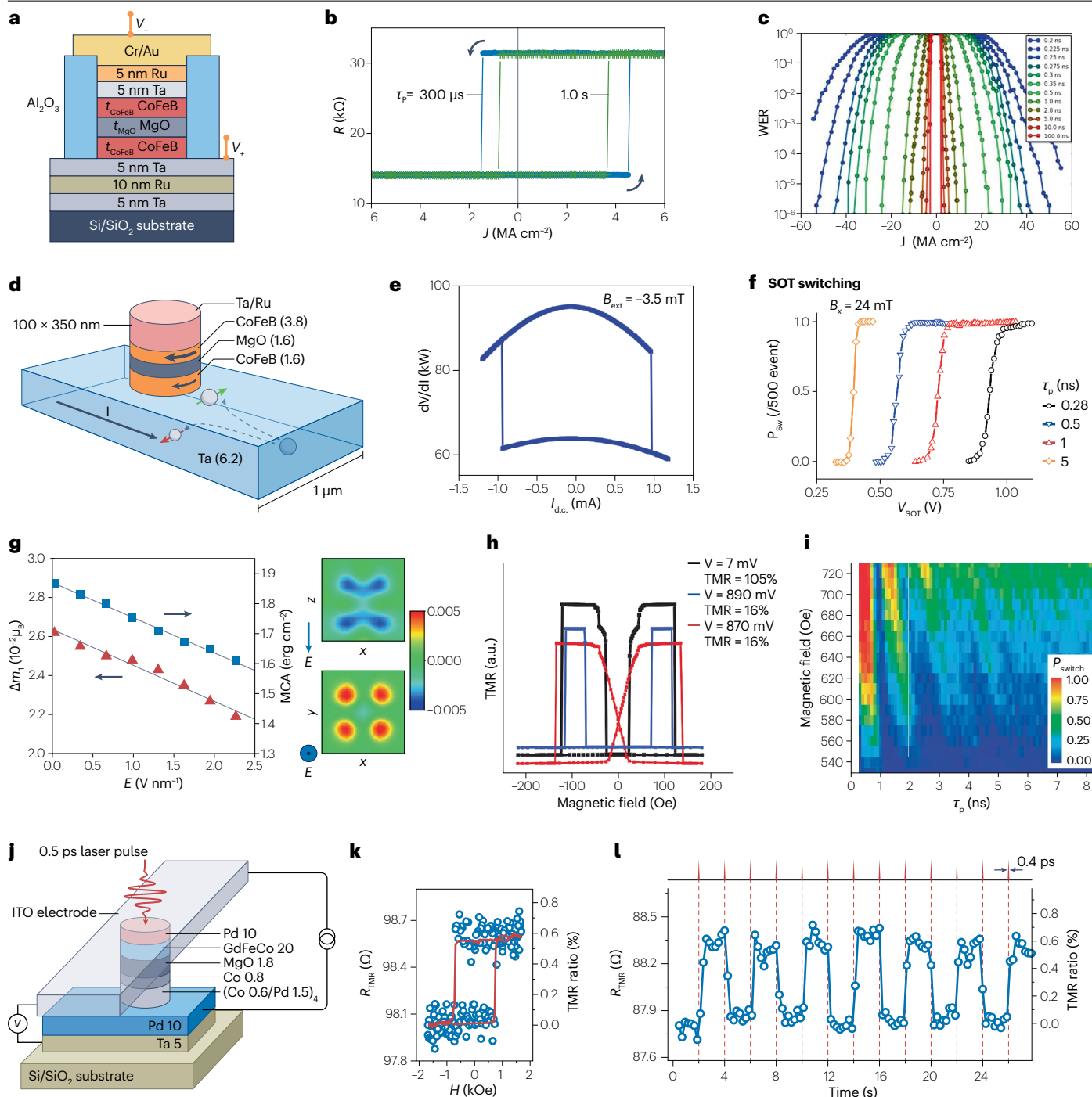
the free layer, they carry spin angular momentum aligned with the pinned layer. As these electrons enter the free layer, they transfer angular momentum and rotate its magnetization once the current density exceeds critical current density J_c (typically 10^6 – 10^7 A cm $^{-2}$), efficiently switching the MTJ into the parallel state (Fig. 5b). Reversing the current by driving electrons from the free layer to the pinned layer switches the MTJ into the antiparallel state. Microscopically, STT consists of an antidamping-like torque that counteracts the intrinsic Gilbert damping and drives the magnetization towards reversal, and a field-like torque that acts as an effective transverse magnetic field, modifying precession trajectories and influencing switching speed and stability^{12,15}. STT enables fast switching in the nanosecond regime, typically ~ 2 – 10 ns, whereas novel structures using an additional spin polarizer have demonstrated sub-nanosecond switching as fast as 140 ps, with switching energies as low as 45 fJ (ref. 114) (Fig. 5c). This enhanced energy efficiency builds upon earlier double-barrier MTJ research and the associated dual-spin-polarizer architecture, in which the angular dependence of the spin-transfer torque is effectively optimized by introducing an additional spin polarizer^{115,116}. Furthermore, STT can achieve high endurance of 10^{12} cycles (ref. 117) (10^{14} cycles at -25 °C (ref. 118)), far surpassing flash memory. However, the need for high current densities leads to significant stress on the tunnel barrier, resulting in long-term reliability concerns and ultimately limiting write-cycle lifetimes. Current research focuses on reducing J_c and further accelerating switching by using new material with reduced M_s (including antiferromagnets), engineering low-damping interfaces¹⁰³ and tailoring spin polarization¹¹⁹ to maximize torque efficiency.

SOT switching. SOT switching uses a three-terminal approach in which the spin current is generated in-plane via a heavy metal adjacent to the ferromagnet, rather than passing directly through the barrier. SOT arises from two complementary mechanisms. The first is the spin Hall effect in heavy metals, such as Pt, W or Ta, in which a charge current generates a transverse spin current that diffuses into the adjacent

ferromagnetic free layer and exerts a torque on its magnetization¹⁷. The second is the Rashba–Edelstein effect at asymmetric interfaces, in which spin–momentum locking due to strong interfacial spin–orbit coupling creates a non-equilibrium spin accumulation that similarly acts on the magnetization¹⁶. The advantages of SOT include the decoupling of read and write paths: the MTJ is read conventionally through the tunnel barrier, whereas writing is performed via a separate electrode (Fig. 5d). This architecture eliminates read-disturb issues and enables potentially higher endurance, as the tunnel barrier is not stressed during write operations. Additionally, SOT generally achieves faster switching than STT, owing to the orthogonal orientation of the injected spin torques relative to the free layer's magnetization (Fig. 5e,f). This configuration significantly accelerates the initial phase of switching, as schematically illustrated in Fig. 4c.

MTJs driven by SOT have shown endurance up to 10^{15} cycles (ref. 120) and switching energy down to 60 fJ (ref. 121). However, a key limitation of early SOT implementations was the requirement of an external in-plane magnetic field to break the symmetry in p-MTJs. Recent innovations, however, have enabled field-free SOT switching, marking a significant step towards practical SOT-based devices¹²². Although SOT offers fast switching and high endurance, ongoing challenges such as optimizing current efficiency and reducing footprint (owing to the three-terminal structure required) are active areas of research aimed at improving scalability and energy performance.

VCMA switching. VCMA is a promising ultralow-power switching mechanism that uses an electric field across the MTJ barrier to modulate the magnetic anisotropy of the free layer. DFT calculations first predicted that an applied electric field at an Fe–MgO interface can significantly change interfacial magnetic anisotropy (and even the local magnetization) by altering electron occupancies^{21,123,124}. When a voltage is applied across the MgO barrier, electron accumulation or depletion occurs at the ferromagnet–MgO interface, modifying the PMA of the free layer¹²³ (Fig. 5g). If a sufficiently strong voltage pulse is applied,



the PMA can be temporarily reduced nearly to zero, allowing the free layer to enter precession under a small constant in-plane magnetic field (Fig. 4d). When the voltage is removed at the appropriate moment, the magnetization relaxes in the opposite direction, achieving switching in approximately half a precession period¹²⁵. Additional contributions to the VCMA effect, such as electric-field-induced changes in spin-orbit coupling¹²⁶ and orbital quadrupole redistribution¹²⁷ have also been studied.

Experimentally, the VCMA effect is most pronounced in p-MTJs with relatively thick MgO barriers (>1.5 nm), in contrast to STT-MTJs, in which MgO is typically ~1 nm. It has been shown that an applied voltage can strongly reduce or enlarge the coercivity of the MTJ, an effect not expected from classical electrostatics, enabling unipolar switching at current densities as low as 10⁴ A cm⁻² (ref. 128) (Fig. 5h). Sub-nanosecond voltage pulses induce clear precessional motion, demonstrating that voltage control can drive ultrafast magnetization

