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Two-dimensional Materials Prospects for Non-volatile Spintronic Memories

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Non-volatile magnetic random access memories such as spin-transfer torque (STT)-MRAM and next generation spin-orbit torque (SOT)-MRAM are emerging as key enabling low-power technologies, which are expected to spread over large markets from embedded memories to the Internet of Things. Concurrently, the development and performances of devices based on two-dimensional (2D) van der Waals heterostructures bring ultra-compact multilayer compounds with unprecedented material-engineering capabilities. Here, we first provide an overview of the current developments and challenges in the field, and then outline the opportunities which can arise by implementing 2D materials into spin-based memory technologies. We highlight the fundamental properties of atomically smooth interfaces, the reduced material intermixing, the crystal symmetries and the proximity effects as the key drivers for possible disruptive improvements for MRAM at advanced technology nodes.

Emerging technologies generally follow a hype cycle before reaching the mature production stage. When NAND Flash memory was first commercialized in 1989, it competed against conventional non-volatile memories such as electrically erasable programmable read-only memory (EEPROM)¹. Even when its market size reached over \$1.8B in 1995, the semiconductor industry was still uncertain about the full potential of this technology. However, new applications such as MP3 players and smart phones, which rapidly increased end-use demands, fuelled NAND Flash development to reduce cost per bit, resulting nowadays in 3D NAND Flash innovation². Mobility and miniaturization trends in consumer electronics have continuously driven the NAND Flash market, which reached over \$50B in 2020.³ On the other hand, while their potential in terms of low power and speed is proven, spintronic memories are still emerging in terms of market size. The most advanced emerging generation of MRAM, based on spin-transfer torque mechanism (Fig. 1), is already addressing a few market segments. However, it is envisioned that, in the near future, the MRAM market will expand significantly by addressing the power and data-transfer (memory-wall bottleneck) challenges in a variety of embedded applications, including neural networks and in-memory computing^{4,5}. Considering that the embedded emerging non-volatile memory market is forecasted to grow from \$20M in 2019 to \$2.5B by 2025,⁶ it could well drive MRAM growth, as mobile consumer electronics has driven NAND Flash in the past. In order to achieve such a growth, MRAM technology will meet a variety of challenges requiring material and device integration breakthroughs, in which two-dimensional materials (2DMs) could play a key role.

Indeed, since the discovery of graphene, followed by an ever-growing family of related materials⁷, 2DMs have emerged as potential enablers for potentially ultra-compact device architectures or radically new concepts for spin information processing^{8,9}. Scientific advances of 2DM-based spintronic devices as well as recent progress in large-scale co-integration of

2DMs with conventional microelectronics materials^{10,11}, open a promising perspective for developing innovative MRAM technology.

Here, we provide an overview of the most recent developments, identify challenges and opportunities brought by 2DMs for MRAM and give a vision about how progress in 2DMs research could morph into a game changing solution for future generations of spintronic memory technologies. We first describe fundamental MRAM concepts and the prospects for MRAM commercialisation, including the main roadblocks for broader deployment. We then highlight the unique opportunities brought by 2DMs and van der Waals (vdW) heterostructures to overcome some of the technological challenges. Afterwards, we analyse the requirements and challenges for further advances concerning growth, processing, and integration of 2DMs to enable an impact in next generation spintronic-memory development. Finally, an outlook provides a vision of 2DM-MRAM technologies.

STT-MRAM and next generation SOT-MRAM

Non-volatile MRAM technologies are built on magnetic tunnel junctions (MTJ) comprised of two ferromagnetic (FM) layers separated by a thin insulator. One of the FM layers, known as the free layer (FL), stores information, while the other, the reference layer (RL), provides a stable reference for reading the FL information. Two main technologies relying on electrically generated spin-currents have emerged to control the FL magnetization: spin transfer torque (STT)¹² and spin orbit torque (SOT)¹³.

The STT concept was first introduced in 1996^{14,15} and implemented at STT-MRAM chip level in 2005¹⁶. STT is observed in a two-terminal geometry, in which a vertical current is injected through the MTJ (Fig. 1a). The current tunnelling through the barrier is spin-polarized, leading to the FL magnetization reversal for large enough currents, due to the transfer of angular momentum. The relative magnetization orientation of the FL and RL layers

determines the resistance of the device, which is monitored by the tunnelling magnetoresistance (TMR).

SOT-MRAM is based on three-terminal devices, where an additional conducting path is added adjacent to the FL (Fig. 1b). A charge current flowing through this path results in the injection of a spin-polarized current into the FL in virtue of the spin-Hall and/or Rashba-Edelstein effect^{13,17-19}. In such devices, SOT can switch the FL magnetization without passing a current through the MTJ tunnel barrier. At the expense of adding another terminal, the decoupling of the write and read current paths prevents write errors during read operation and reduces the risk of voltage breakdown. It further enables versatile cell designs by allowing the spin torque direction to be set independently of the anisotropy direction in the stack²⁰. Using SOT, magnetization switching has been observed in the ps time scale²¹.

Commercialization and challenges of spin memory

Successful commercialization of STT-MRAM in solid-state drives (SSD) and wearable electronics (Box 1) has been achieved after several major breakthroughs in MTJ technologies²², including enhanced STT-switching efficiency and TMR amplitude, interfacial perpendicular magnetic anisotropy (PMA) at magnetic metal/oxide interfaces²³⁻²⁵, synthetic antiferromagnets (SAF), the suppression of etch-induced sidewall re-deposition and reduction in process variability (Fig. 2). To cover a broader range of envisioned applications (Box 1), further development of cost-effective and versatile MRAM technology will be crucial. It will also be necessary to ensure proper downscaling to maintain competitiveness at advanced technology nodes, in particular regarding MTJ diameter and cell-to-cell pitch. For example, because of the required analog circuitry, as a rule of thumb it is desirable to keep the STT-MRAM bitcell about 3 times smaller than the SRAM cell size at a given technology node so that the benefit is worth the technology change.

Improving the MTJ stacks and their versatility using conventional materials and integration processes is a difficult challenge. The actual stacks consist of dozens of ultra-thin layers (Fig. 1) in which each material and interface plays an important role in determining the device performance (Fig. 2). Below, we discuss some of these important aspects. In terms of materials, modern MRAMs rely on the crystalline MgO tunnel barrier, while the FM layers that are in contact with MgO are typically made of crystalline CoFeB (Fig. 2a). The CoFeB/MgO/CoFeB combination is attractive because of its high TMR ratio originating from the spin filtering effect in crystalline-MgO/FM, as predicted in 2001²⁶ (Fig. 2b). The structure appears to be simple but practical devices are far more complex. The RL layer requires a much higher magnetic anisotropy than the FL to be stable during memory operation. For this purpose, almost all MRAMs use a multilayer SAF to pin the RL (Fig. 2c), which relies on strong antiferromagnetic coupling between two ferromagnetic layers, and gives rise to a magnetically hard structure.

