2D materials are attractive for nanoelectronics due to their ultimate thickness dimension and unique physical properties. A wide variety of emerging spintronic device concepts will greatly benefit from the use of 2D materials, leading a better way to manipulating spin. In this review, we discuss various 2D materials, including graphene and other inorganic 2D semiconductors, in the context of scientific and technological advances in spintronic devices. Applications of 2D materials in spin logic switches, spin valves, and spin transistors are specifically investigated. We also introduce the spin-orbit and spin-valley coupled properties of 2D materials to explore their potential to address the crucial issues of contemporary electronics. Finally, we highlight major challenges in integrating 2D materials into spintronic devices and provide a future perspective on 2D materials for spin logic devices.

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INTRODUCTION

The unprecedented success of silicon-CMOS technology has been primarily driven by transistor scaling. The early era of Dennard scaling\(^1\) had two important consequences for modern computing systems; speed performance has been improved by scaling of physical dimensions while power density has been kept practically constant by scaling of voltages. However, since around 2005, the voltage scaling has become a challenging task\(^3\) because further reduction of the supply voltage (requiring the threshold voltage to be simultaneously decreased to maintain the capability to drive high current) was leading to an exponential increase in the leakage current. This is due to the fundamental limit of subthreshold swing (SS) greater than 60 mV/decade at room temperature, which arises from the Boltzmann statistics that govern the thermionic operation of conventional MOSFETs.\(^4\) Although tunnel FETs,\(^5\) negative capacitance FETs,\(^6\)\(^9\)\(^10\), and electrostatic FETs\(^11\)\(^12\) have recently emerged as novel device concepts for steep SS, they still require much work to improve the device performance and/or answer fundamental questions on scalability, reliability, and viability. On the other hand, scaling of physical dimensions has still continued until today, towards the technology nodes of 5 nm and beyond\(^13\)\(^14\). This led to an inevitable increase in power density in high-performance microprocessors, thus requiring complex power management techniques\(^15\)\(^16\). In view of this, spintronics, which utilizes the quantum mechanical property of elementary particles, called spin, has the potential to become an innovative pathway beyond transistor scaling to satisfying the speed and energy-efficiency needs of the emerging computing paradigm (e.g., neuromorphic\(^17\)\(^18\) or quantum\(^1\)\(^9\)\(^20\) computing).

Spintronics is an emerging form of electronics that harnesses the intrinsic angular momentum (spin) of electrons, leading researchers to treat them as tiny bar magnets with strong magnetic moment (Bohr magneton, \(\mu_B \sim 10^{-23} \text{ Am}^2\)). Immediately after the discovery of giant magnetoresistance (GMR) in 1988 (the GMR ratio of 10–50%, as compared with the anisotropic MR effect of at most a few percent at that time)\(^19\)\(^22\), which has been the foundation for constructing the hard-drive read head, research on nanomagnetism and spintronics has made remarkable strides over the last few decades. In 1991, the oscillatory behavior of the interlayer exchange coupling was formulated in terms of the Fermi surface of the spacer material\(^3\)\(^24\), leading a way to constructing a synthetic magnetic free layer in the modern magnetic tunnel junction (MTJ) device\(^25\)\(^26\). The concept of “spin valve” ignited numerous research efforts exploring the ferromagnetic sandwiches spaced by a nonmagnetic metallic layer\(^27\)\(^28\), logical “1” or the high-resistance state is represented by the antiparallel configuration of two ferromagnetic layers while logical “0” or the low-resistance state is dictated by the parallel configuration. This is an important milestone in spintronics because spin valve currently serves as the most fundamental building block for advanced spintronic devices. In 1995, insertion of a thin insulator as the spacer layer (i.e., as the tunnel barrier) resulted in a much higher read-out signal through the effect of TMR (tunneling magnetoresistance)\(^29\), which continued to be further optimized to reach 604% at room temperature in 2008\(^30\). Combined with the write mechanism of spin-transfer-torque (STT), theoretically predicted in 1996\(^31\)\(^32\) and observed in the experiments of switching the magnetization direction\(^33\) and inducing domain-wall motion\(^34\) or high-frequency oscillation\(^35\), both the spin valve and MTJ structures (especially, MTJs employing the crystalline MgO tunnel barrier\(^36\)\(^37\)) have gained great attention in the field. The recent discovery of the perpendicular magnetic anisotropy (PMA) in various heterostructure thin films and interfaces offered a new opportunity for low-power data storage applications\(^38\)\(^39\)\(^40\). The reviving interest in the Hall effect\(^41\) will link the spin Hall effect (SHE) with measurable quantities such as spin accumulation, aiming at driving magnetization dynamics more efficiently for the development of energy-efficient spintronic devices.

The ability of spintronics to perform previously impossible experiments and test fundamental theories of magnetism has recently been made possible through the use of 2D materials. Layered materials have, indeed, existed for eons (i.e., studied scientifically for more than 150 years\(^42\)). However, only recently have researchers begun to realize the true potential of these layered materials for advanced technological applications. Each layered material, when thinned down to its physical limits, exhibits novel properties different from its bulk counterpart. Therefore, these materials are specifically referred to as “2D materials”. The most widely studied 2D material is graphene\(^43\), which is an atomically-thin sheet of carbon atoms with a bonding length of 1.42 Å. Pristine graphene behaves as a zero-bandgap semimetal,

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constituting an important class of carbon allotropes exhibiting unique 2D hexagonal structures. Readers interested in recent advances and a broad range of commercial applications of graphene will find the 2019 review article by Kong et al., an excellent resource. A wide spectrum of other 2D inorganic materials is also experiencing numerous research efforts owing to their versatile crystal structures and physical properties, including insulators (e.g., hexagonal boron nitride, h-BN), semiconductors (e.g., transition metal dichalcogenides such as MoS$_2$), superconductors (e.g., NbSe$_2$), and even magnets (e.g., CrI$_3$).

This review discusses 2D materials in the context of spintronic device technologies, focusing on their progress, prospects, and challenges. We examine how 2D materials can be interfaced with other classes of materials, including ferromagnets (FMs), to enable, develop, and advance spintronic devices. Spin-dependent properties of 2D materials are also highlighted in terms of spin-orbit and spin-valley couplings. Major challenges and future perspectives for the development of spintronic devices using 2D materials are finally discussed.