Fig. 5 | Representative experimental results of MTJ switching by various mechanisms. **a**, Schematic structure of a magnetic tunnel junction (MTJ) with perpendicular magnetic anisotropy using spin-transfer torque (STT). **b**, A typical STT switching hysteresis loop measured under a direct current (d.c.), showing sharp transitions between the parallel and antiparallel states, corresponding low and high resistance R , respectively. **c**, Demonstration of fast STT switching dynamics with switching times reaching down to 100 ps. **d**, Schematic of a three-terminal spin-orbit torque (SOT) MTJ device, in which an in-plane charge current (I) through a heavy metal layer generates a transverse spin current. This spin current exerts torques on the free layer magnetization, enabling switching without current passing through the tunnel barrier. **e**, SOT switching hysteresis loop measured under d.c., confirming bidirectional switching via SOTs. **f**, Switching probability P_{sw} as a function of the applied SOT voltage V_{SOT} for current pulses of varying duration τ_p , demonstrating the dependence of switching speed and threshold on pulse width. An in-plane magnetic field B_x is applied to enable deterministic switching. **g**, Results of density functional theory calculations illustrating the modulation of surface magnetic moment (Δm_i) and magnetocrystalline anisotropy energy (MCA) as a function of the applied electric field E . The applied electric field redistributes charge from out-of-plane d_{xz}/d_{yz} orbitals (blue) to in-plane d_{xy} orbitals (red), as seen in the corresponding charge

accumulation (red) and depletion (blue) maps. **h**, Significantly different tunnelling magnetoresistance (TMR) curves for perpendicular MTJs measured under different d.c. bias voltages, due to the voltage-controlled magnetic anisotropy (VCMA) effect. **i**, Oscillatory behaviour of switching probability (P_{switch}) versus pulse duration (τ_p) in VCMA switching, consistent with precessional switching dynamics. **j**, Schematic of an MTJ designed for all-optical switching (AOS), in which a femtosecond laser pulse is directed onto the free layer through a transparent indium-tin oxide (ITO) electrode. **k**, TMR response of an AOS-capable MTJ. Resistance (R_{TMR}) and TMR ratio as functions of applied magnetic field H for the MTJ shown in panel **j**, under sub-picosecond infrared laser excitation. **l**, Reversible switching of MTJ resistance (R_{TMR}) induced by 0.4 ps laser pulses, demonstrating successful sub-picosecond all-optical magnetization reversal. a.u., arbitrary units; B_{ext} , external magnetic field; t_{CoFeB} , thickness of CoFeB layer; t_{MgO} , thickness of MgO layer; WER, write-error rate. Parts **a** and **b** reprinted from ref. 79, Springer Nature Limited. Part **c** reprinted with permission from ref. 114, IEEE. Parts **d** and **e** adapted with permission from ref. 17, AAAS. Part **f** reprinted with permission from ref. 236, IEEE. Part **g** reprinted with permission from ref. 123, AIP. Part **h** reprinted from ref. 24, Springer Nature Limited. Part **i** reprinted from ref. 23, Springer Nature Limited. Part **j** reprinted from ref. 237, Springer Nature Limited. Parts **k** and **l** reprinted with permission from ref. 141, APS.

dynamics²³ (Fig. 5i). Because VCMA switching involves minimal current flow, the switching energy is at least an order of magnitude lower than STT, reaching only a few femtojoules^{129,130}. Recent experiments have demonstrated the switching energy of 3.5 fJ using remote-doping-enhanced VCMA¹³¹. Owing to the ultrafast dynamics involved, switching faster than 100 ps (at 50% probability) has also been achieved¹³².

A major challenge for VCMA is the write-error rate. Owing to VCMA requiring precise pulse timing, the process is intrinsically sensitive to thermal fluctuations. Reported write-error rates for VCMA-only switching are at best in the 10^{-2} – 10^{-4} range^{107,125}. Very recently, a write-error rate below 10^{-6} has been achieved in MgFeO-based MTJs, attributed to the very low damping constant (as low as 0.008) of the high-quality CoFe free layer deposited at 100 K (ref. 133). Further reduction of the write-error rate will require the PMA of the free layer to be increased, improving VCMA efficiency or supplementing VCMA with an additional torque, such as a small-concurrent STT or SOT, to stabilize the switching trajectory. Another challenge is the magnitude of the VCMA coefficient, which determines the write voltage. For compatibility with CMOS, typically write voltages below 1 V are required. This has been recently achieved in VCMA-MTJs with Mo capping and optimized free-layer composition, which exhibit both large VMCA and TMR effects^{134,135}. Beyond standard VCMA, other voltage-controlled phenomena, such as voltage-controlled exchange bias¹³⁶, voltage-controlled interlayer exchange coupling^{137,138} and voltage effects involving antiferromagnets^{139,140}, are also being actively pursued as energy-efficient methods to manipulate the MTJs.

AOS. All-optical switching (AOS) offers a pathway to achieve MTJ reversal on timescales far shorter than those accessible by the electrical methods discussed above^{141,142}. In AOS, a single femtosecond laser pulse heats the magnetic free layer on an ultrafast timescale, rapidly driving the electron, spin and lattice temperatures far out of equilibrium¹⁴³ (Fig. 4e and Fig. 5j,k). When the free layer is a ferrimagnet (commonly a transition-metal–rare-earth alloy such as CoGd) the two magnetic sublattices demagnetize at different rates owing to their distinct magnetic moments. This transient imbalance, mediated by ultrafast exchange scattering, produces a transient ferromagnetic-like state, enabling deterministic reversal without an external magnetic field¹⁴⁴.

As a result, magnetization switching can occur in the sub-picosecond regime¹⁴³ (Fig. 5l). Such ultrafast optical switching has been successfully incorporated into MTJ structures, in which the free layer is reversed by femtosecond laser pulses whereas the TMR signal confirms electrical readout of the state^{140,141}. In addition to thermal mechanisms, several non-thermal effects such as the inverse Faraday effect and magnetic circular dichroism have been proposed to contribute to AOS. Although helicity-dependent switching observed in certain material systems suggests a possible role of these effects, their quantitative contribution and universality remain subjects of ongoing debate^{145–147}.

Although AOS provides an attractive route to picosecond-scale and photonics-compatible MTJ switching, its practical limitations include optical diffraction limits and challenges in scaling to dense memory arrays. Consequently, current MTJ research aims to replicate these ultrafast reversal mechanisms electrically, using picosecond electrical pulses or novel free-layer designs to achieve AOS-like speed within CMOS-compatible architectures¹⁴⁸.

Other switching methods. In addition to purely electronic or optical switching, strain-mediated and heat-assisted magnetization reversal have been explored. In strain-mediated schemes, a voltage applied to a piezoelectric layer generates strain that transfers to an adjacent magnetostrictive ferromagnet, modulating its anisotropy and enabling low-energy switching with little to no current¹⁴⁹. Thermally assisted approaches momentarily heat the MTJ to reduce its coercivity, allowing a smaller field or STT current to write the bit; even a 50–100 K temperature rise can cut the required STT current substantially¹⁵⁰. Although strain and thermal methods are not as widely implemented as STT, SOT and VCMA, they offer additional degrees of freedom to reduce energy or help to write stubborn high-barrier bits.

Table 2 shows a comparison of different switching methods.

Noise characterization

MTJs exhibit several types of noise that affect device performance and reliability, particularly in sensors and memory applications¹⁵¹. Thermal and shot noise form the white noise floor, scaling with resistance and bias. $1/f$ noise dominates at low frequencies, driven by charge traps or magnetic fluctuations, and is sensitive to area and interface quality.

Table 2 | Comparison of different MTJ switching methods

Method	TMR (typ. at room temperature)	Switching time (typ./min.)	Switching energy (typ./min.)	Device size (typ./min.)	Endurance (cycles; typ./max.)	Write-error rate (typ.)	Thermal stability (typ.)
STT	~100%	10 ns/<100 ps (ref. 114)	100 fJ/45 fJ (ref. 114)	50 nm/2.3 nm (ref. 101)	10^{10} / $>10^{15}$ (ref. 227) ^a	10^{-9}	~60
SOT	~100%	5 ns/10 ps (ref. 122)	200 fJ/60 fJ (ref. 121)	50 nm/NA	10^{14} / 10^{15} (ref. 120)	10^{-6}	~60
VCMA	~150%	0.5 ns/<100 ps (ref. 228)	20 fJ/3.5 fJ (ref. 131)	50 nm/30 nm (ref. 135)	10^{10} (ref. 135)/NA	10^{-2} – 10^{-6} (refs. 107, 133, 228)	~30–40
AOS	~70%	1 ps/50 fs (ref. 229)	~69 fJ (ref. 229)/NA	10 μ m/100 nm (ref. 230)	NA/NA	NA	NA
Thermal-assisted	10–100%	20 ns/500 ps (ref. 150)	>1 pJ	NA/100 nm (ref. 150)	NA/ 10^{12} (ref. 230)	NA	~160 (ref. 231)
Strain-mediated	30–100%	~1 s (ref. 232)/NA	~100 pJ ^b (ref. 233)/~20 aJ ^{c,d} (ref. 234)	~10 μ m (ref. 234)/NA	1–10 (ref. 235)/NA	NA	NA

When available, both typical (typ.) and minimum (min.) values are provided. Minimum switching times for spin-transfer torque (STT), spin-orbit torque (SOT) and voltage-controlled magnetic anisotropy (VCMA) are reported at 50% switching probability. AOS, all-optical switching; max., maximum; MTJ, magnetic tunnel junction; NA, not available in the literature; TMR, tunnelling magnetoresistance. ^aModelled based on the experimental results. ^bEstimated from the parameters provided in the paper. ^cScaled to a 100 nm thin-film device. ^dPerformed on a thin film, rather than MTJ.

Magnetization noise stems from thermal fluctuations in ferromagnetic layers, particularly under low fields. Random telegraph noise arises from discrete resistance jumps due to individual defect traps, especially near switching. In deliberately engineered MTJs with very small TSF, random telegraph noise can produce high-frequency resistance fluctuations in the gigahertz region, which are harnessed for probabilistic computing. Together, these noise types provide diagnostic insight into barrier quality, magnetic stability and interface defects. The noise floor in modern MTJs is in the sub-picotesla range, enabling the detection of extremely small magnetic fields¹⁵².