Another crucial point is PMA²³⁻²⁵ (Fig. 2d) because perpendicularly magnetized stacks have a better scalability than the in-plane magnetized counterparts. Due to the switching dynamics induced by STT, a better trade-off between the thermal stability of the FL magnetization and the write current is obtained in out-of-plane magnetized MTJs²⁷. Interfacial PMA can originate from spin-orbit interactions deriving from electronic hybridization effects, magnetocrystalline anisotropy, and interfacial strain. PMA was demonstrated in a Ta/CoFeB/MgO structure²⁴ but requires very thin CoFeB, which results in increased damping from the spin pumping effect and less efficient STT, while the anisotropy strength is insufficient for small devices (< 30 nm). A solution for these issues involves double MgO barriers, such as MgO/CoFeB/MgO and MgO/CoFeB/Ta/CoFeB/MgO (Fig. 2d). Here, having the FL between two oxide barriers effectively increases the anisotropy^{28,29}, providing thermal stability of the magnetization down to ~20-nm cell diameter³⁰. Other approaches to enhance

PMA below 20 nm rely on vertical shape anisotropy^{31,32}, but these concepts face manufacturing challenges due to the large MTJ aspect ratio.

As the MTJ size is downscaled, the TMR must remain high enough while an increase in the PMA is required to maintain thermal stability and data retention. However, the enhanced anisotropy of these structures forces the use of large current densities to achieve reliable magnetization switching, which increases energy consumption. As such, introducing voltage controlled magnetic anisotropy (VCMA) to assist or induce the switching could be helpful (Fig. 2e). It has been shown that a voltage across the MgO tunnel barrier results in charge accumulation near the FL/MgO interface, inducing atomic-orbitals occupancy changes that modulate the magnetic anisotropy³³⁻³⁵. VCMA-assisted writing could therefore reduce the energy dissipation and memory cell area by lowering the driving current. Unfortunately, the strength of the VCMA effect in CoFeB/MgO remains insufficient for practical implementations.

Pitch scaling also tends to increase the failure rate by forming shunting paths on the sidewall due to metallic re-deposition during MTJ patterning.³⁶ The physical and chemical damages on the pillar sidewall become even more problematic for downscaled MTJ devices. Broken symmetry of atomic bonding on the sidewall from physical bombardment or chemical diffusion of etching gases significantly degrades both the spin polarization and the magnetic anisotropy. Finally, another important issue is related to atomic intermixing at interfaces, taking place between the metallic layers in the MTJ during the post thermal annealing at ~400 °C required to improve the MTJ crystallinity and CMOS integration (Fig. 2f). When intermixing reaches the tunnel barrier, it leads to performance deterioration. This issue becomes more relevant as the thickness of the layers is reduced at advanced nodes, since the risk of failure of the tunnel barrier increases when the layer roughness becomes comparable to its thickness.

There are also various integration and material challenges associated to SOT-MRAM (Fig. 2g). SOT-MRAM uses the technological platform of STT-MRAM, thus knowledge and solutions developed for STT-MRAM could be transferable to SOT-MRAM development. However, a fundamental difference lies in the stack design. While in STT-MRAM the FL generally is on the top of the MTJ stack (bottom pinned, Fig. 1c) in SOT-MRAM, it is on the bottom (top pinned, Fig. 1d). This forces to re-design material growth protocols and to introduce specific seed layers to achieve the desired crystallinity of MTJs. Stacks with in-plane magnetization increase the SOT cell size, although they have the benefit of magnetic field-free switching. In contrast, for deterministic switching of perpendicular anisotropy SOT devices, an in-plane external magnetic field along the current direction is required (Fig. 2g). This magnetic field is a major hurdle for practical SOT-MRAM applications. Various solutions have been proposed to obtain field-free switching such as complex shapes^{37,38}, the use of in-plane MTJ³⁹ that limits scalability and speed, the insertion of an in-plane magnet below the SOT line increasing writing currents⁴⁰, or using antiferromagnetic heavy metal SOT lines⁴¹. Although a solution embedding a magnet in 12-inch wafer integration process was demonstrated⁴², this solution comes at the expense of uniformity, cost, security, and MTJ stability.

Opportunities with 2DMs for MRAM

Major progress in spin-torque memory technologies have been achieved by material developments. However, to date, only a very limited number of optimal material combinations have been identified, in particular CoFeB/MgO has played a prominent role for nearly two decades since no alternative has been found yet. Consequently, MRAM technology faces severe constraints, threatening its future evolution and broad deployment. In recent years, wide varieties of novel emerging 2DMs and heterostructures have shown the potential to address the aforementioned issues and challenges. In a monolayer form, 2DMs are atomically thin and their interfaces are atomically smooth. They interact weakly, through vdW interaction, with

minimal element intermixing. In addition, given their atomically-thin nature, their properties could be tuned by external electric fields or proximity effects⁹. They exist in metallic, insulating, semiconducting, ferromagnetic and antiferromagnetic forms without or with broken crystalline symmetries, and presumably, they can be stacked in any preferred combination and order.

Therefore, the properties and versatility of 2DMs make them very attractive for spintronics and, in particular, for memory technologies, which strongly rely on ultrathin materials and their interfaces to harness the required functionalities (Fig. 2). Although 2DMs-based technologies are far from reaching the level of maturity of MgO/CoFeB based MTJs (for example the first 2D magnets were isolated in a monolayer form just a few years ago and are right now barely exceeding room temperature operation)⁴³⁻⁴⁶ vdW heterostructures are taking an increasingly prominent role in spintronics research.

Interfacial PMA and synthetic antiferromagnets

As the MTJ size scales down, the energy barrier to switch the FL decreases, which in turn increases its bit-to-bit variation, hence degrading data retention⁴⁷. In principle, intrinsic interfacial PMA (Fig. 2d) can be enhanced by using FM materials with large spin-orbit coupling²³. However, the use of an amorphous FM alloy is preferred to achieve epitaxial crystallization of the MgO barrier upon annealing,⁴⁸ which constrains the selection of the FM material. Besides, increasing the spin-orbit coupling in the FL would increase the damping and the write current²³. Accordingly, there is a crucial need for innovative material alternatives to enable STT-MRAM below 15-20 nm.

In this context, 2DMs have been investigated as promoters of large PMA. The combination of graphene with Co, Fe, and/or FePd has shown promising results⁴⁹⁻⁵³. For example, calculations show that the PMA of Co films coated by graphene (on one or both surfaces) is enhanced by up to 100% compared to the PMA of pure cobalt, reaching an upper value of ~ 2 mJ/m².⁵¹ The critical thickness of Co at which the out-of-plane to in-plane

magnetization transition occurs (>13 ML or >2.6 nm) increases, as confirmed experimentally with graphene/Co/Ir(111) samples^{50,51} (Fig. 2d). In comparison, the PMA of pure Co vanishes beyond 7 ML. Downscaling potential to a MTJ pillar diameter of 10 nm has been estimated when both Co surfaces are covered by graphene or for FePd/Graphene interfaces⁵⁴ (Fig. 2d). Interestingly, graphene also presents potential for implementing SAFs, as revealed by the strong antiferromagnetic exchange coupling across a graphene spacer in out-of-plane magnetized FM/graphene/FM structures (Fig. 2c)^{51,52,55}. The integration of graphene-based FL in STT/SOT-MRAM could minimize the Dzyaloshinskii–Moriya interaction arising at Co/graphene interfaces⁵⁶, which has a detrimental effect on device switching performance⁵⁷⁻⁶⁰.