**GRAPHENE FOR SPIN LOGIC**

Among various device concepts for beyond-CMOS logic switches, spin-based, non-volatile digital logic (Fig. 1a) has attained much attention because it offers the functionality at lower power consumption by building logic units with magnetic elements. In particular, the proposal of all-spin logic (ASL) switch has been considered to be quite attractive for a future computing paradigm due to its potential for extremely low-power consumption. This is because, in the ASL, nonlocal spin currents are used to selectively route communication signals between the input and output magnets without spin-to-charge conversion (Fig. 1b). However, a major challenge has been to develop a suitable spin transport channel material that simultaneously achieves a high spin injection efficiency (from FM to the channel material) and a long-distance spin propagation (within the channel material).

Graphene, a hexagonal 2D arrangement of sp2-bonded carbon atoms, may be uniquely suited for this purpose due to its (1) relatively long spin diffusion length and lifetime (theoretically predicted, and experimentally being examined) and (2) ability to be readily interfaced with other classes of materials, including FMs.

Spin injection, transport, and relaxation in graphene

Graphene exhibits properties attractive for spintronic device applications. It has intrinsically low spin-orbit coupling (SOC); at the f point, the spin-orbit splitting of the d band is calculated to be as low as 8.8 meV. This can lead to spin coherence maintained over the long distance. Graphene also features ultra-high carrier mobility of reaching up to more than 200,000 cm$^2$ V$^{-1}$ s$^{-1}$ in a suspended device structure, which can enhance the diffusive transport of spin. Advances in spin injection into graphene, experimental determination of spin transport properties of graphene, and understanding of the spin relaxation mechanism in graphene will ultimately contribute to the development of the spin logic device adopting graphene as a spin transport channel.

Nonlocal spin valve (NLSV)

The NLSV is the most commonly used device geometry for generating pure spin currents. When the spin-polarized current is injected from a FM contact into a channel material, the accumulated spin in the vicinity of the FM/channel interface can diffuse laterally, thus forming a pure spin current. This nonlocal spin current constitutes a key part of the ASL switch, enabling the input logic bit to control the state of the corresponding output through the spin-torque mechanism. Moreover, the spin-dependent properties of graphene have been quantitatively understood by measuring the NLSV built upon graphene, consisting of two FM (one as a spin injector and the other as a spin detector) and two corresponding nonmagnetic (NM) metallic contact electrodes integrated on top of the graphene spin transport channel (Fig. 2a). In this graphene-based NLSV structure, sweeping the in-plane magnetic field ($H_x$) allows both parallel and antiparallel configurations of two FM electrodes with different shape anisotropy, thus resulting in the nonlocal spin signal, $\Delta R_{NL} = \Delta V_{NL}/I$ (Fig. 2b). $\Delta V_{NL}$ is the nonlocal voltage difference between parallel and antiparallel states of two FM measured at the FM detector side ($\Delta V_{NL} = V_{NL}^P - V_{NL}^A$) and I is the injection current through the FM injector. This four-terminal measurement geometry is called nonlocal because the voltage is measured “outside” the (charge) current loop. One key advantage of this NLSV geometry is that background noise signals from charge currents are greatly reduced due to the absence of net charge flow. Importantly, the nonlocal spin signal will only be dependent on the relative orientation of the FM detector’s spin with respect to those accumulated at the FM injector. Thus, it is possible that $\Delta R_{NL}$ is measured by varying the injector and detector separation ($L$) because the magnitude of spin accumulation will decay as it diffuses away from the injection point, with a characteristic length known as spin diffusion length ($L_D$). This is described by the

**Fig. 1. Spin logic devices.** a) Reconfigurable spintronic logic gate, showing a NAND operation between X and Y. A and B are chosen to be “1” for NAND, but one may adjust the magnetization alignments of A and B to set different logic operations. The output is given by a transient current response, $I_{out}(t)$, whose amplitude is proportional to the spin accumulation in the semiconductor. A transient current is allowed to pass through the probing contact (M) during the magnetization rotation, where the potential level inside M is perturbed and the capacitor (C$_M$) tries to restore the new steady-state condition ($I_{out} = 0$). In order to write the magnetization directions of the contacts in cascaded logic gates, $I_{out}(t)$ needs to be converted to a binary voltage signal. $V_{dd}$ is the supply voltage. b) All-spin logic (ASL) switch, where nonlocal pure spin currents transport information between nanomagnets (i.e., digital spin capacitors). The state of the output magnet is determined by two spin torques with the information provided from the input magnet: one relatively large torque is exerted by the application of $V_{supply}$ and the other small torque is exerted by the application of $V_{bias}$ (for “receive” and “send” respectively, in the cascaded logic gates). 1: magnetic free layer, 2: isolation layer (electrostatic barriers or insulation layers), 3: tunneling layer (oxides or Schottky barriers), 4: spin-coherent channel, 5: contact, 6: spacer layer, and 7: magnetic fixed layer. Image of a reprinted by permission from Springer Nature: ref. 52, Copyright 2007. Image of b reprinted by permission from Springer Nature: ref. 51, Copyright 2010.
In this equation, \( \sigma \) is the conductivity, \( W \) is the width of the graphene channel, and \( L \) is the contact spacing. \( \eta \) is the spin injection efficiency, often represented by the spin polarization of the injection of the parallel (antiparallel) state, \( \eta_{\text{majority}} \) (\( \eta_{\text{minority}} \)), where majority (minority) means the spin direction parallel (antiparallel) to that of the FM injector. Fundamentally, \( \eta \) is directly related to the spin polarization of the FM contact electrode \( \langle \text{DOS}_{\text{majority}} - \text{DOS}_{\text{minority}} \rangle \), where DOS is the density of states at the Fermi level, modulated by any presence of spin-flip scattering at the FM/channel interface. It is noted that above definitions, including Eq. 1 and spin polarization of FM electrodes, are only valid for the case of tunnel barrier contacts.