Applications

In this section, we review several established and emerging applications of MTJs. Owing to their large magnetoresistance, MTJs provide a highly sensitive means of detecting magnetic fields and are widely used in magnetic sensors, including HDD read heads and TMR-based biosensors. MTJs also form the core storage element in MRAMs, in which TMR enables reliable readout, whereas different current-driven or voltage-driven mechanisms are used for writing. Beyond memory technologies, the integration of MTJs with conventional semiconductor platforms opens new opportunities for unconventional computing paradigms, such as neuromorphic and probabilistic computing. Finally, MTJs are finding increasing use in radio-frequency applications, including microwave oscillators and detectors.

Magnetic field sensors

HDD read heads. MTJ sensors have played a pivotal part in advancing HDD technology, evolving from earlier anisotropic magnetoresistance and giant magnetoresistance (GMR)¹⁵³ sensors to today's high-performance TMR read heads¹⁵⁴. A key distinction between MTJs used in memory versus sensor applications lies in the orientation of their magnetic easy axes. In memory applications, the free and pinned ferromagnetic layers typically have collinear easy axes, enabling two well-defined stable magnetization states for storing binary data. By contrast, for sensor applications such as HDD read heads, the easy axes of the two layers are orthogonal, set at 90° to each other in the absence of an external magnetic field. This configuration biases the MTJ at an intermediate resistance state (approximately halfway between

R_{AP} and R_P), in which sensitivity to small field-induced rotations of the free layer is maximized. As a magnetized bit passes beneath the read head (Fig. 6a), its stray magnetic field slightly tilts the free layer magnetization, altering its relative orientation with respect to the pinned layer. This shift causes a measurable change in resistance, enabling precise readout of magnetic data.

The first TMR read heads, using amorphous Al-O or Ti-O barriers, were introduced around 2004–2005, supporting areal densities near 80–100 Gbit in⁻². These offered modest magnetoresistance (tens of percent) but surpassed prior anisotropic magnetoresistance (<5%) and GMR (~10–15%) sensors. By 2007, crystalline MgO barriers had supplanted AlO_x in commercial read heads, enabling much higher TMR ratios and supporting recording densities exceeding 500 Gbit in⁻². Today, MgO-based MTJ read heads remain the industry standard, supporting recording densities of up to 1.5 Tbit in⁻². Next-generation read heads targeting more than 3 Tbit in⁻² are currently under development, featuring ultralow resistance-area products (~0.2 $\Omega \mu$ m²) and high TMR ratios (~100%).

Biosensors. MTJ sensors also found wide applications in biomedicine and precision sensing owing to their compact size and high magnetoresistance and sensitivity. In biomedical diagnostics, MTJs are used to detect magnetic nanoparticles bound to target biomarkers, such as cancer cells, proteins or viruses, through lab-on-chip immunoassays¹⁵⁵. In a typical assay, superparamagnetic nanoparticles (commonly iron oxide beads functionalized with DNA strands or antibodies) bind selectively to target molecules, such as proteins or DNA, through molecular recognition. The MTJ chip surface is likewise functionalized, with capture antibodies or DNA probes immobilized directly on the sensor junctions. In a sandwich assay format, target antigens bound to magnetic nanoparticles are captured by the surface probes (Fig. 6b). The stray dipolar magnetic fields from these particles perturb the magnetization of the MTJ's free layer, leading to a detectable change in resistance and enabling precise identification of the biomarkers¹⁵⁶.

MTJ-based arrays have been developed to detect tagged biomolecules in microfluidic channels, offering fast, label-specific detection without optics. One promising application demonstrated a CMOS-integrated MTJ sensor platform that could support cultured

neurons for extended periods, suggesting future potential in neural interfacing¹⁵⁷. Recent MTJ sensor arrays incorporating magnetic flux concentrators have achieved detectivities in the sub-picotesla range, approaching the performance of SQUIDS¹⁵². These sensors have successfully detected cardiac R-waves at 100–200 pT and evoked brain responses in the hundreds of femtotesla range, validating their capacity for high-resolution biomagnetic signal capture. With the ability to sense magnetic fields at or below the scale of neural signals, MTJ sensors are now poised to have transformative roles in neuroscience, brain–machine interfaces and bio-integrated artificial intelligence systems.

MRAM

MRAM is a non-volatile memory technology that uses MTJs to store information. Each MTJ encodes one bit by adopting either a parallel or antiparallel alignment of magnetization in its two ferromagnetic layers. The stored bit is read electrically via the resistance contrast generated by the TMR effect. Given that larger TMR ratios enable faster and more reliable readout, modern MRAMs usually rely on CoFeB/MgO/CoFeB MTJs, which offer both high TMR performance and excellent compatibility with large-scale manufacturing. Writing operations in MRAM are performed by switching the magnetization of the free layer using a magnetic field, an electric current or a voltage. Multiple MRAM architectures with distinct writing mechanisms have been developed, including toggle MRAM, STT-MRAM, SOT-MRAM and voltage-controlled MRAM (VC-MRAM) – some already commercialized and others still in development.

Toggle MRAM. Toggle MRAM is the first-generation MRAM that uses a magnetic field generated by an electric current for the magnetization switching¹⁵⁸. Toggle MRAM uses i-MTJs. Although megabit-class commercial toggle MRAM has been available since the mid-2000s, its magnetic field-induced switching mechanism is not scalable, limiting its use to niche applications.

STT-MRAM. STT-MRAM is the second-generation MRAM that uses an electric current for magnetization switching^{159,160}. When a relatively large tunnel current flows through an MTJ via a pass transistor (Fig. 7a), a spin-polarized current is injected from the pinned layer into the free layer. The transfer of spin angular momentum from the spin-polarized conduction electrons to the free layer magnetization generates STT on the magnetization¹². When the current density exceeds a critical threshold, STT amplifies the magnetization precession and ultimately reverses the magnetization (Fig. 4b). This STT-based switching mechanism is inherently scalable, as the electric current required for switching is approximately proportional to the lateral area of the MTJ. In the first prototype of STT-MRAM, i-MTJs were used¹⁶¹. Later, p-MTJs were found to offer superior scalability owing to their lower switching current densities and higher thermal stability¹⁶². This led to the development of p-MTJs based on the CoFeB/MgO/CoFeB structure, which leverages PMA arising from the CoFeB–MgO interface^{79,80,163}. Today, CoFeB/MgO/CoFeB-based p-MTJs are the mainstream technology for STT-MRAM.

Gb-class STT-MRAM was commercialized in the late 2010s as both stand-alone memory and embedded non-volatile memory. Although the detailed MTJ stack used in commercial products has not been disclosed, these devices are believed to use complex multilayer structures containing several tens of layers¹⁶⁴ (Fig. 8). Such MTJ films can be deposited uniformly across 300 mm Si wafers using d.c. magnetron sputtering followed by post-oxidation of Mg.

SOT-MRAM. SOT-MRAM is an emerging MRAM that uses the spin Hall effect for writing¹⁸. When a charge current flows through a wire made of a material with a strong spin Hall effect (the spin Hall channel), a transverse pure spin current (a flow of spin angular momentum) is generated. When the free layer of an MTJ is placed on top of this channel (Fig. 7b), the spin current is injected into the free layer, exerting SOT on its magnetization. Once the current density exceeds a critical value, this torque can induce magnetization switching (Fig. 4c). Because the

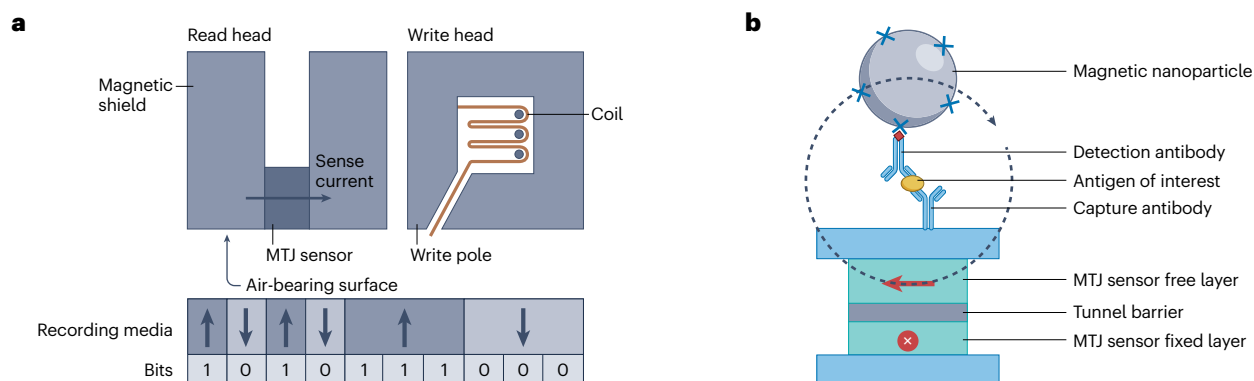


Fig. 6 | Schematic of HDD read/write head and MTJ biomagnetic field sensor. a, Schematic illustration of a hard-disk-drive (HDD) read-write head incorporating a magnetic tunnel junction (MTJ) sensor. The MTJ sensor is embedded within the read head and is surrounded by magnetic shields to enhance spatial resolution and reduce noise. A sense current is applied through the MTJ to detect resistance changes arising from the magnetic bits recorded in the underlying media. Adjacent to the read head is the write head, which consists of a coil and a write pole used to generate localized magnetic fields for writing data onto the recording media. The entire head structure is positioned above the air-bearing surface, which separates it from the moving recording media.

The magnetization direction of the bits in the recording media (illustrated as binary states) produces stray fields that are sensed by the MTJ element during readout. **b**, Schematic of the MTJ configured as a biosensor for antigen detection. The MTJ sensor, positioned beneath the sensing region, detects stray magnetic fields from functionalized magnetic nanoparticles that are bound to target antigens via specific antibody–antigen interactions. The presence of bound nanoparticles induces a measurable change in the MTJ resistance through its high sensitivity to local magnetic fields, allowing for label-based biosensing with high sensitivity and specificity.

spin current is typically polarized within the film plane, SOT is naturally suited for switching i-MTJs. By contrast, switching p-MTJs by SOT generally requires a mechanism for in-plane symmetry breaking¹⁶⁵, which can be either an external magnetic field or spin Hall materials with reduced crystal symmetry^{16,166,167}.