Encapsulation and intermixing suppression

As the lateral dimension of MTJs shrinks, device morphology profiles become very rough and non-uniform. Chemical vapour based 2DMs embedded in the MTJs can help overcome fabrication challenges and improve the device morphology as the tunnel barrier thickness and lateral dimension downscale (Fig. 2). Their atomically thin, flexible and generally inert nature can minimize defects related to dangling bonds, interface states and interfacial alloy formation⁶¹. For example, graphene can be simultaneously used as a contact and heat dissipation layer and hBN as an encapsulation and insulating layer.

2DMs can suppress diffusion of atoms in MTJs. Intermixing reaching the tunnel barrier eventually leads to device performance deterioration. Graphene and hBN have a dense electron cloud structure and a low chemical reactivity due to their compact hexagonal honeycomb-lattice, making it difficult for even the smallest He atom to spread. For this reason, 2DMs have been heralded as atomically thin impermeable membranes^{62,63} to prevent the oxidation and corrosion of metals^{64,65} and allow novel processes for spintronics such as atomic layer deposition (ALD)^{66,67}. Large area 2DMs uniformly grown by CVD can therefore be used as an encapsulating layer to protect patterned MTJ cells from the post thermal and inter-diffusion of

BEOL processes (Fig. 2f). Similarly, many organic materials (as used in OLED for instance) hold tailoring potential for spintronics⁶⁸, which 2DMs integration could unleash by stabilizing interfaces.

Thickness engineering of material spacers follow a trade-off relationship.^{25,69,70} A thick spacer could provide suitable texture decoupling and diffusion barrier, but the magnetic coupling weakens. 2DMs could provide ideal spacers since the trade-off relationship can be efficiently optimized. Large-scale 2DMs grown by CVD on FMs⁷¹⁻⁷³ preserve interfaces with spin polarized metallic states even after exposure to oxidative conditions.^{66,67,74,75} Graphene and hBN have demonstrated outstanding performance as atomic diffusion barriers down to the monolayer.^{67,76,77} Notably, large-scale graphene growth on high magneto-crystalline anisotropy and low magnetic damping FePd L1₀ PMA ordered alloy was recently achieved⁵³.

Additionally, the oxidation issue of FMs usually forbids low-cost ambient/oxidative processes such as ALD, which are widely used in the microelectronics industry.^{78,79} ALD based Al₂O₃ and MgO tunnel barrier integration in spin valves have been demonstrated^{66,80,81}, showing high quality coverage with conformal and layer-by-layer growth at the angstrom limit (Fig. 2f). This hints the potential of 2DMs to unlock processes (ALD, use of organics) with implications to oxidation-resistant and enabled low-cost approaches.

Alternative tunnel barriers

2DMs cover a wide range of electronic properties from metallic (TiS₂) and semimetallic (graphene, WTe₂, MoTe₂) to semiconducting (MoS₂, MoSe₂, WS₂, WSe₂, black phosphorous, etc) and insulating (hBN) and can also exhibit topological properties (Bi₂Se₃, Bi₂Te₃, WTe₂, MoTe₂).⁸²⁻⁸⁴ 2D magnets such as CrI₃, CrTe₂, Cr₂Ge₂Te₆ and Fe₃GeTe₂ have been recently added to this family^{43,85-88}, offering great potential for the replacement of bulk FMs and, perhaps, TMR enhancement.

The demand for controlling the thickness of oxide tunnel barriers with atomic level

precision represents a serious challenge. The spintronics community is struggling to achieve and control ultra-thin MgO tunnel barriers with homogeneous thickness over a large scale.^{89,90} The natural aptitude of 2DM tunnel barriers, which can be defined layer by layer with atomic precision, is one of the key advantages (Figs. 2b and 2f).⁹¹⁻⁹⁶ Nonmagnetic materials, such as graphene, hBN and transition metal dichalcogenides (TMDC) MoS₂ and WS₂, have been demonstrated as a tunnel barrier in MTJs, exhibiting novel band structures or hybridization spin filtering effects and leading to a sizeable TMR value up to 80% with predictions as high as 10¹²%.^{76,77,80,91,97-107} Experimental demonstration of the direct integration of graphene in TMR devices has been carried out in CMOS compatible processes (< 450 °C with large-scale CVD)⁶⁷. Owing to the development of large-scale technologies, such as CVD, molecular beam epitaxy (MBE) and pulse laser deposition (PLD), other 2DMs have been investigated for MTJs^{76,101,108-114}.

It is important to note that theoretical *ab-initio* studies on CoFe/MgO/CoFe based MTJ have predicted TMRs²⁶ in the range of several 1000% whereas experimentally the room-temperature record is 604%, while the TMR in commercial products is ~200%.^{115,116} This discrepancy is due to defects in the MgO tunnel barrier, lattice mismatch between MgO and FM, diffusion of boron or other elements towards the MgO barrier, etc. With 2DMs, the MTJ stack could be closer to the ideal one thanks to their high stability, suppressed diffusion, and well-defined interfaces, which would favour downscaling. For example, all-2D based MTJs comprising a 2D tunnel barrier and 2D magnetic layers could be envisioned (Fig. 2f). A TMR of 160% at low temperature has been reported in a MTJ entirely made of 2DMs (Fe₃GeTe₂/hBN/Fe₃GeTe₂), with PMA and a spin polarization exceeding 60% gate tunability⁹⁹. Even a larger TMR was predicted in Fe₃GeTe₂-based MTJs for various vdW spacers¹¹⁷.

Furthermore, the fact that 2DMs and their heterostructures are atomically thin promises less technological efforts to process them into functional devices, avoiding

technological steps such as planarization. They could further enable novel memory elements as alternatives to traditional MTJs (Fig. 2b). A low-temperature magnetoresistance as large as 19000% was observed in tunnel junctions of four-layer CrI₃, a layered insulating antiferromagnet^{118,119}, while a TMR up to 100000% was predicted for VSe₂¹²⁰.

Spin-orbit torques

Compared to SRAM, the stand-by power of SOT-MRAM is negligible, but projected write (< 75 fJ) and read energies (< 25 fJ) using state-of-art stacks must be reduced¹²¹. Reading is directly linked to the minimum current detectable by the sense amplifiers and stand-by power. For fast reading < 5 ns with ~150–200% TMR, the read current should be ~50–80 μ A. Typical transistor current capabilities in sub-28 nm technology nodes with minimum footprint is on the order of 30-100 μ A, while state-of-the-art perpendicular SOT-MRAM projects a critical write current of ~300 μ A per bit cell^{121,122}. Hence, to prevent CMOS from dominating the cell size, a straightforward way is to improve the SOT efficiency ξ , the conversion ratio between spin and charge currents, to $\xi > 1$, while heavy metal layers, such as Pt and W, yield $\xi = 0.1-0.5$ ¹²²⁻¹²⁴.