The graphene-based NLSV also enables a precise characterization of spin precession signals in graphene by applying an out-of-plane magnetic field and then measuring the nonlocal resistance (\( R_{\text{NL}} \)) as a function of the magnetic field strength (the Hanle effect) (Fig. 2c). Many experimental studies on the spin transport properties of graphene have been performed by conducting the Hanle measurement in the nonlocal geometry because the Hanle spin precession curve is a strong indicator of pure spin currents in graphene. The Hanle measurement offers a more reliable way to study spin transport in graphene because the approach based on Eq. 1 requires the NLSV device structure to be repeatedly fabricated for varying the separation distance, often encounters a significant challenge in reproducing the same FM/graphene tunnel contacts. The spin lifetime (\( \tau_s \)) and the spin diffusion constant (\( D_s \)) can be extracted as fitting parameters to the following equation (Eq. 2)\(^{61,72,74} \):

\[
R_{\text{NL}} \propto \pm \int_0^\infty \frac{1}{\sqrt{4\pi D_s t}} \exp\left(-\frac{L^2}{4D_s t}\right) \cos(\omega t) \exp\left(-\frac{t}{\tau_s}\right) dt
\]

(2)

Here, the \( + (-) \) sign is for the parallel (antiparallel) magnetization state, and \( \omega \) is given by \( g\mu_B B / h \), where \( g \) is the Landé factor \( (g = 2.0023) \) and \( h \) is the reduced Planck’s constant. Once \( \tau_s \) and \( D_s \) are determined from the Hanle measurement and analysis, the corresponding spin diffusion length \( (L_d) \) can be calculated by \( L_d = (D_s \tau_s)^{1/2} \).

Spin injection into graphene

The difficulty in utilizing the conventional semiconductor materials (e.g., silicon) for emerging spin logic applications arises from the facts that (1) their spin transport properties tend to degrade with the decreasing film thickness (i.e., poor scalability)\(^{75} \), and (2) the spin injection from a FM metal contact into a semiconducting channel material has been a great challenge due to a fundamental conductivity (or mode) mismatch problem\(^{76} \). Noticeably, a recent experimental study has reported that graphene can transport spin signals over a relatively long distance of up to 30.5 \( \mu \text{m} \)\(^{77} \) (this distance can be increased even up to 90 \( \mu \text{m} \) using carrier drift\(^{78} \)). If spin injection from the FM electrode into the graphene channel can be made with a high injection efficiency, the use of graphene as a spin transport channel may be considered as a practically viable route for the development of emerging spin logic devices.

Since the first demonstration of spin transport in graphene at room temperature in 2007\(^{79} \), spin injection efficiency into graphene has been continuously improved. Inserting a thin tunnel barrier (TB) at the FM/graphene interface has been widely utilized to mitigate the conductivity mismatch problem and, thus, increase the spin injection efficiency into the graphene layer. Injection efficiencies of up to \( \sim 30\% \) have been experimentally demonstrated using a variety of TB materials such as TiO\(_2\)^{79,80}, MgO\(^{81} \), TiO\(_2\)-seeded MgO\(^{82,83} \), h-BN\(^{84} \), and Al\(_2\)O\(_3\)^{85–87} (Table 1). More recently, even the fluorinated graphene was used as a homoepitaxial TB material to the graphene channel, achieving the tunneling spin polarization of up to \( 60\% \)\(^{88} \). It is worth, however, noting that these TB-based approaches may still experience the...
Spin transport parameters of graphene (L_D, τ_D, D_S) are experimentally measured at room temperature by using the four-terminal NLSV device geometry. Most works directly measure two of these parameters via the Hanle effect^{61,72} and then calculate the other parameter based on the fundamental relation of L_D = (τ_D D_S)^{1/2}. Spin injection efficiency (η) is typically estimated by the spin polarization of the tunneling current (Eq. 1). FM/TB indicates the type of ferromagnetic (FM) contact and tunnel barrier (TB) materials. Prep. method lists how each work prepares the tunnel barrier (TB) and graphene (Gr.) channel materials. Most works used the mechanical exfoliation technique to integrate graphene into the NLSV device. The substrate type (Sub.) is also shown for each work, implying that the use of h-BN tends to enhance spin transport characteristics due to increase in graphene mobility. 

Enhancing the spin injection efficiency is very important from the power perspective; the lower spin injection efficiency means that more charge currents would be pumped into the graphene channel to form a sufficiently large spin accumulation that can switch the corresponding output magn. Most experimental studies have used Eq. 1 to estimate the spin injection efficiency parameter (η) by performing the NLSV experiment. A fundamental limitation of this approach is that the measurement accuracy of η will strongly depend on measurements of other parameters in the equation. Most notably, the spin diffusion length (L_D) of graphene seems to largely vary among different studies (Table 1). Without any further optimization or new development of the graphene integration process (otherwise, the device integration process may not be further optimized or new development of the graphene transport channel. Spin transport and relaxation in graphene Table 1 summarizes the experimental measurements of graphene's spin transport properties, with various substrate materials, FM contact electrodes, TBs, and preparation methods. Taking a close look at this table will provide several useful insights into the spin transport phenomena in graphene.

First, as seen in Fig. 3a, the use of h-BN as a substrate for graphene tends to increase the spin diffusion constant (D_S) of graphene, thus enhancing the long-distance propagation of spin signals in the graphene channel layer^{77,92,93}. This is due to the high carrier mobility in graphene, having h-BN as the substrate; experiments have already shown that the measured Hall mobilities of graphene devices fabricated on the h-BN substrates are even comparable to the best-reported values of the suspended graphene devices^{68}. By the Einstein relation, the high carrier mobility leads to a high diffusion constant for charge carriers. Consequently, the diffusion constant increases for spin because spin current is carried by charged particles in the NLSV. The graphene/h-BN or other 2D van der Waals (vdW) heterostructures^{95–97} may be considered as the high-performance spin transport channel.

The phenomenon of spin relaxation in graphene can be understood by examining Table 1 on how the spin transport parameters change with other independent variables. For example, investigation of a possible relation between spin lifetime (τ_S) and charge carrier mobility (µ) has been a topic of great scientific interest because it would help reveal the relevant spin scattering mechanism. A linear dependence of τ_S on µ is suggestive of the Elliott–Yafet (E–Y) spin scattering mechanism^{68}, while the inverse relation (τ_S ~ 1/µ) indicates the dominance of the Dyakonov–Perel (D–P) mechanism^{69}. A previous study on spin relaxation in bilayer graphene films on SiO_2^{106} observed a clear inverse dependence of τ_S on µ, suggesting the D–P model as a dominant mechanism that correlates the spin and charge transports; spin phases are randomized between collisions as electrons precess with different frequencies depending on their momenta. However, as summarized in Table 1, it is possible that both the E–Y. and D–P. mechanisms are simultaneously relevant^{80,92}, or the E–Y. scattering, where the precession frequency is conserved between collisions and the phase loss occurs only in the short time during collision, becomes a major causative factor for spin relaxation in graphene^{82}. 