SOT-MRAMs remain under active research and development, although prototype chips have already been demonstrated¹⁶⁸. A central challenge for advancing SOT-MRAM is the enhancement of spin-conversion efficiency, which is the ratio of the generated spin current to the applied charge current. Conventional spin Hall materials, such as Ta, β -W and W-based alloys, exhibit spin Hall angle values up to ~0.4 (refs. 17,169,170). For practical SOT-MRAM, substantially higher spin Hall angle values, together with field-free switching of p-MTJs, are required. In principle, SOT-MRAM can achieve faster operation and endurance than STT-MRAM because its read and write current paths are physically separated. However, a fundamental limitation of SOT-MRAM is the relatively large footprint associated with its three-terminal cell structure (Fig. 7b), which reduces memory density. As a result, SOT-MRAM may be suitable for high-speed cache applications in which fast switching is prioritized over density.

VC-MRAM. VC-MRAM is another emerging MRAM technology that uses short voltage pulses for writing. The cell structure of VC-MRAM (Fig. 7c) is essentially identical to that of STT-MRAM (Fig. 7a). The main difference is the resistance-area product of the MTJs. In VC-MRAM, the resistance-area product is typically on the order of $100 \Omega \mu\text{m}^2$ or larger, whereas in STT-MRAM it is usually below $10 \Omega \mu\text{m}^2$. Owing to this difference, magnetization switching in VC-MRAM is driven by an applied voltage rather than by a large current. As discussed in the section on VCMA switching, a sub-nanosecond voltage pulse with a duration equal to half the magnetization precession period can induce switching of the free layer magnetization^{23,125} (Fig. 4d). In VC-MRAM, the application of unipolar voltage pulses induces parallel-to-antiparallel and antiparallel-to-parallel switching in an alternating manner (Fig. 7c). A key advantage of VC-MRAM is its ultralow write-energy consumption, on the order of 1–5 fJ per bit. Equally important, the voltage-driven

switching mechanism allows for the use of minimum-sized select transistors, given that they do not have to drive a large current through the MTJ. This makes VC-MRAM cells inherently smaller than STT-MRAM or SOT-MRAM cells¹³⁴. However, VC-MRAM remains in the research and development stage owing to several outstanding technical challenges. The most significant among these is the high incidence of write errors inherent to its dynamic, precessional switching mechanism, as well as device-to-device variations of the precession frequency. Substantial progress has been recently achieved in improving VCMA coefficients of MTJs with high TMR, leading to sub-volt switching of voltage-controlled MTJs^{61,133,134}. Furthermore, a significant reduction in the write error rate has been demonstrated by using a synthetic AFM structure as a free layer¹⁷¹. Nevertheless, the magnitude of the VCMA effect achievable in current materials is still insufficient for realizing high-density VC-MRAM¹²⁵. Further research and development are required to address these technical challenges.

Table 3 summarizes features and specifications of the four types of MRAM.

Industry outlook. Despite its technological success, today's MTJ technology is still in the early stages of broader adoption by the semiconductor industry. Further progress will require both fundamental advances and engineering optimization. Below, we outline the key requirements, focusing on two major directions.

The first research direction focuses on high-performance MTJs embedded in advanced logic foundry processes. Early industrial adoption of MRAM has been driven primarily by its non-volatility and its suitability as a replacement for embedded Flash, which does not scale efficiently below the ~40 nm technology node. As a result, STT-MRAM technology has been integrated into commercial foundry nodes ranging from 16 nm to 40 nm (refs. 172,173), with more advanced nodes down to 5 nm currently in development. However, STT-MRAM suffers from a fundamental trade-off between speed and endurance, as well as speed and bit density, owing to the higher currents required for faster switching¹⁷⁴. This limits the prospect of utilizing STT-MRAM in applications such as static random-access memory, which requires

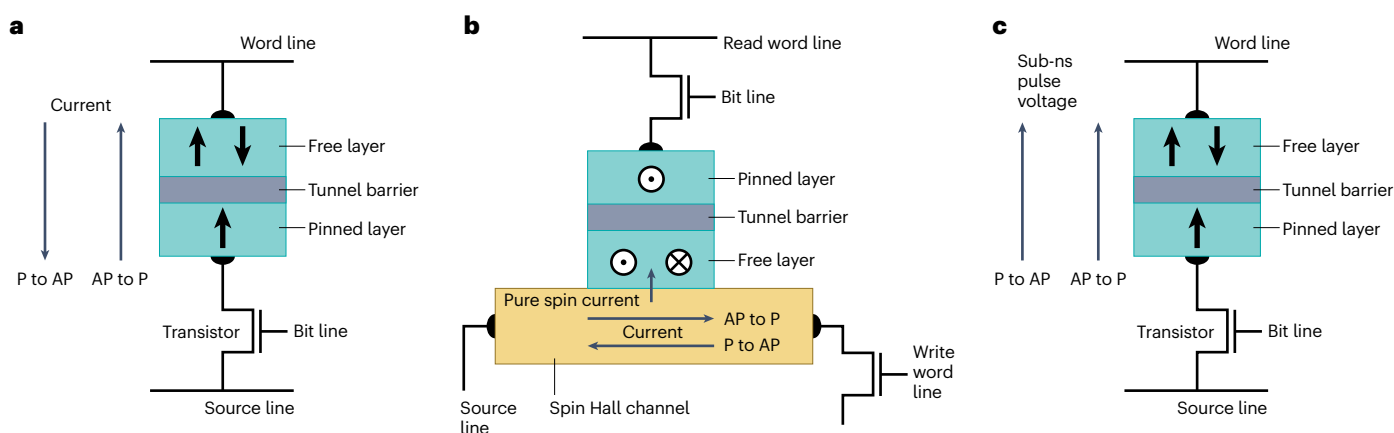


Fig. 7 | MRAM memory cells of various types. a, Spin-transfer torque (STT)-magnetoresistive random-access memory (MRAM). A two-terminal magnetic tunnel junction (MTJ) consisting of a pinned layer, tunnel barrier and free layer integrated with a transistor. A current flowing through the stack induces STT that switches the free-layer magnetization between parallel (P) and antiparallel (AP) states. **b,** Spin-orbit torque (SOT)-MRAM. A three-terminal device in

which a lateral charge current in the spin Hall channel generates a transverse spin current that switches the free layer via SOT, while the MTJ stack is used for readout. **c,** Voltage-controlled MRAM. Voltage-controlled switching of an MTJ, in which a voltage pulse across the tunnel barrier modulates magnetic anisotropy and enables switching between P and AP states. Word lines and bit lines are orthogonal conductive lines in a memory array used to address, read or write data.

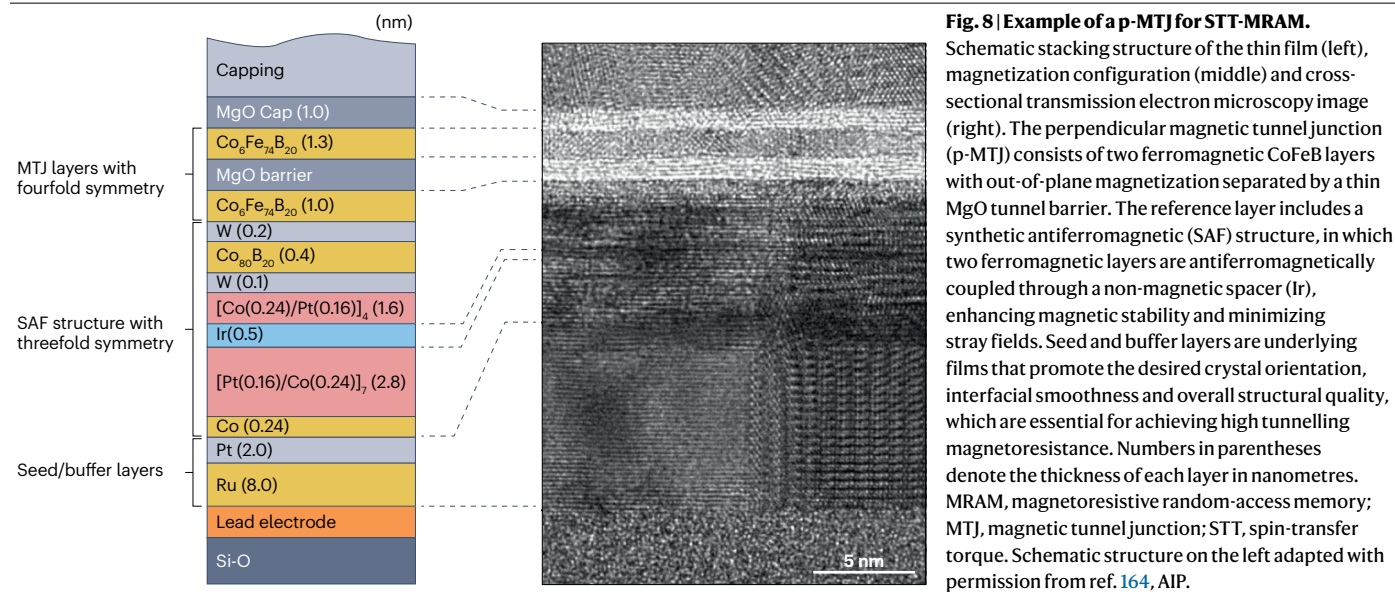


Fig. 8 | Example of a p-MTJ for STT-MRAM.