The integration of 2DMs provides appealing opportunities for SOT-MRAM. The large spin-orbit coupling and associated spin textures of 2DMs, including TMDCs and topological insulators (TIs), make them serious candidates for inducing large spin torques. The most studied TIs are the Bi₂Se₃ and (Bi_{1-x}Sb_x)₂Te₃ family of materials. The observation of large damping-like torques and the achievement of room-temperature magnetization switching confirms their potential for SOT-MRAM.^{125,126} Because of the reduced crystal symmetry of some TMDCs, unconventional torque components are also expected. Of significant relevance, an out-of-plane damping-like torque can be induced by WTe₂ and NbSe₂^{127,128} (Fig. 2g), which could enable field-free SOT switching in perpendicular SOT-MRAM. A pronounced SOT is expected not only from the bulk but also from the surface in topological Weyl semimetals.

Room-temperature magnetization switching in a regime of domain wall motion has been reported in WTe_2/Py and $WTe_x/Mo/CoFeB$ heterostructures^{127,129,130}.

Magnetization switching by SOT was also achieved in hybrid 2D/3D systems. Such is the case of Fe_3GeTe_2 or $Cr_2Ge_2Te_6$ at low temperature using an adjacent heavy-metal layer¹³¹⁻¹³⁴. Large SOTs have also been reported in Py/WS_2 and $CoFeB/(MoS_2 \text{ or } WSe_2)$ bilayers^{135,136}. A modulation of the coercivity with currents has been reported in Fe_3GeTe_2/WTe_2 ¹³⁷, and SOT switching was observed up to the Curie temperature (~ 200 K) of Fe_3GeTe_2 in WTe_2 (12.6 nm)/ Fe_3GeTe_2 (7.3 nm) with PMA¹³⁸.

Engineering and tuning material properties

The control of the magnetic anisotropy with electric fields (VCMA) provides an engineering knob to optimize the trade-off between data retention and writability as well as to reduce the energy consumption. In current MTJs using metalling FMs, electric fields only penetrate a few Angstroms into the film surface, limiting the efficiency to control the magnetic properties. In contrast, the 2D magnets magnetic properties, Curie temperature and magnetic anisotropy, and spin filtering thru MgO are largely tunable using external stimuli such as electric fields⁸⁷, strain¹³⁹⁻¹⁴² or light.

Another exciting aspect is to leverage on the asset of hybridization (proximity or interface effect)^{9,68,92,143} that could allow spin filtering and resistance-area product reduction ($< \Omega \cdot \mu m^2$). In proximity with a FM, the large gap insulating hBN have already shown to become metallic leading to spin filtering and a TMR of 50% in an 2D-MTJ⁷⁶. Similarly, for graphene it was also possible to reach a TMR of 80%.⁷⁷ Other 2DMs such as TMDCs (with specific thickness dependent band structure mechanisms) are now explored to further tailor spin selection at FM interfaces¹⁰¹. Finally, graphene can further increase the current at the boundary between large spin-orbit coupling material and the FM. Room-temperature, proximity-induced spin orbit coupling effects, which are tunable by gating, have been recently observed in

graphene/WS₂¹⁴⁴. In combination with the proximity-induced effect, an enhanced spin torque could be obtained.

Material and integration challenges

Material challenges

MRAM is expected to progressively become mainstream in rapidly expanding areas such as IoT and Artificial Intelligence-based devices (Box 1) for which the development of cost-effective, downscaled MRAM technology will be essential¹⁴⁵. However, the limited portfolio of the available state-of-the-art 3D materials and architectures could become an unsurmountable obstacle for the industry. In this regard, 2DMs offer unique opportunities; to advance their use, several notable challenges lie ahead that require material research and development, in hand with engineering efforts^{146,147}.

There are thousands of predicted stable 2DMs, including insulators, semimetals, magnets and novel electronic phases, such as Weyl semimetals or topological insulators¹⁴⁸⁻¹⁵⁰. Many of them have properties that make them potentially attractive for magnetic memory technologies. Substantial attention must therefore be directed towards identifying and characterizing the most promising candidates to optimize MRAM performance. MTJs incorporating 2DM tunnel barriers⁹² currently present TMR values⁷⁷ that are already comparable to those of the first generation of crystalline MgO barriers¹⁵¹ that later became technologically relevant devices^{115,116}. This is reinforced by the added potential of the newly developed 2D magnets. While we cannot predict whether such a suitable 2DM for memories will be available anytime soon, we can highlight tremendous efforts by the community in this direction⁴³⁻⁴⁶. Indeed, considering that the first 2D magnets were reported in 2017^{85,86} already observing 2D magnets with a Curie temperatures near room temperature is impressive and efforts are undergoing to achieve this objective, relying on new material sets, improved control and sample quality, and doping approaches.¹⁵²⁻¹⁵⁷ Hence, despite the results being not yet

competitive for nowadays room temperature standards, the tremendous effort made by the community and the fast pace of progress made in the recent years (from tunnel barriers to 2D magnets) to target functional large-scale spin-based technologies allow to envision the possibility of functional large-scale spin-based technologies operating at room temperature in the not so distant future.

Reported SOT efficiencies with 2DMs, especially TIs, largely surpass those of heavy metals. Crystal-dependent symmetries for field-free switching and VCMA are phenomena not easily implemented in today's MRAM materials. However, most SOT studies use micron-scale devices, where magnetization switching may occur via mechanisms with low activation barriers, such as domain motion. Future research efforts are required to extend these studies to practical sub-100-nm devices. In hybrid systems, the reactivity between 3D transition metals and 2D chalcogenides changes the nature of the interface, which may form uncontrolled interfaces due to chemical reaction¹⁵⁸⁻¹⁶¹. Alloys and magnetic dead layers can modify the underlying SOT mechanisms^{160,161}. However, if mastered, hybridization could become an asset for moving toward ultra-compact geometries^{68,160}. All-2D vdW heterostructure would provide an opportunity to control SOT phenomena and may help overcome diffusion issues.

Explorative experiments with 2DMs are typically carried out using micrometre-sized flakes exfoliated mechanically from bulk materials. This technique is not up-scalable. The development of 12-inch wafer-scale CMOS-compatible growth process (direct growth on process wafer or layer transfer, Fig. 3a) is thus necessary to address the scalability issue; this remains a critical challenge for any 2DM implementation in microelectronics^{146,147}. Furthermore, follow-up integration processes will need to maintain the original structure and device performance of 2DMs (delamination risk elimination, surface treatments, low damage co-integration with MRAM stacks, Figs. 3b and 3c).