### Table 1. Summary of spin injection and transport properties of graphene.

| FM/TB      | Sub. | Prep. method | L_D (µm) | τ_D (ns) | D_S (m²/s) | Gr.       | I.  | Graphene mobility (cm²/Vs) | Spin transport Parameters | Mecha.  | Ref. |
|------------|------|--------------|----------|----------|------------|-----------|-----|--------------------------|--------------------------|---------|------|
| Co/TiO_2   |       | Exfoliation | 0.4 nm Ti, oxidation | N      | 40,000    | 4.5       | 0.39 | 0.052         | EY + DP                  |         | 79  |
|            |       | Exfoliation | 0.5 nm Ti, oxidation | N      | 2,500     | 0.75      | 0.075| 0.0075       | –                        |         | 79  |
|            |       | Exfoliation | 0.4 nm Ti, oxidation | CVD    | SIO_2     | 2,000     | 6    | 1.2 0.026  | EY + DP                  |         | 80  |
| Co/MgO     |       | Exfoliation | 1 nm MgO MBE | Y      | 20,000    | 10        | 2    | 0.05        | –                        |         | 93  |
|            |       | Exfoliation | 1.2 nm MgO MBE | Y      | 20,000    | 30.5      | 12.6 | 0.074       | –                        |         | 77  |
|            |       | Exfoliation | <3 nm MgO MBE | N      | 3,000     | 0.7       | 0.135| 0.0032      | DP                      |         | 100 |
|            |       | Exfoliation | 0.8 nm MgO MBE | Y      | 2,000     | 2.4       | 0.447| 0.013       | EY                      |         | 83  |
| Co/Al_2O_3 |       | Exfoliation | 0.8 nm MgO MBE | Y      | –         | 3         | 0.495| 0.018       | –                        |         | 82  |
|            |       | Evaporation | 1 nm Al_2O_3 Evaporation | Y      | 100,000   | 2         | 0.2  | 0.02        | DP                      |         | 87  |
|            |       | Exfoliation | 0.6 nm Al, Oxidation | N      | 2,000     | 2         | 0.17 | 0.02       | –                        |         | 71  |
|            |       | Exfoliation | 0.6 nm Al, Oxidation | N      | 3,500     | 2         | 0.145| 0.027       | EY                      |         | 86  |
| Py/Al_2O_3 |       | Exfoliation | ALD at 100 °C | N      | 2,500     | 4.2       | 0.175| 0.1         | –                        |         | 85  |
| Py/h-BN    |       | Exfoliation | 0.34nm h-BN | N      | 2,300     | 1.1       | 0.055| 0.034       | –                        |         | 84  |
| Py/f-Gr.   | 63%  | Fluorinated Gr. (with XeF_2) | CVD      | SIO_2   | N         | 1.5      | 0.2  | 0.012       | –                        |         | 88  |
Another piece of information available from Table 1 is that $\tau_s$ and $L_D$ values largely vary among different studies using the same TB material. This indicates that the microscopic origin for such a large discrepancy among various studies on spin transport in graphene could be best understood by examining the experimental details and setups of each study. One important conclusion from such deep analyses is that some special treatment of the graphene interface has resulted in significant improvement of the spin transport characteristics in graphene (Fig. 3b). For example, the thermal annealing technique ($@ 400 ^\circ C$ in Ar/H$_2$) that has been applied after transferring the CVD graphene on SiO$_2$ substrate$^{71,79,81}$, and angle evaporation of the tunnel barrier oxides on the graphene surface$^{82}$. Besides the recent discovery of 2D magnets$^{69}$, the graphene itself has experienced significant research efforts to induce magnetic moments by extrinsic factors. Introducing light adatoms (point defects) such as hydrogen (H)$^{109,110}$ or fluorine (F)$^{111,112}$ has been the most popular approach to inducing localized magnetic moments in graphene. This is possible because the hydrogen or fluorine can be reversibly chemisorbed on graphene$^{113,114}$, thus creating a sublattice imbalance by removing one $p_z$ orbital from the $\pi$ band. According to the Lieb's theorem$^{115}$, the single hydrogen adatom can induce a quasi-localized state in graphene with magnetic moment of 1$\mu_B$. A recent theoretical study even predicted that graphene in the form of quantum dots (e.g., zigzag graphene nanoflakes) can exhibit strong edge magnetism at room temperature due to the presence of localized edge states$^{116}$. Despite the fact that magnetic moments in graphene have been experimentally observed by adopting the various techniques of SQUID (superconducting quantum interference device, using the Josephson junction to characterize the dependence of supercurrents on magnetic fields)$^{111}$, MFM (magnetic force microscopy)$^{117}$, and nonlocal$^{113}$ or local$^{112}$ spin transport measurements, making graphene permanently magnetic (beyond just inducing the localized magnetic moments) still remains a great challenge.

**2D MATERIALS FOR MTJ AND TRANSISTORS**

This section reviews recent experimental efforts to integrate 2D materials in other equally-important classes of spintronic devices—namely, MTJs and spin transistors. Owing to the unique ability of 2D materials to gain the highly homogenous atomic control over their thickness, researchers began to consider them as a critical element for these emerging spintronic devices. Many perspectives are being opened up in exploring the vast amount of 2D material family and their heterostructures, aiming to achieve specific spin device properties.

MTJs

The MTJ is a modern spintronic device that can be used for processing the bit information stored in the nanomagnet$^{29}$. 

Inducing magnetic moments in graphene

Fundamentally, pristine graphene is strongly diamagnetic as it does not consist of $d$ or $f$ electrons. However, any possibility of inducing magnetic moments in graphene has been the great scientific and technological interest in the field. In particular, from the perspective of advancing the spin logic device, the existence of atomically-thin permanent magnets would mean that conventional FM thin films can be replaced by a highly scalable, novel spin injector (or detector) material. This is important because conventional FM thin films with thicknesses of less than 200 nm typically experience noticeable changes in their magnetic properties such as magnetic anisotropy$^{107}$. It is also known that for the magnetic thin films even in the monolayer or few-layer range, the magnetic ordering (Curie) temperature is strongly affected by a variety of topological effects such as vacancies, substrate roughness and atomic intermixing, and incomplete crystal structures$^{108}$.