Schematic stacking structure of the thin film (left), magnetization configuration (middle) and cross-sectional transmission electron microscopy image (right). The perpendicular magnetic tunnel junction (p-MTJ) consists of two ferromagnetic CoFeB layers with out-of-plane magnetization separated by a thin MgO tunnel barrier. The reference layer includes a synthetic antiferromagnetic (SAF) structure, in which two ferromagnetic layers are antiferromagnetically coupled through a non-magnetic spacer (Ir), enhancing magnetic stability and minimizing stray fields. Seed and buffer layers are underlying films that promote the desired crystal orientation, interfacial smoothness and overall structural quality, which are essential for achieving high tunnelling magnetoresistance. Numbers in parentheses denote the thickness of each layer in nanometres. MRAM, magnetoresistive random-access memory; MTJ, magnetic tunnel junction; STT, spin-transfer torque. Schematic structure on the left adapted with permission from ref. 164, AIP.

access times of ~1 ns to 10 ns. This is an area in which newer MRAM write mechanisms such as VCMA (owing to the absence of reliance on write current), SOT (owing to its potentially faster writing and decoupled read/write paths) and AFMTJs (owing to their higher-frequency dynamics) could be fruitful directions for further research.

High-density MTJ arrays with two-terminal or three-terminal select devices represent a second key direction towards high-capacity memory applications, in which MRAM has not yet achieved broad adoption owing to scaling challenges and the need for tighter pitch and lower manufacturing cost. A representative example is dynamic random-access memory (DRAM), in which achieving competitive densities remains difficult for STT-MRAM, owing to the access-transistor size required by the write current and to increased sensitivity to device-to-device resistance variations at reduced pitch, which in turn demands larger TMR ratios for reliable operation. Here, new mechanisms such as VCMA can be of interest as they inherently require less current while also having unipolar write characteristics that are amenable to a wider range of two-terminal select devices than STT-controlled MTJs¹⁷⁵. Note that the actual chip-level energy consumption per bit can be significantly higher than the intrinsic single-device switching energy listed in Table 3 owing to peripheral circuitry and system-level overhead. New MTJ material platforms, such as van der Waals and antiferromagnet-based MTJs, represent another promising direction, as they rely on fundamentally different mechanisms of TMR and magnetization switching that could potentially be engineered to achieve DRAM-competitive performance.

Table 4 summarizes and compares the key characteristics of MRAM with conventional charge-based memory technologies, including DRAM, static random-access memory and Flash, as well as emerging next-generation memories. These include resistive random-access memory, which stores information via memristive switching; phase-change random-access memory, which relies on resistance changes associated with phase transitions; ferroelectric random-access memory, which uses ferroelectric capacitors integrated with a transistor; and ferroelectric field-effect transistors, in which the transistor gate oxide itself is ferroelectric.

Spintronic logic devices

Spintronic logic devices have been proposed to add functionality alongside established CMOS logic in future electronic systems. A key benefit derived from them can be low static power dissipation, given that non-volatile magnetic states are preserved in the absence of an applied voltage^{176,177}. Owing to their unique physics, spintronic logic devices may also provide certain functionalities in a more compact and energy-efficient manner than purely CMOS solutions.

A key distinction between memory and logic is that, in a typical computing scenario, the bit-level dynamic energy dissipation of a logic device can matter much more than in memory. Early studies pointed out that the large discrepancy between the dynamic energy dissipation of CMOS transistors (<1 fJ) and STT-switched MTJs (~100 fJ to 1,000 fJ) necessitates a more energy-efficient spintronic switching mechanism, if a fine-grained integration of CMOS and MTJs (for example, in a non-volatile gate or flip-flop) is desired¹⁷⁸. In this context, the improved energy efficiency of VCMA as a control switching mechanism of MTJs is of great interest because it facilitates far more energy-efficient magnetization switching^{129,134}.

Probabilistic and neuromorphic computing

MTJs can be engineered to have a small energy barrier between their free layer states. This can be done either statically, by optimizing the free layer to have a small anisotropy energy density and/or volume, or dynamically, by temporarily reducing the energy barrier using the VCMA effect^{135,179–181}. As a result of a small energy barrier, the MTJ resistance will statistically fluctuate between two well-defined values determined by the TMR ratio. In addition, the fraction of time spent in each state (that is, the probability of finding the MTJ in its parallel or antiparallel state) can be controlled by deterministic current-induced torques such as STT or SOT^{182–184}. Such a device is then referred to as a probabilistic bit^{182,185,186}.

Stochastic behaviour of MTJs has been used in many emerging computing scenarios. For example, stochastic bitstreams can be utilized for stochastic computing architectures, in which numbers are represented as probabilities of finding 0s and 1s within a bitstream

rather than using the conventional binary representation. This allows for a much more compact realization of multiplication and addition circuits, which are important in neural networks that are used for machine learning and artificial intelligence¹⁸⁴. Networks of MTJ-based probabilistic bits with digital or analogue tunable connections can also be used to produce probabilistic Ising machine computers, which can serve as accelerators for difficult computing tasks such as optimization^{179,185,187–190}. Besides computing, high-quality random bitstreams generated by MTJs with high throughput can also find applications in cryptography and hardware-level security^{181,191}.

Radio-frequency applications

STOs. Beyond magnetization switching, STT can drive large-angle steady-state magnetization precession at the FMR frequency, depending on the applied d.c. and magnetic field (Fig. 9a). In this regime, the magnetoresistance effect converts the precessional dynamics into a radio-frequency voltage, manifested as peak(s) in the power spectral density (for example, radio-frequency power per unit frequency), in the gigahertz to tens-of-gigahertz range (Fig. 9b), enabling nanoscale magnetoresistive devices to function as microwave sources known as spin-torque oscillators (STOs), or spin-torque nano-oscillators.

STOs were first demonstrated in current-perpendicular-to-plane giant magnetoresistance nanopillars¹⁹², but the small magnetoresistance ratios (~1%) limited the radio-frequency output power to ~10 nW. Owing to the emitted power scaling approximately with the square of the TMR ratio, MgO-based MTJs with large TMR enable orders-of-magnitude higher output, reaching the milliwatt range¹⁹³. The output power increases with the MTJ area. However, for lateral dimensions exceeding ~100 nm, coherent magnetization precession is lost, degrading both the output power and the quality (*Q*) factor. The highest reported radio-frequency powers are a few microwatts for coherent-precession STOs^{194,195}, and about 10 μW for magnetic-vortex STOs¹⁹⁶. Further enhancement of output power and spectral purity has been achieved through synchronization of multiple STOs¹⁹⁷.

A distinctive advantage of STOs is their nanoscale footprint, as they do not require bulky resonant circuits comprising large inductors and capacitors. However, a major challenge for practical microwave applications is their relatively large phase noise, whereas many radio-frequency systems demand spectrally pure signals. To mitigate this limitation, phase-locked loop architectures have been implemented, in which an STO operates as a voltage-controlled oscillator whose phase is locked to a highly stable, lower-frequency reference

clock^{198,199}. This approach substantially suppresses the phase noise compared with free-running operation. Nevertheless, even phase-locked loop-stabilized STOs exhibit phase noise that remains more than an order of magnitude higher than that of conventional LC-tank or transistor-based radio-frequency oscillators.

The dominant source of phase noise in STOs is the intrinsic thermal fluctuation of magnetization²⁰⁰. Consequently, enhancing the thermal stability of STOs is a key requirement for their deployment in practical microwave technologies. Beyond conventional radio-frequency applications, STOs are also being explored in emerging paradigms in which compactness and non-linearity are more critical than ultralow phase noise. Notably, STO-based neuromorphic computing has been proposed, in which STOs act as artificial neurons enabling low-power pattern-recognition tasks, such as vowel recognition^{201,202}.

Spin-torque ferromagnetic resonance. When a radio-frequency current at frequency *f*, $I \sin(2\pi ft)$, is injected into an MTJ, the radio-frequency component of the STT can excite FMR of free layer magnetization (Fig. 9c), a phenomenon known as spin-torque FMR. Owing to the combination of spin-torque FMR and the magnetoresistance effect, the MTJ resistance (*R*) is modulated at the frequency *f* with a modulation amplitude of ΔR . ΔR takes a maximum value at the FMR frequency. As both *I* and *R* are modulated at the same frequency and phase, voltage $\Delta V = I \Delta R [1 + \sin(4\pi ft)]$ is generated. The d.c. component of $\Delta V = I \Delta R$ peaks at the FMR frequency²⁰³ (Fig. 9d). Because the d.c. component can be readily measured, an MTJ can operate as a nanoscale microwave detector. This phenomenon, known as the spin-torque diode effect by analogy with a semiconductor diode, enables quantitative evaluation of the magnitudes of the STT and the field-like torque as functions of the applied bias voltage^{204,205}. The spin-torque diode effect therefore provides a powerful experimental tool for investigating STT-related phenomena in spintronic materials and devices.

Reproducibility and data deposition

Reproducibility of data and proper data deposition are critical for building trust, validating results and accelerating development, especially in MTJs, for which performance depends sensitively on fabrication details and measurement conditions.