Large scale growth

Growth methods to obtain uniform 2D layers on large areas could be based either on chemical methods (e.g. CVD) or on physical deposition such as MBE, PLD, and sputtering^{113,114,146,162-169} (Fig. 3a). Chemical routes are arguably the most promising thanks to their low cost and compatibility with large wafer processing but progress so far is limited to a few selected materials. Single-crystal graphene and hBN growth has been scaled beyond 6-inch wafer at over 1000 °C using CVD¹⁷⁰⁻¹⁷² although single-crystal growth remains to be achieved, polycrystalline graphene growth has been demonstrated at 450 °C with plasma CVD^{173,174}. During CVD growth, precursors react in the vapour phase in the wafer surface (650 –1000 °C). A low nucleation rate leads to the formation of large isolated flakes of high crystalline quality, which cover only a very small fraction of the substrate, with randomly oriented domains and poor control of the number of layers. The use of less stable metal and chalcogen precursors in TMDCs growth reduces the growth temperature (300–560 °C) and increase the nucleation rate¹⁷⁵⁻¹⁷⁷. Precursor control growth could drastically reduce the thermal budget for the fabrication, which is a promising approach for direct growth in BEOL compatible wafers. Using this technique, monolayers of TMDCs are grown over a wafer scale, but they remain polycrystalline, which degrades their electrical properties.

Processing and integration

After the growth over large areas of high crystalline quality 2DMs, their transfer from the growth to the target substrate is required for further processing and device integration (Fig. 3b). In this respect, the technological challenge consists of maintaining the 2D layer integrity during the process. The most widely used approach is the polymer-assisted transfer, in which a polymer film is used to mechanically support the 2DM¹⁷⁸⁻¹⁸⁰. The release from the growth substrate could be achieved in a solution by electrochemistry, chemical dissolution of the substrate or simply intercalation of water between the substrate and 2DM. Recently, another transfer method called spalling has been developed where the 2DM is detached from the

substrate by the strain induced by a metallic film grown onto it^{181,182}. The metal/2DM stack is then transferred onto the target substrate and the metallic film is chemically etched.

Although 2DMs are generally compatible with standard integration processes such as photolithography, etch, and deposition, significant process optimization would still be needed to maintain the original structure and properties of the 2DMs. Of particular relevance are reducing damage in plasma-based processes, increasing adhesion and suppressing material lifting in chemical processes, and patterning by etching in combination with selective stop techniques¹⁸³⁻¹⁸⁷. Another point of attention is to retain the original structure of 2DMs without self-deformation, degradation and interference with other layers. For instance, the deposition of a conventional MRAM stack is carried out using sputtering, which can expose the 2DM seed to a plasma that can easily damage the 2DM. Some solutions have been proved viable (off-axis, flipped chip)¹⁸⁸ and have to be adapted to large scale tools, such that the deposition condition can be modified to be damage-free (see Fig. 3c as an example) while not degrading magnetic properties and stack performances.

Outlook and roadmap

Today, a variety of memory technologies complement each other for computing, data storage, and embedded applications. Figure 4 outlines a roadmap for MRAM. STT-MRAM has been already commercialized for persistent memory in storage devices and servers as well as wearable electronics. MRAM is fostering key emerging markets, such as wearable, automobile, IoT, biosensor, various cache, and buffer memory applications. Its development over recent years has been astonishing and it is clear that it will shortly play a central role in the embedded non-volatile memory market.

However, the requirements of each application vary significantly as summarized in Table 1. Flash-replacement STT-MRAM requires high data retention (> 20 years) but accepts low endurance (10^6 cycles). In contrast, SRAM-replacement STT-MRAM requires high

endurance ($> 10^{12}$ cycles) and high bandwidth but needs much less data retention, even down to a few seconds. One major challenge for automotive applications is reliable chip operation even under extreme environment such as a high temperature of 150 °C or exposure to external magnetic fields that can increase the bit error rate. Good read margin up to 150 °C and magnetic immunity to guarantee 10 years reliability were demonstrated^{47,189,190}. Finally, both bit-cell size reduction and operation speed enhancement are key factors in order to expand into the SRAM-replacement area. Recently, a write/read speed less than 10 ns and 10^{12} cycling endurance was demonstrated¹⁹¹ showing a promise for SRAM replacement. On the other hand, SOT-MRAM is still a topic of intense research and under industrial initial assessment¹²²⁻¹²⁴. In order to move forward, the first step is to establish the manufacturability using industrial CMOS compatible processes. In fact, SOT-MRAM was recently demonstrated up to 12-inch scales^{42,122} with reliable sub-ns switching, low error rates and high endurance on Ta/CoFeB/MgO or W/CoFeB/MgO stacks using either perpendicular^{42,192-194} or in-plane^{39,195} magnetization.

It is however unknown how scaling beyond the 14-nm node will be achieved with conventional materials, when the MTJ feature size is projected to be below 30-40 nm (Fig. 4). Current technologies with bulk materials and conventional MgO-based MTJs will reach their limit in various fronts, including PMA and tunnel barrier roughness. Within this context, the development of 2DM-based spintronic devices has been spectacular, providing opportunities for technological progress. In particular, magnetization switching by SOT has been recently observed in stacks incorporating 2DMs¹³⁴ while practical VCMA could become a reality by taking advantage of their ultrathin, atomically smooth properties. Large-scale integration of 2DMs in a fab environment will be accelerated in the coming years by efforts such as the 2D Experimental Pilot Line (Fig. 4), which will be the first foundry to integrate graphene and layered materials into semiconductor platforms¹⁹⁶. Therefore, it is natural to envision that the large family of 2DMs could frame the roadmap for future advances of non-volatile spin-torque

memory technologies. Many technical material and technical challenges remain. However, given the unprecedented speed at which progress is achieved and the high pace at which new 2DMs are discovered and characterized, we shall be optimistic for the forthcoming steps towards moving to higher technology readiness levels. This could not only potentially frame further commercial exploitation of 2DM-based non-volatile memory technologies, but also serve as pathfinders for exploration of spin-based logics and functionalized other spintronics devices^{4,197}.

Table. 1. Specification comparison for various MRAM applications. Target applications are indicated with brackets. Relevant 2DM technologies discussed in the main text are listed in the last column.