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The active area of MTJ typically consists of two FM electrodes with a thin insulating barrier sandwiched between them. The spacer layer is extremely thin (e.g., MgO in the nanometer or sub-nanometer range), leading electrons to tunnel through it. The MTJ has enabled the development of STT-MRAM (spin-transfer-torque magnetic random-access memory) for high-performance data storage and computing applications, where spin-polarized currents exert a STT to change the magnetization direction of a nanomagnet. With its close-to-market position towards commercialization (e.g., in 2019, Everspin announced the sampling of 1 Gb STT-MRAM chips), STT-MRAM now becomes the most promising candidate to replace SRAM to bring the emerging paradigm of non-volatile embedded memory. However, further improvement of device performances and bit-cell scaling are still the great challenges due to issues related to controlling the TB and interfaces, the thermal stability, and the robustness. In this context, 2D materials possess the potential to address some or all of these issues because they offer a precise control of the ultimate thickness while still affording sharp interfaces with other classes of materials. This will allow 2D materials to serve as an atomically-thin spacer layer in MTJ.

Graphene as a tunnel barrier
An early theoretical study on the FM/graphene interface triggered research on harnessing graphene as an atomically-thin spacer layer in MTJ. This was driven by the facts that (1) the in-plane lattice constant of graphene (2.46 Å) matches almost perfectly that of (111) Co or Ni (the lattice mismatch between them is only less than 1.3%), and (2) their electronic band structures in the reciprocal space overlap at the Fermi level only for one spin direction (spin filtering). Indeed, the theoretically predicted TMR ratio of the FM/graphene/FM stack was as high as about 100% owing to the perfect spin filtering effect assumed for the FM/graphene interface. Although Mohiuddin et al. demonstrated the first experimental work, adopting the exfoliated monolayer graphene in a Permalloy (NiFe)-based MTJ structure, the reported TMR ratio was only 0.4%. Many other follow-up studies on the similar device stack, either using monolayer, bilayer, or few-layer graphene or other 2D materials (e.g., MoS2, WS2, h-BN), also produced the TMR ratios of less than a few percent. For example, Fig. 4a shows the magnetic hysteresis with TMR of about 2% measured with the Co/graphene/NiFe structure. This is mainly due to the integration difficulties in inserting 2D materials between oxidation-prone FM metals; unlike the conventional in situ physical vapor deposition (PVD) process that fabricates the whole MTJ stack without breaking the vacuum, most of these previous works on FM/2D material/FM made the bottom FM electrode exposed to air during the exfoliation or transfer of 2D materials.
method, and the use of FM oxides. An example of the first category was to insert a thin noble metallic layer (e.g., Au) at the FM/graphene interface, as shown in the early work of fabricating the NiFe/graphene/Au/NiFe stack (from top to bottom) with the graphene flakes exfoliated onto the Au-coated NiFe electrode. The flip-transfer method employed more complicated process steps of exfoliating graphene on the substrate coated by the LOR (lift-off resist)/PSS (poly (4-styrenesulfonic acid)) bi-layer, depositing the patterned NiFe electrode, separating the NiFe/graphene/LOR stack from the substrate by dissolving the PSS layer in water, and flipping it onto another SiO2/Si substrate. However, in both the first and second approaches, the obtained TMR ratios were still limited to only about 5%. This was attributed to reduced spin polarization due to the inserted 2 nm-thick Au layer and the antiferromagnetic coupling between FM electrodes, respectively. In 2014, Li et al. used a FM half-metal oxide layer of LaSrMnO3 (LSMO) to replace one of the conventional FM metal electrodes, leading to the MTJ stack of Co/graphene/LSMO. Although LSMO is known to exhibit a very high spin polarization (about 95%), this third approach also produced negligibly small enhancement in the TMR ratio, due to contamination of the LSMO interface during the graphene transfer process.

Other 2D materials as a tunnel barrier h-BN, a wide-bandgap 2D dielectric, can possibly better serve as a TB in MTJ due to its intrinsic insulating nature (bandgap energy, E_g ~ 6 eV). Several recent works studied the FM/h-BN/FM structures with h-BN thin films prepared by wet-transfer or direct CVD growth onto the FM electrode, yielding the TMR ratios of up to 6% (Fig. 4b). The MBE (molecular beam epitaxy) technique also enabled the direct growth of h-BN onto the FM layer, thus providing an alternative pathway to better tailoring the FM/2D material interface and ultimately creating the MTJ structure having the atomically-thin, robust TB. Despite these promising early results on the direct growth of h-BN on FM, it is noted that both CVD and MBE growth of monolayer or few-layer h-BN crystals would require in-depth investigation of the parameter space for the specific FM substrate. For example, whereas graphene has already been routinely synthesized by CVD on FM catalysts such as polycrystalline Nickel (Ni), the CVD parameter space has only recently been carefully tuned (e.g., lowering the temperature down to about 450 °C) to ensure the monolayer growth of graphene on Ni.

In 2015, Wang et al. introduced the CVD-grown monolayer TMD (MoS2) in MTJ (Fig. 4c), by using the Au-coated NiFe electrode to minimize the same oxidation issue already encountered with graphene and h-BN. In this work, the insertion of Au still led to degradation of spin polarization in MTJ, thus producing only a marginal increase in the TMR ratio (from 0.4% to 0.7%). The technique of using the FM oxides was also employed to integrate MoS2 with Fe3O4 electrodes, but the spin signal still remained far from expectations (TMR ~0.2%). A more recent study demonstrating the MTJ device with exfoliated WS2 flakes (Fig. 4c) also resulted in a poor TMR ratio of 0.47% due to the oxidation of the bottom FM electrode. Collectively, the use of TMD materials in MTJ seems still at early stage as compared with graphene and h-BN, requiring more advanced studies in optimizing the MTJ integration process with TMD materials.

Spin transistors Most spintronic devices discussed so far are passive in the sense that they are not capable of amplifying an electrical signal. An active spintronic device, if successfully implemented, can find it useful in signal processing, logic circuits, etc. A transistor is the three-terminal (neglecting the body effect) active device where the electrical current flow between two terminals is modulated by a voltage (or a current) applied to the third terminal. Inspired by the seminal proposal of the Datta and Das spin modulator, many studies have been devoted to electrical control of the spin current, which is key to implementing an emerging device concept of spin transistor. In spin transistor, owing to the Rashba spin-orbit interaction (i.e., generation of an effective magnetic field by an electric field applied to the gate terminal), the spin injected from the source FM contact travels towards the drain FM contact via Larmor precession. Typically, spin transistor is normally ON (i.e., depletion mode) because no precession at zero gate voltage leads to the spin direction parallel to the drain FM. Varying the gate voltage can then alter the spin precession angle to result in a periodic modulation of the source-to-drain current. Although spin transistor promises performances of higher speed and energy-efficiency than conventional transistors, finding the optimal device structure employing the best-suited materials for each element still requires extensive research efforts. This may open up new opportunities for 2D materials and vdW heterostructures due to their versatile crystal structures and functionalities.