Reproducibility of experimental data

Reproducibility of experimental MTJ data is limited by several factors. Device-to-device variability can be substantial, with TMR, resistance

Table 3 | Features and specifications for various types of MRAM

	Toggle MRAM	STT-MRAM	SOT-MRAM	VC-MRAM
Tunnel barrier material	Al-O or MgO	MgO	MgO	MgO
MTJ type	i-MTJ	p-MTJ	Mainly i-MTJ	p-MTJ
Energy consumption to switch a bit	~100 pJ	20–100 fJ	50–100 fJ	<10 fJ
Bit density	<1 Mb mm ⁻²	10–40 Mb mm ⁻²	Half that of STT-MRAM	Similar to STT-MRAM
Write pulse width	10–30 ns	10–30 ns	<10 ns	<1 ns
Technology level	Commercialized	Commercialized	Research and development	Research and development
Technological challenges	Scalability	Write endurance at high-speed writing	Improvement of spin conversion efficiency, scalability	Suppression of write errors, enhancement of VCMA effect

i-MTJ, in-plane-magnetization magnetic tunnel junction; MRAM, magnetoresistive random-access memory; MTJ, magnetic tunnel junction; p-MTJ, perpendicular magnetization magnetic tunnel junction; SOT, spin-orbit torque; STT, spin-transfer torque; VC, voltage-controlled; VCMA, voltage-controlled magnetic anisotropy.

Table 4 | Comparison of major memory technologies

Memory technology	Storage mechanism	Volatility	Write energy	Write speed	Read speed	Endurance (cycles)	Retention	Scalability	CMOS logic compatibility	Key advantages	Key limitations
SRAM	Charge in bistable latch	Volatile	Moderate	1–10 ns	<1 ns	$>10^{16}$	While powered	Poor	Excellent	Fastest memory, no refresh	Large cell size, high leakage
DRAM	Charge on capacitor	Volatile	Moderate	~10 ns	~10 ns	$>10^{16}$	ms (refresh)	Good	Moderate	High density, low cost	Hard to integrate with logic, volatility
Flash (NAND/NOR)	Charge in floating gate	Non-volatile	High	μs –ms	~10–100 ns	10^4 – 10^5	≥ 10 years	Excellent (NAND)	Poor	Ultrahigh density, low cost	Slow write, limited endurance
STT-MRAM	MTJ (STT switching)	Non-volatile	Moderate	~5–20 ns	~1–5 ns	10^{10} – 10^{12}	≥ 10 years	Good	Good	Fast, high endurance	Write current scaling, speed-endurance trade-off
SOT-MRAM	MTJ (SOT switching)	Non-volatile	Low–moderate	<1–5 ns	~1–5 ns	$>10^{12}$	≥ 10 years	Moderate	Moderate	Ultrafast write, high endurance	Extra write path, larger footprint
VCMA-MRAM	MTJ (voltage-assisted switching)	Non-volatile	Very low	~1–10 ns	~1–5 ns	10^{10} – 10^{12}	≥ 10 years	Good	Good	Lowest write energy MRAM	Thermal stability trade-off, error rate
RRAM (ReRAM)	Conductive filament formation	Non-volatile	Very low	~1–10 ns	~10 ns	10^6 – 10^9	≥ 10 years	Excellent	Good	Simple cell, 3D integration	Variability, endurance limits
PCRAM (PCM)	Phase change (amorphous/crystalline)	Non-volatile	High	~10–100 ns	~10 ns	10^7 – 10^9	≥ 10 years	Good	Moderate	Multi-level storage, scalability	High write energy, thermal crosstalk
FeRAM	Ferroelectric polarization	Non-volatile	Very low	~10–50 ns	~10 ns	$>10^{14}$	≥ 10 years	Limited	Good	Ultralow power, high endurance	Poor scaling, destructive read
FeFET	Ferroelectric gate polarization	Non-volatile	Very low	~10 ns	~10 ns	10^5 – 10^8	≥ 10 years	Good	Excellent	CMOS-friendly, embedded NVM	Retention–endurance trade-off

Key performance metrics, scalability, complementary metal–oxide–semiconductor (CMOS) compatibility, and representative advantages and limitations of charge-based, magnetic, resistive, phase-change and ferroelectric memory technologies. DRAM, dynamic random-access memory; FeFET, ferroelectric field-effect transistor; FeRAM, ferroelectric random-access memory; MRAM, magnetoresistive random-access memory; MTJ, magnetic tunnel junction; NAND, not AND logic gate; NOR, not OR logic gate; NVM, non-volatile memory; PCRAM, phase-change random-access memory; RRAM, resistive random-access memory; SOT, spin–orbit torque; SRAM, static random-access memory; STT, spin-transfer torque; VCMA, voltage-controlled magnetic anisotropy.

area and switching currents varying even within the same wafer. These variations arise from film-level sensitivities such as barrier thickness fluctuations, interface roughness and nanoscale non-uniformities, as well as fabrication effects including sidewall redeposition during etching. Magnetic inhomogeneities, such as local grain orientations and associated anisotropy variations, further contribute to performance spread.

Reproducibility is also affected by batch-to-batch differences across fabrication runs or laboratories, in which nominally identical stacks can yield different TMR values, even in highly optimized industrial processes. Such variations originate from differences in deposition conditions, annealing protocols and fabrication details. In addition, incomplete reporting of growth parameters, annealing profiles and statistical device data limits reproducibility, while lab-specific environmental factors, such as base pressure,

deposition pressure, oxygen contamination and material degradation due to air or humidity exposure, are rarely documented but can be critical.

There are certain known measurement artefacts that can be avoided during the design of experiments. Particularly in large-area devices, non-uniformity of the current distribution can significantly distort the measured resistance and TMR values compared with the real ones. Researchers should adopt the best practice of ensuring that vertical MTJ resistance is significantly larger than in-plane lead resistances to minimize this artefact, and, when needed, utilize available models to estimate their measurement error^{206,207}.

Best practices for ensuring reproducibility

We recommend reporting the mean, standard deviation and number of devices measured for key MTJ metrics, including the TMR ratio,

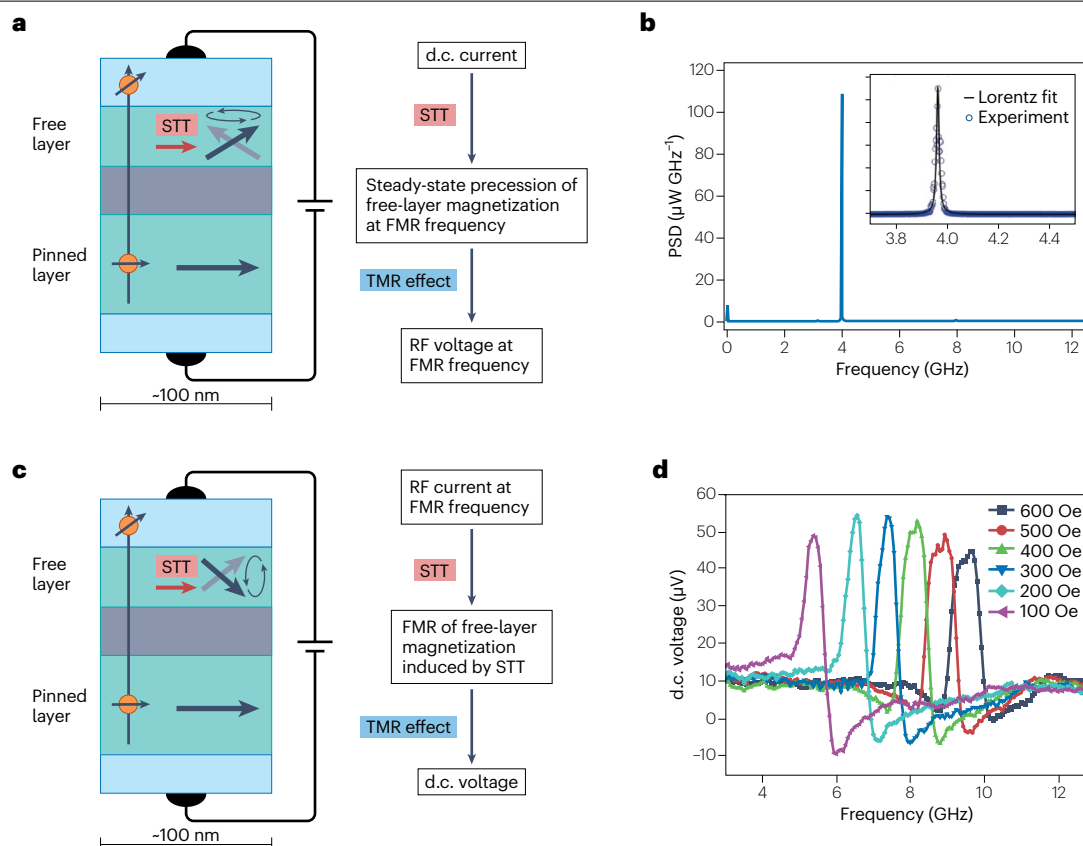


Fig. 9 | STO and spin-torque diode. **a**, Operating principles of spin-torque oscillator (STO) based on magnetoresistive nano-pillar device. A direct current (d.c.) drives spin-transfer torque (STT) on the free-layer magnetization, leading to steady-state precession at the ferromagnetic resonance (FMR) frequency. This dynamical magnetization produces a radio-frequency (RF) voltage via the tunnelling magnetoresistance (TMR) effect. The long vertical arrow indicates the flow of electrons, the thick black arrows denote the magnetization directions of the free and pinned layers, the red arrow shows the STT acting on the free layer, and the arrowed ellipse represents the trajectory of the precessing magnetization. **b**, Power spectral density (PSD) of a magnetic tunnel junction (MTJ)-based STO, which quantifies how the output signal power is distributed

over frequency (that is, RF power per unit frequency). **c**, Mechanism of the spin-torque diode effect in an MTJ nano-pillar device. An RF current drives magnetization dynamics of the free layer via STT, leading to FMR and oscillatory resistance, which results in rectification and a d.c. voltage. The vertical arrow indicates the flow of electrons, the thick black arrows denote the magnetization directions of the free and pinned layers, the red arrow shows the STT acting on the free layer, and the arrowed ellipse represents FMR. **d**, d.c. voltage generated by spin-torque diode effect as a function of frequency of applied RF current. Part **b** reprinted with permission from ref. 194, IOP. Part **d** reprinted from ref. 203, Springer Nature Limited.

resistance-area product, switching field or current and TSF, rather than highlighting only best-case devices. Whenever possible, distributions of directly measured quantities should be provided instead of derived parameters; for example, showing the distributions of low-resistance and high-resistance states across an MTJ array is more informative than reporting only the TMR distribution. In addition, spatial wafer maps of TMR and resistance area, when available, should be included to demonstrate device uniformity and to support process optimization and troubleshooting.