	STT (eFlash replacement)	STT (SRAM replacement)	SOT (SRAM replacement)	Relevant 2DM tech.
MTJ size	60-80 nm	30-50 nm	30-60 nm	PMA enhancement
TMR value	170-190%	180-200%	> 200%	2D tunnel barrier Stress barrier
Write speed	200 ns - 1 μ s	< 10 ns	< 5 ns	2D spin source, gating, proximity
Read speed	20 ns	< 10 ns	< 5 ns	TMR enhancement
Retention	> 20 yr	10 s	10 s	PMA enhancement
Endurance	> 10^6 cycles	> 10^{12} cycles	> 10^{14} cycles	Stress/diffusion barrier, encapsulation layer

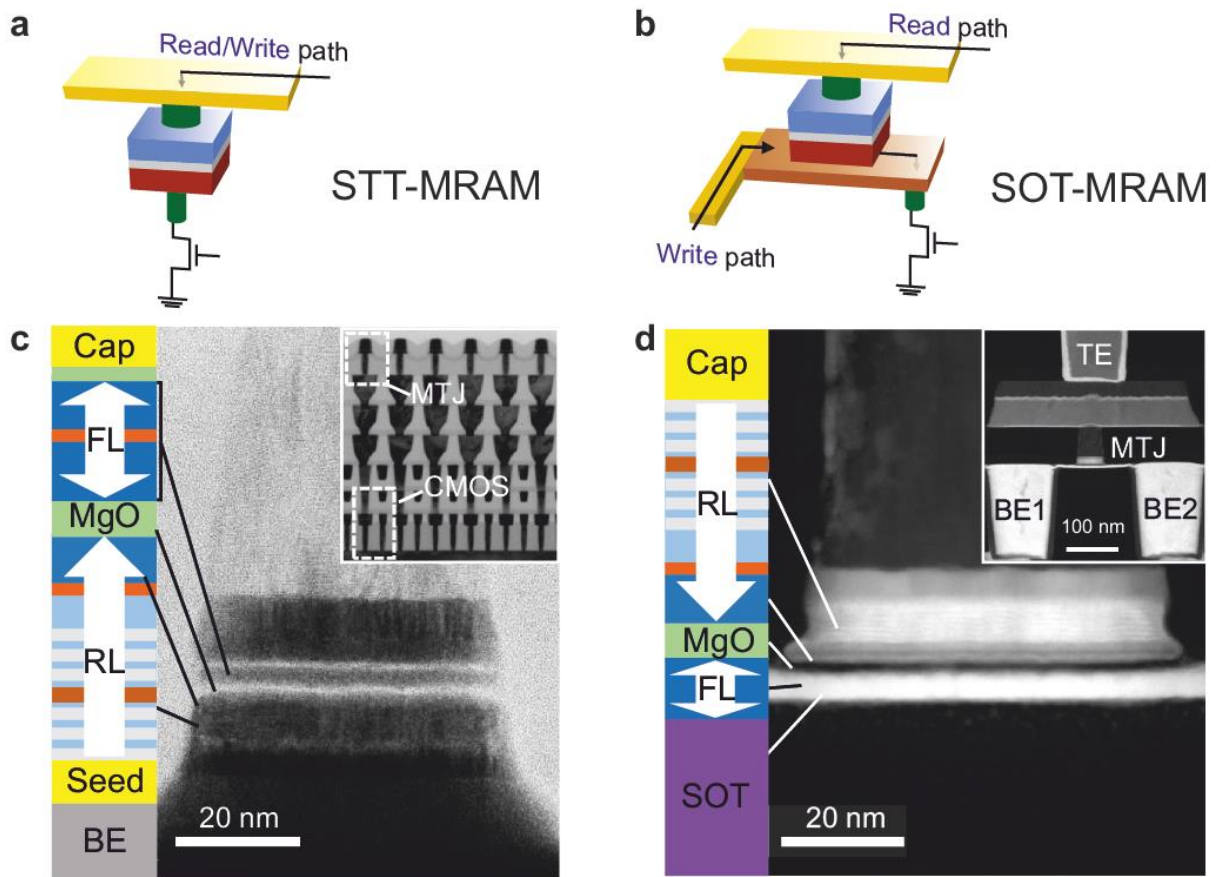


Fig. 1 | State-of-the-art MRAM technologies. **a** and **b**, Schematics of STT-MRAM and SOT-MRAM cells with perpendicular magnetic anisotropy (PMA), respectively. **c**, Bottom-pinned STT-MTJ sketch and transmission electron microscopy (TEM) cross section of 45 nm diameter STT-MTJ consisting of a CoFeB free layer (FL), MgO tunnel barrier and CoFeB/spacer/Co/Ru/[Co/Pt] reference layer (RL). The inset shows TEM cross section of STT-MRAM array (top dash box) controlled by CMOS (bottom dash box). **d**, Top-pinned SOT-MTJ sketch and TEM cross section of 60 nm SOT-MTJ. The inset shows a typical SOT-MRAM cell where the write current is injected from bottom electrode BE1 to BE2, and the read current from top electrode (TE) to BE2. Images from GlobalFoundries and IMEC.