TMD/graphene heterostructures as a spin channel Yan et al. investigated the vdW heterostructure of graphene/MoS2 as a novel spin transport channel. This study aimed to synergistically combine the unique spin-related properties of graphene and TMD; graphene allows a long-distance spin transport due to its low SOC, originating from the d-orbitals of the heavy metal (the spin-orbit splitting is 148 meV in monolayer MoS2), while TMD/graphene heterostructures with h-BN, MoS2/graphene and TMD; graphene allows a long-distance spin transport mechanism in such a vdW heterostructure. The great tunability of spin current was rather attributed to the gate tuning of the Schottky barrier at the MoS2/graphene interface, leading to the modulation of MoS2’s conductivity. For example, at high gate voltages applied, the reduced Schottky barrier and MoS2’s conductivity allowed spin to tunnel into MoS2, making it dephasing due to the high SOC of the MoS2 channel. It is also important to note that graphene, when interfaced with TMD, exhibits a unique spin lifetime anisotropy (SLA) effect. The SLA, defined as the ratio of lifetimes for spins pointing out of the graphene plane to those pointing in the plane, was theoretically predicted to reach values of tens to hundreds in the TMD/graphene heterostructures. This phenomenon was experimentally demonstrated in MoSe2/graphene and WS2 (or MoS2)/graphene heterostructures, showing an order of magnitude longer lifetime for out-of-plane spins (i.e., SLA ~10).

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while serving as direct evidence of strong spin-valley coupling in the TMD material (this topic will be revisited in a later section), may provide an alternative route for manipulating spin relaxation in 2D material-based spintronic devices.

**2D magnets to realize a spin tunnel transistor**

A very recent effort to enable spin transistor by 2D materials led to the development of a novel form of spin transistor—namely, spin tunnel field-effect transistor (spin TFET)\(^{146}\). In contrast to the originally proposed (Datta and Das) spin transistor concept, relying on the electrical control of spin current in the high SOC channel material, spin TFET is constructed by incorporating the emerging 2D magnetic crystal as the magnetic TB (Fig. 5b). Among many 2D magnetic materials recently discovered\(^{49,147}\), bilayer CrI\(_3\) is a perpendicularly FM, whereas monolayer CrI\(_3\) is an antiferromag-}

**Fig. 5 2D materials for spin transistor.** a The device schematic of MoS\(_2\)/graphene heterostructure-based spin transistor (left) and measured nonlocal resistances (R\(_{nl}\)) with a wide range of gate voltage biases (V\(_g\)) applied (right)\(^{15}\). For the nonlocal measurement, a DC current of 10 \(\mu\)A is injected into graphene from the Co/TiO\(_2\) tunnel contact electrode. The measured nonlocal voltage (V\(_{nl}\)) (and thus, resistance R\(_{nl} = V_{nl}/I\)) varies with V\(_g\) due to the spin current (flowing in graphene) modulation by the MoS\(_2\) spin absorber (sink). b The spin tunnel FET (spin TFET) concept is proposed as an alternative way to implement spin transistor (left)\(^{146}\). Instead of controlling the spin current in the spin transport channel, the spin TFET harnesses electrical switching of the magnetization configuration (in much the same way as MTJ) to create the transistor output. The recently discovered 2D magnet, bilayer CrI\(_3\), is used as the active switching medium due to its spin-flip transition behavior. The fabricated device offers a large ON/OFF ratio approaching 400% (right). Image of a was reprinted from Springer Nature with permission under a CC-BY 4.0\(^{139}\). Image of b reprinted by permission from Springer Nature: ref.\(^{146}\), Copyright 2019.

**Spin-orbit coupling in 2D materials**

Spin-orbit coupling (SOC) refers to the relativistic phenomenon of exerting a torque on the elementary particle with spin, approaching the nearby atom to “feel” the orbital motion. SOC is responsible for many inspiring physical properties of 2D materials, including the room temperature quantum Hall effect (quantization of Hall resistance under a large magnetic field) observed in monolayer graphene\(^{157,158}\). From the technological point of view, SOC is of great importance because it provides an effective means of generating a pure spin current even in nonmagnetic materials via the SHE (spin accumulation with no Hall voltage)\(^{159}\). Indeed, the room temperature SHE was recently observed in the graphene/MoS\(_2\) vdW heterostructure (Fig. 6a)\(^{160}\), which is best attributed to the valley- Zeeman type of SOC imprinted from TMD to graphene (i.e., the proximity-induced enhancement of SOC in graphene due to a weak hybridization with the heavy atoms in TMD)\(^{161}\). The charge-to-spin conversion can also occur in the graphene/TMD heterostructure via the Rashba-Edelstein effect (due to the broken out-of-plane symmetry)\(^{162}\), which was recently demonstrated with graphene in conjunction with the monolayer WS\(_2\)\(^{163}\). The SOC-induced pure spin current is currently being widely researched in the field, for the purpose of developing the advanced spin-orbit torque (SOT) devices such as SOT-MRAM\(^{164}\) and SHO (spin Hall oscillator)\(^{165}\). Most early experimental studies on these devices interfaced FM with a heavy metal of large SOC (e.g., Ta, Pt) to effectively induce magnetization switching or oscillation. However, the state-of-the-art SHA (spin Hall angle, \(\theta_{SH}\), an important metric for charge current-to-spin current conversion efficiency) of heavy metals is limited to \(\theta_{SH}\) of less than 0.1, with greatly varying values among different studies\(^{166}\). This imposes a significant challenge in developing energy-efficient, high-performance spintronic devices because the large SHA value means that a large amount of charge currents will still need to be supplied. This may offset the benefits of using spin for electronics. With the giant SOC-induced spin splitting already reported for
TMD (as shown in Fig. 6b, the maximal spin splitting of the uppermost valence band at the K point is as high as 456 meV for WS2 monolayer) and the relatively high SHA measured for TMD (θSH ~ 0.14 for MoS2) and topological insulator (TI) (θSH of up to 425 for (Bi0.5Sb0.5)2Te3 at 1.9 K), further research like the recent work on the FM/Ti heterostructure (see Fig. 6c for the SOC-induced magnetization switching observed in Bi2Se3 films) can be committed to design, fabricate, and understand the ultralow-power SOT devices enabled by 2D materials. A very recent experimental work on the SOC enhancement in graphene by the proximity effect of WS2 also provided the great promise for practical device applications due to the electric-field tunability demonstrated.