Data sharing

As the field moves towards more transparent and reproducible research, data sharing becomes increasingly important. In many cases, this is now mandated by funding agencies and academic journals, which is a welcome development. We recommend that the MTJ community establish a practice of full data sharing to accelerate progress; it would

be helpful to share unsuccessful results to inform others about previous attempts. Results of electrical measurements and material-level analyses should be shared alongside publications. Importantly, details of film deposition and subsequent fabrication processes should also be shared to the maximum extent possible.

MTJ data can be deposited in a variety of open, FAIR (findability, accessibility, interoperability and reusability)-compliant repositories that support long-term preservation and DOI assignment. Commonly used platforms include Zenodo and Figshare, which are well-suited for hosting datasets, raw measurement files and analysis scripts. For materials science data, Materials Cloud and NOMAD offer specialized environments designed for sharing first-principles calculations and related workflows. In addition to these public repositories, many researchers also use institutional or lab-specific archives provided by their universities, which can store MTJ device data, metadata and supplementary files in a citable and accessible form.

When depositing MTJ data in a repository, the dataset should include: raw measurement data such as current as a function of voltage (I – V) curves, resistance as a function of magnetic field (R – H) loops, and TMR as a function of bias or temperature; complete device meta-data, including layer stack, thicknesses, junction area, and growth and annealing conditions; analysis and plotting scripts (such as Python, MATLAB, Origin) used to process the data; source data for all figures reported in the publication, with clearly labelled axes and units; and statistical summaries, such as device-to-device histograms, wafer maps and total device counts, rather than only representative curves.

For citing and referencing data, a DOI from repositories like Zenodo or Figshare should be generated and included in a data availability statement in all publications.

Limitations and optimizations

At the material level, the performance of MTJs is highly sensitive to the structural and chemical quality of their ultrathin layers and interfaces. Small deviations in interface sharpness, barrier thickness, crystallinity or stoichiometry can disrupt coherent tunnelling and reduce TMR. Structural studies have revealed a range of defects that critically influence device performance, including interface roughness and oxygen vacancies in the barrier, which are known to be detrimental to TMR^{208,209}. Additional defects include dislocations, grain boundaries in polycrystalline MgO, interdiffusion and magnetically dead layers at interfaces, as well as local barrier thinning or pinhole formation that can lead to dielectric breakdown^{210,211}. Because these parameters

are strongly interdependent, MTJ materials growth demands precise control of deposition conditions, optimized annealing and careful material selection.

In research-scale devices and specialized products, epitaxial growth can provide superior control over lattice matching, interface roughness and grain boundaries. However, for industrial MRAM production, specialized sputter deposition in near-ultrahigh vacuum systems is the norm owing to its higher throughput and better compatibility with silicon technology. Hence, many techniques have been developed over time – and have been gradually transferred to industrial 300 mm wafer-level deposition systems – which specifically apply to sputtering deposition of MTJs. An example of this is cryogenic-temperature deposition to improve interface quality and the development of textured seed layers for improved crystallinity of subsequently sputtered layers.

Table 5 summarizes the main limitations and challenges encountered during MTJ fabrication and the corresponding strategies used to mitigate them and enhance device performance, emphasizing the primary device-level or material-level parameters affected by each limitation, such as the TMR, PMA (which affects data retention and stable bit diameter in MRAM applications), write efficiency (such as STT switching current), process compatibility with CMOS, endurance and breakdown voltage. However, it should be noted that MTJ performance metrics are generally highly interdependent, and one parameter cannot be improved or optimized without also considering the others.

Table 5 | Key limitations in engineering and optimization strategies for MTJ fabrication

Limitation	Device parameter affected	Technical challenge	Engineering and optimization strategies
Interface roughness	TMR PMA	Atomic-scale roughness and intermixing reduce spin polarization and coherence	Low-temperature deposition process Low deposition rate Epitaxial MBE growth
Inter-diffusion	Compatibility with CMOS back-end of line process	Requires MTJ material stability up to 400 °C	Engineering seed, cap and interface layers to reduce inter-diffusion
Barrier thickness	RA	Tunnelling current depends exponentially on barrier thickness	Alternative barrier materials with lower band gaps Reduced underlayer roughness enabling thinner tunnel barriers
Barrier crystallinity	TMR Switching current	Amorphous or polycrystalline MgO barriers suppress coherent tunnelling	Growing epitaxial MgO (001) on lattice-matched Fe/CoFe Post-annealing at 300–400 °C to enhance crystallinity
Grain boundaries and defects	Breakdown voltage Endurance	Polycrystalline MTJs contain grain boundaries, causing scattering, pinholes, leakage	Epitaxial growth Post-annealing to reduce defect and grain boundary density
Lattice mismatch and strain	TMR Switching current	Strain generates dislocations and defects, causing degraded spin transport and reduced TMR	Select lattice-matched materials, for example spinel oxides such as MgAl ₂ O ₄ Introducing buffer layers to reduce mismatch-induced strain
Oxidation control	TMR PMA	Over-oxidation and under-oxidation are detrimental to TMR and PMA	Plasma/radical oxidation for controlled barrier formation Control of the adatom energy and/or using an ultrathin Mg layer for MgO barrier fabrication by radio-frequency sputtering
Anisotropy and magnetization of free layer	PMA Scalability Field sensitivity	Ferromagnetic electrode material with large PMA and small M_s is essential for scalability of MRAM	Developing new electrode materials without boron, such as Mn-based alloys, tetragonal ordered alloys or exchange-coupled composites
Magnetically dead layers	TMR PMA	Ultrathin ferromagnets lose magnetism at interfaces due to interdiffusion	Using materials with strong anisotropy Optimizing annealing to crystallize CoFeB without over-diffusion

CMOS, complementary metal–oxide–semiconductor; MBE, molecular beam epitaxy; MRAM, magnetoresistive random-access memory; M_s , saturation magnetization; MTJ, magnetic tunnel junction; PMA, perpendicular magnetic anisotropy; RA, resistance area; TMR, tunnelling magnetoresistance.

Outlook

Despite major advances in MTJ technology, several fundamental challenges continue to limit device performance and scalability. As MTJs shrink to the few-nanometre regime, maintaining high TMR while keeping switching currents low becomes increasingly difficult, and thermal stability must be preserved for dense MRAM arrays. The intrinsic speed of operation remains limited by ferromagnetic switching dynamics, motivating strong interest in faster and more energy-efficient mechanisms. Interfacial engineering also remains a critical bottleneck: atomically sharp and chemically uniform interfaces are essential for reproducible TMR, yet achieving such interfaces reliably at scale is challenging. In parallel, reducing the current density required for STT or SOT switching and taking advantage of VCMA for ultralow-power operation remain active priorities. Finally, integrating MTJs with CMOS electronics demands careful co-optimization of materials, thermal budgets and device architectures.

Beyond CoFeB-MgO MTJs

AFMTJs. AFMTJs represent an emerging class of spintronic devices that use spin-split antiferromagnets as active electrodes⁴⁴ (Supplementary Note B and Supplementary Fig. 2a,b). In these junctions, spin-dependent tunnelling arises from MDSP, which enables a substantial TMR even in the absence of a net macroscopic magnetization^{35–37} (Supplementary Note B and Supplementary Fig. 2). AFMTJs provide several inherent advantages over their ferromagnetic counterparts, including ultrafast spin dynamics, no stray magnetic fields and greater resilience to external magnetic perturbations, making them promising candidates for high-speed, high-density spintronic applications⁴⁵.

A central challenge stems from the lack of net magnetization in antiferromagnets, which limits the applicability of conventional spin-transport probes and complicates both deterministic control and electrical readout of the AFM order vector. Despite these difficulties, significant experimental progress has been made, including the demonstration of TMR in non-collinear Mn₃Pt-based and Mn₃Sn-based non-collinear AFMTJs^{38–41}, with reported TMR ratios in some cases exceeding 100% at room temperature. Furthermore, electrical manipulation of the AFM order has been achieved via SOTs^{40,212–216} and STTs⁴¹, despite the absence of macroscopic magnetization (Supplementary Note B and Supplementary Fig. 3).

Further progress in this field relies on identifying spin-split antiferromagnets, both collinear and non-collinear, that exhibit large MDSP and thereby enable high TMR in AFMTJs. At the same time, the role of the tunnel barrier in AFMTJs remains largely unexplored. It is not obvious whether the strong symmetry filtering provided by MgO in conventional MTJs is beneficial in this context, as it may overemphasize regions of the Brillouin zone in which the MDSP is weak. Developing barrier materials, crystallographic orientations and interface terminations optimized specifically for MDSP-rich transport channels is therefore essential. In addition, AFMTJs introduce new challenges in understanding spin-torque physics, as STT and SOT mechanisms can be more complex than those in ferromagnetic systems. Establishing a systematic theoretical framework, together with clear experimental guidelines for elucidating these spin-torque mechanisms, will be essential to accelerate progress. Exploring alternative control approaches, such as VCMA or strain, is also desirable, as these methods may enable ultrafast switching of antiferromagnets and provide additional functionality for AFMTJ devices.

vdW-MTJs. vdW-MTJs offer a complementary and rapidly emerging platform in which long-standing MTJ challenges, particularly those related to interface quality, can be addressed from an entirely new angle. Atomically flat, defect-free two-dimensional ferromagnetic and insulating layers can be stacked without lattice-matching constraints, eliminating interfacial mixing and roughness that limit conventional sputtered stacks. Because the atomic structure is known exactly, theory can directly match experiment, enabling precise engineering of Bloch states and momentum-resolved tunnelling pathways. A vast design space, including material choice, layer number, twist angle, sliding registry, strain and electrostatic doping, can be systematically explored to tune both propagating and evanescent states for optimized TMR (Supplementary Fig. 4). These features position vdW-MTJs as a uniquely tractable platform in which interface perfection and theoretical predictability converge.