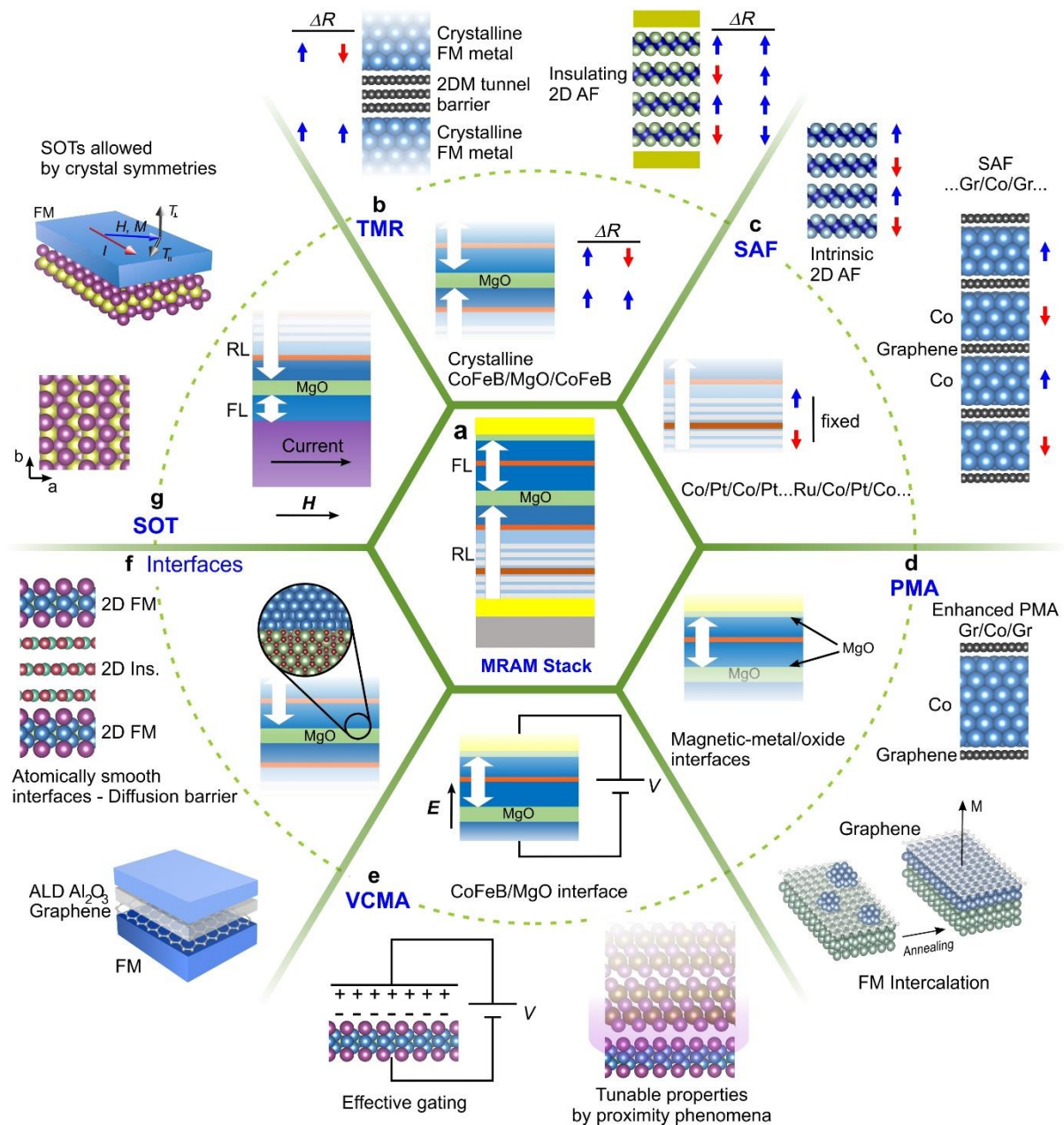


Fig. 2 | Fundamental phenomena of MRAM cells and 2DM prospects. Current solutions are represented inside the dashed circle. **a**, Typical STT-MRAM stack. FL and RL refer to the free and reference layer, respectively. The yellow top and bottom rectangles represent cap and seed layers, respectively. **b**, Tunnelling magnetoresistance (TMR). A change (ΔR) in the resistance is observed when the magnetization of FL switches, indicated by a switching from a blue to a red arrow. Modern MRAM technologies rely on coherent tunnelling across an MgO crystalline barrier. Similar performances are predicted with 2DM barriers (left). Large magnetoresistance has been observed in layered insulating antiferromagnets (right). **c**, Synthetic antiferromagnets (SAFs) are used to pin the magnetization of the RL. Equivalent magnetic structures are observed in layered materials (top) or can be artificially created (for example with Co/graphene, bottom). **d**, Interfacial perpendicular magnetic anisotropy (PMA) is found at the interface of magnetic metals and oxides but also on graphene/FM heterostructures. **e**, Voltage controlled magnetic anisotropy (VCMA) is observed at the interface of magnetic metals and oxides. Due to their atomically thin nature, 2DMs enable enhanced tunability of their properties, including gating and proximity effects. **f**, Intermixing and interface roughness becomes critical when scaling requires very thin (< 1 nm) tunnel barriers. This results in tunnel-barrier performance degradation and lack of reproducibility, which can be circumvented with atomically smooth 2DMs and 2DM diffusion barriers. **g**, For perpendicularly magnetized MTJs, an in-plane external magnetic field (H) along the current direction is typically required for switching. Low-symmetry 2DMs could help to eliminate the need for such a magnetic field.

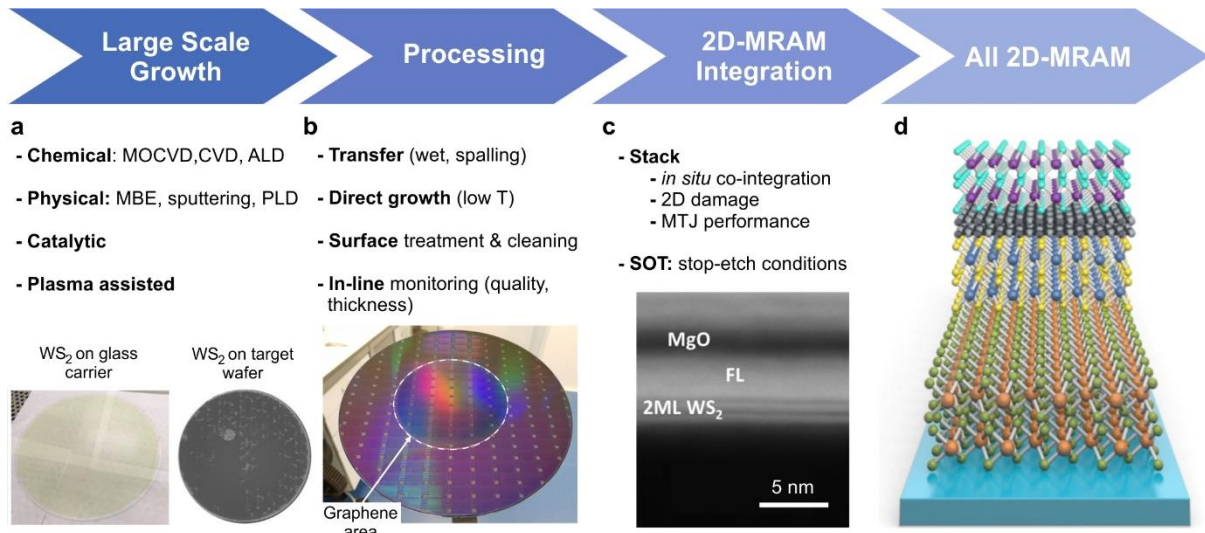


Fig. 3 | Challenges for integrating of 2DMs into MRAM technologies. **a**, Although significant progress has been achieved in small-scale demonstration, 2DM technology faces challenges in large scale growth of the materials for which several processes are being explored, from chemical, such as CVD, to physical such as sputtering and MBE (WS₂ on 300-mm glass carrier and target wafer is shown). **b**, Processing of 2D materials is under development, in particular regarding transfer and patterning of multilayers. For large-scale production, the development of suitable monitoring tools is also key. Graphene on a large wafer is shown. **c**, Integration in 2D-MRAM technologies. TEM cross section of top-pinned MTJ stack deposited on large scale grown 2DM (here WS₂) [ref.¹⁹⁸], showing no degradation of WS₂. **d**, Potential implementation of 2DM in MRAM technologies as seed, tunnel barrier, FMs, encapsulation and SOT layers.