It is highlighted that with semi-metallic TMD materials with reduced crystalline symmetry (e.g., WTe2), an out-of-plane SOT can be generated to possibly induce magnetization reversal for adjacent magnetic thin films with PMA. The out-of-plane SOT that exists exclusively for currents applied along a low-symmetry axis has already been demonstrated for the (mechanically exfoliated) WTe2/Permalloy bi-layer structure. This could provide great potential for the SOT device design in terms of directions of charge current injection and spin current detection (unlike the conventional settings of the heavy-metal/FM or high-symmetry TMD/FM structures where the component of spin torque is required to lie within the device plane to induce most effectively the anti-damping switching). Indeed, PMA devices can provide great flexibility to the SOT device design in terms of field tunability

Using the valleys in 2D materials

Fundamentally, the phenomenon of spin polarization in conventional FM metals originates from their unique band structure. In the presence of the 3d energy band splitting with respect to the Fermi level (i.e., DOSmajority is mostly filled up being located under the Fermi level while DOSminority is mostly empty being located above the Fermi level), only charge carriers with the majority spin direction can pass through the FM layer because minority spin carriers find enough empty states in FM to scatter into. This separation of charge carriers by spin has been best studied by the anomalous Hall effect (AHE) where the measured Hall voltage

\[ V_H = \frac{\Delta \theta}{2e} \]

is related to the spin splitting \( \Delta \) and the electric field \( E \) through the transverse resistance \( R_{\text{t}} \). The AHE is a robust effect that can be observed in various 2D materials, including graphene, TMDs, and topological insulators. It is a consequence of the spin-orbit coupling (SOC) and the asymmetry of the electronic structure. In a magnetic field, the AHE can be tuned, leading to a large Hall voltage

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is proportional to the FM’s magnetization (c.f., the Hall voltage is proportional to the external magnetic field in the ordinary Hall effect).

Electrons in 2D atomic crystals with a honeycomb lattice structure possess a valley degree of freedom in addition to charge and spin. Like the AHE observed in the FM material, this unique 2D system is predicted to exhibit a similar Hall effect, yet with its sign depending on the valley index. In 2014, Mak et al. reported the observation of so-called valley Hall effect (VHE) in monolayer MoS2 by illuminating the MoS2 transistor with circularly polarized light to preferentially excite electrons into a specific valley (Fig. 6d)\textsuperscript{178}. In this experiment, electrons from different valleys moved in opposite directions across the MoS2 sample, with one valley being overrepresented with respect to the other. Valleytronics is a recent research paradigm that makes use of the valley of electrons; the energy bands of certain crystal lattices have two or more minima (i.e., valleys) at equal energies but at different positions in the momentum space. If the number of electrons in these valleys can be precisely controlled, thus producing so-called, valley polarization, it would be possible to create a novel form of valleytronic devices. In this context, monolayer MoS2 is a promising valleytron material because its conduction and valence-band edges have two energy-degenerate valleys at the corners (K points) of the first Brillouin zone\textsuperscript{175}.

Valley polarization in MoS2

In much the same way that spintronic devices require spin polarization, valley polarization (non-equilibrium charge carrier imbalance between valleys) serves as the essential mechanism to realize the future valleytronic devices. Valley polarization has previously been demonstrated using strain\textsuperscript{176,177} or magnetic fields\textsuperscript{178–180}. However, none of these approaches allowed dynamic control of charge carriers. More importantly, most of these studies relied on a special device geometry such as quantum well (e.g., AlAs-based two-dimensional electron system). In 2012, Cao et al. performed first-principles calculations on monolayer MoS2, suggesting that valley polarization is achievable via valley-selective circular dichroism (the two valleys absorb left- and right-handed photons differently) arising from its unique symmetry\textsuperscript{181}. In monolayer MoS2, each Mo sits in the center of a trigonal prismatic cage formed by six sulfur atoms, thus forming the stable honeycomb lattice structure with the broken inversion symmetry. This is the essential condition for valley-selective circular dichroism (VSCD), which is further enhanced by the strong SOC associated with the transition metal’s d orbitals. Experimental demonstrations of valley polarization in monolayer MoS2 quickly followed up using the optical pumping technique\textsuperscript{182,183}.

More recently, valley polarization was generated in MoS2 by the electrical method, either in a gated bilayer MoS2 transistor structure (the perpendicular gate bias broke the inversion symmetry in bilayer MoS2)\textsuperscript{184} or using a nonlocal Hall bar device geometry with monolayer MoS2\textsuperscript{185}. It is important to note that the inverse valley Hall effect also made it possible to detect valley polarization in MoS2 electrically\textsuperscript{185}. These studies provide researchers with rich insights on generating, controlling, and detecting valley polarization in MoS2, which can ultimately form the basis of developing the future valleytronic devices based on 2D materials.

Spin-valley coupling in TMD

The broken inversion symmetry together with strong SOC directly leads to spin-valley coupled properties (spin and valley indices of charge carriers are coupled) in monolayer MoS2 and other group-VI dichalcogenides\textsuperscript{175}. From the device perspective, this means that monolayer TMD can provide a unique integrated platform to use valley for better manipulating spin. The strong spin-valley coupling in these 2D materials has two specific consequences for device applications. First, spin and valley relaxation are suppressed at the valence-band edges as flipping each index alone is prohibited by the valley-contrast spin splitting (0.1–0.5 eV) caused by inversion symmetry breaking. For spintronic devices requiring a long-range spin transport, this large spin-valley coupling may offer a solid mechanism to enhance the spin propagation by controlling the polarization of valleys in 2D materials. Secondly, the valley-dependent optical selection rule (e.g., VSCD\textsuperscript{181}) also becomes spin-dependent, thus possibly resulting in photon-induced spin and valley Hall effects. This may be used to produce long-lived spin and valley accumulations on monolayer TMD’s boundaries, which is key to the operation of spintronic and valleytronic devices.