Recent theoretical studies indeed predict giant TMR values in vdW-MTJs based on Fe₃GeTe₂ (~6,000–8,000%)^{217,218} or Fe₄GeTe₂ (~700%)²¹⁹ electrodes. However, experimentally observed values remain far lower, typically 150–200% at cryogenic temperatures^{46,48,220}, indicating the gap between idealized theoretical models and real devices. This discrepancy underscores the need for more extensive experimental optimization across the large vdW parameter space, as current results are largely proof of concept; for improved theoretical treatments that incorporate subtle spacer–electrode interactions, which can modify evanescent states even across vdW gaps^{221,222}; and for achieving large TMR at room temperature⁴⁸, which remains a formidable challenge.

Two major obstacles must be overcome for practical high-performance vdW-MTJs. First, although several vdW magnets such as Fe₃GeTe₂ exhibit values for the Curie temperature that are near or above room temperature²²³, thermal fluctuations at elevated temperatures rapidly suppress TMR. For example, TMR in Fe₃GeTe₂/WS₂/Fe₃GeTe₂ MTJ drops from ~175% at 10 K to ~11% at room temperature⁴⁸. By contrast, a room-temperature TMR of ~85% achieved in Fe₃GeTe₂/WSe₂/Fe₃GeTe₂ MTJs was only modestly reduced from ~164% at 10 K (ref. 47). Therefore, room-temperature ferromagnetism alone is insufficient; robust spin polarization at operational temperatures is required and strongly influenced by fabrication, barrier choice and interfacial atomic structure. Second, wafer-scale synthesis of high-quality vdW materials remains a significant challenge. Mechanically exfoliated flakes possess extremely low defect densities, but scalable growth methods typically introduce substantial disorder, undermining one of the key advantages of vdW-MTJs. Achieving wafer-scale, defect-minimal vdW heterostructures is therefore essential for translating laboratory prototypes into manufacturable technologies.

Future perspectives

MTJs. Over the next decade, progress in MTJ research will likely be driven by the convergence of three major themes: materials discovery, interface and barrier engineering, and device-level integration. For conventional MTJs, continued scaling will require new ferromagnetic materials with faster dynamics, lower damping and higher anisotropy, along with improved SOT and VCMA efficiencies. Atomically engineered interfaces, potentially enabled by artificial-intelligence-accelerated materials screening and in situ characterization, will be central to achieving reproducible, wafer-scale high-TMR devices with ultralow switching energy. Integration with CMOS at advanced technology nodes will necessitate hybrid architectures combining logic, memory and possibly neuromorphic functionality within a single spintronic platform.

AFMTJs. For AFMTJs, the key breakthroughs will come from discovering and optimizing antiferromagnets, both collinear and non-collinear, that exhibit strong MDSP at room temperature. High-throughput theoretical searches, combined with epitaxial synthesis and spin-sensitive

spectroscopies, will be essential for mapping the vast landscape of AFM materials capable of supporting TMR. Parallel progress is expected in understanding spin-torques at a microscopic level and elucidating electrically induced switching mechanisms on a picosecond time

Glossary

Antidamping-like torque

A torque component that counteracts Gilbert damping, enabling magnetization precession or switching.

Antiferromagnetic tunnel junctions

(AFMTJs). Magnetic tunnel junctions with antiferromagnetic electrodes.

Bloch states

Quantum states of single electrons in individual periodic crystal lattices characterized by plane waves modulated by lattice-periodic functions.

Cap layer

A thin protective layer deposited on top of a device or film to prevent oxidation, contamination or degradation.

Coherent tunnelling

Quantum tunnelling in which the phase and transverse crystal momentum of electronic states are conserved across the barrier.

Curie temperature

The critical temperature above which a ferromagnet loses its spontaneous magnetization.

d.c. sputtering deposition

A physical vapour deposition technique using direct current (d.c.) plasma to deposit conductive materials.

Damping constant α

A dimensionless parameter that quantifies the strength of Gilbert damping in magnetization dynamics.

Evanescent states

Quantum states of single electrons in tunnel barriers characterized by exponentially decaying wavefunctions.

Exchange stiffness

A material parameter that quantifies the energy cost associated with the spatial variation of magnetization.

Ferromagnetic resonance

(FMR). A spectroscopic technique probing dynamic response of magnetization under microwave excitation.

Field-like torque

A torque component that acts as an effective magnetic field on magnetization.

Free layer

The magnetic layer in a magnetic tunnel junction whose magnetization can be switched between stable states.

Gilbert damping

A phenomenological description of energy dissipation during magnetization dynamics.

Magnetic anisotropy

The directional dependence of magnetic energy that defines preferred magnetization orientations.

Magnetic tunnel junction

(MTJ). Nanoscale device consisting of two magnetic layers separated by an insulating tunnel barrier.

Magnetization precession

Rotational motion of magnetization around an effective magnetic field.

Magnetization switching

The process by which the magnetization of a magnetic element reverses between stable states.

Magnetoresistive random-access memory

(MRAM). A non-volatile memory technology based on magnetic tunnel junctions as storage elements.

Momentum-dependent spin polarization

(MDSP). Spin polarization of electronic states that varies as a function of crystal momentum.

Neuromorphic computing

A computing paradigm that mimics the structure and dynamics of biological neural systems.

Pinned layer

The magnetic layer in a magnetic tunnel junction whose magnetization is fixed by exchange bias or by antiferromagnetic coupling.

Quantum tunnelling

The quantum-mechanical phenomenon in which a particle passes through a classically forbidden potential barrier.

Radio-frequency sputtering deposition

A sputtering method using radio-frequency power, enabling deposition of dielectrics.

Resistance-area product

The resistance-area product of a magnetic tunnel junction characterizing the intrinsic tunnelling resistance, independent of device size.

Spin Hall angle

The ratio of the generated transverse spin current density to the applied longitudinal charge current density.

Spin polarization

The imbalance between spin-up and spin-down electron populations contributing to electric transport.

Spin-orbit torque

(SOT). A torque on magnetization produced by a spin current generated by an in-plane charge current in an adjacent heavy metal layer.

Spin-transfer torque

(STT). A torque exerted on magnetization by a spin-polarized current flowing through a magnetic layer.

Thermal stability factor

(TSF). A dimensionless parameter defined as the ratio of the magnetic energy barrier to the thermal energy, determining data retention reliability.

TMR ratio

The relative change in resistance of a magnetic tunnel junction between antiparallel and parallel magnetization states, defined as $(R_{AP} - R_P)/R_P$.

Tunnelling magnetoresistance

(TMR). The relative change in resistance of a magnetic tunnel junction between parallel and antiparallel magnetic configurations of the electrodes.

Van der Waals magnetic tunnel junctions

(vdW-MTJs). Magnetic tunnel junctions assembled from van der Waals layered materials.

Voltage-controlled magnetic anisotropy

(VCMA). The modulation of magnetic anisotropy at a magnetic interface induced by an applied electric field.

Write-error rate

The probability that a memory cell fails to switch to the desired magnetic state during a write operation.

scale. New barrier designs tailored specifically to MDSP-rich transport pathways may enable AFMTJs with fast, reliable readout and switching. In the longer term, AFMTJs could serve as foundational building blocks for ultrafast memory and terahertz-frequency devices.

vdW-MTJs. For vdW-MTJs, the next decade will likely see rapid advances in material synthesis, interface perfection and device reproducibility. Realization of room-temperature vdW magnets with robust spin polarization, possibly through alloying, interface stabilization or moiré engineering, will be essential for translating vdW-MTJs from low-temperature demonstrations to practical technologies. An intriguing route is to explore vdW-MTJs with A-type AFM electrodes, in which the interfacial magnetization can be precisely controlled to yield sizable TMR^{128,224}. The emergence of wafer-scale, defect-minimal vdW heterostructures would transform the field, enabling systematic exploration of twist angle²²⁵, strain, sliding registry and electrostatic control in a way not possible with traditional MTJs. As vdW heterostructures become more controllable, the combination of perfect interfaces and device tuneability may allow vdW-MTJs to surpass conventional MTJs in both TMR magnitude and functionality, positioning them as promising building blocks for next-generation non-volatile spintronic memories²²⁶.

Conclusions

Overall, the coming years promise a period of transformative growth for the MTJ landscape, one in which ferromagnetic MTJs mature, AFMTJs emerge and vdW-MTJs open entirely new horizons. The synergy between advanced materials, transport theory and innovative device architectures will shape new spintronic technologies capable of meeting the demands of ultrafast, energy-efficient and scalable computing.

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Author contributions

Introduction (D.-F.S. and E.Y.T.); Experimentation (S.Y., W.W. and P.K.A.); Results (W.W. and E.Y.T.); Applications (S.Y., W.W. and P.K.A.); Reproducibility and data deposition (P.K.A. and E.Y.T.); Limitations and optimizations (S.Y., W.W. and P.K.A.); Outlook (E.Y.T., P.K.A. and C.G.). All authors contributed to the conceptualization, writing and editing of the Primer, with the overall effort led by E.Y.T.

Competing interests

The authors declare no competing interests.

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