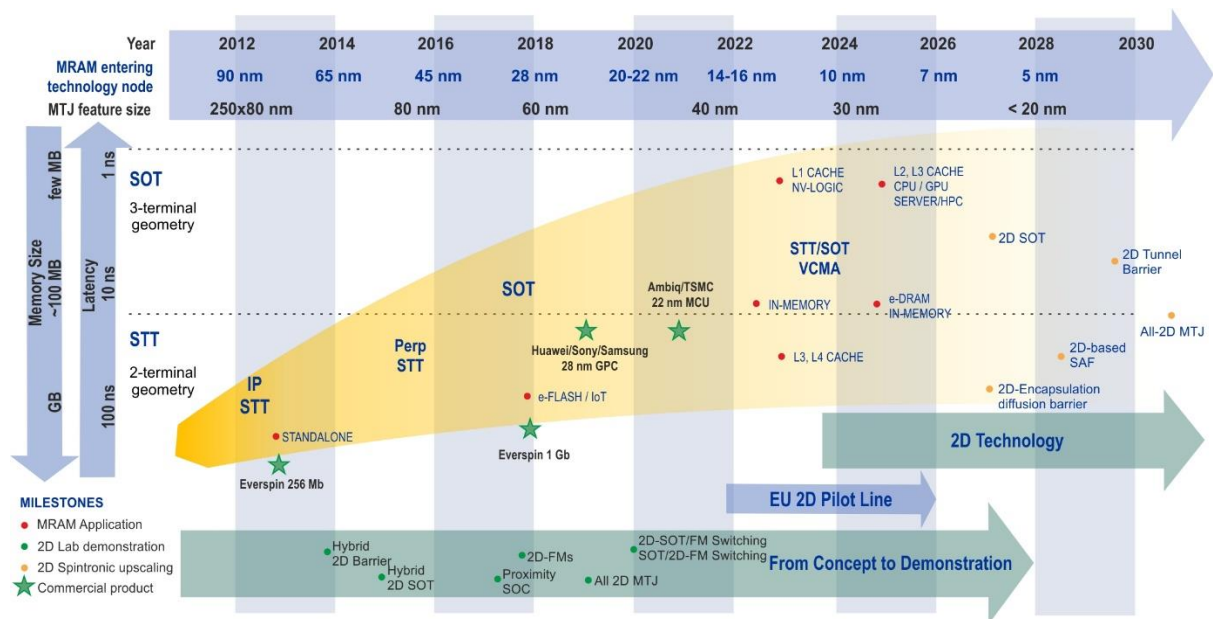


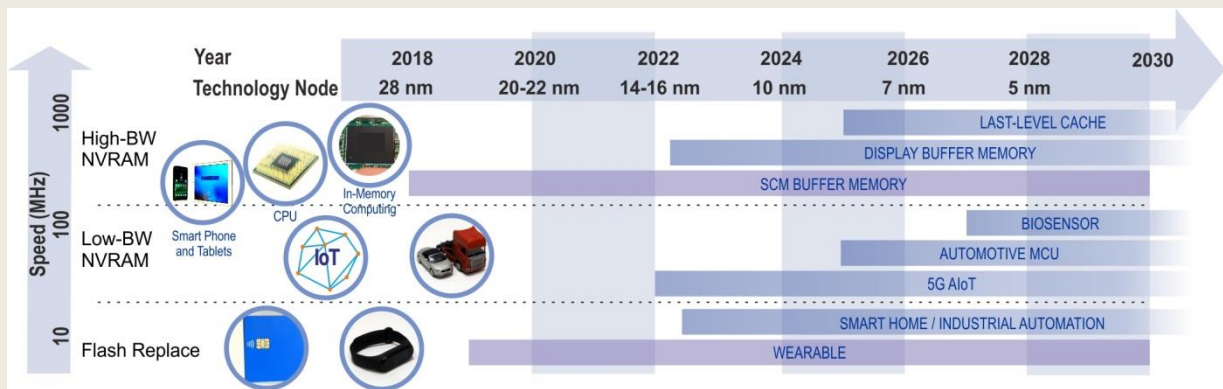
Fig. 4 | Spin torque memory technology roadmap. The projected feature size of the magnetic tunnel junction (MTJ) is shown at the top of the chart, together with the technology node at which a given MTJ size would be introduced. STT-MRAM offers non-volatility together with low power consumption, which is ideal for low-power microcontroller units (MCUs), wearables and IoT applications (Box 1). In terms of embedded non-volatile memory (eNVM) technology, eFlash scaling will likely reach its end at the 28/22nm node. STT-MRAM is also promising for automotive and SRAM replacement. Chipmakers and foundries started mass production for eFlash-type STT-MRAM in 2018 and started to develop SRAM-type applications for cache. SOT-MRAM can address high-speed and high-endurance applications such as cache and in-memory computing. The memory speed is best characterized by the latency time, which includes electrical time delays induced by routing from selector control to memory points and associated parasitic resistances and capacitances. As the memory size increases, the speed tends to decrease. Current MRAM technologies based on bulk materials are expected to reach their limits at about 20-nm MTJ feature size, after which 2DMs could play a key role to maintain MRAM downscaling. Actual 2DM milestones are shown at the bottom of the chart, including recent demonstrations of magnetization switching in heterostructures comprising 2DM-SOT materials and/or 2D FMs. Enabling 2DM-based technologies are indicated with STT and SOT technology projections and should be introduced at the indicated timelines to offset today's MRAM materials limitations. Efforts like the EU 2D Experimental Pilot Line are expected to accelerate the path to production (see Ref⁹⁶). HPC stands for high-performance computing.

Box 1

MRAM markets and commercialization

STT-MRAM is the only non-volatile memory capable of high-density, high-endurance and fast-write operation and is considered as the best candidate for embedded non-volatile applications. The microcontroller units (MCU) market in 2020 was over \$25B and will be driven by 5G internet of things (IoT), wearable, general-purpose MCUs and automotive electronics¹⁹⁹. STT-MRAM can replace SRAM and NOR Flash in low-power MCUs, decreasing cost and power consumption. STT-MRAM is also promising for memory replacement in the automotive and biosensor sectors. There, embedded Flash (eFlash) is either not available or less cost-effective than embedded MRAM beyond the 28-nm node. SOT-MRAM is under development and their applications would be primarily as SRAM cache-memory replacement from L3/L4 to L2/L1 cache levels and registers in central (CPU) and graphical processing units (GPU). SOT-MRAM has also potential in non-volatile logic elements^{200,201} and for in-memory computing.²⁰²

STT-MRAM has been released down to 28 nm, where eFlash technology co-exists. However, eFlash scaling is reaching its limits, while SRAM scaling becomes challenging due to stand-by leakage currents²⁰³. Applications include enterprise SSD, storage-class memory and wearable electronics. In 2017, Everspin shipped standalone 256Mb STT-MRAM using GLOBALFOUNDRIES (GFs) 40-nm technology²⁰⁴ and started the production of 1Gb STT-MRAM at the 28-nm node²⁰⁵. TSMC has also developed a 22-nm technology, while Samsung Foundry commercialized in 2019 embedded STT-MRAM macro built upon low-power 28-nm fully depleted silicon-on-insulator (FDSOI) platform²⁰⁶ (see Fig. 4). GFs has also delivered embedded STT-MRAM on its 22-nm FDSOI platform for IoT and automotive applications²⁰⁷. Embedded STT-MRAM is expected to expand in low-power wearable and RF applications, as demonstrated by Intel²⁰⁸.



Box Fig. 1 | Potential markets. MRAM is considered as the only non-volatile memory with high-density, endurance and fast writing speed. Applications can be divided in three different categories: low-bandwidth (BW) non-volatile random access memories (NVRAM), high-BW NVRAM, and NOR Flash replacement. The MRAM memory cell is formed at the back-end-of-line (BEOL) without disturbing pre-established front-end processes (Fig. 1), which simplifies its implementation across multiple technology nodes. SCM stands for storage class memory and AIoT for artificial intelligence of things.

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Author contributions

All authors wrote and commented on the manuscript.

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