CONCLUSIONS

The last few decades of nanomagnetism and spintronics research featured remarkable advances in the development of information storage devices based on multilayers of magnetic metals and insulators. However, high-volume information processing and communication devices, either enabled or assisted by spin, still have a long way to go before commercialization, mainly due to relatively slow progress in semiconductor spintronics (in particular, searching for right materials in right places). Recently, researchers have begun to realize the great potential of 2D materials for advanced spintronic device applications. In this section, several challenges and future perspectives are discussed in terms of material development and device integration for 2D spintronics.

2D magnets

Ferromagnetic order in 2D materials is a coveted property that would allow fundamental studies of spin-dependent properties in low-dimensional nanostructures and further enable novel spintronic device applications. Cr-based vdW crystals such as CrI3 and Cr7Ge3Te16 were reported to be intrinsically ferromagnetic\textsuperscript{98,147}, showing the great promise to build practical spintronic devices through the use of atomically-thin ferromagnetic materials. The discovery of intrinsic ferromagnetism in these layered structures attracted significant attention in the field because making 2D materials magnetic by defect engineering\textsuperscript{109–112} may not be practically applicable (i.e., the induced magnetism is quite weak and lacks robustness). However, the low Curie temperature (\(T_c\)) of these materials (\(T_c\) is about 45 K for monolayer CrI3). For a complete list of \(T_c\) values reported for a variety of 2D magnetic materials, readers find a recent review article\textsuperscript{186} a useful resource) still remained a great challenge in adopting them for practical room-temperature operation of spintronic devices. More recently, room-temperature ferromagnetism was observed in the V2Se2/MoS2 vdW heterostructure\textsuperscript{149}, MnSe2 epitaxial films\textsuperscript{150}, Fe7GeTe9\textsuperscript{151}, and transition metal dihydride (MH2) monolayers\textsuperscript{152}, leading the possible pathway to offer spin-polarized carriers through 2D materials at room temperature. For the purpose of electrical spin injection, 2D magnets with half-metallicity (i.e., acts as a metal in one spin direction and an insulator in the other direction)\textsuperscript{152} may be worth more research efforts because it offers nearly perfect spin polarization, making it possible to achieve a very high spin injection efficiency in spin transistors or logic switches. For metallic spintronic devices such as MTJs, all-2D MTJ structures (the FM electrodes and the TB are all made of 2D materials) may be constructed by combining with the recent progress in integrating 2D materials as the atomically-thin TB\textsuperscript{123}. The device functionality based on 2D magnets already started to be reported, for example, by demonstrating the SOT-induced magnetization switching in Fe7GeTe9\textsuperscript{157}.

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Interfacing 2D materials with FM
Although, in principle, 2D materials are expected to be readily interfaced with other classes of materials, including FMs, largely due to its excellent flexibility and other mechanical properties\(^\text{118}\), one practical challenge is to prevent oxidation or any other surface contamination of the substrate material during the integration process. Recalling that many existing strategies developed for addressing this issue suffered from degradation of spin polarization in the MTJ structure\(^\text{122,125–127,132–134}\), other new approaches may be implemented to better integrate 2D materials with FM thin films. Indeed, researchers have already started growing graphene or h-BN directly on top of the FM catalytic substrate using the carefully-controlled CVD or MBE technique\(^\text{128–131}\) instead of relying on ex-situ processes such as exfoliation or transfer. Direct growth of TMD materials onto FM substrates has not been demonstrated yet. A recently developed intercalation technique of inserting the FM layer (Co) into an already formed graphene/substrate interface may provide another path for creating an excellent FM/graphene interface\(^\text{189}\). However, the impact of these new processes on the specific spintronic device performance still remains unknown, requiring more advanced studies of applying novel integration processes to create and evaluate the 2D spintronic devices.

Implementation of spin logic
Using spin as a state variable in logic devices provides several advantages over conventional charge-based information processing technologies; non-volatility, faster and more energy-efficient data processing, and increased integration densities. Especially, theorists predict that in spin-based computing, if the rate of spin relaxation is maintained much slower than the switching rate, energy dissipation can be even less than the thermal limit ($10^{-21} \text{J/bit}$\(^\text{190}\)). If properly implemented, spintronic computing could better satisfy the rapidly increasing performance needs of emerging abundant-data applications\(^\text{37}\). All-spin logic (ASL)\(^\text{117}\) has been considered as one of the most effective ways to implement spin logic with the highest energy-efficiency because both its internal and terminal quantities are spin, requiring no spin-to-charge conversion. To date, despite its great promise, the experimental demonstration of ASL has not been made yet. As already discussed in this article, 2D materials have the potential to address some of the challenges of ASL, such as developing the long-range, high injection-efficiency spin transport channel material.

The concept of ASL, however, continues to evolve towards other device approaches that are more easily implementable or can better represent the emerging computing paradigm. For example, the charge-coupled spin logic (CSL)\(^\text{18,192}\) uses robust charge currents for long-distance transport as terminal quantities. In the original proposal of CSL, the SHE was suggested as the write mechanism while MTJ served as the read unit. Recently, the CSL device was experimentally implemented based on a vertically-coupled pair of in-plane and PMA nanomagnets, clearly demonstrating its functionality as a logic gate and a true random number generator\(^\text{193}\). More recently, the newer concept of a probabilistic bit (p-bit)\(^\text{18}\) was introduced as an intermediate computing scheme between the conventional bits of digital electronics and the emerging quantum bit (qubit). In the probabilistic spin logic (PSL), low-barrier nanomagnets (i.e., engineered to be purposely unstable) provide a natural physical representation for p-bit, which is the classical entity that fluctuates rapidly between 0 and 1. The PSL may open up new application spaces in an emerging computing hardware domain because of their similarity. For example, the p-bit MTJ, involving the low-barrier nanomagnet as a free layer, can be easily combined with the MOS transistor to create the conventional 1T1R (one transistor-one resistor) circuitry. This could offer an efficient hardware platform to accelerate deep learning computation like the binary stochastic neuron\(^\text{194}\). A new spin logic device concept was also proposed by combining the spin-orbit coupling (for reading) and the magnetoelectric effect (for writing), showing that this magnetoelectric spin-orbit logic exhibits superior energy efficiency than the CMOS technology (by a factor of 10 to 30)\(^\text{195}\). This may benefit greatly from the unique spin properties (large spin Hall angles, long spin lifetime) of 2D materials and their heterostructures\(^\text{196}\). Looking further into how 2D materials can better enable or advance these newer forms of the spin logic device will potentially pave the way for the post-silicon spintronics era.

DATA AVAILABILITY
The authors declare that data supporting the findings of this study are available within the article.

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